Isotope Shift Measurement in Ytterbium Ions to Search for a Dark Matter Boson

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***Summary*—We determined the absolute frequencies of the $^2S_{1/2} \rightarrow {}^2D_{5/2}$ and the $^2S_{1/2} \rightarrow {}^2F_{7/2}$ transitions in all five stable even isotopes of Yb^+ to the ~10 Hz level. The extracted isotope shifts have a 10- to 100-fold reduced uncertainty compared with previous studies and reproduce the observed nonlinearity in the King plot of Yb [1]. With the improved accuracy, we hope to shed light onto the source of the observed nonlinearities and investigate a possible coupling from a dark matter boson beyond the previously explored parameter range.**

Keywords*—isotope shift measurement; ytterbium; King plot; dark matter boson

I. Introduction

The existence of dark matter is supported by astronomical observations, but its origin and composition are unknown. A dark matter boson coupling neutrons and electrons in an atom would induce an energy shift between different isotopes. A search for such a coupling can be conducted with accurate isotope shift (IS) measurements and a so-called King plot analysis [2-4]. In this analysis, first order atomic and nuclear effects that dominate the isotope shift follow a linear scaling and can be separated from shifts caused by other effects, such as the fourth-moment shift, quadratic field shift, and a potential energy shift from a dark matter boson coupling the neutrons and electrons. Here we present our latest results on IS measurements and the corresponding King plot analysis for ytterbium ions. We reached a 10- to 100-fold higher accuracy and with the results reproduced the nonlinearity observed in Ref. [1]. The nonlinearity decomposition plot [1] combines all possible transitions of ytterbium and can analyze one additional source of nonlinearity compared to the King plot. By adding our measurements to this plot, we hope to investigate a coupling from a new boson beyond the previously explored parameter range.

II. Methods/Results

We directly compared the frequencies of two narrow transitions in Yb^+, the $^2S_{1/2} \rightarrow {}^2D_{5/2}$ electric quadrupole (E2) transition near 411nm and the $^2S_{1/2} \rightarrow {}^2F_{7/2}$ electric octupole (E3) transition near 467nm, to the frequency of the $^2S_{1/2}(F=0) \rightarrow {}^2F_{7/2}(F=3)$ clock transition in $^{171}Yb^+$, which is realized by an independent optical clock [5]. Using the recommended value of its standard frequency [6], we were able to determine the absolute frequencies of the two transitions in all five even isotopes (168, 170, 172, 174, 176) and obtain ISs with an uncertainty of about 10 Hz. With these, we generated a King plot, see Fig. 1, where the y-axis is the IS frequency of the E3 transition (ν_γ) scaled to the IS frequency of the E2 transition (ν_α) and the x-axis is the inverse-mass difference μ scaled to ν_α. From the insets, we see that the largest uncertainty involved in the fit is the uncertainty of the absolute mass of the 168 isotope.

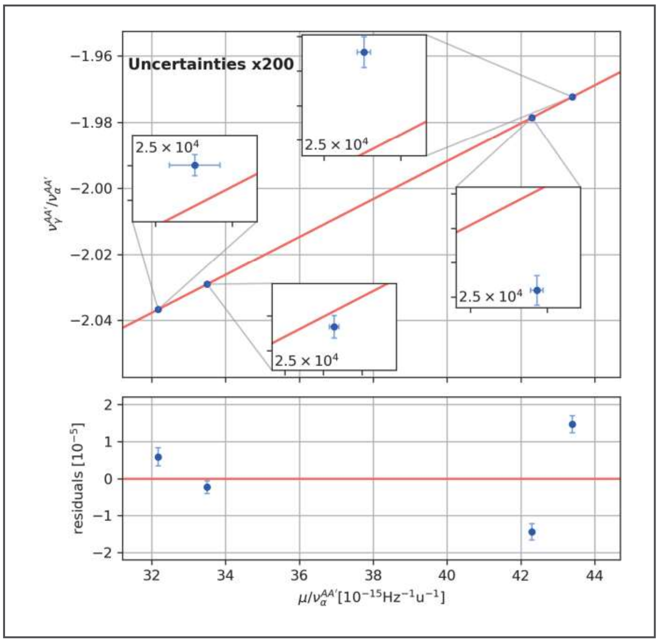

Fig. 1. Linear King plot with the $^2S_{1/2} \rightarrow {}^2D_{5/2}$ electric quadrupole (E2) transition near 411nm and the $^2S_{1/2} \rightarrow {}^2F_{7/2}$ electric octupole (E3) transition near 467 nm. Both the IS of the E3 transition ν_γ and the inverse-mass difference μ are scaled to the IS of the E2 transition ν_α. A and A' are neighboring isotopes, $A' = A + 2$ ($A = 168, 170, 172, 174$). The uncertainties for both axis are multiplied by a factor of 200 for visibility. Upper plot: the linear King plot of ν_γ/ν_α with respect to ν_α/μ. The insets features a magnification of 2.5×10^4.

The red solid line is a line fit to the measurements. Lower plot: the residuals of the fit in units of 10^{-5}.

III. DISCUSSION/INTERPRETATION

We find a nonlinearity at 2018σ of significance in the King plot analysis. By adding our measurements to the nonlinearity decomposition plot analysis of all measured ISs of ytterbium [1,7-9], we find strong evidence at the 87.6σ level for two sources of nonlinearity, which may come from more unconsidered Standard model effects or a potential energy shift from the coupling of a dark matter boson.

IV. CONCLUSIONS

We have measured ISs in Yb^+ ions at the level of $\sim$10 Hz to search for a new boson coupling electrons to neutrons. We find strong evidence for at least two separate sources of nonlinearity. From our results, we hope to better investigate a possible dark matter boson in a yet unexplored parameter range.

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