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Our work on this project has been devoted to achieving two goals: (1) Developing techniques for controlling the precise superposition state of a multilevel quantum system; (2) Utilizing this control to store and manipulate quantum information.

Quantum Control

For the past decade, with the support from this MURI center and from a previous ARO sponsored URI center we have pioneered the techniques of forming and manipulation atomic Rydberg electron wave packets. These wave packets are tailored superpositions of many of many highly excited atomic states. There may be from five or six to hundreds, or even thousands of states in the superpositions. There is probably no other multilevel quantum system in all of physics that can be controlled as well. This means a Hilbert space of for example 128 states, or equivalently seven qubits, can be controlled. We have demonstrated this control in a particularly nice form by creating an approximately transform-limited three-dimensionally localized Rydberg electron wave packet travelling in a classical orbit[1]. The wave packet forms what is essentially a "quantum pixel" of the atomic wave function. Through a series of such excitations of a single atom, each pulsed excitation placing a small fraction of the total population into the excited state, an arbitrary complex wave function can be fabricated.

In a recent invited review of this work we presented five important physical conclusions that have been demonstrated in this work[2].

- a) The phase space paths contributing to the Feynman propagator describing the revivals and fractional revivals of Rydberg wave packets are quantized, and are in general Bohr-Sommerfeld orbits generalized to allow fractional quantum numbers.
- b) Ehrenfest's theorem holds generally for spatially localized wave packets, even in the presence external fields, so long as the fields are not too strong.
- c) Most classical states are not directly accessible from the ground state, and similarly most classical states decay to other classical states rather than to a low-lying distinctly quantum state.
- d) Classical limit states provide important tools for quantum information processing. (See following section).
- e) Entanglement can persist even in classical limiting states.

The detailed proofs of these statements are contained in the referenced manuscript and are too lengthy to be given here. They do provide a framework for applying quantum control of atomic electrons to problems of interest in quantum information.

Multi-level Quantum Information

Most of classical information theory, computer science, and indeed most of quantum information theory and quantum computation is based on binary logic with the associated bits and qubits. While it is certainly true that quantum systems and indeed transistors have more than two states available, one generally utilizes only two states per memory element. The reasons for this apparent waste of resources are of two types. First, the error rate is lessened by having to distinguish only two states. Second, the information capacity of the system is only increased as the logarithm of the number of states, thus offering marginal benefit for very large data sets.

We have been pursuing multilevel logic in spite of these arguments because of the following considerations: (a) While classical transistors are cheap, quantum entanglement between qubits is an expensive and fragile resource. For quantum information storage and manipulation at the level of tens or

hundreds of qubits the logarithmic advantage of multilevel logic is quite significant. For example, thirty-two level logic would reduce the number of entangled systems by a factor of five. (b) The scope of this Center goes beyond quantum computing to the general subject of quantum information: the interface between information theory and quantum mechanics. Most quantum systems, even simple ones like single atoms or single photon wave packets are described by large Hilbert spaces. The information describing such systems is inherently multilevel, not efficiently reducible to a representation in terms of qubits. In particular, entanglement between two multilevel systems is not efficiently reducible to entanglement of a number of qubits.

These are reasons for extending quantum information theory to multi-state logic, and we have done so in a series of publications and a doctoral dissertation. [3-6]. The main results of those publications are the demonstration of a universal gate for multi-state logic along with a proposed physical realization of it; the description of a wave packet basis particularly suited for multilevel logical operations; the demonstration of a simple method by which a discrete Fourier transform can be performed using a single atom; and finally a proposal for a method by which the center-of-mass angular momentum and internal angular momentum states of a single atom can be entangled.

Future work will be directed towards laboratory realization of these multilevel logical systems using both atomic wave packets and photon wave packets.

1. "Excitation of a three-dimensionally localized atomic electron wave packet," Jake Bromage and C. R. Stroud, Jr. *Phys. Rev. Lett.* **83**, 4963 (1999).
2. "Quantum Mechanics at the Classical Limit," C. R. Stroud, Jr., D. Aronstein, and A. Muthukrishnan, presented at Physics of Quantum Electronics, Snowbird, January 2002; manuscript in preparation for submission to special issue of *J. Mod. Opt.*
3. "Entanglement of internal and external angular momenta in a single atom," A. Muthukrishnan and C. R. Stroud, Jr., submitted to *J. Opt. B: Quant. Semi. Opt.*, Special Issue
4. "Multivalued logic gates for quantum computation," A. Muthukrishnan and C.R. Stroud, Jr., *Phys. Rev. A* **62**, 052309 (2000).
5. "Quantum fast Fourier transform using multilevel atoms," A. Muthukrishnan and C.R. Stroud, Jr., to be published in *J. Mod. Opt.*
6. "Quantum information and computing in multilevel systems," Ashok Muthukrishnan, doctoral dissertation, University of Rochester, The Institute of Optics, Carlos Stroud, Thesis Advisor, December 2001.