High precision spectroscopy using quantum logic

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QUEST Institute for Experimental Quantum Metrology, PTB, Braunschweig, Germany, (October 2014)

Application Note

Introduction

The fine-structure constant α determines the strength of the electro-magnetic interaction and therefore the energetic positions of electronic levels in atoms and molecules. A change in α results in shifts of the atomic levels, which can be calculated with high accuracy. To investigate the temporal variation of α one can compare spectral absorption lines from distant intergalactic clouds imprinted on light emitted by quasars [1] with laboratory spectra. However, accurate laboratory data on isotopic shifts for some critical transitions of metal ions are not available.

Experiment

Laser spectroscopy provides the most precise measurements of the internal states of atoms and molecules. To perform high precision spectroscopy experiments, the system under investigation needs to be well isolated from environmental perturbations to avoid shifts in the transition frequency. Trapped ions are particularly well suited for such high precision experiments. The ions are stored in an almost field-free environment and can be laser-cooled to eliminate Doppler shifts. These features have enabled record accuracies in optical clocks.

Laser spectroscopy is performed in two different flavors. For long-lived excited states, efficient state detection is performed using the electron shelving technique where quantum noise limited SNR can be achieved. But this technique requires a special level structure to perform the state preparation, cooling, and state detection. The invention of quantum logic spectroscopy (QLS) [2] removed the need to detect the signal on the spectroscopically investigated ion (spectroscopy ion) directly by transferring the internal state information through the motional state to the co-trapped logic ion where the signal is observed via the electron-shelving technique. However, this original implementation of QLS requires long-lived spectroscopy states to implement the transfer sequence. For transitions with a short-lived excited state, spectroscopy of trapped ions is typically implemented through detection of scattered photons in laser induced fluorescence (LIF) or detection of absorbed photons in laser absorption spectroscopy (LAS). Neither of the two techniques reaches the fundamental quantum projection noise limit as in the electron shelving technique [3] due to low light collection efficiency in LIF and small atom-light coupling in LAS. We combine the advantages of these techniques and demonstrate an extension of quantum logic spectroscopy which provides a highly sensitive, quantum projection noise-limited signal for the spectroscopy of broad transitions. It is based on detection of momentum kicks from a few absorbed photons near the resonance of a single spectroscopy ion through a co-trapped logic ion.

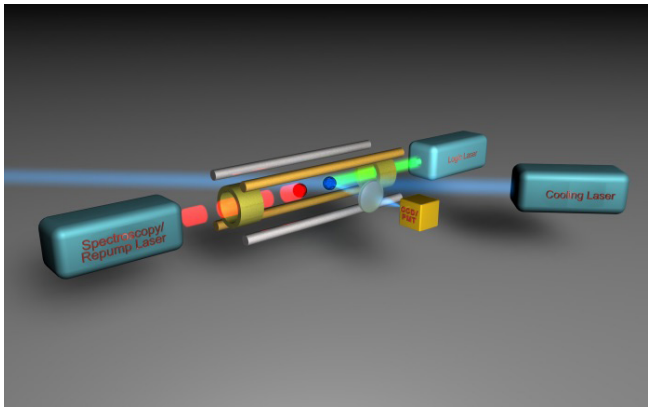

Figure 1. Schematic representation of the experimental set-up for photon-recoil spectroscopy. An auxiliary ion (the logic ion, blue) is trapped in an ion trap together with the ion to be investigated (the spectroscopy ion, red). The logic ion is cooled down to the ground state of motion by means of laser cooling (cooling laser and logic laser). Due to the strong coupling of the two ions, the spectroscopy ion is cooled along with the logic ion. The spectroscopy ion is then excited by means of laser pulses (spectroscopy/repump laser) which puts both ions into motion. This motion represents the spectroscopy signal and can be read out via the logic ion (logic, cooling laser) which becomes dark in the event of motion.

In our implementation of photon recoil spectroscopy we use $^{25}Mg^+$ as the logic ion and $^{40}Ca^+$ as the spectroscopy ion. The investigated $^2S_{1/2} \leftrightarrow {}^2P_{1/2}$ transition in $^{40}Ca^+$ has a natural linewidth of 21.6 MHz. Different systematic effects for the absolute frequency measurement are examined. These include the Zeeman shift, AC Stark shifts from the spectroscopy laser, the envelope shift of the short spectroscopy pulses and a lineshape error caused by the Doppler effect. The first three are determined experimentally whereas the latter is modelled with an analytical and numerical model. In total, we determine the absolute frequency averaged over five individual measurement days to be 755,222,765,896 kHz with an uncertainty of 88 kHz. This result stays in agreement with the previous measurement but the accuracy is improved by more than an order of magnitude [4].

The Andor EMCCD camera iXon DV885 LC-VP is used to determine the presence of an ion in the trap. Therefore the Doppler cooling laser is tuned close to the resonance frequency of the desired ion species. The presence of an additional dark ion (e.g. Ca^+) in the Paul trap is detected by a position shift of the fluorescing ion.

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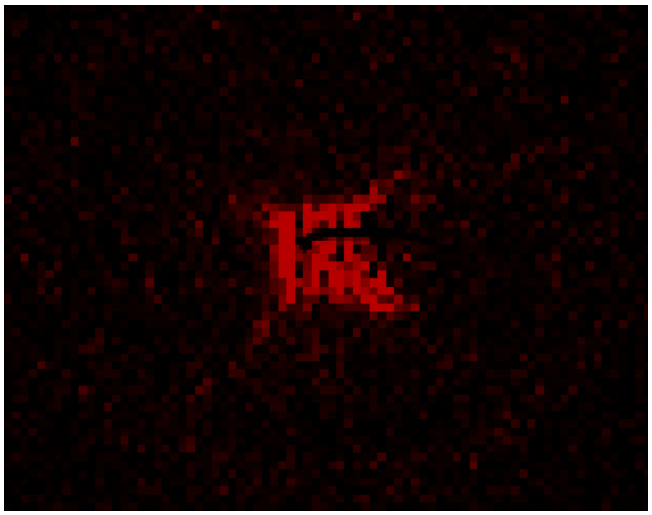

Figure 2: Fluorescence of a single Mg^+ ion recorded with iXon DV8585 LC-VP EMCCD camera

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References:

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[3] Itano et al., PRA 47, 3554 (1993)
[4] Wan et al., Nature Comm. 5, 3096 (2014)