CEWQOnline Program

Monday, 28th June 3:00pm CEST

Sabrina Maniscalco, University of Helsinki (FIN)
Learning to Measure: adaptive informationally complete generalised measurements for quantum algorithms

Just like their classical counterparts, quantum algorithms require a set of inputs, provided for example as real numbers, and a list of operations to be performed on some reference initial state. Unlike classical computers, however, information is stored in a quantum processor in the form of a wavefunction, thus requiring special procedures to read out the final results. In fact, it is in general neither possible nor convenient to fully reconstruct this quantum state, so that useful insights must be extracted by performing specific observations.

Unfortunately, the number of measurements required for many popular applications is known to grow unsustainably large with the size of the system, even when only partial information is needed. This is for example the case for the so-called Variational Quantum Eigensolver, which is based on the reconstruction of average energies. Here we propose a scheme to tackle this problem.

We employ a generalised class of quantum measurements that can be iteratively adapted to minimize the number of times the target quantum state should be prepared and observed. As the algorithm proceeds, it reuses previous measurement outcomes to adjust its own settings and increase the accuracy of subsequent runs. We make the most out of every sample by combining all data produced while fine-tuning the measurement into a single, highly accurate estimate of the energy, thus decreasing the expected runtime by several orders of magnitude. Furthermore, all the measurement data contain complete information about the state: once collected, they can be reused again and again to calculate other properties of the system without additional costs.

Monday, 28th June 4:00pm CEST

Carlton Caves, *University of New Mexico (USA)*
How to perform the coherent measurement of a curved phase space by continuous isotropic measurement. Spin and the Kraus-operator geometry of SL(2,C)

I will discuss how to perform the measurement of the spin-coherent-state POVM by making weak, continous isotropic measurements of the three spin components. Starting from the standard approach to weak, continuous measurements, the analysis becomes distinctive by focusing on the Kraus operators that develop over the course of the continuous measurements, analyzing their evolution by path integrals, diffusion equations, and stochastic differential equations. The Kraus-operator-centric approach reveals the representation-independent geometry of SL(2,C) in which the Kraus operators move. The spin coherent states make up a 2-sphere phase space on the boundary of the space of Kraus operators. I will discuss how all this can be generalized to phase-space correspondences for any compact semi-simple Lie group and indicate how the realization that all of physics, classical and quantum, occurs on (possibly curved) phase spaces opens up new avenues for research.

This work was carried out with Christopher S. Jackson.

Tuesday, 29th June 3:00pm CEST

Giulia Ferrini, *Chalmers University of Technology (SWE)*
What can quantum optics say about magic?

Abstract:
TBA

Tuesday, 29th June 4:00pm CEST

Janos A. Bergou, *City University of New York (USA)*
Complementarity beyond wave-particle duality: A historic perspective

Einstein in 1905, in his explanation of the photoelectric effect, postulated that light, the quintessential wave, had to possess particle-like properties. In the course of 1923-24, de Broglie, analyzing electron scattering from metal surfaces, postulated that electrons, the quintessential particles, must possess wave-like properties. In 1928, Bohr made the first attempt to reconcile the two viewpoints and introduced the concept of complementarity (or, in a more restricted sense, wave-particle duality), and thus the now 90 years history of complementarity has started.

We begin with a brief overview of the history of quantitative complementarity relations. A particle going through an interferometer can exhibit wave or particle properties. The first quantitative duality relation was obtained by Greenberger and Yasin [1], between the strictly single-partite properties: predictability $P = |\rho_{11} - \rho_{22}|$ and visibility V, of the form $P^2 + V^2 \leq 1$. In a seminal study of the two-path interferometer, Englert introduced detectors into the interferometer arms and defined the path distinguishability, D, as the discrimination probability of the path detector states [2]. He derived a relation between this type of path information and the visibility $V = 2|\rho_{12}|$ of the interference pattern, in the form

$$D^2 + V^2 \leq 1. \quad (1)$$

In a follow-up [3], Englert and Bergou showed that D is a joint property of the system and the meter to be clearly distinguished from predictability, which is a strictly single partite property. They showed that (1) corresponds to the so-called which-way sorting (post-selection) of the measurement data. They also introduced the quantum erasure sorting, which led to the duality relation $P^2 + C^2 \leq 1$, where the coherence C is a joint property of the system and detectors. and, most importantly, conjectured that D should be related to an entanglement measure. Taking up this conjecture, the complete bipartite (particle-meter) complementarity relation, connecting complementarity, i.e., visibility of the interference pattern, V, and path predictability, P, to entanglement, was found in [4], in the form of a triality relation,

$$P^2 + C^2 + V^2 \leq 1. \quad (2)$$

Here C is the concurrence, emerging naturally as part of the completeness relation for a bipartite system. In [5], this triality relation was further generalized to multi-path (n-path) interferometers. These works completed the research on quantitative complementarity and brought the Bohr-Einstein debate to a very satisfying closure. In particular, Eq. (2), displays explicitly what is the truly quantum contribution and what can be regarded as the classical contribution. The triality relation is the culmination of research on quantitative complementarity and, in a way, closes the debate.

In all of the works discussed above, the l_2 measure of coherence was employed. Recently, however, a resource theory of quantum coherence was developed and two new coherence measures were introduced [6]. The l_1 measure is the trace distance, the entropic measure is the entropic distance of a given state to the nearest incoherent state. In the second part of the talk we present our recent results for multi-path interferometers and finite groups, employing the new measures. Using these measures, we derived entropic and l_1 based duality relations for multi-path interferometers [7, 8]. The l_1 based duality relation for n-path interferometers is

$$\left(\frac{C+D-\frac{n-2}{n-1}}{\frac{\sqrt{n}}{n-1}}\right)^2+\left(\frac{C-D}{\sqrt{\frac{n}{n-1}}}\right)^2\leq 1, \quad C, D>0,$$

where C is the l_1 measure of coherence, generalizing the visibility V . To close, we will discuss two entropic duality relations and present recent results generalizing duality relations to finite groups [9].

[1] D. M. Greenberger and A. Yasin, ”Simultaneous wave and particle knowledge in a neutron interferometer,” Phys. Lett. A 128, 391 (1988).
[2] B.-G. Englert, ”Fringe Visibility and Which-Way Information: An Inequality,” Phys. Rev. Lett. 77, 2154 (1996).
[3] B.-G. Englert and J. A. Bergou, ”Quantitative quantum erasure,” Opt. Commun. 179, 337 (2000).
[4] M. Jakob and J. A. Bergou, ”Quantitative complementarity relations in bipartite systems: Entanglement as a physical reality,” Opt. Commun. 283, 827 (2010) [also as arxiv:0302075].
[5] M. Jakob and J. A. Bergou, ”Complementarity and entanglement in bipartite qudit systems,” Phys. Rev. A 76, 052107 (2007).
[6] T. Baumgratz, M. Cramer, Tand M. B. Plenio, ”Quantifying Coherence,” Phys. Rev. Lett. 113, 140401 (2014).
[7] E. Bagan, J. A. Bergou, S. S. Cottrell, and M. Hillery, ”Relations between Coherence and Path Information,” Phys. Rev. Lett. 116, 160406 (2016).
[8] E. Bagan, J. Calsamiglia, J. A. Bergou, and M. Hillery, ”Duality Games and Operational Duality Relations,” Phys. Rev. Lett. 120, 050402 (2016).
[9] E. Bagan, J. Calsamiglia, J. A. Bergou, and M. Hillery, ”A generalized wave-particle duality relation for finite groups,” Journal of Physics A: Math. Theor. 51, 414015 (2018).

Wednesday, 30th June 10:00am CEST

Margaret Reid, *Swinburne University of Technology (AUS)*

Macroscopic realism, macroscopic Bell inequalities, retrocausality and a microscopic objective model for measurement based on the Q function

We first examine the meaning of macroscopic realism and the measurement problem. We give examples of violations of Leggett-Garg's macrorealism, and of macroscopic Bell inequalities, where all necessary measurement need only distinguish between two macroscopically distinct coherent states. More generally, we are able to map from microscopic paradoxes to macroscopic paradoxes, where the polarising beam splitters that enable unitary rotations to determine measurement settings are replaced by macroscopic unitary interactions, arising from nonlinear interactions. This leads us to consider two definitions of macroscopic realism: weak macroscopic realism (wMR) and deterministic macroscopic realism (dMR), where the system is regarded as being in one or other state either after or prior to the unitary rotation, respectively. We find failure of dMR, but consistency with wMR. We then analyse delayed choice tests with Leggett-Garg inequalities, showing violation of the dimension witness inequality for a macroscopic setup with entangled cat states. This negates non-retrocausal two-dimensional models, suggesting an apparent macroscopic retrocausality. However, a macroscopic retrocausality is avoided by considering extra dimensions that give consistency with wMR.

Finally, we explore a microscopic theory (the Objective Quantum Field Theory model) for a quantum measurement, based on microscopic Q function trajectories that propagate forward and backward in time. Interestingly, this allows a retrocausality at a microscopic level, but we show remains consistent with wMR, which helps elucidate the measurement problem. We show that wMR implies an Einstein-Podolsky-Rosen-type paradox at a microscopic level: If wMR is valid, then the system is regarded to be in one or other of two macroscopically distinct *states*; but one can show that these *states* cannot be described as quantum states. Using the OQFT model, we demonstrate trajectories consistent with wMR that realise this paradox and that also realise Bell nonlocality, as well as giving insight into the creation of entanglement.

Wednesday, 30th June 11:00am CEST

Howard M. Wiseman, *Griffith University (AUS)*

The Heisenberg limit for laser coherence

To quantify quantum optical coherence requires both the particle- and wave-natures of light. For an ideal laser, it can be thought of as the number of photons emitted into the beam with the same phase. For some 60 years, it had been believed that for a laser with an ideal output beam (described by a phase-diffusing coherent state), this number, C, was limited by the Schawlow-Townes limit to the linewidth [1]. Specifically, the S-T limit implies that the coherence C is at most of order the square of the mean photon number μ in the laser itself: $C = O(\mu^2)$. Here, assuming nothing about the laser operation except that its inputs are incoherent, and that its output is close to the ideal beam, we find the ultimate (Heisenberg) limit: $C = O(\mu^4)$ [2]. For μ large this is enormously greater. Moreover, we find a laser model that can achieve this scaling, and show that, in principle, it could be realised with familiar physical couplings [2].

[1] A. L. Schawlow and C. H. Townes, "Infrared and Optical Masers", Phys. Rev. 112, 1940-9 (1958).
[2] Travis J. Baker, Seyed N. Saadatmand, Dominic W. Berry, and Howard M. Wiseman, "The Heisenberg limit for laser coherence", Nature Physics **17**, 179–183 (2021).