Quantum Memory and Teleportation
Using Collective, Continuous Quantum Variables

Summary and Overview

- It is widely believed that the best scheme for a practical, extensible quantum information network will be to use light as the "transmitter" which is used to couple "elements" of the network and that matter-based systems will be used for these quantum information storage and processing elements. Our contribution to the MURI center is to investigate, demonstrate and develop a particular strategy for the storage and processing elements. Our technique is distinguished from single atom strategies in that we use the continuous collective quantum variables of a macroscopic system, a thermal atomic vapor as our quantum system. In our work, we study the quantum entanglement of "free-space" atomic ensembles and we achieve the entanglement through their interaction with coherent light. This kind of coupling does not require a cavity in order to get good transfer efficiency between the light and the collection of atoms, and therefore provides a far simpler set-up than competing proposals that involving a single atom trapped in an optical cavity. To date we have successfully demonstrated that we can use simple laser light to fully entangle the collective spin of such a sample and have very long observed entanglement life-times, on the order of milliseconds [1,2,3].

- An additional important necessity for the toolbox of quantum informatics is to develop the ability to control and transmit an unknown quantum state from one massive particle system to another, particularly for the case of "disembodies transport" where the second particle is at some distant location [4]. This process is referred to as teleportation. Using our platform and the framework of continuous quantum variables, we will demonstrate the ability to teleport the quantum state of a massive particle system following the methodology established in our original entanglement experiments and recently proposed protocols [5].

Advantages of Collective Quantum Variables and Our Entanglement Technology

- Ensemble of entangled states allow protocols which circumvent problems of noisey channels and channel capacity [5] using methods such as dense coding.
- Entanglement in the atomic system is present in the *collective* variables, making the entangled state robust to the loss of coherence of any individual atom.
- Entangled states are realized using the interaction of the atomic ensemble – the collective spin – with readily available coherent light sources. The build-up of entanglement is selective to the forward scattered light making the system comparatively immune to the undesirable decohering effects of spontaneous emission. The apparatus for this work is simple, robust and compact.
- Taking advantage of techniques of atomic physics for preparing spin polarized samples with exceptionally long lifetimes, we can create **long lived entanglement**. The long lifetime is crucial for realistic application to quantum memory and for use in entanglement purification [6] and quantum information repeater protocols [7]. Such quantum repeaters are vital for long-haul quantum information networks as they will permit the elimination of exponential fidelity decay with only polynomial increase in communication time (for a given distance).
- The atomic vapor-coupled-to-light platform is ideally suited to cascading as needed for complex networks.

Relationship to Other MURI Activities

Quantum state control ultimately relies on strong coupling between systems. In practice this implies the ability of one particle to change the state of another with certainty during an interaction. If the interaction energy is small, this means that interaction must take place for a long time, and therefore automatically raises important technical issues of the interaction of radiation and matter and of environmental decoherence. For applications in quantum computing and communications, the further requirement that the coupling between pairs or small numbers of particles be strong is an even tighter constraint, yet appears to be necessary for quantum memories and quantum networks. To date there has been significant progress on the use of atoms as the quantum information carrier and storage elements. Techniques based on trapped ions and atoms in high-finesse cavities have made dramatic advancements, yet it is still difficult to imagine these approaches as being extensible for large-scale application in the near future. A different approach is to turn to the solid state environment of micro- and nano-electronics and to seek strong coupling in the Fermi-liquid of the rhost electronic structure. An allied approach is to work with the macroscopic quantum system of the superconductor using devices such as the SQUID as tools for the quantum information tool box. These latter two approaches are being developed within the MURI center's activites. Our team's approach based on simple atomic vapors shares many common features with these other MURI activities yet is distinct in that our atomic system uniquely adapted for convenient coupling to optical fields. Common to these alternate approaches is that we do not attempt particle-by-particle, many-particle entanglement, but instead we create entanglement of many particles through a *continuous,* collective variables.

Background on Work-to-date: As stated, our new approach to the problem of strong coupling is to use optical coupling to the collective spin of a non-degenerate (thermal) vapor. As a start of this work, we developed a theoretical framework for interpreting the quantum optical nature of the interaction of off resonant light with the collective spin of the vapor [1]. This framework allows one to identify aspects of the interaction that can be used to manipulate the quantum states of the individual spins in a collective manner so as to create and tailor the collective quantum state of the system. Inspired by these possibilities we first carried out an experiment in which we demonstrated the use of an off-resonant optical interaction to perform a QND-type measurement of the collective atomic spin state of an atomic vapor [2]. By exploiting the state preparation character of the QND interaction, we showed that the optical interaction could be used to entangle the sample of atoms [3]. In particular, in this work, we used the atom-field interaction to create of a particular non-classical state referred to as spin-squeezed.

In our system, strong coupling can be realized even with weak optical fields because the oscillator strength of many atoms can be combined into a single collective response. This means that a single photon interacts with many atoms simultaneously. Such a system would provide a test bed for the sort of teleportation schemes proposed by Duan et al. [5], using coherent light or members of our group, using squeezed light.

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