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Testing high-Z QED with SuperEBIT: An estimate of the U^{91+} $1s$ two-loop Lamb shift based on a measurement of the $2s_{1/2}$–$2p_{1/2}$ transition in U^{89+}

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Abstract

Starting from the results of a recent measurement of the $2s_{1/2}$–$2p_{1/2}$ transition in U^{89+} has been made on the SuperEBIT electron beam ion trap, which provided a determination of the $2s$ two-loop QED contribution, we estimate 1.27 ± 0.45 eV for the two-loop contribution to the $1s$ level in U^{91+}. This estimate could be improved by a factor of two or more, if the uncertainties associated with the three-photon exchange in the theoretical calculations were eliminated in the future.

Key words: QED, Two-loop Lamb shift, Heavy ion physics, electron beam ion trap
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1 Introduction

Measurements of transitions involving electrons in the $1s$, $2s$, $3s$, or $4s$ level provide a window to quantum electrodynamical (QED) effects in high-Z ions. The reason is that s electrons sample the fields inside the nucleus, where these are strongest and thus produce the largest QED contributions. The nuclei of the heaviest ions have the strongest fields, and measurements of the QED contributions have concentrated on the ions of uranium, which is the heaviest naturally occuring element. The QED contributions to the $1s$, $2s$, $3s$, and $4s$ levels of uranium ions are about 267 eV, 48 eV, 7 eV, and 3 eV, respectively, and measurements to determine these contributions have been made over the

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past two decades, when sources of highly charged ions became first available. In Fig. 1 we have plotted the accuracy with which QED has been tested by these measurements. Here the figure of merit used to assess how well the QED contributions are determined is given by the accuracy of the measurement divided by the size of the total QED contributions.

In the past three years, we have made a concerted effort to revisit QED measurements in uranium. We utilized the EBIT-I and SuperEBIT electron beam ions traps at Livermore to determine the QED contributions to several of the $4s$, $3s$, and $2s$ configurations in highly charged uranium ions. As shown in Fig. 1, an order of magnitude improvement over previous measurements was achieved in the case of the $4s_{1/2}$-$4p_{3/2}$ transition in copperlike U^{63+} [1]. A similar improvement was achieved in the case of the $3s_{1/2}$-$3p_{3/2}$ transition in sodiumlike U^{81+} and magnesiumlike U^{80+} [2].

Recently, we have measured the energy of the $2s_{1/2}$-$2p_{1/2}$ transition in lithiumlike U^{89+} [3]. Our measurement was carried out on the Livermore SuperEBIT electron beam ion trap, and an accuracy of 0.015 eV was achieved. This represents almost an order of magnitude improvement over the accuracy achieved by Schweppe et al. [4], who achieved an accuracy of 0.10 eV, and recently by Brandau et al. [5], who achieved an accuracy of 0.099 eV.

In the following, we show that the recent measurement of the $2s_{1/2}$-$2p_{1/2}$ transition in lithiumlike U^{89+} [3] can be used to test $1s$ QED calculations of U^{91+} at the 0.45 eV level. As theory improves, that same measurement may ultimately provide a test at the 0.22 eV level or better.

2 Results

In our recent U^{89+} measurement of lithiumlike U^{89+} [3] we determined a wavelength of 44.1783 ± 0.0024 Å for the $2s_{1/2}$-$2p_{1/2}$ transition. This corresponds to 280.645 ± 0.015 eV. Our value is in good agreement with the value of 280.59 ± 0.10 eV obtained with Doppler-tuned spectroscopy by Schweppe et al. on the Bevalac heavy-ion accelerator [4]. However, it is significantly larger than the value of 280.516 ± 0.099 eV inferred by Brandau et al. from measurements of $1s^2 2p_{1/2} n\ell$ dielectronic resonance peaks on the ESR heavy-ion storage ring, which had to be combined with calculated values of the binding energy of the $n\ell$ Rydberg electron [5].

As shown in Fig. 1, the recent measurement represents the highest precision achieved in high-field bound-state QED. The roughly 42 eV QED contribution to the $2s_{1/2} - 2p_{1/2}$ transition in lithiumlike U^{89+} was measured with an accuracy of 3.6×10^{-4} or 360 ppm. In fact, this accuracy is an order of magnitude better than necessary to determine the two-loop QED contributions.

Rigorous calculations of all two-electron contributions of order α^2 have recently been completed. These include the two-photon exchange term as well as estimates of higher-order photon exchange contributions [6–8]. Adding these to the one-photon exchange, first order QED, nuclear recoil, nuclear polarization, and one-electron finite size contributions yields a value for the $2s_{1/2}$-$2p_{1/2}$ transition energy that misses only the two-loop Lamb shift contribution. For example, Yerokhin et al. [6] calculated a value of 280.44 ± 0.10 eV for the two-loop Lamb shift contribution-free transition energy. The theoretical error limits are dominated by the uncertainty in the nuclear finite size correction to the binding energies and by the estimate of the three photon exchange contribution. Subtracting their value from our measured transition energy yields the two-loop Lamb shift of 0.205 eV. Using the theoretical values of Andreev at al. (280.47 ± 0.07 eV) [7] and Sapirstein et al. (280.43 ± 0.07 eV) [8] provides additional values of the two-loop Lamb shift. The average value for the two-loop Lamb shift affecting the $2s_{1/2}$-$2p_{1/2}$ transition is 0.20 ± 0.07 eV [3].

We can use the derived Lamb shift for the U^{89+} transition to estimate the two-loop Lamb shift of the $1s$ electron in hydrogenlike U^{91+}. To do so, we seek guidance given by one-loop QED calculations.

First, we note that the one-loop Lamb shift of the $2s$ level is about 15% larger than that of the $2s_{1/2}$-$2p_{1/2}$ transition, because the $2p_{1/2}$ level is also affected by QED effects. For example, Blundell calculated 41.43 eV for the total QED contribution to the $2s_{1/2}$-$2p_{1/2}$ transition, while calculating 47.58 eV for the QED affecting the $2s_{1/2}$ electron in U^{89+} [9]. Second, we note that the U^{91+} $1s$ first-order Lamb shift is about 264.7 eV, as given by Johnson and Soff [10]. This is about 5.6 times larger than that of the U^{89+} $2s$ level. Finally, we estimate the U^{91+} $1s$ two-loop Lamb shift by multiplying the 0.20 ± 0.07 eV [3] inferred two-loop Lamb shift from our recent measurement by -6.39. The result is -1.27 ± 0.45 eV. The error limits associated with this result reflect the scaled uncertainty of the theoretical values needed to derive the $2s_{1/2}$-$2p_{1/2}$ two-loop Lamb shift in U^{89+}.

One may think that additional uncertainties with the above result arise from the fact that different authors provide different values for the one-loop QED terms. For example, Indelicato and Desclaux give 41.10 eV [11], Blundell in a subsequent paper gives 41.68 eV [12], and Chen et al. give 41.69 eV [13] for the QED contribution to the $2s_{1/2}$-$2p_{1/2}$ transition. The differences are in part due to how the QED contributions (including screening) were obtained in these older results and whether some higher-order terms such as radiative corrections were included. Similarly, the one-loop QED contribution to the $1s$ level in U^{91+} was recently given by Gumberidze to be 266.5 eV [14]. Here the difference with the value of Johnson and Soff seems to arise because of the use of a different value for the size of the uranium nucleus. Using these different values affects our multiplier used to scale the U^{89+} $2s_{1/2}$-$2p_{1/2}$ two-loop QED term to the U^{91+} $1s$ two-loop QED term by less than 1 %. The associated uncertainty (about 0.01 eV) is thus negligible compared to the 0.45 eV uncertainty associated with our estimate, which, as we would like to point out, already includes the uncertainties associated with the finite nuclear size of uranium and the higher-order photon exchange terms.

3 Conclusions

Our estimate of the $1s$ two-loop Lamb shift value is the first such number based on experimental data. We can compare our estimate to the $1s$ two-loop Lamb shift value of -1.26 ± 0.33 eV calculated recently by Yerokhin et al. [15]. The agreement is excellent, albeit the agreement is perhaps fortuitous.

Despite the fact that the uncertainty of the $1s$ two-loop Lamb shift estimated from our measurement of U^{89+} by invoking theory is much larger than that associated with our measurement on its own, it is still much better than the uncertainties associated with a direct measurements of U^{91+}. This is illustrated in Fig. 2. The uncertainty associated with our estimate is an order of magnitude better than the best direct measurement of U^{91+} to date reported by Gumberidze et al. [14].

Theoretical values for the U^{89+} $2s_{1/2}$-$2p_{1/2}$ transition will undoubtedly improve in the near future, especially when the three-photon exchange contributions can be calculated with higher accuracy. In principle, the theoretical calculations are then only limited by the uncertainty of the nuclear size of uranium. It limits the uncertainty of the calculations at the 0.02 eV level [16]. This unceratinty is comparable to the uncertainty in our recent measurement [3]. After such progress in theory and combining theoretical and experimental uncertainties linearly (quadratically), our recent measurement would test the $1s$ QED contribution at the 0.22 eV (0.16 eV) level. This is twenty (thirty) times better than the best direct measurement [14] of the QED contribution to the $1s$ level in U^{91+} to date.

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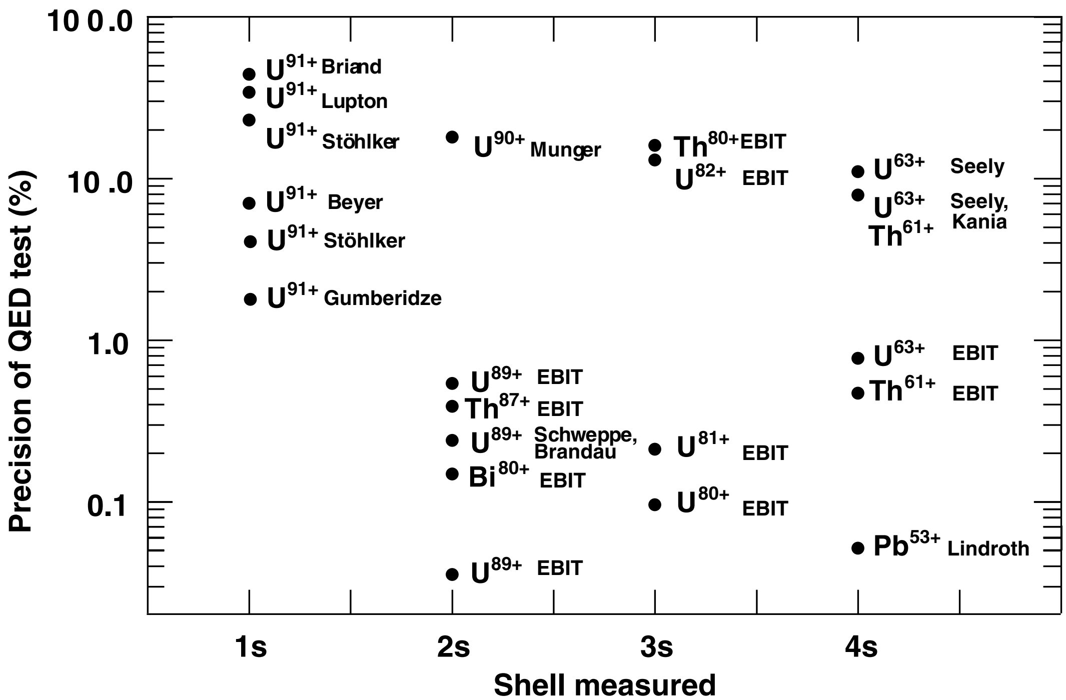

Fig. 1. Overview of the precision achieved in measurements of the QED terms in high-Z ions by studying transitions in different shells. The y-axis shows the experimental accuracy of given measurement divided by the size of the total QED contributions. The 1s measurements are from [14,17–21]. The 2s measurements are from [3–5,22–25]. The 3s measurements are from [2,26,27] The 4s measurements are from [1,28–30]. Points labeled "EBIT" are from the Livermore electron beam ion trap facility.

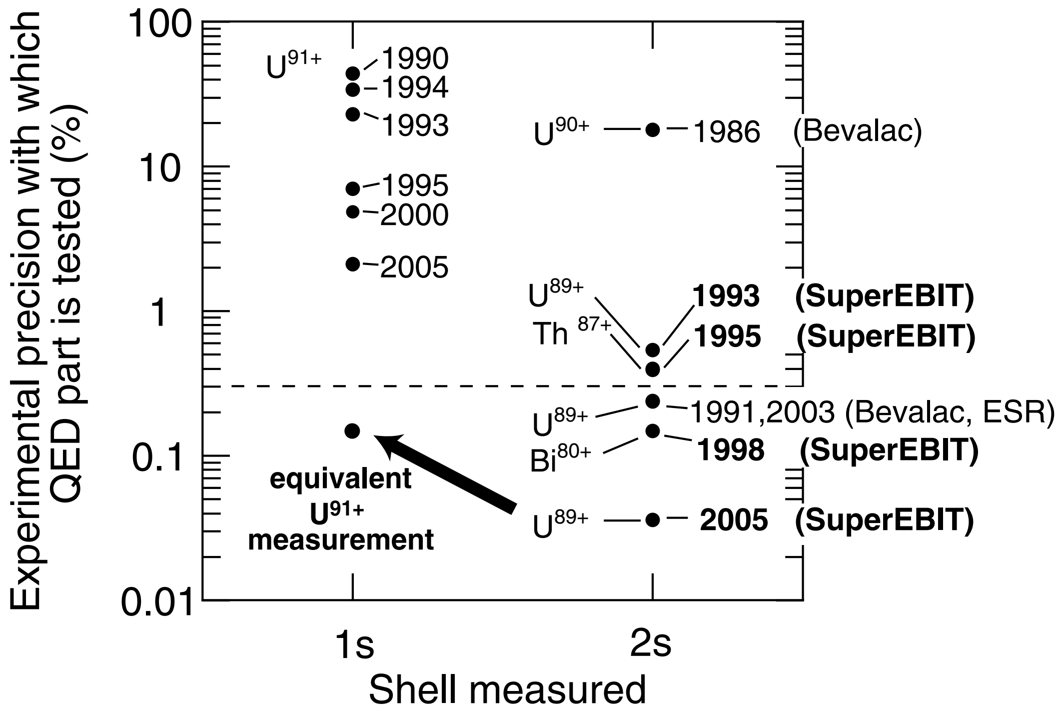

Fig. 2. Equivalent precision obtained by estimating the 1s QED from the 2s QED measurement of U^{89+} relative to direct measurements of the the 1s and 2s QED contributions. The dashed line indicates the measurement accuracy equal to the two-loop Lamb shift in uranium. References for the data points shown with year of publication are given in Fig. 1.