Precision Measurements of Isotope Shifts in the 729 nm E2 Transition of $^{40-42,44,48}Ca^{+}$

by
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Abstract

We have conducted a precision measurement of the isotope shifts on the electric-quadrupole (E2) transition at 729 nm of the even isotopes of Ca^+. The isotope shift is measured to be 2,771,872,458.7 (8.4) Hz for $^{40-42}Ca^+$, 5,340,887,395.3 (6.2) Hz for $^{40-44}Ca^+$, and 9,990,381,868.6 (4.9) Hz for $^{40-48}Ca^+$. To achieve this parts-per-billion precision, we used frequency sidebands derived from a narrow linewidth laser to simultaneously interrogate this narrow E2 transition in co-trapped ions of two isotopes. This measurement provides valuable spectroscopic data for comparison to atomic and nuclear theory and offers a path towards direct probes of physics beyond the Standard Model at the level of sensitivity suggested by theorists. Precise measurement of the $^{40-44}Ca^+$ isotope shift will also enable future work in the Doret laboratory exploring nanoscale heat transport in mixed-species ion chains.

Executive Summary

This thesis presents several Hz scale precision measurements of the isotope shifts on the 729 nm $4^2S_{1/2} \rightarrow 3^2D_{5/2}$ electric dipole forbidden (E2) transition in $^{40-42,44,48}Ca^+$ using co-trapped ions in surface-electrode ion traps. These precise isotope shift measurements are of interest to theorists studying atomic structure and can be used to make a King plot, a tool which can provide a nearly-theory-independent probe of physics beyond the Standard Model. The best previous isotope shift measurements achieved a precision of 0.1 MHz, so our measurements provide 5 orders of magnitude more sensitivity [1] and attain the sensitivity suggested by theorists as an effective probe of new physics [2]. The longer term goal of our lab is to study heat transfer in dual species ion chains of $^{40}Ca^+$ and $^{44}Ca^+$. The vibrational state of the ions will be extracted by measuring the spectrum of the 729 nm E2 transition for both isotopes, which requires precise knowledge of the E2 transition isotope shift and thus motivates our measurement. Due to the identical level structure of the even isotopes of singly ionized calcium, our system was easily adapted to make the further measurements required to make a King Plot.

The first step of the thesis project was to finish relocating the lab to a new building and complete the characterization of our ion trap system. Upon completion of the trap characterization, we implemented software to automate the isotope shift measurement and fine-tuned the hardware of the lab. Notably, we constructed a nearly-athermal scanning Fabry Perót cavity that is used in conjunction with a stabilized HeNe laser to frequency stabilize our external cavity diode lasers (ECDLs), thus allowing us to reliably hit the transition frequencies of the ions. The stability of the magnetic field used to define a quantization axis is currently the limiting factor of our coherence times for driving the E2 transition. We therefore constructed a low-noise current supply for the magnetic coils to improve the magnetic field stability in the trap environment. Finally, we added a precise, Rb stabilized frequency clock to which our synthesizers are referenced. Having implemented these new components, data collection began for the isotope shift measurements.

An isotope shift is the frequency shift of an atomic transition that results from the difference in mass, volume, and shape of the nuclei of different isotopes of the same element. The difference in neutron number causes only a small perturbation of the electronic energy levels, so isotope shifts are very small compared to the full transition. Therefore, they are conveniently measured by splitting the frequency of a single laser to coarsely span the isotope shift and

then simultaneously scan the two frequency components such that each is resonant with the transition in one isotope. We span the isotope shift with an electro-optic modulator (EOM), which creates radio frequency sidebands, and use an acousto-optic modulator (AOM), which adds a tunable, radio frequency shift, to scan the laser frequencies. Figure 1 presents an overview of our system as used for the isotope shift measurement.

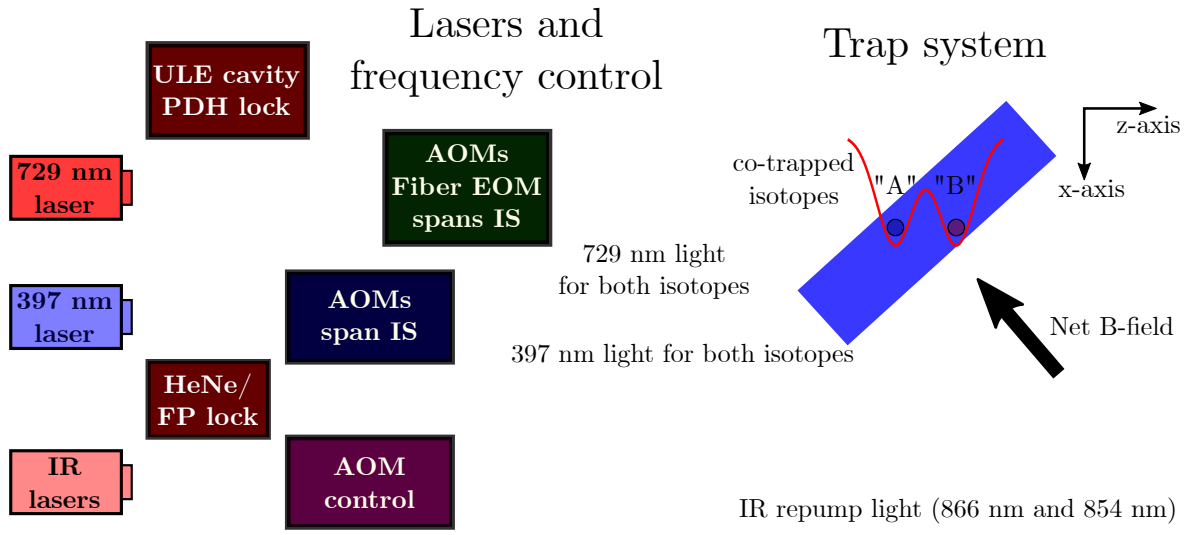

Figure 1: This schematic gives a high level overview of the laser system used for the isotope shift measurement.

As traditional absorption/emission spectroscopy is not viable on a transition that scatters only one photon per second on resonance, we use a technique called electron shelving spectroscopy. This technique makes use of the metastable character of the $3^2D_{5/2}$ state. If successfully driven to this state by a 729 nm laser π-pulse, the electron will be "shelved" there for $\sim$1 s. Subsequent illumination of the ion with the 397 nm fluorescence laser (also used for Doppler cooling) will then scatter no fluorescence photons as there is no available electron to be driven. If, on the other hand, the electron remains in the ground state, fluorescence photons are recorded. Many individual electron electron shelving trials are combined to record a frequency spectrum of the E2 transitions for both isotopes simultaneously.

The simultaneous measurement and close spatial proximity of the two isotopes makes our measurement insensitive to many potential systematic effects. Nevertheless, we went through many iterations of data collection and careful characterization of potential systematic shifts to thoroughly validate our final values. The dominant systematic effect on our measurement was due to a differential Zeeman shift caused by spatial variation of the magnetic field between the two ion locations. We negated this effect by interleaving measurements on transitions to Zeeman sublevels with equal and opposite differential splitting and then averaging to get a zero-magnetic field value for the isotope shift. The next most significant effects are Stark shifts due to leaked light during the 729 nm π-pulse and due to excess micromotion. We experimentally put a bound on the Stark shifts caused by leaked light from the 397 nm

and 854 nm lasers and added additional attenuation to reduce these shifts to negligible values. Lastly, we collected data with each isotope alternately in the left ("A") or right ("B") potential well (Figure 1). This averaging over the two spatial configurations also makes our measurement insensitive to several further potential systematic effects such as the 2^{nd}-order Zeeman effect or electric quadrupole shifts.

After carefully bounding any possible residual systematic shifts, we can use the data represented in Figure 2 (where one can see the slight difference in mean values for the "AB" vs "BA" geometry) to quote values for the three isotope shifts with parts-per-billion precision: $\nu_{IS}(40-42) = 2,771,872,458.7 \pm 8.4$ Hz, $\Delta\nu_{IS}(40-44) = 5,340,887,395.3 \pm 6.2$ Hz, and $\Delta\nu_{IS}(40-48) = 9,990,381,868.6 \pm 4.9$ Hz. We achieve Hz level precision on these GHz-scale isotope shifts due to the narrow linewidth of the E2 transition, the narrow linewidth and stability of our 729 nm laser, the precise nature of electron shelving spectroscopy, and the insensitivity of our measurement method to most systematic effects. We plan to build on this measurement in the immediate future by repeating the isotope shift measurements for these three isotope pairs on the 732 nm $4^2S_{1/2} \rightarrow 3^2D_{\mathbf{3}/2}$ transition and thus provide a full set of data for a King plot.

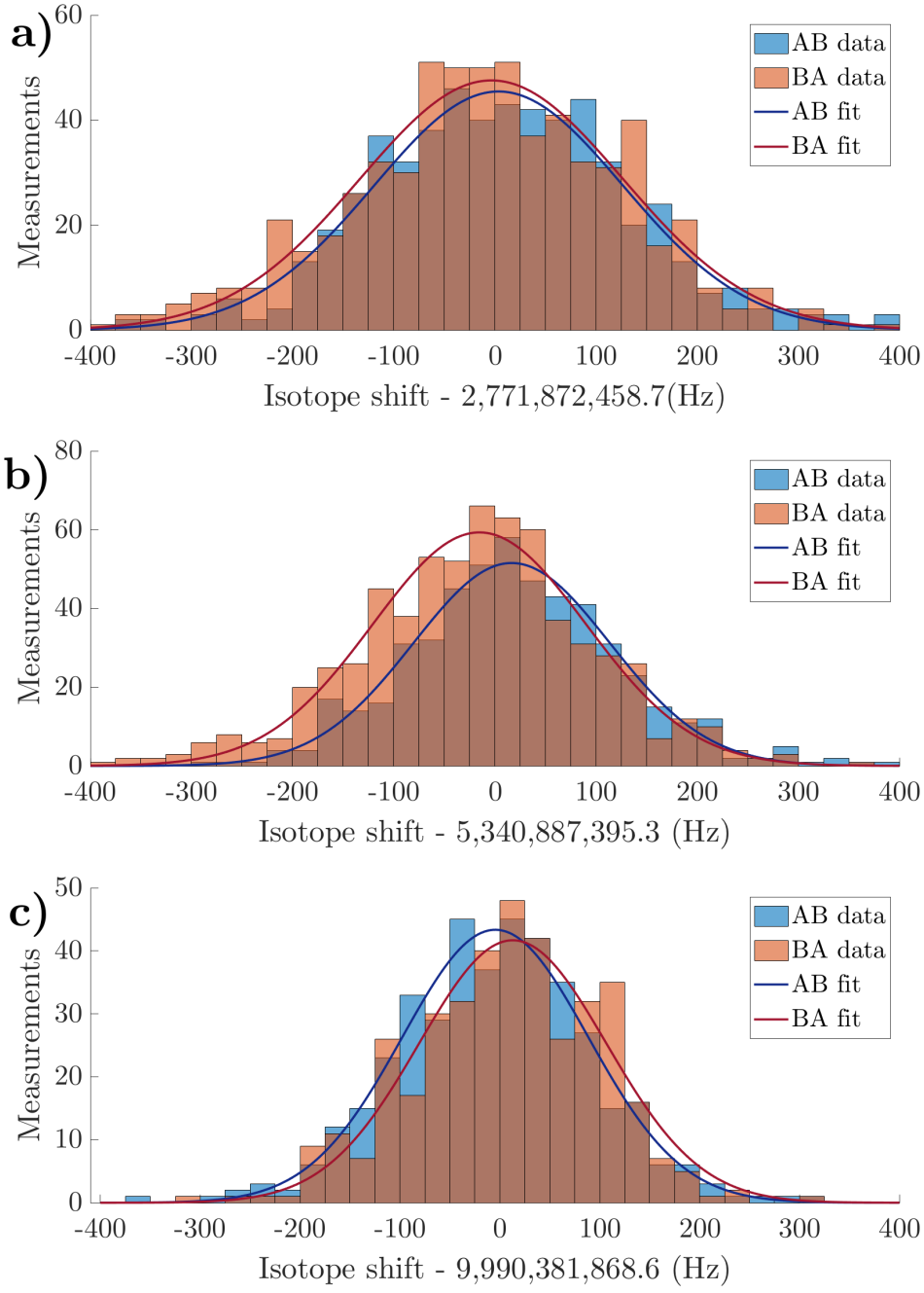

Figure 2: **a)** is the $^{40-42}Ca^{+}$ data, **b)** is the $^{40-44}Ca^{+}$ data, and **c)** is the $^{40-48}Ca^{+}$ data. Each figure shows two overlaid histograms of isotope shift measurements with the quoted center frequency subtracted for readability. The blue histogram represents the data collected in the spatial configuration with $^{40}Ca^{+}$ in potential well "A" and $^{4x}Ca^{+}$ in "B," while ochre represents the opposite "BA" configuration and the region of overlap is brown. Fits to Gaussian profiles are also included as guides to the eye.