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Spontaneous Density Grating Formation in Hot Atomic Vapor

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Recently a new gain mechanism has been observed in a nonlinear optical system: The spontaneous formation of a density grating in an atomic vapor through interaction with a strong pump field.[1] A sodium filled cell is pumped by a high intensity ($I \approx 10^4$ W/cm^2) circularly polarized laser beam detuned from resonance and is probed by a weak field degenerate in frequency with the pump and with the same polarization. The probe beam is introduced into the cell in two different geometrical configurations: Nearly parallel (angle $\approx 5°$) and nearly antiparallel (same angle, but opposite direction) to the pump. For sufficiently high pump intensity, and for appropriate values of detuning and atomic density, the probe beam displays a gain as large as 30% (pumping only a small fraction of the probe cross section) at the expense of the pump, only in the nearly counterpropagating geometry.

The existence of a threshold for the effect and the strong dependence of gain on the relative orientations of pump and probe, indicate that the already known nonlinear scattering processes (Rayleigh and Raman, for example) cannot explain the observations. Thresholds are signatures of collective phenomena, such as the crossing of a critical point. The ponderomotive force—which results from the coupling of total field and atomic polarization—tends to displace the atoms towards its "zeroes." For a large enough pump, this force is sufficiently strong to start regrouping atoms into velocity classes. As soon as the homogeneous spatial distribution is broken, there is a net scattering of the pump into the probe field, which reinforces the strength of the ponderomotive potential. The resulting periodic structure thus strengthens itself because it is automatically phase-matched to the field and because it adapts itself to the changes that it induces on field and atomic polarization. We have not found any clear dependence of the strength of the gain on the probe intensity—the weak field that we inject initiates the process, but does not control it once it has started.

The "mechanical" nature of the process is demonstrated by the role of collisions: Increasing the buffer gas pressure reduces and, eventually, suppresses the gain. Hence, we understand why no gain is observed in the nearly copropagating geometry. In this (nonresonant) interaction, momentum conservation imposes such strong constraints on the scattering process that the grating is destroyed by thermal fluctuations before it has time to develop.

This new gain mechanism may have interesting applications in atom manipulation. One can indeed force "hot" atoms (hundreds of degrees Kelvin), that cannot be handled with standard techniques, into packets that propagate as "waves" of atomic density. For example, coupled with transverse cooling of a dense atomic beam, this technique might make the formation of high density packets of moving atoms possible.

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QUANTUM OPTICS

Single-Atom Quantum Logic Gate and "Schrödinger Cat" State

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One of the fundamental tenets of quantum mechanics is the existence of superposition states, or states whose properties simultaneously possess two or more distinct values. Although quantum superpositions and entanglements seldom appear outside of the microscopic quantum world, there is growing interest in the creation of "big" superpositions and massively entangled states for use in applications such as a quantum computer.[1] We report first steps toward this goal by demonstrating a fundamental two-bit quantum logic gate and a "Schrödinger cat"-like state of motion with a single trapped ^{9}Be$^+$ ion. Both experiments allow sensitive measurements of decoherence mechanisms which will play an important role in the feasibility of quantum computation.

A quantum computer is composed of quantum bits (two-level systems), which can store superpositions of 0

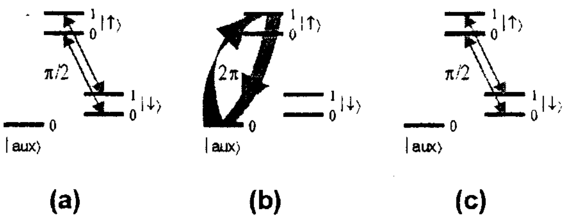

Figure 1. Energy levels of a single trapped ^{9}Be$^+$ ion, including the internal hyperfine levels $|S\rangle = |\downarrow\rangle$ and $|\uparrow\rangle$ and an auxiliary level $|aux\rangle$, each dressed by the motional quantum harmonic oscillator states $|n\rangle = |0\rangle$ and $|1\rangle$. The "controlled-NOT" quantum logic gate results in a spin flip ($|\downarrow\rangle \leftrightarrow |\uparrow\rangle$) if and only if $|n\rangle = |1\rangle$. This transformation is realized with a sequence of three pulses of laser light which couple the states indicated by red arrows: **(a)** A $\pi/2$ pulse couples states $|\downarrow\rangle|n\rangle$ to $|\uparrow\rangle|n\rangle$. **(b)** A 2π pulse couples state $|\uparrow\rangle|1\rangle$ to $|aux\rangle|0\rangle$, resulting in a sign change of any component in the $|\uparrow\rangle|1\rangle$ state. **(c)** A $-\pi/2$ pulse couples states $|\downarrow\rangle|n\rangle$ to $|\uparrow\rangle|n\rangle$ (same as step (a) with a π phase shift). If $|n\rangle = |0\rangle$, then step (b) is inactive since it only couples to the $|\uparrow\rangle|1\rangle$ state , and the two $\pi/2$ pulses cancel, leaving the initial state unaffected. If $|n\rangle = |1\rangle$, then the sign change in step (b) causes the two $\pi/2$ pulses to add, resulting in a net spin flip ($|\downarrow\rangle \leftrightarrow |\uparrow\rangle$).

and 1. When extended to many quantum bits, the parallelism of quantum superpositions allows speed to increase exponentially over classical computers in certain algorithms.[1] Cirac and Zoller[2] showed that a collection of trapped ions is well-suited for quantum computation. In their scheme, the quantum bits are represented by internal electronic levels that are "wired" together by virtue of their collective motion in the trap, and externally applied laser light entangles quantum bits and allows the construction of quantum logic gates.

We demonstrate a two-bit quantum controlled-NOT gate with a single $^9\mathrm{Be}^+$ ion confined in a rf (Paul) trap.[3] The two quantum bits are represented by a vibration bit $|n\rangle$, spanned by the lowest two quantum harmonic oscillator states $|0\rangle$ and $|1\rangle$, and a spin bit $|S\rangle$, spanned by the F=2, $m_F=2(|\downarrow\rangle)$ and F=1, $m_F=1$ ($|\uparrow\rangle$) electronic hyperfine ground states. Following laser cooling to the $|S\rangle|n\rangle = |\downarrow\rangle|0\rangle$ vibrational ground state, pairs of laser beams are applied to the ion which drive two-photon stimulated Raman transitions between spin states and can entangle the spin and vibration bits. The controlled-NOT gate is realized by applying three appropriately tuned pulses of the Raman beams. These pulses flip the spin state ($|\downarrow\rangle \leftrightarrow |\uparrow\rangle$) if and only if the vibration bit is high ($|n\rangle = |1\rangle$), as depicted in the figure. We verify the controlled-NOT truth table by studying the evolution of several coherently prepared states as they propagate through the gate. The gate speed of 20 kHz is several times the observed decoherence rate, implying a loss of coherence after approximately 10 gates. Extended computations will require suppression of this decoherence, which will likely be dominated by relaxation of the motional degree of freedom.

To further our understanding of decoherence of motional superpositions, we have created an atomic "Schrödinger cat" state by preparing the $^9\mathrm{Be}^+$ ion in a superposition of two widely separated locations.[4] Following cooling to the n=0 ground state, we create a superposition of spin states $|\uparrow\rangle$ and $|\downarrow\rangle$. The internal superposition is then transformed into a larger superposition of motional states by applying a resonant driving force with laser beams which effectively displaces the $|\uparrow\rangle$ component one direction and the $|\downarrow\rangle$ component in another direction. By interfering these two coherent state wavepackets, we are able to ascertain the maximum spatial separation ($\approx$ 84 nm, as opposed to the $\approx$ 7 nm rms size of each wavepacket) and the degree of coherence of the motional superposition.

Acknowledgments

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Polarization-entangled Photons and Quantum Dense Coding

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Entangled states of particles form the cornerstone of the newly emerging field of quantum information: they are central to tests of nonlocality, have been proposed for use in quantum cryptography schemes, and would arise automatically in the operation of quantum computers. Polarization-entangled photons are preferable because they are easier to handle. Unfortunately, until recently, no adequate source of polarization-entangled photons has been available. In Innsbruck, we have developed a down-conversion source of truly

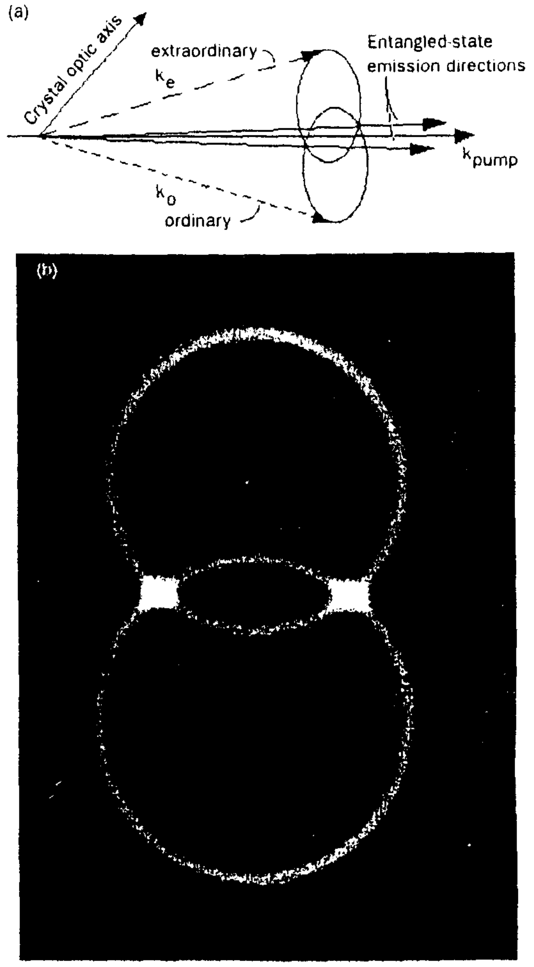

Figure 1. (a) Spontaneous down-conversion cones present with type-II phase-matching. Correlated photons lie on opposite sides of the pump beam. (b) Down-converted photons (from a BBO source), showing the overlap directions in which the polarization-entangled photons are emitted.