Quantum information storage using spin-echo and stationary light

Ping Koy Lam
National Australian University

Abstract: In this talk, I will present the storage of optical information with optically dense Rb atoms. Our Rb system can operate at optical density larger than OD = 1000. We show that optical information can be stored predominantly as atomic coherence via the Gradient Echo Memory (GEM) technique, and also as electromagnetic field via stationary light.

Using GEM, we show how an atomic spinwave system, with no physical mirrors, can behave in a manner that is analogous to an optical resonator. We characterise the build-up of the polariton resonance and show that our Rb memory is equivalent to a free-space optical resonator with an FSR = 83kHz and a round-trip path length of 3.6km. These cavity parameters can be dynamically controlled with the spinwave coupling and gradient magnetic field.

By introducing counter-propagating control fields, we demonstrate a new type self-stabilising stationary light. We show that an initial input state can evolve into a stable optical excitation that will be trapped within the atomic ensemble. This phenomenon is experimentally verified by side imaging the atomic cloud. We show that electromagnetic excitation is indeed present and stationary. We anticipate that stationary light can be used to enhance cross-phase modulation and can potentially be useful for constructing deterministic entangling gates.

Quantum state reconstruction for confined continuous-variable systems

Alessandro Ferraro
Queens University

Abstract: It has recently been demonstrated that various types of mechanical oscillators can operate deeply in the quantum regime. This offers a novel platform for quantum information processing over continuous variables where the latter are encoded in massive and physically confined systems, rather then travelling waves as in standard optical fields. In this context, it is necessary to develop suitable tomographic strategies to measure the state of system. Addressing this issue, we introduce a scheme to reconstruct an arbitrary quantum state of a mechanical oscillator network. In particular, we assume that a single element of the network is coupled to a cavity field via a linearized optomechanical interaction, whose time dependence is controlled by a classical driving field. By designing a suitable interaction profile, we show how the statistics of an arbitrary mechanical quadrature can be encoded in the cavity field, which can then be measured. We discuss in some details the important special case of Gaussian state reconstruction – including continuous-variable cluster states, a universal resource for measurement-based quantum computation.

How not to use entangled coherent states in classical information processing

Kentaro Kato
Quantum ICT Research Institute, Tamagawa University, Tokyo, JAPAN

Abstract: With great efforts of quantum information scientists, various ideas that are tuned for information and communications technology have been proposed. Each idea is theoretically and experimentally examined to see whether or not it has potential to be technology. Actually, there are many reports on information and communications technology that utilizes quantum phenomena in order to break the performance limits that are expected from the associated classical ICT system or to develop novel technology that is never imagined in the classical framework. Through the reports, one can learn that appropriate choice and design of the resource of quantum information processing is one of important problems to realize the idea. For example, the coherent state of light is employed to realize the quantum stream cipher by Y00 protocol, because coherent states are robust against the energy loss of optical fiber channel and easy to modulate. Conversely, the use of coherent states provides the advantage of the quantum stream cipher by Y00 protocol in practical use. Thus the analysis of physical property of quantum states of light is of the importance to judge whether or not it can be the light source for information processing.

In this talk we focus on entangled coherent states. Some physical properties of an entangled coherent state are reported in the cases of a lossy channel and a thermally noisy channel. Based on the results obtained in the analysis for these cases, we discuss how not to use the entangled coherent states in classical information processing.

Detecting continuous-variable entanglement and discord by local orthogonal observables

Chengjie Zhang
Soochow University

Abstract: We shall present a family of entanglement witnesses based on continuous-variable local orthogonal observables (CVLOOs) to detect and estimate entanglement of Gaussian and non-Gaussian states, especially for bound entangled states. By choosing an optimal set of CVLOOs our entanglement witness is equivalent to the realignment criterion and can be used to detect bound entanglement of a class of *2+2* mode Gaussian states. Via our entanglement witness, lower bounds of two typical entanglement measures for arbitrary two-mode continuous-variable states are provided. Furthermore, we propose a necessary and sufficient condition for nonzero quantum discord in continuous variable systems based on CVLOOs, which is simple and easy to perform in terms of a marker Q_r.

All-optical quantum computation and communication beyond single-photon qubits

Hyunseok Jeong
Seoul National University

Abstract: Methods for all-optical quantum information processing have been developed mainly using single-photon qubits. Such an approach to quantum computation using single-photon qubits, entangled photon pairs, passive linear optics elements and photodetectors is well known as "linear optics quantum computation." A formidable limitation of this method is that quantum teleportation, which is essential for major quantum gate operations, cannot be performed in a deterministic way, or it can be done only with increasingly large resources. Recently, several approaches have been developed to overcome this obstacle. One of them is based on coherent-state qubits. This scheme enables one to perform the Bell-state measurement, an essential element for quantum teleportation, in a nearly deterministic manner while the requirement of photon-number resolving measurements is a disadvantage. Another one utilizes optical hybrid qubits, where both single-photon states and coherent states are used to construct a logical qubit basis. This method is found to outperform major previous approaches in terms of fault-tolerant limit and resource requirement. Finally, a scheme based on multi-photon qubits was suggested to perform nearly-deterministic quantum teleportation and universal gate operations without photon-number resolving detectors. In this talk, I will review and discuss these schemes that have been suggested and developed to overcome limitations of single-photon qubits, together with some related fundamental issues such as quantum macroscopicity of photonic superpositions and entanglement.

Experimental quantum simulation of the Rabi model with deep-strong coupling

N. K. Langford,[1,2] R. Sagastizabal,[1,2] M. Kounalakis,[1,2] A. Bruno,[1,2] C. Dickel,[1,2] F. Luthi,[1,2] D. J. Thoen,[2] A. Endo,[2] and L. DiCarlo[1,2]

[1]*QuTech, Delft University of Technology, Delft, The Netherlands*
[2]*Kavli Institute of Nanoscience, Delft University of Technology, Delft, The Netherlands*

Abstract: It is widely believed that quantum simulations will provide some of the first applications of a working quantum computer. These applications typically focus on "digital" simulations with networks of qubits with possible error correction. But quantum simulations may already outperform classical simulations in the "pre-threshold" age of quantum information science using a more targetted simulator, sometimes referred to as an "analog" quantum simulator. In this domain, the potential of continuous-variable elements, such as cavities, becomes particularly interesting. In this work, we perform a hybrid quantum simulation of the quantum Rabi model over a wide range of coupling strengths, from so-called "ultrastrong" well into "deep-strong" coupling, with g/omega ratios exceeding 2. Our experiment incorporates both digital and analog simulation elements and we demonstrate the creation of a hybrid qubit-coherent-state entanglement which is a key signature of deep-strong coupling.

The Rabi model is one of the simplest models of quantum light-matter interaction, describing how the light field couples to an electric dipole. Coupling strengths in physical systems are typically much less than natural component frequencies. In this regime, the Rabi model reduces to the analytically solvable and extensively studied Jaynes-Cummings interaction via a rotating-wave approximation. However, in ultrastrong and deep-strong coupling regimes, where this approximation breaks down, the Rabi model becomes surprisingly difficult to solve analytically, despite its simplicity, because the many continuous-variable basis states become highly intercoupled, even in the system ground state. Reaching this regime experimentally remains very challenging despite rapid progress towards stronger coupling in diverse cavity QED platforms. To date, only a handful of experiments have reached ultrastrong coupling, e.g., [1, 2], and only very recently have signatures of deep-strong coupling been observed [3, 4]. These experiments show only broad spectroscopic features and have not been able to study system dynamics.

Here, we study ultrastrong and deep-strong coupling dynamics in the Rabi model using a circuit QED quantum simulator based on transmon qubits [5] coupled to microwave coplanar waveguide resonators [6]. Extending a proposal by Mezzacapo et al. [7], we achieve deep-strong coupling using weakly anharmonic transmon qubits where it is not possible to observe ultrastrong coupling directly. Using a two-transmon, three-resonator device, we probe both qubit and resonator dynamics, measuring the resonator via a dispersively coupled ancilla qubit. Combining fast flux pulsing and qubit control, we realise up to 90 Trotter steps of the Rabi Hamiltonian and show that second-order Trotterisation is critical to achieving accurate simulation. Finally, we study resonator dynamics under deep-strong coupling via the Wigner function, showing that the initial vacuum state breaks into two well-resolved coherent states. Conditioning on the qubit creates nonclassical resonator cat states, demonstrating a Schroedinger "cat"-like qubit-resonator entanglement, a key feature of deep-strong coupling dynamics.

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