EXPERIMENTS AT NIST WITH TRAPPED IONS: 3-D ZERO-POINT COOLING, QUANTUM GATES, BRAGG SCATTERING, AND ATOMIC CLOCKS*

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ABSTRACT

We have recently used stimulated-Raman transitions in the resolved sideband regime to cool single ions to the $n = 0$ zero-point energy. This has allowed realizations of the Jaynes-Cummings model interaction for atomic motion and a quantum controlled-NOT gate applicable to a quantum computer. Bragg scattering has revealed long-range order in a sample of $\approx 10^5$ laser-cooled ions in a Penning trap. Progress toward the realization of a cryogenically-pumped trapped ion frequency standard is reported.

1. Coherent Quantum Manipulation of a Single Trapped Ion

1.1 Raman sideband cooling

We report cooling of a single trapped ion to the $n = 0$ state with the technique of resolved-sideband Raman cooling[1] (n is the quantum number of the (harmonic) ion motion). A $^9Be^+$ ion is held in a strong rf (Paul) ion trap[2] with vibrational frequencies $(\omega_x,\omega_y,\omega_z)/2\pi \approx$ (11.1, 18.0, 29.5) MHz. We identify two internal states, labeled $|\downarrow\rangle$ and $|\uparrow\rangle$, with two $^2S_{1/2}$ hyperfine ground states, separated by $\omega_0/2\pi = 1.250$ GHz. Transitions between these states are driven by applying two counterpropagating laser beams tuned so that their difference frequency δ is very near ω_0. Cooling proceeds as follows: The difference frequency is tuned to the first red sideband ($\delta = \omega_0 - \omega_i$, $i = x,y,z$), and the ion is exposed to the Raman beams, driving the stimulated Raman transitions $|\downarrow\rangle|n\rangle \rightarrow |\uparrow\rangle|n-1\rangle$. The beams are switched off, and resonant "recycling" beams populate the short-lived $^2P_{3/2}$ state (radiative linewidth $\gamma/2\pi \approx 19.4$ MHz), which immediately returns the ion predominantly to the $|\downarrow\rangle|n-1\rangle$ state by spontaneous emission. This process is repeated until steady-state is reached. By measuring the asymmetry in the absorption spectrum[3] after cooling, we determine $n_x = 0$ is reached 98% of the time (x cooling only), and $n_x=n_y=n_z=0$ is reached 92% of the time (3-D cooling).

1.2 Jaynes-Cummings model for trapped atom motion

When the Raman beams are tuned to the blue or red motional sidebands, the coupling between the internal levels and ion motion is formally equivalent to the Jaynes-Cummings interaction, which describes the coupling between a two-level atom and a single-mode radiation field in a cavity.[4] In the trapped ion experiments described above, relaxation can be relatively weak, so that we are able to realize the Jaynes-Cummings type interaction in the limit of weak relaxation.[5]

1.3 A quantum controlled-NOT gate

Recently Cirac and Zoller[6] have proposed a very attractive quantum computer architecture based on laser-cooled trapped ions in which the quantum bits ("qubits") are associated with internal states of the ions, and information is transferred between qubits through a shared motional degree of freedom (assumed to be the center-of-mass motion). Recently we have been able to implement a quantum controlled-NOT (or XOR) gate using a single ion;[7] this type of gate is the basic building block for any quantum computation. The two qubits are comprised of two internal (hyperfine) states and two external (quantized motional harmonic oscillator) states of the ion. Although this minimal system is not useful for computation, it illustrates the basic operations necessary for, and the problems associated with, constructing a large scale quantum computer based on the scheme of Cirac and Zoller.[6]

2. Laser-cooled ions in Penning traps

2.1 Bragg-Scattering Probe of Long-Range Order in Laser-Cooled, Atomic-Ion Wigner Crystals

We report the observation of Bragg scattering from $^9Be^+$ ions in a Penning trap[8]. A laser beam (λ = 313 nm) propagates along the axis of the trap. This laser beam cools the ions, first into a fluid state and subsequently (at even lower temperatures) into a solid. Photons scattered by the ions interfere to form Bragg-scattering peaks at particular angles determined by the spatial correlation of the ions. Since the ions scatter far fewer photons than the vacuum windows, care is required to separate this diffraction pattern from the background due to stray light scattered from the apparatus. A simple schematic diagram of the set-up is given in Fig. 1. A set of mirrors is used to deflect the laser beam away from the detector. We minimize the potentially strong background by using a set of crossed polarizers and by imaging the ion fluorescence through a small aperture before relaying the diffraction pattern to the photocathode of a photon-counting camera. Fig. 1 shows an example of the observed Bragg scattering pattern from a collection of N = 170,000 ions (density $\simeq 4\text{x}10^8$ cm^{-3}). The Bragg peaks consists of concentric rings, rather than dots as in a Laue pattern, because of the rigid rotation of the ions about the confining magnetic field. The large number of observed Bragg peaks reveals longer correlation lengths than can be found in the fluid and shell phases. The lattice structure may be determined by the positions of the Bragg peaks. With collections of greater than 2.7×10^5 ions, we obtain Bragg scattering patterns characteristic of a bcc lattice (the minimum-energy structure predicted for $N \rightarrow \infty$).

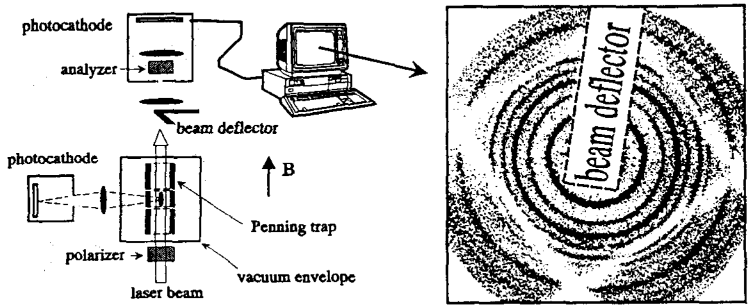

Figure 1. Apparatus and Bragg scattering image from $^9Be^+$ ions in a Penning trap.

2.2 Penning Trap Laser-Cooled Positron Source

An apparatus is being constructed for the confinement of positrons which are sympathetically cooled by simultaneously stored, laser-cooled $^9Be^+$ ions.[8,9] The idea is that positrons emitted from a moderator pass through the trap where they are captured through collisions with trapped $^9Be^+$ ions. After the positrons are cooled, they form a high-density column along the trap axis, interior to the $^9Be^+$ ion cloud. This apparatus might be useful for (1) the formation of anti-hydrogen by passing antiprotons through the positron sample[10] or (2) the study of a plasma state in which the mode dynamics must be treated quantum mechanically.

3. Frequency Standards

3.1 Cryogenically-Cooled Linear Trap for $^{199}Hg^+$ Ions

We have been working toward the realization of high-accuracy, laser-cooled trapped ion frequency standards which use either microwave or optical transitions. The group's long-range goals are to realize a microwave frequency standard based on the 40.5 GHz ground-state hyperfine transition in $^{199}Hg^+$ and an optical standard based on the $^2S_{1/2} \rightarrow {}^2D_{5/2}$ transition[11] of $^{199}Hg^+$ ions which are confined in a linear trap.[12] In order to avoid ion loss and frequency shifts caused by collisions of $^{199}Hg^+$ ions with background gas constituents, we are developing a cryogenically pumped trap apparatus.

The trap and support structure, Helmholtz coils (used for B-field adjustment), microwave horn for the 40.5 GHz radiation, HgO oven for producing Hg, ionizing filament for creating Hg^+ ions in the trap, and $\simeq$ f/1 objective lens, are contained in an evacuated chamber (approximately 13 cm diam. x 4 cm high) which forms the bottom plate of a liquid-He dewar. Windows on the perimeter of the chamber allow introduction of 194 nm laser light and extraction of scattered light which is imaged onto a position-sensitive photon detector. Above the pill box (in the liquid-He bath) is a $\simeq$ 12 MHz superconducting resonator used to provide rf trapping voltages.

When the trap is cooled to 4 K, the lifetime of $^{199}Hg^+$ ions appears to be arbitrarily long as long as weak laser cooling is applied. The hyperfine transition has been observed with linewidths of approximately 0.02 Hz.[13,14] Recent efforts have been devoted to minimizing charge build-up on the electrodes (by heating the electrodes during ion loading), reducing magnetic field inhomogeneities (caused by construction materials which are magnetic at 4 K), and the development of a "smart" computer program which will record the positions and states of each trapped ion.[14]

3.2 *Laser Development*

For the optical frequency standard based on the 282 nm $^2S_{1/2} \rightarrow {}^2D_{5/2}$ quadrupole transition in $^{199}Hg^+$, a quadrupled solid-state Nd:FAP laser at 1.126 μm is being developed. Pumping with 807 nm, we achieve single frequency efficiency of approximately 30% at 1.126 μm. This laser will be frequency doubled to 563 nm in a monolithic cavity and then doubled again to 282 nm in a single-pass configuration. The better inherent frequency stability of a diode-pumped, all solid-state laser system should give a compact, reliable source for the optical local oscillator.

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