Centre for Theoretical Atomic, Molecular and Optical Physics
CTAMOP
Queen's University Belfast

Ph.D. Project 2020-2023

Universal resources for quantum information processing

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State of the art and motivations

We know that classical systems can compute, and we exploit this everyday in our modern electrical devices where classical bits of information are routinely processed. A similar computation can happen at the quantum level as well: electrons, photons, and quantum systems in general can store and process quantum bits (qubits) of information. The extraordinary fact is that quantum systems can compute in an unparalleled way, much better than their classical counterpart, with a consequent revolutionary impact for our technologies [1, 2].

To make this promise a reality, it is necessary to identify controllable physical systems able to support the processing of quantum information. Most of the concepts of quantum information were originally developed for finite dimensional systems (qubits). However it was soon realised that a valid and promising alternative is offered also by infinite dimensional systems — continuous variables in jargon — the most familiar examples being position and momentum of a quantised harmonic oscillator [3, 4]. This Ph.D. programme will deal with the latter approach, exploring the possibilities offered by continuous-variable systems for quantum information processing.

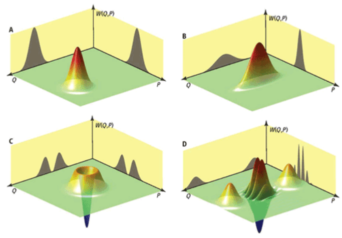

Fig. 1: The Wigner function is a way to describe how "quantum" a light pulse is. Progressing from most classical to most quantum, the Wigner function is a Gaussian function for (A) and (B), but it takes negative values for the strongly quantum states (C) and (D) [3]. These negative features are due to non-linearities and guarantees universality of quantum information processing.

Objectives & Methodology

Universal quantum information processing over continuous variables is achievable once single- and two-mode linear operations are at disposal, provided that a single non-linear operation is also available. Whereas linear operations have been both demonstrated experimentally and fully characterised theoretically, much less has been achieved for what concerns the essential non-linear operations (see Fig.1). The Ph.D. programme will comprise three parts. The focus of the first part will be the characterisation of non-linearities using the innovative theoretical approach of **quantum resource theories** [5]. The latter is a powerful mathematical framework that has been recently applied to a variety of contexts in quantum information, including continuous variables [6]. In the second part of the programme, the physical settings in which non-linearities are starting to become technologically achievable (such as **quantum**

optics and opto-mechanics) will be investigated with the aim of proposing actual implementations of the findings of the first part of the project. The third part concerns applications to continuous-variable quantum error correction of the emergent field of **quantum machine learning** [7].

Collaborations

The project will involve interactions with long-term collaborators of the supervisor, including M.G.A. Paris and his group (UniMI, Milan). Those are recognised experts in the field of quantum information science, and continuous-variable quantum information processing in particular. Collaborations with them will be of clear benefit for the student.

Required skills

The interested student will have a passionate and inquisitive approach toward mathematics and physics. A good knowledge of Quantum Theory and Mathematical Methods of Physics is required. Advanced computing skills are not required, although the student will become familiar with tools such as Mathematica, Matlab, Python.

Further information

The student will be a member of the Quantum Technology group at Queen's University Belfast and will participate to its activities (group meetings, seminars, meetings with guest scientists) and it is expected the participation at international conferences and schools.

References

[1] M.A. Nielsen, I.L. Chuang, *Quantum Computation and Quantum Information* (Cambridge (UK): Cambridge University Press; 2000).

[2] `http://youtu.be/T2DXrs0OpHU`

[3] P. Grangier, Make It Quantum and Continuous, Science **332**, 313-314 (2011).

[4] A. Ferraro, S. Olivares, M.G.A. Paris, `arXiv:quant-ph/0503237`.

[5] M. Horodecki and J. Oppenheim, Int. J. Mod. Phys. B **27**, 1345019 (2013). `https://arxiv.org/abs/1209.2162`.

[6] F. Albarelli, M.G. Genoni, M.G.A. Paris, A. Ferraro, Phys. Rev. A **98**, 052350 (2018). `https://arxiv.org/abs/1804.05763`.

[7] `https://en.wikipedia.org/wiki/Quantum_machine_learning`.