Trapped Calcium Ions for Quantum Information Experiments

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We have been working on methods to distinguish the $m_s = \pm 1/2$ angular momentum sub-levels of the ground state of $^{40}\mathrm{Ca}^+$, for use as a qubit. This is achieved by selectively exciting transitions from one of the sub-levels, but in such a way as to avoid optical pumping between them. If excitation takes place, the population subsequently decays into a metastable 'shelf' level ($D_{5/2}$). The presence or absence of shelved population is readily detected by applying lasers on the Doppler cooling transitions (figure 1(a)) and collecting the fluorescence.

We do not make a direct transition to the shelf, because the laser power and linewidth requirements to do this are stringent. Instead we have investigated two ways to achieve the required spin-state discrimination which have much less stringent requirements. Our second method has the further interest that it directly detects the angular momentum (rather than the energy) difference of the spin states, and consequently it achieves good discrimination even at zero magnetic field.

We need the excitation to complete population transfer to the shelf before the spin state relaxes by optical pumping between the $m_s = \pm 1/2$ states. This requires that the desired excitation from $m_s = -1/2$ is on the cycling transition $S_{1/2}^{-1/2} \rightarrow P_{3/2}^{-3/2}$ excited by σ^- polarized radiation. We need to suppress $S_{1/2}^{+1/2} \rightarrow P_{3/2}^{-1/2}$ which is driven by the same 'shelving' laser. A simple method of doing this is to apply a magnetic field of 100G or more to split the two Zeeman components until they are separated by an energy several times greater than the natural linewidth of the transition. However a field this large is undesirable as it introduces other problems. Our two methods use an intense 'dressing' laser to modify the absorption profile of the shelving transition allowing operation at lower or zero fields.

In our first method, the unwanted transition is suppressed by making the shelving laser off-resonant. The off-resonant dressing laser, also σ^- polarized, creates a feature in the shelving transition spectrum which is narrower than the natural linewidth, allowing a lower magnetic field to be used.

In our second method, we use electromagnetically induced transparency (EIT) to suppress the unwanted excitation - see figure 1(b). The dressing laser is on-resonance and σ^+ polarized. The shelving laser is also resonant. Since the desired transition driven by the shelving laser is uncoupled to the dressing laser, the excitation rate on this transition is high. However for the unwanted transition, the presence of the dressing laser suppresses the excitation; the system evolves into a 'dark' state. This method does not rely on an energy splitting caused by a

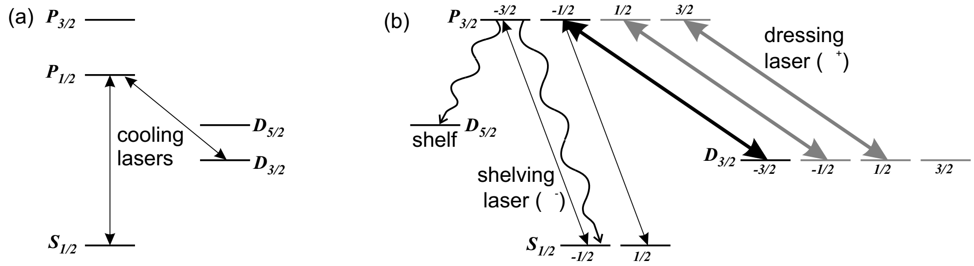

Figure 1: (a) ^{40}Ca$^+$ energy level diagram. Lasers used for Doppler cooling shown. (b) Levels and lasers used for EIT method of shelving.

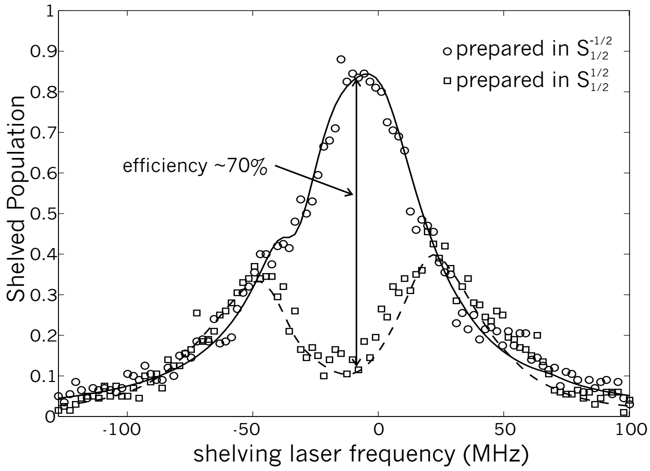

Figure 2: Experimental results showing the population shelved from each of the ground state sub-levels as a function of the shelving laser frequency. The fitted lines are calculated by solving the optical Bloch equations for the system with parameters $\mathrm{I}_{\mathrm{shelving}} = 1.4 \times 10^{-3}\mathrm{I}_{\mathrm{sat}}$, $\mathrm{I}_{\mathrm{dressing}} = 1800\mathrm{I}_{\mathrm{sat}}$ and linewidth of 1 MHz for each laser.

magnetic field, instead it relies on the angular momentum properties of the ion and the laser light. Figure 2 shows the population that is shelved as the shelving laser is scanned over the ion resonance and hence through Raman resonance with the dressing laser. The effect of forming this dark state can clearly be seen.

We have also implemented a photoionization system to load Ca$^+$ ions into our trap. This has many advantages over the electron bombardment ionization we have previously used. These include no charge build-up on trap electrodes and isotope selectivity. We have loaded pure crystals of ^{43}Ca$^+$ from an atomic beam in which its relative abundance was 0.14%. ^{43}Ca$^+$ is of interest as a qubit as it possesses hyperfine structure.