

The Thirteenth International Conference on the Physics of Highly Charged Ions



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Book of Abstracts

Edited by

J T Costello, G F Gribakin, M P Scott and E Sokell

HCI 2006

The Thirteenth International Conference on the Physics of Highly Charged Ions

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FOREWORD

This book of abstracts contains the invited review lectures, progress reports and contributed papers of the 13th International Conference on the Physics of Highly Charged Ions (HCI2006). The HCI conference series has been held in many countries around the world such as Austria (Vienna 1994), France (Caen 2002), Germany (Giessen 1990, Bensheim 1998), Japan (Omiya 1996), USA (Kansas 1992, Berkeley 2000) with the most recent meeting in Lithuania (Vilnius 2004). The local organising committee of HCI2006 as well as having members from Queen's University Belfast includes colleagues from University College Dublin and Dublin City University.

The topics of the conference include:

- Fundamental aspects, structure and spectroscopy
- Collisions with electrons, ions, atoms and molecules
- Interactions with clusters, surfaces and solids
- Interactions with photons, plasmas and strong field processes
- Production, experimental developments and applications

The programme comprises review lectures, progress reports and contributions selected from the contributed papers with two poster sessions. We particularly welcome the participation of young researchers.

We hope you have a stimulating conference, enjoy your stay in Belfast and have some time to experience the scenic beauty of Northern Ireland.

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Review Lectures

COLLIDING-BEAMS EXPERIMENTS FOR STUDYING FUNDAMENTAL ATOMIC PROCESSES

Ronald Phaneuf

Department of Physics, University of Nevada, Reno, NV 89557-0058, U.S.A.

Following the pioneering experiment of Dolder, Harrison and Smith [1] nearly a half-century ago, experiments based on the colliding-beams technique became a major source of fundamental data on the electronic structure and interactions of ions. The subsequent development of powerful new sources of multiply charged ion beams and large-scale national facilities such as heavy-ion storage rings and synchrotron light sources provided new applications for established techniques, and inspired the development of new interacting-beams methods designed to take advantage of their unique capabilities.

This talk will focus on experimental developments primarily within the last decade involving multiply charged ions using crossed and merged beams. Examples will be selected to highlight such experiments and their impact on our knowledge of the electronic structure of multiply charged ions, as well as their interactions in plasmas. Atomic processes considered will include excitation, ionization, recombination and electron transfer.

Reference

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THE POTENTIAL OF HIGHLY CHARGED IONS: POSSIBLE FUTURE APPLICATIONS

John D. Gillaspay*

National Institute of Standards and Technology, Gaithersburg, MD 20899-8421

Highly charged ions are interesting, but are they really useful for anything? Will they ever have a practical impact on the lives of a large number of ordinary people? After a brief survey of possible applications that have appeared previously in the literature, I will discuss a few new ones, including the modification of materials properties for use in the fabrication of thin film (nanoscale) electronic devices, and the generation of monoenergetic x-rays for use in biomedicine. Some materials modification data from the upgraded NIST Electron Beam Ion Trap Facility will be presented.

*<http://physics.nist.gov/MajResFac/EBIT/gillaspay.html>

X-RAY AND EXTREME ULTRAVIOLET EMISSION FROM COMETS

Carey Lisse

John Hopkins University, Maryland, USA

The discovery of high energy x-ray emission in 1996 from C/1996 B2 (Hyakutake) has created a surprising new class of x-ray emitting objects. The original discovery (Lisse *et al.* 1996) and subsequent detection of x-rays from more than 20 other comets have shown that the very soft ($E < 1$ keV) emission is due to an interaction between the solar wind and the comet's atmosphere, and that x-ray emission is a fundamental property of comets. Theoretical and observational work has demonstrated that charge exchange collisions of highly charged solar wind ions with cometary neutral species is the best explanation for the emission. Now a rapidly changing and expanding field, the study of cometary x-ray emission appears to be able to lead us to a better understanding of a number of physical phenomena: the nature of the cometary coma, other sources of x-ray emission in the solar system, the structure of the solar wind in the heliosphere, and the source of the local soft x-ray background.

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TRAPPED AND COOLED: ATOMIC PHYSICS EXPERIMENTS WITH HIGHLY-CHARGED IONS IN PENNING TRAPS

H.-Jürgen Kluge

GSI/Darmstadt and University of Heidelberg, Germany

Highly-charged ions (HCI) confined in Penning traps have been applied for mass measurements at Seattle and Stockholm, for producing and studying Wigner crystals in Livermore, and at Mainz for determining the g-factor of the bound electron in $^{12}\text{C}^{5+}$ and $^{16}\text{O}^{7+}$ via a measurement of the Larmor and cyclotron frequencies of a single stored ion. Since it was found that the experimental and theoretical g-factor values agree within the uncertainty caused by the knowledge of the mass of the electron, it was possible to extract a new value for the mass of the electron m_e with a four-fold improved accuracy. Storage and cooling of HCI in ion traps are prerequisites for such high-accuracy experiments in which even a single stored particle can be observed. In the case of a radioactive ion, the fate of an individual ion, undergoing a nuclear decay, can be studied in detail by observing the disappearance of the signal of the mother and the appearance of that of the daughter isotope. Since the mass resolving power of Penning trap mass spectrometry increases with the charge state, charge breeding and the use of HCI is planned for quite a number of Penning trap mass spectrometers installed at radioactive beam facilities.

Few-electron ions are simple systems which are calculable by theory with high accuracy. In such systems, the electric field strength increases roughly with the third power of the nuclear charge and reaches values much larger than presently achievable with the most powerful short-pulse lasers. These HCI up to hydrogen-like U^{91+} are testing grounds for QED in the little explored regime of extreme electromagnetic fields. In order to increase the accuracy further for investigating simple systems, the Highly-charged Ion TRAP (HITRAP) facility is presently being built up at GSI. Stable or radioactive HCI are produced by stripping relativistic ions in a target and injecting them into the storage ring ESR at GSI. After electron cooling and deceleration to 4 MeV per nucleon, these ions are ejected out of the storage ring, decelerated further in a linear decelerator, and injected into a Penning trap where a temperature of 4 K is reached by electron and resistive cooling. From here, the cooled HCI are transferred at low energies to experimental set-ups. A large number of unique experiments with very heavy ions up to hydrogen-like U^{91+} are being prepared by the international HITRAP Collaboration:

- Clean samples of stored and cooled HCI in a chosen specific charge state can be investigated by observation of x-rays from a quasi point-like source.
- If the accuracy of QED calculations is further improved, the fine structure constant α can be determined with high accuracy via a measurement of the g-factor of the bound electron.
- Mass measurements can be performed with extreme accuracy of better than 10^{-11} and with single-ion sensitivity by using stored HCI.
- A measurement and comparison of the nuclear g-factor of the bare nucleus with that of the neutral atom allows one to check calculations of the diamagnetic correction for the first time.
- The hyperfine structure of the ground state in hydrogen-like systems can be determined. Optical pumping of the M1 transition will result in electronic and nuclear polarization enabling clean nuclear-decay experiments and, in this way, sensitive tests of weak interaction.
- Recoil ion momentum spectroscopy, ion-surface interaction experiments, and hollow-atom spectroscopy can be performed in a regime of extremely low energies with heavy HCI.

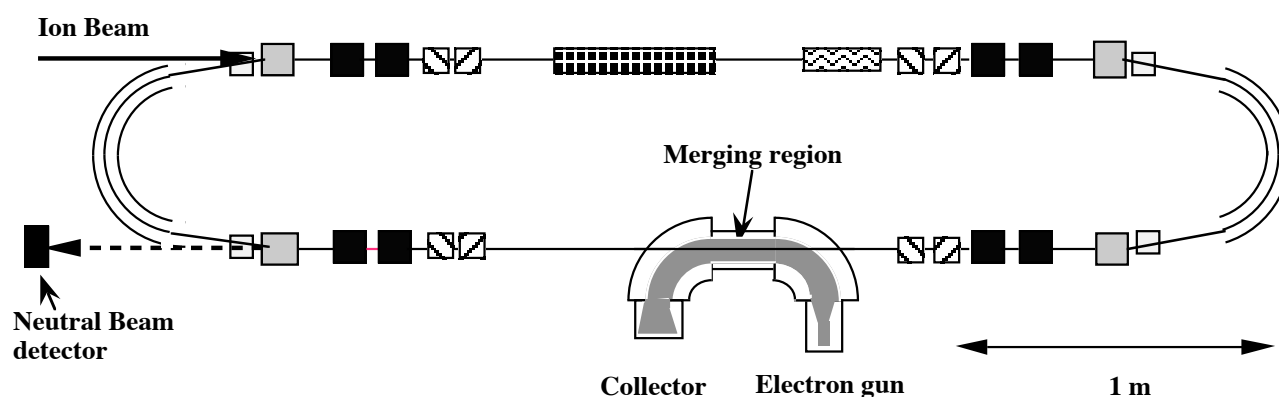
NEUTRAL-PARTICLE EMISSION FROM MULTIPLY CHARGED BIOMOLECULAR IONS IN COLLISIONS WITH ELECTRONS

Tetsumi Tanabe

High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Japan

One of the important features of electrostatic storage rings is that they can store ions independently of their masses. This makes it possible to store biomolecular ions with a variety of masses. In this talk, collisions of biomolecular ions having various masses and charges with electrons are reviewed, which have been studied with an electrostatic storage ring.

The figure represents the experimental setup. Biomolecular ions produced with an electrospray ion source are accumulated in an ion trap and ejected as a bunch after an appropriate storage time. Ions are then accelerated to 20 keV/charge and injected into the electrostatic storage ring [1] after being mass-analyzed. Circulating ions merge with electrons [2] produced outside and injected into the straight section of the ring. Neutral particles emitted in electron-ion collisions are detected with an MCP installed in the vacuum extension.



For singly protonated peptide cations, strong neutral-particle emission at collision energies of around 6.5 eV was found in addition to neutrals from recombination at low energies. The rate of the high-energy peak greatly decreased with a slight decrease in the number of amino-acid residues. These results suggest that some peptide bonds were selectively cleaved [3].

For multiply deprotonated deoxyoligonucleotide anions, the rate of neutral particles emitted in collisions started to increase from definite threshold energies, which increased regularly with the ion charges in steps of about 10 eV. These threshold energies were almost independent of the length and sequence of DNA, but depended strongly on the ion charges. The step of the threshold energy increase approximately agreed with the plasmon excitation energy. It is deduced that plasmon excitation is closely related to the reaction mechanism [4].

For singly protonated deoxyoligonucleotide cations, resonant neutral particle emissions were also observed. The resonance parameters depended on the DNA base composition. The origin of this phenomenon will be analyzed.

References

- [1] T. Tanabe *et al.*, Nucl Instr. and Meth. A 482, 595 (2002).
- [2] T. Tanabe *et al.*, Nucl Instr. and Meth. A 532, 105 (2004).
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- [4] T. Tanabe *et al.*, Phys. Rev. Lett. 93, 043201 (2004).

Crystal assisted experiments with swift highly charged ions

Denis Dauvergne

Institut de Physique Nucléaire de Lyon, IN2P3/CNRS and Université Lyon 1
69622 Villeurbanne cedex, France

A review on recent experiments on the interaction of high-energy, highly-charged ions with ordered matter will be presented.

The anisotropy of the target atoms distribution inside a crystal can lead to a flux redistribution of charged particles. On the one hand, when the incident ion beam is aligned along a crystallographic axis or plane, channelling takes place, i.e. the positively charged projectiles are repelled from the atomic strings and planes. On the other hand, particles scattered or emitted from a crystal lattice site are prevented from escaping the crystal along the crystallographic directions (blocking effect).

Both channelling and blocking can be used as spatial probes for ion-matter interaction at a 10-100 pm scale, which is used in material sciences (defect location, impact parameter dependent energy deposition) or atomic physics (charge exchange at selected impact parameters).

Accordingly, this spatial probe is equivalent to a sub-femtosecond time probe with fast ions, with applications in nuclear sciences (fission time measurements) and atomic physics (superdensity effect for ions in glancing collisions along an atomic string, Resonant Coherent Excitation by the periodic potential of the crystal).

Beam handling with crystals will also be discussed (deflection of charged particles, deceleration of highly charged ions).

This review aims at communicating our interest for the very broad and transdisciplinary field opened by ion-crystal interaction. It will be made accessible for a broad audience of non-specialists recovering from the conference banquet.

ATOMIC COLLISIONS IN TOKAMAK FUSION PLASMAS

HP. Winter

Institut für Allgemeine Physik, Vienna University of Technology, Austria
winter@iap.tuwien.ac.at

Abstract

This lecture will first shortly describe the current status of world wide thermonuclear magnetic fusion research. The field is dominated by the construction of the by far largest tokamak experiment ITER¹ within the next ten years at the European site Cadarache (France). ITER is the cornerstone of the recently adopted “Broader Approach to Fusion” strategy which aims for building the first fusion demonstration reactor (“DEMO”) for electricity generation until the year 2040. We conclude this first part by assessing the possible role of electricity generation from fusion on the way to an environmentally benign and sustainable world energy supply toward the end of the this century.

In further consequence, we will discuss the relevance of atomic collisions in present day magnetic fusion research on their way toward ITER and DEMO for the following areas.

- (a) Core and edge plasma transport processes and modelling, in particular for the formation of plasma transport barriers and advanced tokamak discharges
- (b) Plasma-wall interaction, radiative cooling and fuel recycling at the first wall
- (c) Plasma heating and current drive by neutral beams and electromagnetic waves
- (d) Divertor plasma modelling for optimizing impurity exhaust
- (e) Core, edge and divertor plasma diagnostics.

By way of illustrative examples it will be argued that atomic collision physics is of importance for present day plasma fusion research as well as the next generation of fusion experiments comprising ITER and other evolving large magnetic fusion devices.

¹<<http://www.iter.org>>

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SHORT WAVELENGTH FREE-ELECTRON LASERS: INTERACTIONS WITH ATOMS AND IONS

Eugene Kennedy

National Centre for Plasma Science and Technology,
School of Physical Sciences, Dublin City University, Dublin 9 Ireland

Advances in the study of the interaction of short wavelength ionizing radiation with atoms and ions depend on the development of more powerful light sources. Recent progress in linear accelerators has made possible the construction of single pass Free Electron Lasers (FELs) based on self-amplified spontaneous emission (SASE). In a SASE FEL the kinetic energy of an ultra-relativistic electron bunch from the accelerator is converted to coherent electromagnetic radiation, in a single pass of the low emittance electron bunch through an ultra-precise long magnetic undulator. Such so-called fourth generation sources can provide uniquely intense, polarized, short-pulse coherent radiation potentially tunable throughout the VUV, EUV and ultimately X-ray regimes; exceeding modern synchrotron radiation and laser plasma sources by many orders of magnitude in peak and average brilliance and thereby opening up completely new areas of investigation.

The German research centre DESY (Hamburg) developed the world's first FEL to operate at short wavelengths, achieving a decisive milestone in February 2000 when the first coherent output was observed [1]. By 2001 the FEL had produced the first saturated output and achieved GW pulses in the femtosecond regime [2]. The first scientific results were reported in [3] and involved the interaction of the VUV photons (at $\sim 90\text{nm}$) with xenon atoms and clusters. The clusters absorbed many FEL photons and burst apart by Coulomb explosion. The behaviour was strikingly different to that which occurs with intense optical laser light.

Further developments at the Free Electron Laser at Hamburg (FLASH) user facility have since enabled, during 2005 and 2006, laser operation at 32 nm [4] and most recently the 13 nm regime. Several beam-lines are in position and are being exploited by user groups carrying out first experiments. The development of an associated time-synchronized femtosecond optical laser facility provides an important added dimension by enabling pump-probe techniques [5]. Many scientific areas including physics, chemistry, biology and materials science will benefit.

The presentation will include an introduction to SASE FELs and their potential for future investigations of atoms and ions. Some recent results obtained at FLASH will illustrate the capability of the new sources. An outline of international efforts towards ultimately achieving FEL operation at x-ray wavelengths will also be included.

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Progress Reports

FRAGMENTATION OF MOLECULES IN FAST ION COLLISIONS

C. Dimopoulou^{1,2}, R. Moshhammer¹, P.D. Fainstein³, M.E. Galassi⁴, R.D. Rivarola⁴,
D. Fischer¹, C. Höhr¹, A. Dorn¹ and J. Ullrich¹

(1) Max-Planck Institute for Nuclear Physics, Heidelberg, Germany

(2) GSI, Darmstadt, Germany

(3) Centro Atomico Bariloche, Argentina

(4) Instituto de Fisica Rosario, Argentina

Single ionization of simple molecules as well as Van der Waals dimers, e.g. H₂, CO₂, Ar₂ by fast charged particle impact has been studied using a reaction microscope. By measuring the momenta of the emitted electron and the recoil ionic fragment in coincidence, channel-selective low-energy electron spectra have been recorded. The experiments have been carried out at the Max Planck Institute for Nuclear Physics in Heidelberg. Experimental cross sections are presented, compared with the predictions of state-of-the-art CDW-EIS (Continuum Distorted Wave-Eikonal Initial State) calculations and discussed in terms of molecular effects such as (i) autoionization and predissociation channels and (ii) interference patterns resulting from the two-center geometry of the diatomic molecule, in analogy to Young's double-slit experiment.

In non-dissociative ionization of H₂ by 6 MeV protons, the emission of very low-energy electrons (below 1 eV) is significantly enhanced in comparison to the theoretical results. This is due to the autoionization of rovibrational levels of Rydberg states of H₂, which occurs by converting vibrational energy into kinetic energy of the emitted electron. First fully differential cross sections have been obtained bearing the "signature" of this molecular mechanism, which lies beyond the Born-Oppenheimer approximation [1]. The two-center interference patterns recently observed in the electron emission from ion impact ionization of H₂ [2], are predicted to be more pronounced if the orientation of the molecular axis could be fixed in space at the instant of the collision [3]. In the case of dissociative ionization of H₂, we obtained, for the first time in a collision experiment, molecular-frame angular distributions of emitted electrons within the axial recoil approximation [4].

The experimental data for different channels of dissociative ionization of CO₂ by 6 MeV protons have been compared with the predictions of a CDW-EIS calculation for molecular orbitals [5]. A good qualitative agreement is observed even though the vibrational motion of the molecule is not taken into account in the model. The low-energy electron spectra show a rich structure which may be attributed to the presence of molecular excitation channels, which undergo radiationless decay, via autoionization and also via predissociation. This interpretation is supported by photoionization studies of CO₂ [6].

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X-RAYS FROM SOLAR WIND CHARGE EXCHANGE AT MARS

H. Gunell, M. Holmström, E. Kallio*, R. Jarvinen*, P. Janhunen*, and K. Dennerl**

Swedish Institute of Space Physics, Box 812, SE-981 28 Kiruna, Sweden

(*) Finnish Meteorological Institute, Helsinki, Finland

(**) Max-Planck-Institut für extraterrestrische Physik, Garching, Germany

Wherever the solar wind meets a neutral atmosphere, X-rays are emitted by a charge exchange process between the neutrals and heavy solar wind ions. We review the fundamentals of solar wind-Mars interaction in general and the generation of charge exchange X-rays in particular.

X-rays from Mars were first observed in 2001 using the Chandra telescope [1]. Mars was also observed in X-rays in 2003 by XMM-Newton [2].

The X-ray emissions from the disc of Mars are caused by fluorescence of X-rays from the sun. Around Mars there is a ring shaped halo of X-ray emissions that can be explained by the solar wind charge exchange (SWCX) process. We have studied these emissions using a hybrid simulation of the solar wind-Mars interaction and a test particle simulation of heavy ion trajectories near Mars. A comparison with the observations indicates that the solar wind charge exchange process is a likely candidate for the production of the X-ray halo at Mars.

The calculations were performed in three steps. First the solar wind parameters on the day of the observation were estimated. The second step was running a hybrid simulation of the interaction between the solar wind and Mars to obtain the electric and magnetic fields around Mars. As a third step a test particle simulation was run, calculating the trajectories of heavy solar wind ions in the electric and magnetic fields that were obtained from the hybrid simulation. The X-ray emission density was saved on a grid for each time step of the test particle simulation. A hundred thousand trajectories were calculated for each of the ion species O^{7+} , C^{6+} , O^{6+} , O^{8+} , Mg^{10+} , Mg^{9+} , Si^{9+} , N^{6+} , C^{5+} , Ne^{8+} , Fe^{9+} , S^{9+} , Si^{8+} , Fe^{11+} , and Mg^{8+} . These simulations show that the contribution from the solar wind charge exchange process to the X-ray emissions from the halo is large enough to explain the observed X-ray flux [3].

Finally, we compare Mars to Venus, which has also been observed in X-rays [4].

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THE COOLER –STORAGE-RING PROJECT IN LANZHOU AND THE INTERNAL TARGET DEVICES

Xiaohong Cai¹, Jiawen Xia, Wenlong Zhan¹, Rongchun Lu¹, Caojie Shao¹, Fangfang Ruan¹,
Deyang Yu¹, Mingsheng Li¹ and D. K. Torpokov² and D. Nikolenko²

¹Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, P. R. China

²Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russian Federation

ABSTRACT

HIRFL-CSR, a cooler-storage ring (CSR) project, is the upgrading system of the Heavy Ion Research Facility in Lanzhou (HIRFL). It consists of a main ring CSRm and an experimental ring CSRe [1]. The heavy ions from the HIRFL will be accumulated, cooled and accelerated to energy up to 1100MeV/u ($^{12}\text{C}^{6+}$) in CSRm, and then extracted to produce radioactive ion beams or highly charged heavy ions. The produced radioactive ion beams or highly charged ions can be used in CSRe for internal target experiments or for high precision mass spectroscopy. The experimental ring CSRe may accept highly charged ions with energy up to 750 MeV/u ($^{12}\text{C}^{6+}$) and 500MeV/u ($^{238}\text{U}^{92+}$). Up to now, all devices of HIRFL-CSR have been assembled and tested. The facility is now in commissioning.

The first stored beam in CSRm was observed on January 23, 2006 using 6.897MeV/u C^{4+} as the injection beam using the stripping injection mode. The stored beam with lifetime of more than 10 s was observed using Schottky spectroscopy (Fig.1).

The internal target is located at one straight section of CSRe which is designed to operate both in the unpolarized mode and in the polarized mode. The unpolarized target is a cluster-jet target and may provide the gas target of H_2 , N_2 , inert gases and small molecular gases with the expected density of $\geq 10^{12}$ atoms/cm². HIRFL-CSR cluster target [2] has been finished and installed to the due position. The test experiments have been done for H_2 , N_2 and Ar gases. The vacuum of 9.0×10^{-12} mbar and 1.0×10^{-11} mbar are obtained in the scattering chamber in case of without and with gas in, and which are better than the expected value of 5.0×10^{-11} mbar proving that the arrangement of the vacuum system is successful. The target thicknesses of 6.6×10^{12} atoms/cm², 1.2×10^{13} atoms/cm² and 1×10^{13} atoms/cm² are obtained for H_2 , N_2 and Ar gases, respectively. The long-time running stability of the cluster target is tested for 99.99% N_2 . The pressure in the nozzle was stable during the continuous running of 30 hours suggesting that the cluster target can continuously run for a long time.

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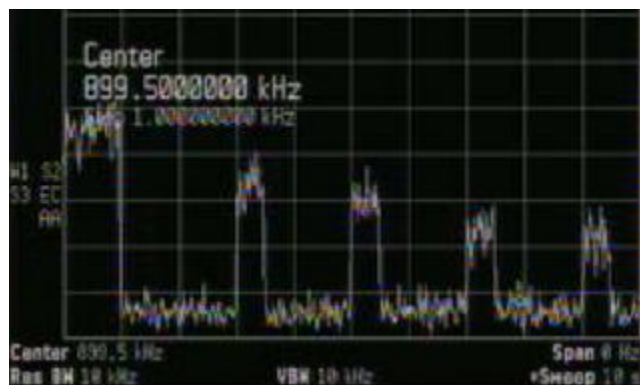


Fig. 1 Schottky spectrum of the stored beam

HYPERTHERMAL (0.1 - 20 eV/amu) HEAVY ION DAMAGE TO DNA

Michael A. Huels

Ion Reaction Laboratory, Department of Nuclear Medicine and Radiobiology, Faculty of Medicine and Health Sciences, University of Sherbrooke, Sherbrooke, Quebec, J1H 5N4, Canada

Recent studies [1] have shown that, unlike for electron or photon tracks, along the radiation tracks of highly charged ions (MeV range), abundant secondary ions (e.g. C^{n+} , O^{n+} , N^{n+} , $n=1-3$) with *hyperthermal energies reaching up to several hundreds of eV* can be produced from DNA bases. Here it is shown that atomic and molecular ions with *precisely* such low energies (1–100 eV) are capable of causing substantial damage to plasmid DNA and its components (nucleosides, bases, or RNA/DNA sugars) via molecular fragmentation, and direct and indirect physico-chemical reactions, and are thus capable of causing substantial clustered DNA lesions in irradiated cells. Measurements involve *soft-landed* ion beams and plasma-ion irradiation.

For example, we find that He^+ , N^+ , N_2^+ and Ar^+ ions can induce severe molecular fragmentation of DNA components and physico-chemical reactions at energies *down to 10 eV* (0.25 eV/amu for Ar^+). The fragments of thymidine originate from both thymine and the sugar moiety, including H^+ , CH_3^+ , H_3O^+ , $C_2H_3^+$, $HNCH^+$, CHO^+ , CH_3O^+ , $C_3H_3^+$, $HNC_3H_4^+$, $[T-OCNH]^+$, $[T-O]^+$, $[T+H]^+$, H , O^- , OH^- , CN^- and OCN^- , etc. Most arise from the sugar moiety, suggesting its vulnerability. The mechanisms responsible for molecular damage above 10 eV ion energy are mainly physical (i.e. kinetic & potential scattering). However, secondary reaction cascades involving ions (fragments or projectiles) in the films of are also observed, such as the formation of H_3O^+ from sugars and thymidine during Ar^+ , He^+ , N^+ , and N_2^+ impact, or the formation of HeH^+ during He^+ impact. Most importantly, *below 10 eV, reactive scattering is observed* during N^+ and N_2^+ ion irradiation. N^+ ions efficiently abstract hydrogen and carbon atoms from the target molecules to form NH^- and CN^- anions. The energy threshold of CN^- desorption is found to be 5 eV, and NH^- are observed at energies down to 1 eV (< 0.1 eV/amu) without threshold. Furthermore, we find that *C abstraction is highly site and energy specific*. N^+ ion irradiation of 5- ^{13}C D-ribose reveals that CN^- formation is highly selective for C5, which in DNA bonds to the backbone phosphates. The branching ratio of $^{13}CN^-$ yield in total CN^- desorption increases up to 80% at the lowest energies. Compared to its stoichiometric ratio of 20% in D-ribose, it indicates a significant preference for C5. Meanwhile, hyperthermal Ar^+ (2.5 eV/amu) interacting with double stranded plasmid DNA lead to single and double strand breaks, fragmentation and chemical modification of nucleosides, and site specific rupture along the N1-C1 glycosidic bond, resulting in base release.

In cells, such clustered molecular damage will enhance the severity of DNA strand lesions, thus making them harder to repair. Our measurements underscore a fundamental difference between conventional (sparsely ionizing radiation) and heavy particle radiation effects, and suggest a fundamentally different picture of heavy ion therapy from conventional radiation therapy, which reaches beyond single ionization or simple bond cleavage, or diffusion limited radical reactions. **Research supported by the Natural Science and Engineering Research Council of Canada, and the Canadian Space Agency.**

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THE STATUS OF CHARGED-PARTICLE MICROBEAMS FOR RADIATION BIOLOGY

Melvyn Folkard, Borivoj Vojnovic, Kevin M Prise

Gray Cancer Institute, PO Box100, Mount Vernon Hospital, Northwood, HA6 2JR, UK

Radiotherapy remains an important method for the treatment of many cancers and improvements in the use of ionising radiation in cancer medicine continue to be sought. However, it is also the case that exposure to ionising radiation can cause cancer and despite a century of research, the risks associated with occupational and environmental levels of radiation are not well understood. To address these issues, radiobiological research seeks to improve our understanding of how ionizing radiation interacts with living systems. An important branch of radiobiology studies the effects of ionising radiations at the cellular and tissue level. Historically, this is achieved by irradiating and observing biological effect in cultured cell populations. More recently however, cellular micro-irradiation techniques have been used to provide experimental opportunities not possible with typical 'broad-field' irradiation methods. Using microbeams, it is possible to deliver precise doses of radiation to selected individual cells, or sub-cellular targets *in vitro*. This technique continues to be applied to the investigation of a number of phenomena currently of great interest to the radiobiological community. In particular, it is the study of so-called 'non-targeted' effects (where cells are seen to respond *indirectly* to ionizing radiation) that are benefiting most from the use of microbeam approaches. One important non-targeted effect is the 'bystander-effect' where it is observed that unirradiated cells exhibit damage in response to signals transmitted by irradiated neighbours. There is now considerable interest in the bystander-effect (and other non-targeted effects) as they undermine the current estimates of the risk associated with low-dose exposure to radiation, (which are largely based on a linear extrapolation of known risks at higher doses). The bystander effect is also of potential relevance to the advancement of the treatment of cancer by radiotherapy. One possibility being considered is to increase the 'therapeutic benefit' by selectively modifying the response of either the tumour, or the healthy tissue to radiation by chemical action directed at the signalling molecules involved in the bystander effect.

The Gray Cancer Institute is one of a small number of laboratories worldwide routinely using microbeam techniques for radiobiological applications. Our charged particle microbeam makes use of energetic protons or helium ions (accelerated using a 4MV Van de Graaff accelerator) to irradiate individual mammalian cells with counted and collimated particles, such that it is possible to precisely deliver a single particle to a single cell. The collimator is a 1 μ m bore glass capillary, and the overall targeting accuracy is $\pm 2\mu$ m. Automated cell finding and micropositioning systems are used to locate and align cells, such that up to 10,000 cells per hour can be individually irradiated. Through our studies, we have been able to gain some insight into both the magnitude of non-targeted effects and the mechanisms that underpin them.

PRODUCTION OF A NM SIZED SLOW HCI BEAM WITH A GUIDING EFFECT

Tokihiro Ikeda*, Takao M. Kojima*, Yoshio Iwai*, Yasuyuki Kanai*, Tadashi Kambara*, Takuya Nebiki[#], Tadashi Narusawa[#], and Yasunori Yamazaki*[§]

(*)Atomic Physics Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

([#]) Kochi University of Technology, Tosa-Yamada, Kochi 782-8502, Japan

([§])Institute of Physics, University of Tokyo, Meguro, Tokyo 153-8902, Japan

Nanobeams of slow highly charged ions (HCIs) could realize the pinpoint deposition of their large potential energy on the surface of a sample, and offer a unique opportunity of surface characterization by scanning microscopy. However, if a collimator is installed to make the nanobeam, a slow HCI could change its energy and charge state by touching the inner-wall. Moreover, when the number of generated HCIs is small, the beam intensity becomes quite low. We demonstrate a new technique with a tapered glass capillary producing nano sized slow HCI beams, which is based on a guiding effect [1]. Originally, focusing with a tapered glass capillary was studied for MeV light ions by Narusawa *et al.* [2], where a multiple small-angle scattering plays an essential role. In the case of slow HCIs, the hit part of the inner-wall of the glass capillary charges up, which prevents the following ions from touching the wall. The beam is thus guided within the glass capillary and exits from the outlet having smaller diameter and higher areal density than the incident beam (focusing effect). By this way, a nano-size HCI beam keeping the initial charge state is formed.

The schematic view of the setup is shown in Fig. 1. The inner diameter of the glass capillary used varied from 0.9 μm to 24 μm . The guided ions were monitored by a position sensitive detector (PSD) 75 or 100 mm downstream from the capillary. The inset of Fig. 2 shows such images of 8 keV Ar^{8+} ions guided through the capillary for its tilting angle from -100 mrad to 100 mrad. Figure 2 shows the guided angle as a function of the tilting angle of the capillary. The charge changed fraction of the guided beam was found to be less than 1 %, and the beam divergence was of the order of mrad. At the conference, the recent results including the focusing effect and the transmission stability will be reported.

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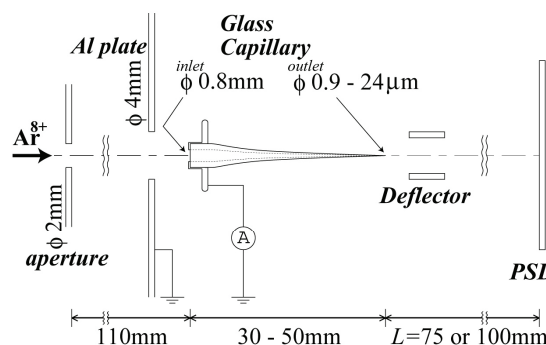


Figure 1. Schematic view of the setup

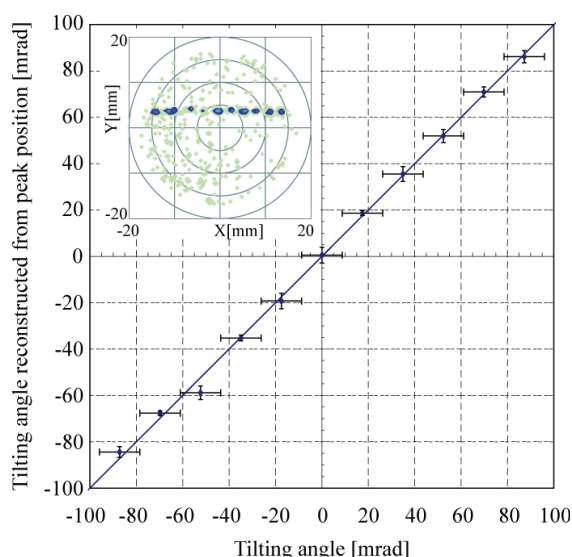


Figure 2. Tilting angle dependence of the peak position for the beam intensity around 0.1 pA. ($\phi_{\text{outlet}} 24 \mu\text{m}$)

Laser-accelerated high-energy ions: state-of-the-art and applications

M.Borghesi

School of Mathematics and Physics
The Queen's University of Belfast, Belfast BT7 1NN

The acceleration of high-energy ion beams (up to several tens of MeV per nucleon) following the interaction of short ($t < 1\text{ps}$) and intense ($I\lambda^2 > 10^{18} \text{ W cm}^{-2} \mu\text{m}^{-2}$) laser pulses with solid targets has been one of the most important results of recent laser-plasma research [1]. The acceleration is driven by relativistic electrons, which acquire energy directly from the laser pulse and set up extremely large ($\sim\text{TV/m}$) space charge fields at the target interfaces. The properties of laser-driven ion beams (high brightness and laminarity, high-energy cut-off, ultrashort burst duration) distinguish them from lower energy ions accelerated in earlier experiments at moderate laser intensities, and compare favourably with those of “conventional” accelerator beams. In view of these properties, laser-driven ion beams can be employed in a number of innovative applications in the scientific, technological and medical areas. Among these, their possible use in hadrontherapy, with potential reduction of facility costs, has been proposed recently [1].

This talk will briefly review the current state-of-the-art in laser-driven proton/ion source development, and will discuss the progress needed in order to implement some of the above applications [2]. Recent results relating to the optimization of beam energy and collimation will be presented. These include the use of ultra-high contrast laser pulses, and the use of laser-driven impulsive fields for proton beam collimation and focusing. The application of laser-driven protons as a particle probe for the detection of highly transient electromagnetic fields in plasmas will also be discussed [4].

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THE ROLE OF MULTIPLY EXCITED STATES IN ELECTRON RECOMBINATION AND MULTIPLE IONISATION

G. F. Gribakin

Department of Applied Mathematics and Theoretical Physics, Queen's University, Belfast, UK

Measurements of electron recombination with multicharged ions such as Au^{25+} or U^{28+} [1] revealed a nearly uniform two-order of magnitude enhancement over the radiative recombination rate in the 1–100 eV range of energies. Furthermore, in Au^{25+} no resonances were observed, while in U^{28+} the peaks in the recombination rate could not be identified with dielectronic recombination resonances that would explain the enhancement.

To understand this effect we have proposed that recombination is mediated by multiply excited states rather dielectronic resonances [2]. In our theory dielectronic excitations populated through capture of the incident electron play the role of *doorway* states. Owing to strong configuration interaction, these states are mixed with other, multiply excited states. This results in a dense spectrum of narrow resonances. Its density is so high (estimated at 10^3 eV^{-1} in Au^{25+}) that individual resonances cannot be resolved even at the current level of storage ring experiments. Also, the degree of level mixing in Au^{25+} is so strong [3] that the system is in the regime of many-body quantum chaos. This in turn justifies the use of statistical methods for the calculation of the recombination cross section [2].

In this picture the enhancement of the recombination rates observed in Au^{25+} and U^{28+} is explained by suppression of the autoionisation widths of the resonances due to sharing of the dielectronic autoionisation strength between many (chaotic) multiply excited eigenstates. It is important that their radiative widths are of “normal” size (i.e., comparable to those of single-electron transitions). This makes the fluorescence yields of the resonances large (close to unity in Au^{25+} and only 3–10 times smaller in U^{28+}).

It appears that similar multiply excited states can also be responsible for the near-threshold energy dependence in multiple ionisation. According to Wannier-type theories, the near-threshold behaviour of multiple ionisation cross sections [e.g., by electron impact, $e^- + A \rightarrow A^{n+} + (n+1)e^-$] is a power law, $\sigma \propto (E - E_{\text{th}})^{\mu_n}$. Here $E - E_{\text{th}}$ is excess energy of the system above the n th ionization threshold, and μ_n is the characteristic threshold index. Calculation of μ_n is a nontrivial problem, but in general it behaves as $\mu_n \sim n$. Recent experiments in noble-gas atoms agree with theoretical μ_n for $n \leq 2$, but yield values lower than theoretical μ_n for $n > 3$. We suggest that this can be due to a secondary threshold law [4]. It results from a two-step mechanism for the production of multiply charged ions. The first step is double ionisation. It leaves the ion in an excited state, which subsequently autoionises with the emission of one or several electrons. Owing to a dense spectrum of multiply excited states of the doubly charged ion, the onset of the secondary threshold law is very close to the actual E_{th} , and its effective threshold index is $\mu_2 + 1 = 3.27$.

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ELECTRONS SUBJECT TO ULTRA-HIGH FIELDS – DIELECTRONIC RECOMBINATION IN THE REALM OF STRONG FIELD QED AND NUCLEAR PHYSICS

C. Brandau^{a,b}, C. Kozhuharov^a, A. Müller^b, K. Beckert^a, P. Beller^a, D. Bernhardt^b, F. Bosch^a, S. Böhm^b, F.J. Currell^c, B. Franzke^a, A. Gumberidze^a, Z. Harmann^d, J. Jacobi^b, H.-J. Kluge^a, P.H. Mokler^{a,b}, F. Nolden^a, R. Reuschl^a, S. Schippers^b, E.W. Schmidt^b, U. Spillmann^a, Z. Stachura^e, M. Steck^a, Th. Stöhlker^a, A. Wolf^d

^aGesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany

^bInstitut für Atom- und Molekülphysik, Justus-Liebig-Universität, Gießen, Germany

^cQueen's University, Belfast, U.K.

^dMax-Planck Institut für Kernphysik, Heidelberg, Germany

^eInstytut Fizyki Jądrowej, Kraków, Poland

The atomic system comprising a single electron orbiting around a uranium nucleus is the prototypical, most extreme case of a ‘laboratory’ for strong electromagnetic fields. The strength of the field seen by the electron exceeds that of the strongest lasers by more than 4 orders of magnitude and the one seen by the electron in hydrogen by more than 6 orders of magnitude. As is readily imagined, the tightly bound electrons in HCI are also sensitive and selective probes of the nucleus itself. The method of choice to study this extreme case of matter is the technique of resonance reaction spectroscopy (RRS) through the electron-ion collision process of dielectronic recombination (DR). Experimental results from recent DR studies of HCI at the electron cooler of the heavy-ion storage ring ESR of GSI will be presented that employed the technique of RRS in two complementary ways.

The first part will focus on DR of one-electron heavy-ions. The initial dielectronic capture phase creates a doubly excited (‘hollow’) ion. Its investigation provides access to relativistic and QED effects on the level structure and the recombination dynamics. Until very recently, the most fundamental and intriguing one- and two electron heavy-ion systems such as U^{91+} were not accessible with DR at electron coolers due to the high collision energy that is needed to excite the K-shell electron. The novel technique of DR measurements with a stochastically cooled ion beam resolves this problem.

DR of few-electron heavy-ions is also a promising novel approach to study nuclear properties such as charge radii and hyperfine effects. Isotope shift measurements of HCI by means of DR complement optical (laser) spectroscopic techniques in neutral atoms or moderately charged ions since the interpretation of the energy shift is not hampered by many-body effects. A combined analysis offers the opportunity to link together accurate data from laser measurements with the DR isotope shift data and hence to significantly improve the overall accuracy. In contrast to experiments with muonic atoms and—up to now—the technique of high-energy electron scattering, DR isotope shift experiments with unstable exotic species seem feasible. The potential of DR for the investigation of nuclear properties has been successfully demonstrated in a recent pilot experiment at the ESR with the two Li-like neodymium isotopes ${}^A\text{Nd}^{57+}$ with $A=142$ and $A=150$.

In addition to the recent results obtained at the present accelerator complex of GSI a brief outlook on the future scientific perspectives of DR at the future “Facility for Antiproton and Ion Research” (FAIR) will be given. As part of FAIR the successor of the ESR, the NESR will be equipped with a dedicated ultra-cold electron target that operates independently of any beam cooling tasks and is optimised to produce an electron beam as monoenergetic as possible. It can be expected that these new installations, the technological advances, the combination with other new in-ring equipment and the increased beam intensities of stable and unstable species will lead to a boost in versatility, resolution and sensitivity.

PRECISION TESTS OF QED IN STRONG FIELDS: EXPERIMENTS ON HYDROGEN- AND HELIUM-LIKE URANIUM

A. Gumberidze^{1,2}, Th. Stöhlker^{1,2}, D. Banas³, H.F. Beyer¹, F. Bosch¹, X. Cai⁴, S. Hagmann^{1,2}, C. Kozhuharov¹, D. Liesen¹, X. Ma⁴, P.H. Mokler¹, D. Sierpowski⁵, M. Steck¹, S. Tashenov¹, A. Warczak⁵, Y. Zou⁶

(1) GSI, Darmstadt, Germany

(2) IKF, University of Frankfurt, Frankfurt, Germany

(3) Institute of Physics, Kielce, Poland

(4) Institute of Modern Physics, Lanzhou, China

(5) Jagiellonian University, Krakow, Poland

(6) Fudan University, Shanghai, China

The quantum electrodynamics (QED) can be regarded as one of the most precisely tested theories of physics. However, despite the enormous accuracies achieved in experimental tests of the QED in weak fields, the domain of extremely strong electromagnetic fields of high-Z highly-charged ions remained mostly unexplored with this respect until the recent years. During the last years there has been an increasing interest and substantial progress in investigation of this regime both from theoretical and from experimental sides.

Precision measurements of x-ray transitions from bound or continuum states into the ground state of the heavy ion-electron systems are best suited to deduce characteristic QED phenomena in intense fields and a comparison of predicted with experimentally determined level energies provides a critical test of theory in this regime. Here, we report on x-ray spectroscopic investigation addressing QED effects for the ground states in the heaviest hydrogen- and helium-like systems. The experiment was carried out at the ESR storage ring at GSI Darmstadt which has proven throughout the years to provide unique conditions for precision spectroscopy in the domain high-Z systems. Exploiting the deceleration capability of the ESR in combination with 0 deg spectroscopy at the electron cooler enabled us to obtain a precise value for the two-electron contribution to the ground state binding energy in helium-like uranium [1]. In addition, the ground state binding energy and hence the Lamb shift in the corresponding hydrogen-like system was derived [2]. For hydrogen-like uranium the obtained result is about 3 times more precise than the most accurate value available up to now. When compared with the most recent theoretical result [3], our value provides a test of the first order (in α) QED corrections at the 1.5 % level and thus represents the most stringent test of the bound-state quantum electrodynamics for one-electron systems in the strong field regime. In addition, from the measured x-ray centroid energies the two-electron contribution to the ionization potential of He-like uranium could be obtained with a precision of 9 eV. This achieved accuracy represents the most accurate determination of two-electron effects in the domain of high-Z He-like ions and reaches already the size of the specific two-electron radiative QED corrections [4].

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Poster Category 1

**Fundamental Aspects,
Structure and Spectroscopy**

EXPERIMENT AND THEORY IN INTERPLAY ON HIGH-Z FEW-ELECTRON ION SPECTRA FROM FOIL-EXCITED ION BEAMS AND ELECTRON BEAM ION TRAPS

E. Träbert¹, P. Beiersdorfer, E. H. Pinnington², S. B. Utter³, M. J. Vilkas⁴, Y. Ishikawa⁴

Lawrence Livermore National Laboratory, Livermore, CA 94550-9234, U.S.A.

(1) also at Ruhr-Universität Bochum, D-44780 Bochum, Germany

(2) University of Alberta, Edmonton AB, Canada T6G 2J1

(3) now at Spectra-Physics, Mountain View, CA 94039, U.S.A.

(4) University of Puerto Rico, San Juan, Puerto Rico 00931-3346, U.S.A.

The spectra of highly charged ions feature various interesting properties, because relativistic contributions dominate atomic structure, and quantum electrodynamical corrections become notable. However, the spectra also pose a number of challenges. One of the major problems for the study of such spectra is the ion production. Neither tokamaks nor laser-produced plasmas have, for example, been able to reach ionization stages as high as Na-, Mg- or Al-like Au ($Z=79$) ($\text{Au}^{68+,67+,66+}$). Only two techniques so far have achieved the production of any charge state in any of the elements up to U ($Z=92$). One of these is the interaction of high-energy ion beams with thin solid targets, thus permitting the application of beam-foil spectroscopic techniques in the extreme-ultraviolet (EUV) and X-ray ranges. The other approach employs an electron beam ion trap (EBIT). In the first technique, the fast ions interact mostly with the practically free electrons in a solid-state target at rest. In the second, a beam of fast electrons interacts with trapped target ions practically at rest. Ion energies of about 14 MeV/amu are needed in the first arrangement to produce Na-like ions of Au, and this calls for some of the largest heavy-ion accelerators available. By correspondence, the electron-proton mass ratio lets expect the same achievement with about 7-keV electrons in Livermore's smaller trap, EBIT-II.

Beam-foil observations of highly charged Au ions have been made more than a decade ago using the UNILAC accelerator at GSI Darmstadt. The theoretical information available at the time was inconsistent, however, and our new calculations have incited a reanalysis of the line identifications in the beam-foil spectra that suffered from the need for massive Doppler shift corrections and from insufficient references for a reliable wavelength calibration. Electron beam ion traps with the ion cloud practically at rest do not need Doppler corrections of the wavelengths, and a reliable wavelength calibration is easier to achieve. We have recorded Au spectra at the Livermore electron beam ion trap EBIT-II that show one line each of the aforementioned Na- through Al-like Au ions. The wavelengths of Na-like ions have been calculated reliably a long time ago. The results of our new calculations by multi-reference many-body perturbation theory for F- through P-like ions of Au are in excellent agreement with the wavelengths determined at EBIT-II. They identify the lines of Na-, Mg-, and Al-like Au ions with ground state transitions, which reflects the (low-density) excitation properties in the EBIT light source. Thus validated, the calculations have been applied with confidence also to the beam-foil spectroscopic data, which contain many lines also from other levels, since the ion-foil interaction is decidedly taking place under high-density conditions.

SPECTROSCOPIC STUDIES OF XENON EUV EMISSION IN THE 40-80 nm WAVELENGTH RANGE USING AN ABSOLUTELY CALIBRATED MONOCHROMATOR

H. Merabet^{1,2}, R. Bista², R. Bruch², S. Füllung², and A.L. Godunov³

¹*Mathematic and Sciences Unit, Dhofar University, Salalah 211, Sultanate of Oman*

²*Department of Physics, University of Nevada Reno, Reno, NV 89557 USA*

³*Department of Physics, Old Dominion University, Norfolk, VA 23529 USA*

In this work we have measured and identified numerous EUV radiative lines arising from Xenon ions from charge state $q = 1$ to 10 in the wavelength range 40-80 nm. To obtain reasonable intensities of different charged Xenon ions, we have used a compact microwave plasma source which was designed and developed by Leung *et al.* [1] at the Lawrence Berkeley National Laboratory (LBNL). The EUV emission of the ECR plasma has been measured by a 1.5 m grazing incidence monochromator that was absolutely calibrated in the 10-80 nm wavelength range using a well known and calibrated EUV light at the Advanced Light Source (ALS) at LBNL [2]. This calibration has enabled us to determine absolute intensities of previously measured EUV radiative lines [3] in the investigated wavelengths regions for different ionization stages of Xenon. In addition, emission spectra of Xenon ions for corresponding measured lines have been calculated. The calculations have been carried out within relativistic Hartree-Fock (HF) approximation. Results of calculations are found to be in good agreement with current and available experimental and theoretical data. For example, figure 1 indicates the Xenon spectral segment between 60 and 80 nm (43 lines). We show here only few prominent peaks and a more detailed classification will be presented.

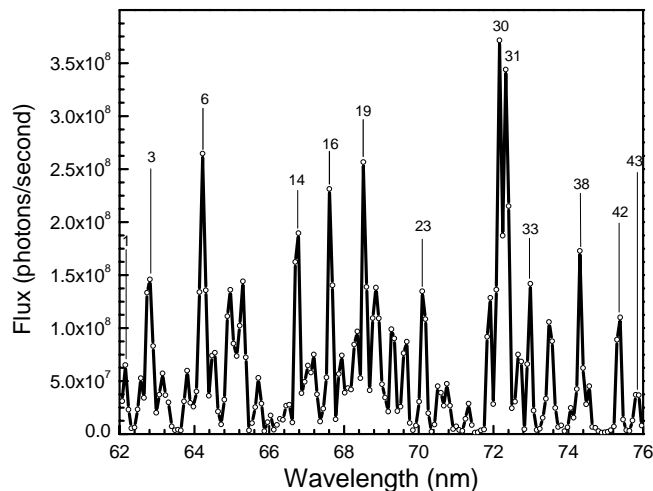


Fig. 1: Medium resolution Xenon EUV spectrum between 60 and 80 nm.

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RELATIVISTIC MANY-BODY CALCULATIONS ON HIGHLY-IONIZED GOLD IONS Au^{40+} - Au^{50+}

Marius Jonas Vilkas and Yasuyuki Ishikawa

Department of Chemistry, University of Puerto Rico, P.O. Box 23346 San Juan, Puerto Rico
00931-3346 USA

High-accuracy relativistic multireference Møller-Plesset (MR-MP) perturbation theory [1] calculations of term energies and transition probabilities in highly-ionized gold ions Au^{40+} - Au^{50+} have been performed as benchmarks in the quest for accurate theoretical treatments of relativity, electron correlation, and quantum electrodynamic effects in multivalence-electron systems. Computed wavelengths of the $n = 4$, $\Delta n = 0$ electric-dipole transitions are compared with the recent high-resolution wavelength measurements using electron-beam ion traps [2,3]. We have applied the MR-MP method to Cu-, Zn-, Ga-, Ge-, As-, Se-, Br-, Kr-, Rb-, Sr- and Y-like gold ions, where the presence of multiple valence shell electrons exhibits very complex spectra. A number of unidentified extreme ultraviolet spectral lines were successfully identified and reassignments of experimentally misidentified lines were made. Theory-experiment deviations in decay wavelengths in these systems range typically from 0.01 to 0.05 Å.

The state-averaged multiconfiguration Dirac-Fock self-consistent field procedure was applied for the ground and low-lying excited states in gold ions. Subsequent relativistic configuration interaction

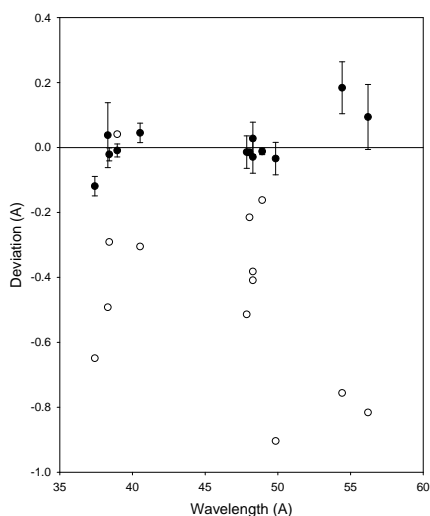


Figure 1. Deviations in wavelengths of experiment (●) and HULLAC (○) from the MR-MP.

(RCI) procedure included all the configuration state functions arising from the configurations, $4s^m 4p^n 4d^p 4f^q$ with $p \leq 2$ and $q \leq 1$ (restricted active space of the $n=4$ manifold). Each of the RCI eigenstates was subjected to state-specific MR-MP refinement to account for the residual dynamic correlation. All electrons have been included in the MR-MP perturbation theory calculations to determine accurately the effects of relativity on electron correlation. MR-MP correlation energy contributions to transition energies from partial wave $L_{max}=12$ and higher are on the order of 10 cm^{-1} . Radiative corrections, the Lamb shifts, were estimated for each state by evaluating the electron self-energy and vacuum polarization. First-order frequency-dependent and independent Breit interaction, and normal and specific mass shifts on the ground and excited states, were estimated in the lowest order of the perturbation theory. In Figure 1, the deviations in wavelengths of experiment [3] and HULLAC from MR-MP are plotted to exemplify the accuracy of the MR-MP theory and display a few notable discrepancies. We expect the theoretical prediction of unidentified decay lines to be accurate to 0.01 %.

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ALLOWED TRANSITIONS AMONG $2s^22p^4$, $2s2p^5$ AND $2p^3(^4S, ^2D, ^2P)3\ell$ LEVELS OF OXYGEN-LIKE MAGNESIUM

N. C. Deb, A. Hibbert

School of Mathematics and Physics, Queen's University Belfast
Belfast BT7 1NN, Northern Ireland, UK

A full Breit-Pauli calculation with a large number of interacting configurations having one-, two- and three-electron promotions up to the $n = 8$ complex is presented. The optimized orbitals $2p$, $3s$, $3p$, and $3d$ are taken to be spectroscopic and remaining $4s$, $4p$, $4d$, $4f$, $5s$, $5p$, $5d$, $5f$, $5g$, $6s$, $6p$, $6d$, $7p$, $7d$, $8p$, and $8d$ orbitals are taken to be either correction orbitals (included to represent the effects of ns -dependencies of the orbitals) or correlation orbitals. With this choice of orbitals we expect to get accurate 86 fine-structure levels belonging to $2s^22p^4$, $2s2p^5$, $2p^6$ and $2p^3(^4S, ^2D, ^2P)3\ell$ configurations. These configurations give rise to 18 even parity and 26 odd parity LS states which will subsequently produce 34 and 52 fine-structure levels belonging to even and odd parities respectively. Using the CIV3 program of Hibbert [1] we then calculate first the *ab initio* energies of these levels. Adopting a further fine-tuning process we make small adjustments to the Hamiltonian matrix elements in such a way that they produce eigenvalues very close to the corresponding experimental values given by the NIST [2] database. We then calculate oscillator strengths, transition probabilities and line strengths for various optically allowed transitions among these fine-structure levels. Results will be presented at the conference.

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Laser spectroscopy of hyperfine structure in highly-charged ions: a test of QED at high fields

D.F.A. Winters^a, M. Vogel^a, J. Krämer^{a,b} and W. Nörtershäuser^{a,b},
D.M. Segal^c, R.C. Thompson^c and the HITRAP-RETRAP Collaboration

^a GSI Darmstadt, Germany

^b Johannes Gutenberg-University Mainz, Germany

^c Imperial College London, United Kingdom

Accurate measurements of ground state hyperfine splittings (HFS) in highly-charged ions (HCI) can test quantum electrodynamics (QED) at extreme electric fields (10^{15} V/cm) to the level of a few percent [1]. Such high fields cannot be produced using conventional laboratory techniques, but naturally exist close to the nuclei of almost completely stripped heavy elements like Pb, Bi or U. A measurement of the wavelength of the magnetic dipole ($M1$) transition between the hyperfine levels gives information on the QED corrections to the HFS, or on the spatial distribution of the nuclear magnetisation (Bohr-Weisskopf effect) [2]. Its measurement thus allows for critical tests of nuclear models. Moreover, from a comparison of measurements of the HFS in hydrogen- and lithium-like ions of the same heavy isotope (*e.g.* $^{209}\text{Bi}^{82+}$ and $^{209}\text{Bi}^{80+}$), the nuclear effects can be eliminated such that the QED effects can be determined [1].

In order to reach the necessary resolution, a bunch of $\sim 10^5$ highly-charged ions will be captured and confined in a cylindrical open-endcap Penning trap [3,4]. Electron capture (neutralisation) by collisions is strongly reduced by operating the trap at cryogenic temperatures under UHV conditions. Once trapped, the ion cloud will be cooled by ‘resistive cooling’ and radially compressed by the ‘rotating wall’ technique. Cooling is essential because the ions’ thermal (and oscillatory) motion will lead to a Doppler broadening of the linewidth. Compressing the cloud is necessary to obtain enough fluorescence from the slow $M1$ transitions (lifetimes of ms) between the hyperfine levels. A spectrum of the ground state hyperfine transition can be obtained by scanning the laser wavelength across the resonance, while recording the fluorescence from the trapped excited HCI [3,4]. Such laser spectroscopy measurements have a resolution of the order of 10^{-7} , which is 3 orders of magnitude better than before [5,6].

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High-precision mass measurements for fundamental applications using highly-charged ions at SMILETRAP

Sz. Nagy^{1,2}, T. Fritioff¹, M. Suhonen¹, A. Solders¹, K. Blaum^{2,3}, I. Bergström¹, R. Schuch¹

¹ Atomic Physics, AlbaNova, Stockholm University, S-106 91 Stockholm, Sweden

² Johannes Gutenberg-University Mainz, Staudingerweg 7, D-55128 Mainz, Germany

³ GSI Darmstadt, Planckstraße 1, D-64291 Darmstadt, Germany

This contribution includes a number of recent high precision mass measurements performed with the SMILETRAP Penning trap mass spectrometer [1], which are relevant for several of today's fundamental physics problems. First, the masses of the hydrogen- and lithium-like ^{40}Ca ions have been determined as shown in Fig. 1. [2]. These mass values are indispensable when determining the g -factor of the bound electron in $^{40}\text{Ca}^{17+,19+}$ for a test of quantum electrodynamics in strong fields [2]. The uncertainty in the mass was improved by one order of magnitude compared to available literature values.

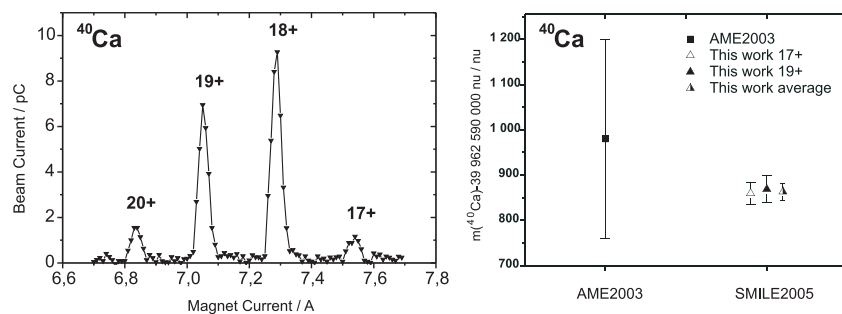


Figure 1: A charge state spectrum (left) and the results of the mass measurements (right).

Second, a new mass value has been obtained for ^7Li with an unprecedented relative uncertainty of 6.3×10^{-10} , important for nuclear charge and mass measurements of the prominent short-lived halo nuclei $^9,^{11}\text{Li}$ [3]. A large deviation of $1.1 \mu\text{u}$ (14σ) compared to the literature value has been found. In order to find the reason for this large deviation and to look for possible systematic errors, we have measured the mass of ^4He and ^6Li and concluded that the $^6\text{Li}(n,\gamma)^7\text{Li}$ reaction Q -value used in the literature when calculating the ^7Li mass is wrong by as much as 1 keV.

Third, the Q -value of the tritium β -decay, i.e. the mass difference between ^3He and ^3H , is of utmost importance in the search for a finite rest mass of the electron antineutrino with the Karlsruhe Tritium Neutrino KATRIN experiment. By adding an accurate mass measurement of $^3\text{He}^{1+}$ to previous mass measurements of $^3\text{H}^{1+}$ and $^3\text{He}^{2+}$, we have improved our previous Q -value by a factor of 2. The present Q -value determined by SMILETRAP mass measurements is presently the most accurate having an uncertainty of 1.2 eV [4].

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FLUORESCENCE YIELDS FOR HIGHLY-CHARGED IONS: STATE DEPENDENCE

M. F. Hasoglu, I. Dumitriu, T. W. Gorczyca, D. W. Savin, * **S. T. Manson**, ** N. R. Badnell***

Department of Physics, Western Michigan University, Kalamazoo, MI 49008, USA

*Columbia Astrophysics Laboratory, Columbia University, 538 West 120th Street, New York, NY 10027, USA

**Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30303, USA

***Department of Physics, University of Strathclyde, John Anderson Building, 107 Rottenrow, Glasgow G4 0NG, UK

Calculations of fluorescence yields resulting from K-shell vacancies for a number of isoelectronic sequences have been performed including electron correlation effects *via* configuration interaction, and spin-orbit effects. The calculations were performed for N-electron ions ($N = 3$ through 10) up to $Z = 30$. The results show that, in these cases, both configuration-interaction and spin-orbit effects are important for quantitative accuracy. Of greatest significance is that the fluorescence yields display a dramatic dependence upon the initial state of the K-vacancy configuration; significant variations are found among the various LS multiplets of the configuration, *and* there is significant J-dependence as well. Furthermore, it has been found that the LSJ dependence is not primarily the result of dynamic effects, i.e., radial wave function difference among the various LSJ states of a given configuration. Rather, they are a consequence of the geometry, angular momentum geometry, of the various radiative and Auger transitions that constitute the fluorescence yields. These results show that for many K-shell vacancy ions, the use of central-field or configuration-averaged fluorescence yields can be significantly in error.

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X RAY AND EUV SPECTROSCOPIC MEASUREMENTS OF HIGHLY CHARGED TUNGSTEN IONS RELEVANT TO FUSION PLASMAS

R. Radtke^{1,2}, C. Biedermann^{1,2}, R. Seidel¹, T. Pütterich²

(¹) Institut für Physik der Humboldt-Universität zu Berlin, Lehrstuhl Plasmaphysik,
Newtonstraße 15, D-12489 Berlin

(²) Max-Planck-Institut für Plasmaphysik, EURATOM Association, Germany

The use of tungsten ($Z=74$) for certain plasma facing components in future large tokamaks (e.g., the International Thermonuclear Experimental Reactor (ITER)) has induced new experimental and theoretical activity to gain atomic data for tungsten emission modelling. Tungsten offers a promising alternative to graphite used on present-day tokamaks because it exhibits excellent thermal properties and long erosion lifetime to withstand the high heat load on divertor plates and heat shields. However, on the negative side, if sputtered tungsten penetrates into the central fusion plasma it ionizes to high charge states and produces power losses by radiating line emission in the x ray and EUV spectral ranges. To establish a quantitative method of measuring tungsten impurities in fusion plasmas and estimate the radiated power, knowledge of the spectral emission from the high charge states of tungsten is an important issue.

In the present measurement, we used an electron beam ion trap (EBIT) to produce tungsten ions and confine them for spectroscopic observations. EBIT has the advantage over experiments on tokamak plasmas that the ion's charge state distribution can easily be controlled by varying the energy of the ionizing electron beam. To introduce tungsten into the trap, we have followed a new path by directing a continuous flow of $W(CO)_6$ to the electron beam. Compared to other techniques, a significant greater amount of x and EUV emission is observed in this operation due to greater abundances of W ions confined in the trap. The tungsten ions in EBIT were sampled using electron beam energy increments of as low as 100 eV. Observations of the x and EUV radiation were made for Ni-like W^{46+} to Ne-like W^{64+} ions, which are of particular relevance to the analysis of spectral emission data from nuclear fusion plasmas. The x ray and EUV emission diagnostics was accomplished by means of a flexible vacuum flat-crystal spectrometer and a 2 m grating incidence spectrometer, respectively.

We present a survey of our spectroscopic measurements and make comparisons with earlier data obtained from controlled fusion experiments (ASDEX Upgrade). The experimental wavelengths are compared with the results from HULLAC and GRASP calculations.

THE TWO-PHOTON DECAY OF HIGHLY-CHARGED IONS

L. Borowska^{1,2}, S. Fritzsche¹, A. Surzhykov³

¹ *Fachbereich Physik, Universität Kassel,
Heinrich--Plett--Str. 40, D--34132 Kassel, Germany*

² *Institute for Nuclear Research, Nat. Acad. Sci. of Ukraine,
Nauky Prosp. 47, 03680 Kyiv, Ukraine*

³ *Max--Planck--Institute for Nuclear Physics,
Heidelberg, Germany*

The knowledge of the two-photon decay of highly-charged ions is important for the study of atomic structure. Almost all information about such process can be found due to researching the angular correlations in the two-photon decay. The angular correlations is investigated by using second-order perturbation theory, based on Dirac's equation. Particular attention has been paid to those effects which arise from higher (non-dipole) terms in the expansion of the electron-photon interaction. In this contribution, we present detailed computations on the photon-photon angular distribution for the $3d_{5/2} \rightarrow 1s_{1/2}$ transition in hydrogenlike uranium (U^{91+}), taking the alignment of the ions into account, our computations are compared with previous results [1] which was not aligned before.

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STOKES LINES, QUANTUM DEFECTS AND THE YUKAWA POTENTIAL

C.J. McGrath, S.F.C. O'Rourke, D.S.F. Crothers

Department of Applied Mathematics and Theoretical Physics, Queen's University Belfast, Belfast
BT7 1NN, Northern Ireland

We wish to generalize previous work on the semiclassical treatment of quantum defect theory [3]-[7] and relate the quantum defect in the Rydberg formula

$$E = -\frac{Z^2}{2(n - \mu)^2}$$

to the Stokes phenomenon. This work involves both analytical and numerical calculation of Stokes constants and quantum defects. It relates to ion-atom collisions at low velocities of impact and also to multichannel quantum defect theory, where previously the emphasis has been on numerical treatment rather than allowance for the Stokes phenomenon.

We consider the Yukawa (or screened Coulomb) potential of Linnaeus [7],

$$V(r) = 2e^2 \frac{\exp(-\alpha r)}{r}, \quad (1)$$

where e is the electron charge and α is a small screening parameter. The Yukawa potential is of particular interest to nuclear physicists as it is a good approximation to the strong force between nucleons.

Phase-integral and Newton-Raphson methods were used to calculate real turning points, energy eigenvalues and hence quantum defects ($\mu_{n,l}$). Stokes and anti-Stokes lines were traced using a complex Newton-Raphson method.

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TOWARDS A g - FACTOR DETERMINATION OF THE ELECTRON BOUND IN HIGHLY CHARGED CALCIUM IONS

B. Schabinger¹, J. Alonso^{1,2}, K. Blaum^{1,2}, H.-J. Kluge^{2,3}, W. Quint², S. Stahl⁴ and G. Werth¹

¹Institut für Physik, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany

²GSI Darmstadt, 64291 Darmstadt, Germany

³Universität Heidelberg, 69120 Heidelberg, Germany

⁴Stahl-Electronics, 67582 Mettenheim, Germany

Bound state-quantum electrodynamical (BS-QED) calculations can be tested by high-precision measurements of the magnetic moment of the electron bound in hydrogen-like and lithium-like ions. In the past, measurements have been performed by a GSI - University of Mainz collaboration using a double Penning-trap setup on hydrogen-like carbon [1] and oxygen [2]. A relative experimental uncertainty as low as 5×10^{-10} has been achieved. Assuming the QED calculations to be correct we derived a new value for the electron mass improving the previous value by a factor of 4 [3, 4].

The influence of the BS-QED contribution to the g -factor increases with the nuclear charge. Therefore, it is of interest to perform experiments with heavier ions. In the current experiment [5] we plan to measure the g -factor of hydrogen-like and lithium-like calcium. The ions are created in-trap by a mini electron beam ion source [6] and the charge breeding process is followed on-line by use of a Fourier Transform-Ion Cyclotron Resonance detection technique. The g -factor measurement of a single ion in a double Penning-trap setup is based on the “continuous Stern-Gerlach-effect”, and the possibility of detecting the spin orientation of the single ion is performed by means of a phase-sensitive detection method [7]. The aim is to reach a relative uncertainty in the order of 10^{-9} . In the future, we plan to extend our g -factor measurements to heavy highly charged ions up to uranium $^{238}\text{U}^{91+}$ at the HITRAP facility [8].

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DETERMINATION OF THE FINE STRUCTURE CONSTANT FROM THE BOUND-ELECTRON g FACTOR

D. A. Glazov^{1,2}, V. M. Shabaev^{1,3}, A. V. Volotka^{1,2}, N. S. Oreshkina¹, G. Plunien², and W. Quint³

¹ Department of Physics, St.Petersburg State University, Oulianovskaya 1, Petrodvorets, St.Petersburg 198504, Russia

² Institut für Theoretische Physik, TU Dresden, Mommsenstraße 13, D-01062 Dresden, Germany

³ Gesellschaft für Schwerionenforschung, Planckstrasse 1, D-64291 Darmstadt, Germany

A possibility for a determination of the fine structure constant in experiments on the g factor of highly charged ions is examined. It is found that for a specific difference of the g -factors of B- and H-like ions of the same spinless isotope in the Pb region the uncertainty due to the nuclear size and nuclear polarization effects is several times smaller than the uncertainty due to the presently accepted value of α . Therefore investigations of this specific difference to the currently accessible experimental accuracy of 7×10^{-10} would lead to a determination of α to an accuracy which is better than that of the currently accepted value. Further improvements of the experimental and theoretical accuracy could provide a value of the fine structure constant which is several times more precise than the currently accepted one.

The Resonant States of LiII and BIV below the N=2 Threshold

Ming-Keh Chen

Department of Physics, National Chung-Hsing University, Taichung, Taiwan 40227

Doubly excited states of two-electron atom and ions have been intensively studied by physicists experimentally and theoretically. These states of two-electron ions have been observed in photoabsorption, electron impact, and ion impact experiments. Some have been identified in a solar flare and in the solar Corona. Although some resonances have been studied [1-3], more theoretical data on the resonance energies and widths of these states are needed to understand the experimental results.

We studied doubly excited $^1,^3P^o$ resonant Li^+ and B^{3+} by saddle-point complex rotation method with B-spline functions [4-5]. In a Configuration Interaction scheme, we constructed the wave functions in terms of B splines of order k and total number N , defined between two end points, $r_{min}=0$ and $r_{max}=R$, and build vacancies into the wave functions. By saddle-point variation method, we obtained the saddle-point energies and wave functions. After the saddle-point variation is carried out, we calculate the resonance energies and widths by a complex-rotation method. In the present, the values of R for end points are chosen to be 400 a.u. so that the saddle-point energies are converged to within uncertainty of 10^{-8} a.u. We included 8 and 7 partial waves at least in calculating the resonant states of Li^+ and B^{3+} respectively to ensure the saddle-point energies converged within uncertainty of 10^{-8} a.u. For each partial wave, our results converge to within 10^{-8} a.u. with increasing order k and total number N of the B spline. We calculated the expectation value of the angle between the two electrons, $\langle \theta_{12} \rangle$, the average value of r for the inner electron and outer electron, $\langle r_{<} \rangle$, $\langle r_{>} \rangle$, and the average values of r and r^2 , $\langle r \rangle$, $\langle r^2 \rangle$. The doubly excited states are grouped in Rydberg series labeled by the quantum numbers K, T, A . For $^1P^o$ resonant states, there are three members in the ${}_2(1,0)_n^-$ series, four members in the ${}_2(0,1)_n^+$ series and three members in the ${}_2(-1,0)_n^0$ series. There are four members in the ${}_2(1,0)_n^+$ series, three members in the ${}_2(0,1)_n^-$ series and three members in the ${}_2(-1,0)_n^0$ series for $^3P^o$ resonant states.

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He-like Argon, Chlorine and Sulfur Spectra Measurement from an Electron Cyclotron Resonance Ion Trap

M. Trassinelli^{1,2}, S. Boucard², D.S. Covita³, D. Gotta⁴, A. Hirtl⁵, P. Indelicato², E.-O. Le Bigot², J.M.F. dos Santos³, L.M. Simons⁶, L. Stingelin⁶, J.F.C.A. Veloso³, A. Wasser⁶, J. Zmeskal⁵

¹Gesellschaft für Schwerionenforschung, Darmstadt, Germany

²Laboratoire Kastler Brossel, Unité Mixte de Recherche du CNRS n° 8552, Université Pierre et Marie Curie, Case 74, 4, Place Jussieu, F-75005 Paris, France

³Physics Department, University of Coimbra

⁴Institut für Kernphysik, Forschungszentrum Jülich, Jülich, Germany

⁵Stefan Meyer Institut für subatomare Physik, Vienna, Austria

⁶Paul Scherrer Institut, Villigen PSI, Switzerland

We present a new measurement on X-ray spectroscopy of multicharged argon, chlorine and sulfur obtained with the Electron Cyclotron Ion Trap installed in Paul Scherrer Institut (Villigen, Switzerland) [1]. For this purpose, we used a spectrometer with a spherically bent crystal with an energy resolution of about 0.4 eV [2-4]. Using this apparatus, we obtained high intensity $K\alpha$ X-ray spectra from ions with one $1s$ hole ranging from almost neutral to heliumlike charge state (see Fig. 1). In particular we observed the $1s2s\ ^3S_1 \rightarrow 1s^2\ ^1S_0$ M1 and $1s2p\ ^3P_2 \rightarrow 1s^2\ ^1S_0$ transition on He-like argon, chlorine and sulfur with unprecedented statistic and resolution. The values presented here are the result of a preliminary analysis using a new technique to measure energy differences between transitions using a Johann-type Bragg spectrometer. All observed lines energy are being determined with good accuracy, using the heliumlike M1 line as a reference. A recent spectrometer characterization will allow for an improvement of the accuracy of the measurement with a drastic reduction of the systematic errors. The final analysis is on run.

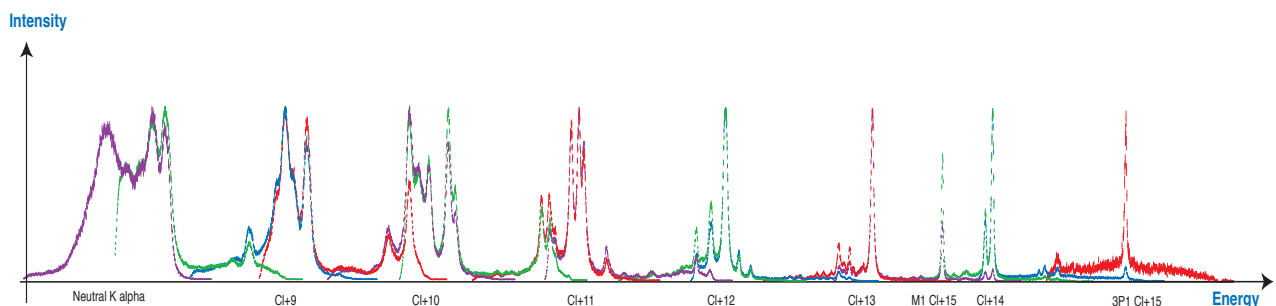


Figure 1: $K\alpha$ transitions from different charged state of chlorine. This is the results of the superimposition of different spectra obtained with the Johann-type Bragg spectrometer.

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CORRELATION AND QUANTUM ELECTRODYNAMIC EFFECTS ON THE RADIATIVE LIFETIME AND RELATIVISTIC NUCLEAR RECOIL IN Ar^{13+} AND Ar^{14+} IONS

Z. Harman¹, U. D. Jentschura¹, C. H. Keitel¹, A. Lapierre¹, R. Soria Orts¹, J. R. Crespo López-Urrutia¹, H. Tawara¹, J. Ullrich¹, A. N. Artemyev^{1,2}, I. I. Tupitsyn^{1,2}, A. V. Volotka², V. M. Shabaev²

¹Max-Planck Institute for Nuclear Physics, Saupfercheckweg 1, D-69117 Heidelberg, Germany

²Department of Physics, St. Petersburg State University, Oulianovskaya 1, Petrodvorets, 198504 St. Petersburg, Russia

The radiative lifetime [1,2] and mass isotope shift [3] of the $1s^2 2s^2 2p^2 P_{3/2} - ^2P_{1/2}$ forbidden M1 transition in B-like argon ions has been determined with high accuracy using the Heidelberg electron beam ion trap (EBIT). This fundamentally relativistic transition provides unique possibilities for performing precise studies of correlation and quantum electrodynamic effects in many-electron systems. The lifetime corresponding to the above transition has been measured with an accuracy on the order of one per thousand and is confirmed very recently by an independent measurement [2]. Theoretical calculations predict a lifetime that is in significant disagreement with this high-precision experimental value. Our mass shift calculations, based on a fully relativistic formulation of the nuclear recoil operator, are in excellent agreement with the experimental results and confirm the necessity to include relativistic recoil corrections when evaluating mass isotope shift contributions in medium- Z ions. A calculation applying the nonrelativistic operator only would yield values for the isotope shift which are smaller than the experimental result by a factor of roughly three.

Lifetime: The lifetime of the Ar^{13+} $1s^2 2s^2 2p^2 P_{3/2}$ metastable state was determined to be 9.573(4)(5) ms (stat)(syst). The accuracy level of one per mill makes this measurement sensitive to quantum electrodynamic corrections like the electron anomalous magnetic moment and to relativistic electron-electron correlation effects. Theoretical predictions cluster around a lifetime that is approximately 3σ shorter than the experimental result. At present we have no explanation for this discrepancy.

Relativistic nuclear recoil: The wavelengths of the $1s^2 2s^2 2p^2 P_{3/2} - ^2P_{1/2}$ M1 transition in Ar^{13+} and the $1s^2 2s^2 2p^3 P_1 - ^3P_2$ M1 transition in Ar^{14+} were compared for ^{36}Ar and ^{40}Ar . The observed isotopic effect has confirmed the relativistic theory of nuclear recoil effects in many-body systems, which corrects major inconsistencies in earlier theoretical methods. Theoretical transition energies and their isotope shifts, including the contributions due to the relativistic recoil operator, have been determined by large-scale configuration interaction Dirac–Fock–Sturm calculations and quantum electrodynamic many-body theory. Nonrelativistic normal mass shift and specific mass shift contributions were also evaluated in the framework of the multiconfiguration Dirac–Fock method. To the best of our knowledge, the relativistic nuclear recoil effect has never been observed experimentally thus far.

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STORAGE-RING MEASUREMENT OF THE HYPERFINE INDUCED $^{47}\text{Ti}^{18+}(2s\ 2p\ ^3P_0 \rightarrow 2s^2\ ^1S_0)$ TRANSITION RATE

S. Schippers¹, E. W. Schmidt¹, D. Bernhardt¹, D. Yu^{1,2}, A. Müller¹,
M. Lestinsky³, D. Orlov³, M. Grieser³, R. Repnow³, and A. Wolf³

¹Institut für Atom- und Molekülphysik, Justus-Liebig-Universität, 35392 Giessen, Germany

²Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, P. R. China

³Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

The $ns\ np\ ^3P_0$ state in divalent atoms and ions is the first excited state above the $ns^2\ ^1S_0$ ground state. Its decay by a one-photon $J = 0 \rightarrow J = 0$ transition is strictly forbidden and the lifetime of the 3P_0 state is nearly infinite provided the ion has zero nuclear spin ($I = 0$). If $I > 0$ the hyperfine interaction mixes levels with different J and, consequently, the 3P_0 level acquires a finite lifetime. This hyperfine quenching has been treated theoretically for Be-like and Mg-like ions [1, 2]. More recent theoretical work on neutral Mg, Ca, Sr and Yb [3] was motivated by the idea to use the hyperfine induced $^3P_0 \rightarrow ^1S_0$ transition in ultraprecise atomic clocks.

So far, the only experimental value for a $ns\ np\ ^3P_0 \rightarrow ns^2\ ^1S_0$ hyperfine induced transition rate was obtained for Be-like N^{3+} from astrophysical observations by Brage et al. [4] with a rather large uncertainty of $\pm 33\%$. Nevertheless, this result allows one to discriminate between the two theoretical results [1, 2] that are available for this ion and that differ by almost a factor of 4.

Here an experimental value for the hyperfine induced $2s\ 2p\ ^3P_0 \rightarrow 2s^2\ ^1S_0$ transition rate in Be-like $^{47}\text{Ti}^{18+}$ (with $I = 5/2$) is presented that is almost an order of magnitude more precise. Moreover, the present result has been obtained under well controlled conditions from a laboratory experiment using the high-resolution electron-ion collision facility [5] at the Heidelberg heavy-ion storage ring TSR.

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STATE SELECTIVE FORMATION OF EXCITED L-SHELL LEVELS IN Li-LIKE URANIUM

S. Trotsenko^{1,2}, Th. Stöhlker^{1,2}, D. Banas⁵, C. Z. Dong³, S. Fritzsche⁷, A. Gumberidze^{1,2}, S. Hagmann¹, S. Hess^{1,2}, P. Indelicato⁴, C. Kozhuharov¹, M. Nofal¹, R. Reuschl^{1,2}, J. Rządkiwicz^{1,6}, U. Spillmann^{1,2}, A. Surzhykov⁷

- (1) Gesellschaft für Schwerionenforschung, D-64291 Darmstadt, Germany
- (2) IKF, Universität Frankfurt, D-60486 Frankfurt, Germany
- (3) Northwest Normal University, Lanzhou 730000, China
- (4) Université P. et M. Curie, F-75252 Paris, France
- (5) Institute of Physics, Swietokrzyska Academy, 25-406 Kielce, Poland
- (6) Andrzej Soltan Institute for Nuclear Studies, 05-400 Swierk, Poland
- (7) Institut für Physik, Universität Kassel, D-34132 Kassel, Germany

The state selectivity in the formation of excited states of He-like high-Z ions was studied recently for the collisions of Li-like uranium with gaseous targets in the ESR storage ring at GSI [1, 2]. The mentioned population of excited ($n=2$) s -states were accompanied by a two-photon decay, which is of particular interest for experimental as well as for theoretical examinations [1, 2]. In the present study, these investigations were extended to initially Be-like uranium ions allowing us to produce almost exclusively the $1s(2s)^2$ level in the Li-like species which is expected to undergo predominantly an exotic two-electron one-photon decay (TEOP). In turn the sensitivity of the TEOP transition to electron correlation provides a new access for detailed investigations of the interplay of relativistic and correlation effects on the atomic structure of few electron systems.

The experiment was performed with cooled Be-like uranium ions colliding with N_2 gas target at the energy of 90 MeV/u in the storage ring ESR. The x-rays produced in this process were measured under different angles. In particular the radiative transitions in the Li-like uranium ions caused by K -shell ionization of the initial Be-like projectile were studied, where in contrast to the low-Z ions [3], a fast M1 transitions may play an important role according to the theoretical predictions [4]. A report on the current status of the data analysis will be given.

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STUDY OF THE INTRA-L SHELL TRANSITIONS IN BE-LIKE URANIUM

J. Rządkiwicz¹, H. F. Beyer², C. Brandau², S. Fritzsche⁴, A. Gojska¹, A. Gumberidze^{2,3},
S. Hagmann^{2,3}, C. Kozhuharov², T. Nandi², R. Reuschl², D. Sierpowski⁴, U. Spillmann²,
Th. Stöhlker^{2,3}, A. Surzhykov⁴, S. Tashenov^{1,2}

¹The Soltan Institute for Nuclear Studies, 05-400 Swierk, Poland

²GSI, Darmstadt, Germany

³Universität Frankfurt, Germany

⁴Universität Kassel, Germany

Recently we have investigated the production of the $n=2$ S-states in the fast collisions of the Li-like uranium with gas targets [1]. Now we extend our study to the deexcitation of the berylliumlike ions via intra-L-shell transitions. The excited states of the Be-like ions can be produced by high-temperature Tokamak plasmas [2] and by a high energy electron beam ion trap SuperEBIT [3]. The study of the $2p_{3/2}-2s_{1/2}$ and the $2p_{3/2}-2p_{1/2}$ transitions, besides others interesting aspects, give direct quantitative information of the magnetic sublevel production in the electron capture process. Note that compared to EBIT-experiment the non radiative electron capture (NREC) contributes significantly to the population cross section.

The electron capture into the $2p_{3/2}$ orbital can populate the 1P_1 and 3P_2 magnetic substates of Be-like U^{+88} . Only the first one ($J=1$) can deexcitate to the ground state of the berylliumlike uranium via E1 transition. If the $[2s2p_{3/2}]_{J=2}$ state is formed, the deexcitation to the $1s^22s^2$ ground state is not dipole-allowed. Such state can deexcitate via the $2p_{3/2} - 2p_{1/2}$ M1 transition. The intensities of the other deexcitation channels are two orders of magnitude smaller than the M1 decay rate. Thanks to these unique features it is possible to obtain precise information on the formation the $J=1$ and $J=2$ magnetic sublevels produced in electron capture processes.

In order to investigate intra-L shell decays of the magnetic 1P_1 and 3P_2 substates produced in electron capture, the measurements of x-ray spectra produced in collisions of 98-MeV/u Li-like U^{89+} with gaseous N_2 target have been performed. The emitted x-rays were registered in coincidence with down-charged Be-like uranium ions by germanium detectors mounted at observation angles in the range from 35° and 90° .

At low energy region of the Be-like spectrum two L-x-ray lines could be well resolved. These intra-L shell transitions correspond to the deexcitation of the 3P_2 and 1P_1 magnetic sublevels. From the comparison of the relative intensities of the $2p_{3/2}-2p_{1/2}$ and $2p_{3/2}-2s_{1/2}$ lines, we have found that in contrary to the ionization processes, the intensity ratio for capture into the P-states is close to the ratio of the $2J+1$ statistical population.

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Cometary Charge Exchange Aurorae from Solar Wind Helium Ions

D. Bodewits^{*}, R. W. McCullough[†], A. G. G. M. Tielens[‡], **R. Hoekstra**^{*}

^{*} KVI, Atomic Physics, Rijksuniversiteit Groningen
Zernikelaan 25, 9747 AA Groningen, The Netherlands

[†] Queen's University Belfast
BT7 1NN, Northern Ireland, UK

[‡] NASA Ames Research Center
MS 245-3, Moffet Field, CA 9435-1000, USA

Charge exchange X-ray and FUV aurorae can provide detailed insight in the interaction between solar system plasmas. Using the two complementary experimental techniques of photon emission spectroscopy and translation energy spectroscopy we have studied state selective charge exchange in collisions between fully ionized helium and target gasses characteristic for cometary and planetary atmospheres (H₂O, CO₂, CO and CH₄). The experiments were performed at velocities typical for the solar wind (200–1500 km/s). Data sets are produced that can be used for modelling the interaction of solar wind alpha particles with cometary and planetary atmospheres. These data sets are used to demonstrate the diagnostic potential of helium line emission. Existing observations of comets Hyakutake and Hale–Bopp are analyzed in terms of solar wind and coma characteristics. The case of Hale–Bopp illustrates well the dependence of the helium line emission both to collision velocity. For Hale–Bopp, our model requires low velocities in the interaction zone. We interpret this as the effect of severe post bow shock cooling in this extraordinary large comet [1].

The Extreme UV-Explorer burnt in the Earth atmosphere in early 2002. There is currently no observatory that can observe the helium FUV emission discussed here. Cometary X-ray emission however offers an even larger wealth of information on the interaction between comets and the solar wind, as every ionic species in the solar wind leaves its own fingerprint. This also implies that the observation and interpretation of these data will prove to be much more complex than the FUV data discussed here. Once more, this stresses the need for experiments involving highly charged carbon, oxygen, nitrogen and neon with 'cometary' atoms (O) and molecules (H₂O, CO). Only the combination of both high-quality laboratory data and detailed interaction models will allow for the use cometary FUV and X-ray aurorae as a unique, new diagnostic of solar system plasmas.

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AUTOIONIZATION EFFECTS ON THE PROMINENT X-RAY LINES OF THE CORE-EXCITED TRANSITIONS IN FE XVI

Marius Jonas Vilkas and Yasuyuki Ishikawa

Department of Chemistry, University of Puerto Rico, P.O. Box 23346 San Juan, Puerto Rico 00931-3346 USA

The interest in the core-excited energy levels above ionization limit is fueled by the fact that for heavier ions the radiative decay is predominant compare to the autoionization. This results in very strong emission in the x-ray region. While numerous authors published studies on the one-valence electron systems, high-accuracy theoretical studies of the core-excited states are rare. We have recently developed fully relativistic multireference Møller-Plesset (MR-MP) many-body perturbation theory [1] for general openshell, multi-valence-electron systems and successfully applied to simulate x-ray spectrum in Fe XVI. The state-averaged multiconfiguration Dirac-Fock self-consistent field procedure was applied for the ground and low-lying excited states in Na-like iron. Subsequent relativistic configuration

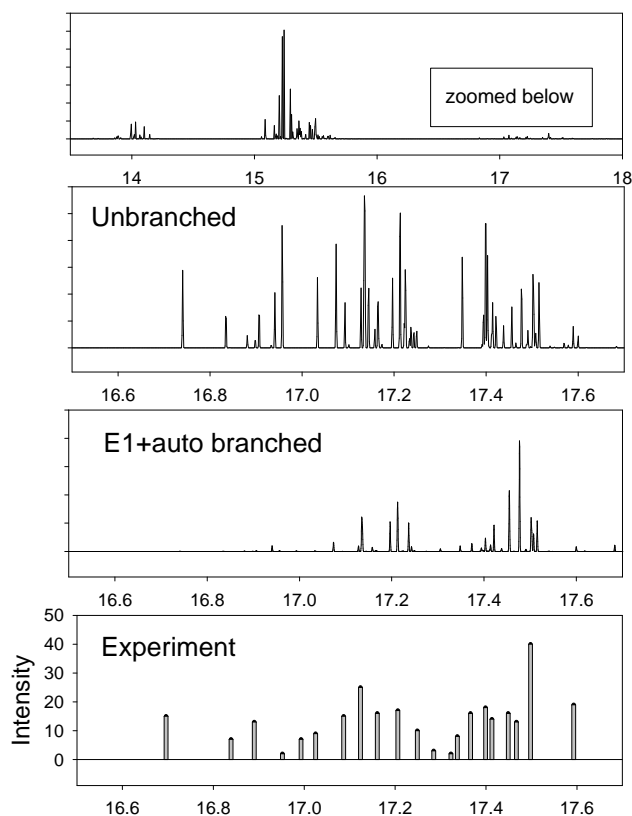


Figure 1. Comparison of MR-MP synthetic spectra with NIST Atomic Database.

interaction model space in MR-MP calculations [1] was limited to no more than two holes in $2s^22p^6$ core. Radiative corrections, the Lamb shifts, were estimated for each state by evaluating the electron self-energy and vacuum polarization. First-order frequency-dependent and independent Breit interaction, and normal and specific mass shifts on the ground and excited states, were estimated in the lowest order of the perturbation theory. In Figure 1, the simulated x-ray spectrum is compared with experimental data [2]. While major part of the x-ray emission is around 15.3 \AA and 14.0 \AA , the experimental data (consisting of 38 lines) is available only in $16.5\text{-}17.5 \text{ \AA}$ region. Including branching of the electric-dipole transition and autoionization in simulation substantially reduce the amount of theoretical prominent lines. In fact, the autoionization is the predominant decay channel for most of the core-excited states in sodiumlike iron. We found several incorrect tentative experimental identifications in the $16.5\text{-}17.0 \text{ \AA}$ region. Our calculated second-order MR-MP x-ray wavelengths are accurate to within 0.004 \AA compared with the solar lines. The radiative and autoionization rates have been calculated in the second-order of perturbation theory.

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RELATIVISTIC STUDY ON ATOMIC STRUCTURE FOR HYDROGEN-LIKE ATOMS IN SUPER-STRONG MAGNETIC FIELDS

M. Ozaki, H. Kamanaka and **T. Kagawa**

Department of Physics, Nara Women's University, Nara 630-8506, Japan

Recently the existence of strong magnetic fields of the order of 10^{10} - 10^{11} Gauss in the vicinity of white dwarfs has been confirmed through comparison between the theoretical results for energy levels in the hydrogen atom in strong magnetic fields [1,2] and the measured spectra from hydrogen atoms near the astrophysical objects [3,4]. In the nonrelativistic treatment of hydrogen-like atoms in a uniform and constant magnetic field, a simple scaling relation for the energy

$$E(Z, B) = Z^2 E(1, B/Z^2),$$

can be obtained from the Schrödinger equation so that it will be enough to consider only the hydrogen atom in arbitrary homogeneous magnetic fields when calculating energy levels for hydrogen-like systems with $Z > 1$ in any homogeneous magnetic fields. Even if the strength of the magnetic field becomes larger than that of the Coulomb attractive force due to the proton, that is, $\beta > 1$, $\beta = B/B_0$ and $B_0 = 4E_H\mu/(\text{e}\hbar) \approx 4.7 \times 10^9$ G, one can obtain very accurate energies for the systems under consideration by expanding a total wave function with the Landau-orbital basis set. On the other hand, in the relativistic treatment for the system the nonseparability between of the motion of the center-of-mass (c.m.) system and the relative motion for a two-body system in a homogeneous magnetic field brings various difficulties to obtain a relativistic wave equation suitable for practical calculations for the hydrogen-like systems. However if the infinite mass and no nuclear spin are assumed for the proton in the hydrogen atom, one can use the Dirac wave equation for it in a constant magnetic field as a starting relativistic wave equation. In this case various expansion methods developed in the nonrelativistic treatment for them depending on the magnetic field strength can be extended to the relativistic cases. It has been so far found from nonrelativistic and relativistic treatments an adiabatic approximation can also yield good energies for them when a super-strong magnetic field such as $\beta > 10^3$ exists. However there have been reported few studies on the relativistic effects on the energy for hydrogen-like systems in super-strong magnetic fields except those by Lindgren et.al. [5] and by Doman [6], where they have shown that the relativistic effects on the energies belonging to both the ground and the lowest excited Landau levels are very small. So it is still necessary to study on the relativistic effects on the energies for hydrogen-like systems to see how the scaling law for the energy given above is changed by the relativistic effects.

In this work, we carry out relativistic calculations for energy levels belonging to not only the ground Landau level but the excited Landau levels in hydrogen-like systems in homogeneous super-strong magnetic fields using the same way as that of Lindgren et.al. to see the validity of scaling relation described above for the relativistic energies for them. We also calculate atomic spectra from hydrogen-like systems in various super-strong magnetic fields. Numerical results will be seen in our poster.

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RCI SIMULATIONS FOR EUV SPECTRA FROM Sn AND Xe IONS

T. Kagawa, H. Ohashi*, H. Tanuma* and K. Nishihra**

Department of Physics, Nara Women's University, Nara 630-8506, Japan

*Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

**Institute of Laser Engineering, Osaka University, Suita, Osaka 565-0871, Japan

It has been confirmed with the observation of spectra from some elements in plasmas produced by high-power laser radiation and by discharge, that Sn is one of promising elements, which emit strong lines in the narrow wavelength region of 13.5 nm, in developing the EUV light sources for next-generation lithography machines. Recently Ohashi et. al. have measured EUV spectra from each Sn^{q+} and Xe^{q+} ions with the charge state of $q = 5$ through 16 produced by charge-exchange collisions between a charge-selected Sn or Xe ion and a rare gas such as He or Xe. Using the relativistic-configuration-interaction (RCI) atomic structure code we have carried out simulations for EUV spectra from Sn and Xe ions and shown that strong lines concentrated around 13.5 nm wavelength region observed are mainly due to overlap of lines emitted from Sn^{q+} and Xe^{q+} ions with the charge state of $q = 10$ through 12 around.

In this work we report comparison of the RCI simulated spectra from Sn and Xe ions with experiment of Ohashi et.al. In obtaining the simulated spectra for a particular ion, the wavelength range is divided into narrow intervals of 0.1 nm and the line intensity for each wavelength interval is then obtained as a sum of line intensities for the transitions whose wavelengths are included in this interval. In order to make clear assignment of the spectra observed, we carry out simulations for the spectra from all Sn and Xe ions considered by taking three values of 100 eV, 150 eV and 200 eV as the excitation-energy limit. When the magnitude of the limit of the excitation energy increases, new lines due to the transitions from higher excited levels newly taken into account appear in the simulated spectra so that one can assign these lines as a result of transitions related to the higher excited states. Since there are a number of states arising from configurations having many open shells with larger principal quantum numbers than three in the systems, it is difficult to assign each line observed as a single transition between one-electron states. Therefore we focus on the spectral shape of simulated spectra because it can be used to guess the maximum excitation energy for a Sn or Xn plasma leading to an electron temperature for a corresponding plasma produced in the experiment. In Fig., RCI simulated spectrum for Sn^{10+} ion with the electron temperature of 30 eV and the 150 eV excitation-energy limit is compared with the experimental one obtained by Ohashi et. al.. It is found from the figure that the RCI spectral shape of two broad peaks in the wavelength region between 12.5 nm and 17 nm is very similar to that of experimental one, although the peak positions in the simulated spectra are about 0.5 nm shifted to the short wavelength side compared to the experimental ones.

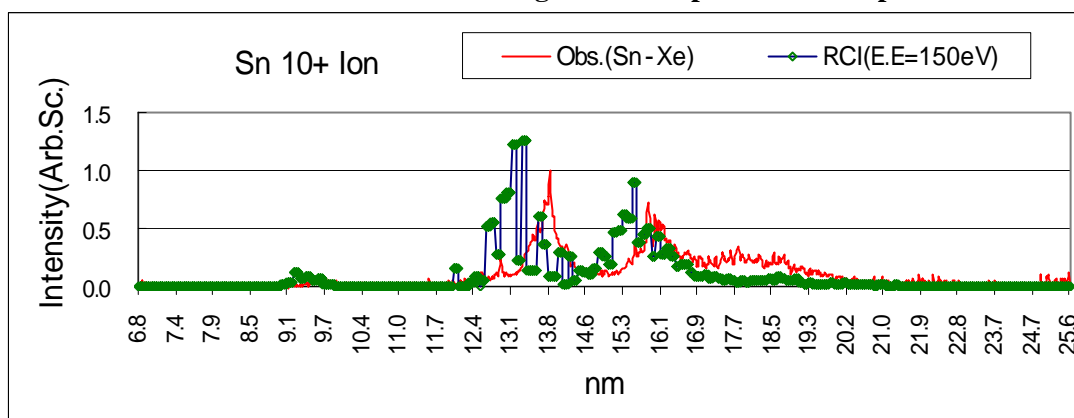


Fig. Comparison of RCI spectrum for Sn^{10+} with the excitation energy limit of 150 eV with the experimental one obtained by Ohashi et. al.

MULTIREFERENCE RELATIVISTIC CONFIGURATION INTERACTION CALCULATIONS OF E1 TRANSITIONS FOR SN IONS

Konrad Koc, L. Głowacki, J. Migdałek, T. Kagawa*

Department of Computer Science, Pedagogical University, ul. Podchorążych 2, 30-084 Kraków,
Poland

(*)Department of Physics, Nara Women's University, Nara 630-8506, Japan

Transition energies, E1 transition rates and oscillator strength for Sn^{+8} to Sn^{+20} ions have been calculated by using multireference relativistic configuration interaction method based on the no-pair Dirac-Coulomb-Breit Hamiltonian. Large even-tempered basis sets of Gaussian-type functions are employed to expand the upper and lower components of the Dirac four-spinors in the matrix Dirac-Fock self-consistent field and relativistic multireference RCI procedures. Energy levels and oscillator strength for transitions around 13.5nm were also calculated, for checking purposes, by means of RCI based on numerical DF SCF method.

RELATIVISTIC ATOMIC DATA FOR EUV AND X-RAY SPECTRA OF HIGHLY CHARGED Cu-, Zn-, Ga- AND Ge-LIKE IONS ($70 \leq Z \leq 92$)

P. Quinet^{1,2}, E. Biémont^{1,2}, P. Palmeri¹, E. Träbert³

¹ Astrophysique et Spectroscopie, Université de Mons-Hainaut, B-7000 Mons, Belgium

² IPNAS, Sart Tilman B15, Université de Liège, B-4000 Liège, Belgium

³ Physics and Advanced Technologies, Lawrence Livermore National Laboratory, Livermore, CA 94550-9234, USA

Recently, accurate experimental wavelengths for high Z ($Z \geq 70$) elements were measured at the Livermore electron beam ion trap (EBIT) for some transitions in the EUV and X-ray spectra of highly charged ytterbium ($Z=70$), tungsten ($Z=74$), osmium ($Z=76$), gold ($Z=79$), lead ($Z=82$), bismuth ($Z=83$), thorium ($Z=90$) and uranium ($Z=92$) along the copper, zinc, gallium and germanium isoelectronic sequences [1–4]. In these latter works, it was pointed out that available calculations for these ions, carried out with different theoretical approaches, featured different isoelectronic trends (relative to the experimental trend).

In the present work, a multiconfiguration Dirac-Fock (MCDF) technique [5–7] has been used for computing the wavelengths and transition probabilities for EUV and X-ray lines of Cu-, Zn-, Ga- and Ge-like ions from $Z=70$ to 92. Results are reported for the $n=4$, $\Delta n=0$ electric dipole transitions (E1) as well as for some forbidden transitions (M1 and E2). A detailed comparison of the calculated wavelengths with the available experimental results is also presented. These new theoretical data will be useful as a test of experimental observations, and their predictive power will be valuable where experimental data are missing.

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MCDF CALCULATIONS FOR EUV-EMISSIONS OF 4d-OPEN SHELL IONS BASED ON THE FEATURES OF NON-LOCAL EXCHANGE INTEGRALS

F. Koike, S. Fritzsche*, K. Nishihara**

Phys. Lab. School of Medicine, Kitasato University 1-15-1 Kitasato, Sagamihara 228-8555 Japan
e-mail: koikef@kitasato-u.ac.jp

(*)Universitaet Kassel, Heinrich-Plett-Str. 40, 34132, Kassel, Germany

(**)Institute of Laser Engineering, Osaka University 2-6 Yamadaoka, Suita 565-0871, Japan

The extreme ultra-violet (EUV) emissions of 4d open shell atomic ions are of interest in relation to the semiconductor technologies. Extensive efforts have been made for understanding the emission spectra from plasmas[1,2]. To assign the individual spectral lines, a series of sophisticated charge transfer experiments have been carried out for Xe ions[3], and for Sn ions[4] by Tanuma and his co-workers. To give a theoretical counterpart of these experimental data, we have tried to perform a set of accurate calculations of electronic states and optical processes based on an MCDF method. We employed GRASP92[5] and RATIP[6] for present calculations, of which advantages are that we can treat the two electron non-local exchange integrals as they are and that we can allow the relaxation of the orbitals separately to the upper and lower states.

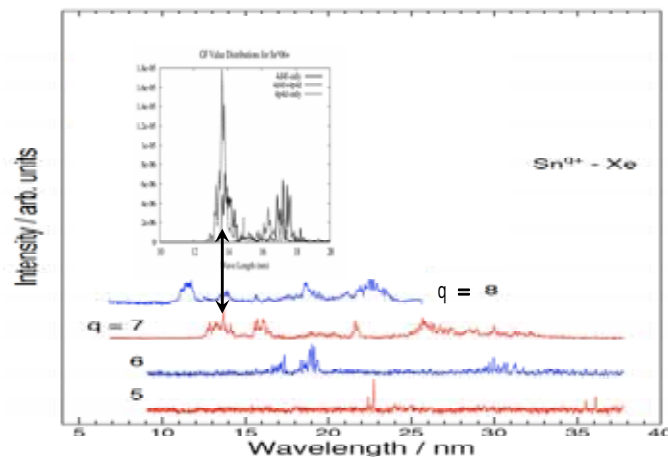


Fig.1. Comparison of the present theoretical calculations for 4d-4f emission spectra of Sn^{6+} with the experimental data of charge transfer in collisions of Sn^{7+} with Xe. The inset in the upper part of the figure is of the theoretical calculations. The line labeled $q = 7$ is of the corresponding charge transfer experiment[4].

Fig. 1. shows a typical example of the results of present calculations together with a couple of experimental data by Tanuma et al[4].

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M_F -Dependent Lifetimes Due to Hyperfine Induced Interference Effects

Martin Andersson¹, Ke Yao^{1,2,3}, Tomas Brage¹, Roger Hutton^{2,3}, Per Jönsson⁴, and Yaming Zou^{2,3}

¹ Department of Physics, Lund University, Box 118, S-221 00 Lund, Sweden

² The Key lab of Applied Ion Beam Physics, Ministry of Education, P.R. China.

³ Shanghai EBIT lab, Institute of Modern Physics, Fudan University, Shanghai, P.R. China

⁴ Nature, Environment, Society, Malmö University, Sweden

We report on a theoretical investigation of M_F -dependent lifetimes due to interference between different types of multipole transitions, and in particular the $3d^{10} \ ^1S_0 - 3d^9 4s \ ^3D_3$ transition in Nickel-like ions. For pure states this decay is only allowed through a magnetic octupole (M3) transition, but in the presence of a nuclear spin an electric quadrupole (E2) transition is induced by the hyperfine interaction, and the interference between the two types of multipoles makes the lifetimes of the hyperfine levels M_F -dependent.

Extensive Multiconfiguration Dirac-Fock calculations were performed to calculate the $3d^{10} \ ^1S_0 - 3d^9 4s \ ^3D_3$ M3 transition element, the $3d^{10} \ ^1S_0 - 3d^9 4s \ ^3D_2$ E2 transition element and the hyperfine interaction matrix elements between 3D_3 and 3D_2 . First order perturbation calculation were used to calculate the hyperfine induced E2 transition element and the M_F -dependent lifetimes.

Detailed results for Ni-like Xenon is presented. Xe consists of 9 different isotopes of which two have a nuclear spin (one with $I = 1/2$ and one with $I = 3/2$) resulting in 25 different lifetimes depending on isotope, F -value and M_F -value. [1] used a single exponential fit to experimentally determine the lifetime of the $3d^9 4s \ ^3D_3$ state in Ni-like Xe. It is shown that a single exponential could be fitted to a theoretical decay curve, where each lifetime was weighted according to a gas of natural mixing of isotopes, with good accuracy. Depending on which interval the single exponential was fitted to, different lifetimes was obtained.

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Poster Category 2

**Collisions with Electrons,
Ions and Molecules**

ANGULAR DISTRIBUTIONS AND DALITZ PLOTS FOR C^{6+} IONIZATION OF He

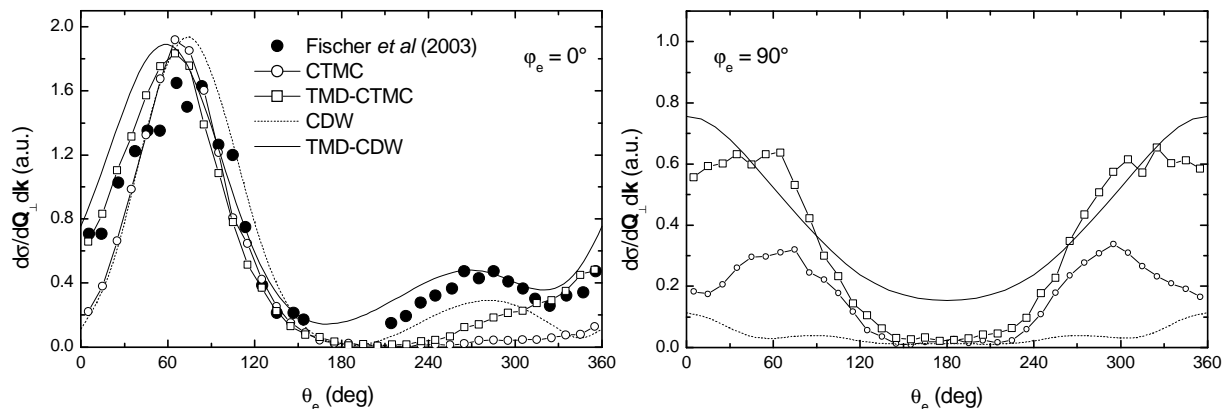
S.Otranto^{1,2}, J. Fiol³, R. E. Olson¹

- (1) Physics Department, University of Missouri-Rolla, Rolla MO 65401, USA.
(2) CONICET and Dto. de Física, Universidad Nacional del Sur, 8000 Bahía Blanca, Argentina.
(3) CONICET and Centro Atómico Bariloche, 8400 S. C. de Bariloche, Argentina.

Single ionization fully differential cross sections for 2 MeV/amu $C^{6+} + He$ collisions are presented and analyzed using the classical trajectory Monte Carlo (CTMC) and Continuum Distorted Wave (CDW) models. The present theoretical results are compared with recent experimental data of Fischer *et al* [1]. The published experimental conditions are considered in the theoretical models. The inclusion of the target atom momentum uncertainty leads to an improved description of the forward electron emission. Moreover, we present cross sections in the plane perpendicular to that of the collision, and describe how the inclusion of the target momentum spread modifies the angular structures and the intensities.

We show that previously reported theory-experiment discrepancies may be removed by convoluting the theoretical cross sections with the experimental resolutions. In the Figure are shown fully differential cross sections (FDCS) in the parallel and perpendicular planes for 2 MeV/amu $C^{6+} + He$ collisions. The emitted electron energy is 4 eV and the projectile momentum transfer is $Q=0.65$ a.u. It can be clearly seen that accounting for the target momentum distribution (TMD) improves the theoretical description in the forward direction where the electronic emission is increased by almost a factor 5. This also introduces a sharp increase of the theoretical cross sections in the perpendicular plane.

Dalitz plots for single ionization fully differential cross sections in ion-atom collisions will be presented and are used to help elucidate the collision dynamics [2].



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X-RAY EMISSION CROSS SECTIONS FOLLOWING CHARGE EXCHANGE BY MULTIPLY CHARGED IONS OF ASTROPHYSICAL INTEREST

S. Otranto^{1,3}, R. E. Olson¹, P. Beiersdorfer²

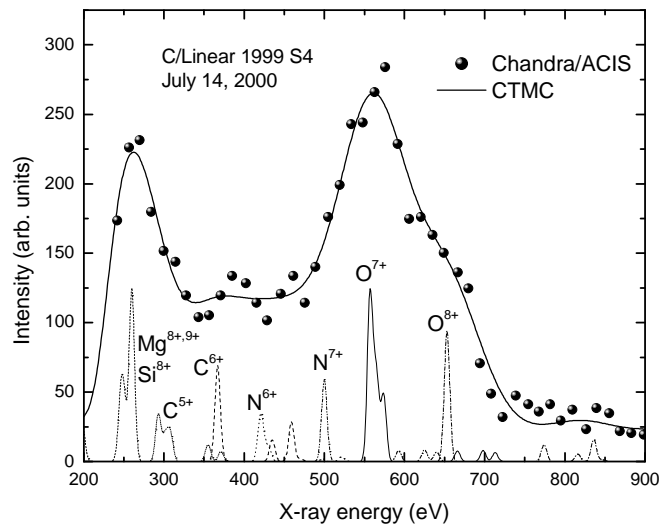
(1) Physics Department, University of Missouri-Rolla, Rolla, MO 65401, USA

(2) Department of Physics, Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

(3) CONICET and Dto. de Física, Universidad Nacional del Sur, 8000 Bahía Blanca, Argentina.

State selective nl -electron capture cross sections calculated using the classical trajectory Monte Carlo (CTMC) model are presented for highly charged ions with $Z = 6-10$ colliding with atoms and molecules. These nl -cross sections are used to determine x-ray line emission following decay from high-lying states. The emission cross sections compare favorably with measurements made by Greenwood *et al* [1] for O^{8+} and Ne^{10+} at 3 keV/amu, and with recent x-ray emission cross sections measured with the EBIT machine at LLNL using O^{8+} and $Ne^{9+,10+}$ on different targets at 10 eV/amu [2]. The calculated cross sections are used to present an *ab initio* determination of the soft x-ray spectrum of comet C/Linear 1999 S4 that was observed by the Chandra X-ray Observatory [3]. In the Figure below, we show the obtained spectrum which was built by using the CTMC absolute line emission cross sections and fitting the ion abundances. We explicitly show in the bottom 8eV FWHM resolution lines to indicate the different ions and number of emission lines considered for each ion. The obtained abundances will be compared to the recently published measurements of the Advanced Composition Explorer ACE/SWICS-SWIMS and those tabulated by Schwadron and Cravens [4].

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ELECTRON IMPACT EXCITATION OF Ne-LIKE Ni XIX

K. M. Aggarwal and F. P. Keenan

Department of Physics and Astronomy, Queen's University, Belfast BT7 1NN

Emission lines of Ni XIX have been observed in the spectrum of the solar corona, and are useful for plasma diagnostics. Additionally, nickel is an important impurity element in fusion reactors, and hence atomic data (namely energy levels, radiative rates, collision strengths, excitation rates, etc.) are required in order to estimate the power loss from the walls of the reactors. Furthermore, Ne-like ions are also very useful in lasing plasmas. Since there is a paucity of experimental data for most of the above named parameters, theoretical results are desirable. Therefore in this work, we report our results for transitions among 89 levels of the $(1s^2) 2s^2 2p^6$, $2s^2 2p^5 3\ell$, $2s 2p^6 3\ell$, $2s^2 2p^5 4\ell$, and $2s 2p^6 4\ell$ configurations of Ni XIX.

For the calculations of energy levels and radiative rates (A- values), we have adopted the *General purpose Relativistic Atomic Structure Package* (GRASP: [1]), and for the computations of collision strengths (Ω) the *Dirac Atomic R-matrix Code* (DARC: [2]). Additionally, resonances are resolved in a fine energy mesh in order to calculate excitation rate coefficients over a wide energy range up to 10^7 K. The *R*-matrix radius has been adopted to be 3.64 au, and 25 continuum orbitals have been included for each channel angular momentum for the expansion of the wavefunction. This allows us to compute values of Ω up to an energy of 240 Ryd. The maximum number of channels for a partial wave is 401, and the corresponding size of the Hamiltonian matrix is 10086. In order to obtain convergence of Ω for all transitions and at all energies, we have included all partial waves with angular momentum $J \leq 39.5$, although a higher range would have been preferable for the convergence of allowed transitions. However, to account for the inclusion of higher neglected partial waves, we have included a top-up, based on the Coulomb-Bethe approximation for allowed transitions and geometric series for forbidden ones.

Earlier calculations for this ion have been performed by Zhang et al. [3], who adopted the Coulomb-Born-exchange method. However, their calculations are deficient mainly because they did not resolve resonances, and reported values of Ω only at a few energies above thresholds. Since the contribution of resonances is often significant, even at the high temperatures at which data are required for Ni XIX, as demonstrated by Chen et al. [4] for transitions in Ne-like Fe XVII, there is an urgent need to include their contribution. Additionally, they calculated values of Ω for the resonance transitions only, whereas data are required for *all* transitions. Therefore, in this work we are attempting to make a significant improvement over their work. A detailed comparison with their results, along with our atomic data for all the desired parameters, will be presented during the conference.

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ABSOLUTE ELECTRON IMPACT EXCITATION CROSS SECTIONS FOR THE $\text{Fe}^{11+} 4\text{S}^0 \rightarrow 2\text{D}^0$ AND $\text{Fe}^{13+} 2\text{P}^0_{1/2} \rightarrow 2\text{P}^0_{3/2}$ TRANSITIONS

Sabbir Hossain¹, Steven J. Smith¹, Swaraj Tayal², and Ara Chutjian¹

¹Jet Propulsion Laboratory/Caltech, Pasadena CA 91109, USA

²Clark Atlanta University, Atlanta GA 30314, USA

The strong spectral lines of *Fe*, covering a wide wavelength range, are important for interpreting astrophysical observations obtained from the HST, EUVE, FUSE, *Chandra* and *Newton* missions. The Fe^{13+} coronal green line ($\lambda 5303 \text{ \AA}$) is the strongest forbidden line in the coronal spectrum; and is the most abundant high-*Z* element in galactic emission spectra. The theoretical status of cross sections (collision strengths) has improved considerably (*IRON Project*), but the calculations require verification using experimental data.

Reported herein are the first experimental cross sections for the dipole-forbidden transitions $3s^23p^3 4\text{S}^0 \rightarrow 3s^23p^3 2\text{D}^0$ in Fe^{11+} at 5.71 eV, and $3s^23p 2\text{P}^0_{1/2} \rightarrow 3s^23p 2\text{P}^0_{3/2}$ in Fe^{13+} at 2.34 eV. The experiments were conducted using the JPL 14.0 GHz electron-cyclotron resonance (ECR) ion source, along with the energy loss technique, in a merged electron-ion beams geometry [1,2]. The center-of-mass interaction energies for Fe^{11+} are from 5.0 eV (below threshold) to 7.5 eV for the $4\text{S}^0 \rightarrow 2\text{D}^0$ transition and for Fe^{13+} 1.5 eV (below threshold) to 6.5 eV for the $2\text{P}^0_{1/2} \rightarrow 2\text{P}^0_{3/2}$ transition. Comparisons are made between present experiments and R-matrix theoretical results [3]. Cross sections for the $\text{Fe}^{13+} 2\text{P}^0_{1/2} \rightarrow 2\text{P}^0_{3/2}$ excitation are presented in Figure 1. The error bars represent

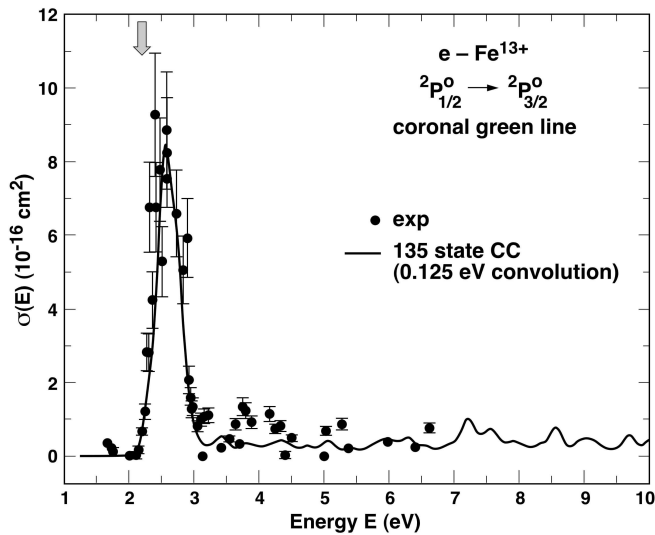


Figure 1. Absolute excitation cross sections for excitation of the forbidden M1 coronal green line in Fe^{13+} , with comparison to a 135 state R-matrix calculation. The vertical arrow indicates the transition threshold for this excitation (Hossain et al., unpublished).

only statistical uncertainties. For comparison with experiment the results of a 135 state R-matrix theoretical calculations have been convoluted with an experimental Gaussian energy beam distribution of 0.125 eV FWHM. There is good agreement between experimental results and the calculation.

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MOLECULAR ORIENTATION EFFECTS ON IONIZATION OF CO IN CHARGE-CHANGING COLLISIONS OF 6 MeV O⁴⁺ ION

T. Mizuno, T. Majima*, H. Tsuchida, Y. Nakai**, and A. Itoh

Department of Nuclear Engineering, Kyoto University, Kyoto 606-8501, Japan

*Genesis Research Institute, Inc., Ichikawa 272-0001, Japan

**RIKEN (The Institute of Physical and Chemical Research), Wako, Saitama 351-0198, Japan

In the past decade, orientation dependence of multiple ionization of molecules have been intensively investigated owing to remarkable experimental progress of multiple coincidence techniques involving momentum 3D imaging [1]. Evidence for the orientation effect has been observed for rather high charge states of prefragmented molecule such as (CO)^{r+}, (N₂)^{r+} and (NO)^{r+} with $r > 4$ [2] and not observed for lower charge states. We attribute this reason to a fact that final charge states of projectile particles have not been measured in these experiments.

In this work, we study collision-induced fragmentation and ionization of CO in collisions with 6 MeV O⁴⁺ ions by means of a technique of momentum 3D imaging in coincidence with projectile final charge states. The present method enables us to determine molecular orientation and kinetic energy release from momentum vectors of fragment ions for individual charge-changing collisions. Data analysis is carried out by using an axial recoil approximation [1] valid in fast ion impacts since molecular fragmentation is a fast process compared with a duration of molecular rotation. Thus, one can identify individual reaction channels of, e.g.,

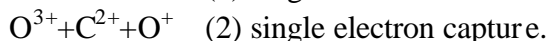
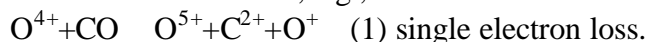


Fig.1 shows orientation dependence of cross sections for the production of C²⁺+O⁺ in single electron loss (1e-loss) and capture (1e-capture) collisions. One can see obviously that a strong anisotropic dependence is observed for loss collisions and a weak dependence for capture collisions. Namely, 1e-loss events occur preferentially in near-parallel orientation with respect to the beam axis, while 1e-capture events take place in perpendicular orientation. Since the ionization potential of O⁴⁺ is about 114 eV which is considerably large and only violent collisions, or small impact-parameter collisions, may be important for electron loss events. On the other hand, electron capture by O⁴⁺ is expected to occur in relatively soft collisions. Present results of different behaviours in loss and capture collisions are qualitatively in good agreement with above arguments. It should be noted that both product ions C²⁺ and O⁺ originate from (CO)^{3+*} of which charge state is considerably low compared with those in other experimental results [2]. Hence, we conclude that a coincidence technique involving charge-changing collisions can serve as a promising tool to achieve close inspection of orientation effects on molecular ionization.

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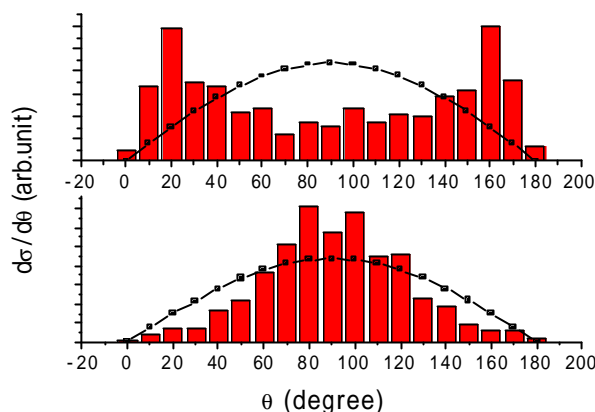


Fig.1 Orientation dependence of production cross sections of C²⁺+O⁺ in single electron loss(upper) and capture (lower) collisions. Dotted lines show isotropic distributions expressed by a sine curve .

FINE STRUCTURE EFFECTIVE COLLISION STRENGTHS FOR THE ELECTRON IMPACT EXCITATION OF SV

Claire Hudson, Ken Bell

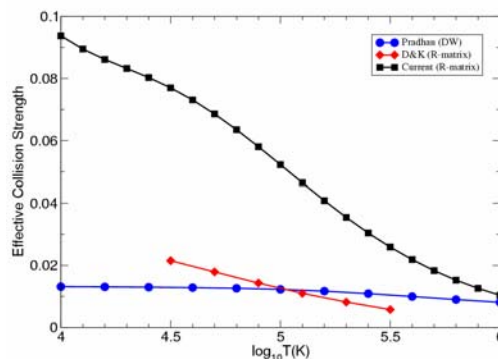
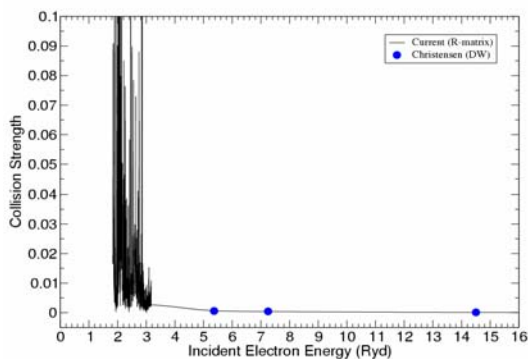
Dept. of Applied Maths & Theoretical Physics, Queen's University Belfast, Belfast BT7 1NN, UK

Sv emission lines have been observed in solar flares, solar upper atmospheres, quiet sun regions and broad band absorption line quasars, with particular lines being used as diagnostics for electron temperature and density. Accurate collision strengths are needed to analyse the observed data and to date the best available calculations for this ion have not included contributions from resonances.

The most recent theoretical evaluations are the R-matrix calculation of Dufton & Kingston [1] and the distorted-wave approximation of Pradhan [2]. Discrepancies have been noted between the earlier calculations and observed data. For example, Doschek et al [3] have used the results of Pradhan [2] for the $786.48\text{\AA}/1199.13\text{\AA}$ ratio i.e. $(3s^2\ ^1S_0 \rightarrow 3s3p\ ^1P^o_1)/(3s^2\ ^1S_0 \rightarrow 3s3p\ ^3P^o_1)$, and find that theory predicts an intensity ratio which is a factor of five larger than the observed ratio.

In this work, Configuration Interaction (CI) wavefunctions describe the target 'N electron' system. The target states are the 14 lowest *LS* states of SV, and the wavefunctions are calculated by the CIV3 code [4]. The ion-plus-electron (N+1) system is described by the R-matrix method of Burke & Robb [5], using computer codes detailed by Berrington et al [6]. Fine structure collision strengths are obtained by transforming to a *jj*-coupling scheme using the JAJOM program of Saraph [7].

Collision strengths and Maxwellian averaged effective collision strengths have been determined for the 325 transitions arising from the 26 *j*-levels considered. To illustrate the comparison with the earlier works, the $3s^2\ ^1S_0 \rightarrow 3p^2\ ^3P_1$ transition is shown below. The enhancement at low temperatures in the current calculation arises from the inclusion of and a careful treatment of the resonances.



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SINGLE AND DOUBLE ELECTRON CAPTURE FOR SLOW He²⁺ IMPACT ON ATOMS AND MOLECULES

S. Figueira da Silva, G. Kowarik, F. Aumayr, HP. Winter
Institut für Allgemeine Physik, Vienna University of Technology, Austria

Abstract

A new compact experimental setup has been utilized for measuring absolute cross sections for single (SEC) and double electron capture (DEC), and transfer ionization (TI) in collisions of slow (impact energy typically 0.1 – 1 keV x q - ion charge state) singly and multiply charged ions with gaseous atoms and molecules. The technique combines the collection of slow ions and electrons with primary ion beam attenuation and stopping in a differentially pumped target gas chamber in which the pressure is measured by an absolutely calibrated capacitance manometer. The primary ions are furnished by a 14.5 GHz all-permanent magnet ECR ion source with its extraction geometry optimized for low ion beam energy [1].

Reliability of the new experimental setup has been demonstrated by proof-of-principle measurements in comparison with available SEC and DEC data for impact of slow singly and doubly charged noble gas ions (He, Ne, Ar) on their own atoms. For slow doubly charged primary ions, resonant DEC is the clearly dominant contribution. Furthermore, SEC by He²⁺ from Ne has been studied where at low impact energy only one SEC channel is open [2].

The interaction of slow alpha particles (He²⁺) on H₂ and O₂ will be of considerable relevance for radiation cooling in the outer edge of magnetically confined burning fusion plasmas. In particular, impact of slow He²⁺ on H₂ and O₂ gives rise to DEC, direct SEC into radiative excited states, and dissociative TI [2,3], as will be demonstrated and discussed in this paper.

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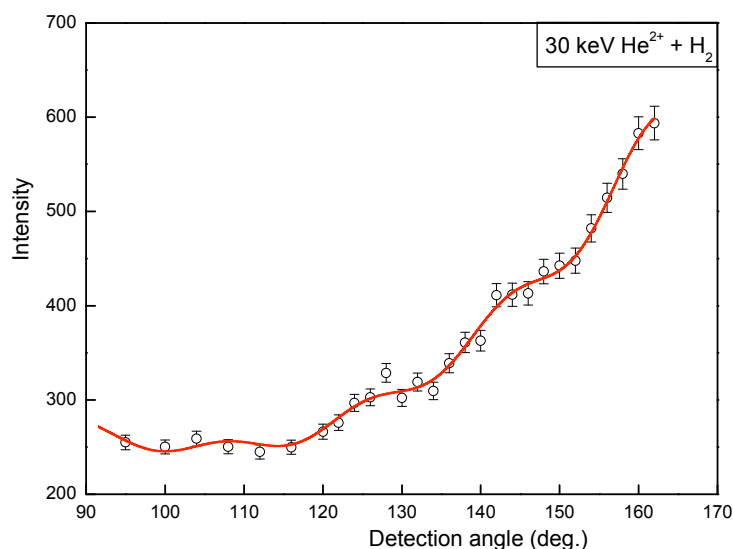
EXPERIMENTAL EVIDENCE FOR YOUNG'S INTERFERENCE EFFECTS IN AUTOIONIZATION FOLLOWING 30 keV He²⁺ + H₂ COLLISIONS

F. Frémont, A. Hajaji, R. O. Barrachina* and J.-Y. Chesnel

CIRIL Ensicaen, 6 bd du Mal Juin, 14050 Caen Cedex France

* Centro Atómico Bariloche, R8402AGP S. C. de Bariloche, Río Negro, Argentina

Recently, post-collision interaction effects produced on the autoionization effects of doubly excited states He^{**} atoms in slow He²⁺ + H₂ collisions have been studied theoretically [1]. Oscillations could be evidenced in the angular distributions of the Auger electrons emitted by the projectile. These oscillations were attributed to Young's interference effects due to the interaction of the emitted electron and both H⁺ target centres.



In the present work, emitted electrons following double capture in 30 keV He²⁺ + H₂ collisions have been analyzed at detection angle θ_d ranging from 90° up to 162°. The measured intensity for total Auger electron emission is presented in Fig. 1 (circles). To derive the corresponding differential cross section $d\sigma_A/d\Omega$, one would have to multiply this intensity by a geometrical factor which takes into account the experimental conditions. Although this factor is practically proportional to $\sin\theta_d$, it is not accurately known and, thus, only the raw data are shown here.

At first sight, the intensity is found to increase with increasing θ_d . However, more importantly, the data show clear evidence for a periodic oscillation superimposed on the main dependency. To emphasize the visibility of this oscillation, the intensity is fitted by the sum of a polynomial of order 2, and a Bessel function (Full curve in Fig. 1). The period of the oscillations is $\sim 17^\circ$, which is close to the value found theoretically [1]. The observation of oscillations suggests that the present experiment provides an unprecedented proof of the wave nature of the electron, by showing that a unique electron interferes with itself while passing a Young-like two centre system.

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CHARGE EXCHANGE OF HIGHLY CHARGED ARGON IONS AS A FUNCTION OF PROJECTILE ENERGY

C. Biedermann, F.I. Allen, R. Radtke, G. Fußmann

Institut für Physik der Humboldt-Universität zu Berlin, Lehrstuhl Plasmaphysik, Newtonstraße 15, D-12489 Berlin and Max-Planck-Institut für Plasmaphysik, EURATOM Association, Germany

Line emission from charge transfer reactions between highly charged ions and neutral gas atoms can be used as diagnostic of laboratory plasmas in fusion devices or astrophysical objects such as comets or solar flares. When a highly charged ion approaches a gas neutral, electrons are captured into Rydberg states of the ion. The process can be described by the classical over-the-barrier model, predicting the principle quantum number of the state into which the electron is transferred. The excited electron then cascades to the ground level resulting in a radiative emission spectrum characteristic of the interacting species and the capture state. The relative intensities of emission lines depends on the orbital angular momentum of the capture state which varies from a statistical population at high collision velocities to lower angular momentum values for slow collisions.

Highly charged ions are produced nearly at rest with the Berlin Electron Beam Ion Trap and extracted with a potential of 5 kV for interactions with a gas target. Ions in the extracted pulse are selected according to their mass-to-charge ratio using a Wien filter arrangement and target gas is injected into the beamline via a pulsed supersonic jet. The radiation emitted after electron transfer collisions is observed with a solid-state x-ray detector of large acceptance angle.

For charge exchange between Ar^{q+} ($q=17, 18$) and Ar atoms the model predicts preferential capture into the $n=8$ level. Theoretical emission spectra for electron capture into all orbital angular momentum states of $n=8$ have been calculated and are compared with the experimental spectra.

Using a deceleration grid assembly just in front of the target area projectile ions can be retarded from $125q$ eV/u energies to below $0.25q$ eV/u. Thereby the projectile velocity is determined and the angular momentum of the capture state can be controlled. The observed x-ray spectrum varies significantly with the collision velocity. The so-called hardness ratio, the ratio of $n>2 ? 1$ emission to $n=2 ? 1$ emission, increases with decreasing collision velocity and the values deviate from the results of simulations and earlier observations.

In addition charge exchange is studied with ions confined in the EBIT during magnetic trapping mode, when the electron beam is periodically switched off, by observing x-rays from charge exchange with residual gas atoms. In this mode the projectile velocity of the highly charged ions is given by the trapping conditions and is not precisely known. The resulting charge exchange spectrum differs from the spectra of extracted ions.

The authors would like to acknowledge the fruitful collaboration with S. Fritzsche, Universität Gh Kassel.

K-SHELL AND TOTAL IONIZATION CROSS SECTIONS FOLLOWING ELECTRON + MOLECULE COLLISIONS : A SCALING LAW

A. Hajaji, J.-Y. Chesnel and F. Frémont

Centre Interdisciplinaire de Recherche Ions Lasers, Unité Mixte CEA-CNRS-EnsiCaen-Université de Caen Basse-Normandie, 6 bd du Mal Juin, F-14050 Caen Cedex France

Very recently, the ratio σ_K/σ_{tot} between K -shell ionization cross sections and total ionization cross sections following collisions of electrons and H₂O vapor target has been determined experimentally for projectile energies E_{proj} ranging from 600 eV to 4 keV. At energies below 1 keV, the present ratio is close to that found for a O atomic target. At higher projectile energies, it reaches that determined for a Ne target. At present, no successful explanation is given for such result.

Since σ_K/σ_{tot} for H₂O differs significantly from that extrapolated for atomic targets, we performed experiments with various molecular targets (N₂, CH₄, C₃H₄). In these experiments, the electrons originating from direct ionization and from autoionization were detected at angles in the range 30° – 130° with respect to the incident beam direction. Projectile energies ranging from 350 eV to 4 keV were explored. The shape of the ratio is strongly dependent on the nature of the target. In the case of electron projectiles colliding on X_nH_m molecules, the ratio follows that of the corresponding X atom at low energies, and deviates at higher energies. In contrast, the ratio for N₂ is very similar to that found for N.

From the well known formula developed by Kim and Rudd [2], we show that the ratio σ_K/σ_{tot} is dominated, at large projectile energies, by the parameter $\alpha = N_K B / N B_K$, where N and N_K are the number of electrons in the outer and K shells, respectively, and B and B_K are the corresponding binding energies. Hence, we represented the ratio $(\sigma_K/\sigma_{tot})/\alpha$, in the case of the electron-molecules we investigated, as a function of the reduced parameter $U = E_{proj}/B_K$. We find that, within 10 %, the present ratio is well fitted using the function $R \ln U / U^p$, with $R = 0.25 \pm 0.02$ and $p = 0.19 \pm 0.04$. This result does not apply to electron-atom collisions.

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The role of the charge numbers of heavy particles on the dose distribution

Kengo Moribayashi

Advanced Photon Research Center, Quantum Beam Science Directorate,
Japan Atomic Energy Agency, ,8-1, Kizu-cho, Kyoto, 619-0215, Japan

The collision of highly charged ions with materials is good research objects for physics of atomic and molecular, radiation, and biological, medical science, and nano-technology. When we study them, we need to treat the dose distribution (or stopping powers). Then, the charge number of the ions, which changes as a function of time, plays an important role [1]. When we treat protons as a projectile, the charge numbers are mainly determined by processes of charge transfer ($A^{z+} + B \rightarrow A^{(z-1)+} + B^+$), and electron loss of the projectile ($A^{z+} + B \rightarrow A^{(z+1)+} + B + e^-$), where A^{z+} , B , and e^- are a heavy particle, a target molecule, and an electron, respectively, and z is the charge number of the particle [2]. For highly charged ions, the charge transfer processes have often produced excited states of ions or atoms. The excited states may play an important role for the change of the charge number [3, 4]. In this paper, we study the role of charge numbers and excited states on the dose distribution by treating the projectile of He, Li, and C ions and the targets of H_2 molecules.

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ELECTRON CAPTURE BY O^{3+} IONS FROM He, H₂O and CO₂

O. Abu-Haija, J. A. Wardwell, and E. Y. Kamber

Physics Department, Western Michigan University, Kalamazoo, MI 49008, USA

A number of mechanisms have been suggested for the charge balance of astrophysical plasmas and the origin of the x-ray emission from comets and planetary atmospheres. One of those is the electron capture mechanism between multiply charged ions present in the solar wind and atmospheric and cometary gases. Electron capture processes can also significantly affect the thermal and ionization structure of a wide variety of astrophysical plasmas. Data for electron capture are therefore essential to the understanding and interpretation of the O^+ and O^{2+} emission lines in interstellar medium [1,2].

Using the translational energy-gain spectroscopy technique [3], we have measured the energy-gain spectra and absolute total cross sections for single and double-electron capture in collisions of O^{3+} ions with He, H₂O, and CO₂ at laboratory impact energies between 0.3 and 1.2 keV. At the lowest collision energy, 300 eV, the energy-gain spectrum for O^{3+} - He collisions indicates that capture into the $2s2p^3\ ^3P$ state of the product O^{2+} is the dominant reaction channel observed with smaller contributions from capture into the $2s2p^3\ ^1D$, 3S and 1P states. For O^{3+} - H₂O collisions, the dominant peak correlates with capture into the $2p3p$ state of O^{2+} , with a significant contribution involving capture into the $2p3s$ state. In O^{3+} - CO₂ collisions, the dominant reaction channel is due to capture into the $2p3s$ state of O^{2+} , with contributions from capture into the $2p3p$ state.

These processes are observed to be the dominant reaction channels over the entire impact energy region studied and at the laboratory scattering angles between 0° and 5° . The energy-gain spectra are interpreted qualitatively in terms of the reaction windows, which are calculated using the Landau-Zener model and the extended version of the classical over-the-barrier model.

The energy dependence of total cross-sections for single-electron capture are also measured and found to slowly increase with increasing impact energies. The measured cross sections are also compared with the available and theoretical results based on the multi-channel Landau-Zener model.

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USING COLD ATOMS TO INVESTIGATE CHARGE TRANSFER PROCESSES

V. G. Hasan, S. Knoop*, R. Morgenstern, R. Hoekstra

KVI, Atomic Physics, Rijksuniversiteit Groningen, The Netherlands
(*Institut fuer Experimentalphysik, Innsbruck, Austria)

Laser cooling and trapping of atoms is an ideal tool to obtain cold targets in atomic collision studies. Because of the low temperature and thus small velocity spread of the atomic sample it facilitates experiments with well-localized and low-momentum target atoms. Furthermore, it naturally provides the possibility to study collisions with laser excited atoms.

MOTRIMS combines two concepts of the cold atoms and atomic collision community, namely magneto-optical trapping (MOT) and recoil-ion momentum spectroscopy (RIMS). We have applied MOTRIMS to study (multi-) electron capture and ionization processes in keV (highly charged) ion - atom collisions, using Na atoms as target. By measuring the small recoil momentum of the target ion both the final state distributions as well as impact parameter sensitive information are obtained.

We will present here several recent results. We have investigated single ionization of ground state Na(3s) and excited Na*(3p) by low energy impact of highly charged ions: Xe¹⁸⁺, O⁶⁺ and He²⁺. It is found that ionization of these weakly bound alkali systems yields larger cross sections than predicted from scaling laws derived from H and He targets.

Regarding multi-electron processes a spin-blocking phenomenon is observed in the production of Na³⁺ recoil ions in He²⁺ + Na(3s) collisions. Also we have identified distinct two-electron transfer processes in O⁶⁺ + Na(3s) collisions and found that correlated capture of two non-equivalent electrons contributes significantly.

ELECTRON CAPTURE AND IONIZATION IN COLLISIONS OF MULTIPLY CHARGED IONS WITH H(2s)

L. F. Errea, F. Guzmán¹, Clara Illescas, **L. Méndez**, B. Pons*, A. Riera and J. Suárez

Laboratorio Asociado al CIEMAT de Física Atómica y Molecular en Plasmas de Fusión.

Departamento de Química, Universidad Autónoma, 28049 Madrid, Spain.

(*) CELIA (UMR CNRS), Université de Bordeaux I, 351 Cours de Libération, 33405 Talence
Cedex, France.

In recent works [1], we have employed semiclassical molecular expansions and CTMC methods to evaluate nl partial cross sections for electron capture in Ne^{10+} and $\text{Ar}^{(16,17,18)+} + \text{H}(1s)$ collisions in a large energy range ($0.2 < E < 1000 \text{keV/amu}$); these cross sections are needed in diagnostics (CXRS) of tokamak plasmas. In this work we have studied collisions of He^{2+} , B^{5+} and Ne^{10+} with $\text{H}(2s)$, which can be formed by electron collisions with the atoms of the diagnostic H beam. For the particular case of $\text{B}^{5+} + \text{H}(2s)$ (fig.1), we have employed in the semiclassical calculation a large basis set (223 molecular orbitals), which includes the orbitals dissociating into $\text{Be}^{4+}(n = 2 - 10) + \text{H}^+$, and $\text{Be}^{5+} + \text{H}(n = 1, 2)$ that are required to obtain converged cross sections for the most populated capture channels ($\text{B}^{4+}(n = 6 - 8)$). In the classical calculation we have used a gaussian-type initial distribution for $\text{H}(n = 2)$ (see [1]), and we have retained only those trajectories with normalized angular momentum \bar{L}_c fulfilling [2] $0 < \bar{L}_c < 1$, which yields a reasonable agreement with quantal spatial and momentum distributions. Results for He^{2+} , and Ne^{10+} collisions with $\text{H}(2s)$ will be presented at the conference.

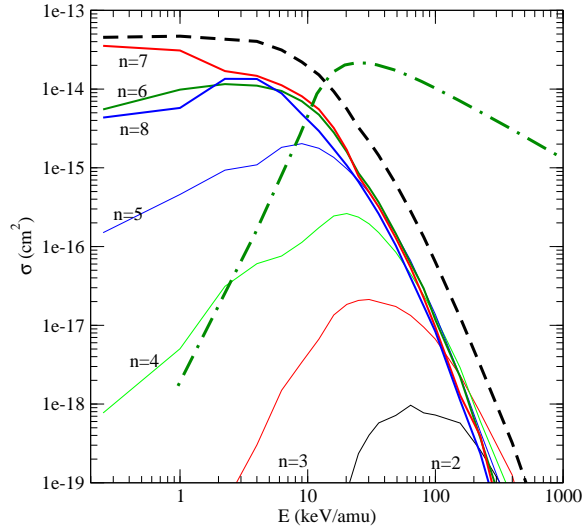


Figure 1: Cross sections for electron capture in $\text{B}^{5+} + \text{H}(2s)$ collision: Full thin lines, partial cross sections; dashed line, total cross section. Dashed-dotted line, ionization cross section.

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¹Also at Laboratorio Nacional de Fusión (CIEMAT)

FULLY DIFFERENTIAL CROSS SECTIONS FOR 3.6 MeV u^{-1} $Au^{Z_P^+} + He$ COLLISIONS

D.S.F Crothers, C.J. McGrath, R.T. Pedlow, S.F.C. O'Rourke

Department of Applied Mathematics and Theoretical Physics, Queen's University Belfast, Belfast
BT7 1NN, Northern Ireland

Recent experimental data for fully differential cross sections (FDCS) have been compared to various continuum-distorted-wave eikonal-initial-state (CDW-EIS) models without much success, despite good agreement with double-differential cross sections. We will present theoretical results from a four-body problem for FDCS of 3.6 MeV/u $Au^{Z_P^+} + He$ collisions, $Z_P = 24, 53$, with ejected electron energy of 4 eV. Theoretical results for the inclusion and omission of the internuclear potential will be given. Results are an improvement on current CDW-EIS calculations for these collisions, especially in the Au^{24+} case. The experimental forward scattering peak is visible in the form of a "bulge" in the theoretical results.

The inclusion of the internuclear potential has shifted all the Au^{24+} results to the left, resulting in improved agreement with the shape of the experimental data.

In the case of Au^{53+} it is seen that the inclusion of the internuclear potential has had very little effect on the shape of the theoretical data. However, due to lack of other absolute theoretical data it is difficult to compare these results though other recent results have been published [4]. Nevertheless, the shapes of all sets of data are in good agreement.

The discrepancies between theory and experiment might be resolved if and when magnetic quantum numbers are taken into consideration using the generalized CDW-EIS method.

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ANGULAR ANALYSIS OF PHOTON EMISSION FROM THE HEAVY, FEW-ELECTRON IONS

Andrey Surzhykov, Ulrich D. Jentschura, Stephan Fritzsche*, and Thomas Stöhlker**

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

(*) Universität Kassel, Germany

(**) Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany

Studies of the charge transfer in relativistic ion-atom collisions have a long tradition at the GSI storage ring [1]. In the radiative electron capture (REC), for instance, a free (or quasi-free) electron is captured into a bound state of the heavy projectile ion, accompanied by the simultaneous emission of a recombination photon. The angular and polarization properties of such x-ray recombination emission have been explored in a number of experiments and have revealed important information on the dynamics of the electron capture in the presence of strong electromagnetic fields [1]. Apart from measuring the recombination photons, recent studies have also focused on the subsequent *radiative decay* of heavy ions following the electron capture into their excited states. In particular, several experiments have been performed to explore the capture into the $1s\ 2p_{3/2}\ ^{1,3}P_{1,2}$ states of (initially) hydrogen-like U^{91+} uranium ions and their subsequent radiative $K\alpha_1$ ($^{1,3}P_{1,2} \rightarrow ^1S_0$) decay [2, 3]. This bound-bound transition gave rise to an almost *isotropic* angular distribution of the characteristic radiation, quite in contrast to expectations from a "one-electron" model where the Lyman- α_1 ($2p_{3/2} \rightarrow 1s_{1/2}$) following REC into (initially) bare ions is known to exhibit a strong angular dependence. A more detailed theoretical analysis is, therefore, required to understand the formation of the excited states of few-electron ions and their subsequent radiative decay, including a careful treatment of electron correlations.

In this contribution, we present a density matrix approach [4] for the description of the REC into excited ionic states and their subsequent decay, including many-electron effects and non-dipole contributions of the radiation field. By using such an approach, we perform detailed calculations for the L -shell electron recombination of (initially) hydrogen-like U^{91+} uranium ions and the subsequent $K\alpha_1$ decay. From these calculations, it is seen that the isotropy of the $K\alpha_1$ radiation results from the mutual compensation of its (strongly anisotropic) fine-structure components $^1P_1 \rightarrow ^1S_0$ and $^3P_2 \rightarrow ^1S_0$ which are usually not resolved in nowadays experiments [5]. Theoretical values for the anisotropy parameter of the $K\alpha_1$ decay are computed for a wide range of projectile energies and are compared to available experimental data.

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MULTIPLE IONIZATION OF LIQUID WATER BY SWIFT HEAVY IONS

Mariel E. Galassi, Pablo D. Fainstein*, Benoit Gervais** and **Roberto D. Rivarola**

Instituto de Física de Rosario (IFIR-UNR), Av. Pellegrini 250, 2000 Rosario, Argentina

(*) Centro Atómico Bariloche, Av. Bustillo 9500, 8400 Bariloche, Argentina

(**) Centre Interdisciplinaire de Recherches Ions Laser, F-14070 Caen, Cedex 05, France

The processes of multiple ionization (MI) and fragmentation of water molecules by ion impact are present in many subfields of physics, chemistry, and radiobiology. For example, the most important processes occurring during irradiation of biological tissue with fast heavy ions are the electronic ionization and excitation of the target molecules. In particular, ionization of water molecules produces an indirect effect on the DNA molecules due to formation of free radicals (water radiolysis), which provokes biological damage. Thus, an accurate theoretical computation of single and multiple ionization cross sections is very important for modelling purposes.

Previous calculations of MI cross sections (MICS) of water by heavy ions were made using a Monte Carlo approach, including one adjustable parameter determined by comparison with experimental data [1]. However, the computation of this parameter is more difficult when experimental results are not available.

In the present work we determine theoretical MICS of liquid water in the framework of the Independent Particle Model (IPM). So, the computation of single particle probabilities as a function of the impact parameter is necessary. To obtain these probabilities, we have used two different methods: the Exponential Model (EM) and the Continuum Distorted Wave - Eikonal Initial State (CDW-EIS) approximation [2]. Within the Exponential Model, it is assumed that the molecular orbitals present a spherical form (centered in the oxygen atom). The single-electron emission probability for each shell are described by exponential functions $p_i(\rho) = p_{i0}e^{-\rho/r_i}$, where p_{i0} is the ionization probability from the shell i at $\rho = 0$ and r_i is the radial expectation value. The p_{i0} values are chosen as adjustable parameters to reproduce CDW-EIS cross sections. The radii are calculated taking into account the binding energies of the corresponding orbitals for liquid water. Details on the molecular CDW-EIS approximation are described in reference [2]. We have checked that the use of any of these methods does not change strongly the proportion of multiple ionization. When double ionization is considered it is shown that ejection from two different orbitals dominates the reaction, being largely preferable than emission of the two outer-shell electrons.

Theoretical MICS were employed as input data in a Monte Carlo code to study water radiolysis by ion impact [3,4]. A very good description of experimental radiolytical yields was obtained.

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INTERFERENCES IN ELECTRON EMISSION SPECTRA FROM 1, 3, AND 5 MeV H^+ + N_2 COLLISIONS

J.A. Tanis, J.L. Baran, F. Jarai-Szabo* and L. Nagy*

Department of Physics, Western Michigan University, Kalamazoo, MI 49008 USA
(*) Faculty of Physics, Babes-Bolyai University, 400084 Cluj, Romania

Previously, we investigated interference structures in the electron emission spectra of H_2 resulting from 1-5 MeV H^+ impact [1]. These structures are due to coherent electron emission from the identical atomic centers of H_2 producing both primary (Young-type) and secondary oscillations. The primary oscillations depend strongly on the electron observation angle and to a lesser extent on the collision velocity. In contrast, the secondary oscillations, attributed to intramolecular scattering [2], show little variation with either emission angle or collision velocity.

To date, electron interferences for diatomic molecules other than H_2 (or D_2) have been studied only for K-shell electron ejection from N_2 by photons [3], in which the observed interference was attributed solely to intramolecular scattering. In the present work, our previous studies for H^+ + H_2 collisions [1] are extended to N_2 for which electron ejection is expected to occur primarily from the L-shell, which has a binding energy nearly identical to that of H_2 . Since the internuclear separation of N_2 is somewhat larger than that of H_2 (2.1 a.u. compared to 1.4 a.u.), equivalent to increasing the “slit” separation in Young’s experiment, a higher oscillation frequency for the primary interference structure is expected for N_2 compared to H_2 .

Electron emission spectra for 1, 3, and 5 MeV H^+ + N_2 collisions, obtained using the Western Michigan University tandem Van de Graaff, were measured for several observation angles ranging from 30° to 150° and for ejected electron energies from 5-400 eV. To extract interference structures, the measured molecular N_2 cross sections were divided by calculated atomic N cross sections in a manner similar to that used for H_2 [1,2]. Typical results from this analysis are shown in Fig. 1.

In contrast to H_2 , the primary oscillation frequencies for N_2 , determined by fitting the cross section ratios with a damped sine function as in Ref. [1], appear not to depend strongly on the electron observation angle or the collision velocity. The frequencies are ~ 1.5 times higher than for H_2 at 30° , a value that is consistent with the larger internuclear separation. A brief analysis for N_2 indicates that a unique oscillation frequency cannot be expected for each angle because the cross section ratio must be represented by a superposition of oscillations with different frequencies and phases, resulting from six different molecular orbitals. Furthermore, preliminary calculations for 30° suggest a behavior for the cross section ratio similar to that in the figure.

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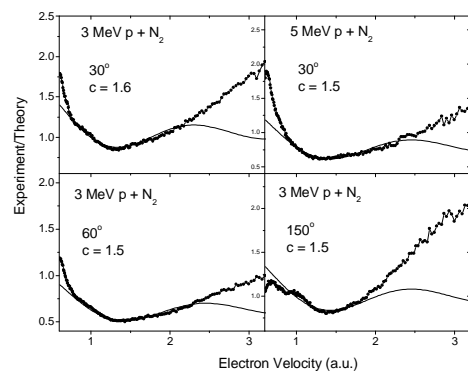


Fig. 1: Measured cross sections for N_2 divided by calculated N cross sections. Smooth curves are damped sinusoidal fits to the data.

CUSP FORMATION IN CLASSICAL TRAJECTORY MONTE-CARLO CALCULATIONS OF SINGLE ATOMIC IONIZATION BY THE IMPACT OF NEUTRAL PROJECTILES

L. Sarkadi, **R. O. Barrachina**^{*}, P. Macri[†]

Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), H-4001 Debrecen,
Pf. 51, Hungary

(^{*}) Centro Atómico Bariloche and Instituto Balseiro, 8400 Bariloche, Argentina

([†]) Departamento de Física, FCEyN, Universidad Nacional de Mar del Plata, 7600 Mar del Plata,
Buenos Aires, Argentina.

The velocity distribution of electrons emitted in atomic collisions often exhibits a peak centered at the velocity v_P of the incident projectile. Classical-trajectory Monte-Carlo (CTMC) simulations provide an excellent description of this structure whenever the interaction between the electron and the outgoing projectile is of a Coulomb [1] or even of a dipolar type [2]. However, serious doubts were recently cast over the general validity of any classical approach for the description of more general atom-atom ionization collisions [3]. These questionings are due to the visualization of the cusp as the result of a smooth continuation across the ionization limit of *capture* into highly excited electron-projectile bound states. By mimicking a bound spectrum accumulating at zero energy by a continuum, any classical description would succeed in describing the “electron capture to the continuum” divergence observed whenever the electron-projectile interaction is of Coulomb or dipolar nature. But, whenever the electron-projectile interaction decreases faster than a dipole potential at large distances, the energy spectrum does not accumulate at zero energy, and any classical description should be doomed to failure. Our purpose in this communication is to elucidate, through CTMC calculations [4], this limitation of the classical description of cusp formation. To this end we consider the ECC peak formed in He-Ar ionization collisions for the case of neutral He outgoing projectiles in the 2^1S metastable state, as first measured by the Debrecen group in 1989 [5]. Both the experimental data and the quantum-mechanical calculations show a cusp that is much sharper than the one produced by He^{2+} projectiles [6]. This phenomenon was attributed to a low-lying virtual state on the electron-projectile system [7], an effect that no classical description can reproduce. Actually, in this communication we demonstrate that the CTMC calculation produces a peak that is much broader and smaller than for a Coulomb interaction, a result that testifies against any supposedly classical origin of the ECC phenomenon.

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ELECTRON-ION RECOMBINATION MEASUREMENTS OF IRON M-SHELL IONS MOTIVATED BY ACTIVE GALACTIC NUCLEI X-RAY ABSORPTION FEATURES

E. W. Schmidt¹, S. Schippers¹, C. Brandau¹, D. Bernhardt¹, D. Yu¹, A. Müller¹,
M. Lestinsky², F. Sprenger², J. Hoffmann², D. A. Orlov², M. Grieser², R. Repnow², A. Wolf²,
D. Lukić³, M. Schnell³, D. W. Savin³

¹Institut für Atom- und Molekülphysik, Justus-Liebig-Universität, 35392 Gießen, Germany

²Max-Planck-Institut für Kernphysik, 69029 Heidelberg, Germany

³Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA

Recent observations of active galactic nuclei (AGN) have shown a prominent absorption feature in the 15–17 Å bandpass. This has been identified as an unresolved transition array (UTA) of $2p \rightarrow 3d$ inner shell absorption by iron ions with an open M-shell (Fe I–Fe XVI). This UTA can be used as a powerful diagnostic tool for the absorbing material surrounding the AGN’s super massive black hole. However, recent model calculations of the X-ray absorbing gas have failed to reproduce the shape of the UTA. This has been attributed to the fact that the available dielectronic recombination (DR) rate coefficients of iron M-shell ions, which are so far only known from theoretical calculations, are too low at the temperatures where these ions are formed in photoionized plasmas. In a series of studies, aimed at providing reliable DR data for astrophysical modeling, we have measured DR rate coefficients of several iron M-shell ions ranging from Fe VIII to Fe XV using the ion storage ring TSR at the Max-Planck-Institut für Kernphysik in Heidelberg, Germany. Already in our first measurement, that is for Fe XIV [1], we find unusually strong DR resonances at low electron-ion collision energies (Figure 1), leading to low temperature plasma DR rate coefficients orders of magnitude larger than the presently available theoretical results. More results and their implications for astrophysics will be discussed.

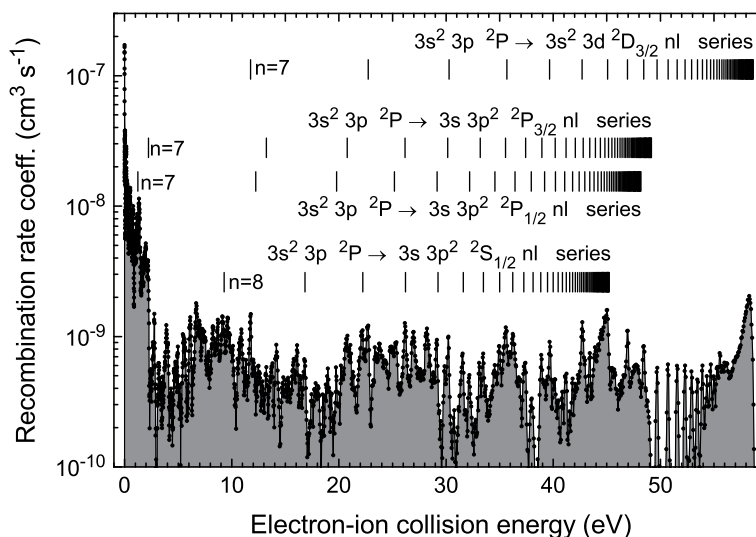


Figure 1: Measured Fe XIV to Fe XIII merged-beams electron-ion recombination rate coefficient. The vertical bars denote DR resonance positions as expected on the basis of the hydrogenic Rydberg formula. Only the $(3s^2 3d^2 D_{3/2}) nl$ series of Rydberg resonances can unambiguously be identified. Note that the resonances below 2.3 eV exceed all other resonances in height by an order of magnitude.

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RESONANCES IN ELECTRON CAPTURE TOTAL CROSS SECTIONS FOR ION-H(1S) COLLISIONS

P. Barragán L. F. Errea, F. Guzmán*, L. Méndez, **I. Rabadán** and A. Riera

Laboratorio Asociado al CIEMAT de Física Atómica y Molecular en Plasmas de Fusión.
Departamento de Química, Universidad Autónoma, 28049 Madrid, Spain.

(*) Also at Laboratorio Nacional de Fusión (CIEMAT)

Electron capture (EC) in collisions of multicharged ions with H are important processes in astrophysical and fusion plasmas. At low impact energies ($E < 0.1 \text{ eV/amu}$), the EC cross section is approximately described by the classical Langevin model, which assumes that the electron capture probability is equal to one for collisions where the projectile overcomes the centrifugal potential barrier (e.g. [1]); this model yields to cross sections $\sigma \sim E^{-1/2}$. Since the EC probability is smaller than 1, quantal calculations lead to smaller cross sections than predicted by the Langevin model. Besides, these cross sections exhibit resonance structures, which have not been studied in previous quantal calculations. In a recent work [2], we have evaluated EC cross sections in collisions of N^{2+} and O^{2+} with H, which show many shape resonances. In this communication we consider collisions of C^{4+} and B^{5+} with H(1s). Our results for $\text{C}^{4+} + \text{H}(1s)$ collisions are illustrated in Figure 1.

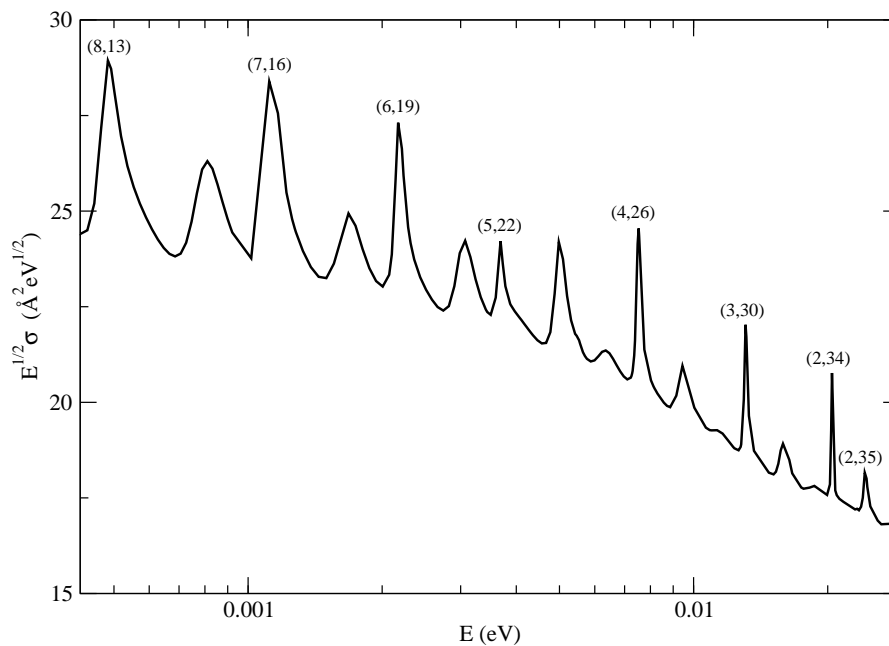


Figure 1: Total cross sections for the reaction $\text{C}^{4+} + \text{H}(1s) \rightarrow \text{C}^{3+}(nl) + \text{H}^+$. The numbers in brackets are the vibro-rotational quantum numbers (v, J) of the shape resonances.

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ELECTRON IMPACT EXCITATION OF NEON-LIKE BARIUM

S. Nakazaki[†] and E. Kimura[‡]

[†] Department of Applied Physics, Faculty of Engineering, University of Miyazaki,
Miyazaki 889-2192, Japan.

[‡] Miyakonojyo Technical High School, Miyakonojyo 885-0084, Japan.

Transition wavelengths, oscillator strengths and collision strengths in neon-like ions have been widely used for application to the modeling of X-ray laser systems and plasma diagnostics. There are a few measurements[1,2] of excitation cross section of neon-like barium. Nakamura *et al*[2] obtained relative collision strengths for electron-impact excitation to $(2p^{-1}_{1/2}3s_{1/2})_{J=1}$ and $(2p^{-1}_{3/2}3d_{5/2})_{J=1}$ in Ba^{46+} at 5.02 keV. They used an experimental method developed for the collision strength measurement from X-ray observations by using the Tokyo electron beam ion trap. The experimental collision strength ratio was higher than the distorted-wave results of Zhang and Sampson[3]. Here, we calculated collision strengths for transitions from the ground $2p^6\ ^1S_0$ state to the fine-structure levels of all excited states of $2p^53\ell$ by using the Dirac Atomic R-matrix Code (DARC)[4,5]. The lowest 37 target states are included in the expansion of the total wavefunctions of the system in the present calculation. The target wavefunction is represented by a configuration interaction wavefunction. The ns , np and nd orbitals with $n \leq 3$ are generated by the GRASP(General Relativistic Atomic Structure Package) code[6]. The resulting 37 energies are in agreement within 0.1% with experiments. The ratio of oscillator strengths in the velocity form to those in the length form is equal to 1.0 for the majority of strong transitions. These results for the excitation energies and the oscillator strengths indicate the reliability of the present wavefunctions of the target ions.

We included 29 continuum orbitals in each angular symmetry and calculated the R-matrix on the boundary of the sphere, whose radius was taken to be 1.0 au. Our collision strengths for the transitions from the ground state to $(2p^{-1}_{3/2}3d_{5/2})_{J=1}$ and $(2p^{-1}_{3/2}3d_{3/2})_{J=1}$ levels are in good agreement with the experimental results of Marrs *et al*[1]. It is difficult to compare the experimental ratio of Nakamura *et al*[2] at 5.02 keV with ours because we have a lots of resonances at around the energy.

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FRAGMENTATION OF H₂O AND CH₄ MOLECULES IN COLLISIONS WITH 800 keV He⁺

B. Sulik¹, Z. Juhász¹, T. Ricsóka¹ and N. Stolterfoht²

¹Institute of Nuclear Research (ATOMKI), Bem tér 18/c, H-4026 Debrecen, Hungary

²Hahn-Meitner Institute Berlin, Glienickerstr. 100, D-14109 Berlin, Germany

The study of fragmentation mechanisms of H₂O and CH₄ molecules is important for understanding direct and indirect radiation damages in biological tissues [1].

The energy distributions of fragments produced in 800 keV He⁺ + H₂O and He⁺ + CH₄ collisions have been measured at the beamline of a Van de Graaff electrostatic accelerator in ATOMKI, Debrecen. An electrostatic analyzer, ESA-21 has been utilized for taking the ion spectra simultaneously at 13 different observation angles. The data compare well to those measured earlier for He²⁺ and Ne^{q+} + H₂O collisions at much lower projectile energies in HMI, Berlin [1,2].

In the present work, we study the low recoil-ion energy group, which extends up to 50 eV, and corresponds to Coulomb explosion (CE) of the ionized target. The ionization mechanisms are direct ionization and excitation for the present ATOMKI data, while it was mainly electron capture for the earlier HMI data [1,2].

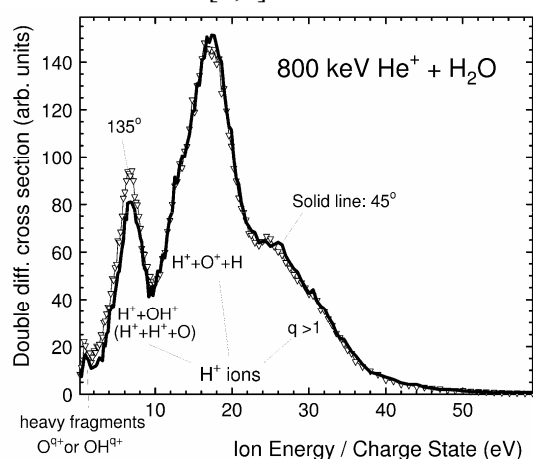


Figure 1. Energy spectra of the ion-fragments O^{q+}, OH^{q+} and H⁺ in 800 keV He⁺ + H₂O collisions at 45° and 135° observation angles. The supposed charge state of the heaviest fragment is denoted by q.

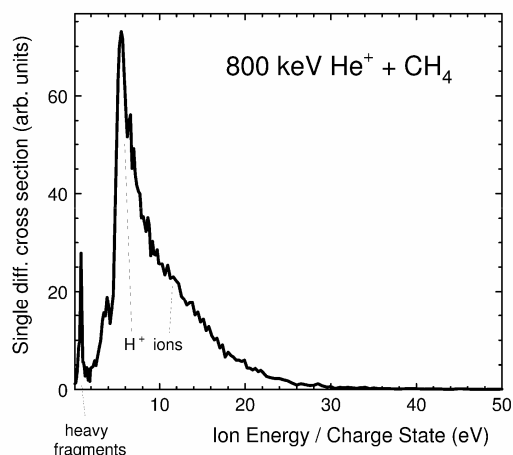


Figure 2. Single differential energy spectra of the heavy and H⁺ ion-fragments in 800 keV He⁺ + CH₄ collisions. The yield, observed in 13 individual angular channels, has been integrated over the observation angle.

The spectrum of ion fragments from CH₄ is different from that of water, especially for the relative yields belonging to low energy dissociation channels. Further measurements with improved accuracy have been performed and will be presented.

Acknowledgements

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DYNAMICS AND INTERFERENCE IN FAST CHARGE TRANSFER COLLISIONS

D. Fischer, M. Gudmundsson, K. Støchkel, H. Cederquist, P. Reinhed, H. Zettergren, R. Schuch, A. Källberg*, A. Simonsson*, and H. T. Schmidt

Department of Physics, Stockholm University, S-10691 Stockholm, Sweden
(*) Manne Siegbahn Laboratory, Stockholm University, S-10405 Stockholm, Sweden

We studied electron capture in proton-helium and proton-molecule (H_2 and N_2) collisions for projectile energies ranging from 1.3 MeV up to 12.5 MeV. At such high projectile energies, when the collision velocity is significantly higher than typical orbital velocities of the bound electrons, the charge transfer cross section is dominated by the “kinematic” capture of inner-shell electrons in a one-step process and the so-called Thomas mechanism where the electron is transferred in a two-step process. For the experiments we used the heavy ion storage ring CRYRING and its supersonic gas-jet target equipped with a recoil-ion momentum spectrometer, which enables to acquire the complete kinematic information of the collisions with high resolution.

For proton-helium collisions we obtained cross sections differential with respect to the projectile scattering angle and could for the first time achieve a complete separation of the kinematic and the Thomas charge transfer process. Thus, we could test the projectile energy dependence of these two mechanisms. Moreover, the data allowed a comparison with theoretical results on a much more detailed level than what was previously possible [1].

For proton-molecule collisions we investigated electron capture accompanied by the subsequent dissociation of the molecule. Also multiple ionization of the target molecule followed by Coulomb explosion can occur and we observed, in the case of the nitrogen target, fragments N^{q+} with charge states up to $q=3$. By measuring the momentum of the ionic fragments the orientation of the internuclear axis at the collision time can be determined. Here we found a strong variation in the capture cross section depending on the angle between the molecular axis and the projectile beam (see Fig. 1). This variation is explained as a result of quantum mechanical interference related to the two undistinguishable atomic centers of the molecule [2].

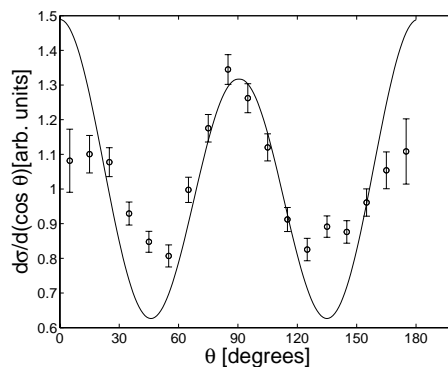


FIG. 1: Electron capture cross section in 1.3 MeV proton- H_2 collisions as a function of the angle between the internuclear axis and the projectile beam.

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4d-4f UNRESOLVED TRANSITION ARRAYS OF XENON AND TIN IONS IN CHARGE EXCHANGE COLLISIONS

H. Tanuma, H. Ohashi, S. Fujioka*, H. Nishimura*, A. Sasaki**, and K. Nishihara*

Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

(*) Institute of Laser Engineering, Osaka University, Suita, Osaka 565-0871, Japan

(**) Advanced Photon Research Center, Japan Atomic Energy Agency, Kizu, Kyoto 619-0215, Japan

High temperature plasmas of heavy elements can be used as sources of extreme ultra-violet (EUV) light. Not only line emissions but also widely spread emissions called unresolved transition arrays (UTA) have been observed from the EUV light source plasma. It is known that the UTA around 11 nm of Xe plasma and that around 13.5 nm of Sn plasma have quite strong emissivity. In particular, the 13.5 nm of Sn plasma is applied to the promising light source for the next generation photolithography. In order to understand the physics of plasma, the spectroscopic data is necessary for the component ions of plasma. However, the energy levels and transition wavelengths of multiply charged Xe and Sn ions have not been sufficiently investigated yet at present.

In this work, the EUV emission spectra have been measured from the multiply charged Xe and Sn ions in collisions with He gas. In collisions of Xe^{q+} ($q = 11-18$), the UTA has been observed around 11.0 nm. Also the UTA has been observed around 13.5 nm in collisions of Sn^{q+} ($q = 10-15$). According to the theoretical investigation, these UTAs consist of a number of the 4d-4f transition lines.

Generally speaking, in collisions of multiply charged ions with He gas, the single-electron capture can be regarded as the most dominant reaction process. Therefore, we can assume that the observed emissions come from the ions in one less charge states than the incident ions. In Figure 1, the peaks of the observed UTA have been compared with the theoretical results calculated with the HULLAC code. Even though we can see the systematic deviation of 0.5 nm between the observation and the calculation, the properties of the 4d-4f UTA, such as the charge state dependence, have been reproduced sufficiently by the theoretical calculation.

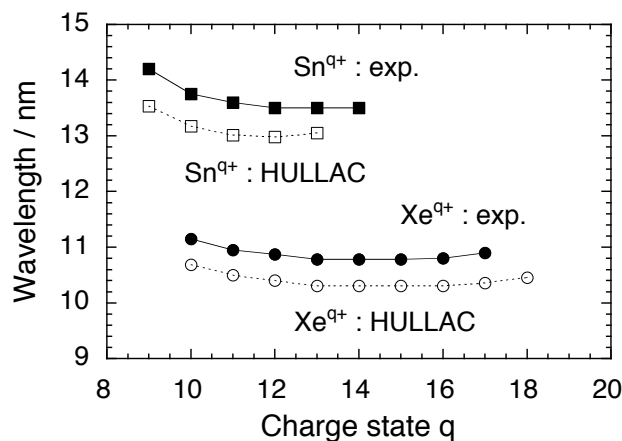


Figure 1: Wavelengths at the peaks of the observed 4d-4f UTA in charge exchange spectroscopy, and the averaged transition wavelengths calculated with the HULLAC code.

CHARGE EXCHANGE SPECTROSCOPY IN Sn^{q+} ($q = 6-15$) - He COLLISIONS

H. Ohashi, H. Tanuma, S. Fujioka*, H. Nishimura*, A. Sasaki**, and K. Nishihara*

Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

(*) Institute of Laser Engineering, Osaka University, Suita, Osaka 565-0871, Japan

(**) Advanced Photon Research Center, Japan Atomic Energy Agency,
Kizu, Kyoto, 619-0215, Japan

Recently, the development of an extreme ultra-violet (EUV) light source is making great progress for the next generation semiconductor lithography. For the EUV lithography, the wavelength of 13.5 nm was chosen because Mo/Si multilayer coated mirrors have a maximum of reflectivity around this wavelength. Tin plasma has been receiving attention as the EUV light source among some candidates, because of its favorable emissions near 13.5 nm. Some emission spectra of tin plasma have been reported. However, there are few emission spectra of tin ions in a selected charge state. Spectroscopic data of tin ions in individual charge states is necessary to understand the plasma for the development of the EUV light source.

The multiply charged tin ions were produced in a 14.25 GHz ECR (electron cyclotron resonance) ion source. The ions were extracted with an electric potential of 20 kV and selected by a magnet according to their mass-to-charge ratios. The ion beam was directed into a collision chamber, where the ion beam interacts a He target gas jet ejected from a capillary plate. The EUV emission from the collision center was observed at 90° to the ion beam direction with a compact flat-field grazing-incident spectrometer equipped with a liquid nitrogen cooled CCD camera as a photon detector.

Measured spectra in collisions of Sn^{q+} ($q = 6-15$) with He are shown in Fig. 1. In these collision systems, the transfer ionization might have a significant contribution in the total cross-section, while the true double electron capture probably has very small cross-section. The spectra, therefore, are considered as the emissions from one less charge states of projectile ions. Comparing with theoretical calculations using the HULLAC code, some intense emissions can be identified to the 4d-4f, 4d-5p, and 4d-5f transitions. Since these ions have vacancies in the 4d shell, the number of fine structure levels is huge for the same electronic configurations. The 4d-*nl* transitions, therefore, make band-like emissions. In particular, the 4d-4f transitions appear at the same wavelength around 13.5 nm for the range of charge states $q \geq 10$.

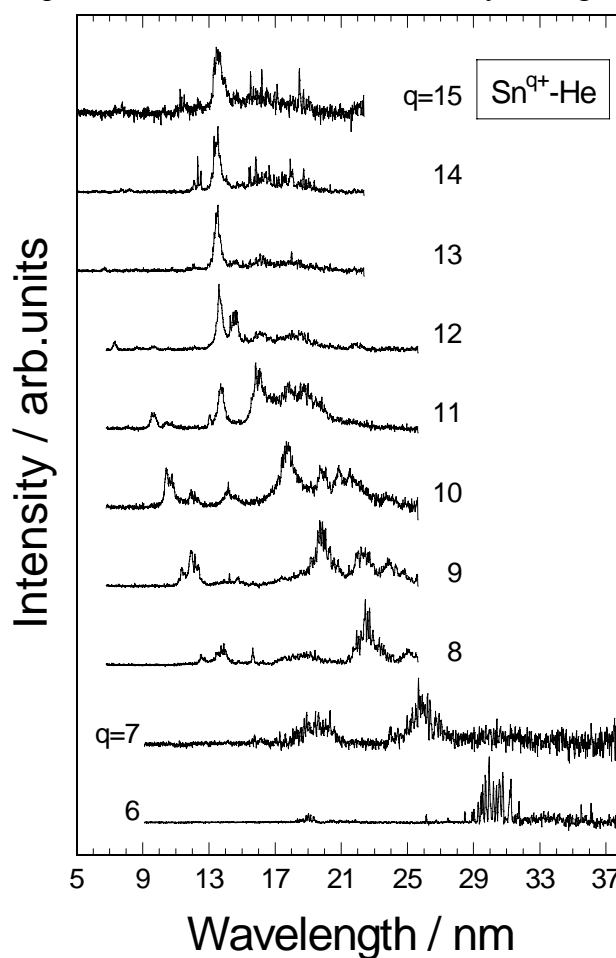


Fig. 1. EUV emission spectra in collisions of Sn^{q+} ($q = 6-15$) with He.

HCI-Induced Ionization of Water : *from the primary process to the selectivity of the bond cleavage*

S.Legendre, M.Tarisien*, A.Cassimi, B.Gervais, E.Giglio, **L.Adoui**
CIRIL (UMR CEA/CNRS/ENSICaen/Université de Caen) rue Claude Bloch, BP5133,
F-14070 Caen cedex 5 (France)

* CENBG, Le Haut Vigneau, BP120, F-33175 Gradignan Cedex, France

Understanding of the molecular bond breakage selectivity, in order to control the bond cleavage, is one of the most exciting challenge in chemistry. It requires a detailed knowledge as well of the potential energy surfaces as of the dynamics that governs the dissociation. Among all the simple molecules, the description of water fragmentation is probably one of the most important task as this one intervenes in a lot of applications on the border of many branches of science. For example, water radiolysis represents an important field of research and is involved in a great number of fundamental or applied physical processes. In particular, it can play a major role in the understanding of radiation damage in biological tissue as, from the radiobiological point of view, the greatest part of the energy deposited by ionizing radiations in biological matter is absorbed by water molecules, leading to formation of various radical or molecular species. Thus, a refined description of water fragmentation is of interest to modelize the subsequent chemistry in solution [1].

We will present results about relative multiple ionization cross sections, fragmentation pathways, branching ratios and Kinetic Energy Release distributions of the fragments in the case of high Linear Energy Transfer highly charged ions. A special attention has to be paid to the large multi-ionization cross sections as well as to the production of atomic oxygen following double ionization. This is important since atomic oxygen is presented as a possible precursor of different radical production. Obviously, the question arises to know if the ionization cross sections determined in the gaseous phase are still relevant in the case of more dense medium in which fast neutralization can occur. From water molecule to water cluster, a first step can be realized towards more dense systems in order to study the role of the environment on this primary ionization. Furthermore, the goal of describing radiation damage of biomolecular systems at the molecular level requires the knowledge of the most evident solvent behaviour under irradiation. First results about stability, energetics and charge mobility inside the clusters will be reported.

Finally, the isotopomer of water HOD provides a three-atom prototype for studying bond selectivity. Focusing on double ionization of the molecule, we evidence a strong preferential cleavage of the O–H bond rather than the O–D bond. Moreover, the coincident measurement of high resolution Kinetic Energy Release (KER) distributions shows a clear difference of approximately 1 eV between the mean KER value of the two-body dication fragmentation channels $H^+ + OD^+$ and $D^+ + OH^+$. We analyze the two aspects of this isotopic effect by means of a semi-classical calculation simulating the dissociation dynamics *via* the $X^3\Sigma_g^- H_2O^{2+}$ dication electronic groundstate. Thus, the conjunction of experiment together with semi-classical calculations allow to discuss the results and to propose some *scenarii* about the fragmentation dynamics [2].

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INTERFERENCE BETWEEN DIELECTRONIC AND RADIATIVE RECOMBINATION IN ELECTRON - HIGHLY CHARGED Bi COLLISIONS

Hirotsugu TOBIYAMA, Hiroaki NOHARA, Anthony P. KAVANAGH^A,
Nobuyuki NAKAMURA, Hirofumi WATANABE^B, Hiroyuki A. SAKAUE^C, Yueming LI^D,
Daiji KATO^C, Fred J. CURRELL^A, Chikashi YAMADA and Shunsuke OHTANI

The University of Electro-Communications, Chofu, Tokyo 182-8585, JAPAN

^AQueen's University Belfast, Belfast BT7 1NN, United Kingdom

^BCREST, Japan Science and Technology Agency

^CNational Institute for Fusion Science, Toki, Gifu 509-5292, JAPAN

^DInstitute of Applied Physics and Computational Mathematics, P.O.Box 8009, Beijing 100088

Radiative recombination (RR) is non-resonant radiative electron capture by an ion, while dielectronic recombination (DR) is an indirect process which proceeds via doubly excited states produced resonantly by dielectronic electron capture;

$$RR: A^{q+} + e \rightarrow A^{(q-1)+} + h\nu,$$

$$DR: A^{q+} + e \rightarrow A^{(q-1)+**} \rightarrow A^{(q-1)+} + h\nu.$$

These two processes can interfere because they can have identical initial and final states. In this paper, we present observation of interference between RR and DR in electron - highly charged Bi ion collisions made by observing emitted X-rays with the Tokyo electron beam ion trap (EBIT) [1].

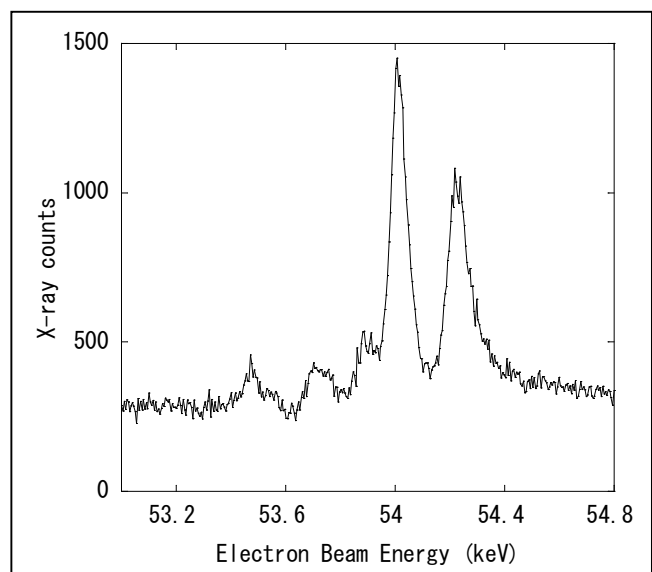
Bi was continuously injected from an effusion cell into the EBIT. X-rays from the trapped Bi ions were observed with a solid state Ge detector which was located at 90° with respect to the electron beam with scanning the electron energy from 53keV to 55keV. Figure 1 shows the X-ray intensity integrated along the radiative recombination line corresponding to the L₁₂ vacancy as a function of electron energy. The structures appearing in the figure correspond to KL₁₂L₃ DR resonance for highly charged Bi ions. As seen in the figure, these DR peaks show asymmetric features due to the interference effect. The data was fitted to Fano line shapes and q-values have been determined similarly to the previous work for highly charged Hg and U ions [2,3].

Comparison with the previous measurements and Z-dependence will be discussed at the poster.

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Figure1. KL₁₂L₃ DR resonances for highly charged Bi ions. The asymmetric structure is due to the interference between DR and RR. It is noted that the horizontal scale is not calibrated.



Radiative processes studied for bare uranium ions in collisions with H₂

G. Weber ^{a,b}, Th. Stöhlker ^a, A. Gumberidze ^a, R. Reuschl ^a, S. Hess ^a, U. Spillmann ^a, S. Trotsenko ^a, S. Hagmann ^a, M. Nofal ^a, M. Trassinelli ^a, C. Kozhuharov ^a, D. Banas ^c

^a Gesellschaft für Schwerionenforschung, Planckstr. 1, 64291 Darmstadt, Germany

^b University of Heidelberg, Grabengasse 1, 69117 Heidelberg, Germany

^c Akademia Swietokrzyska, ul. Zeromskiego 5, 25-369 Kielce, Poland

This report concentrates on angular distribution studies of radiative processes occurring in collisions of bare uranium ions with hydrogen molecules.

The experiment was performed at the gas target of the ESR storage ring with a beam energy of 98 MeV/u. X-ray spectra were recorded by Ge and Si detectors for observation angles of 0, 35, 60, 90, 120 and 150 deg, respectively. The most intense lines observed in the spectrum can be attributed to radiative electron capture transitions into the ground and excited states as well as to the characteristic Lyman- α transitions (see figure 1a). Several topics of interest will be discussed including the alignment of the $2p_{3/2}$ state. Particular emphasis will be given to the Bremsstrahlung x-ray continuum. By using decelerated ions in addition to a hydrogen target the narrow compton profile allows a clear identification of the tip region (see figure 1b). The shape of the spectrum near the tip is, in particular, affected by Coulomb distortions caused by the large nuclear charge of the projectile [1, 2, 3].

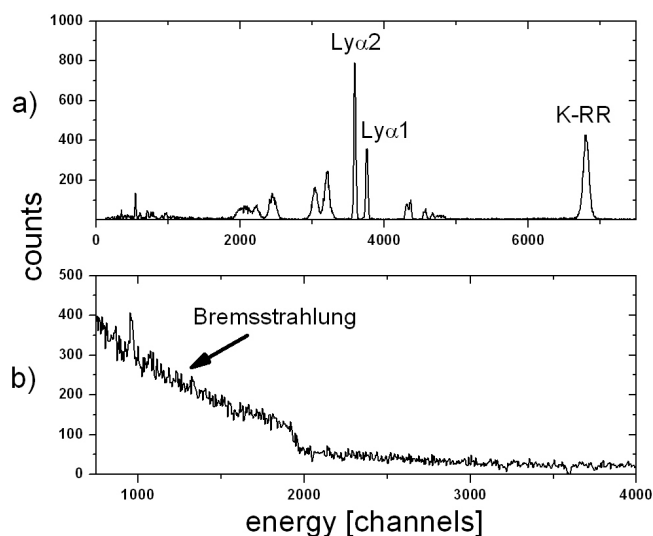


Figure 1: a) preliminary X-Ray spectrum at 150 degree recorded in coincidence with capture of one electron into a projectile ion, b) preliminary Bremsstrahlung spectrum recorded in anti-coincidence with electron capture

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ELECTRON LOCALIZATION AMONG THREE MOVING CENTERS: COULOMB EXPLOSION WITH SLOW HIGHLY CHARGED IONS

Tomoko Ohyama-Yamaguchi and Atsushi Ichimura*

Tokyo Metropolitan College of Industrial Technology, Shinagawa, Tokyo, Japan

*Institute of Space and Astronautical Science, JAXA, Sagamihara, Japan

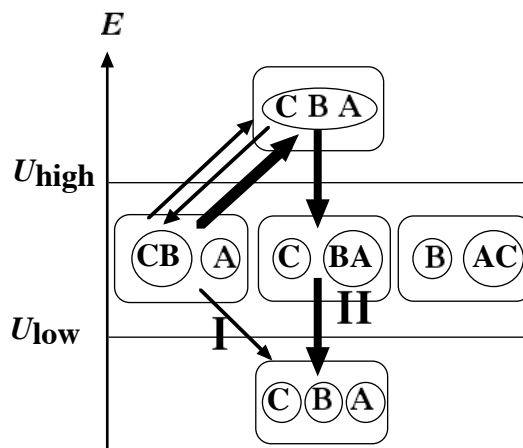
We address the process of multiple electron transfer from a diatomic molecule in collisions with a slow highly charged ion. For this process, we have developed the three-center Coulombic over-the-barrier model [1]. We apply the model to the experiments performed at Tokyo Metropolitan University by Ehrich, Kaneyasu and coworkers [2,3]. They have measured the Coulomb explosion of a target N_2 molecule colliding with Kr^{8+} ion beam in perpendicular to the beam axis in coincidence with the scattered ion, with which the charge-asymmetry effect is observed between the fragment ions in the explosion. In their results, the far site is ionized more highly than the near site. In the former paper [4], we have qualitatively explained this asymmetry by assuming that residual electrons in the dissociating molecular ion are localized into the two atomic sites at a certain internuclear distance. The asymmetry obtained comes from the asymmetry of the phase space volume between the near and far sites from the projectile trajectory.

In the previous analysis [4], however, we made an unrealistic assumption that the electrons are localized directly from the target molecule BC into atomic sites B and C. In fact, it should be taken into account that the electron forms a three-center quasimolecule ABC during a collision. Thus, we have to consider succeeding two-step localization processes associating with two saddle points U_{high} and U_{low} (see the figure). Two possible processes are involved in this scheme:

- I $[ABC \rightarrow A+BC] \times [BC \rightarrow B+C]$
- II $[ABC \rightarrow AB+C] \times [AB \rightarrow A+B]$.

Thus, we should analyze the process of electron localization in moving three centers.

In a slow collision, the dissociation of the target molecule may start before the incident ion approaches the closest distance. In such a situation the process II is expected to be important for the asymmetry above. We try to explain the asymmetry effect by calculating the probabilities for these two processes.



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FRAGMENTATION OF ADENINE VERSUS THE EXCITATION ENERGY.

R.Brédy, J.Bernard, L.Chen and S.Martin

Laboratoire de Spectrométrie Ionique et Moléculaire (UMR CNRS 5579), Université Claude Bernard Lyon1, 43 Bd du 11 Novembre 1918, F-69622 Villeurbanne Cedex, France

Keywords: biomolecules, DNA base, mass spectrometry, dissociation, electron, charged ion

We have used recently a new method to measure the evolution of DNA base under a well controlled electronic excitation energy. This method is based on the formation of negative ions from the collision of highly positively charged ions (up to 3) on the DNA base. The analysis of the kinetic energy of outgoing negative ions is linked to the energy deposition on the DNA base.

We report on the dissociation of DNA base adenine in the gas phase. Singly- and doubly-charged adenine are formed by electron capture processes in collisions with H^+ and F^{q+} ions at different collisional energies. The initial charge of the target before fragmentation is determined using a highly selective technique based on triple coincidence measurements between the charge of the outgoing projectile, the time-of-flight of the recoil ions and the number of ejected electrons. For doubly charged adenine, the time-of-flight spectrum and the time correlation between fragments allow us to clearly identify some specific fragmentation channels of the molecule. Results obtained with this method will be compared with some results provided by other commonly used methods (CID/ECD). Effects with the projectile energy on the dissociation of the molecule are observed and will be discussed.

COMPETITION BETWEEN RADIATIVE RECOMBINATION AND NUCLEAR EXCITATION BY ELECTRON CAPTURE

Adriana Pálffy, Zoltán Harman*, Andrey Surzhykov*, Werner Scheid

Institut für Theoretische Physik der Justus-Liebig-Universität Giessen,
Heinrich-Buff-Ring 16, 35392 Giessen, Germany

(*)Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

A free electron can be captured into a bound state of a highly charged ion. Here we study two possible recombination processes. The direct process is the radiative recombination of the electron (RR) where a photon is subsequently emitted by the system. In the case that the electronic and nuclear transition energies match, the resonant process of nuclear excitation by electron capture (NEEC) competes with RR. NEEC is the nuclear analogue of dielectronic recombination (DR), in which a free electron is captured into a bound atomic shell with the simultaneous excitation of the nucleus. The radiative decay channel for the excited nuclear state corresponds to the final state of the considered recombination process. Partly due to the omnipresent RR background, NEEC has not been observed experimentally yet, although other experimental observation of atomic physics processes with regard to the internal structure of the nucleus have been reported, such as the bound internal conversion [1] and the nuclear excitation by electron transition [2]. Theoretical studies of NEEC occurring in scattering measurements are therefore particularly useful in finding candidate isotopes and transitions suitable for experiments. In Ref. [3] we derived NEEC rates and cross sections for the case of both electric and magnetic multipole transitions, paying particular interest to collision systems where experimental requirements for the observation of NEEC are likely to be fulfilled. If observed experimentally, NEEC would offer the possibility to explore spectral properties of heavy nuclei through atomic physics experiments.

Considering the same initial and final states for RR and NEEC followed by the radiative decay of the excited nucleus, quantum interference between the two processes can occur. We investigate the role of RR in the NEEC recombination mechanism and present theoretical estimations of the magnitude of the interference between the two processes for various electric and magnetic multipole transitions. As energy resolutions comparable to the natural width of the excited nuclear state are not available experimentally at present, we convolute the NEEC and interference cross sections with the presumable energy distribution of the continuum electrons.

The angular distribution of the emitted photons in the recombination process offers another means of discerning NEEC from RR. We use the same density matrix formalism used for RR [4] to calculate the angular distribution of the photons emitted in the radiative decay of the nucleus. We present the asymmetry parameters and the angular distribution of the photons emitted in the radiative E2 decay of the nuclear state for the capture of the electron into the K shell of several bare ions. The angular pattern of the photon emission for NEEC can serve as a signature for the occurrence of the process.

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HYPERFINE STRUCTURE AND QED SHIFTS IN DIELECTRONIC RECOMBINATION OF LI-LIKE $^{45}\text{Sc}^{18+}$

M. Lestinsky, E. W. Schmidt,* D. A. Orlov, F. Sprenger, C. Brandau,*[‡]
E. Lindroth,[†] S. Schippers,* A. Müller,* A. Wolf

Max-Planck-Institut für Kernphysik, Heidelberg, Germany

(*) Institut für Atom- und Molekülphysik, Justus-Liebig-Universität, Giessen, Germany

(†) Atomic Physics, Stockholm University, Sweden (‡) GSI, Darmstadt, Germany

Highly charged ions are an interesting field for studies of bound state QED in strong fields. A developing experimental method in order to obtain the energy levels of excited states in such systems is the observation of dielectronic recombination (DR) resonances in an ion-electron merged-beam setup, which features highest resolution at low electron-ion collision energies as a consequence of its kinematics.

Low energy DR resonances in the Li-like Scandium ion, $\text{Sc}^{18+}(1s^2 2s) + e^- \rightarrow [\text{Sc}^{17+}]^{**}(1s^2 2p_{3/2} 10l_j)$, appear at c.m. collision energies given by $E(2s \rightarrow 2p) - E_{\text{bind}}(nl)$. The binding energy $E_{\text{bind}}(nl)$ of the outer electron with respect to the excited ionic core can be calculated with high accuracy using RMBPT without radiative corrections. This allows to relate the resonance positions to the energy level of the $2p_{3/2}$ excited state of the Li-like Sc^{18+} [1]. In the previous experiment, using only a single electron beam device (electron cooler) in an ion storage ring, uncontrolled changes in the ion velocity and the electron temperature of $kT_{\perp} = 7.2$ meV limited the accuracy to 1.9 meV. Using the new electron target [2] with a cryogenic GaAs photocathode [3] we have $kT_{\perp} \approx 0.7$ meV and safely control the ion velocity. We clearly resolve and assign the hyperfine structure (HFS) [4] and from the resonance position we derive a new, more accurate value for the $\text{Sc}^{18+} 2p_{3/2} - 2s_{1/2}$ splitting of 44.3096(4) eV (preliminary) and achieve a test of radiative screening corrections to this splitting with $\pm 1.5\%$. This is better than the present theoretical uncertainty of this correction [5].

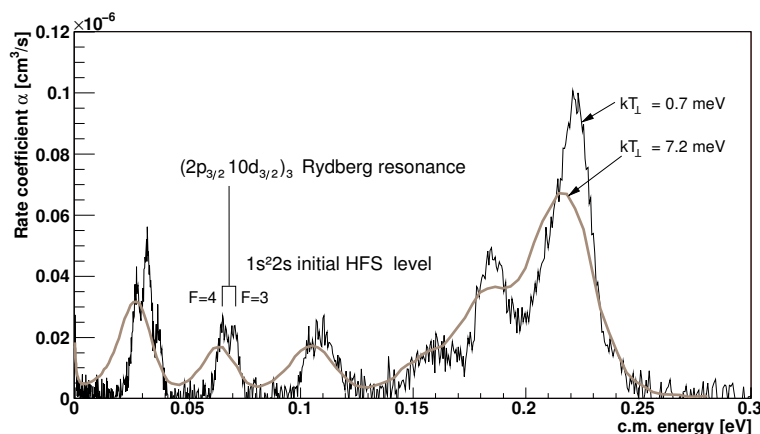


Figure 1: Experimental Sc^{18+} DR rate coefficient. The grey curve shows [1], the black curve has been measured with the photocathode electron target. The nuclear spin $I = 7/2$ forms two hyperfine states $F = 3$ and $F = 4$ of the $2s_{1/2}$ target ion ground state [4].

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PROJECTILE FOCUSING NEAR THE RECOIL-ION THRESHOLD

Vladimir D. Rodríguez, P. A. Macri, R. O. Barrachina*

Departamento de Física, Universidad de Buenos Aires, 1428 Buenos Aires, Argentina.

(*) Instituto Balseiro, 8400 S. C. Bariloche, Argentina.

Quite recently it has appeared a renewed interest on ion atom ionisation collision studies. These last studies deal with projectile scattering in single atomic ionisation by ion impact. The main concern in the subject is the fact that projectile scattering is determined by not only internuclear interaction, but also by the projectile interaction with the remaining electron(s) in the residual target. Recent advances on experimental techniques have made possible to measure highly differential cross sections [1]. In this work we are interested in the simultaneous determination of both the projectile scattering angle and the longitudinal recoil-ion momentum. This sort of doubly differential cross sections has the advantage of allowing us the study of the projectile scattering when the electron capture to the continuum (ECC) is dominant. In fact, when approaching the longitudinal recoil-ion distribution threshold, the emitted electron velocity reaches that of the projectile. Under such conditions, the dominant interaction is the projectile-electron one. As first introduced in [2], one could expect the projectile to be focused on the forward direction by an attractive projectile-electron interaction (positive ion impact), and, alternatively, to be defocused by a repulsive interaction (antiproton impact). A quantitative measure of this mechanism is the determination of the mean projectile scattering angle as one approaches the longitudinal recoil-ion threshold. In Fig. 1, we present theoretical calculation of this magnitude for Helium ionisation by 50 keV proton and antiproton impact. Two well known theoretical approaches are presented: the continuum distorted wave-eikonal initial state (CDW-EIS) and the Classical Trajectory Monte Carlo (CTMC). An active electron model is employed. Both theories account for the projectile-residual target interaction with an effective target charge $Z_{\text{eff}} = 1.35$. Although quantitative differences are observed, the calculations agree in two important features: mean proton scattering angle decreases as we approach to threshold, and, on the contrary, mean antiproton scattering angle shows an increase as we get near the threshold.

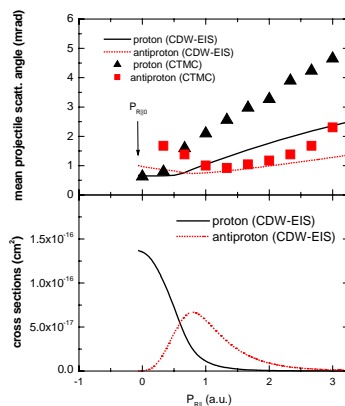


Figure 1: Mean projectile scattering angle and recoil-ion longitudinal momentum distribution as a function of the longitudinal recoil-ion momentum for single ionization of He by 50keV proton and antiproton impact.

Curves: CDW-EIS calculation, symbols: CTMC calculations.

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IONIZATION OF HELIUM BY FAST AND HIGHLY CHARGED IONS

Pablo A. Macri, Vladimir D. Rodríguez*, Raúl O. Barrachina**

Departamento de Física, Universidad Nacional de Mar del Plata, 7600 Mar del Plata, Argentina.

(*) Departamento de Física, Universidad de Buenos Aires, 1428 Buenos Aires, Argentina.

(**) Centro Atómico Bariloche, S. C. Bariloche, 8400 Río Negro, Argentina.

Recent advances on experimental techniques [1] have made possible the so-called complete experiment in atomic ionization by ion impact. The theoretical framework should account for projectile-residual target interaction in order to analyze the available data. For many electrons target atoms, the not ionized electrons screen the pure Coulomb interaction between the nuclei making the required calculation very involved. In this work, the role of the passive electrons on the total projectile-residual target ion interaction is considered through a static Hartree-Fock potential V_S and a dynamic polarization potential V_P . Although for target residual ions in its ground state the dipole polarizability is not expected to be large, the full interaction scales as the square of the projectile charge (Z_P^2). Therefore, for highly charged projectiles as considered here, the effect introduced by the polarization potential could be actually important. We employ the continuum distorted wave-eikonal initial state theory. This approximation has demonstrated to be a successful theoretical tool to predict the electron distributions of atoms ionized by fast ions [2]. In Fig. 1, we present doubly differential cross section (DDCS) as a function of transverse projectile momentum transfer η at fixed emitted electron energies E_e , for single ionization of He by 3.6 MeV/u Au⁵³⁺ impact. We compare the experimental data [3] with previous results using an effective charge $Z_{eff} = 1.35$ and with present calculations employing V_S and $V_S + V_P$ potentials. For an electron energy $E_e = 50$ eV the use of Z_{eff} gives the general tendency of the experiments although it lacks to show the bump around $\eta = 2$ au. Surprisingly, the use of the more precise V_S makes this comparison worst. On the other hand, the use of both V_S , V_P enables to recover the general description. This can be confirmed for $E_e = 130$ eV where the use of Z_{eff} or V_S fails to follow the experimental data. We see that the inclusion of V_P improve the results at low η and reproduce de bump at higher transverse transfer momentum.

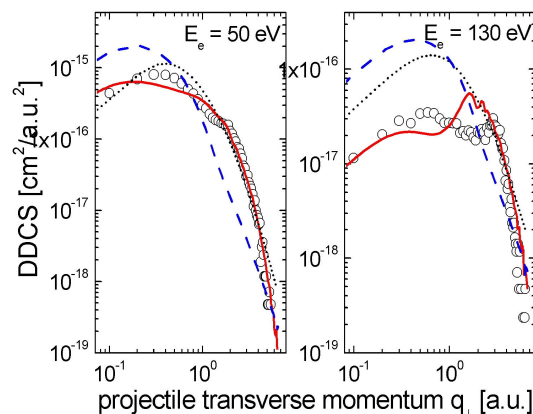


Figure 1: DDCS as a function of η at fixed E_e , for single ionization of He by 3.6 MeV/u Au⁵³⁺ impact. Dotted line: $Z_{eff} = 1.35$, dashed line: V_S , full line $V_S + V_P$ calculations. Circles: experiments Ref. [3].

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THEORETICAL MULTICONFIGURATION DIRAC-FOCK METHOD STUDY ON THE STRUCTURE OF L-X-RAY SATELLITE AND HYPER-SATELLITE LINES OF ZIRCONIUM

Katarzyna Słabkowska, Marek Polasik

Faculty of Chemistry, Nicolaus Copernicus University, 87-100 Toruń, Poland

A very complex origin of the X-ray spectra of target atoms, resulting from multiple ionization, makes it absolutely essential to carry out theoretical study on the effect of the ionization of various shells on the positions and shapes of different K -, L - and M -X-ray lines. Recently a very complex origin $L\alpha_{1,2}$ ($L_3M_{4,5}$) and $L\beta_1$ (L_2M_4) lines in the X-ray spectra of zirconium, molybdenum and palladium [1] induced by oxygen and neon ions have been measured by means of a high-resolution von Hamos crystal spectrometer having the energy resolution of about 1 eV. In the present work extensive multiconfiguration Dirac-Fock calculations with the inclusion of the transverse (Breit) interaction and QED corrections have been carried out on zirconium to elucidate the structure of various satellite (additional vacancies in M and/or N shells) and hypersatellite (additional vacancies in L or L and M shells) $L\alpha_{1,2}$ ($L_3M_{4,5}$) and $L\beta_1$ (L_2M_4) lines in its X-ray spectra. For each type of lines two theoretical spectra have been synthesized: one being a sum of the Lorentzian natural line shapes and the other one being a convolution of the sum of the Lorentzian natural line shapes with the Gaussian instrumental response. The obtained results are very helpful in reliable and quantitative interpretation of very complicated structure of $L\alpha_{1,2}$ and $L\beta_1$ satellite and hypersatellite lines in various high-resolution L -X-ray spectra of zirconium target bombarded by different light and heavy projectiles.

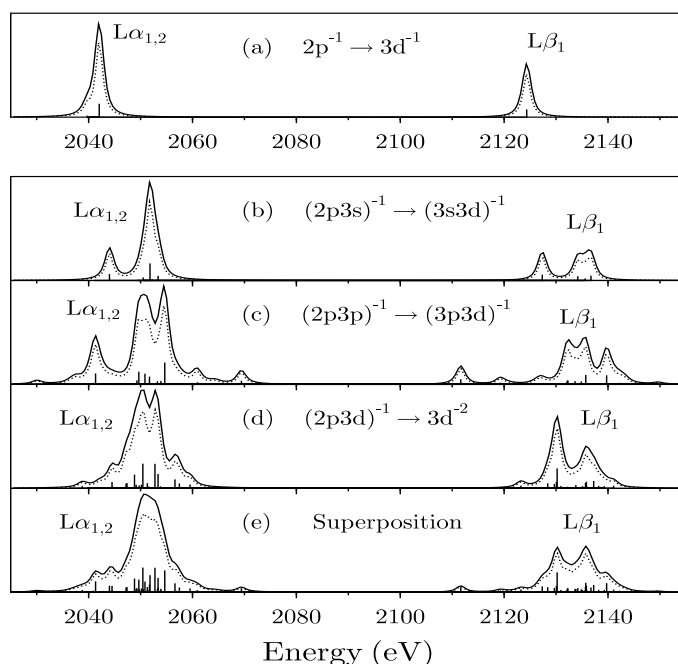


Figure 1: Calculated M -satellite $L\alpha_{1,2}$ and $L\beta_1$ lines in the X-ray spectra of zirconium.

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RESONANT ELECTRON PROCESSES WITH OPEN-SHELL HIGHLY CHARGED ION TARGETS

Nobuyuki NAKAMURA, Hirotsugu TOBIYAMA, Hiroaki NOHARA,
 Anthony P. KAVANAGH¹, Hirofumi WATANABE², Hiroyuki A. SAKAUE³, Yueming LI⁴,
 Daiji KATO³, Fred J. CURRELL¹, and Shunsuke OHTANI

Inst. for Laser Science, The Univ. of Electro-Communications, Tokyo 182-8585, JAPAN

¹Queen's University Belfast, Belfast BT7 1NN, United Kingdom

²CREST, Japan Science and Technology Agency

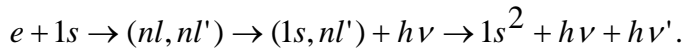
³National Institute for Fusion Science, Toki, Gifu 509-5292, JAPAN

⁴Institute of Applied Physics and Computational Mathematics, P.O.Box 8009, Beijing 100088

Resonant ionization and recombination are both initiated through capture of a free electron by a highly charged ion (HCI) while a bound electron is excited. The resultant unstable system may decay by photon emission: Dielectronic Recombination (DR), or by emission of two electrons due to successive autoionization: Resonant Excitation/ Double Autoionization (REDA). There have to date be few measurements of these processes reported involving change of principle quantum number for few-electron HCIs other than the well established DR measurements for closed-shell He-like systems (see [1] and refs therein).

These resonant processes can be studied efficiently by measuring the charge state distribution inside an electron beam ion trap by keeping the system at the equilibrium while slowly varying the electron beam energy [2]. Using this technique we have made the first observation of REDA in Li-like highly charged heavy ions [3]. We will also present the first reported results for KLn DR processes for various open shell system (e.g. Li-, Be-, B-, C-like ions) made using this technique.

In DR of H-like ions, doubly excited He-like ions with two K-vacancies are produced. These doubly excited systems can decay, sequentially emitting two photons:



The decay of such doubly excited states is not only important for the charge balance in hot plasmas but also interesting because such a doubly excited state can be considered as the simplest “hollow” atom; it will be very useful to test relativistic theories which treat the electron-electron interaction in many-electron system. Using a flat crystal spectrometer, we have clearly resolved for the first time the x-ray spectrum due to the decay of the two K-vacancies as is shown in the figure below. By analyzing this spectrum, we can obtain the resonant strength for each resonant state as will be presented at the poster along with details of the experimental setup and procedure.

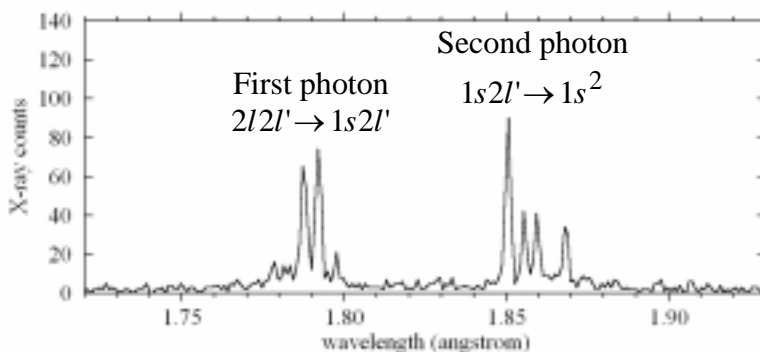


Figure 1. X-ray spectrum from the sequential decay of doubly excited He-like Fe produced by KLL DR between H-like Fe and electrons.

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ATOMIC CHARGE EXCHANGE PROCESSES FOR FAST HELIUM IONS IN SOLIDS

A. Gójska¹, D. Chmielewska¹, J. Rządkiwicz¹, Z. Sujkowski¹
for the Świerk – Osaka Collaboration

¹The Andrzej Soltan Institute for Nuclear Studies, 05-400 Otwock – Świerk, Poland

Interactions of 150 MeV/amu ${}^3\text{He}^{++}$ ions with solid C, Ni, Ag and Au targets have been studied at the isochronous cyclotron of the RCNP in Osaka. The singly ionized helium ions resulting from capture of the target electrons to the projectile were observed with the use of large magnetic spectrograph, Grand Raiden, set at $\theta = 0^\circ$ with respect to the beam. The yield ratios of singly to doubly ionized helium ions emerging from thin foils, $\text{He}^+/\text{He}^{++}$, have been measured as a function of the foil thickness. By extrapolating the results to zero target thickness one is able to determine the cross section values separately for electron stripping from ${}^3\text{He}^+$ ions and for electron capture to ${}^3\text{He}^{++}$ ions. The results are compiled with earlier data for lower He energies as functions of target atomic number as well as of projectile velocity. The eikonal approximation shows relatively good agreement with experimental data for the capture cross sections. No satisfactory description of the stripping results is observed.

THEORETICAL STUDY OF MULTIPLE IONIZATION OF DIATOMIC MOLECULES BY ION IMPACT

Carmen A. Tachino, Mariel E. Galassi and **Roberto D. Rivarola**

Instituto de Física de Rosario (IFIR-UNR), Av. Pellegrini 250, 2000 Rosario, Argentina

The study of multiple ionization in ion-molecule collisions is a subject of principal interest in many areas of physics, astrophysics, hadrontherapy and radiobiology. In particular, N_2 , CO and O_2 gases are present in planetary and cometary atmospheres, where the solar wind and cosmic rays stimulate the multi-electron emission. These gases are also present in ionization chambers used to calibrate accelerators employed for radiotherapy.

Stimulated by this interest, in the present work we calculate differential and total multiple ionization cross sections for impact of ions on the above mentioned molecules, at intermediate and high collision energies. To this end, we work within the framework of the Independent Particle Model (IPM), where the multiple ionization probabilities are calculated using binomial distributions [1]. The impact parameter probabilities for single-ionization are obtained applying different approximations: the Exponential (EM) [2] and the Continuum Distorted Wave - Eikonal Initial State (CDW-EIS) [3] models. The molecules are described as separated atoms or using molecular wavefunctions. The influence of the molecular orientation on differential cross sections is analyzed. An adequate description of existing experimental data is obtained. At high enough impact energies, the role played by post-collisional mechanisms in total cross sections is discussed.

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INNER- AND OUTER-SHELL VACANCY PRODUCTION IN THE COLLISIONS Ti + Pt, Au AND Bi AT 0.25-2 MeV/u

C. Ciortea, D.E. Dumitriu, A. Enulescu, D. Flueraşu, M.M. Gugiu, I. Piticu and A.C. Scafes

National Institute for Physics and Nuclear Engineering “Horia Hulubei”, 77125 Bucharest, Romania

Inner- and outer-shell vacancy production in some collision systems in the near of the K–L level matching region, namely Ti + Pt, Au and Bi collisions, at $0.25 \div 2$ MeV/u bombarding energies, have been studied by measuring projectile-K and target-L X-ray production cross sections. Using the X-ray energy and yield shift method [1], the mean numbers of spectator vacancies in the outer shells of both collision partners were estimated and the projectile charge states have been derived.

The measurements were done at the Tandem accelerator of NIPNE, Bucharest. Ion beams of Ti^{q+} ($q = 3 \div 11$) bombarded a thin selfsupported target and the emitted X-ray spectra were measured by an HPGe detector placed at 90° to the beam axis. Coulomb scattered projectiles were measured using a thin (50 μm) scintillation foil placed at 5.7° and/or 90° to the beam.

K–shell and L_i -subshells ($i = 1,2,3$) ionization cross sections, using vacancy decay widths corrected for multiple ionization effects, have been determined. Model calculations using direct ionization from both atomic and quasi-molecular orbital states have been done and compared to the experiment. As the results for the collision Ti + Pt (Figs. 1 and 2) show, some features of the inner-shell vacancy production in the collision systems studied here could be understood in the frame of the quasi-molecular excitation model [2].

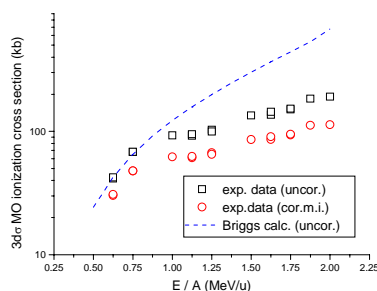


Fig. 1. Experimental $3d\sigma$ molecular orbital (MO) cross sections for the collision Ti + Pt in dependence of bombarding energy. Corrected (\circ) and uncorrected (\square) values for multiple ionization effects are given. The line gives Briggs model in the united-atom limit [3] calculations, uncorrected for binding effects.

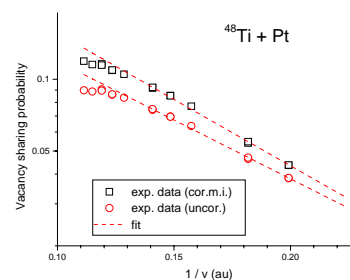


Fig. 2. Experimental $3d\sigma - 2p_{3/2}\sigma$ MOs vacancy sharing probability for the collision Ti + Pt in dependence of reciprocal collision velocity. The symbols are the same as in Fig. 1, and the lines are exponential fits to data. As data show, the exponential dependence in function of reciprocal velocity [4] is less fulfilled at higher velocities.

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X-ray imaging and spectroscopy of collisions between hot dense plasmas

J. Dardis¹, C. L. S. Lewis², J. T. Costello¹

¹National Centre for Plasma Science and Technology (NCPST) and School of Physical Sciences,
Dublin City University, Dublin 9, Ireland)

²International Research Centre for Experimental Physics (IRCEP) and School of Physics and
Mathematics, Queens University Belfast, Belfast BT7 1NN, Northern Ireland

We report on the development and construction of a soft X-ray (SXR) imaging and spectroscopy system used to study freely expanding plasmas as well as plasma-plasma and plasma-surface interactions. Colliding plasmas play a key role in areas such as pulsed laser deposition [1], inertial confinement fusion [2], X-ray lasers [3] and laboratory-scale astrophysical simulations [4]. We investigate the collision and interpenetration of laser produced plasmas in the soft X-ray region where the emission is from highly charged ions. Briefly, a pair of point plasmas are formed at the focus of either (i) 250mJ/170ps/1064nm or (ii) 1250mJ/12ns/1064nm pulses. Spectra of the individual source plasmas obtained using a system described in [5] are used to identify dominant ion stages. Time integrated pinhole images of the collision of plasmas expanding along the target surface are also presented. Low, medium and high Z targets, specifically Magnesium, Copper and Tungsten are used in these imaging and spectroscopy experiments.

The collisionality depends on the ion-ion mean free path (mfp) and the plasma geometrical scale length. At high temperatures the ion-ion mfp is quite large and preliminary results indicate, as one might expect, that there is little or no stagnation. This work will hopefully lead on to the study of plasma-surface interactions.

Work supported by the Irish government's National Development Plan, Science Foundation Ireland Research Frontiers Programme and the Higher Education Authority North-South Co-operation Grants Scheme.

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COLLISION DYNAMICS OF MULTIPLY CHARGED LIGHT IONS IN COLLISIONS WITH HYDROGEN AT ENERGIES BELOW 1 keV/u

Y. Inoue, K. Yoshimura, K. Ishii¹, H. Ogawa¹ and N. Sakamoto¹

Graduate school of Humanities and Science, Nara Women's University, Nara, 630-8506, Japan

¹Department of Physics, Nara Women's University, Nara, 630-8506, Japan

Experimental study of collision dynamics of multiply charged ions (MCI) with atoms and molecules in the energy range below 1keV/u is important not only in atomic physics but also in various applied fields such as astrophysics and fusion plasma researches. To clarify a collision dynamics of MCI with diatomic molecule below 1 keV/u, we have developed an experimental apparatus for triple-coincidence measurements of post-collision MCI and two fragment ions produced from a target molecule after charge transfer. A beam of MCI extracted from a Mini-EBIS is collided with an effusive target gas of H₂. Outgoing projectile ions from a collision region are analyzed by a parallel plate electrostatic analyzer with a 2D-PSD which resolves energy and scattering angle of the particles. Two fragment ions are detected separately by two time-of-flight analyzers installed respectively at 90° and -90° with respect to the projectile beam axis. All signals are directly recorded by PC through digitizers as a single event.

Collisions of light ions such as C, N and O with H₂ target have been extensively studied for a long time. For He-like ions of C, N and O, absolute total electron capture cross sections and absolute state-selective electron capture cross sections have been determined below 1 keV/u [1,2]. For C⁴⁺ and O⁶⁺, the sum of state-selective single electron capture cross sections into 3*l* and 4*l* states corresponds to the total cross section, while that for N⁵⁺ does not. This indicates that, in collisions of N⁵⁺ with H₂, the predominant process is double electron capture into autoionizing states. In order to confirm this, we studied collision dynamics of C⁴⁺, N⁵⁺ and O⁶⁺ + H₂ below 1 keV/u. Energy gain spectrum of single electron capture process for N⁵⁺+H₂ at 200 eV/u is shown in Figure 1. We find that the single electron capture into the *n* = 3 states is the dominant channel. More detailed discussion including double electron capture measured in coincident with fragment target ions will be presented.

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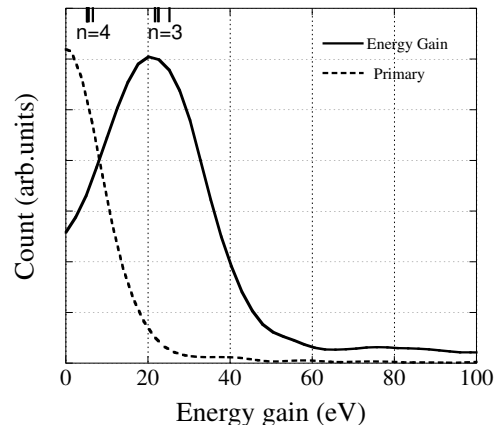


Figure 1: Energy gain spectrum of single electron capture process of N⁵⁺+H₂. Energy distribution of primary ion is also presented as a reference.

CHARGE CHANGING CROSS SECTIONS IN COLLISIONS OF LIGHT IONS WITH He AT ENERGIES BELOW 1 keV/u

K. Ishii¹, A. Itoh² and K. Okuno³

¹Dept. of Physics, Nara Women's University, Nara, 630-8506, Japan

²Quantum Science and Engineering Center, Kyoto University, Kyoto 606-8501, Japan

³Dept. of Physics, Tokyo Metropolitan University, Minami-Ohsawa, Hachioji, 192-0397, Japan

Charge changing cross sections of multiply charged ions in collisions with He are fundamental data in atomic physics and of practical importance in various application fields. In particular, cross sections of light ions such as C^{q+} , N^{q+} and O^{q+} at low energies below 1 keV/u are of great interest for plasma physics, astrophysics and thermonuclear fusion researches.

Previously, we determined charge changing cross sections of C^{q+} , N^{q+} and O^{q+} in collisions with He target for $q = 2 - 6$ [1]. It was found that charge changing cross sections for those collision systems vary strongly in an energy region below 1 keV/u.

In this work, we present single electron capture cross sections for $O^{7+} + He$ collision system at energies from 1 eV/ q to 1000 eV/ q as shown in Figure 1. Our cross sections connect reasonably with those of Iwai et al [2] at highest energies investigated. Single electron capture cross sections depend weakly on the collision energy, contrary to cross sections of lower charged projectiles presented in [1]. In the poster we present the experimental charge changing cross sections of C^{q+} , N^{q+} and $O^{q+} + He$ collision systems including this new data. Cross sections will be examined in detail within the framework of the modified over-barrier model developed in [1].

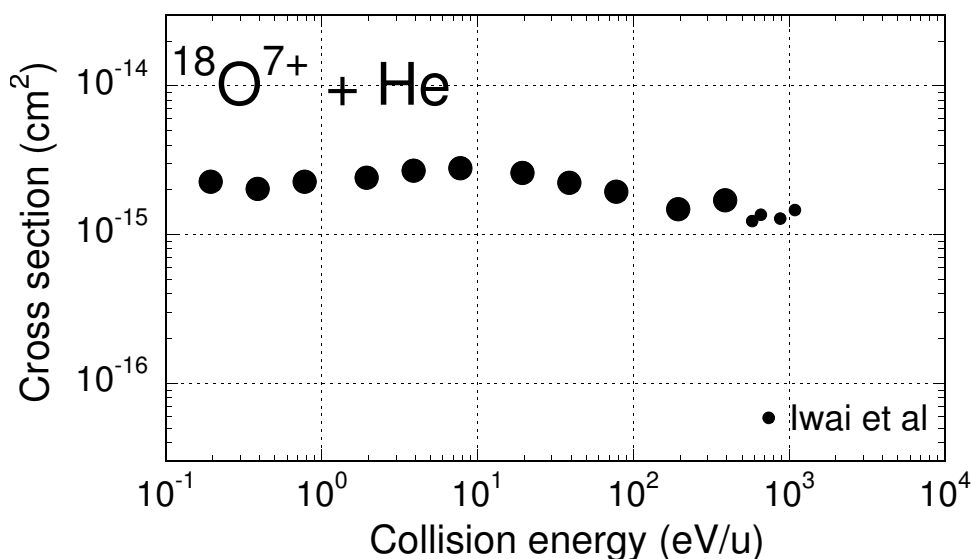


Figure 1: Single charge changing cross section of $O^{7+} + He$.

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ELECTRON-IMPACT EXCITATION OF Fe II

C. A. Ramsbottom¹, C. J. Noble², V. M. Burke², M. P. Scott¹ and P. G. Burke¹

¹ *Department of Applied Mathematics and Theoretical Physics, The Queen's University of Belfast.*

² *CSE Department, CLRC Daresbury Laboratory, Warrington WA4 4AD, UK*

The spectra of singly ionised iron is extremely important in astronomical observations, and Fe II emission has been observed from nearly every class of astrophysical object at infrared-to-ultraviolet wavelengths. Of critical importance to the interpretation of these spectral lines are the electron impact collision strengths and effective collision strengths. However, the accurate evaluation of this atomic data for the important low-ionised species in the near-neutral iron-peak region has proved impossible until now, due to the complexity of dealing with open d-shell ions. The computational effort for such investigations is formidable, with up to a thousand target states and several thousand coupled channels being involved. These complications are aggravated by the presence of Rydberg resonances located in the low-energy regions. Computational problems arise due to the necessity of including thousands of distinct energies in the scattering calculations, to properly delineate the resonance structures, thereby producing accurate excitation cross sections and ultimately Maxwellian averaged collision rates. To address these problems a parallel R-matrix package, PRMAT [1], has been developed to enable the evaluation of excitation rates of greater accuracy than has been previously possible. This will also provide a greater understanding of the important factors which influence these electron-ion collisions.

An initial calculation [2] for electron-impact excitation of Fe II, involving a 38-state LS-coupled calculation within the three electronic configurations $3d^64s$, $3d^7$ and $3d^64p$, uncovered large differences in the effective collision strengths amongst low-lying terms when compared with previous works. This calculation has since been extended to include the additional target states which arise from the $3d^54s^2$ and $3d^54s4p$ configurations, giving 113 LS-coupled levels and a maximum of 350 coupled channels [3,4]. A detailed study of low-energy electron collisions with Fe II in which configuration interaction effects were systematically included in both the target wavefunction and the collision wavefunction was carried out. It was shown that in order to obtain accurate low-energy partial wave collision strengths, configuration interaction effects in both the target and collision wavefunctions must be carefully balanced. In addition two-electron excitations from the 3p shell to the 3d shell must be included to achieve close to converged low-energy partial wave collision strengths.

We are at present pushing the calculation of electron-impact excitation rates for transitions between the fine-structure levels of Fe II, a formidable task even for the smallest LS-coupled approximation referred to in [2]. The inclusion of relativistic effects into the basic 4-configuration model of [2] leads to a jump from 117 to 1800 coupled channels and from 38 to 262 individual target levels. A Breit-Pauli calculation is near completion for this model and at the same time the PRMAT parallel R-matrix package is being extended to include relativistic effects. The availability of the HPCx and the proposed HECToR facility, together with innovative algorithm design, has meant that an approach similar to the Breit-Pauli method is now viable within the PRMAT framework. This should allow us to attempt the more sophisticated 26-configuration model of [4], and produce for the first time the amount and quality of atomic data required to perform a meaningful synthesis of the Fe II spectrum.

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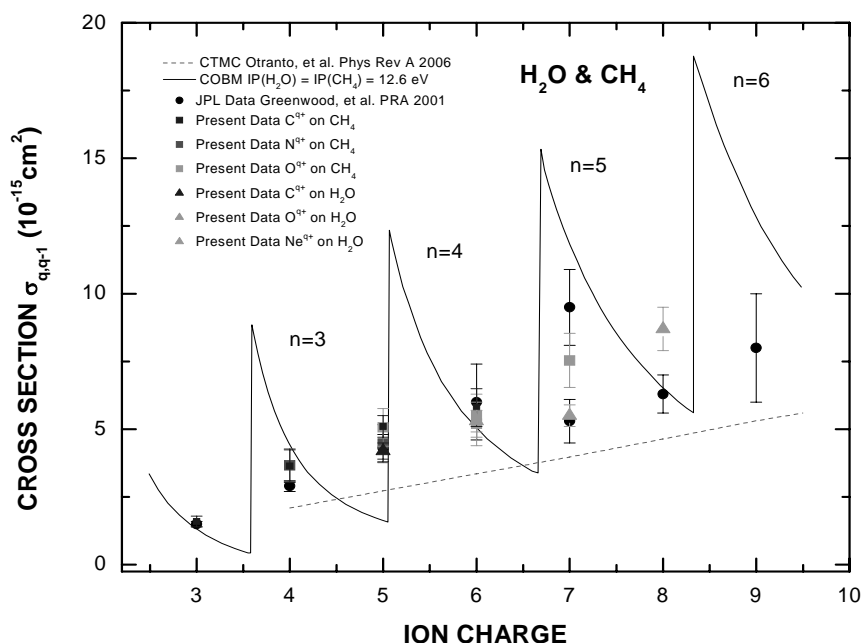
ABSOLUTE CHARGE EXCHANGE CROSS SECTIONS FOR $C^{3,4,5,6+}$, $N^{4,5+}$, $O^{5,6,7+}$, & $Ne^{7,8+}$ COLLISIONS WITH H_2O , CH_4 , CO , & CO_2

R.J. Mawhorter^{*}, N. Djurić, S. Hossain, J. MacAskill, S.J. Smith, I.D. Williams[#], & A. Chutjian

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA

^{*}JPL & Department of Physics & Astronomy, Pomona College, Claremont, CA 91711, USA

[#]Physics Department, The Queen's University, Belfast BT7 1NN, UK



The success of the Deep Impact and Stardust missions is advancing our understanding of the structure and composition of comets. This information drives and enhances ongoing cometary EUV and X-ray studies. In turn, our experimental absolute charge exchange cross sections for collisions of highly-charged solar wind ions with cometary gases are necessary for detailed modeling and analysis of these studies. For systems studied earlier, the current data agree with the previous measurements made with smaller apertures [1], demonstrating reproducibility and complete angular collection. The ion beam accelerating potential was typically 7 kV, which yields energies of 1.62 – 3.06 keV/amu for the ion species listed above and ion velocities consistent with the fast component of the solar wind. Slow solar wind velocity data (1.5 kV, 0.56 keV/amu) for O^{6+} on CO and CO_2 will also be presented, along with intermediate energy data (3.5 kV, 1.09 keV/amu) for O^{5+} on CO. Trends in the cross sections are discussed in comparison with the classical over-barrier model and more recent theoretical work- see the figure below. This work was carried out at JPL/Caltech, and was supported through contract with NASA. N. Djurić and S. Hossain also acknowledge support through the NASA-NRC program.

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NONSTATISTICAL ENHANCEMENT OF THE $1s2s2p$ 4P STATE IN ELECTRON TRANSFER FOR 0.5-1 MeV/u $C^{4,5+} + He$ and Ne COLLISIONS

Diane Strohschein, J. Baran, and J.A. Tanis

Department of Physics, Western Michigan University, Kalamazoo, MI 49008, USA

Intensities of the autoionizing metastable $(1s2s2p)$ 4P state compared to the similarly configured $(1s2s2p)$ $^2P_-$ and $(1s2s2p)$ $^2P_+$ states have been investigated for single electron transfer to $C^{4+}(1s^2+1s2s\ ^3S)$ and $C^{4+}(1s^2)$ and for double transfer to $C^{5+}(1s)$. Previously, nonstatistical enhancements were observed in the population of the 4P metastable state resulting from electron transfer in ~ 1 MeV/u $F^{7,8+} + He$ and Ne collisions [1]. The enhancements were attributed to a dynamical Pauli exchange mechanism involving electrons having the same spin. Recently, it has been suggested that the 4P intensity can be enhanced due to cascading effects following electron transfer to states with $n > 2$ [2].

To further understand the mechanisms responsible for producing the 4P state, new measurements of Auger emission spectra produced in collisions of 0.5, 0.75 and 1 MeV/u $C^{4,5+}$ with He and Ne targets were conducted. This work was done at Western Michigan University using the tandem Van de Graaff accelerator. Auger electrons emitted at zero degrees were detected using a high-resolution parallel-plate electron spectrometer located downstream from the target cell. The long lifetimes of the 4P states [3] cause most ($\sim 80\%$) of the excited ions in 4P state to decay after passing the spectrometer, so the observed intensities of this state were corrected for this loss. Because the single transfer measurements of Ref. [1] were conducted only for the mixed-state beam $F^{7+}(1s^2+1s2s\ ^3S)$, formed by post-stripping following acceleration, it was not clear what fraction of the observed 4P intensity was due to the respective beam components. Thus, for single transfer to incident C^{4+} spectra were collected for both ground-state $C^{4+}(1s^2)$, formed directly by gas-stripping at the terminal of the accelerator, as well as mixed-state $C^{4+}(1s^2 + 1s2s\ ^3S)$ ions.

Ratios of the corrected 4P intensities to the sum of the 2P states for the collision systems studied are shown in Fig. 1. For single transfer, the $1s2s2p$ intensities produced in the mixed-state beam $C^{4+}(1s^2+1s2s\ ^3S)$ are compared with intensities for the ground-state beam $C^{4+}(1s^2)$ to determine the contribution due solely to the $1s2s\ ^3S$ metastable beam. The ratios produced by the ground state beam are close to the statistically expected value of 2, while the mixed-state beam collision system gave ratios of ~ 3 -4 for each energy investigated, indicating the presence of nonstatistical effects. The lack of appreciable energy dependence in these ratios seems to rule out a significant contribution to the 4P intensity from cascading effects, leaving open the possibility of dynamical Pauli exchange or some other mechanism as the cause of the enhanced 4P state.

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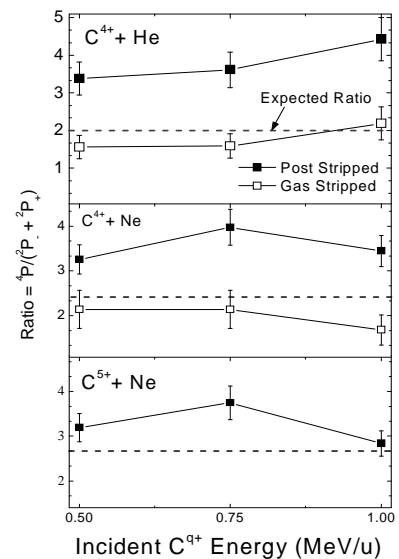


Fig. 1 : $^4P/(^2P_-+^2P_+)$ intensity ratio vs. projectile energy.

ELECTRON CAPTURE PROCESSES FOR FAST HELIUM IONS IN SOLID TARGETS

A. Gójska¹, D. Chmielewska¹, J. Rządkiwicz¹, Z. Sujkowski¹, Th. Stöhlker²

¹The Andrzej Soltan Institute for Nuclear Studies, 05-400 Otwock – Świerk, Poland

²Gesellschaft für Schweirionenforschung, 64220 Darmstadt, Germany

The radiative and non-radiative electron capture cross sections have been studied both theoretically and experimentally. The electron capture process into ${}^3\text{He}^{++}$ ions from the solid target has been theoretically investigated with eikonal approximations for non-radiative electron capture (NREC) [1] and using dipole and exact relativistic approximations for radiative electron capture (REC) [2]. In this work the eikonal calculations are extended for capture from and to various shells. The electron capture cross section is summed over all states with initial state n_i (up to $n_i = 4$) and summed over all final states with n_f ($n_f \leq 20$). It was found that for the relativistic collisions of ${}^3\text{He}^{++}$ (150 MeV/u) ions with low-Z targets the main contribution to non-radiative electron capture derive from the K-K transfer (more than 80%). For the relativistic collisions of ${}^3\text{He}^{++}$ ions with high-Z atoms a dominant contribution to the NREC processes coming from the L-K and M-K transfers (~42% and ~31%, respectively) and the electron capture from K-shell becomes much smaller (~4%). For all relativistic collisions the contribution to the total NREC decreases with the principal quantum number of the projectile. The contribution from all transfers into shells with $n_f \geq 5$ can be neglected (less than 0.7%). The theoretical calculations are discussed as a function of target atomic number and projectile velocity and are compared with experimental data for various energies (from 17.3 MeV/u to 150 MeV/u) [3,4]. In the case of the NREC cross sections, there is relatively good agreement between experimental data and theoretical predictions. It was found that in order to proper theoretical description of electron capture process into the relativistic He^{++} ions from low-Z atom the radiative electron capture have to be taken into account. The contribution of the REC to the total cross section for 150-MeV/u ${}^3\text{He}^{++} \rightarrow \text{C}$ collisions predicted by theory (~86%) is significantly higher than that observed at the experiment (~42%). The REC processes for H^+ and He^{++} ions are of great importance for astrophysical studies. Primordial hydrogen and helium might exist in the intergalactic medium (IGM). Totally ionized H^+ and He^{++} escape optical observations. The REC process could be a tool to detect completely ionized plasma placed in the intergalactic space.

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VIOLATION OF THE WIGNER THRESHOLD LAW BY RESONANCE AND TRANSPARENCY EFFECTS

P. A. Macri, R. O. Barrachina*

Departamento de Física, FCEyN, Universidad Nacional de Mar del Plata, 7600 Mar del Plata,
Argentina.

(*) Centro Atómico Bariloche and Instituto Balseiro, 8400 Bariloche, Argentina

The interaction of highly charged ions with matter produces cross sections which, at thresholds are widely believed to be governed by the Wigner law [1]. This general law presents, however, several difficulties. In first place, it is not clear the energy domain where it is valid. On the other side, the Wigner threshold law does not link, by itself, the measured cross sections with the system interactions and therefore, cannot be used to extract important collision features as for instance scattering lengths. Although it is possible to extend the Wigner law by effective range expansion [2], a direct determination of the scattering length is only feasible in few cases with collision experiments sufficiently close to the reaction threshold. In recent works [3], we showed that the Jost function [4] establishes a clear link between the threshold behavior in a multichannel collision and the low-energy elastic scattering process by the same final-state interaction. In this work, we show how the introduction of the Jost function enables us to construct a threshold law which generalizes the Wigner threshold law beyond the scope of the effective range approximation. This generalization makes it possible to extract scattering parameters from most of the experiments. Moreover, we show how this new law describes conditions where the Wigner law is violated even at threshold ought to the presence of resonance and transparency effects.

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DIELECTRONIC RESONANCE ENERGIES AND STRENGTHS IN HIGHLY-CHARGED MERCURY IONS TO INVESTIGATE CORRELATED HIGH-FIELD FEW-ELECTRON DYNAMICS AND QED CONTRIBUTIONS

Z. Harman¹, A. J. González Martínez¹, H. Tawara¹, A. N. Artemyev^{1,2},
J. R. Crespo López-Urrutia¹, U. D. Jentschura¹, C. H. Keitel¹, A. Lapierre¹, J. H. Scofield³,
R. Soria Orts¹, I. I. Tupitsyn^{1,2}, J. Ullrich¹

¹Max-Planck Institute for Nuclear Physics, Saupfercheckweg 1, D-69117 Heidelberg, Germany

²Department of Physics, St. Petersburg State University, Oulianovskaya 1, Petrodvorets,
198504 St. Petersburg, Russia

³Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

The photorecombination of highly charged few-electron mercury ions ($\text{Hg}^{75+} - \text{Hg}^{78+}$) has been explored with the Heidelberg electron beam ion trap [1]. By monitoring the emitted x-rays (65 – 76 keV) and scanning the electron beam energy (45 – 54 keV) over the KLL dielectronic recombination (DR) region, the energies of state-selected DR resonances were determined to within ± 4 eV (relative) and ± 14 eV (absolute). At this level of experimental accuracy, it becomes possible to make a detailed comparison to various theoretical approaches and methods, all of which include quantum electrodynamic (QED) effects and finite nuclear size contributions.

Theoretical resonance energies for KLL dielectronic recombination into He-, Li-, Be- and B-like Hg ions are calculated by various means and discussed in detail [2]. We apply the multiconfiguration Dirac-Fock and the configuration interaction Dirac-Fock-Sturmian methods, and quantum electrodynamic many-body theory. The different contributions such as relativistic electron interaction, quantum electrodynamic contributions, and finite nuclear size and mass corrections are calculated and their respective theoretical uncertainties are estimated. The comparison of theoretical values with the experimental energies shows a good overall agreement for most transitions and illustrates the significance of relativistic electron interaction contributions including correlation, magnetic, and retardation effects and quantum electrodynamic corrections. Few discrepancies found in specific recombination resonances for initially Li- and Be-like Hg ions are pointed out, suggesting the need for further theoretical and experimental studies along these isoelectronic sequences.

The DR strengths have been determined relative to the calculated RR cross sections [3]. The DR cross sections have also been calculated in the framework of the multiconfiguration Dirac-Fock (MCDF) method. Such a comparison highlights the significance of relativistic electron-electron correlation and configuration mixing effects in dynamical processes involving heavy ions. Combining the present data of Hg ions with those for other ions available so far, simple scaling formulae for the Z -dependence of total as well as partial ($1s2s^2$) KLL DR strengths for He-like ions have been deduced. The scaling of total and partial strengths is found to be substantially different.

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EMISSION CHARACTERISTICS OF K CASCADE PHOTONS AFTER RADIATIVE ELECTRON CAPTURE AT STRONG CENTRAL FIELDS

P.H. Mokler^{1,2}, X. Ma^{2,3}, E.G. Drukarev⁴ and A.I. Mikhailov⁴

¹Justus-Liebig University, 35292 Giessen, Germany; ²GSI, 64291 Darmstadt, Germany;

³Institute of Modern Physics, Lanzhou 73000, China;

⁴Nuclear Physics Institute, Gatchina, St. Petersburg 188300, Russia.

A drastic difference in the angular distribution of Ly- α_1 and K- α_1 photons from initially bare and hydrogen-like uranium ions (U^{92+} and U^{91+} , respectively) was observed after radiative electron capture (REC) to the L-shell. In the first case, for the Ly- α_1 cascade photons a strong directional emission preferentially perpendicular to the incoming ion direction (in the ion frame) was observed [1.] This is caused by a strong alignment of the $p_{3/2}$ electrons captured to the L shell in U^{91+} . Here the strong anisotropy increases with decreasing ion energy in the investigated range between 90 and 360 MeV/u and was well explained theoretically [2]. In contrast, for initially H-like uranium ions, U^{91+} , the K- α_1 cascade photons show in the experiment a practically isotropic emission pattern (in the emitter frame) [3]. This change in the emission characteristics is caused by the presence of the second electron in the He-like system, U^{90+} . Despite in uranium the electron-electron interaction is small compared to the central potential governing the REC process the Pauli principle prevails for the structure in the two-electron system. Analytical calculations for the REC-cascade process were carried out for initially bare and H-like U in lowest order of a perturbative approximation using relativistic Coulomb wave functions in $(Z\alpha)^2$ expansion. For the low relativistic velocity region (around 100 MeV/u) it was found. that the two experimentally not resolved x-ray transitions contributing to the K- α_1 line starting from the intermediate 2^1P_1 and 2^3P_2 levels show a strong anisotropic emission pattern. However, these emission patterns are rotated by 90° to each other (in the emitter frame): Where in the ion frame the E1 transition $2^1P_1 \rightarrow 1^1S_0$ prefers emission directions perpendicular to the ion direction, the M2 transition $2^3P_2 \rightarrow 1^1S_0$ prefers the emission along the ion direction. Both opposing anisotropies are caused by an equivalent alignment of the $p_{3/2}$ electron from the REC process; and both components cancel each other for the composed K- α_1 line. A good agreement between theory and experiment is found. Moreover, just recently, similar results are being found by other authors using extended calculations based on a density matrix theory and applying a multi-configuration Dirac-Fock approach [4].

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Young type interference in electron emission from H₂ induced by 80 MeV C⁶⁺ ions and its effect on the forward-backward angular asymmetry

D. Misra, A.H. Kelkar, U. Kadhane, Ajay Kumar, P.D. Fainstein⁺, Lokesh C. Tribedi*

Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai-5

⁺Centro Atomico Bariloche, 8400 Bariloche, Argentina

Recent observation of Young type interference in ion-impact ionization of diatomic molecule H₂ [1,2] unfolds yet another important aspect of ion-atom ionization besides the well known mechanisms i.e. the soft collision, two center effect, binary encounter and electron capture in continuum. Since the two indistinguishable H-atoms may be termed as a coherent source of electrons in a large impact parameter collision with a fast projectile, their contributions to the ionization add coherently and an interference effect may be expected and has been observed [1,2]. Since the double differential cross section (DDCS) varies over several orders of magnitudes in an energy range of few hundred eV, it becomes difficult to observe a small variation in the DDCS spectrum owing its steep variation. Therefore, to enhance the visibility of the structure, the molecular cross sections are divided by the corresponding atomic cross sections, which are either obtained theoretically [1] or in an experiment with atomic H [2]. We have now demonstrated [3] an independent way of obtaining the interference structure by using the forward backward asymmetry parameter of electron DDCS which is independent of the theoretical model calculations and neither require a complementary experiment with atomic H. Bare C ions of energy 5-7 MeV/u were available from the BARC-TIFR Pelletron accelerator at TIFR. The experiments were carried using low pressure H₂ gas. Energy and angle resolved electrons were detected, using a hemi-spherical electrostatic analyzer, at several forward and backward angles between 20^o and 160^o. The difference in the oscillation frequency for the forward and backward angles causes the oscillation in the forward backward asymmetry parameter which is also reproduced by the molecular CDW-EIS calculation[4]. A model calculation based on peaking approximation[1] also fits the spectrum well.. Since this study does not need any atomic target, can be applied for other diatomic molecular targets: a step forward towards the study of Young type interference in ionizations of molecule.

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* lokesh@tifr.res.in

Multiple ionization of C₆₀ in collisions with 2.33 MeV/u highly charged Si ions and giant plasmon resonance

Aditya Kelkar, U. Kadhane, D. Misra, Ajay Kumar, L.C. Tribedi

Tata Institution of Fundamental Research, Colaba, Mumbai 400005, India

There have been several investigations on the fast heavy ion induced ionization and fragmentation of C₆₀ molecules [1,2,3,4]. Collision with fast highly charged ions is an important probe to investigate the structural aspects and the interaction mechanisms of molecules and clusters. However, it is of current interest to explore the effect of collective excitation, namely the giant dipole plasmon resonance (GDPR) on the multiple ionization [5]. It has been predicted that the cross section of plasmon excitation is quite sensitive to the perturbation strength (q/v). To test the prediction of this model we present results on the projectile charge state (q) dependence of single, double, triple and quadruple ionization cross sections. The Si projectile (with velocity $v=9.7$ a.u.) was chosen in order to have a wide variation of q between 6+ and 14+. The Si ions were obtained from the BARC-TIFR 14 MV Pelletron accelerator facility at TIFR, Mumbai. A C₆₀ vapor source was used for the collisions. The reaction products were detected using a Wiley-McLaren type time of flight mass spectrometer combined with MCP+delay line detector assembly. The charge state dependence of the multiple ionization yields of C₆₀^{r+} ($r=1-4$) were compared with GDPR^[1] model as well as the SED-LPA^[2] model. The relative yields of single and double ionization are in excellent agreement with the GDPR model showing an almost linear dependence with q , whereas triple and quadruple ionization yields show better agreement with SED-LPA (statistical energy deposition-local plasma approximation) calculations which predict a very weak dependence on ' q '. This difference can be understood in terms of underlying assumptions of the two models. Indeed the results are in complete contrast with those for noble gaseous target which may indicate the different mechanisms of ionization processes for ion-atom and ion-fullerene collisions. A quantitative analysis of C₂ evaporated products C_{60-2m}^{r+} ($m=1-7$) suggests that relaxation by evaporating stable C₂ fragments is a preferable process for higher recoil ion charge states. This indicates a strong coupling of electronic excitation to vibrational modes which are supposed to be responsible for C₂ evaporation. The relative yield of evaporation products to the parent recoil ion also shows q dependence similar to the ionization products. Relative fragmentation yields show a linear enhancement with q . The ratio of fragmentation yield to total reaction product seems to saturate for higher q .

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A NEW MOTRIMS SETUP FOR HIGH RESOLUTION MEASUREMENTS IN ION-ATOM COLLISIONS

X. Flécharde, J. Blicke, A. Cassimi*, J. Delaubert, H. Gilles[#], S. Girard[#], and D. Hennecart[#]

LPC-ENSICAEN, 6 Boulevard du Maréchal Juin, 14050 Caen Cedex, France

(*) CIRIL-GANIL, avenue H. Becquerel, 14070 Caen Cedex 5, France

([#]) CIRIL-ENSICAEN, 6 Boulevard du Maréchal Juin, 14050 Caen Cedex, France

In the past several years, the magneto-optical trap (MOT) has become a standard tool for many areas of atomic, molecular, and optical physics. Well-known examples include Bose-Einstein condensate and degenerate Fermi gas formation, photo-association, electromagnetically induced transparency, high resolution spectroscopy, etc...

One of the main advantages of a MOT is to provide a localized and cold sample of atoms, almost at rest in a high vacuum environment. In addition, the trapped atom cloud can be quite easily laser excited and oriented. Such properties are extremely valuable for other studies involving the coupling of a MOT with other experimental techniques:

-In the field of nuclear physics, a MOT of radioactive atoms makes an ideal β -source for precision experiments dedicated to the search for physics beyond the Standard Model, and the test of fundamental symmetries.

-In atomic physics, the MOTRIMS (magneto-optical-trap recoil-ion momentum spectroscopy) technique [1] uses trapped atoms as a cold target for the study of ion-atom collisions. With this outgrowth of the more general RIMS method, the resolution on the recoil momentum measurement can be increased, due to the very low temperature of the atomic cloud. Furthermore, it provides atomic targets with new species that can be prepared in excited states.

Motivated by both topics, the LPC and the CIRIL built recently a Rb MOT designed to be coupled to a recoil-ion spectrometer. The characteristics of the atom cloud have been accurately measured, and the MOT operating parameters optimized to provide the highest target density. We reached 10^{11} atoms/cm³ with a temperature below 200 μ K. In order to achieve the highest momentum resolution, the spectrometer geometry has been determined using the SIMION simulation software. We expect a resolution on the three components of the Rb⁺ recoil-momentum better than 0.03 a.u. To enable the detection in coincidence of the recoils and the emitted electrons in future experiments, a fast switch of the MOT magnetic field will also be developed. The collision systems that will be investigated and the details of the experimental setup will be presented at the conference.

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ELECTRON IMPACT EXCITATION OF Na-LIKE Fe XVI

K. M. Aggarwal and F. P. Keenan

Department of Physics and Astronomy, Queen's University, Belfast BT7 1NN

In a recent paper [1] we reported energy levels, radiative rates, collision strengths, and excitation rate coefficients for transitions among 39 levels of the $(1s^2 2s^2 2p^6) nl; n \leq 7, \ell \leq 4$ configurations of Fe XVI. For the calculations of energy levels and radiative rates (A- values), we adopted the *General purpose Relativistic Atomic Structure Package* (GRASP: [2]), and for the computations of collision strengths (Ω) the *Dirac Atomic R-matrix Code* (DARC: [3]). Additionally, resonances were resolved in a fine energy mesh in order to calculate excitation rate coefficients over a wide energy range up to 10^7 K. Thus the results presented there were a substantial improvement over the earlier ones [4]. However, many lines of Fe XVI in the 15-17 Å x-ray range are frequently observed in the astrophysical and laboratory plasmas, and these arise from the *inner* (L) shell excitation of Fe XVI, such as: $2p^6 3s + e^- \rightarrow 2p^5 3\ell 3\ell'$. Therefore, in this paper we focus on the inner shell electron impact excitation of Fe XVI, and adopt the same codes as earlier to generate the desired atomic data.

In the present work, we include 134 levels among the $(1s^2 2s^2) 2p^6 3\ell, 2p^5 3s^2, 2p^5 3s 3p, 2p^5 3s 3d, 2p^5 3p 3d,$ and $2p^5 3p^2$ configurations of Fe XVI. The *R*-matrix radius has been adopted to be 2.44 au, and 20 continuum orbitals have been included for each channel angular momentum for the expansion of the wavefunction. This allows us to compute values of Ω up to an energy of 340 Ryd. The maximum number of channels for a partial wave is 666, and the corresponding size of the Hamiltonian matrix is 13330. In order to obtain convergence of Ω for all transitions and at all energies, we have included all partial waves with angular momentum $J \leq 40$, although a higher range would have been preferable for the convergence of allowed transitions. However, to account for the inclusion of higher neglected partial waves, we have included a top-up, based on the Coulomb-Bethe approximation for allowed transitions and geometric series for forbidden ones.

Earlier calculations for this ion have been performed by Bautista [5], who adopted a semi-relativistic *R*-matrix approach. Since Fe XVI is a moderately heavy ion ($Z = 26$), both configuration interaction (CI) and relativistic effects are supposed to be important in the determination of wavefunctions, and subsequently of Ω . He observed that the contribution of resonances has enhanced the *effective* collision strengths (Υ) up to three orders of magnitude, depending on the temperature, and the relativistic effects have enhanced these by several orders of magnitude, for some of the transitions. Since both of these observed enhancements are unusually high, one of our *aims* is to assess the accuracy of his reported results, apart from making other improvements. A detailed comparison with his results, along with our atomic data for all the desired parameters, will be presented during the conference.

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VACANCY REARRANGEMENT PROCESSES IN MULTIPLY IONIZED ATOMS

M. Czarnota¹, D. Banaś¹, M. Pajek¹, J.-Cl. Dousse², Y.-P. Maillard², O. Mauron², M. Berset², P. A. Raboud², D. Chmielewska³, J. Rządkiwicz³, Z. Sujkowski³, M. Polasik⁴, K. Słabkowska⁴, J. Hoszowska⁵

¹Institute of Physics, Świętokrzyska Academy, 25-406 Kielce, Poland

²Physics Department, University of Fribourg, CH-1700 Fribourg, Switzerland

³Sołtan Institute for Nuclear Studies, 05-400 Otwock-Świerk, Poland

⁴Faculty of Chemistry, Nicholas Copernicus University, 87-100 Toruń, Poland

⁵European Synchrotron Radiation Facility (ESRF), Grenoble, F-38043, France

The X-rays excited in collisions of heavy ions with atoms exhibit, apart from the diagram lines, the so called x-ray satellites corresponding to the different multi-vacancy configurations present in the moment of X-rays emission. The high resolution measurements of the X-ray satellites give thus access to study the structure of multi-vacancy states as well as the dynamics of multiple ionizations.

In multiply ionized atoms the fluorescence yields (ω_i) and Coster-Kronig (f_{ij}) yields can be modified substantially due to, in simple approximation, two main processes: a reduction of a number of electrons for relaxation processes and closing of Coster-Kronig transitions. The first effect can be described using the Larkins statistical scaling [1], while the closing of Coster-Kronig transitions was accounted for [2] by calculating the modified electron binding energies to identify the CK transitions which are energetically forbidden in multiply ionized atoms. These modifications changed directly the radiative, Auger and Coster-Kronig widths, which were further used to calculate the modified fluorescence and CK yields.

In order to interpret the x-ray satellite in terms of theories of multiple ionization, despite of modification atomic parameters in multiply ionized atoms, one has to take into account the vacancy rearrangement process which takes place between the moments of ionization and x-ray emission. We demonstrate that the vacancy rearrangement process can be described in terms of the rearrangement factor, which can be calculated by solving the system of rate equations modelling the flow of vacancies in the multiple ionized atom. Using this factor, the ionization probability at the moment of ionization $P_i(0)$ can be obtained from the measured ionization probabilities $P_X(0)$ corresponding to the moment of X-ray emission.

These calculations were performed to interpret the measured M-shell satellite structure of Pd $L\alpha_{1,2}$ x-ray transition excited by O^{6+} ions of energy 279 MeV [3]. In this experiment the x-rays were measured by high resolution crystal spectrometer with energy resolution about 0.6 eV. The measured x-ray spectra will be discussed in details.

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ANGULAR DISTRIBUTION OF X-RAYS FROM RECOMBINATION OF BARE URANIUM IONS WITH LOW-ENERGY ELECTRONS

M. Pajek¹, D. Banaś¹, M. Czarnota¹, Th. Stöhlker², H. F. Beyer², F. Bosch², C. Brandau², S. Chatterjee², A. Gumberidze², S. Hagmann², C. Kozhuharov², D. Liesen², P. H. Mokler², R. Reuschl², U. Spillmann², S. Tachenov², S. Trotsenko², P. Verma², D. Sierpowski³, A. Warczak³, S. Böhm⁴, A. Müller⁴, E. W. Schmidt⁴, J.-Cl. Dousse⁵, J. Szlachetko^{1,5}

(¹) Świętokrzyska Academy, Kielce, Poland

(²) GSI, Darmstadt, Germany

(³) Jagiellonian University, Cracow, Poland

(⁴) Justus-Liebig Universität, Giessen, Germany

(⁵) University of Fribourg, Switzerland

In radiative recombination (RR) a free electron is captured into bound state of an ion with emission of a photon. This process has been studied extensively in cooler/storage rings, where the ions are cooled by the dense electron beams of equal mean velocity. The radiative recombination of high-Z bare ions with low-energy cooling electrons is expected to be well described within the nonrelativistic dipole approximation. However, the angular distributions of emitted x-rays become sensitive to relativistic effects. Under the cooling condition the relative energies of the electrons are characterized by the transverse electron beam temperature kT_{\perp} and, usually much smaller, the longitudinal temperature ($kT_{\parallel} \ll kT_{\perp}$). The RR experiments at different ion storage rings (TSR, CRYRING, ESR), performed by observing down-charged ions, have revealed that the measured recombination rates exceed substantially the theoretical predictions for relative electron energies below the transverse electron beam temperature kT_{\perp} . This, so-called, "enhancement" effect is well established experimentally for a number of bare ions, up to U^{92+} [1].

In order to study the enhancement effect in more detail an x-ray state-selective recombination experiment at off-cooling condition has been performed at the ESR storage ring [2]. In the experiment the recombination of bare U^{92+} ions (23 MeV/u) with electrons was studied at relative energies of range $E_{rel} = 0 - 1000$ meV. The x-rays emitted from the recombination process were measured by two germanium detectors placed close to 0° and 180° with respect to the ion beam direction. In order to interpret these data the RR recombination rates were calculated using both relativistic and nonrelativistic approaches. The radiative recombination rate coefficients $\alpha_{nl} = \langle \sigma_{nl}(v)v \rangle$ were calculated for estimated temperatures of the flattened electron beam ($kT_{\parallel} \ll kT_{\perp}$) and for different relative electron detuning energies $E_{rel} = 0 - 1000$ meV. The calculations show a drastic change of the angular distributions of the emitted x-rays for different relative electron energies. This is explained by the fact that for flattened electron beam and for very low energies ($E_{rel} \ll kT_{\perp}$) the electrons are moving mainly perpendicular to the ion beam axes, while for higher energies ($E_{rel} \geq kT_{\perp}$) they are moving along the ion beam direction. The calculated recombination rate coefficients will be discussed in context of the recent RR state-selective x-ray experiment [2] performed at the GSI for off-cooling conditions.

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RECOMBINATION OF BORONLIKE NEON

S. Böhm, P. Glans*, I. Orban, and R. Schuch

Atomic physics, Fysikum, Stockholm University, Alba Nova 106 91 Stockholm, Sweden
Department of Engineering, Physics and Mathematics, Mid Sweden University, S-851 70 Sundsvall,
Sweden

One important process that governs charge state balance in a plasma is dielectronic recombination [1]. Accordingly, DR-rate coefficients form a basic ingredient in plasma modeling codes that are employed for the analysis of spectra obtained from astrophysical observations. To date, most DR-rate coefficients stem from theoretical calculations. Calculating DR-rate coefficients is a challenging task since an infinite number of states is involved in this process. Hence experimental benchmarks are required for testing and improving the theoretical methods [1-3]. Here we present the experimentally derived DR-rate coefficients for boronlike Neon.

The recombination of Ne^{5+} ions with electrons has been measured at the ion storage ring CRYRING of the Manne-Siegbahn Laboratory in Stockholm. For these measurements the electron cooler was used as an electron target [2] and the center of mass energy range was scanned between 0 – 135 eV. This covered all $\Delta n = 0$ and most $\Delta n = 1$ excitations. By convoluting the experimental DR cross section with a Maxwellian electron energy distribution the plasma rate coefficient was obtained [3]. Huge DR resonances were measured at low energies (see figure 1). In this range many of the atomic codes used for plasma modeling deviate by up to orders of magnitude from the experimental data. Hence, our experiment helps to reduce the uncertainties in plasma modelling significantly.

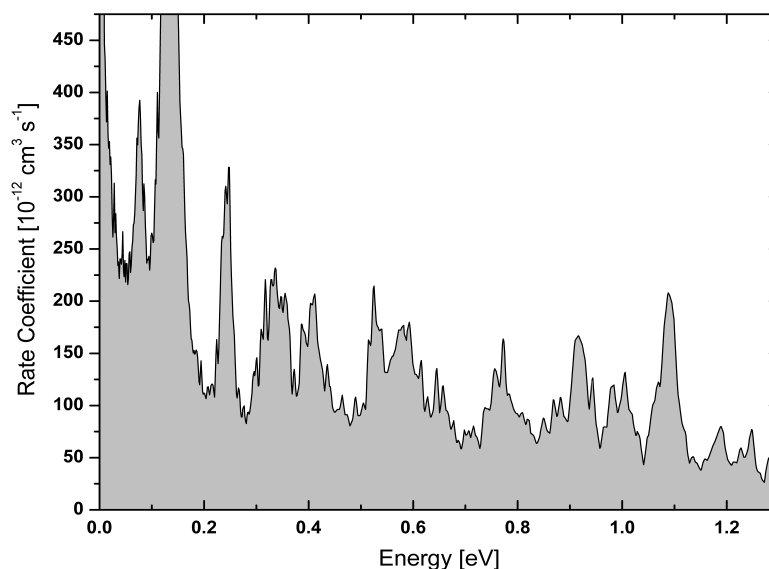


Figure 1: Low energy part of the recombination spectrum of boronlike neon.

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RECOMBINATION STUDIES OF HIGHLY CHARGED SI IONS AT THE STOCKHOLM ELECTRON BEAM ION TRAP

T. Fritioff, S. Böhm, I. Orban, and R. Schuch

Atomic physics, Fysikum, Stockholm University, Alba Nova 106 91 Stockholm, Sweden

A new laboratory for highly charged ions is being built up at Stockholm university. An electron beam ion trap (EBIT) (3 T magnet, ≤ 30 keV electron beam) was installed. It is used for spectroscopic studies and investigations in electron ion collisions. It is also used as an electron beam ion source. At one beam line an ion trap has been built up to cool ions. These ions can be extracted into the ion trap SMILETRAP [1] used for precision mass measurements. Another beam line has been built up for measurements with nanocapillaries [2].

The EBIT was used to do first recombination studies of highly charged silicon ions. X-rays emitted from radiative recombination (RR) and dielectronic recombination (DR) were observed as the electron beam energy, and hereby the electron ion center of mass energy, was scanned. The x-ray energy together with the electron energy were recorded in list mode following the procedure described in reference [3]. In figure 1 the data is presented with the x-axis corresponding to the photon energy and the y-axis to the electron energy. The blobs represent the DR resonances and the diagonal lines represent RR. Silicon is an astrophysical abundant element and accurate knowledge of the recombination process will help to improve theoretical methods used to model astrophysical plasmas.

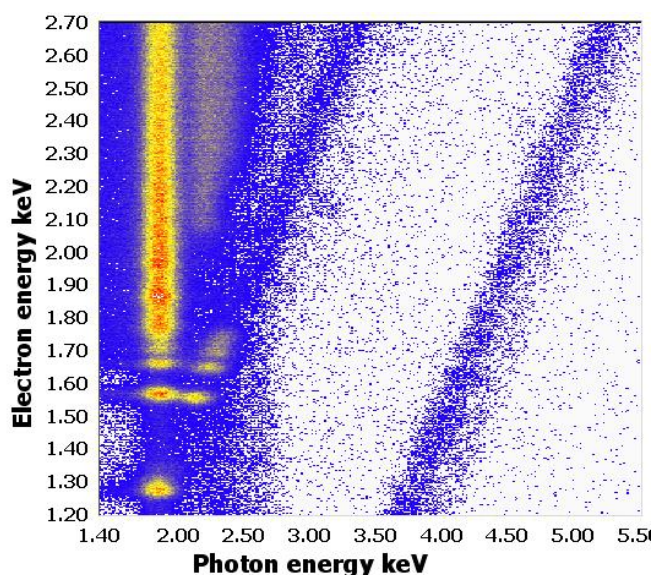


Figure 1: Recombination of highly charged silicon ions.

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EFFECT OF TARGET POLARISATION IN ELECTRON-ION RECOMBINATION

A. V. Korol[†], G. F. Gribakin^{*}, F. J. Currell^{*}

[†]Department of Physics, St Petersburg State Maritime Technical University, St Petersburg, Russia

^{*}School of Mathematics and Physics, Queen's University, Belfast, Northern Ireland, U.K.

We present the results of a study of the effect of target polarization, i.e., virtual dipole excitation of the target electrons by the incident electron. Coherent radiation by target electrons gives a large contribution to the electron-ion recombination rate, significantly modifying the nonresonant photorecombination background. We call it polarisation radiation (PR). This contribution leads to the same final states as the radiative recombination (RR), where the photon is emitted by the incident electron.

A procedure is devised whereby the total contribution of RR and PR can be evaluated independently of that for the dielectronic recombination (DR) component, thereby allowing the importance of target polarization to be determined on a case-by-case basis in recombination calculations. This is valuable because the DR contribution can be calculated by well established means and then added to RR+PR background. Numerical results are presented for Ni-like Zn^{2+} , and Pd-like Cd^{2+} , Sn^{4+} , and Xe^{8+} .

The importance of the effect is illustrated in the figure below, which shows that PR doubles the recombination rate in the energy region devoid of DR resonances. Details of the numerical calculations can be found in Ref. [1]. The figure also shows that the effect of PR in Zn^{2+} is dominated by target excitations into the continuum.

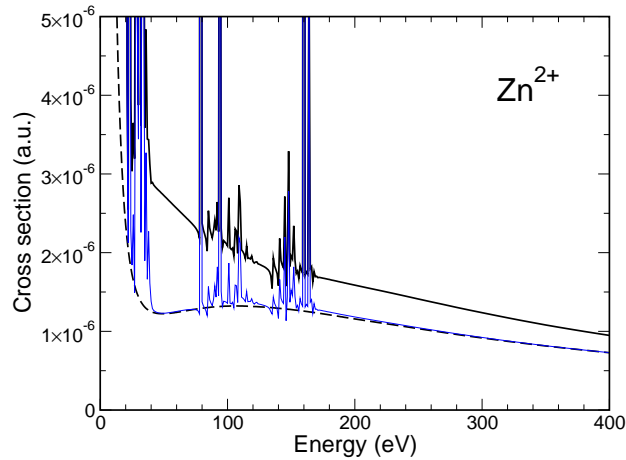


Figure 1: Recombination cross sections for Zn^{2+} : full RR+PR (thick solid curve), with discrete excitations in PR only (thin solid curve), and pure RR (dashed curve).

To gauge the physical significance of PR, we have evaluated the Maxwellian recombination rates with and without this effect. For all ions studied, PR has a significant effect on the recombination rates. For Zn^{2+} , Cd^{2+} , and Sn^{4+} it comes in the form of enhancement at characteristic energies of dipole excitations from the outer d^{10} subshell. For Xe^{8+} the influence of PR is mostly through destructive interference with the RR amplitude observed at lower energies.

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RADIATIVE ELECTRON CAPTURE TO CONTINUUM IN 90 AMEV U⁸⁸⁺ + N₂ : THE SHORT WAVELENGTH LIMIT OF ELECTRON NUCLEUS BREMSSTRAHLUNG

M. Nofal^{1,3}, S. Hagmann^{2,3}, Th. Stöhlker³, C. Kozhuharov³, X. Wang⁴, A. Gumberidze³, U. Spillmann³, R. Reuschl³, S. Heß³, S. Trotsenko³, D. Banas³, F. Bosch³, D. Liesen³, D. Jakubassa⁵, R. Moshhammer¹, J. Ullrich¹, R. Dörner², M. Steck³, P. Beller³, K. Beckert³, B. Franczak³,

¹Max Planck Inst. f. Kernphysik, Heidelberg, ²Institut f. Kernphysik, Univ. Frankfurt, ³GSI-Darmstadt, ⁴Fudan University, Shanghai, ⁵Mathem.Institut, LMU-München

At relativistic velocities, the radiative electron capture to the continuum (RECC) increasingly competes with the non-radiative capture to continuum ECC. This allows investigating the role of the additional radiative degree of freedom in relativistic collisions dynamics. Using the imaging forward electron spectrometer in the ESR storage ring at GSI we have measured coincidences between x rays and cusp electrons with $v_e \approx v_{proj}$ and identified the coincident photons as coming nearly exclusively from the short wavelength limit (SWL) of electron nucleus bremsstrahlung. We found a strong asymmetry of the coincident RECC electron cusp distribution which is skewed towards the high energy side of the electron spectrum (Fig.3), as predicted by theory/1/. This asymmetry is opposite to the one found for the non-radiative electron capture to the continuum ECC/1/. The electron decelerates in the projectile frame from $\epsilon' = (\gamma-1)mc^2$ to $\epsilon' \approx 0$ during photon emission. This means that the electron bounces back with subsequent forward emission in the laboratory frame/1/.

Interestingly, this inverse kinematic technique where the electron is detected with $v_e \approx v_{proj}$ offers the only configuration to investigate total differential cross sections (TDCS) at the theoretically interesting short wavelength limit of electron nucleus Bremsstrahlung; this has never been accomplished in the standard configuration as it implies detecting an electron of zero energy.

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MULTIPLE CHARGE TRANSFER BY SLOW MULTI-CHARGED Xe IONS

Hiroaki Ito, Yuta Chihara, Yoshihisa Suzuki, Tetsuo Koizumi*, Takato Hirayama*

Department of Physics, Rikkyo University, Toshima, Tokyo

(*) Research Center for Measurement in Advanced Science, Rikkyo University, Toshima, Tokyo

Multi-electron capture processes between low energy multi-charged ions and atoms are studied by an energy loss spectroscopy technique. Energy-loss spectra of charge-state-changed projectile ions scattered in the forward direction in collisions of Xe^{q+} ($q=5,6,7,8,9$) ions with He and Ar atoms have been measured at collision energies below $1.5q$ keV.

Multi-charged ions are generated by a 10GHz ECRIS (NANOGUN). Extracted ions are selected m/q values by an analyzing magnet and injected into a collision chamber. The ion beam is interacted with an effusive target gas after the ion-beam is monochromatized by an energy selector. Scattered ions in the forward direction are analyzed by an energy analyzer. The energy selector and analyzer are same type of 52-mm radius hemispherical electrostatic analyzer. The geometric resolution $E/\Delta E$ is 50.

Measured spectra for one-electron capture in the Xe^{q+} -He collisions are shown in Fig.1. The Xe ion energy levels given by Saloman [1] are also shown in Fig.1. These spectra show excitation energy of charge-changed Xe ions assuming that the He^+ is in the ground states. It seems that the excitation energy of Xe ion is increasing as the valency of incident ion rises. The principal quantum number of Xe-excited state derived from the classical over-barrier model [2] agree with those from the spectrum except for $q = 7, 9$. Detailed analysis is now in progress.

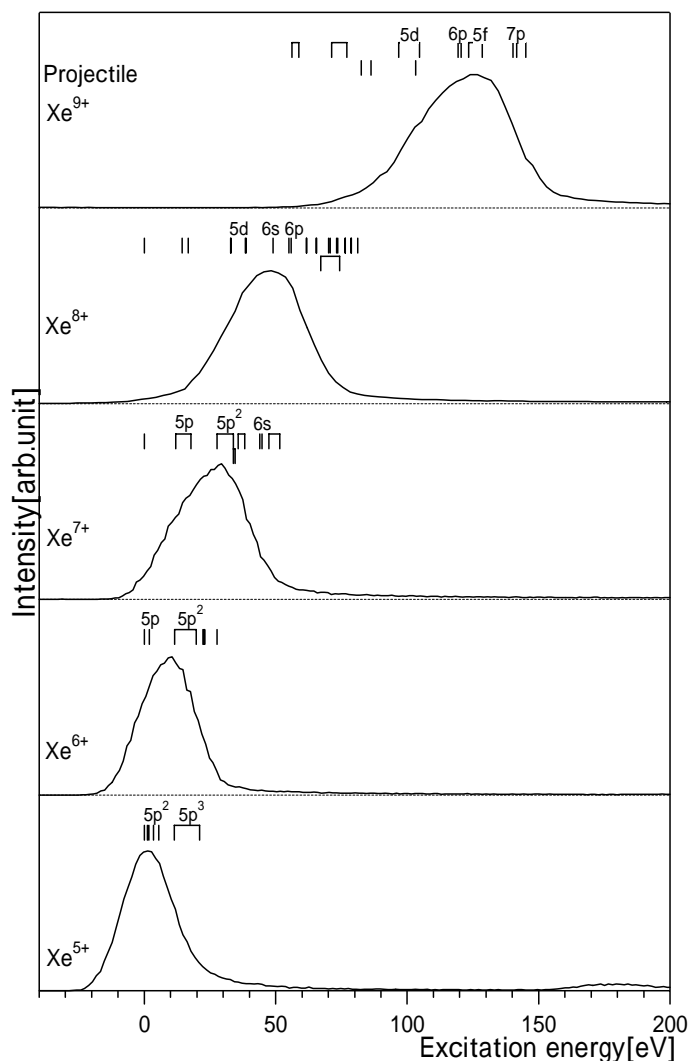


FIG. 1. Excitation-energy spectra of $Xe^{(q-1)+}$ ions for the one-electron-capture process, $Xe^{q+} + He \rightarrow Xe^{(q-1)+} + He^+(1s)$, at incident energy q keV.

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STUDIES OF DI-ELECTRONIC RECOMBINATION OF LI-, BE-, B- AND C-LIKE XE USING THE SHANGHAI ELECTRON BEAM ION TRAP.

W.D. Chen, Y. Liu, F.C. Meng, T.M. Shen, S. Wu, B. Wei, R. Hutton and **Y. Zou.**

The Key Lab of Applied Ion Beam Physics,
Ministry of Education, P.R. China
Shanghai EBIT lab., Modern Physics Institute,
Fudan University. Shanghai, P.R. China

Di-electronic recombination resonances (DR), i.e. the recombination of an ion with a free electron at very specific electron energies, have important consequences for the charge state balance in hot plasmas. In the work presented here we studied the KLL DR resonances for Li-, Be-, B- and C-like Xe. DR always leads to the excitation of doubly excited states which can decay by either auto-ionization or photon decay, i.e. a completed DR process. The emitted photon is most often in the X-ray region of the spectrum and the branching ration for photon decay vrs auto-ionization increases as a function of the nuclear charge. The spectral lines from the decay of the DR populated levels belong to the class of lines known as satellite lines and have important applications in plasma diagnostics. Xenon has extra importance, as it is an element likely to be used for diagnostics at the ITER tokamak,

The work presented here was done utilizing the Shanghai Electron Beam Ion Trap (EBIT) at Fudan University. Xenon atoms were ionized and trapped by an intense electron beam, 70 mAs at around 20 keV and compressed by a 2 T magnetic field. The DR resonances were investigated by sweeping the beam energy over the energy region of interest 20-22 keV. The electron beam energy was varied slowly such that, at each energy the charge state distribution had time to stabilize, so-called steady-state mode. X-rays from the DR populated doubly-excited states were energy analyzed and recorded, for each beam energy, using a high-purity Germanium detector. Hence a so-called scatter plot, number of counts for each resonance as a function of beam energy, was obtained. In this plot not only the KLL resonances are clearly observed but also the radiative recombination, RR, to $n = 2$ and $n = 3$ levels was seen. The RR data was used to normalize the DR measurements.

Finally, to compare with our experimental results, we made Flexible Atomic Code, FAC, calculations of the relevant DR cross-sections. Our experimental and calculational results were found to be in good agreement. Comparisons with other data, where available, will also be presented.

Fully differential cross-sections of mutual target and projectile ionization in 200-keV $H^- + He$ collisions

T. Ferger¹, M. Schulz², B. Najjari¹, D. Fischer³, R. Moshhammer¹ and J. Ullrich¹

¹ Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

² University of Missouri-Rolla, Physics Dept. and LAMOR, Rolla, MO 65409, USA

³ Stockholm University, Atomic Physics, Alba Nova, S-106 91 Stockholm, Sweden

We measured the mutual target and projectile ionization in collisions of He atoms with 200 keV H^- projectiles in a kinematically complete experiment [1]. The two emitted electrons as well as the recoiling He^+ target ion were detected in coincidence to the neutral projectile core H^0 . Fully differential cross sections (FDCS) for the electron detachment of both the projectile and the target were obtained.

Since the additional electron of the H^- projectile is loosely bound with only 0.75 eV, the ionization of the He target is comparable to an $(e,2e)$ collision with a free electron of 109 eV. This similarity gets even stronger considering that the remaining projectile core is neutral after the collision. Thus after the collision Coulomb interaction occurs only among the fragments of the target and the emitted projectile electron. We will demonstrate in comparison with theoretical predictions and latest $(e,2e)$ experiments, that the ionization of the target can essentially be described in terms of a pure electron-electron interaction.

In the case of the electron detachment of the H^- projectile the theoretical predictions disagree with the experiment. This is surprising because the above mentioned ionization of the target can be very well described through the interaction with the active projectile electron. We will show that for projectile detachment the interaction with the He core is as important as the interaction with the target electron.

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RELATIVISTIC DISTORTED-WAVE CALCULATIONS OF ELECTRON IMPACT EXCITATION CROSS SECTIONS OF BE-LIKE C^{2+} ION

J.Jiang , **C.Z. Dong**, L.Y. Xie, J.G. Wang*, J.Yan* , S. Fritzsche**, Th. Stöhlker ***

College of Physics and Electronic Engineering, Northwest Normal University,
Lanzhou 730070, China

*Institute of Applied Physics and Computational Mathematics, Beijing 100088, China

**Institute für Physik, Universität Kassel, D-34132 Kassel Germany

***Gesellschaft für Schwerionenforschung, 64291 Darmstadt, Germany

Electron impact excitation (EIE) cross sections are widely required for calculating level populations and spectral line intensities in the diagnostics of plasmas occurring in fusion experiments, X-ray lasers and astrophysics [1]. With the development of experimental techniques, for example, electron beam ion traps (EBIT), merged electron-ion beams energy-loss (MEIBEL), atom trap-based, synchronous photo detection, radiation trapping etc., the EIE cross sections can be measured with very high accuracy. In order to explain such experimental results, corresponding accurate calculations are necessary. In the past decade years, several different methods, such as the distorted-wave approximation (DW), R-matrix and close-coupling (CC) etc., have been developed. However, it is well known that R-matrix and CC methods are accurate approaches for neutral atoms or lowly charged ions, but they will be more computationally intensive and often be limited to low collision energies. Therefore, the DW is regarded as an easier and more effective method for producing a large amount of EIE cross sections.

Recently, we have developed a new rapid and accurate fully relativistic distorted-wave (RDW) program to calculate EIE cross sections based on the well-known package Grasp92 [2] and Ratip [3]. As an application of the program, the EIE processes of Be-like C^{2+} ion were investigated. Although, these processes have attracted considerable interests both in theory and experiment in the recent years due to their importance in the studies of solar plasmas, cataclysmic variable binary systems and cool stars [4], there are still some big discrepancies between the available calculations and various experiments [4-6]. In the present work, the EIE cross sections from the $1s^22s^2\ ^1S$ to $1s^22s2p\ ^1P$, $1s^22s2p\ ^3P$ to $1s^22p^2\ ^3P$ and $1s^22s^2\ ^1S$ to $1s2s^22p\ ^{1,3}P$ have been calculated systematically. Meanwhile, the effects of configuration interaction (CI) of the target states to the EIE cross sections have been discussed. It is found that the configuration interaction plays a very important role in the metastable $1s^22s2p\ ^3P$ to $1s^22p^2\ ^3P$ excitation. Furthermore, the contributions of indirect excitations, i.e. capture-autoionization processes, have also been discussed. Comparing with some existing calculations [5] and measurements [4,6], an excellent agreement has been found.

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Poster Category 3

**Interactions with Clusters,
Surfaces and Solids**

ELECTRON EMISSION DURING SCATTERING OF N^{6+} IONS FROM A MAGNETIZED IRON SURFACE

B. Solleder, C. Lemell, K. Tőkési*, J. Burgdörfer

Institute for Theoretical Physics, Vienna University of Technology, A-1040 Vienna, Austria

(*) Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI), H-4001
Debrecen, P.O. Box 51, Hungary

A detailed understanding of the properties of magnetized surfaces is important in view of many technical applications. Spectroscopy of such surfaces using highly charged ions (HCI) has emerged only recently [1,2]. We focus on extracting information on spin polarization by electron emission during HCI-surface interaction.

We investigate the impact of N^{6+} ions on a magnetized iron surface using Monte Carlo simulations. Our calculations include potential emission of electrons as well as production and transport of secondary electrons in the solid. Potential emission is modelled using the Classical-Over-the-Barrier (COB) model [3]. Several channels for electron exchange during the ion-surface interaction are implemented, such as resonant transfer, autoionization, Auger processes, and peeling-off of outer shell projectile electrons. Electron transport in the solid is simulated as a stochastic sequence of elastic and inelasting scattering processes [4]. In addition to spin conserving scattering, Stoner excitations are taken into account leading to an enhancement of the polarization for very low emission energies in agreement with measurements by J. Kirschner *et al.* [5].

We apply the present theory to an experiment performed by R. Pfandzelter *et al.* [1] investigating 150 keV N^{q+} ions ($q \leq 6$) scattered from a magnetized Fe(001) surface under a grazing angle of incidence of $\Phi = 1.5^\circ$. For K-Auger electrons of N^{6+} , polarization values are close to the mean polarization of the conduction band electrons in magnetic iron (27%). For low energies an increase of the polarization up to 70% is detected. Our results show good agreement with these values.

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SIMULATION OF GUIDING OF MULTIPLY CHARGED PROJECTILES THROUGH INSULATING CAPILLARIES

K. Schiessl^a, W. Palfinger^a, K. Tőkési^{a,b}, H. Nowotny^a, C. Lemell^a, and J. Burgdörfer^a

^a Institute for Theoretical Physics, Vienna University of Technology, Wiedner Hauptstraße 8-10, A-1040 Vienna, Austria

^b Institute of Nuclear Research of the Hungarian Academy of Sciences, (ATOMKI), H-4001 Debrecen, P.O.Box 51, Hungary

Recently, capillaries through insulating foils (PET or “Mylar”) with aspect ratios $\sim 1 : 100$ have received interest as a target for beams of slow highly-charged ions (HCIs). Significant transmission probabilities for projectiles in their initial charge state have been measured for incidence angles as large as $\sim 20^\circ$ [1]. Apparently, ions are guided along the capillary axis and do not closely interact with the inner walls of the capillary. More recently, ion guiding could even be observed through macroscopically large, tapered glass capillaries [2]. Key to such processes is a self-organized charge-up of the internal insulator walls due to preceding ion impacts. Ion guiding through the capillary ensues as soon as dynamical equilibrium of the charge-up is established [1].

A theoretical description and simulation of this process poses a considerable challenge in view of the widely disparate time scales simultaneously present in this problem, ranging from charge transport on the internal capillary wall (hopping time $\tau_h < 10^{-15}$ s) to the average time interval $\overline{\Delta t}$ between two HCIs entering the same capillary which is (for present experimental current densities of nA/mm²) of the order of $\overline{\Delta t} \approx 0.1$ s. Additionally, characteristic (bulk) discharge times τ_b for Mylar can be estimated from conductivity data to typically exceed $\tau_b \gtrsim 10^3$ s, while discharging arising from surface charge transport is about a factor 100 faster [3].

As a fully microscopic *ab-initio* simulation covering all relevant scales is undoubtedly out of reach, the present approach represents a mean-field classical transport theory, based on a microscopic classical-trajectory Monte Carlo (CTMC) simulation for the transported HCI. Calculation of the ion trajectory is self-consistently coupled to the charge-up of the internal capillary walls, employing appropriate models of charge diffusion [3]. In order to explain certain experimental features such as the transmission function, we find it crucial to distinguish between fast surface- and slow bulk charge transport. With this theoretical model, we are also able to reproduce charging- and discharging characteristics which manifest in a time-dependent HCI transmission function of the capillary.

Experimental data for the angular spread of the transmitted HCIs, which is found to be close to the geometrical opening angle ($\approx 1^\circ$) in our CTMC simulation, varies but reaches several degrees in some experiments [1]. Phenomenological inclusion of imperfect target preparation (alignment of capillary axis) and multi-capillary effects could offer an explanation for this discrepancy [3].

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CHARGING AND DISCHARGING OF NANO-CAPILLARIES DURING ION-GUIDING OF MULTIPLY CHARGED PROJECTILES

M. Fürsatz^a, W. Meissl^a, S. Pleschko^a, M.C. Simon^a, I.C. Gebeshuber^a,
N. Stolterfoht^b, HP. Winter^a, and F. Aumayr^a

^aInstitut f. Allgemeine Physik, Vienna University of Technology, Vienna, Austria

^bHahn Meitner Institut Berlin, D-14109 Berlin, Germany

Efficient guiding of slow (typ. keV) highly charged ions (Ne^{7+}) through insulating nano-capillaries has been observed even for cases where the capillaries were considerably tilted by up to 20° with respect to the ion beam direction [1]. Surprisingly, the majority of the projectile ions was found to survive the surface scattering events inside the insulating capillary in their initial charge state. Measured 1-dim. scattering distributions of the transmitted particles indicated propagation of the projectile ions along the capillary axis. As reason for this “guiding effect” a charging-up of the inner walls of the capillaries in a self-organized way due to impact of preceding projectile ions has been proposed [1-4].

Theoretical modelling of the experimental observations has so far proven to be a challenging task [1-3]. Difficulties arise especially due to the different characteristic times observed in the experiment for capillary-wall charging and discharging [3, 4].

To gain more insight in this interesting phenomenon we have measured the 2-dim. scattering distribution of transmitted projectiles during the charging-up process. The capillary target for these experiments made of PET has been obtained from HMI-Berlin and was characterized with atomic force microscopy-AFM at TU Wien (mean capillary diameter of $180 \text{ nm} \pm 25\%$). The transmitted ions are registered on a 2-D position sensitive channel-plate detector. The variation of the scattering distribution during the charge-up process could be monitored as a function of time and/or total charge.

The obtained experimental results are compared to recent modelling calculations [3, 4] for self-organized charge-up. Good agreement between simulation and experiment is found.

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ANGULAR DISTRIBUTION OF IONS TRANSMITTED BY AN ANODIC NANOCAPILLARY ARRAY

H. F. Krause, C.R. Vane, and F.W. Meyer, and H. M. Christen*

Physics Div., Oak Ridge National Laboratory, Oak Ridge, TN 37831-6372 USA

* Condensed Matter Sciences Div., Oak Ridge National Laboratory, Oak Ridge, TN 37831 USA

The transmission of incident 200 MeV Ti^{12+} ions and 10–20 keV/q multicharged Ar and Ne ions (e.g., Ne^+ , Ne^{3+} , and Ne^{7+}) in Al_2O_3 nanocapillary arrays was studied using two different methods. The Al_2O_3 array (Anodisc, Whatman, Inc.) consists of a dense distribution of nanopores ($\sim 3 \times 10^9$ pores/cm² produced by an anodic process) typically 100 nm in diameter and 60 μm in length. Initially, tilting experiments at 200 MeV estimated the co-alignment of nanopores in the target to be 1.6° full width at half maximum (FWHM). Charge-state-selected angular distributions were studied later at low energy. Ion beams produced by the CAPRICE ECR source, selected by magnetic analysis, were highly collimated ($\sim 0.02^\circ$ beam divergence) before they reached a capillary array mounted in a precision goniometer (beam current < 3 na). To minimize target charging (insulator), entrance ions passed through either i) a high-transmission (>80%) grounded grid (~ 100 lines/cm Mo) mounted on the entrance side or ii) 7 nm Au films deposited on both sides of the array. Emergent ions were deflected electrostatically in the vertical direction so that final q-state selected angular distributions could be separated from the in-line emerging neutrals. Resultant 2D angular distributions were measured using a two-dimensional position sensitive detector, which could also be rotated horizontally.

The principal transmitted q-state observed was the incident q-state in all cases, similar to 3 keV Ne^{7+} results obtained using much thinner PET films [1]. Observed angular distributions consist of many well-resolved peaks sitting on a continuum distribution; at 140 keV the peak width corresponds to the nanopore angular width. The angular distribution and sharp peaks can be steered in the direction of the pores within about ± 0.5 degrees without significant loss of transmitted intensity by rotating the sample with respect to the incident beam (total peak displacement is 2x the rotation angle). All data suggest that structure in the scattered ion angular distributions arises when ions bounce at ultra-low grazing angles in very large impact parameter Coulomb collisions with electrically charged nanopore walls.

The transmitted fraction is orders of magnitude smaller than the array's surface porosity ($\sim 35\%$). The fraction was about 2×10^{-8} for the target with wire mesh and 3×10^{-7} for the Au-plated sandwich target for each incident ion beam and energy (10-140 keV). For the Au sandwich target, the impact of additional low-energy electrons on the entrance surface was required to obtain significant ion transmission. No evidence of significant energy loss was observed for any incident ionic species and at any incident energy. Yields in lower q-states and neutrals formed by e-capture were typically below 1% of the entrance q-state yield.

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STARK MIXING OF IONIC INTERMEDIATE STATES IN RADIATIVE RECOMBINATION OF CHanneLED IONS

K.Yu.Bahmina, V.V.Balashov, A.A.Sokolik, A.V.Stysin

Institute of Nuclear Physics, Moscow State University, Moscow 119992, Russia

Radiative electron capture (REC) by channeled ions [1,2] takes place under strong non-central ion-crystal interaction determining specific features of the electron cloud of the produced ion which differ from those in case of recombination of a free ion. We consider theoretically Stark mixing of the intermediate excited ionic states due to the combined crystal lattice and polarization wake potential and its influence on the yield of characteristic X-ray radiation of the ion, its polarization and angular anisotropy parameters and its possible angular correlation with the primary X-ray radiation in the REC event. The analysis is based on our approach [3,4] to treat the channeled ion as an open quantum system involved into coherent and incoherent (relaxation) interactions with the target and, on the other hand, on the statistical tensor formalism [5,6] to describe polarization and correlation phenomena in cascade ion recombination processes. The work is performed in the framework of INTAS-GSI project 03-54-3604.

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SPM STUDIES OF SELF ASSEMBLED MONOLAYER SURFACES IRRADIATED WITH HIGHLY CHARGED IONS

B. E. O'Rourke¹, V. A. Esaulov², Y. Mitsuda^{1,3} and Y. Yamazaki^{1,4}

(1) Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan

(2) Laboratoire des Collisions Atomiques et Moléculaires, bat.351 Université Paris Sud, Orsay 91405, France

(3) Institute for Laser Science, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan

(4) Graduate School of Arts and Sciences, The University of Tokyo, Tokyo 153-8902, Japan

Self-assembled monolayers (SAM) of thiols prepared on gold plated mica have been irradiated with highly charged ions (HCI's) from a compact electron beam ion source (EBIS) at RIKEN^[1]. The resulting damage to the surface was investigated in-situ with scanning tunnelling microscopy (STM) and atomic force microscopy (AFM) using a commercial (JEOL JSPM4500) apparatus connected directly to the ion beam line.

Despite the large volumes of research that has been published on SAM's since their discovery over twenty years ago there have been very few previous results on the effects of HCI irradiation^[2]. We present preliminary results for the irradiation of Ar⁺ and Ar⁸⁺ ions on 11-Mercapto-undecanoic acid (C₁₁H₂₂O₂S) SAM on Au(111) surfaces. Figure 1 shows a typical STM image of the damage sites, it is assumed that each HCI causes sputtering of the carboxylic functional group and possible breaking of the carbon backbone over a localised area. The damage is observed as a random distribution of pits several nanometers wide and a fraction of a nanometer deep. The dose was kept low (<5×10¹¹ ions/cm²) to avoid overlap of the damage sites. Based on these preliminary experiments we plan to measure the size of the pits as a function of ion charge and thiol type (functional group and chain length) in order to further understand the interaction between HCI's and organic monolayers.

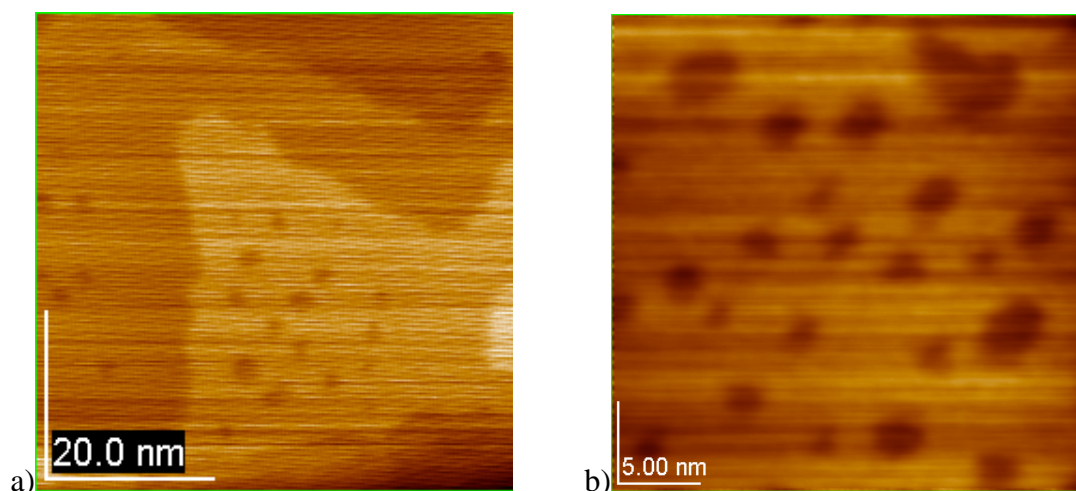


Figure 1. (a) Thiol SAM surface after Ar⁸⁺ irradiation (larger features are terraces on the Au(111) surface) and (b) Close-up view of damage pits

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OBSERVATION OF HCI-INDUCED NANOSTRUCTURES WITH SCANNING PROBE MICROSCOPE

Masahide Tona^{1,2}, Hirofumi Watanabe^{1,2}, Satoshi Takahashi¹, Nobuyuki Nakamura¹,
Nobuo Yoshiyasu¹, Chikashi Yamada¹, Makoto Sakurai³, and Shunsuke Ohtani^{1,2}

¹Institute for Laser Science, University of Electro-Communications, Chofu, Tokyo 182-8585, Japan

²CREST, Japan Science and Technology Agency, Chofu, Tokyo 182-8585, Japan

³Department of Physics, Kobe University, Kobe, Hyogo 657-8501, Japan

A highly charged ion (HCI) modifies a solid surface in the nanometer-sized region as a consequence of the deposition of its large potential energy to the surface at a short interval (~ 10 fs). The mechanism of this modification at the surface is thought to be essentially different from that induced by collisions of energetic particles with solids where the momentum and the kinetic energy are the important parameters, and the kinetic-induced radiation effect occurs not only at the surface but also along the track in the solid. To understand the microscopic mechanism of the HCI-interaction with the surface we have observed morphologies of HCI-impact sites formed on various kinds of surfaces in an atomic resolution by using a scanning probe microscope (SPM).

HCI's were produced in an electron beam ion trap (EBIT) at the University of Electro-Communications. The EBIT was operated with electron beam energy up to 90 keV. A collision chamber (base pressure: 2×10^{-8} Pa) along the HCI-beam line was connected to the observation chamber equipped with the SPM. After exposure of HCI's for several hours, the sample was transported to the SPM-chamber in the vacuum.

Typical results shown below are scanning tunneling microscope images from (a) a highly oriented pyrolytic graphite surface (HOPG) and (b) a Si(111)-(7 \times 7) reconstruction surface. In (a) (Xe²⁹⁺-impact), the protrusion structure was observed with $\sqrt{3} \times \sqrt{3}R30^\circ$ surface reconstruction around the impact site. In (b) (Xe⁴⁵⁺-impact), on the other hand, the crater-like structure was observed with the brighter sites on the edges around the missing topmost layers. In addition to such STM images, atomic force microscope images of impact sites formed on insulator surfaces will be presented.

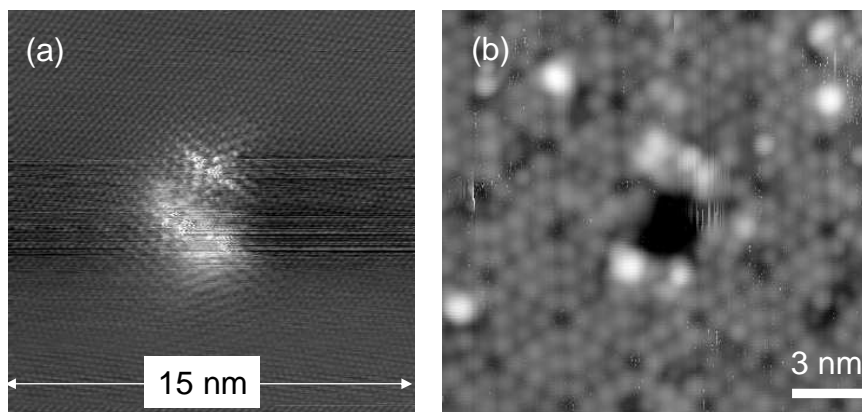


Figure 1: STM images of HCI-induced impact sites obtained from (a) HOPG and (b) Si(111)-(7 \times 7) surfaces.

GUIDING OF SLOW Ne^{6+} IONS THROUGH Al_2O_3 CAPILLARIES

Z. Juhász¹, Gy. Víkor², S. Biri¹, É. Fekete¹, I. Iván¹, K. Tőkési¹, E. Takács², J. Pálinkás², S. Mátéfi-Tempfli³, M. Mátéfi-Tempfli³, L. Piraux³, N. Stolterfoht⁴, and B. Sulik¹

¹ Institute of Nuclear Research (ATOMKI), Bem tér, 18/c, H-4026 Debrecen, Hungary

² Department of Experimental Physics, University of Debrecen, Egyetem tér 1, H-4032 Debrecen, Hungary

³ Unité de Physico-Chimie et de Physique des Matériaux, Université Catholique de Louvain (UCL), Place Croix du Sud, 1, B-1348 Louvain-la-Neuve, Belgium

⁴ Hahn-Meitner Institute Berlin GmbH, D-14109 Berlin, Germany

The ion guiding ability of nanocapillaries was first discovered for PET polymer capillaries [1]. Experiments with other materials are necessary for the understanding of the physics of the guiding effect. In this work, investigation of Al_2O_3 capillaries is presented. The highly ordered arrays of Al_2O_3 capillaries were prepared by a two step anodization process at UCL.

The experiments have been performed at ATOMKI with slow Ne^{6+} ions of impact energies of 3 keV and 6 keV. Ions were transmitted through the capillary arrays with pore diameter of 150 nm and 290 nm. It has been found that ions with larger incidence angles than the one belongs to the geometric transparency can pass through the Al_2O_3 capillaries similarly as for PET. The ions leave the capillaries along the capillary axis with a narrow angular distribution. Systematic measurements have been performed for different energies and incidence angles, which could be changed by tilting the capillary array. Time dependences of the transmission, charge and angular distributions of the transmitted ions are obtained. Angular distributions with FWHM of $3\text{-}4^\circ$ have been found. These are close to the values observed for PET capillaries [1], but are higher than for SiO_2 [2].

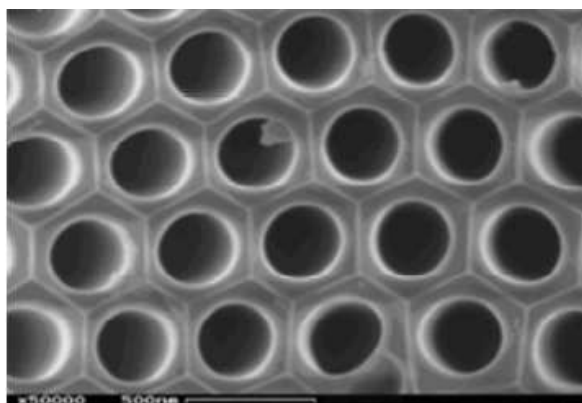


Figure 1: SEM view of an array of Al_2O_3 capillaries.

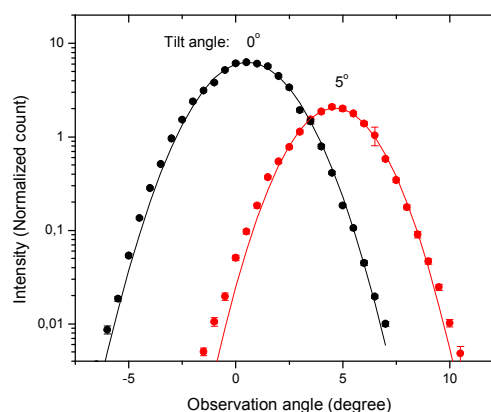


Figure 2: Angular distribution of 3keV Ne^{6+} ions transmitted through Al_2O_3 capillaries with pore diameter of 290 nm.

To explain capillary guiding different models have been developed [3, 4]. These are based on the assumption that the guiding effect is due to charge deposition on the capillary walls. However the phenomenon is not yet fully understood. To get a microscopic view we are developing a model, in which individual local events of charge deposition and migration are traced.

Acknowledgements

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CRYSTAL-DRESSED HCI OBSERVED THROUGH DOUBLE-RESONANT COHERENT EXCITATION

T. Azuma¹, Y. Nakano¹, C. Kondo², A. Hatakeyama², K. Komaki², Y. Nakai³, Y. Yamazaki^{2,3},
E. Takada⁴, T. Murakami⁴

¹Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

²Institute of Physics, University of Tokyo, Komaba, Meguro, Tokyo 153-8902, Japan

³Atomic Physics Laboratory, RIKEN, Wako, Saitama 351-0198, Japan

⁴National Institute of Radiological Sciences, Inage, Chiba, 263-8555, Japan

An ion passing through a crystal feels a spatially periodic crystal potential as a temporally oscillating field. When one of the frequencies matches with the transition energy of the ion, resonant coherent excitation (RCE) occurs. We have observed RCE by the periodic array of the atomic planes of a three dimensional (3-D) crystal in the non-channeling condition employing a relativistic ion and a thin crystal. The oscillating field felt by the traveling ion has no dependence on the ion position in the transverse direction with respect to its velocity vector, i.e., they are regarded as a plane wave. Hence, there exists essentially no trajectory dependence of the RCE probability in 3D-RCE in contrast to the conventional RCE under the channeling condition. The oscillating field consists of various frequency components originating from a variety of atomic planes. Making use of two different frequency components simultaneously, doubly- resonant excitation is attainable in the three-level system of the Λ -type configuration. It is noted that we can readily prepare the resonance condition by varying two parameters of crystal angles with respect to the direction of the incident beam keeping its velocity constant. We recently have observed the RCE transitions among the electronic levels, $1s^2(1^1S)$, $1s2s(2^1S)$, and $1s2p(2^1P)$ of 416 MeV/u Ar^{16+} ions passing through a $1\text{-}\mu\text{m}$ thick Si crystal by monitoring increase in the ionized fraction of the transmitting ions along with increase in the yield of the de-excitation X-ray from the excited ions. We scanned one of the frequencies, ω_{12} , in the region close to the value corresponding to the transition energy of 1^1S - 2^1P , while we kept the other frequency, ω_{23} , to the fixed value corresponding to the transition energy of 2^1S - 2^1P . The obtained resonance profile shows a striking Autler-Townes Doublet in the condition of the strong coupling between 2^1S - 2^1P by the oscillating field of ω_{23} . This situation is equivalent to the dressed state in the photon-atom interaction, which is often observed for the intense laser irradiation. It is stressed that we have produced and observed such a dressed state of heavy ions by the periodic crystal potential of two frequency components in the VUV and X-ray regions.

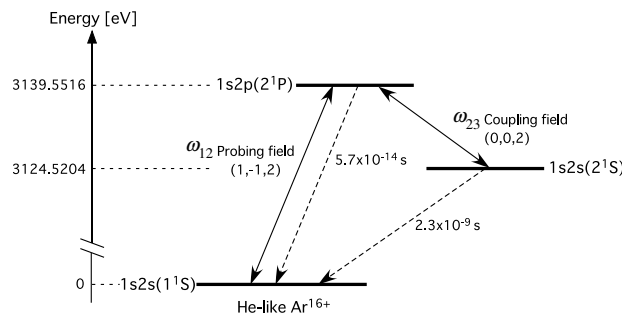


Figure 1: The energy levels of He-like Ar^{16+} and their spontaneous decay rates. Miller indexes (k, l, m) specify the array of atomic planes for the “coupling field” and the “probing field”.

AUGER ELECTRONS EMITTED FROM EXCITED IONS AFTER A METALLIC MICRO CAPILLARY

Y. Kanai¹, Y. Nakai¹, Y. Iwai¹, K. Nishio², H. Masuda², and Y. Yamazaki^{1,3}

¹ RIKEN, Wako, Saitama 351-0198, Japan

² Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

³ University of Tokyo, Meguro, Tokyo 153-8902, Japan

When highly charge ions(HCIs) approach a metallic surface, multi-electrons from the surface transfer to the excited states of ions and hollow atoms/ions are produced. We have measured X-rays[1-3] and visible lights[4] emitted from such excited ions in order to study hollow atom formation and its decay processes. We have used a metallic micro capillary foil[5] as a target to produce such excited ions, which permits us to study final stage of decay processes for the excited ions[6]. Recently, we started the measurements of Auger electrons emitted from the excited ions produced by the interaction between HCIs and an inner wall of micro capillary, which gives us the complementary information to our previous X-ray measurements.

Experiments were performed at Highly Charged Ion facility in RIKEN[7]. Auger electrons, which were emitted from the excited ions, were measured by an electro-static analyzer at an observation angle of 0° with respect to the beam direction. A preliminary spectrum is shown in Fig.1. Here, the energy resolution is about 6 eV. Taking into account of previous study[8] with a flat metal target and spectroscopic data, the higher energy side of spectrum may be attributed to the K-LL Auger electrons emitted from the hollow atoms, which have one K vacancy and many electrons in the L- and M-orbitals, and the lower energy side to the K-LL Auger electrons from Li- and Be-like excited states, which are products in the decay processes of hollow ions in vacuum.

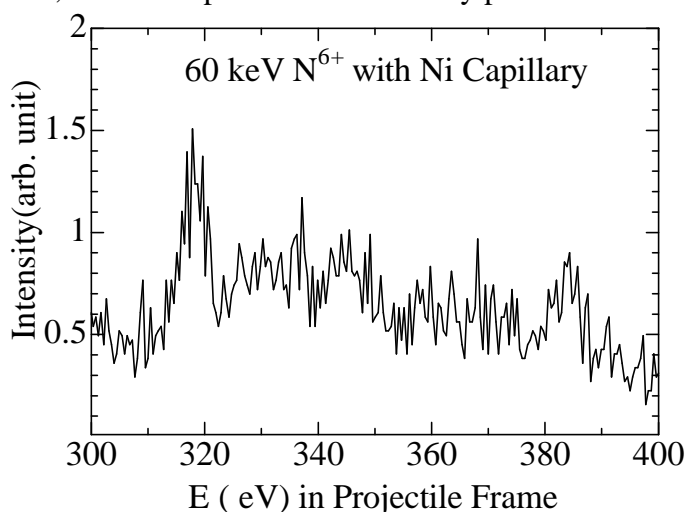


Fig1. K-LL Auger electron spectrum for 60 KeV N^{6+} ions with a Ni micro capillary. Possible energy region for K-LL Auger electrons emitted from L-like and Be-like excited states is from 312 to 350 eV and that for hollow atom states ($1s2l^r3l'^{(6-r)}$, $r \geq 2$) from 350 to 390eV[8]. Energy resolution is about 6 eV.

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X-RAY EMISSION IN SLOW HIGHLY CHARGED ION-SURFACE COLLISIONS

H. Watanabe^{1,2}, T. Abe¹, Y. Fujita¹, J. Sun¹, S. Takahashi¹, M. Tona^{1,2}, N. Yoshiyasu¹,
N. Nakamura¹, M. Sakurai³, C. Yamada¹ and S. Ohtani^{1,2}

¹Institute for Laser Science and Department of Applied Physics and Chemistry, University of Electro-Communications, Chofu, Tokyo 182-8585, Japan

²CREST, Japan Science and Technology Agency, Chofu, Tokyo 182-8585, Japan

³Department of Physics, Kobe University, Kobe, Hyogo, 657-8501, Japan

The potential energy possessed by a highly charged ion is a sum of the binding energies of the electrons that have been removed, which reaches several hundreds of keV for the bare ion of heavy elements. During the collision of the highly charged ion this energy is being released in the area of several nm² on the surface.

The mode of the potential energy deposition into the solid has been investigated quantitatively for Ne-like Au and He-like Xe irradiated on a silicon solid state detector [1] and for Ar^{q+} ($q = 1 - 9$) on a copper target [2]. While the projectiles were quite different, about 40% of the potential energies was equally released into the solid. The rest of the energy is dissipated through several paths, for example, through the emissions of low energy electrons, secondary ions and photons. We have measured x-rays from highly charged ions interacting with the surface to study energy dissipation paths during slow highly charged ion-surface collisions.

A typical spectrum is shown in the figure. The projectile was He-like iodine and the target was tungsten. This spectrum was from the projectile hollow atoms. Similar spectra were measured for the different projectiles and targets. The number of x-ray photons per an incident ion and the potential energy dissipated through x-ray emissions were estimated from the spectra. It turned out that significant amount of the potential energy was dissipated through x-ray emissions.

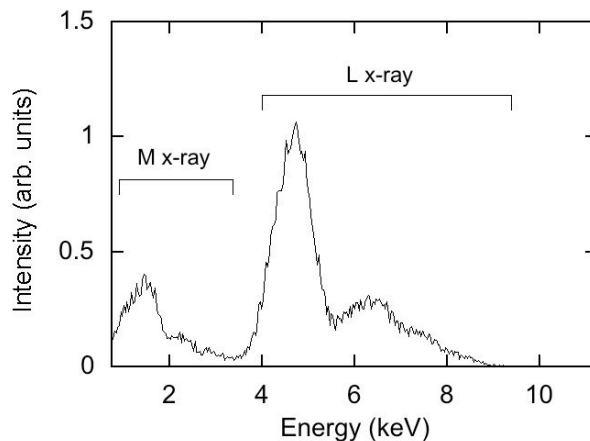


Figure 1: The x-ray spectrum obtained in the collision of the He-like I ion on the W surface.

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GUIDING OF HIGHLY-CHARGED IONS THROUGH INSULATING NANO-CAPILLARIES

P. Skog¹, R. T. R. Kumar¹, A. Johansson², M. B. Sahana¹, I. L. Soroka¹, Gy. Viktor¹, and R. Schuch¹

¹ Atomic physics, Fysikum, AlbaNova University Centre, S-106 91 Stockholm

² Dept. of Materials Chemistry, The Ångström Laboratory, Uppsala

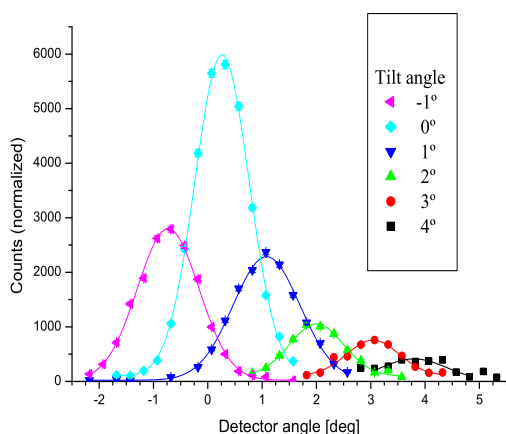
The transmission of highly charged ions (HCI) through nano-capillaries has attracted considerable attention during recent years [1-5]. There is, in the case of HCI impinging on insulating capillaries at angles greater than the angle given by the aspect ratio, substantial transmission of ions in the initial charge state and at the initial kinetic energy.

The transmission of slow HCI through insulating capillaries in PET was first reported by Stolterfoht *et al.* [2], where Ne^{7+} ions at 3 keV was transmitted at capillary tilt angles, with respect to the incident beam, of up to 25°, with the peak at an angle corresponding to the capillary tilt angle. There is a spread in the directions of the capillary axes in the PET membranes due to the production method; etching of ion tracks formed by fast heavy ions.

The guiding of HCI through insulating capillaries has been attributed to the formation of near-entrance charge patches, preventing incident ions from coming in close contact with the walls [2,3]. The further propagation of ions, after the first deflection near the entrance, through the capillaries is attributed to guiding of an electric field from all charge deposited on the capillary walls. The angular distributions are then broadened by the inhomogeneous electric field at the capillary exit due to end effects. The guiding effect is time dependent; ions hitting the capillary walls deposit positive charge, which will deflect ions incident at a later instant. Full transmission is achieved when equilibrium between deposition and diffusion of charge is reached.

In order to avoid the geometrical uncertainties inherent in the PET capillary membranes our group manufactured highly ordered, parallel, capillaries in Si through electrochemical etching. These capillaries were then thermally oxidized to produce insulating SiO_2 capillaries, 25 μm in length, 100 nm in diameter and with wall thicknesses of 100 nm [6]. Both surfaces of the capillary membrane were coated with 30 nm gold to prevent charge-up of the surface. We also produced highly ordered capillaries in Al_2O_3 with diameters of 60 nm and 10 μm in length [7].

We have performed experiments on capillary membranes in PET (diam. = 100 nm, length = 10 μm) [4], in SiO_2 and in Al_2O_3 using Ne^{7+} ions at 7 keV from the 14 GHz ECR ion source located at the Manne Siegbahn Laboratory, Stockholm. We measured angular and charge distributions for capillary tilt angles of up to 4°. The widths of the angular distributions was found to be $<1^\circ$ (FWHM) for the SiO_2 capillaries, $\approx 1^\circ$ for capillaries in Al_2O_3 and $\approx 3^\circ$ for the PET capillaries. An example for capillaries in Al_2O_3 is shown in figure 1. More results will be presented on the conference.



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Figure 1. Angular distributions of Ne^{7+} ions transmitted at 7 keV through nano-capillaries in Al_2O_3

Modification of Solid Surfaces by Slow Highly Charged Ions: Effects of Highly Confined Excitation

R. Heller*, S. Facsko*, D. Kost*, G. Zschornack*

(*) Institute of Ion Beam Physics and Materials Research, Forschungszentrum Rossendorf, Bautzner Landstrasse 128, 01328 Dresden, Germany

(*) Institute of Applied Physics, Technische Universität Dresden, Mommsenstrasse 13, 01062 Dresden, Germany

Due to their high amount of potential energy highly charged ions induce various changes in morphology and electronic structure of solid surfaces [1,2]. The potential energy which is the sum of the ionization energies of all removed electrons, is released on a very small localized area of a few nm² and in very short times of tens of fs. Hence the power density deposited into the surface can reach values of up to 10¹⁴ Wcm⁻² depending on the ions incident charge state. The changes in surface topology depend strongly on the electronic excitation in the surface and its lateral and longitudinal confinement. Focus of our investigations is the interaction of slow HCIs with surfaces that have a high confinement of excitation. Such surfaces are mainly all kind of insulators, but also samples with an additional confinement due to a layered structure. In this case the electron transfer between different layers is suppressed and the interacting system becomes quasi two dimensional.

Investigations were performed at the Rossendorf Two Source Facility, an ion beam facility consisting of two sources: a 14.5 GHz ECR ion source and an Electron Beam Ion Source, the Dresden EBIT [3]. Ions of both sources are decelerated by a common deceleration unit to suppress kinetic effects during ion surface interaction. The combination of these both sources offers ions of various charge states (up to $q = 44$ for Xe), species (He, Ne, Ar, Xe, C, N, O) and kinetic energies ($< q \cdot 100$ eV to $q \cdot 25$ keV).

We present scanning probe microscopy studies of surface modifications induced by single ion impacts. HOPG, MICA and ultra thin SiO₂ layers were irradiated with ions of argon (charge states $q = 1 \dots 16$) and xenon (charge states $q = 1 \dots 40$). The diameter and the height of created nano structures were investigated in dependence on the ion charge state for both ion species. Additional to SPM investigations Raman spectroscopy of HOPG before and after irradiation was performed to get information about structural changes induced by the HCI impact.

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Relaxation of slow highly charged ions penetrating a solid surface - energy deposition and reemission -

Daniel Kost, Stefan Facsko, Rolf Hellhammer*

Institute of Ion Beam Physics and Materials Research, Forschungszentrum Rossendorf

* Hahn-Meitner-Institute Berlin

Highly charged ions carry a large amount of potential energy, which is defined as the sum of the binding energy of all removed electrons. Approaching the solid surface the ions are neutralized, relax to the ground state, and their potential energy is released. Thereby different mechanisms, such as surface sputtering, secondary ion emission, secondary electron emission and X-ray emission take place [1]. We present results of a complementary study to determine the part of the deposited potential energy and the part of the reemitted potential energy, respectively. The experiments are done at the Rossendorfer Two Source Facility, which consists of an ECR ion source, an EBIT ion source, and a shared electrostatic deceleration unit, and at the ECR facility at the HMI in Berlin. On the one hand a calorimetric measurement setup [2] is used for the determination of the retained potential energy and on the other hand energy resolved electron spectroscopy [3] is used for measuring the reemitted energy. To study the mechanism of the energy retention in detail materials with different electronic structures were investigated: Cu, n-Si, p-Si.

By means of the calorimetric method we measure a quadratic increase of the deposited potential energy with increasing charge and an almost constant part of the total potential energy, which remains in the solid, of $80\% \pm 10\%$. With charge states higher than Ar^{7+} the deposited part decreases slightly. The results of different materials show no significant difference. Therefore we conclude that the difference in energy deposition between copper, n-doped Si and p-doped Si is below 10%.

In the case of the electron spectroscopy the complementary picture is obtained. For Cu and Si surfaces we also observe a quadratic increase of the reemitted energy with increasing charge state up to Ar^{7+} . The reemitted energy amounts to $10\% \pm 5\%$ of the total potential energy of the incoming ion, almost independent of the ion charge state. For Ar^{8+} and Ar^{9+} the increase is steeper due to the contribution of the projectile LMM Auger electrons and the reemitted energy amounts up to 20%. These results are in good agreement with the calorimetric results.

In addition, the results are compared with simulations based on the extended dynamical over-the-barrier model [4]. From this calculations we estimate the part of energy which is transformed in kinetic energy due to the image charge acceleration.

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Formation of Hollow Atoms above diamond surfaces

J.P.Briand*^{1,2}, M.Benhachoum², S. Terracol³, J.Achard⁴, A. Anders⁵, D.Hitz⁶ and R.Phaneuf⁷

¹ Ion Surface Advanced Processes, 2 Square F. Couperin, 92160 Antony, France

² Université P. et M. Curie, 4 Place Jussieu, 75252 CEDEX 05 Paris

³ Lawrence Livermore National Laboratory, Livermore, CA 94557

⁴ LIMHP-CNRS, Université Paris 13, 99 Av. J. B. Clément, 92430 Villetaneuse LIMHP

⁵ A. Anders, Lawrence Berkeley National Laboratory, Berkeley, CA 94720

⁶ CEA- Grenoble, Département de Recherche Fondamentale sur la Matière Condensée, SBT, 17 Avenue des Martyrs, 38054 Grenoble CEDEX 9

⁷Department of Physics, University of Nevada Reno, NV 89557.

The interaction of Highly Charged Ions (HCI) with surfaces mainly depends on the work function W of the target electrons as well as of the electric properties of the first layer(s) of the surfaces (metal, dielectrics...). These two main characteristics define the distance z_0 at which the ion starts extracting electrons ($z_0 \propto 1/W$), and the kinematics of the ion along the last few nm above these surfaces. Over metals the kinematics of the ions is determined by the ion image acceleration; above dielectrics by the balance between the acceleration of the ion by their electric image and the deceleration of the ions by the remnant electric charges staying on the surface during the interaction.

Most studies in the last few years of the interaction of HCI with insulators have been carried out with LiF, a dielectric allowing to get rid, by heating the targets, of the building up of static charges. We have studied the interaction of HCI with diamond surfaces. The diamond surfaces may be passivated by one atomic monolayer of hydrogen or oxygen which make respectively the surfaces conductive or insulating, or covered by graphitic layers appearing during the preparation of Diamondlike Carbon (DLC) or microcrystalline diamonds prepared by Chemical Vapor Deposition (CVD). We present in this contribution a summary of experiments carried out with the ECR sources of Grenoble and Reno on the interaction of HCI on various kinds of CVD and DLC diamond surfaces on which these conductive layers may be present or clean sputtered by the ions themselves or by exposition to an oxygen plasma.

We have studied the hollow atom X-ray spectra emitted in flight by Ar^{17+} ions approaching the considered surfaces, which we decelerated down to the energy range of 0 -12 eV/q with a precision of 1 or 2 eV/q. We have studied the changes in the interaction due to the negative electron affinity (1) of H passivated diamond surfaces, which own a small work function, giving the hollow atom more time to decay above the surface, as well as the influence of the surface conductivity which hinders the trampoline effect (2).

We also studied the changes in the X-ray spectra induced by the graphitic layers covering the surface of some DLC diamonds. It is emphasized how it may be possible with HCI to characterize and at the same time, on line, to modify the surface of the DLC or CVD diamonds by using the atomic clock property of the hollow atoms approaching or penetrating these surfaces.

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* jpbriand920@aol.com

FIRST RESULTS ON ION-CLUSTER INTERACTION WITH THE SIMPA¹ ECR SOURCE

N. Adrouche^{*}, E. Healy^{*}, P. Indelicato[§], E. Lamour^{*}, J. Mérot^{*}, Z. Pesic^{*¶}, **C. Prigent^{*}**, J.-P. Rozet^{*}
and D. Vernhet^{*}

(^{*}) INSP, CNRS UMR 7588, Université Pierre et Marie Curie, Campus Boucicaut,
75015 Paris, France, EU

([§]) LKB, ENS- CNRS UMR 8552, Université Pierre et Marie Curie,
75252 Paris cedex 05, France, EU

([¶]) *present address*: ALS, Lawrence Berkeley National Lab, Berkeley, CA 94720, USA

The study of free clusters under intense Coulomb perturbation shows a particular behaviour (“cluster effect”) compared to atoms, molecules or even solid. Previous works performed with rare gas cluster submitted to intense femtosecond laser pulses have already demonstrated an efficient energy coupling between light and matter, which in particular, leads to an intense emission of keV x-ray for relatively low laser intensity ($< 10^{16}$ W/cm² [1]). This specificity comes from the fact that large clusters combines a high local atomic density (close to a solid target 10^{22} at/cm³) supporting collective effect and a low average density (close to a gas target 10^{15} at/cm³) avoiding screening of the laser electric field like it occurs in laser-solid interaction.

Alternatively, collisions of slow Highly Charged Ion (HCI) with free clusters represent an interesting tool for investigating the static properties of clusters and for determining basic interaction mechanisms in electron dynamics involved in the creation and decay of multiply excited projectiles, as well. During the interaction, the projectile ion captures one or several electrons inducing an electric charge on the cluster that causes its fragmentation on a time scale larger than a picosecond. With rare gas clusters, it has been demonstrated [2] recently that large charge localization occurs because of the high insulator properties of rare gas material (gap > 10 eV) and leads to cluster explosion into ionic multicharged fragments contrary to the case of fullerene [3] which becomes conductor when charge builds up on the surface.

Moreover, interesting feature of this target is that clusters have a wide and variable surface compare to bulk when varying the cluster size. When an HCI approaches the cluster, a multiply-excited ion is formed but with an excited state population, a charge state and an energy loss depending upon the cluster region the HCI interacts. Studying x-ray emission from the projectile in coincidence with its charge state, we should be able to separate ions interacting with surface from those crossing the bulk of the cluster (as it has been done in [4] for fullerene but looking at fragmentation pattern and electron emission in coincidence).

After an optimisation of the performances of our ECR source where we measured X-ray emission to characterize the plasma itself, in correlation with the extracted ion beam, we begin experimental investigation of the interaction of slow highly charged ions (like Ne⁹⁺) with large Van der Waals – rare gas cluster (Ar_N with N $\sim 10^3$ to 10^6 atoms). The first experimental results obtained with the SIMPA facility will be presented at the conference.

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¹ French acronym for “Multicharged Ions Source from PAris”.

FORMATION OF NEGATIVE IONS IN COLLISIONS BETWEEN FLUORINE IONS ($q=1-3$) AND C_{60} MOLECULE.

S. Martin, L. Chen¹, R. Brédy¹, J. Bernard¹, X. Ma², B. Wei²

¹ Laboratoire de Spectrométrie Ionique et Moléculaire (UMR CNRS 5579),
Université Lyon1, Campus de la Doua, F-69622 Villeurbanne Cedex, FRANCE

² Institute of Modern Physics, Lanzhou, CHINA

We have recently measured a high formation yields of negative ions in multicharged fluorine F^{q+} ($q=1-3$) – C_{60} collisions (7.1% for F^+ and 1.1% for F^{3+}) [1]. These values are close to those measured using surface target and show that the C_{60} can be considered to a nanosurface in the formation of negative ions when the impact parameter is close to the size of C_{60} . In contrast with the ions-surface interaction, where the energy deposition (exciton, plasmon,...) is difficult to measured (dilution of excitation energy on the bulk), in the ions- C_{60} interaction the excitation can be precisely analysed through the electron emission and fragmentation scheme.

In this work, the formation yields of F^+ have been measured versus the projectile velocity (0.1 to 0.4 a.u.). We have observed an increasing of yield when the velocity decrease. Tentative interpretation of this result will be presented using a classical theoretical model (Landau Zener). Measurements of fragmentation scheme of the C_{60} and energy loss of the F^+ projectile have been also measured versus the velocity and will be discussed.

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EXPERIMENTAL STUDIES OF HIGHLY CHARGED FULLERENE DIMERS

H. Cederquist, H. Zettergren, H. T. Schmidt, P. Reinhed, J. Jensen*, P. Hvelplund**,
S. Tomita[§], B. Manil^{§§}, J. Rangama^{§§}, and B.A. Huber^{§§}

Department of Physics, Stockholm University, S-10691 Stockholm, Sweden

(*)Division of Ion Physics, Angstrom Laboratory, Uppsala University, Box 534, SE-75121
Uppsala, Sweden

(**)Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark,

([§])Institute of Applied Physics, University of Tsukuba, Tsukuba, Ibaraki 305-0006, Japan

(^{§§})Centre Interdisciplinaire de Recherches Ions Lasers (CIRIL),

Bd. Henry Becquerel, BP 5133, F-14070 Caen Cedex 05, France

We have studied the ionization of fullerene dimers in slow collisions between Xe^{30+} projectiles and $[\text{C}_{60}]_2^-$ and $[\text{C}_{60}\text{C}_{70}]^-$ dimers. In such collisions, the target molecules are ionized through single- and multiple-electron transfer to the projectile, which may or may not emit one or several of the transferred electrons in downstream autoionisation processes. In the present study, we have measured the relative cross sections for producing $[\text{C}_{60}]_2^{r+}$ dimers in the charge states, r , ranging from $r=2-7$ and the relative ionization cross sections of $[\text{C}_{60}\text{C}_{70}]^{r+}$ for $r=2-6$. In both series we find significant even-odd oscillations. Such behaviours are very surprising as they are clearly different from the ones reported for monomer fullerene targets, for which the ionization cross sections decrease monotonically with the charge state r [1].

The experiment was performed at CIRIL (Centre Interdisciplinaire de Recherche Ions Lasers) in Caen, France. The essential parts of the experimental set up consisted of an ECR (Electron Cyclotron Resonance) ion source, a fullerene cluster aggregation source, and a 1-m long linear time-of-flight mass spectrometer. The fullerene sublimation oven in the cluster aggregation source was operated at 565 °C, and after leaving the oven the hot fullerene monomers (internal energies of roughly 5 eV) were cooled through collisions with He at 80 K. The internal cooling of the fullerenes was necessary for the formation of dimers (and larger clusters of fullerenes [2]) as the binding energy for the neutral $[\text{C}_{60}]_2$ van der Waals dimer only is around 0.3 eV. Here, it is important to note that $\text{C}_{60}\text{-C}_{60}$ collisions at 80 K are much too slow to overcome the (fusion) barrier of about 1.6 eV required to form stable dimers in a [2+2] cycloaddition or to break the internal fullerene cage structure. Thus the, $[\text{C}_{60}]_2$ (and $[\text{C}_{60}\text{C}_{70}]$) dimers in the present experiment must be of the van der Waals type.

In order to discuss the present surprising results, we have calculated the sequence of ionization potentials for a model $[\text{C}_{60}]_2^{r+}$ dimer consisting of two conducting spheres with radii $8.37 a_0$ [3], a separation of $19 a_0$, and an efficient electrical contact between them such that the sphere charges (r_1, r_2) are equal $r_1=r_2=r/2$ (r even) or differing by one unit of charge $r_1=r_2\pm 1$ (r odd). This assumption is fully consistent with the present experimental findings of strong propensities for charge symmetric dissociation channels leaving both fullerenes intact. These model dimer ionization energies exhibit oscillations which correlate to the ones observed in the experiment.

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Ion-induced radiation damage to DNA-building blocks

T. Schlathölter, F. Alvarado, S. Bari, **R. Hoekstra**, V. Bernigaud[†], B. Manil[†], J. Rangama[†], B. Huber[†]

KVI Atomic Physics, Rijksuniversiteit Groningen, Zernikelaan 25, 9747AA Groningen, The Netherlands, [†]Centre Interdisciplinaire de Recherches Ions Lasers (CIRIL), CEA-CNRS-ENSICAEN, Bd. Henry Becquerel, BP 5133, F-14070 Caen Cedex 05, France

In the context of bio-molecular radiation damage, singly and multiply charged ions (MCI) can be of importance as both, primary and secondary particles. For instance, in heavy ion therapy and proton therapy the pronounced Bragg peak of fast (typically a few 100 MeV/u) ions in biological tissue is utilized. The Bragg peak is located at a depth, where the ions are slowed down to velocities of the order of the target valence electron velocities. Such keV ions have maximum linear energy transfer (LET) to the medium. Severe biological effects mostly occur, when double strand breaks of DNA or clustered DNA lesions are induced. A primary particle interacting with individual molecules within the DNA or its environment leads to molecular excitation, ionization and fragmentation. In the process, the primary particle loses energy and slow secondary electrons and ions are formed, which might induce further damage. For a deep understanding of biological radiation damage on the level of individual molecules it is thus important to quantify excitation, ionization and fragmentation cross sections as well as kinetic energies of the various primary and secondary species. The most straightforward technique to study the fundamental processes involved in interactions of keV ions with DNA are collisions studies on e.g. isolated DNA/RNA building blocks [1,2] and water [3]. Relative and absolute cross sections as well as fragment kinetic energies have been measured e.g. by means of coincidence time-of-flight spectrometry. Fragment ion kinetic energies exceeding 10 eV are observed in such studies and single decay channels can be identified.

It has to be pointed out, however, that radiation damage in living cells always involves the condensed phase where the affected molecules are surrounded by a medium. Therefore, ion irradiation studies on nucleobases in the solid phase [4,5] and on DNA deposited on solid surfaces [6] have been performed. Such studies are hampered by the great complexity of the systems under study. A natural solution to avoid these difficulties is the investigation of finite systems, which still allow intermolecular interactions, i.e. clusters of DNA building blocks or mixed clusters containing biomolecules and water. Spectroscopic techniques, which proved their value in gas phase studies, can still be used to study the interaction and dissociation dynamics of such clusters. First coincidence studies on the ionization and dissociation of small clusters of nucleobases exhibit striking differences to the gas phase results [7].

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SPM OBSERVATION OF SLOW HIGHLY CHARGED ION INDUCED NANODOTS ON HIGHLY ORIENTED PYROLYTIC GRAPHITE (HOPG)

Yasuharu Mitsuda^{1,2}, Brian E. O'Rourke¹, Nobuyuki Nakamura², Yasuyuki Kanai¹,
Shunsuke Ohtani², Yasunori Yamazaki^{1,3},

¹Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan

²Institute for Laser Science, The University of Electro-Communications, Tokyo 182-8585, Japan

³Graduate School of Arts and Sciences, The University of Tokyo, Tokyo 153-8902, Japan

When a highly charged ion (HCI) approaches and collides with a solid surface, its large potential energy is deposited in a small localized region on the surface. This interaction can cause considerable modification to the surface structure in the localized region. We have been studying the surface modification by HCIs with an SPM (scanning probe microscope) (JEOL JSPM4500). HCIs were extracted from a high-Tc electron beam ion source (EBIS) [1]. Figure 1 shows a typical STM image of a blister type 'nanodot' formed on a highly orientated pyrolytic graphite (HOPG) surface bombarded by a single 2keV Ar⁸⁺ ion. Previous experiments [2] have shown that the size of these nanodots on HOPG varies strongly with the charge state but is independent of the kinetic energy of interaction. However, the exact mechanism for the formation of these features remains unclear and further systematic measurements are necessary.

In the current set-up the beam line from the EBIS is connected directly to the ultra-high vacuum SPM chamber allowing us to perform all measurements *in situ*. By using this new system, we are studying;

- 1) stability of dot size against exposure to atmosphere and the time after exposure,
- 2) difference in size between the dots produced by ions with the same charge but different potential energy,
- 3) dependence of dot shape on the incident angle.

In the poster, details of the new experimental set-up and the recent progress on the above subjects will be presented.

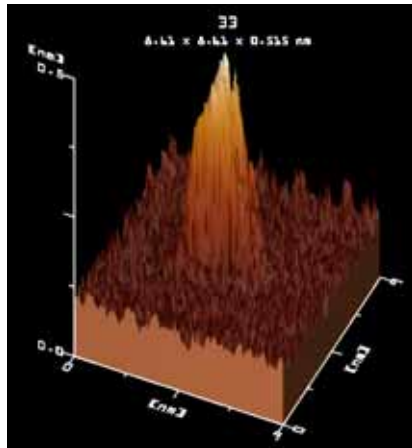


Fig 1. STM image of a nano-dot formed by irradiation of Ar⁸⁺ on a HOPG surface

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Local spin polarization at surfaces probed by hollow atoms

M. Unipan, A. Robin, R. Morgenstern, **R. Hoekstra**

KVI, Atomic Physics, Rijksuniversiteit Groningen
Zernikelaan 25, 9747 AA Groningen, The Netherlands

Highly spin-polarized materials have been intensively studied in recent years for their potential in, e.g., spin electronics. Knowledge on the degree of spin polarization in this class of materials is indispensable for understanding their properties. By using Auger electron emission from hollow atom de-excitation in front of surfaces, the spin polarization of the surface can be probed by linking the relative intensities in the Auger spectra to the capture probability of parallel or anti-parallel spins. The potential of this new method, called MECS (Multiple Electron Capture Spectroscopy) is illustrated by using KLL Auger electron emission from He^{2+} and N^{6+} ions impinging on a ferromagnetic Ni(110) surface [1].

The probability to capture two electrons into specific spin states depends on the availability of majority or minority electrons at the surface. If the surface has a high spin polarization, in average high spin states will be populated in the projectile, while for a low surface spin polarization, low spin states are more likely to be populated. Thus, by varying the spin polarization of a surface (e.g., by varying the temperature of a ferromagnet), changes will occur in Auger peak intensities corresponding to specific spin states. By making use of an atomic model, the relative change in the spectral peak intensities can be linked to the surface spin polarization. Bearing in mind that low energy, multiply charged ions capture electrons from an area of a few \AA^2 , MECS can be used to probe phenomena occurring on a very short length scale (like, e.g., antiferromagnetism).

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Conformational changes to plasmid DNA induced by low energy carbon ions

C.A. Hunniford^{1,2}, D.J. Timson², R.J.H. Davies² and R.W. McCullough¹

1. International Research centre for Experimental Physics, Queen's University, Belfast, UK.

2. School for Biological Sciences, Queen's University, Belfast, UK.

The interaction of low energy (< 500 eV/amu), singly and doubly charged, carbon ions with plasmid DNA (pBR322) has been studied. Strand breakage results in different conformations were confirmed by gel electrophoresis. It was shown that singly charged carbon ions are efficient in producing both single and double strand breakage within the DNA. Multiple double strand breakages (resulting in short linear fragments) were also found to occur in significant numbers – an observation not previously noted in studies with ions or in those using electrons or photons. A clear dose dependence of the various forms of damage was also found, each following a logarithmic growth as the ion dose was increased. The dependence of the damage on the ion energy was also studied (in the region with energy < 500 eV/amu). Both supercoiled and linear conformations show little dependence upon the ion energy, however the change induced in open circle DNA and short linear fragments was seen to increase with increased ion energy. The effect of the ion charge state was studied and it was found that doubly charged carbon ions induce significantly more damage to the plasmid DNA than singly charged ions of the same dose and energy – this suggests that potential energy effects, related to the projectile ion, may play a significant role in the interaction.

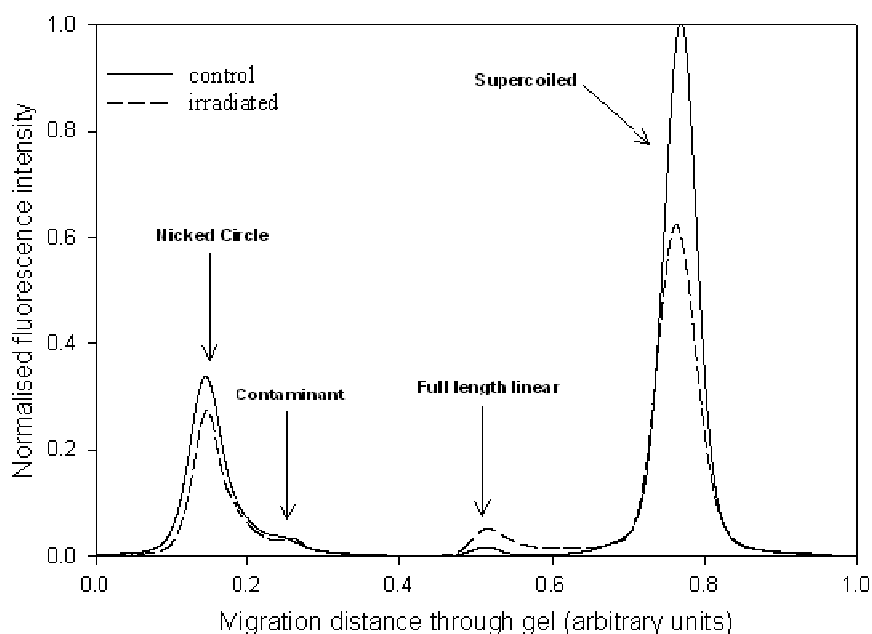


Figure 1 Changes in plasmid DNA conformation following a dose of 125 2 keV C^+ per plasmid DNA molecule. Significant losses are observed in supercoiled and Nicked circle conformations whilst the percentage of material in a full length linear form is increased after irradiation.

CHARGING DYNAMICS OF INSULATORS DURING HCI IMPACT: AN ACCESS TO THE RELAXATION TIMESCALE OF ELECTRONIC DEFECTS

H. Khemliche, P. Rousseau, P. Roncin

Laboratoire des collisions atomiques et moléculaires, UMR8625, Fédération LUMAT
Bât. 351, Université Paris-Sud 11, F-91405 Orsay Cedex, France

Nanopatterning of insulators by slow highly charged ion impact is still the subject of intense debate when discussing the conditions leading to such a spectacular effect. Indeed, although nanopatterning has been demonstrated on some materials, it is yet not possible to deduce the most relevant surface properties and to select those materials for which the high density of electronic excitations would result in a permanent topographic defect. One of the most important issue deals with the relaxation time (compared to the collision time) and mobility of the electronic excitations created at the surface by the incident ion.

On alkali-halides, electronic excitations usually lead to point defects with specific relaxation and diffusion characteristics. Since the ionic conductivity of these materials is driven by the nature and concentration of these point defects, it may be interesting to explore the potential relationship between the nature of the primary excitations (as those created by an HCI impact) and the dynamics of the induced macroscopic charging.

Combining in coincidence surface scattering spectroscopy and electron emission, we propose to compare the charging and discharging dynamics of NaCl(001) during grazing incidence scattering of single and multiply charged ions. The coincidence measurements allow the exact determination of the amount of charges deposited on the surface. Because the charges accumulate initially only at the top surface layer, the incoming ion beam is sensitive to surface potentials as low as few tens of mV. Then simultaneously to the coincidence measurements, the deflection of the incident beam gives access to the density of charges effectively present at the surface. It is then possible to follow in real time the surface response with respect to the charge build up.

We will present preliminary results obtained Ar^{7+} , Ar^+ , O^{3+} , He^+ and H^+ . We propose a method to reduce the measured parameters and gain access to the two main mechanisms: charge diffusion at the surface and charge burying below the surface.

DOUBLY-RESONANT COHERENT EXCITATION OF HCI PLANAR CHanneled IN A Si CRYSTAL

Y. Nakano, S. Masugi, T. Muranaka, T. Azuma, C. Kondo¹, A. Hatakeyama¹,
K. Komaki¹, Y. Yamazaki^{1,2}, E. Takada³, and T. Murakami³

Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan

¹Institute of Physics, University of Tokyo, Komaba, Meguro, Tokyo 153-8902, Japan

²Atomic Physics Laboratory, RIKEN, Wako, Saitama 351-0198, Japan

³National Institute of Radiological Sciences, Inage, Chiba 263-8555, Japan

Doubly-resonant excitation of HCI was observed with relativistic ions from HIMAC (Heavy Ion Medical Accelerator in Chiba) planar channeled in a 26 μm -thick silicon crystal. When fast ions are injected into the crystal parallel to an atomic plane, they travel along the inter-planar spacing, that is, planar channeling. Such “planar channeled” ions feel an oscillating field by traversing periodic arrays of atomic strings on the plane as shown in fig. 1. The oscillating field consists of numerous frequency components specified by the 2D Miller index (k, l) . The electronic state of ions can be resonantly excited if one of the oscillating frequency matches the transition energy, which is called resonant coherent excitation (RCE) under the channeling condition. The doubly-resonant coherent excitation may occur when the resonant conditions of two different transitions is simultaneously satisfied by tuning the incident velocity and incident angle of the ions precisely,

We investigated the V-type and the ladder-type doubly-resonant excitations of 440.62 MeV/u H-like Ar¹⁷⁺ and 387.89 MeV/u He-like Ar¹⁶⁺ as illustrated in Fig. 2. In order to observe the trajectory dependence of the doubly-resonant excitation, we adopted a thin SSD as a target crystal, which was manufactured by ourselves. Since the excited ions are more easily stripped in the crystal, RCE results in the large ionized fraction in the charge state distribution of transmitted ions. In the V-type configuration, in which the resonant conditions for $1s - 2p$ and $1s - 3p$ are simultaneously satisfied, the observed ionized fraction was larger under the double resonant condition compared to those under single resonant conditions. In the Ladder-type configuration, we tried to produce the doubly-excited state through the successive excitation of $1s^2 - 1s2p$ and $1s2p - 2p^2$. The ionized fraction was also enhanced under the double resonant condition. It is confirmed that the doubly-excited $2p^2$ state is selectively produced by the doubly-resonant coherent excitation in the x-ray region.

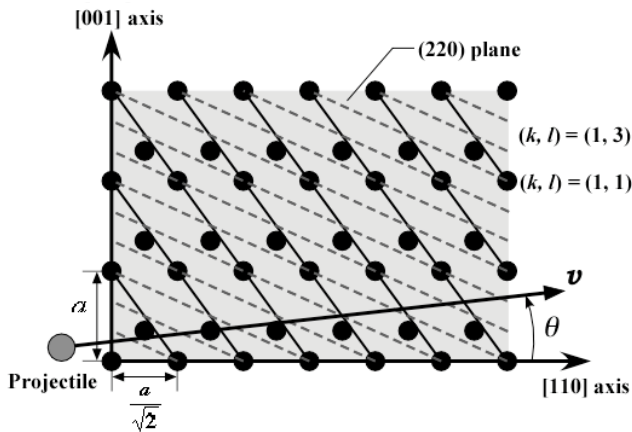


Fig. 1 : Atomic arrangement on the Si (220) plane. The solid and dotted lines show the arrays of atomic strings specified by $(k, l)=(1,1)$ and $(1,3)$, respectively.

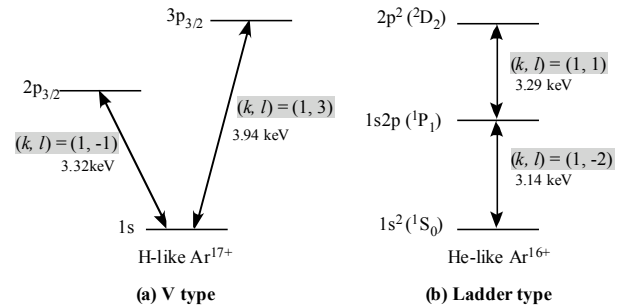


Fig. 2 : V-type (a) and ladder-type (b) configurations and the two frequency components of the oscillating field. The corresponding Miller index and energy difference are presented.

Poster Category 4

**Interactions with Photons, Plasmas
and Strong Field Processes**

ABSOLUTE PHOTOIONIZATION CROSS SECTIONS FOR HIGHLY CHARGED IRON AND XENON IONS

F. Folkmann, J.-M. Bizau*, D. Cubaynes*, F.J. Wuilleumier*, J. Blicck*, C. Blancard**, J.P. Champeaux**, J.L. Lemaire**, G. Faussurier**, D. Kilbane*** and H. de Luna***

Department of Physics and Astronomy, University of Aarhus, DK-Aarhus C, Denmark
(*) Laboratoire d'Interaction des Rayons X avec la Matière (LIXAM), UMR 8624 du CNRS, Université Paris-Sud, Bâtiment 350, and Laboratoire pour l'Utilisation du Rayonnement Electromagnétique (LURE), F-91405-Orsay cedex, France
(**) CEA DAM Ile-de-France, DPTA, Boîte Postale 12, F-91680 Bruyères-le-Châtel, France
(***) National Centre for Plasma Science and Technology, School of Physical Sciences, Dublin City University, Glasnevin, Dublin 9, Ireland

We have performed absolute measurements of photoionization cross sections [1] of charged ions using an Electron Cyclotron Resonance (ECR) ion source for higher charges. An overview of previous measurements at the storage ring ASTRID in Aarhus can be found in [2, 3].

Here we report on results on iron ions where we measured singly charged Fe in [4] and recently completed a study of Fe^{4+} [5] in the photon energy region 59 eV to 140 eV at the ASTRID storage ring, which is followed by studies of other charge states. We have studied the 3p to 3d excitation and compared our results with R-matrix calculations, especially near threshold, and with a special opacity code. This self-consistent average atom code for laboratory plasmas was modified to calculate the total photoionization cross section for the $3p^6 3d^4$ configuration of Fe^{4+} and the result reproduced well the measured gross shape between 60 eV and 85 eV. In the region from 80 eV to 140 eV the measured photoionization cross section [5] gradually decreases from 5 Mb to 3 Mb and is compared with various R-matrix theories, where some are good and other overestimate. But all calculations fail in reproducing quantitatively the measurements in the 3p to 3d excitation region.

For xenon ions we have measured the isonuclear sequence Xe^{3+} to Xe^{6+} in the photon region 30 eV to 160 eV. The measurements were made both at Super ACO in Orsay, Paris, and at ASTRID in Aarhus and they were compared with multiconfigurational Dirac-Fock calculations. Cross sections are obtained both for single and double ionization, e.g. Xe^{4+} to Xe^{5+} and to Xe^{6+} . The excitation of 4d electrons to 5p, 4f or higher orbits up to $n=6$ is found, and integrated oscillator strengths listed with a total sum around 10 for the 4d subshell. Many lines are observed and our results show that studies along isonuclear sequences are powerful tools for following gradual changes in electron effects when outer electrons are successively removed. We could follow the gradual collapse of the 4f wave function in the Xe^+ to Xe^{6+} sequence.

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Multiple photoionization of Cr and Mn atoms in the regions of 3p-nd giant resonance and 3s-np autoionizing resonances

T. Osawa, K. Kato, S. Obara¹, T. Nagata, Y. Azuma¹ and F. Koike²

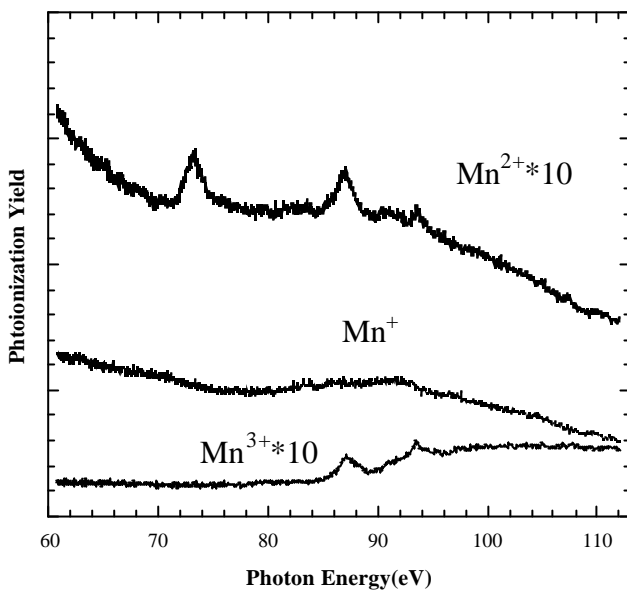
Department of Science and Technology, Meisei University, Hino, Tokyo 191-8506 Japan

¹ Photon Factory, Institute for Material Structure Science, KEK, Tsukuba, Ibaraki 305-0801 Japan

² School of Medicine, Kitasato University, Sagamihara, Kanagawa 228-8555 Japan

Recently, Koide et al. [1] reported that the 3s-np autoionizing resonance series in photoionization of Ar, K and Ca atoms vary drastically in their intensities and profiles with the change of atomic number. Since then, one of our interests has been whether such 3s-np resonance series are present in 3d metal atoms with detectable intensities or not, and if present, what type of resonances appears and how it depends on the atomic number Z .

As the first step, we have made photoion-yield study on Cr and Mn atoms in the 3s region as well as the 3p region and have observed for the first time the 3s-np autoionizing resonance series. The 3s-np spectra for Cr and Mn are quite different in spite of the minimal difference in their outermost 4s shells. Figure below displays, as an example, the observed 3s-np autoionizing resonance series of Mn atom. The 3s-np resonance in Mn atom appears as that of peak type, but the resonance in Cr atom (no shown here) looks that of window type. In the case of Mn, the first member of the 3s-np series appears only in the double ionization curve, in contrast to the second and higher members that appear in both the double and triple ionization curves. This indicates that an inner-shell excited state, which corresponds possibly to a shaken-up state associated with the 3p ionization, lies between the first and the second members and has a probability of Auger decay to triple ionization.



The 3p-nd region, known as the giant resonance region, of these atoms has been studied with the photoabsorption, photoelectron and photoion spectroscopies [2]. Our photoion-yield results have been obtained with an improved resolution, and provide further information about the decay processes of the resonance states.

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Observation of high-lying weak autoionizing resonances of Ne, Na, and Mg atoms by charge-separated photoion-yield method

K. Kato, T. Osawa, S. Obara¹, Y. Tohyama, T. Nagata, Y. Azuma¹ and F. Koike²

Department of Science and Technology, Meisei University, Hino, Tokyo 191-8506 Japan

¹ Photon Factory, Institute for Material Structure Science, KEK, Tsukuba, Ibaraki 305-0801 Japan

² School of Medicine, Kitasato University, Sagamihara, Kanagawa 228-8555 Japan

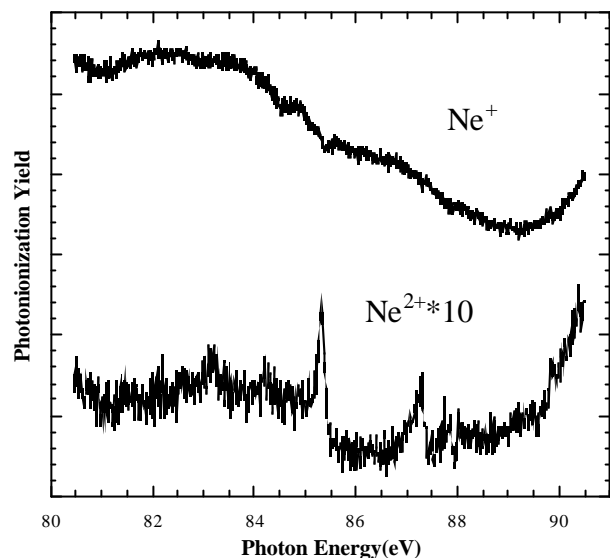
Autoionizing resonances in photoionization of atoms have been a subject of extensive experimental and theoretical studies. Resonances in rare-gas atoms, which show typical Fano profiles, have been precisely studied and have been often used for calibrating the photon energies.

It is quite natural that the spectra of inner-shell resonance-excitations or multiple-electron resonance-excitations are superposed by a strong valence ionization continuum. When such resonance-excitations are quite weak, we may face a difficulty for discriminating the excitations from the spectra of photo-absorptions, total photoions, or photoelectrons. In contrast to those methods, a charge-separated photoion-yield method has a possibility to observe such weaker resonances, because they often lead to productions of ions with multiple charges. We have carried out a charge-separated photoion spectroscopy measurement for Ne, Na, and Mg atoms.

In a figure below, we show the resonance series of Ne atoms lying in the 84-90 eV region. We can compare the present results with the measurement of Codling et al [1], who reported the resonance structures at 73.8 eV and 84.9 eV in their absorption spectrum. Their structure at 84.9 eV may correspond probably to our first member of the resonance series at 85.3 eV. The assignment that they suggested for the structure at 84.9 eV is $2s2p^5(^3P)3p^2(^1P^o)$. If this is the case, the present series can be assigned as $2s2p^5(^3P)3pnp(^1P^o)$.

We have also observed several irregular autoionization features immediately above the $2s^{-1}np$ autoionizing series in Na and Mg atoms. In both cases, the features appear clearly not in the yield curves of singly-charged ions but in ones of doubly-charged ions.

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K-SHELL PHOTOIONIZATION OF C^{3+} AND PHOTORECOMBINATION

A Müller¹, S Schippers¹, R A Phaneuf², S W J Scully^{2,3}, A Aguilar^{2,4}, J D Bozek⁴, C Cisneros⁵, E D Emmons², M F Gharaibeh², G Hinojosa⁵, A S Schlachter⁴, **B M McLaughlin**^{3,6}

¹Institut für Atom- und Molekülphysik, Justus-Liebig-Universität, 35392, Giessen, Germany

²Department of Physics, University of Nevada, Reno, Nevada 89557, USA

³School of Mathematics and Physics, Queen's University of Belfast, Belfast BT7 1NN, UK

⁴Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA

⁵Centro de Ciencias Físicas, Universidad Nacional Autónoma de México, Apartado Postal 6-96, Cuernavaca 62131, Mexico

⁶Institute of Theoretical Atomic and Molecular Physics, Harvard Smithsonian Center for Astrophysics, MS-14, Cambridge, Massachusetts 02138, USA

Absolute cross-sections for the K-shell photoionization of Li-like $C^{3+}(1s^2 2s \ ^2S)$ ions were measured by employing the ion-photon merged-beams technique at the Advanced Light Source. The energy ranges 299.8–300.15 eV, 303.29–303.58 eV and 335.61–337.57 eV of the $[1s(2s 2p)^3P]^2P$, $[1s(2s 2p)^1P]^2P$ and $[(1s 2s)^3S 3p]^2P$ resonances, respectively, were covered using resolving powers of up to 6000. The width of the $[1s(2s 2p)^1P]^2P$ resonance was measured to be 27 ± 5 meV and compares favourably with a theoretical result of 25.5 meV obtained from the R-Matrix method. The present photoionization results are compared with the outcome of previous photorecombination measurements [1] by employing the principle of detailed balance. The agreement between both experimental approaches is within the experimental uncertainties. Further details will be presented at the meeting.

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RELAXATION EFFECT ON PHOTOIONIZATION OF Na-LIKE IRON ION

C. Z. Dong, J. J. Wan, C. C. Sang, X. B. Ding, L. Y. Xie

College of Physics and Electronic Engineering, Northwest Normal University,
Lanzhou 730070, China

Photoionization (PI) can be regarded as a time inverted process of radiative recombination (RR) in which a continuum electron is captured into a discrete state of the atom and the excess energy being radiated as a photon simultaneously. The PI cross section not only implies information of electron correlation in multielectron atom, but also plays an important role in modeling dynamic equilibrium in laboratory and astrophysical plasma, especially in the astrophysical plasma called ‘photoionized plasmas’. For example, the iron group elements are known to occur frequently in the universe [1], and Fe^{16+} is a dominant ionized state over a broad temperature range in coronal equilibrium. This ion can be produced via a PI process of Fe^{15+} ion, and its x-ray spectra have been observed in a wide range of astrophysical sources [2]. If the inner electron of the ion is ionized, a great deal of hollow states of Fe^{16+} ions are produced, which can decay by emitting x-ray photon or a Auger electron to Fe^{17+} ions. Furthermore, due to the removal of inner electron, the rearrangement of the residual electrons (i.e. orbital relaxation) will occur. As a result, some higher order processes, such as shake-up, will accompany the PI process.

In the present work, the relaxation effects on the PI cross section of Na-like iron ions have been investigated systematically. The related energies and wavefunctions of initial ionic state Fe^{15+} ($1s^2 2s^2 2p^6 3s$) and all final ionic states formed by ionizing a 1s, 2s, 2p or 3s electron from the initial state are calculated using GRASP92 package [3]. The corresponding PI cross sections are calculated by a newly developed RERR06 code [4] based on the same MCDF method. Meanwhile, some associated shake-up processes are also studied. It shows that 1) the PI cross sections decrease with the increase of photon energy for each state with a given total angular momentum, 2) in the case of including relaxation effect, the PI cross sections are almost the same as those without relaxation for the 2s, 2p and 3s PI processes, where the results for 2p are in quite good agreement with existing calculations [5], but for 1s the results decrease rapidly with increasing energy of photon. In other words, the relaxation effect on the PI cross section of inner shell is more important, 3) the PI cross section accompanied by shake-up process is smaller than the main PI cross section by 2-3 orders of the magnitudes. Furthermore, the contribution of excitation-autoionization process is also discussed in the 3s PI process.

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QUANTUM REVIVALS IN ULTRASHORT INTENSE FIELD DISSOCIATION OF MOLECULAR IONS

D.S. Murphy, C.R. Calvert, J. McKenna, I.D. Williams and J.F. McCann

School of Mathematics and Physics, Queen's University of Belfast, Belfast BT7 1NN, N.I.

E-mail: domhnall.murphy@qub.ac.uk

Rapid advancements in laser technologies have made it possible to study the dynamics of atomic and molecular systems under extreme dynamic fields. Ultrashort ($< 10\text{fs}$), high intensity ($> 10^{16}\text{W cm}^{-2}$) laser pulses create conditions in which ionization and dissociation processes occur readily. These breakthroughs have presented a host of different directions for experimental investigation, in the general area of intense field physics.

The H_2^+ and D_2^+ molecular ions provide the simplest examples of molecular systems. Understanding the dynamics of such systems is of fundamental importance in the understanding of larger molecular systems and in the quest for quantum control of chemical processes. The study of nuclear dynamics is facilitated by the fact that the vibrational period of the nuclei in D_2^+ ($\sim 25\text{fs}$) can be matched by few-femtosecond infrared pulses. Diagnostics of the molecular response are provided by the fragment ions and electrons.

We present theoretical simulations of recent experiments carried out by the QUB, UCL and RAL groups, by direct solution of the time-dependent Schrödinger equation within the two-state electronic approximation. Recent experiments have shown that, by increasing the delay time between pump and probe pulses, one observes an initial oscillation in the dissociation signal. This initial oscillation dies away within $\sim 100\text{fs}$, only to *revive* once again after $\sim 500\text{fs}$. This behaviour can be reproduced and understood in terms of the current simulations for the nuclear vibrational motion. (See Fig. 1). Details of the numerical model used will be outlined and a selection of some of the calculations will be presented.

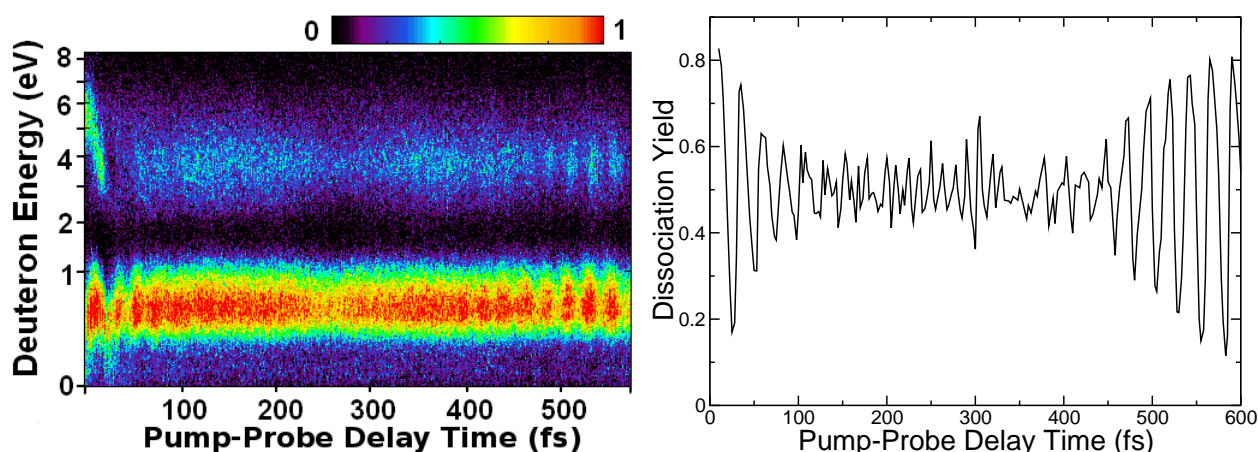


Figure 1: **Left:** Density plot of deuteron energy versus pump-probe delay time (experiment). **Right:** Dissociation yield versus pump-probe delay time (numerical simulation).

Absolute photoionization cross section measurements of the Kr I-Isoelectronic sequence

C. Banahan¹, P. van Kampen¹, J.-M. Bizau², J. T. Costello¹, D. Kilbane¹, H. Kjeldsen³,
F. Folkmann³, M. W. D. Mansfield⁴, S. Scully⁵, J. B. West⁶

¹National Centre for Plasma Science and Technology, Dublin City University, Glasnevin, D9, Ireland

²LURE, Universit Paris Sud, Orsay 91400, France

³Institute of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark

⁴Department of Physics, University College Cork, Cork, Ireland

⁵School of Mathematics and Physics, Queen's University of Belfast, Belfast BT7 1NN, UK

⁶Daresbury Laboratory, Warrington WA4 4AD, UK

Photoionization spectra have been recorded in the $4s$, $4p$ and $3d$ resonance regions for the Kr I-isoelectronic sequence using both the dual laser produced plasma technique at DCU [1,2] to produce photoabsorption spectra, and the merged ion beam and synchrotron technique at ASTRID [3,4] to produce absolute photoionization cross sections. Profile parameters are compared for the $4s - np$ resonances of Rb^+ and Sr^{2+} . Many new $4p \rightarrow ns, md$ transitions are identified with the aid of Hartree-Fock calculations, and consistent quantum defects are observed for the various ns and md Rydberg series.

Partial single and double photoionization cross sections recorded in the $3d$ region for Rb^+ and Sr^{2+} ions show preferential decay via double photoionization. This is the first report where both the DLP technique and the merged beam technique have been used simultaneously to record photoionization spectra, and the advantages of both techniques (i.e. better resolution in the case of DLP and values for absolute photoionization cross sections in the case of the merged beam technique) are highlighted.

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VIBRATIONAL AND ROTATIONAL WAVEPACKET REVIVALS OF D_2^+ INDUCED BY FEW-CYCLE LASER PULSES

J McKenna^b, C R Calvert^b, W A Bryan^{*†}, D Murphy^b, J Wood^{*}, E M L English^{*}, I C E Turcu[†], A J Langley[†], J Collier[†], J F McCann^b, W R Newell^{*} and I D Williams^b

^(b) Department of Physics, Queen's University Belfast, Belfast, BT7 1NN, UK

^(*) Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK

^(†) Central Laser Facility, CCLRC Rutherford Appleton Laboratory, Chilton, Oxon., OX11 0QX, UK

The H_2^+ molecular ion (and its isotopic counterparts, D_2^+ and HD^+) presents itself as the most simplistic of two-atom systems. An in depth knowledge of this fundamental ion is therefore key to groundwork molecular physics. Recently the innovative concept of manipulating nuclear wavepackets (rotational and vibrational) to control this simple 3-body quantum system was realized. Rotational motion has been successfully controlled in small molecules such as O_2 and N_2 . Vibrational control is more difficult to demonstrate due to the shorter timescale (tens fs) involved, but the feasibility of experimental studies has recently been shown with D_2^+ [1].

Using a two-pulse (pump and probe) imaging technique coupled with time-of-flight mass spectrometry, we perform a detailed mapping of both the vibrational and rotational wavepacket dynamics of D_2^+ within a few-cycle laser field. The first pulse creates an ensemble of vibrationally and rotationally excited D_2^+ molecules from their neutral groundstate. The pulse polarization axis is orientated perpendicular to the detection axis to render our imaging free of any dissociation/coulomb explosion events from this pulse. The second pulse is then used to image the real-time evolution of these wavepackets which initially dephase and then subsequently revive after their respective revival periods, T_{vib} and T_{rot} . We image these dynamics via both the molecular dissociation (MD) and coulomb explosion (CE) channels of D_2^+ , see Figure 1.

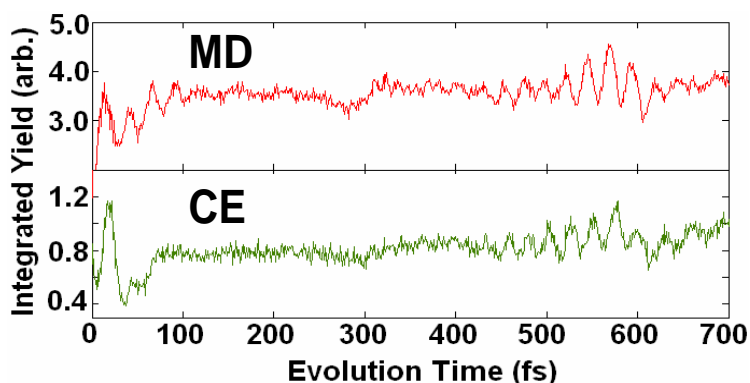


Figure 1. Real-time imaging of vibrational wavepacket dynamics in D_2^+ . The vibrational revival structure is centred at $T_{vib}=580$ fs. MD and CE denote molecular dissociation and coulomb explosion fragmentation channels respectively.

At the conference we will present a comprehensive set of experimental results of wavepacket imaging and compare with a quantum-mechanical approach to simulating the motion -also to be outlined. Favourable agreement between the two is found and we shall illustrate control over the vibrational wavepacket coherence through chirping the duration of the production pulse from ~ 14 fs – 30 fs.

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DYNAMIC IMAGING OF A DISSOCIATIVE D_2^+ NUCLEAR WAVEPACKET IN INTENSE LASER FIELDS

C R Calvert^o, J McKenna^o, J Wood*, E M L English*, W A Bryan^{+*}, I C E Turcu⁺, A J Langley⁺, J Collier⁺, W R Newell*, and I D Williams^o

^o Department of Physics, Queen's University Belfast, Belfast BT7 1NN, UK

* Department of Physics and Astronomy, University College London, WC1E 6BT, UK

⁺ Central Laser Facility, CCLRC Rutherford Appleton Laboratory, Chilton, Oxon, OX11 0QX

Substantial research in intense field molecular physics has recently been geared towards real-time mapping of a quantal nuclear wave packet as it evolves in the presence of the optical field (e.g. Ref [1]). Realisation of this goal should help provide fundamental answers about the dynamical nature of the molecular motion itself, critical to control of chemical and biological reactions. D_2^+ , being a one-electron system, is an ideal candidate for theoretical calculations and is experimentally preferred to H_2^+ and HD^+ for imaging due to its heavier nuclear mass (reduced wavepacket momentum).

Until now such experiments on H_2/D_2 have been limited, largely due to the ultrashort timescale in which the system evolves (typical vibrational periods 15 – 25 fs). However with the advent of few-cycle laser pulses true time-resolved ‘photography’ of the dynamical motion can be accomplished [2, 3].

At this meeting we will present results from a comprehensive experimental study detailing the real time evolution of a dissociating molecular wavepacket. Utilizing two intense few-cycle laser pulses in a pump probe arrangement, we prepare a coherent ensemble of dissociating D_2^+ ions with subsequent imaging via projection onto the repulsive coulomb curve.

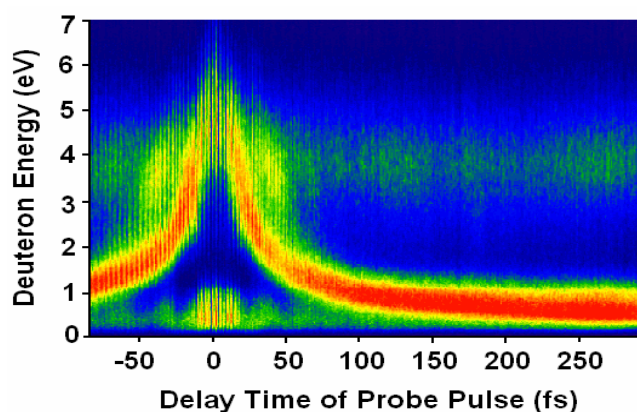


Figure 1: Deuteron kinetic energy spectra, from fragmentation of D_2^+ , plotted as a function of pump-probe delay time. Identical 15 fs, 5×10^{14} Wcm^{-2} laser pulses were used to pump and probe. The band of fragmentation flux shifting from high energy to low with increasing delay time represents coulomb explosion imaging of the dissociating wavepacket as the nuclei spatially separate. Interference stripes are apparent around the overlap of the two pulses (delay time 0 fs).

Our experimental technique enables variation of the pump-probe delay time on a sub-femtosecond timescale and consequently we obtain extremely high resolution in our spectra. As such, detailed interferometric effects near the pulse overlap have been observed, together with well resolved dissociation channels and evidence of revival structure in the bound D_2^+ wavepacket.

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FINE-STRUCTURE RESOLVED PHOTOIONIZATION OF METASTABLE Be-LIKE IONS C III, N IV, and O V

A. Müller, S. Schippers, R. A. Phaneuf*,
 A. L. D. Kilcoyne**, H. Bräuning, A. S. Schlachter**, M. Lu*

Institut für Atom- und Molekülphysik, Justus-Liebig-Universität Giessen, 35392 Giessen, Germany

(*) Department of Physics, University of Nevada, Reno, NV 89557-0058, USA

(**) Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Be-like ions offer a number of scientifically interesting aspects. With the two loosely bound electrons in the L-shell and two tightly bound K-shell electrons, they are almost perfect objects for investigating two-electron effects. The metastable 3P states can be easily populated and provide access to well isolated excited states which are known to be of high importance in the modeling of finite density plasmas. The present work aims at experimental distinction between the fine-structure levels of the 3P term. High-resolution photoionization experiments were carried out with beams of C^{2+} , N^{3+} , and O^{4+} containing roughly equal amounts of ground-state and metastable ions. The energy scales of the experiments are calibrated with uncertainties of 1 to 10 meV depending on photon energy. By employing energy resolutions of the order of 20000, cross section features characteristic for individual states 3P_0 , 3P_1 , 3P_2 and, of course, the 1S_0 ground state are observed. An example is shown in Fig. 1.

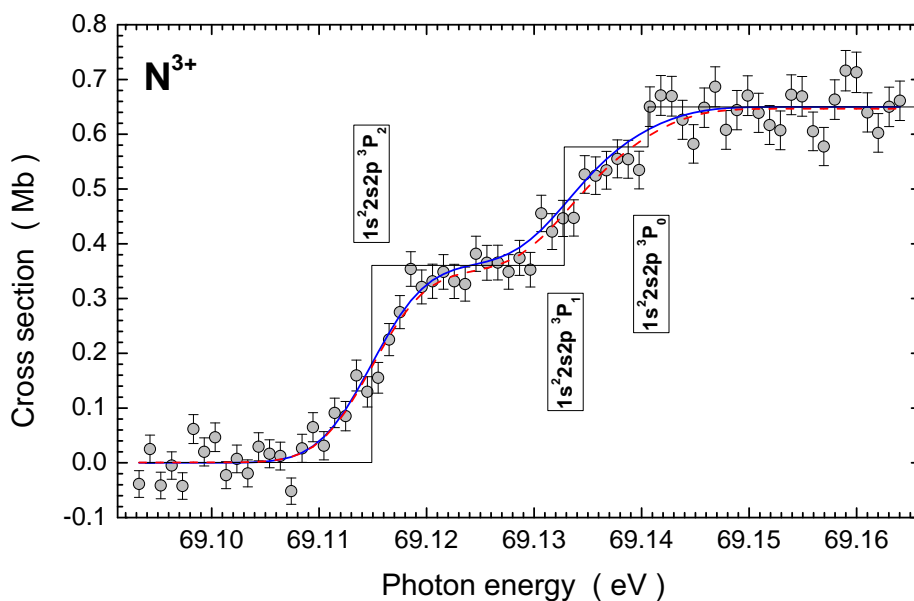


Figure 1: Measurement at the photoionization threshold of $N^{3+}(2s2p^3P)$ ions. The step function shows the spectroscopic threshold energies[?] of the $^3P_{2,1,0}$ states. It was generated by distributing the measured strength according to statistical weights of the individual states involved. The solid line is a fit of the data using the step function washed out by a variable experimental energy spread (determined to be 9.3 meV). The dashed line was obtained by leaving the weights variable in the fit.

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Strong Laser Field Effects in Autoionizing Resonances

Caroline Banahan, John T. Costello, Paul van Kampen

National Centre for Plasma Science and Technology (NCPST)
Dublin City University, Glasnevin, D9, Ireland

The structure arising in the continuum spectrum of an atom due to the strong field coupling of two autoionizing states (AIS) has been studied theoretically for 25 years now [1-3]. Using a pump-probe setup to study this system, a strong inhibition in the ionization of the system is predicted when both the pump and probe lasers are on resonance, while a varying asymmetry is induced as the detuning between the two states and the field increases. The first experimental results achieved by Karapanagioti *et al* [4] for Mg indicate this is so, thus testifying to the existence of a uniform mechanism for the absorption spectra formation. This work aims to provide further validation for the theoretical models.

Using the DLP technique [5] to isolate the autoionizing 3p-3d giant resonance in Ca II, we aim to study the effects on the ionization dynamics when we couple this state to a higher-lying autoionizing resonance by means of an optical parametric oscillator (OPO). This ladder arrangement represents a similarity to double optical resonance (DOR) in the bound spectrum of an atom. By keeping the XUV field strong and on resonance to produce an observable AC Stark splitting, the weak field OPO can be frequency scanned (410-800nm) to serve as a probe of the splitting, thus we can observe different aspects of the interaction.

Work supported by the Irish Governments National Development Plan under the Basic Research Grants Scheme administered by the Irish Research Council for Science Engineering and Technology.

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DOUBLY EXCITED RESONANCES IN THE PHOTOIONIZATION SPECTRUM OF Li^+

S W J Scully^{1,9}, I Álvarez², C Cisneros², E D Emmons¹, M F Gharaibeh¹, D Leitner³, M S Lubell⁴, A Müller⁵, R A Phaneuf¹, R Püttner⁶, A S Schlachter³, S Schippers⁵, C P Ballance⁷ and **B M McLaughlin**^{8,9}

¹Department of Physics, MS 220, University of Nevada, Reno, NV 89557, USA

²Centro de Ciencias Físicas, UNAM, Apartado Postal 6-96, Cuernavaca 62131, México

³Lawrence Berkeley National Laboratory, Berkeley CA 94720, USA

⁴Physics Department, City College of New York, New York, NY 10031, USA

⁵Institut für Atom-und Molekülphysik, Justus-Liebig-Universität Giessen, D-35392 Giessen, Germany

⁶Institut für Experimentalphysik, Freie Universität Berlin, Arnimallee 14, D-14195 Berlin-Dahlem, Germany

⁷Department of Physics, Rollins College, Winter Park, FL 32789, USA

⁸Institute for Theoretical Atomic and Molecular Physics (ITAMP), Harvard Smithsonian Center for Astrophysics, MS-14, Cambridge, Massachusetts 02138, USA

⁹School of Mathematics and Physics, Queen's University of Belfast, Belfast BT7 1NN, UK

Absolute cross-section measurements for resonant double photoexcitation of Li^+ ions followed by subsequent autoionization have been performed in the photon energy range from 148 eV, just below the $(2s2p, {}_2(0,1)_2^+)$ resonance to 198 eV (the region of the double ionization threshold) at high resolution. The measurements have been made using the photon-ion merged-beam endstation at the Advanced Light Source, Lawrence Berkeley National Laboratory. The absolute cross section measurements when compared with theoretical results from the R-matrix plus pseudo-state (RMPS) method show excellent agreement. Comparisons between the present and previous experiments [1],[2] with theory for the Auger resonance energies, autoionization linewidth (Γ) and the Fano line profile index q for several members of the principal $(2snp, {}_2(0,1)_n^+)$ and $(3snp, {}_3(1,1)_n^+)$ Rydberg series found in the photoionization spectra for the ${}^1P^o$ symmetry show good agreement. Further details will be presented at the meeting.

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THE DETERMINATION OF CHARGE STATE, ENERGY AND ANGULAR DISTRIBUTIONS OF TIN IONS EMITTED FROM LASER PRODUCED PLASMA BASED EUV SOURCES.

O. Morris, P. Hayden, P. Dunne, F. O'Reilly, G. O'Sullivan, E. Sokell, S. Srivastava*,
K. Thompson* & D. N. Ruzic*,

Atomic and Molecular Physics Group, U.C.D School of Physics, University College Dublin,
Belfield, Dublin 4, Ireland

* University of Illinois, Department of Nuclear, Plasma, and Radiological Engineering, Urbana, IL
61801, USA

As components used by the semiconductor industry get smaller it is necessary to develop light sources that are of short enough wavelength to fabricate these at the required dimensions. Laser produced plasmas can be made to significantly emit at the appropriate wavelengths [1] but ions that are emitted from these plasmas will cause significant damage to the components in a real world projection lithography system [2]. In order to effectively mitigate this damage it is necessary to understand how fast and in what direction different ions are emitted. Reported here are measurements of the charge state, energy and angular distributions of ions emitted from laser produced plasmas, from tin based targets, that have potential for use as sources of Extreme Ultra-Violet radiation.

We have performed time of flight (T.O.F) analysis to determine the intensity of ion distribution from a tin based plasma for a range of charged tin ions ($\text{Sn}^{1+} - \text{Sn}^{10+}$). A Nd :YAG laser operating at 1064nm with a full width at half maximum (FWHM) of 5.2 ns was used to create the plasma under vacuum with a base pressure of 10^{-6} Torr. The plasma formation occurred on a custom made optical system which could be rotated with respect to the detector so T.O.F analysis could be performed at various angles of incidence, while maintaining a normal angle of incidence for the laser pulse with respect to the target. The detector used was an energy sector analyser (ESA) which is a well-characterised diagnostic capable of measuring ion energy and discriminating by charge state [3]. Analysis was performed on ions of various charge states, with Energy/charge state (E/q) ratios ranging from 3 keV to 50 eV, for angles of incidence ranging from 90 to 15 degrees.

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LASER-CLUSTER INTERACTION : CLUSTER SIZE EFFECT ON X-RAY PRODUCTION

E. Lamour, C. Prigent, J.-P. Rozet, and **D. Vernhet**
C. Deiss^{*}, N. Rorhinger^{*}, and J. Burgdörfer^{*}

Institut des NanoSciences de Paris, CNRS UMR 7588, Université Pierre et Marie Curie,
Campus Boucicaut, 75015 Paris, France, EU

(^{*}) Institute for Theoretical Physics, Vienna University of Technology,
A-1040, Vienna, AUSTRIA, EU

When clusters are submitted to intense femtosecond laser pulses, the energy coupling between radiation and matter is extremely efficient and provides specific features that are not observed with atoms, small molecules or even solids. The energy conversion rate is highly non linear and specificities of laser-cluster interaction, such as emission of atomic ions with MeV energies, hot electrons of few keV, as well as x-rays in the keV range, lead to interesting potential applications.

To provide insight in the dynamics of laser-cluster interaction, we have measured absolute x-ray yields and charge state distributions under well controlled conditions as a function of several physical parameters governing the interaction. Indeed, the x-ray generation related to the production of highly stripped ions resulting from the laser-heated cluster plasma is a direct signature of the inner-shell vacancies creation on a very short time scale (down to few fs). Therefore, x-ray emission can be considered as a microscopic detector for hot electrons ($E \gtrsim 1\text{keV}$), which create vacancies by electron impact ionization.

Recently, we show evidence for a very low laser intensity threshold in the x-ray production, well below the laser intensity where the ponderomotive energy of the electrons is sufficient to create inner-shell vacancies. We found typically $1.2 \cdot 10^{15} \text{ W/cm}^2$ for a pulse duration of 150 fs, down to $3 \cdot 10^{14} \text{ W/cm}^2$ for 610 fs, in the case of Ar clusters [1]. None of the previously proposed theoretical models provides a satisfactory explanation for a high electron temperature at such moderate intensities. Within a Classical Trajectory Monte Carlo simulation to describe the dynamics of the electrons in the cluster, we developed a model showing that beside the field induced by the build-up of an overall charge of the cluster due to electrons leaving the cluster, elastic electron-ion scattering plays an essential role in the heating process. The resulting high-energy tail of the electron distribution is sufficient to produce K-shell vacancies and we find a good quantitative agreement with the measured effective x-ray yields for argon clusters with $N = 2.8 \cdot 10^5$ atoms, excited by 60 fs, $\lambda = 800\text{nm}$ laser pulses [2]. To go a step further, the cluster size dependence has been investigated in the range of 10^5 to 10^7 atoms/cluster. In contradiction with the well-known plasma codes [3, 4], a saturation in the x-ray emission probabilities is found above a critical cluster size while the mean charge state still increases. These results will be presented and discussed at the conference in the light of the CTMC simulation we have developed and where additional investigations are under progress, especially concerning the in-situ charge-state distribution.

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Poster Category 5

**Production, Experimental Developments
and Applications**

14.5 GHZ ALL-PERMANENT ECRIS FOR LOW-ENERGY ION COLLISION STUDIES

E. Galutschek, R. Trassl,^a E. Salzborn,^a F. Aumayr, **HP. Winter**

Institut für Allgemeine Physik, Vienna University of Technology, Austria

^aInstitut für Atom- und Molekülphysik, Justus-Liebig University Giessen, Germany

Abstract

We have built a compact 14.5 GHz electron cyclotron resonance (ECR) ion source with all-permanent magnetic field configuration. Microwave power in the 12.75 to 14.5 GHz frequency range is transmitted from ground potential via a PTFE window into the water-cooled plasma chamber with an optional aluminum liner. The waveguide coupling system also serves as biased electrode. Remotely-controlled gas inlet valves permit plasma operation in the gas-mixing mode. The triode extraction system has been optimized for low final ion energy from 1 to 10 x q keV (q: ion charge state). The fully computer-controlled setup can be remotely operated from any location via Ethernet. For experimental applications of primary interest the final ion impact energy can further reduced by suitable deceleration methods to a few q.eV. We show construction, typical extracted ion charge-state spectra and energy distributions of the new ECRIS, and also shortly discuss three illustrative applications.

- 1) Single and double electron capture in slow collisions between doubly charged noble gas ions and their atoms (S. Figueira da Silva et al., more details see poster presentation at this conference).
- 2) Multiply charged ion guidance through nano-capillaries (M. Fürsatz et al., more details see poster presentation at this conference).
- 3) Scanning probe microscopy of nano-defects on graphite and insulator surfaces produced by slow multicharged ions.

Acknowledgments.

This work has been conducted within EU-FP5 Integrated Infrastructure Initiative HPRI-CT-1999-40012 “LEIF” (Low Energy Ion beam Facilities). Construction of the new ECRIS has been funded as an “Innovative Project” by Vienna University of Technology.

EXPERIMENTAL DETERMINATION OF OPTIMAL IONIZATION TIMES IN THE DRESDEN EBIS/T

R.Heller**, M.Kreller, F.Grossmann*, U.Kentsch*, S.Landgraf, V.P.Ovsiyannikov*, M.Schmidt*,
A.Silze, F.Ullmann*, **G.Zschornack**

TU Dresden, Institute of Applied Physics, Mommsenstr.13, 01062 Dresden, Germany

(*) Leybold Vacuum Dresden GmbH, Zur Wetterwarte 50, 01109 Dresden, Germany

(**) FZ Rossendorf, Institute of Ion Beam Physics and Materials Research, PF 510119, 01314 Dresden,
Germany

Ionization processes in highly dense electron beams generated in the Dresden EBIT [1] are determined by the actual ionization factor. Here we present studies on the evolution of individual ion charge states of argon ions by ion extraction after differently chosen confinement times. By this way we measure the dependence of the argon ion output as a function of the ionization time. This technique makes it possible to determine the state of ionization in the ion trap and to find out optimal ionization times for maximum beam intensity of differently charged ions. The comparison of the experimental data with modelling results yields information about the realized ionization factor in the ion source. For the Dresden EBIS [2] we demonstrate that for an electron beam of 40 mA, an electron energy of 15.5 keV, a gas pressure of $3 \cdot 10^{-9}$ mbar and an ionization time of 100 ms $1.4 \cdot 10^7$ Ar^{12+} ions per second can be extracted. For Ar^{16+} we extract for an ionization time of 550 ms $1.6 \cdot 10^6$ ions per second.

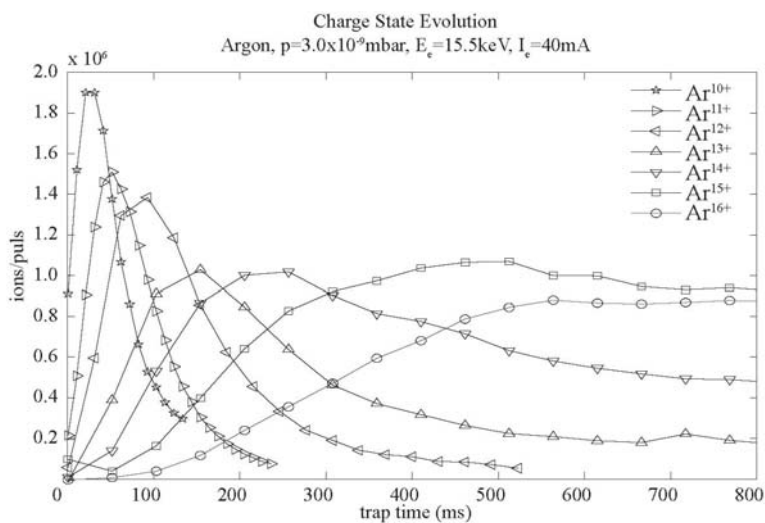


Fig. 1

Extracted from the Dresden
EBIS Ar^{q+} -ions as a function
of the ionization time

Further on, the gained information of the ion production in dependence on the confinement time allows estimating ionization cross-sections by solving the differential equation system for the production of ion charge states. For the absolute electron impact ionization cross-sections the electron beam density and the current overlap factor between the ions and the electron beam must be known from the experiment.

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FIRST INVESTGATIONS ON THE DRESDEN EBIS-A

V.P.Ovsiyannikov*, G.Zschornack, F.Grossmann*, R.Heller**, U.Kentsch*, M.Kreller,
S.Landgraf, M.Schmidt*, F.Ullmann*

TU Dresden, Institute of Applied Physics, Mommsenstr.13, 01062 Dresden, Germany
(*) Leybold Vacuum Dresden GmbH, Zur Wetterwarte 50, 01109 Dresden, Germany
(**) FZ Rossendorf, Institute of Ion Beam Physics and Materials Research, PF 510119, 01314
Dresden, Germany

In the past we reported on the development of the Dresden EBIT and the Dresden EBIS as two ion sources able to produce very high charged ions [1,2,3]. Here we present first experimental investigations on a new ion source generation, the Dresden EBIS-A (see Fig.1).

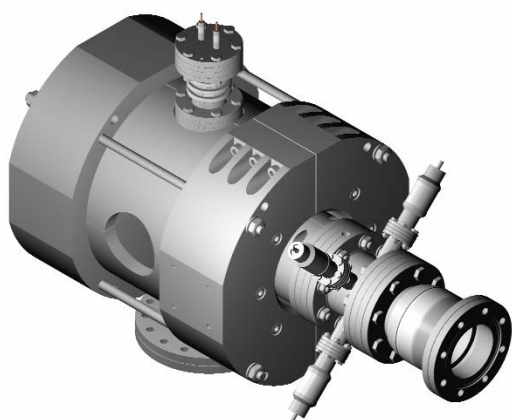


Fig. 1

3D draft of the Dresden EBIS-A

This room-temperature EBIT is characterized by a magnetic field of about 620 mT, produced by a NdFeB ring magnet system. Actually the experimental verified electron current is in the order of 400 mA with a measured reactive current of 300 μ A on the drift tubes ($\Delta I/I = 7.5 \cdot 10^{-4}$). After a certain trainee period the vacuum in the EBIT has been measured to be about $5 \cdot 10^{-10}$ mbar. The measurement of first integral pulses after the ion extraction system of the EBIS imposes extracted charges in the order of $1 \cdot 10^9$ elementary charges per pulse. In dependence on the potential on the third drift tube the pulse FWHM is in the order of 10 μ s up to some ten μ s and can be formed by this potential. Using X-ray spectroscopy we detected ions as Ar^{17+} , Xe^{44+} , Ce^{49+} and Ir^{62+} in the electron beam of the ion source. Thereby the radiation power of selected dipole lines is in the order of up to hundred nW, i.e. the $3d(^1P_1) - 2p(^1S_0)$ transition in Ce^{48+} gives an X-ray yield of about 10^8 photons in $4\pi \text{ sr}^{-1} \text{ s}^{-1}$.

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THE NESR: A VERSATILE STORAGE RING FOR EXPERIMENTS WITH RADIOACTIVE/STABLE HIGHLY CHARGE IONS AND PREPARATION OF LOW ENERGY ANTIPROTONS

C. Dimopoulou, K. Beckert, P. Beller, A. Dolinskii, V. Gostishchev, F. Nolden and M. Steck

GSI, Darmstadt, Germany

The New Experimental Storage Ring (NESR) of the FAIR project has two major modes of operation. These are storage of heavy ion beams for internal experiments and deceleration of highly charged ions and antiprotons before transfer into a low energy experimental area. The heavy ion beams can be either stable highly charged ions or rare isotope beams at 740 MeV/u selected in a magnetic separator. The antiprotons come with an energy of 3 GeV from the production target, they are pre-cooled by stochastic cooling and accumulated in a dedicated storage ring complex. The magnetic structure of the NESR has been optimized for large transverse and longitudinal acceptance allowing storage of multi-component beams with a large range of charge to mass ratio. Highest phase-space density of the stored beams is provided by a powerful electron cooling system, which covers the full energy range for ions and allows intermediate cooling during the deceleration process for antiprotons. Electron cooling compensates the diffusion (blow-up) of the beams during deceleration and thus high efficiency and low losses can be achieved. Accumulation of rare isotope beams in the NESR will be supported by electron cooling. For experiments with short-lived isotopes the cooling time and the time of deceleration will be optimized to a few seconds.

The NESR will be equipped with an internal gas-jet or pellet target where a large variety of atomic and nuclear physics experiments can be performed. The pellet target provides higher density and is particularly suited for nuclear physics studies requiring high luminosity. An electron target, which is essentially an electron cooler at low energy with high quality electron beam, will be used for precision measurements of ion-electron interactions at variable, well controlled, relative velocity between ion and electron. One straight section of the NESR is shared by a separate ring which will provide electrons for high luminosity electron scattering experiments on radioactive nuclei. In the frame of preparation for NESR, benchmarking experiments have been performed in the existing Experimental Storage Ring (ESR) at GSI to gain experience of beam storage, electron cooling, deceleration and interaction with gas-jet target.

THE ORNL MULTICHARGED ION RESEARCH FACILITY UPGRADE PROJECT

F. W. Meyer, M. E. Bannister, J. W. Hale, D. Hitz*, J. W. Johnson, J. Sinclair, C. C. Havener, H. F. Krause, C. R. Vane, E. Bahati, M. Fogle, R. Rejoub, L. Vergara, H. Zhang

Physics Div., Oak Ridge National Laboratory, P. O. Box 2008, Oak Ridge, TN 37831-6372 USA
(*) CEA-Grenoble, 17 Rue des Martyrs, 38054 Grenoble cedex 9, France

A major facility upgrade of the ORNL Multicharged Ion Research Facility (MIRF) has recently been completed [1]. It consists of the installation of a 250-kV high-voltage platform with a new all-permanent magnet electron cyclotron resonance (ECR) ion source, a new beamline switchyard for transporting the higher energy beams to on-line experiments, and the reconfiguration of the present ECR ion source for injecting extracted beams into a floating beamline to permit deceleration to energies as low as a few eV \times q upon entry into grounded experimental chambers. With the two sources, the range of energies available at MIRF has been expanded to more than five orders of magnitude. The new ECR ion source installed on the high voltage platform was designed and built at CEA Grenoble and operates in the frequency range of 12.75 – 14.5 GHz. High-voltage-platform components and beamline components up to the various end-stations are controlled and monitored via Allen-Bradley ControlLogix programmable logic controllers (PLC's) that are integrated into a Linux-hosted, EPICS-based distributed control system. Additional design and performance details of the upgraded facility will be provided at the conference.

The ion energy range between 25 – 250 \times q keV is at present virtually inaccessible for highly charged ion collision experiments requiring beam intensities in the particle- μ A range. Upon completion of the MIRF upgrade, a broad range of new experiments involving high charge state ions will be possible in this energy range. In addition, all the presently online experiments at MIRF will benefit greatly from the higher energy beam capability developed by this project.

The enhanced low-energy capability provided by the floating beamline will make possible investigations of many new low-energy heavy particle interactions as well. These include single, multiple, and dissociative low energy electron capture, lifetime studies of metastable electronically excited multicharged ions (MCI), measurements of X-ray emission and surface modification in low energy MCI-surface interactions, and investigations of plasma wall interactions of relevance to present and future fusion plasma experiments. These and other aspects will be presented in greater detail at the conference.

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DECELERATION OF HIGHLY CHARGED IONS IN A PURE ELECTRON PLASMA

N. Oshima^{1,2}, Y. Kanai², M. Hoshino^{2,3}, Y. Nakai², T. Mohamed², Y. Yamazaki^{2,4}

(1) National Institute of Advanced Industrial Science and Technology (AIST),

Tsukuba Central 2, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan

(2) Atomic Physics Laboratory, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0112, Japan

(3) Department of Physics, Sophia University, 7-1 Kioicho, Chiyoda, Tokyo 102-8554, Japan

(4) Institute of Physics, University of Tokyo, 3-8-1 Komaba, Meguro, Tokyo 153-8902, Japan

Electrons and positrons can be cooled via synchrotron radiation within ~ 1 s in a strong magnetic field. Highly charged ions (HCIs) can accordingly be cooled sympathetically if they are stored simultaneously with electrons and/or positrons in a strong magnetic field.

We proposed a cooling scheme of HCIs utilizing both electrons and positrons simultaneously in the previous meeting (HCI2004) [1]. The advantages of this scheme are (1) quick and efficient cooling of relatively energetic HCIs with the high density electron plasma, and (2) further cooling of slow HCIs down to a few K with cold positrons with negligible loss of HCIs due to recombination with electrons.

We demonstrated quick cooling of HCIs in a dense electron plasma. HCIs ($\text{Ar}^{1,4,8,12+}$) were injected into the pure electron plasma (10^{11} cm^{-3}) with energy of 1.5 keV/q and decelerated close to the plasma potential level very quickly (~ 1 -10 ms). Figure 1 shows one of our results where energy distribution of Ar^{12+} were clearly shifted to the lower energy side with the longer cooling time.

Details of the HCI cooling experiment with a dense electron plasma and some experimental results will be presented during the conference.

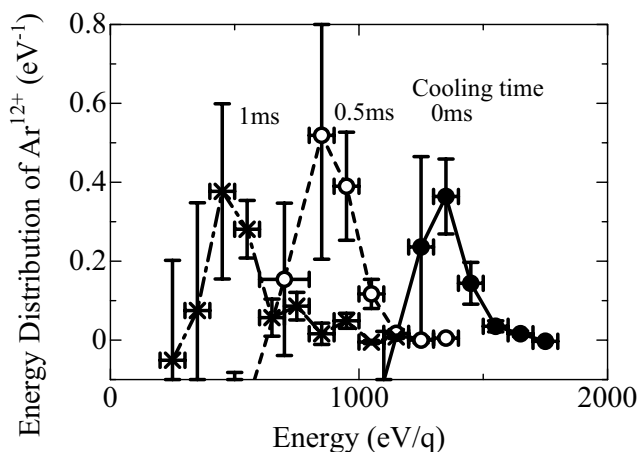


Figure 1: Energy distribution (longitudinal component) of Ar^{12+} ions after the electron cooling. Ar^{12+} ions were extracted from the trap after the cooling time of 0-1 ms, and their longitudinal energies were measured.

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CREATION AND INVESTIGATION OF MULTIPLY CHARGED CLUSTERS IN A PENNING TRAP

Noelle Walsh, Alexander Herlert*, Andreas Lassesson**, Franklin Martinez, Gerrit Marx, Lutz Schweikhard, Falk Ziegler

Institute for physics, Ernst-Moritz-Arndt University, Greifswald

(*CERN, Switzerland)

(**Nanocluster devices, New Zealand)

The ClusterTrap [1] Greifswald, has been used extensively for the investigation of the properties of metal cluster ions [2,3]. Current research at ClusterTrap, involves the investigation of fullerenes and aluminium clusters, both positively and negatively charged. Singly charged clusters are produced in a laser vapourisation source (metal clusters) or via ionisation of neutral fullerenes evaporated from an oven. Multiply charged cations are produced via electron impact ionisation of monocations stored in the Penning trap. Multiply charged anionic clusters are generated using the electron bath technique [4,5]. Figure 1 shows dianion creation following exposure to an electron bath. Activation of the stored cluster ions is achieved via collisions with inert gas atoms, electron impact or photo-excitation.

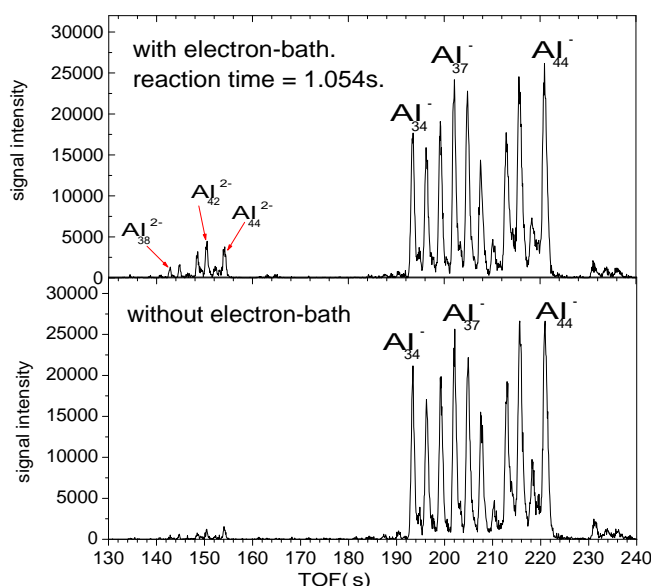


Figure 1: Aluminium dianions Al_{38}^{2-} to Al_{44}^{2-} created by simultaneous storage of aluminium monoanions with low energy electrons for a reaction time of approximately 1s.

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INJECTION OF REFRACTORY METALS INTO EBIT USING A KNUDSEN CELL

C. Yamada, K. Nagata, N. Nakamura, S. Ohtani, S. Takahashi, T. Tobiyama, M. Tona, H. Watanabe, N. Yoshiyasu, M. Sakurai*, A.P. Kavanagh** and F.J. Currell**

CREST/JST, Institute for Laser Science, Department of Applied Physics and Chemistry, University of Electro-Communications, Chofu, Tokyo, 182-8585 Japan

(*) Department of Physics, Kobe University, Kobe 657-8501 Japan

(**) Queen's University of Belfast, Belfast, United Kingdom

Injection of metallic elements into an electron-beam ion trap (EBIT) has so far been achieved by MEVVA (metal vapour vacuum arc) ion sources. However, continuous injection, as is the case of rare gases, is sometimes desirable, especially for stable extraction of highly charged ions. In the course of DR (dielectronic recombination) study, we have developed a method of such a stable injection of metallic elements.

To the Tokyo EBIT, an effusive cell (Knudsen cell) was attached horizontally, which have a cylindrical crucible made of PBN (pyrolytic boron nitride). The opening of the crucible was facing a window on the side-wall of the drift tube of the EBIT. Two pinholes were placed between the Knudsen cell and the drift tube, to facilitate differential pumping. For the bismuth, a small boat of tantalum was placed inside the crucible to sustain the molten metal. Other elements, Fe, Ho, and Er were placed directly in the crucible in the form of pellets or short wires. These metals have sufficient vapour pressure below the melting point.

Figure 1 shows the experimental setup. Figure 2 shows the charge distribution of the extracted Er and Ho ions.

Fig.1
Experimental setup.

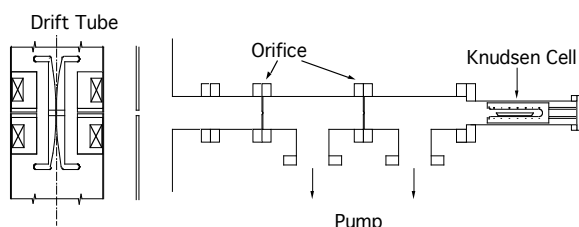
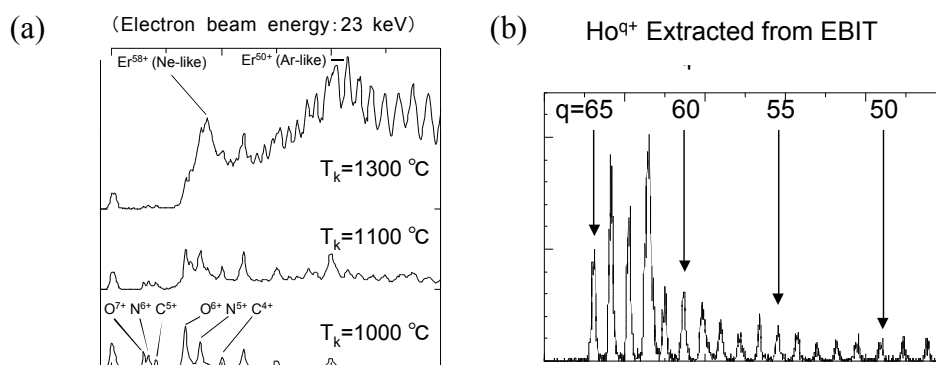


Fig. 2



RECENT EXPERIMENTAL DEVELOPMENTS FOR THE LAMB SHIFT INVESTIGATION IN HEAVY IONS

R. Reuschl^{1,2}, D. Banas³, H.F. Beyer¹, S. Chatterjee¹, A. Gumberidze^{1,2}, S. Hess^{1,2}, T. Krings⁴, D. Liesen¹, D. Protić⁴, U. Spillmann^{1,2}, Th. Stöhlker^{1,2}, M. Trassinelli¹, S. Trotsenko^{1,2}, G. Weber¹
and the FOCAL Collaboration

(1) GSI, Darmstadt, Germany

(2) IKF, University of Frankfurt, Frankfurt, Germany

(3) Institute of Physics, Kielce, Poland

(4) Forschungszentrum Jülich, Jülich, Germany

Aiming at an accurate determination of the effect of QED on the ground state binding energy in high-Z, H-like ions [1], novel high resolution spectrometer setups are presently commissioned for x-ray experiments at the Experimental Storage Ring (ESR) at GSI, Darmstadt. Up to now for the case of H-like uranium an accuracy of 1% could be reached in an experiment performed at the electron cooler [2] due to the deceleration capability of the ESR. A further improvement by almost one order of magnitude is envisaged by a transmission x-ray spectrometer set up in the Focusing Compensated Asymmetric Laue (FOCAL) geometry [3] as well as by the implementation of high-resolution microcalorimeter devices [4,5].

Here we report on the latest commissioning experiment of a two arm transmission x-ray spectrometer along with high-performance position-sensitive microstrip Germanium detectors. Due to a photon efficiency of only 10^{-8} the position sensitivity as well as the energy and time resolution of segmented solid state Germanium detectors are absolutely essential for the experiment. A detector system with the desired properties has become available through a collaboration with the Forschungszentrum Jülich [6]. In the experiment we are reporting about not only a one- but also a newly developed two-dimensional microstrip detector [7] has been used. Both detectors are providing a position resolution of about $200\mu m$.

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Performance Test of a 2D-Strip Ge(i) Detector at the Synchrotron Facility ESRF

Th. Stöhlker^{a,b}, U. Spillmann^{a,b}, H. F. Beyer^a, S. Hess^{a,b}, C. Kozhuharov^a, R. Reuschl^{a,b},
S. Tashenov^{a,b}, S. Trotsenko^{a,b}, T. Krings^c, D. Protic^c, J. Cl. Dousse^d, M. Kavcic^d,
J. Szlachetko^d, D. Banas^e

^a Gesellschaft für Schwerionenforschung, Planckstr. 1, 64291 Darmstadt, Germany

^b Institut für Kernphysik, Universität Frankfurt, Germany

^c FZ Jülich, Leo-Brandt-Str., 52428 Jülich, Germany

^d Universite de Fribourg, Avenue de l'Europe 20, 1700 Fribourg, Switzerland

^e Akademia Swietokrzyska, ul. Zeromskiego 5, 25-369 Kielce, Poland

Novel energy dispersive and position sensitive solid state detectors play an important role for accurate x-ray spectroscopy of exotic atomic systems such as hydrogenlike uranium [1]. Beside applications in x-ray spectroscopy and time-resolved x-ray imaging, the polarization sensitivity for hard x-rays is a further important feature of such devices which allows to address experimentally the polarization properties of elementary radiation processes such as electron bremsstrahlung, recombination processes or photonic processes in warm dense plasmas (compare x-ray spectroscopy program of the SPARC collaboration [2]).

Here we report on a performance test of a first prototype 2D μ -strip germanium detector developed at IKP Jülich. This germanium diode has on the front contact 128 strips on an area of 32 mm x 56 mm and on the rear contact 48 strips, respectively (for details compare [3]). For an accurate determination of the response characteristics of this detector in-beam test measurements were performed at the European Synchrotron Radiation Facility (ESRF) in Grenoble. At the ESRF 98 % linearly polarized synchrotron radiation at energies of 60 keV and 210 keV was provided for the experiment. A particular important aspect of this study was to utilize the detector as a Compton polarimeter and to investigate its polarization sensitivity. By utilizing the kinematical relation between Compton scattering angle and the energy of the scattered photons we were able to determine accurately the spatial intensity distributions for the Compton effect as a function of the scattering angle. The results obtained will be presented and discussed in detail.

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DEVELOPMENT OF A BRAGG SPECTROMETER FOR EXPERIMENTS WITH HIGHLY CHARGED IONS AT STORAGE RINGS

D. Banaś, P. Jagodziński*, M. Pajek, Th. Stöhlker‡, M. Trassinelli‡, R. Reuschl‡, U. Spillmann‡

Świętokrzyska Academy, Kielce, Poland
(*) University of Technology, Kielce, Poland
(‡) GSI, D-64291 Darmstadt, Germany

Investigation of QED effects in heavy few-electron ions allows for the most sensitive tests of quantum electrodynamics in the strong Coulomb fields region. Up to now, mainly for the sake of the experimental method and precise theoretical calculations accessibility, most of the measurements performed in this field concentrate on study of QED effects in hydrogen and lithium isoelectronic sequence. Recent progress in spectroscopy of heavy ions [1] and theoretical calculations [2] open new perspectives for studying of higher-order QED effects also in heavy He-like ions, which structure and levels energy are still not very well know.

Studying of the QED effects is possible mainly by measurement of binding and transition energies with high resolution (~ 1 eV). For such future experiment at the ESR storage ring within the SPARC collaboration a low-energy (1-10 keV) x-ray crystal spectrometer was designed. It is especially suited for the $\Delta n=0$ intra shell transition measurements, e.g. the $1s2p^3P_2 \rightarrow 1s2s^3S_1$ transition in He-like uranium located at an energy close to 4.5 keV. With this instrument also high resolution measurements of Doppler shifted Balmer x-ray transitions and the satellite structure of M-shell transitions excited in collision of mid-Z ions with heavy atoms will be possible.

The spectrometer has the Rowland circle radius equal 0.5 m and it operates in the Johann geometry [3]. It uses Zeiss spherical Si(111) crystal, with a lattice spacing of 3.136 Å, 75 mm diameter and a the radius of curvature of $2R = 1$ m. This arrangement, due to focusing properties of the spherical crystal, maximizes a number of x-rays diffracted to the detector and essentially increases the efficiency without significant influence on the resolution. Spectrometer is equipped with two linear motorized stages for x -axis and one pneumatic linear stage for y -axis movement, both with $1\mu\text{m}$ resolution and two rotation motorized stages with 0.001° angular resolution, one for the crystal and second for the detector rotation. All motors are controlled using a PC computer connected to two Newport motion controllers.

The estimated spectrometer efficiency, calculated using a dynamical theory of the crystals reflectivity, is about 10^{-6} . The energy resolution of the crystal spectrometer expected from simulations is of the order of 0.5 eV. Here, the construction details and results of the simulations will be presented.

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PROGRESS AT THE SHANGHAI EBIT

Mianhong He^{1,2}, Wei Hu^{1,2}, Weidong Chen^{1,2}, Yong Liu^{1,2}, Panlin Guo³, Di Lu^{1,2}, Yunqing Fu^{1,2},
Shimin Wu^{1,2}, Min Huang^{1,2}, Xuemei Zhang^{1,2}, **Roger Hutton**^{1,2}, Leif Liljeby⁴
and Yaming Zou^{1,2}

¹The Key Lab of Applied Ion Beam Physics, Educational Ministry, China.

²Shanghai EBIT Lab., Modern Physics Institute, Fudan University, Shanghai 200433, China.

³Shanghai Institute of Applied Physics, CAS, Shanghai 201800, China.

⁴Manne Siegbahn Laboratory, Stockholm University, Stockholm, Sweden.

To promote Highly Charged Ion (HCI) related physics research in China the Shanghai Electron Beam Ion Trap, EBIT, project was launched in January of 2002. Since then the EBIT has made rapid progress to the situation in which it stands today. The design parameters of our EBIT put it well into the class of so-called super-EBITs, i.e. electron beam energies up to 200 keV at a current of 200-250 milliamps, compressed to a current density of around 5000 A/cm² by a magnetic field up to 5 Tesla. Presently the EBIT can be operated with a minimum of effort at electron beam energies spanning from 1.5 keV to 110 keV. The electron current depends on the beam energy, however at 110 keV the current has reached 110 milliamps. The performance of the Shanghai EBIT is steadily increasing towards the design parameters.

In the first instance our EBIT will be used for spectroscopic research aiming at studies of HCI structure, quantum electrodynamics, and parity non-conservation phenomena.

To this end the EBIT will be equipped with a number of spectrometers and detectors. Currently the EBIT ion plasma can be studied using a 1-meter normal incidence McPherson 225 instrument and a flat crystal spectrometer developed at Fudan University. The EBIT plasma is also viewed by a high purity Germanium detector.

Other instruments are under development at Fudan to ensure wavelength coverage from 0.1 – 1000 nm using only three instruments. Once all the spectrometers are in place the Shanghai EBIT will be an extremely powerful tool for spectroscopy of HCI's.

In this paper we will also discuss a few of the ongoing experiments at the Shanghai EBIT.

NI XIX AS A DIAGNOSTIC FOR ASTROPHYSICAL PLASMAS

E. H. Silver¹, G.X. Chen^{1,2}, K. Kirby^{1,2}, N.S. Brickhouse¹, J.D. Gillaspay³, J. N. Tan³,
J. M. Pomeroy³ and J. M. Laming⁴

¹Harvard-Smithsonian Center for Astrophysics, ²ITAMP
60 Garden Street, Cambridge, MA 02138

³National Institute of Standards and Technology, Gaithersburg, MD 20899-8421

⁴Center for Space Science, US Naval Research Laboratory, Washington DC 20375

Ions from Li-like to Ne-like Ni exhibit prominent transitions from $n=3$ or higher levels to the $n=2$ level. Corresponding spectra in the x-ray and ultraviolet have long been observed in sources such as solar flares and corona as well as stellar coronae. Recently, Ni XIX spectral lines have been observed in active galactic nuclei and galactic black holes by Chandra. Of all the heavy elements with nuclear charge $Z>20$, Ni is the second most abundant after Fe. Next to Fe, therefore, it is potentially one of the most useful diagnostic indicators for high temperature astrophysical and laboratory plasmas. For example, knowledge of the Ni abundance in supernovae, supernova remnants, and gamma ray bursts is extremely important for understanding the detailed mechanism of heavy element formation. Its diagnostic capability, however, has been limited because the line formation mechanism is not well known and spectral modeling codes available to date have large uncertainties. Since there is a dearth of laboratory measurements of Ni L X-ray spectra, only a few accurate calculations of electron impact excitation (EIE) have been made for Ne-like Ni. We present the results of a fully relativistic close-coupling calculation of the of the Ni XIX $3C/3D$ line intensity ratio, with an uncertainty of 5%, together with independent measurements from the NIST EBIT that agree with our calculation. To the best of our knowledge there is no prior *ab initio* calculation in the literature which reliably predicts the astrophysically important $3C/3D$ line ratio in Ni XIX.

Highly Charged Ion Beam Diagnostics at the mVINIS Ion Source

M. Milivojević¹, B. Popeskov¹, J. Cvetić¹, T. Nedeljković² and I. Draganić²

¹Faculty of Electrical Engineering, 73 King Alexander Boulevard, 11000 Belgrade, Serbia and Montenegro

²Laboratory of Physics, Vinča Institute of Nuclear Sciences, P. O. Box 522, 11001 Belgrade, Serbia and Montenegro

This work contains the latest results about the diagnostics of highly charged ion beams extracted from the mVINIS Ion Source. This electron cyclotron resonance ion source enables us to produce intense highly charged ion beams and use them for experiments in the low energy area of the TESLA Accelerator Installation.

The standard diagnostics of highly charged ion beams produced with the mVINIS Ion Source, using the Faraday cups, wire scanning probes and movable slits, have been complemented with the high-resolution measurements of the two-dimensional (2D) digital beam images. We have developed a detection system based on a viewing screen and a commercial digital TV camera. It makes possible the measurements of the position, current and transverse profile of a highly charged ion beam (e.g., the Ar¹⁰⁺ or Xe²¹⁺ beam) of the energy of up to 500 keV and the current in the range of 1-300 eμA (see Fig. 1). The estimation of the corresponding measurement errors will be presented in detail. The relevance of the detection system for our future measurements of the transverse emittances of the highly charged ion beams will be discussed.

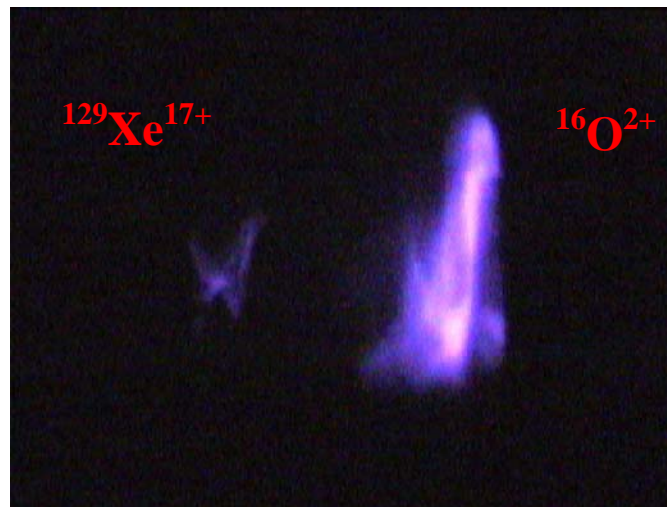


Fig. 1. A 2D image of the $^{129}\text{Xe}^{17+}$ ion beam of the energy of 255 keV and current of 12 eμA extracted from the mVINIS Ion Source, together with the image of the $^{16}\text{O}^{2+}$ beam.

Multiply Charged Ions from Solid Substances with the mVINIS Ion Source

I. Draganić, T. Nedeljković, M. Šiljegović and A. Dobrosavljević

Vinča Institute of Nuclear Sciences, P. O. Box 522, 11001 Belgrade, Serbia and Montenegro

The mVINIS Ion Source, which is an electron cyclotron resonance ion source, can produce intense highly charged ion beams. The new inlet systems have been developed successfully for standard and enriched gases as well as for solid substances. Ion beams are obtained from solid substances using the two well-known methods: (a) the metal evaporation method, in which an inlet system based on a mini-oven is used, and (b) the MIVOC (metal-ions-from-volatile-compounds) method, in which a modified gas inlet system is used. We have utilized the latter method and produced the intense and stable multiply charged ion beams of several solid substances having the high melting points (over 2000 °C) [1].

The spectra of multiply charged ion beams obtained from Zn, B, Fe, Al and Hf will be presented (see Fig. 1).

In addition, we have used, for the first time, the multiply charged ion beams from solid substances generated with the mVINIS Ion Source to modify materials at the channel for modification of materials (L3A) of the TESLA Accelerator Installation. These ions have been implanted into different materials to modify their electrical, optical, mechanical and other properties. Some of the results obtained with polymers, carbon materials and fullerenes will be shown.

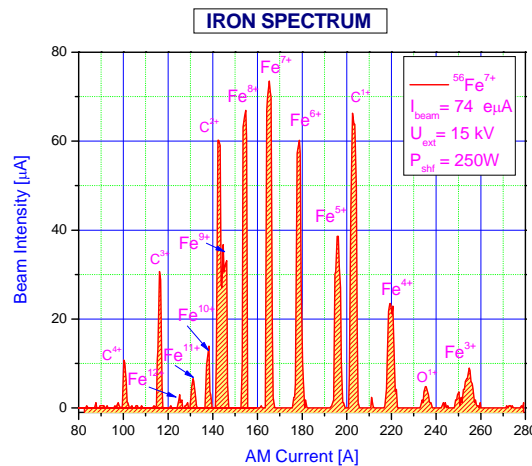


Fig. 1. A characteristic spectrum of the iron ion beams extracted from the mVINIS Ion Source, optimized for the Fe⁷⁺ beam. The beam energy and current are 105 keV and 74 eµA (10 pµA). U_{ext} is the extraction voltage and P_{shf} is the microwave power, at the frequency of 14.5 GHz.

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SPARC: ATOMIC PHYSICS WITH HIGHLY-CHARGED HEAVY IONS

R. Schuch¹ and Th. Stöhlker² for SPARC

(<http://www.gsi.de/sparc>)

¹ Atomic Physics, Fysikum, AlbaNova University Centre, S-106 91 Stockholm

²GSI-Darmstadt, Planckstr.1, 64291 Darmstadt, Germany

An overview about the envisioned program of the research collaboration *SPARC* (Stored Particle Atomic Research Collaboration, <http://www.gsi.de/sparc>) at the future GSI accelerator facility will be given. This program exploits the key features of the future international accelerator *Facility for Antiproton and Ion Research* (FAIR) that offer a range of new and challenging opportunities for atomic physics and related fields [1].

In SPARC we plan experiments in two major research areas: collision dynamics in strong electromagnetic fields and fundamental interactions between electrons and heavy nuclei up to bare uranium. In the first area we will use heavy ions up to the relativistic energies for collision studies (Fig. 1 High-Energy cave). With the extremely short, relativistic enhanced field pulses, the critical field limit (Schwinger limit) for lepton pair production can be surpassed by orders of magnitudes. The detection methods of reaction microscopes will give the momentum of all fragments when atoms or molecules are disintegrating in strong field pulses of the ions down to low energies where the atomic interactions are dominated by strong perturbations and quasi-molecular effects. The cooler ring NESR (see Fig.1.)-a "second-generation" ESR and the low-energy ring LSR will have optimized features and novel installations. The other class of experiments will focus on structure studies of selected highly-charged ion species, a field that is still largely unexplored; with determinations of properties of stable and unstable nuclei by atomic physics techniques on the one hand, and precision tests of quantum electrodynamics (QED) and fundamental interactions in extremely strong electromagnetic fields on the other hand. Different complementary approaches will be used such as relativistic Doppler boosts of optical or X-UV laser photons to the X-ray regime (see Fig.1.), or coherent radiation by channeling of relativistic ions, or electron-ion recombination, or electron and photon spectroscopy that will give hitherto unreachable accuracies. These transitions can also be used to laser-cool the relativistic heavy ions to extremely low temperature. Another important scenario for this class of experiments will be the slowing-down, trapping and cooling of particles in the ion trap facility HITRAP. There high-accuracy experiments in the realm of atomic and nuclear physics will be possible.

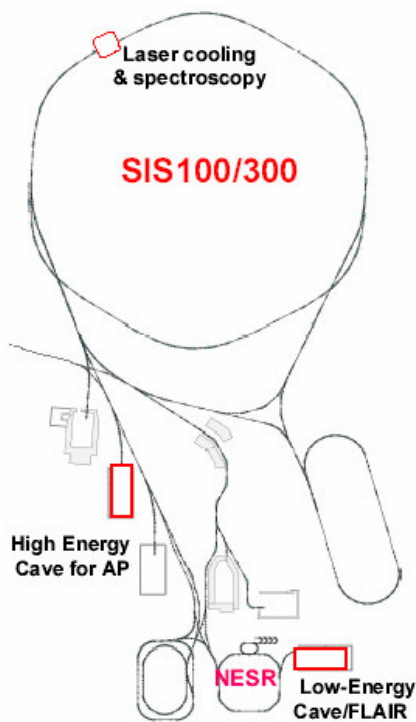


Fig.1. Layout of FAIR with future SPARC installations.

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THE LPCTrap FACILITY : A TRANSPARENT PAUL TRAP FOR THE SEARCH OF EXOTIC COUPLINGS IN THE BETA DECAY OF RADIOACTIVE ${}^6\text{He}^+$ IONS

X. Fléchar, G. Ban, D. Durand, M. Herbane, M. Labalme, E. Liénard, F. Mauger, A. Mery, O. Naviliat-Cuncic and D. Rodríguez

LPC-ENSICAEN, 6 Boulevard du Maréchal Juin, 14050 Caen CEDEX, France

Despite the remarkable success of the Standard Model, for many theoretical reasons, and especially because of the large number of undetermined parameters, the existence of new physics is expected [1]. Nuclear β decay continues to be of capital importance in the search of physics beyond the Standard Model since it is a unique and relatively easy-to-access laboratory for investigations of weak interactions. In the framework of the Standard Model, nuclear β decay is described in terms of current-current couplings either vector or axial-vector. Other current-current couplings such as scalar, pseudo-scalar or tensor are permitted by Lorentz invariance but forbidden by the V-A theory of the Standard Model. The contribution of such exotic interactions can only be decided on through high precision measurements of unambiguously predicted properties like the $\beta - \nu$ angular correlation parameter a . In the case of ${}^6\text{He}$ decay, a deviation of a from the Standard Model value $-1/3$ would imply the existence of tensor currents, mediated by new gauge bosons called *leptoquarks*.

The most precise measurement of the $\beta - \nu$ angular correlation parameter was performed 40 years ago using ${}^6\text{He}$ nuclei ($T_{1/2} = 808 \text{ ms}$) with a relative precision of 1% [2], and constrained possible tensor contributions to less than 13%. In this experiment, only the energies of the recoiling nuclei were measured. Our goal is to improve the precision on the a measurement using the low energy radioactive beam line of SPIRAL in GANIL, and a transparent Paul trap as a confinement device. With the radioactive ions stored nearly at rest in a small volume defined by the driving RF field of a transparent Paul Trap, the measurement of the β - recoil ion coincidence spectrum can be performed. First coincident events from in trap decays were observed during a commissioning run and an experiment is scheduled in July 2006.

The use of a transparent Paul trap was a technological challenge that has made of this experiment a pioneering development of Paul trap techniques applied to radioactive nuclides. The performances and characteristics of the experimental setup will be detailed at the conference.

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FIRST RESULTS OF THE LATEST DEVELOPED HIGH PERFORMANCE NEXT GENERATION 18GHZ ECRIS-SECRAL

L. T. Sun, H. W. Zhao, X. H. Guo, X. Z. Zhang, Z. M. Zhang, P. Yuan, W. L. Zhan, B. W. Wei, X. H. Cai, J. Y. Li, Y. C. Feng, W. He, Y. Cao, M. T. Song, X. X. Li, H. Wang, B. H. Ma, W. Lu, T. Jin

Institute of Modern Physics (IMP), Chinese Academy of Sciences,
Lanzhou, 730000, P. R. China

The latest developed SECRAL (Superconducting Electron Cyclotron Resonance ion source with Advanced design in Lanzhou) ion source is one the best high performance next generation ECR ion source in the world. It is designed to produce high current, high charge state heavy ion beams for HIRFL (Heavy Ion Research Facility in Lanzhou) cyclotrons. HIRFL is a cyclotron and storage ring complex which consists of two cyclotrons and a heavy ion cooling storage ring (HIRFL-CSR) [1]. HIRFL is dedicated for heavy ion nuclear physics research, hadron physics and highly charged atomic physics research. Heavy ion beams with intensity 5×10^{11} - 1×10^{13} pps for Ca, Ni, Zn, Ge, Xe, Pb are requested from HIRFL cyclotrons for radioactive ion beam physics, super-heavy nuclei research and injection to the HIRFL-CSR. To achieve the requirements, intense heavy ion beams with very high charge states, for instance, 50-100 μ A of Xe³¹⁺, U⁴¹⁺ DC beam and 200 μ A pulsed beam, are meant to be delivered by SECRAL ion source. On the other hand, another goal of SECRAL is to develop a compact superconducting ECR ion source with a completely new structure and high performances at 18-28GHz rf frequency. The nominally designed axial fields of SECRAL are 3.6T at the injection and 2.2T at the extraction, and the nominally designed radial field strength at the plasma chamber wall is 2.0T, which make SECRAL a source equipped with powerful 3D ECR plasma confinement structure. In August 2005, the first plasma was obtained at 18GHz. In the following several months of 2005 and 2006, SECRAL ion source was continuously commissioned at 18GHz. Preliminary performances of SECRAL on gaseous elements such as oxygen, argon and xenon are quite promising, such as 0.73mA Ar¹¹⁺, 73 μ A Ar¹⁶⁺, 280 μ A Xe²⁰⁺. In April 2006, metallic ion beam production was tested on SECRAL. Very preliminary but promising results were obtained. This paper will briefly describe the design of SECRAL ion source, the ion beam analyzing system and also the ion beam detection system. Typical gaseous and metallic performances of SECRAL at 18GHz will be presented.

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LOW ENERGY CHARGE EXCHANGE USING THE UPGRADED ORNL ION-ATOM MERGED-BEAMS APPARATUS

C. C. Havener, E. Galutschek, R. Rejoub, C. R. Vane

Physics Div., Oak Ridge National Laboratory, P. O. Box 2008, Oak Ridge, TN 37831-6372 USA

The Oak Ridge National Laboratory (ORNL) Ion-Atom Merged-Beams Apparatus is used to measure absolute charge exchange cross sections for multicharged ions on neutral atoms from keV/u down to meV/u [1]. The apparatus has recently been upgraded and moved to accept beams from an all-permanent magnet electron cyclotron resonance (ECR) ion source mounted on a 20-250 kV High Voltage Platform [2]. Upgrades to the merged-beams apparatus include a dual rotating-wire scanner which provides more accurate beam profiles and a shortened merge-path to increase the angular acceptance of the apparatus. The apparatus, e.g., can now accept the unusually high scattering recently found for $\text{He}^{2+} + \text{H}$ collisions [1]. A high transmission beam line from the HV Platform and the new spherical sector electrostatic mergers provide an observed factor of four decrease in the angular divergence of the ion beam. This translates into a significant improvement in the collision energy uncertainty and allows access to lower energies with higher resolution. The higher velocity ion beams permit charge exchange measurements with heavier ions and measurements with both H and D at eV/u energies and below to directly observe the isotope effect [3]. The observed intense ion beams should permit X-ray emission measurements for a variety of bare and H-like ions (e.g., C, N, O) + H. Such measurements are possible by using a high efficiency detector mounted directly above the merge path. The sounding rocket X-ray calorimeter at the University of Wisconsin [4] is being considered for these measurements. The X-ray detector is characterized by a high energy resolution (5-12 eV FWHM) along with high throughput (1000 times greater than dispersive X-ray detectors).

The new apparatus is being tested using the $\text{N}^{2+} + \text{H}$ (and D) collision system. N^{2+} ion currents of 35 uA have been tuned through the apparatus, a factor of five greater than the previous configuration [5] using a Caprice ECR ion source. Measurements will be made with both H and D to explore the isotope effect and to verify recent theory that predicts the cross section increases at low energies. These and other details will be presented at the conference.

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RADIATION FROM K-SHELL FILLING IN HIGHLY CHARGED IONS: A DRIVER FOR RESONANT COMBINATION CANCER THERAPY?

Anthony Kavanagh, John Gillaspay¹, David Hirst, Marcus Mendenhall², Nobuyuki Nakamura³, Shunsuke Ohtani³, Hirofumi Watanabe³ and Fred Currell

Queen's University Belfast, Belfast BT7 1NN, United Kingdom

¹NIST, Gaithersburg, MD 20899-8421, USA

²Vanderbilt Univ. FEL Centre, Nashville, TN 37235-1816 USA

³ Inst. for Laser Science, The Univ. of Electro-Communications, Tokyo 182-8585, Japan

Irradiation of tumours doped with cis-Platinum shows an energy-specific increase in photoelectric effect and toxicity at a photon energy just above the platinum K-edge [1]. The enhanced absorption at this energy leads to creation of a K-shell hole; the subsequent Auger cascade liberates many electrons able to cause double strand breaks. There is a class of agents known as 'vectors' which preferentially deliver heavy atoms such as Platinum or Gold to tumours. A new form of 'resonant combination therapy' is proposed whereby a monochromatic x-ray source is 'tuned' to the heavy dopant in the tumour (i.e. just above its K-edge), thereby causing cell death in the tumour with little effect on the surrounding tissue. Associated with this new possibility is the need for suitable x-ray sources:

"This preclinical finding, validated by molecular analysis, represents the most protracted survival reported with this radioresistant glioma model and demonstrates the interest in powerful monochromatic x-ray sources as new tools for cancer treatment." [1]

In this poster the possibility of using radiation produced by filling K-shell vacancies of highly charged ions is discussed and some of the key associated challenges are considered. The basic scheme involves impacting slow bare or hydrogen-like heavy ions onto a surface. The resulting Auger cascade, rapidly filling the vacant orbitals of the incoming ion, can be expected to produce one high energy (i.e. >40keV) photon per K-shell vacancy. The exact energy of these photons is dictated by the nuclear charge of the highly charged ion used. A particular ion is selected so that these photons lie just above the K-edge of the heavy atom preferentially incorporated into the tumour. The high energy photons irradiate the tumour, producing K-shell vacancies in the incorporated heavy atom. This large local dose then leads to production of many Auger electrons in the tumour as required.

Recent measurements made using ions extracted from the Tokyo EBIT [2] confirm the expectation that one high energy photon is produced per K-shell vacancy. Furthermore, the measured x-ray spectrum, combined with established radiobiological data, can be used to make preliminary modelling calculations regarding the dose distribution which would be produced from the proposed therapy scheme. From these preliminary predictions, the required fluence of the ion can be estimated. Results from these calculations will be presented.

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THEORETICAL SIMULATION OF EXTREME ULTRAVIOLET SPECTRA OF TIN IN LASER-PRODUCED PLASMAS

Y. E. Luo, M. G. Su, **C. Z. Dong**, L. Y. Xie, P. Hayden *, L. Gaynor *, G. O'Sullivan*, F. Koike **

College of Physics and Electronics Engineering, Northwest Normal University,
Lanzhou 730070, China

*School of Physics, University College Dublin, Belfield, Dublin 4, Ireland

** Physics Department, School of Medicine, Kitasato University, 1-15-1 Kitasato 228-8555, Japan

Recently, laser-produced Sn plasmas have been selected as a prospective light source for extreme ultraviolet lithography (EUVL), due to their emission in the 13.5nm region [1,2]. This wavelength of 13.5nm was chosen because Mo/Si multilayer coated mirrors have very high reflectivity of about 70% within a bandwidth(BW) of 2% around this wavelength [3]. A series of theoretical calculations and experimental observations show that tin ions from SnVIII to SnXIII contribute to the extremely intense quasi-continuum unresolved transition array (UTA) near 13.5nm, and the strongest lines are mainly due to $4p^6 4d^n - 4p^6 4d^{n-1} 4f + 4p^5 4d^{n+1}$ ($2 \leq n \leq 7$) transition arrays [1,2,4]. In order to establish the optimum ion distribution and plasma conditions essential for source optimization, it is necessary to obtain detailed information on the shapes and intensities of the EUV spectra of tin and analyze the mechanisms that determine the relative intensity of the in-band spectra.

In the present work, firstly, systematical calculations on the 4d-nf (n=4,5), 4d-np (n=5,6) and 4p-4d transitions of Sn ions from SnVII to SnXIV are performed by using the multi-configuration Dirac-Fock (MCDF) method [5,6]. It shows that charge states from SnIX to SnXI play a very important role in contributing to the 2% BW around 13.5nm, and SnX is the best emitter. Meanwhile, it is found that the configuration interaction (CI) can strongly narrow the transition array and shift the band to shorter wavelengths. Secondly, two commonly used plasma models, namely the local thermodynamic equilibrium (LTE) and the collisional radiative (CR) models, are used to obtain the ion fraction of all the ion stages in laser-produced plasmas. On the basis of the above, the simulated spectra under LTE and CR models for different electron temperatures and electron densities are obtained, *via* weighting the atomic data by the ions fraction. It shows that the simulated spectra in the LTE and CR models become similar with increasing plasma density, this is expected as increasing the density will drive the system toward LTE. Finally, in order to find the corresponding relationship between the plasma initial parameters and the laser power density, a comparison between the simulated and experimental spectra, which were observed in the 9-17nm region at UCD [7], has been made. A good agreement has been obtained.

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