Frequency comb spectroscopy on calcium ions in a linear Paul trap

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Abstract. To add to the debate on a possible variation of the fine structure constant, we perform frequency comb spectroscopy on laser cooled (calcium) ions in a linear Paul trap.

Introduction

In 1999, Webb et al. claimed a possible variation of the fine structure constant α of $\Delta\alpha/\alpha = 0.57(10) \times 10^{-5}$ over cosmological timescales [1]. These results are based on a comparison of the wavelengths of atomic resonances between absorption lines in quasar spectra observed at high redshift, and the current laboratory values. Since spectral lines have a different dependence on a change in α, such an analysis can be used to find a non-zero value for $\Delta\alpha/\alpha$ over time spans of many billion years. Currently, many ionic lines that are interesting for this analysis are only known to a precision of a few tens of MHz. By using cooled and trapped ions, the lines can be measured to much higher precision.

An interesting ion for comparison to quasar spectra is Ca^+. We have developed a setup for trapping and laser cooling calcium ions to Coulomb crystallization, to obtain a much improved transition frequency for the $4s^2S_{1/2} - 4p^2P_{1/2}$ transition.

Experimental methods

Trapping and laser cooling of calcium ions. Calcium ions are trapped and cooled in a linear Paul trap. Atomic calcium is first ionized in the trapping region using a frequency doubled Ti:Sapphire laser (422 nm) and a frequency tripled Nd:YAG laser (355 nm). A 3.3 MHz radio-frequency potential for trapping the ions is supplied by a waveform generator, resonantly enhanced by a helical resonator. A grating stabilized diode laser at 397 nm is used for laser cooling on the $4s^2S_{1/2} - 4p^2P_{1/2}$ transition, while an additional diode laser at 866 nm is used for repumping of the ions that leak into the $3d^2D_{3/2}$ state. Fluorescence from the trapping region is imaged onto a photomultiplier for signal detection.

On scanning the cooling laser over the transition, an asymmetric fluorescence signal is detected (see Figure 1): at energies below the transition the ions are cooled, above the transition ions are heated, and hence blown out of the laser focus, leading to a loss of fluorescence. The phase transition to a Coulomb crystal is clearly visible as a sudden decrease of the fluorescence on the low frequency side of the transition [2].

To make the spectroscopy independent of the coolig dynamics, the cooling laser frequency is fixed, while an additional weak probe laser is used for the spectroscopy.

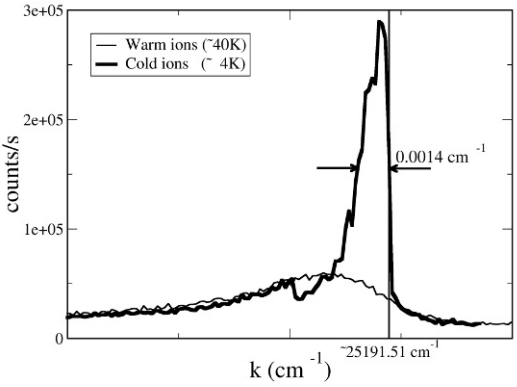

Fig. 1. Measured fluorescence by scanning the 397 nm laser cooling diode laser over the Ca^+ $4s^2S_{1/2} - 4p^2P_{1/2}$ transition

Spectroscopy on calcium ions The $4s^2S_{1/2} - 4p^2P_{1/2}$ transition is measured on the laser cooled calcium ions using a frequency-doubled diode laser. This beam necessarily has a low intensity ($\sim 1\mu$W) to prevent heating of the ion cloud by the spectroscopy laser. To keep the ions cold during the measurement, the ions are alternately cooled and probed. The probe laser is calibrated by referencing it to a frequency comb laser. An interference beat note is generated between the spectroscopy laser and the comb laser modes, by overlapping the near-infrared fundamental output of the spectroscopy laser with the output of the frequency comb laser.

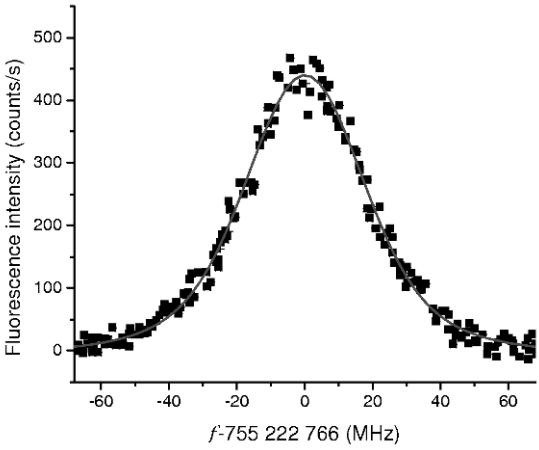

Fig. 2. An example of the measured fluorescence spectrum for the $4s^2S_{1/2} - 4p^2P_{1/2}$ transition in Ca^+ and the corresponding Voigt fit

Results and Discussion

An example of a calibrated scan over the $4s^2S_{1/2} - 4p^2P_{1/2}$ transition in Ca^+, after subtraction of the background and correction for ion loss during the scan, is shown in figure 2. The cooling is insufficient to reach the natural linewidth of the transition, hence a Voigt profile is fitted. The width of the Lorentzian part is fixed to the natural linewidth of the transition (22.4 MHz), while the width of the Gaussian part is fitted. The Gaussian FWHM of the line varies from scan to scan (depending on the cooling conditions), typically between 28 and 43 MHz, corresponding to an average temperature of $T \approx 0.2$K.

Effects that can introduce systematic and statistical errors have been investigated (see table 1). The $^{40}Ca^+$ $4s^2S_{1/2} - 4p^2P_{1/2}$ transition follows from the statistical average of the measurements, corrected for the measured shifts, which in total adds up to 755 222 766.2(1.7) MHz. The present result is consistent with the most accurate previously reported value of $f = 755\,222\,740(60)$ MHz [3].

Table 1. Measured systematic shifts and uncertainty budget (1σ). All values in MHz.

Effect	Shift(MHz)	1σ Uncertainty (MHz)
Zeeman	0.0	0.0
AC Stark repumper	-0.4	0.6
AC Stark spectroscopy laser	-0.4	0.8
RF Stark effect	0.0	1.2
Comb calibration	0.0	0.2
Statistics		0.6
Total	-0.8	1.7

Conclusions

We have measured the $4s^2S_{1/2} - 4p^2P_{1/2}$ transition in $^{40}Ca^+$ to be at 755 222 766.2(1.7) MHz, in a laser cooled ion crystal. The level of accuracy, at $\Delta\lambda/\lambda = 2 \times 10^{-9}$, is such that for comparison with state-of-the-art astrophysical data, the laboratory value can be considered exact. The technique employed in this work will be used for spectroscopy on other transitions and ions in the near future. We intend to measure the $4s^2S_{1/2} - 4p^2P_{3/2}$ and the $4s^2S_{1/2} - 5p^2S_{1/2}$ transitions in Ca^+, the latter using direct two-photon frequency comb spectroscopy [4,5]

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