Progress towards Sideband-Cooling Trapped Calcium Ions

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Trapped, laser-cooled ions are being investigated as one possible implementation of a quantum computer. Crystallized ions in a trap may serve as the individual quantum bits, or qubits, and laser manipulations of the motional and internal electronic states of the ions control the quantum logic operations.

At Los Alamos, we have built a linear radio-frequency quadrupole ion trap and have used it to create strings of cooled Ca^+ ions [1]. A radio frequency drive at 6 MHz with an amplitude of a few hundred volts is applied to two diagonally opposite rods to produce a radially confining, harmonic, pseudopotential. Axial confinement is provided by a static potential applied to two conical electrodes separated by 10 mm, causing an ion oscillation with a frequency proportional to the square root of the end cap voltage. Typical ion oscillation frequencies are 400 - 1000 kHz in the radial and 200 - 500 kHz in the axial direction. Calcium ions are introduced into the trap by intersecting an atomic calcium beam with an electron beam. The ions are Doppler cooled by irradiating them with a laser beam to drive the $S_{1/2}$ to $P_{1/2}$ transition with a slight detuning to the red. The ions are detected by observing the resulting 397 nm fluorescence by an intensified CCD camera and a photomultiplier tube. A second laser at 866 nm is necessary to repump the ions from the metastable $D_{3/2}$ state back to the $P_{1/2}$ state, to return them to the cycling transition.

All necessary laser radiation for Doppler cooling is generated by diode lasers. Based on the McAdam design [2] we have constructed lasers for 866 nm, 794 nm, and for 854 nm, the wavelength required to empty the $D_{5/2}$ states during sideband cooling. We use a single transfer cavity to stabilize these lasers to a commercially available frequency stabilized helium neon laser. To tune the three different lasers independently, we have installed three quartz plates inside the reference cavity so that the light from each diode laser passes through one plate, but the helium neon reference laser does not. Tilting one of the plates changes the effective optical path length of the cavity for the associated laser. The feedback to that laser shifts its wavelength to maintain a lock to the new effective cavity length. The resulting width of the lasers is less than 1 MHz and the long term drift is observed to be of the order of 1 MHz/hour.

The 397 nm light is produced in a power build-up cavity by frequency doubling. The fundamental beam at 794 nm comes from a master oscillator power amplifier (MOPA). The master oscillator output is taken from the zero-order reflection from the grating of the Spectra Diode (SDL 5421) diode laser stabilized to the external cavity described above. Approximately 20 mW of 794 nm radiation is injected into the power amplifier, a SDL-8630-E tapered amplifier with maximum output of 500 mW. The spatial mode of the output from the tapered amplifier is matched to a bow-tie configuration optical cavity that contains a 2.5 cm long lithium iodide doubling crystal. The light reflected at the cavity entrance is sent to a polarimeter, which is used to keep the doubling cavity at resonance using the Hänsch-Couillaud technique. The achieved output power at 397 nm is about 1 mW.

To minimize the temperature of the ions achievable with Doppler cooling, we need to move the ions to the minimum of the rf quadrupole potential, where they experience minimal heating from the rf trapping fields (micromotion). If the ions are not well centered (due to patch potentials on the electrodes) a Fourier analysis of the fluorescence will exhibit a strong component at the rf drive frequency. By adjusting the DC potential on a set of compensation electrodes, this component can be minimized. This method relies on the fact that the ions are periodically shifted in and out of resonance by the rf drive field and is only sensitive to the micromotion along the direction of the cooling laser. To center an ion in the orthogonal radial direction, we use the CCD camera to determine if the ion moves in the radial direction when the rf potential is changed. An ion at the minimum of the potential will not move when the potential well depth is changed, while an ion off center will move.

When the ions' thermal energy becomes less than their Coulomb energy, they undergo a phase transition into a crystallized state. Due to the normal dominance of the radial potential over the axial confinement, the ions crystallize to a linear configuration. If this anisotropy is reduced, theoretical work [3, 4] predicts a phase transition to a zig-zag configuration at a critical value of the ratio of the radial to the axial potential. Using crystals of up to 10 ions, we have experimentally confirmed the scaling behavior for this critical anisotropy value as a function of the number of ions in the crystal [5].

To reduce the ion temperature from the Doppler cooling limit to the vibrational ground state, we are planning to use sideband cooling on the narrow $S_{1/2}$ to $D_{5/2}$ transition. This calls for a laser much narrower in frequency than the typical spacing of the motional sidebands in our trap of 200 - 500kHz. We are using the Pound-Drever-Hall technique to lock our Ti::Sapphire laser to an ultra-stable, high finesse cavity suspended inside a vacuum system. The line width of the laser output from this system is less than 20 kHz, the long term drift is less than 150 kHz/hour, as determined by comparing the output of the Ti::Sapphire laser to an iodine stabilized helium neon laser. Using small crystals as well as single ions we have observed driven quantum jumps between the $S_{1/2}$ and the $D_{5/2}$ states. Applying a small magnetic field along the trap axis, we have resolved the Zeeman sublevels. Setting the appropriate angles between magnetic field, polarization, and laser wave vector we can select a subset of transitions between specific magnetic substates. Efforts to further reduce the linewidth of the observed transitions to resolve the motional side bands are under way.

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