Ground state cooling of a single Yb^+ ion

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I. MOTIVATION

An ion confined in an radiofrequency trap is a good approximation to the ideal quantum harmonic oscillator, with a ladder of equally spaced motional states. A Doppler cooled ion is thermally distributed over these states, with an average vibrational quantum number $\overline{n} \approx 10$ for typical experimental parameters (a cooling transition linewidth of 20 MHz and a vibrational frequency $\omega_{vib} \approx 1$ MHz). As the ion is not in a pure state after Doppler cooling, the motional states cannot be used as qubits in quantum information processing (QIP) schemes. Even if the extra degrees of freedom provided by the motional states are not required, the populations of the different motional states each have slightly different interaction strengths with applied laser fields. This leads to dephasing, limiting the efficiency of coherent operations on the internal states of the ion [1].The residual motion also leads to second-order Doppler and DC Stark shifts of the ion's transition frequencies, limiting the performance of trapped-ion optical frequency standards. For these reasons, it is desirable to be able to prepare the ion in highly pure and well known motional state, preferably the ground state.

II. GROUND STATE COOLING

The spectrum of a narrow optical transition is modified by the ion's motion in the trap, as shown in figure 1. The upper and lower sidebands correspond to motional-state changing transitions. Each photon absorption on the lower ('red') sideband reduces the vibrational motion of the atom by one quantum. Re-emission predominantly occurs on the carrier. The ion can thus be cooled to the ground state of the trap by repeatedly driving the lower sideband of a narrow transition with a suitably stabilised laser. This is resolved-sideband cooling, and it has been demonstrated for several ions, using both direct and Raman transitions.

To perform resolved-sideband cooling, it is necessary that both the laser linewidth and transition linewidth are smaller than the vibrational frequency of the trap. It is generally necessary to use a repumper laser from the excited state of the narrow transition to increase the cooling rate, and to start with a Doppler-cooled ion. Hence the method is suitable for ions with both broad transitions for Doppler cooling and narrow (e.g. electric quadrupole or Raman) transitions for resolved-sideband cooling.

III. EIT COOLING

Recently, a ground state cooling method which requires no extra laser systems other than those required for Doppler cooling has been proposed [2, 3] and demonstrated [4]. This is achieved by exploiting Electromagnetically Induced Transparency (EIT). A three level Λ-system (figure 2(a)) tuned to exact two-photon resonance evolves into a coherent superposition of the lower two states, in which the excitation amplitudes to the upper state cancel and the system ceases to absorb the laser light. If the Rabi frequency of one of the light fields (the coupling laser) is set to be much larger than the other (the probe laser), and the probe laser is tuned across the transition, a spectrum similar to figure 3(a) is observed. Immediately adjacent to the transparency in frequency is a sharp resonance. The splitting between this resonance and the point of transparency is the light shift induced by the laser fields.

When the atomic system is confined, the spectrum is modulated into a carrier and sidebands. Usually it would not be able to resolve the trap sidebands on a broad transition, but it is possible to observe the lower sideband of the narrow EIT resonance when the lasers are blue-detuned, as in figure 3(a).

By setting the coupling and probe lasers to two-photon resonance and tuning the light shift Δ_{LS} such that $\Delta_{LS} = \omega_{vib}$, the probe laser selectively excites the red sideband with no excitation of the carrier. The system decays very rapidly once excited, predominantly without change of vibrational state, making this an intrinsically fast cooling mechanism, capable of reaching the ground state.

Resolved-sideband cooling is not possible on the ytterbium octupole transition at 467 nm due to its ex-

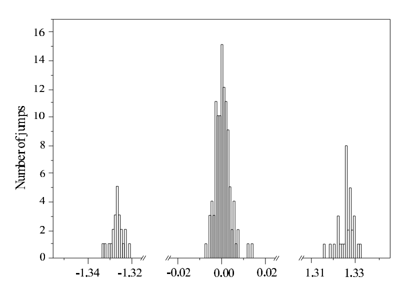

FIG. 1: Experimental data showing the first-order upper and lower vibrational sidebands of the ytterbium octupole transition at 467 nm.

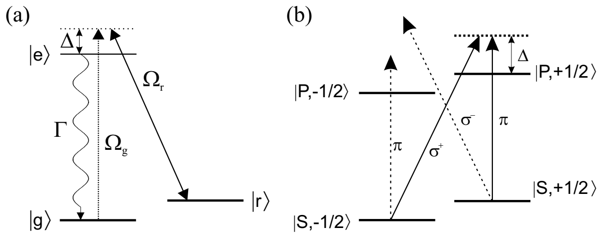

FIG. 2: (a) Level diagram for a Λ-system. The strong coupling laser is detuned from the $|r\rangle \rightarrow |e\rangle$ transition by Δ, while the probe laser is scanned across the $|g\rangle \rightarrow |e\rangle$ transition. (b) Schematic $^{172}Yb^{+}$ level scheme for EIT cooling. All transitions are at 369 nm.

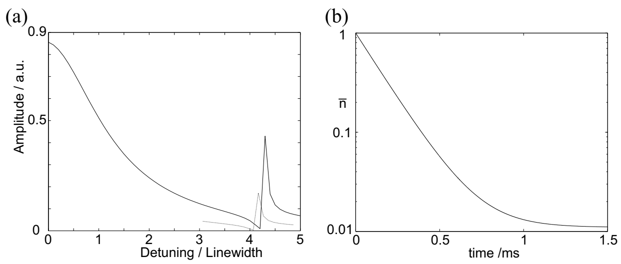

FIG. 3: (a) The solid line shows the steady-state amplitude of $|e\rangle$ as the probe laser is scanned across resonance. The coupling laser is blue-detuned 4.2Γ from resonance. The dashed line schematically shows the red sideband of the transition in the region of EIT. (b) Predicted cooling curve for EIT cooling in $^{172}Yb^{+}$, with both lasers detuned 2.5Γ above line center.

treme weakness. The quadrupole transitions at 411 nm and 435 nm are suitable, but would require narrow-bandwidth laser systems at these wavelengths. EIT cooling is particularly well suited to our circumstances, requiring only light at 369 nm.

Numerical modelling of the cooling mechanism for the $^{172}Yb^{+}$ system has been performed, showing that cooling to 99% ground-state occupation in 1.5 ms should be possible under ideal conditions (Fig 3(b)). The model has also been used to test the susceptibility of the cooling mechanism to imperfect conditions such as detuning mis-match between the two lasers and intensity drift of the coupling laser.

The level scheme for the implementation in $^{172}Yb^{+}$ is shown in figure 2(b). A magnetic field is applied to split the Zeeman components of the S- and P- states. In the existing experimental geometry, no two laser beams are orthogonal. Hence it is impossible to illuminate the ion simultaneously with both pure π- and σ-polarized light. Impure polarisations will lead to off-resonant excitation of the fourth Zeeman level by the cooling lasers and this is expected to be one of the dominant heating mechanisms.

An experiment to implement and further investigate EIT cooling in $^{172}Yb^{+}$ is under construction at NPL, and the current status of the project will be reported.

IV. TEMPERATURE MEASUREMENT

To optimise the cooling process, a good diagnostic for the temperature of the ion is required. There are two common methods of measuring the temperature of a trapped ion - coherent excitation and observation of the vibrational sidebands. Coherent excitation of the ytterbium octupole transition is not currently feasible, though observation of the vibrational sidebands of the transition is (Fig. 1).

The lower sideband, carrier and upper sideband strengths are in the ratio $\eta\overline{n} : 1 : \eta(1+\overline{n})$, where η is the Lamb-Dicke parameter and describes the ratio of the size of the ground state wavefunction to the laser wavelength. By comparing the strengths of the upper and lower sidebands, $\overline{n}$ can be measured without knowledge of η. It is also possible to measure $\overline{n}$ by comparing the carrier with the lower sideband, provided that η has been measured.

While temperature measurement of this type is possible using the octupole transition, it is slow. It is desirable to have a quicker, if less accurate, diagnostic for faster feedback. The EIT cooling process itself can provide such a diagnostic. The photon scattering rate during the cooling is proportional to the strength of the lower sideband. Comparing photon scattering rates on the red sideband (during cooling) and at the EIT resonance peak is a carrier to lower sideband temperature measurement.

Only 0.1% of the photons scattered by the ion are detected, and there is also a background count rate due to the scattering of laser light by the trap electrodes. Despite this, for the predicted experimental parameters of the $^{172}Yb^{+}$ EIT cooling experiment, it should be possible to measure ground state occupations as high as 95% for one minute of fluorescence accumulation. This is a significant improvement over the time required to obtain comparable data on the octupole transition. This method also has the advantage that by time-gating the fluorescence counting, a complete cooling curve can be obtained as part of the cooling process. It is intended to test this measurement technique on the ytterbium experiment in the near future, and current progress will be reported.

[1] D. M. Meekhof, C. Monroe, B. E. King, W. M. Itano, and D. J. Wineland. *Phys. Rev. Lett.*, 76(11):1796, 1996.
[2] G. Morigi. *Phys. Rev. A*, 67:033402, 2003.
[3] G. Morigi, J. Eschner, and C. H. Keitel. *Phys. Rev. Lett.*, 85(21):4458, 2000.
[4] C. F. Roos, D. Leibfried, A. Mundt, F. Schmidt-Kaler, J. Eschner, and R. Blatt. *Phys. Rev. Lett.*, 85(26):5547, December 2000.