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Measurement of the $3s_{1/2} - 3p_{3/2}$ resonance line of sodiumlike Eu^{52+}

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Abstract

We have measured the $3s_{1/2} - 3p_{3/2}$ transition in sodiumlike Eu^{52+} situated at 41.232 Å with an uncertainty of 73 ppm. Our measurement extends previous high-precision measurements into a range of atomic number ($56 < Z < 78$) for which results of comparable accuracy are not yet available. We also present measurements of $3s_{1/2} - 3p_{3/2}$ and $3p_{1/2} - 3d_{3/2}$ transitions in the neighboring magnesiumlike, aluminumlike, and siliconlike europium ions.

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I. INTRODUCTION

Ions with one valence electron outside an otherwise fully closed shell appear as being hydrogenic and thus can be treated with similar high accuracy as hydrogenlike ions, provided the influence of the additional electrons in the core is taken into account. Having a completely filled K and L shell and a $3s$ valence electron, sodiumlike ions fall within this group and the associated $3s - 3p$ transitions have, therefore, provided a fertile ground for testing advanced approaches, such as the many-body perturbation theory, and the treatment of quantum electrodynamical effects [1–3].

The first measurements of the $3s_{1/2} - 3p_{3/2}$ transitions of sodiumlike ions of elements with atomic number Z above 50 were presented by Seely *et al.* from laser-produced plasmas [4]. These measurements extended to elements with Z as high as 64 and established a trend as a function of Z that agreed with calculations at the time that were based on the multi-configuration Dirac-Fock approach (MCDF). This trend, however, was put in doubt when a measurement of sodiumlike Pt^{67+} ($Z = 78$) was performed on the Livermore electron beam ion trap facility with an uncertainty of 440 cm^{-1} [5]. A subsequent measurement of sodiumlike U^{81+} ($Z = 92$) with an uncertainty of 161 cm^{-1}, also performed on one of the Livermore electron beam ion traps, continued the new trend established by the platinum datum and carried it to the element with the highest naturally occurring atomic number [6]. Both measurements favored the theoretical approach utilized by Blundell [7] the results of which differed significantly from those computed with the MCDF approach. Additional measurements of sodiumlike ions between $Z = 62$ and 83 have been reported [8–12], but all have had much larger error bars than the measurements of platinum and uranium and are thus less definitive.

Three new measurements of sodiumlike Xe^{43+} ($Z = 54$) [12–15] have been reported since the original xenon measurement by Seely *et al.* The first of this set was reported by Träbert *et al.* [13] using the Livermore electron beam ion trap and with an error bar similar to that of the Pt^{67+} datum (450 versus 440 cm^{-1}, respectively), i.e., very precise and only slightly larger than that of the original measurement (400 cm^{-1}) of Seely et al. Unlike the platinum and uranium measurements, this xenon value, surprisingly, agreed with and confirmed the trend set by the Seely *et al.* measurements, as illustrated in Fig. 1. A subsequent xenon measurement by Fahy *et al.* [14] in 2007 was performed on the Gaithersburg electron beam ion trap. The $3p_{3/2}$ level result is somewhat less precise than the measurement reported by Träbert *et al.*, but agrees with it very well and, consequently, with the trend set by the Seely *et al.* measurements. The Gaithersburg electron beam ion trap was recently used to provide yet another measurement of sodiumlike xenon [12]. This measurement had a very small uncertainty of 113 cm^{-1}, which is five times smaller than the previous Gaithersburg measurement and four times smaller than the Livermore value and comparable to the uncertainty of the measurement of uranium performed by Beiersdorfer *et al.* [6]. Interestingly, this new xenon datum disagrees with the earlier measurement value from Gaithersburg, the measurement from Livermore, and, consequently, with the trend set by the MCDF calculation. The Gaithersburg electron beam ion trap was also used to provide another datum from a neighboring element, i.e., sodiumlike barium ($Z = 56$), with a similarly low uncertainty [12]. This value again disagrees with the trend set by the MCDF calculations and instead confirms the calculations by Blundell.

There are currently no highly precise measurements between $Z = 56$ and $Z = 78$, i.e, between sodiumlike barium and platinum, that discern between the trend set by the MCDF or Blundell calculations. To address the lack of data in this interval, we have measured the $3s_{1/2} - 3p_{3/2}$ transition in sodiumlike Eu^{52+} ($Z = 63$), achieving an uncertainty of better than 200 cm^{-1}, which is about a factor of seven lower than that of the Seely *et al.* datum for the neighboring element gadolinium ($Z = 64$) and a factor of 2.5 lower than the value for platinum. Moreover, we also report values for several $3-3$ transitions in magnesiumlike, aluminumlike, and siliconlike europium.

II. EXPERIMENT

The experiment was performed at the Livermore electron beam ion trap facility [16]. The measurement employed the higher-energy device of the two configurations available at Livermore, which is dubbed SuperEBIT [17, 18].

Europium was injected into SuperEBIT as an atomic vapor, making use of its high vapor pressure when heated to several hundred degrees Celsius via a tungsten filament [19]. Once ionized by the electron beam, the resultant ions were trapped by the combination of the 3 T magnetic field and the space charge of the electron beam in the radial direction and by electric potentials on the top and bottom drift tubes in the axial direction. Continued collisions with the electron beam further ionized the europium in a stepwise fashion. Ionization ended when the charge state reached had a higher ionization energy than was available as kinetic energy in the electron beam. The electron beam energy necessary to create sodiumlike europium is about 4.7 keV [20].

In our experiment the electron beam energies were varied from about 2 keV to 40 keV in order to explore a wide range of charge states and to identify the prominent lines of interest. The highest charge state identified in our spectra was sodiumlike Eu^{52+}. The europium charge states were also monitored in simultaneous measurements using the EBIT calorimeter spectrometer (ECS) [21–23]. In particular, the ECS measured the $n = 4 \rightarrow 3$ emission, which allowed us to identify several sodiumlike europium transitions [24].

Because Eu vapor was being injected continually, ions in lower charge states were always present and the overall charge balance is lower than it would be, if the trap were filled by other methods, such as laser blow-off injection [25] or a metal vapor vacuum arc [26]. This effect has been seen whenever metals are injected as atomic or molecular vapor, e.g., when injecting iron in form of iron pentacarbonyl [27].

The present measurements employed two flat-field spectrographs [28, 29] operating concurrently. Each was equipped with a 2400 ℓ/mm variable line spaced concave grating and a cryogenically cooled back-thinned charge-coupled device (CCD) camera. The camera chip had 1340 x 1300 pixels of 20 μm $\times$ 20 μm each. The concave gratings imaged the light from the ion trap, using SuperEBIT's $\leq$60 μm diameter electron beam [30] as the source, onto the CCD chip where it resulted in a width of about 3 pixels expected from the source size and the prevalent temperature in SuperEBIT [31, 32]. The CCD images obtained in the typically 60 minutes of exposure time were individually filtered for cosmic rays.

Calibration was performed by recording spectra when injecting CO_2. Upon dissociation and subsequent ionization in the electron beam, CO_2 provides a ready source of highly charged carbon and oxygen ions. The lowest members of the resonance line series of C V and the C VI Ly$_\alpha$ line span almost the full spectral width afforded by the camera, i.e., the wavelength range 32 to 43 Å (see Fig. 2). The carbon reference lines comprise C VI Ly$_\alpha$ at 33.734 Å and the C V lines $1s^2 - 1snp$, with $n = 3$ to 5 at 32 to 35 Å in the lower wavelength half and the C V $1s^2 - 1s2p$ resonance and intercombination lines at 40.267 and 40.730 Å, dubbed w and y in common notation, respectively, in the upper half. The wavelengths of these lines are known to better than 1 mÅ from calculations and or measurement [33, 34] and are readily employed to determine a slightly quadratic calibration curve.

The peaks in the spectra were fit with Gaussian functions. The line width (FWHM) of one instrument was about 24 mÅ, the other was about 32 mÅ. The difference arises from the quality of focusing the instruments. We note that the strongest of the carbon lines persisted even after the CO_2 injection ended and thus can be found to coexist with the europium lines within the same spectrum, as seen in Fig. 2. Contributions to the wavelength errors stem from the statistical analysis of the data, from errors in the calibration, and from the scatter of the individual measurements.

III. RESULTS AND DISCUSSION

The lines shown in Fig. 2 are readily identified as $3s_{1/2} - 3p_{3/2}$ transitions in sodiumlike and magnesiumlike ions as well as n=3 to n'=3 transitions in aluminumlike and siliconlike ions of europium. In addition we see several carbon reference lines. All of the strong europium lines visible in Fig. 2 are absent at electron beam energies below 4 keV where then emission lines from lower charge state ions are seen instead.

We interpret the line pattern in the spectra observed at higher electron beam energies with the help of insight from our earlier studies of xenon and tungsten [11, 13]. These studies utilized one of the present two spectrographs, and these spectra are very similar in shape to the present spectra. The n=3 to n'=3 transition energies scale roughly linearly with Z; hence, our present spectral analysis could make use of an interpolation between our two earlier observations. This procedure is most important for identifying the aluminumlike and siliconlike lines. A summary of our line identifications and of the measured wavelengths is given in Table I.

Our measurement of the Eu^{52+} transition produced a value that follows that trend established by the Xe^{43+} and Ba^{45+} data from Gillaspy *et al.* [12], the Pt^{67+} value from Cowan *et al.* [5], and the U^{81+} value from Beiersdorfer *et al.* [6]. This can be seen in Fig. 1, where we show the comparison between measurement and theory for all currently available measurements for $Z \geq 40$.

Figure 1 also shows a weighted fit of all available measurements using a cubic polynomial. This curve closely follows the trend set by the five measurements with the lowest uncertainties, which includes the four mentioned above and our new value for europium. The fit is slighly above the *ab initio* predictions given by Blundell et al. [7, 12] for $Z \leq 64$ and below for the higher values of Z. In fact, our new value lies somewhat below the value given by Blundell's calculations. In that regard our new value follows our earlier U^{89+} measurements.

Overall, there are somewhat fewer experimental data available for magnesiumlike through siliconlike ion lines with high atomic number than there are available measurements of the corresponding sodiumlike line. Nevertheless, accurate experimental data are available for as high as $Z = 92$. In particular, Chen et al. reported experimental energies obtained on the Livermore electron beam ion trap for several $3s_{1/2} - 3p_{3/2}$ transitions in magnesiumlike, aluminumlike, siliconlike, and phosphoruslike uranium as well for one $3p_{1/2} - 3d_{3/2}$ transition in phosphoruslike uranium [35]. These measurements have uncertainties equal to that of the U^{81+} datum. In some cases they even exceeded this already very high accuracy.

Our measurements provide benchmarks for magnesiumlike, aluminumlike and siliconlike ions in a region of atomic number where essentially no measurements have been available. Because these data also have small uncertainties, they may serve as benchmarks for testing theoretical approaches for calculating atomic systems with a more complex valence electron structure than that afforded by sodiumlike ions. Our measured values are listed in Table I together with theoretical values available in the literature.

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TABLE I: Measured (this work) and calculated wavelengths (in Å) of n=3 to n=3 transitions in the EUV spectra of sodiumlike through siliconlike ions of Eu. The line numbering follows the example of Clementson and Beiersdorfer for W [11].

Ion charge	Isoelectronic sequence	Line label	Transition	Wavelength Experiment	Wavelength Theory
52+	Na	Na-1	$3s_{1/2} - 3p_{3/2}$	41.232 ± 0.003	41.228 [a]
					41.211 [c]
					40.900 [d]
					41.2283 [e]
51+	Mg	Mg-2	$(3s^2)_0 - (3s_{1/2}3p_{3/2})_1$	39.698 ±0.003	39.622 [f]
					39.372 [g]
					39.694 [h]
50+	Al	Al-1	$(3s^2 3p_{1/2})_{1/2} - (3s^2 3d_{3/2})_{3/2}$	34.493 ± 0.003	34.411 [i]
50+	Al	Al-2	$(3s^2 3p_{1/2})_{1/2} - (3s_{1/2}3p_{1/2}3p_{3/2})_{1/2}$	39.133 ± 0.003	38.860 [i]
50+	Al	Al-3	$(3s^2 3p_{1/2})_{1/2} - (3s_{1/2}3p_{1/2}3p_{3/2})_{3/2}$	40.186 ± 0.003	39.991 [i]
49+	Si	Si-1	$(3s^2 3p^2_{1/2})_0 - (3s^2 3p_{1/2}3d_{3/2})_1$	33.368 ± 0.003	33.280 [j]
49+	Si	Si-2	$(3s^2 3p^2_{1/2})_0 - (3s_{1/2}3p^2_{1/2}3p_{3/2})_1$	39.726 ± 0.003	39.524 [j]

[a] Kim *et al.* [2]
[c] Seely *et al.* prediction with semiempirical correction [4]
[d] Ivanov and Ivanova *et al.* [36]
[e] Blundell in Gillaspy *et al.* [12]
[f] Marques *et al.* [37]
[g] Ivanova *et al.* [38]
[h] Santana [39]
[i] Huang [40]
[j] Huang [41]

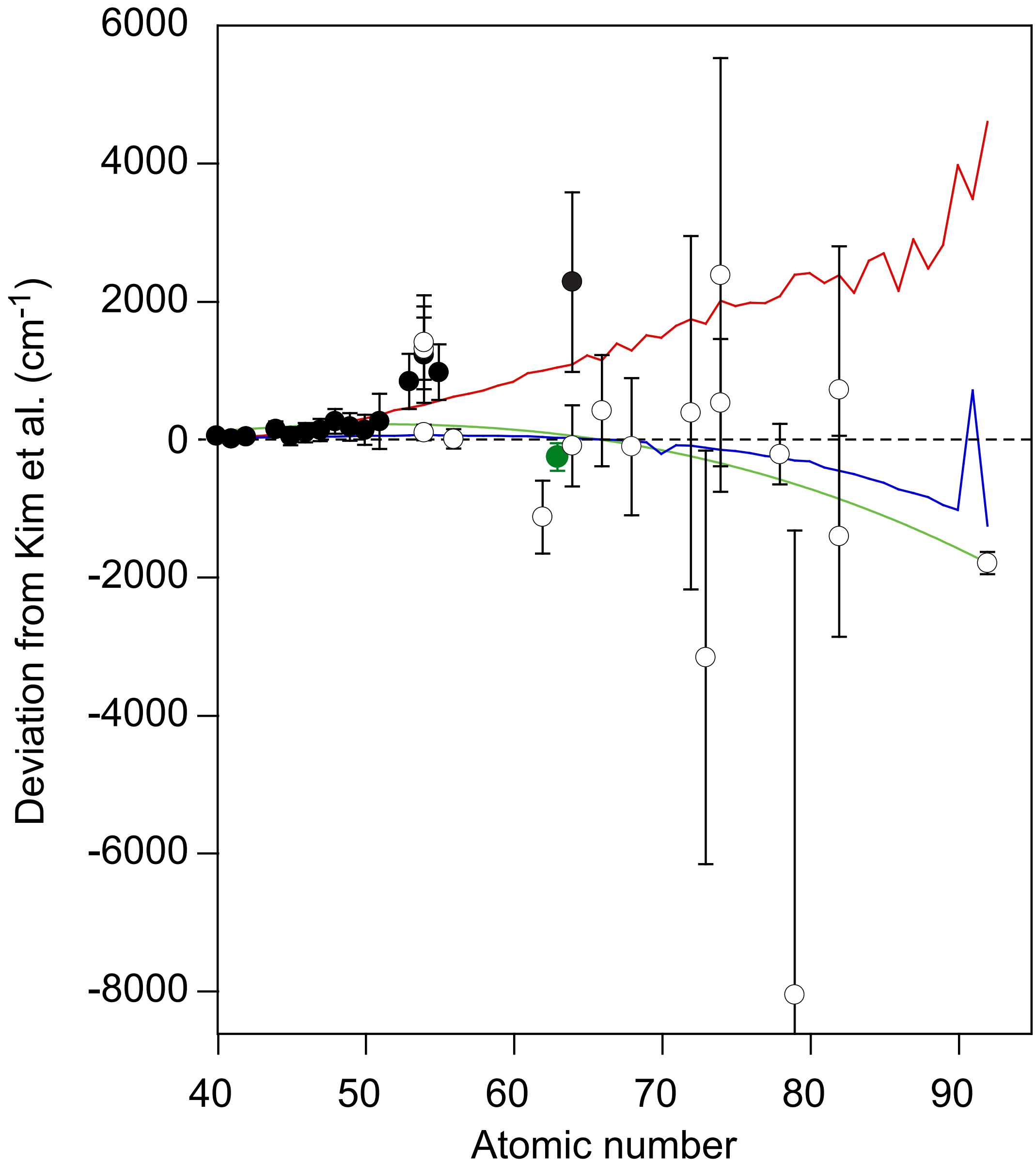

FIG. 1: (Color online only) Comparison of measured and calculated energies of the $3s_{1/2}$–$3p_{3/2}$ transition in sodiumlike ions (from $Z = 40$ to 92). All values are relative to semiempirical values given by Kim *et al.* [2]. Other calculations are semiempirical calculations by Seely et al. [4] (solid red line) and *ab inito* calculations by Blundell [7, 12] (solid blue line). The experimental data points (solid black circles) with $Z \leq 50$ are from a compilation by Reader *et al.* [42]. Data with $Z \geq 53$ from [4–6, 8–14] and are shown as solid black circles, if measured before the measurement of Pt^{67+} by Cowan et al. [5] and as open black circles otherwise. The present measurement is shown as a solid green circle. The weighted fit to all data is shown as a green line.

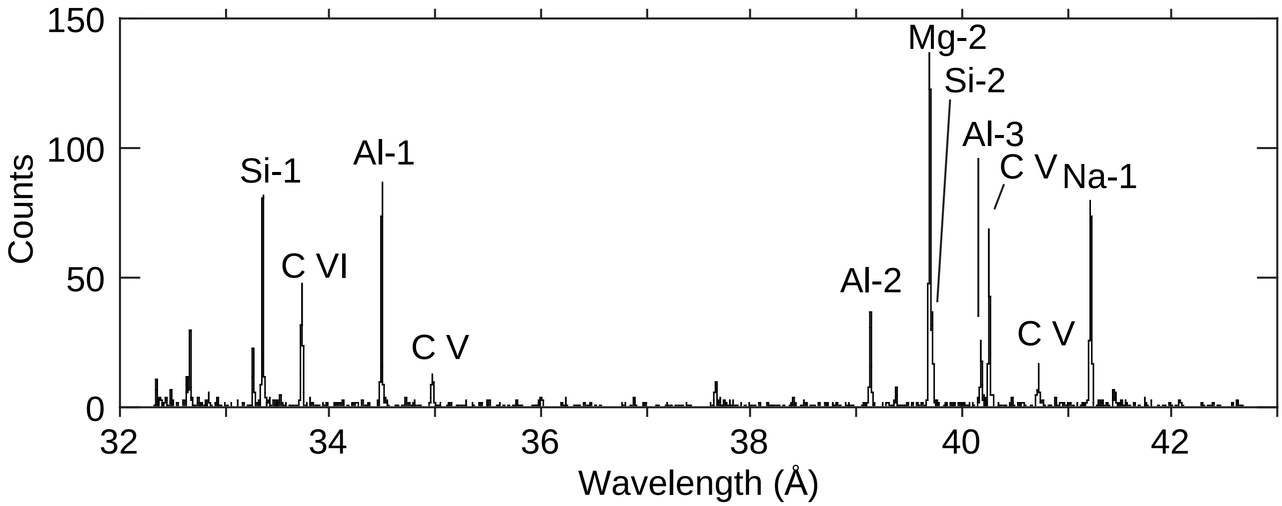

FIG. 2: EUV spectrum of Eu recorded with a flat-field spectrometer at an electron beam energy of about 8 keV. The spectrum shows n=3 to n=3 lines from sodiumlike, magnesiumlike, aluminumline, and siliconlike ions as the strongest ones of europium, as well as calibration lines of hydrogenlike and heliumlike ions of carbon. The labels C V and C VI refer to K-shell transitions in heliumlike and hydrogenlike carbon, respectively; other labels are those used in Table I.