Workshop on Quantum Information Processing in Condensed Matter

Physics Department, Loughborough University, UK.

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1 Invited Talks

1. **Journeys to and in Quantum Phase Space**

   Raymond Bishop (UMIST)

   Quantum information theory (QIT) relies on a triad (at least) of important concepts or principles, namely: – the quantum-classical limit (or quantum-classical interface), – quantum coherence versus decoherence (i.e., in the presence of dissipation), and – quantum entanglement. A complete description of QIT thus requires a formulation of quantum mechanics that can simultaneously and consistently incorporate these three inter-linked themes. We discuss how the concept of quantum phase space can be enlarged to provide just such a description. The usual (x-p) phase-space formulation of quantum mechanics has its practical origin in work of Wigner over 70 years ago. There he originated the idea of a quantum phase-space distribution function, and in particular introduced what has since become known as the Wigner function as an example of such a distribution function. The formalism has since been developed and utilized in many fields of physics, including statistical physics, quantum optics and electronics, collision theory, and quantum chaos. It has the attractive feature that it provides a framework in which quantal phenomena can be described using as much classical language as possible. It requires dealing only with c-number equations, rather than operators, and is hence particularly intuitive. The phase-space formalism provides important insights into the important issue of quantum-classical correspondence or non-correspondence. Here we show how, by going right back to a reformulation of classical mechanics in an extend! ed (x-p-X-P) phase space, a corresponding extended quantum phase space can be introduced with extremely appealing properties for a consistent description of QIT. The doubling of the number of degrees of freedom, which has its roots in classical mechanics, has strong overlaps with a similar feature of thermo-field dynamics, and hence with the treatment of quantum systems subject to thermal noise. We show how the extended (x-p-X-P) phase space also provides a natural means to describe simultaneously the quantum fluctuations or quantum noise (in the x-p variables) and the quantum correlations (in the X-P variables) present in a quantal system. Thus, the extended quantum phase-space framework provides a very natural vehicle to discuss all three of the above triad of concepts inherent to QIT. It also unifies the description of mixed states and provides a means to discuss together the Wigner and Weyl functions of a quantal system.

2. **Nanomaterials for Quantum Information Processing**

   Andrew Briggs (Oxford University)

   Most experts agree that it is too early to say how quantum computers will eventually be built. Developments in nanomaterials offer several possibilities for implementing solid state schemes in which individual quantum states might be controlled and manipulated (www.nanotech.org). Nanofabricated quantum dots can be made in designer configurations, with established technology for controlling interactions and for reading out results. Epitaxial quantum dots can be grown in vertical arrays in semiconductors, and ultrafast optical techniques are available for controlling and measuring their excitations. Single walled carbon nanotubes can be used for molecular self-assembly of endohedral fullerenes, which can embody quantum information in the electron spin. The challenges of individual addressing in such tiny structures could rapidly become intractable with increasing numbers of qubits, but these schemes are amenable to global addressing methods for computation.

   A. Ardavan et al. Nanoscale solid-state quantum computing. Phil. Trans. R. Soc. Lond. A 361, 1473-1485 (2003).

3. **SQUID Rings, Environments and the Quantum-Classical Interface**

   Terry Clark (University of Sussex)

   In this talk we discuss the time dependent behaviour of a quantum mechanical SQUID ring coupled to external electromagnetic (em) oscillator mode degrees of freedom, either classical or quantum mechanical in nature. We show that the behaviour of both the SQUID ring, either isolated or coupled to the external oscillator modes, is determined by the Josephson cosine term in the ring potential. In general this leads to extremely non-perturbative quantum behaviour, seen as solutions of the time dependent Schrodinger equation. As we emphasise in the talk, this has strong analogies with phenomena well known in the field of quantum optics. In particular, energy exchange regions (transition regions) exist in the energy level scheme of coupled SQUID ring-oscillator systems over very small ranges of the static (classical) external magnetic flux applied to the SQUID ring. Within these exchange regions quantum phenomena of great relevance to future quantum circuit technologies can be generated, for example quantum entanglement and quantum frequency conversion. Taken as a model system for probing the quantum-classical interface, clearly related to the measurement problem in quantum mechanics, we presented time dependent results on the interaction of a quantum SQUID ring with a classical em oscillator mode. We demonstrate this leads to intriguing non-linear behaviour (induced by the non-perturbative SQUID ring) in the classical oscillator. We take this as pointer to future investigations of the quantum-classical interface that, perhaps, will throw more light on the quantum measurement problem.

4. **Quantum entanglement and the mysterious absence of high-order correlations in quantum mechanics**

   Noah Linden (University of Bristol)

   Quantum entanglement, the correlations which can exist in multi-party quantum systems, is a key feature of quantum mechanics and is at the core of the new subjects of quantum information theory and quantum information. Despite a considerable international research effort worldwide, characterizing entanglement has proved remarkably difficult, and remains a major open problem. We know, for example, that for any number of particles, N, there are states which have irreducible N-particle correlation (i.e. correlations that cannot be ascribed to the correlations amongst groups of fewer than N particles). However we do not know how many different types of irreducible N-particle correlation there are; indeed there may be infinitely many for any N. Most recent work seems to suggest ever increasing complexity and subtlety as the number of particles grows and the number of degrees of freedom increases.

   I will give an introduction to recent progress in our understanding of quantum entanglement. I will also describe some recent work which has shed a very unexpected light on this body of work. For while, as described above, one can find special states with irreducible correlations at all orders, for almost all states of N quantum particles, the situation is much less complicated. Specifically, for generic pure quantum states of N particles the correlations amongst at most about two-thirds of the particles contain all the information in the state. Expressed differently, the lower order correlations uniquely specify the higher order ones. Thus for almost all pure quantum states, the whole is not greater than the sum of two-thirds of the parts.

5. **Electron spin qubits in quantum dots**

   Lieven Vandersypen (Delft University of Technology)

   Spin-1/2 particles are natural quantum bits (qubits), which can have very long coherence times and can be coherently controlled with remarkable accuracy. The use of electron spins in GaAs/AlGaAs quantum dots as qubits is particularly attractive, for it combines an accessible technology with a potential for scaling to large numbers of qubits. We have developed a set of ideas for the initialization, coherent manipulation, read-out and characterization of electron spins in quantum dots, and have taken the first steps towards the realization of these ideas. First, we succeeded to place on electron on each of two lateral, coupled quantum dots. Then we have directly observed the Zeeman splitting of a single electron via electrical transport through a one-electron quantum dot. Next, we have performed a pulsed transport experiment in order to measure the relaxation time for a single electron in a quantum dot, obtaining a lower bound of 50 microseconds. We are now preparin! g experiments to achieve single-shot read-out and coherent manipulation of the spin of a single electron in a quantum dot.

2 Contributed Talks

1. **Counting Electrons on Liquid Helium**

   Michael Lea (Royal Holloway, University of London)

   Localised electrons on liquid helium have been proposed as qubits. We have now detected individual trapped electrons on a pool of helium, 0.8 μm deep and 3 μm diameter, using a superconducting single-electron transistor (SET) detector. Electrons on the helium surface induce a positive charge in the SET island and a phase shift in the Coulomb blockade oscillations (CBO) in the SET source-drain current. Individual electrons can be detected and counted as they enter and leave the pool.

   The implications for electronic qubits on helium will be discussed.

3 Posters

1. **Some Superconducting Analogues of Quantum Optical Phenomena**

   Mark Everitt (University of Sussex)

   We overview some of our recent work that draws analogies between the physics of superconducting quantum interference device's (SQUID's) and those in quantum optics. We focus in particular on Schrodinger cat states and squeezing in individual ring circuits and the entanglement of SQUID rings with electromagnetic fields.

2. **Controlling quantum walks: what can we do with the coin?**

   Viv Kendon (Imperial College)

   The discrete time coined quantum walk has extra degrees of freedom in the form of the coin and coin flip operator. These can be used to control the progress of the walk in highly non-classical ways that are potentially useful for quantum algorithms.

3. **Harmonic oscillator driven by a quantun current**

   Vlad Koroli (Institute of Applied Physics of the Academy of Sci)

   The interaction between a single-mode cavity field and a string of three-level atoms of cascade type with equally spaced energy levels is investigated. The matrix elements of dipole transitions between adjacent levels may be different. Trapping conditions for the flying time in the cavity as well as the explicit state of the field are found. The results are shown to be qualitatively different from the case in which equal matrix elements are assumed for the two dipole transitions between adjacent levels. The properties of cavity fields are examined. In various limits, the state exhibits vacuum nutation as well as sub-Poissonian statistics and squeezing properties.

4. **Steering of a Bosonic Mode with a Double Quantum Dot**

   Neill Lambert (Umist)

   We investigate the transport and coherence properties of a single damped boson mode coupled to a double quantum dot, which in turn is coupled to electron reservoirs. We begin by finding an efficient numerical solution for the density matrix elements in the stationary limit, perturbative in the reservoir coupling. From this numerical data, the stationary current of the electronic system is investigated. For weak coupling, analysis of the current reveals photo-satellite peaks consistent with the 'emission' of phonons as the electron tunnels through the system.

We then look at how the properties of the single-mode boson distribution can be steered by altering the gate voltages/energy levels of the double dot. From the numerical data, quadrature amplitude variances and the Wigner function are used to illustrate how the boson mode responds to the state of the double dot. We discover the damped mode resides in a coherent state until the resonances at the double-dot transition produce a super-poissonnian distribution. A broadening of the phase space in the Wigner function at the resonant points reinforces this interpretation.

5. **Characterising a superconducting qubit via noise.**

   Jason Ralph (Liverpool University)

   We propose a method for characterising the energy level structure of a persistent current qubit by monitoring the noise in tis environment. We consider a model qubit coupled to a lossy resevoir and demonstrate that the noise in the classical bias field is a sensitive function of the applied field.

6. **Cooper Pair Boxes: Superradiance and Revival**

   Denzil Rodrigues (University of Bristol)

   We consider an array of l_b Cooper Pair Boxes, each of which is coupled to a superconducting reservoir by a capacitive tunnel junction. We discuss two effects that probe not just the quantum nature of the islands, but also of the superconducting reservoir coupled to them. These are analogues to the well-known quantum optical effects 'superradiance,' and 'revival.' In the former, the current out of the array of Cooper Pair Boxes scales as l_b^2, the square of the number of boxes, rather than linearly. In the latter, the coherent superposition properties of an initial quantum state decay through coupling to the quantum degrees of freedom of the reservoir, and then 'revive' at a later time. When this is extended to multiple systems, we discovered that 'entanglement revival' can also be observed. par In order to study the above effects, we propose a highly simplified model for these systems in which all the single-electron energy eigenvalues are set to be the same, as are the charging energies of the Cooper Pair Boxes, allowing the whole system to be represented by two large coupled quantum spins. Although this simplification is drastic, the model retains the main features necessary to capture the phenomena of interest. Given the progress in superconducting box experiments over recent years, it is possible that experiments to investigate both of these interesting quantum coherent phenomena could be performed in the forseeable future.

7. **Phase-space path-integral calculation of the Wigner function**

   John Samson (Loughborough University)

   The Wigner function $W(q,p)$ is formulated as a phase-space path integral, whereby its sign oscillations can be seen to follow from interference between the geometrical phases of the paths. The approach has similarities to the path-centroid method in the configuration-space path integral. Paths can be classified by the mid-point of their ends; short paths where the mid-point is close to (q,p) and which lie in regions of low energy (low P function of the Hamiltonian) will dominate, and the enclosed area will determine the sign of the Wigner function. As a demonstration, the method is applied to a sequence of density matrices interpolating between a Poissonian number distribution and a number state, each member of which can be represented exactly by a discretized path integral with a finite number of vertices. Saddle point evaluation of these integrals recovers (up to a constant factor) the WKB approximation to the Wigner function of a number state.

   J H Samson, J Phys A 33, 5219 (2000)

   J H Samson, J Phys A in press (and at arXiv:quant-ph/0308119)

8. **The Effects of Noise on the Concurrence of a Two-qubit System**

   Jamie Walker (University of Bristol)

   Small superconducting islands have been put forward as a possible physical realisation of a quantum computer. While superposition states corresponding to single qubit systems have been demonstrated experimentally, the same cannot be said of entangled states between two such qubits.

   We show here a simple system of two Cooper Pair Boxes (CPBs) coupled capacitively, and a sequence of voltage pulses that should lead to the charge states of the boxes being entangled. We investigate the effect of inaccuracies in the applied voltage pulses in order to ascertain how these may decrease the level of entanglement of the final state of the system.

4 List of Participants

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