EUV Spectra of Europium – Chasing for Spectral Lines of P- to Ar-like Ions

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Abstract

The understanding of atomic structure implies a combination of accurate measurements and a reliable theoretical framework. Atomic structure computations are employed to bridge the many gaps in the experimental data, but their results need to be tested by measurements. We have selected extreme ultraviolet (EUV) spectra of europium (Eu, Z=63) for such tests. We study the emission spectra of Eu ions produced and excited in an electron beam ion trap by observation with highly resolving spectrographs. General purpose atomic structure computations help us at disentangling the spectra and identifying the emission of specific charge state ions. At the same time the wavelength data provide a tool to judge the quality of the computations. The present study concentrates on ions of the charge states q = 45+ to q = 49+, or P- to Ar-like ions of Eu.

Keywords: Atomic spectroscopy – EUV spectra – Electron beam ion trap – Atomic structure computation

Introduction

Atomic spectroscopy aims at accurate and comprehensive data as well as at a reliable theoretical description of atomic structure. Using two high-resolution grazing-incidence grating spectrographs at the Livermore electron beam ion trap, we have previously measured the wavelengths of resonance lines in Na- and Mg-like ions of Eu (Z=63) to about 100 ppm uncertainty [1]. The best computations (for example, [2-4]) corroborate our results within about the same error range. General purpose atomic structure computations are not expected to be similarly accurate, but they have readily indicated the positions of the strongest lines of Al and Si-like Eu ions in the same spectra [1].

We now employ the Flexible Atomic Code (FAC) [5] to identify further Eu lines in the above section of the EUV spectrum. Working at somewhat lower electron beam energies than before, we expect lower charge state ions to dominate the spectra. Of these we concentrate for now on the P- to Ar-like ions, which in their ground configurations are all 3p shell ions.

Measurement

We produce and excite highly charged Eu ions in the Livermore electron beam ion trap [6], a system of electrostatically charged drift tubes aligned with a 3 T magnetic field in an ultrahigh vacuum vessel. Europium atoms are injected as a dilute vapor from a heated

sample [7]. Atoms that cross the trajectory of an intense electron beam of several keV energy can be ionized; such ions are then trapped and kept exposed to the same electron beam. The charge state distribution in the trapped ion cloud is established as a balance of ionization and recombination. At the upper end the limit is given by the electron beam energy and the steps of the ionization energy ladder. Thus a variation of the electron beam energy affects the highest ion charge state present in the trap and possibly contributing to the overall spectrum.

We have two high-resolution grazing-incidence grating spectrographs (dubbed HIGGS [8,9]) at our disposal. Both use flat-field gratings of 2400 l/mm that are illuminated at 87° angle of incidence; the cryogenically cooled charge-coupled device (CCD) detectors have 1340 x 1300 pixels of 20 μm width each. In the wavelength range of present interest, 32 to 43 Å, the resolving powers of both instruments amount to about 1200 to 1300. Exposures of typically 1 h each were filtered for cosmic ray events and then combined. The spectra were calibrated by reference to n = 1-2 and n = 1-3 transitions in C V and C VI [10,11], produced in the same geometry by injecting CO_2 gas. The wavelengths of these lines are known to better than 1 mÅ. Spectra were recorded at electron beam energies of 3.8 to 6 keV (for samples, see Figure 1). At these settings, the charge state distribution of the trapped ions is expected to comprise Ti-like (22 electrons) to P-like (15 electrons) ions, that is, atomic systems with a partly filled 3p shell to a partly filled 3d shell.

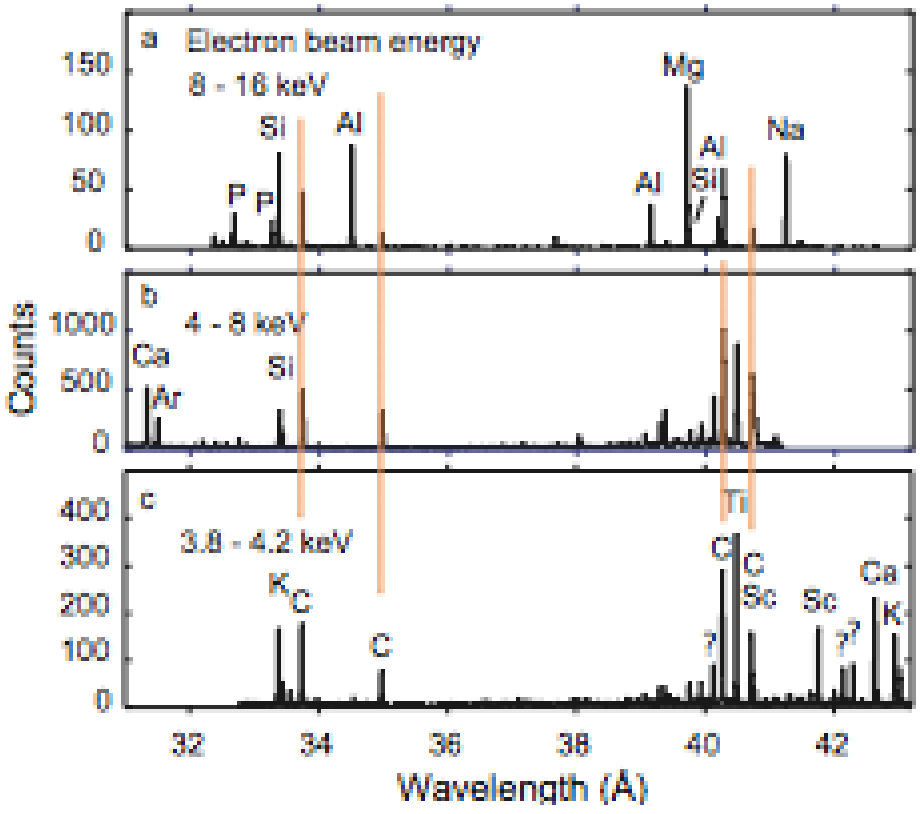

Figure 1: Sample spectra of Eu in the Livermore electron beam ion trap. The elemental symbols identify the four major carbon reference lines (`C' and orange vertical bars) and the iso-electronic sequences of Eu ions. The middle panel is of primary interest here, but the evaluation needs to discriminate the lines of interest from those produced at a higher (top panel) or lower (bottom panel) electron beam energy.

Atomic structure computations

The FAC suite of programs developed by M. F. Gu [5] is a well-tested package of fully-relativistic routines that runs on a laptop computer. It is used to calculate a number of atomic parameters and structure features; we use it in particular to perform collisional-radiative modeling and predict emission line intensities as a function of electron beam energy (2 – 4 keV here) and electron density ($n_e \approx 5 \cdot 10^{11}$ cm^{-3}). The computation of

hundreds of levels for each ion and many thousands of transitions yields simulated spectra with thousands of spectral lines in the EUV. Of these we consider only lines with an intensity higher than several percent of that of the strongest line of the given charge state ion, which reduces the selection to a few lines per ion.

FAC reveals which peculiarities of the emission pattern have to be expected (Figure 2). For example, the spectra of Na-, Mg-, and Si-like Eu ions in this wavelength range are dominated by a single line each, but for P-, S-, and Cl-like ions a fair number of weaker lines are to be expected instead. For Ar-like Eu ions, FAC predicts two prominent, but distantly spaced lines.

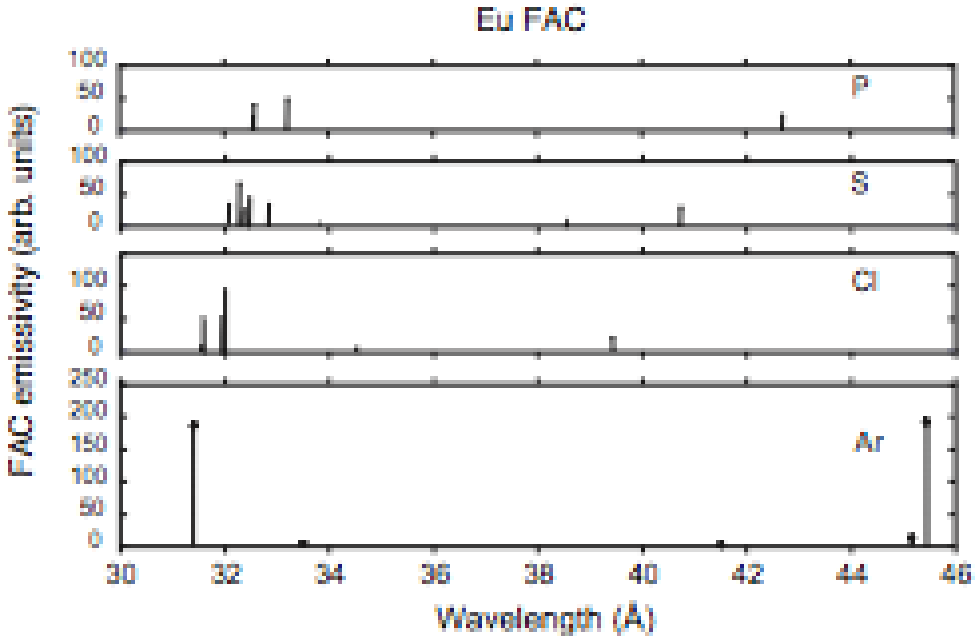

Figure 2: Simulated spectra of P-, S-, Cl-, and Ar-like Eu ions based on a FAC collisional-radiative model.

Spectrum analysis

The most prominent lines predicted by FAC for the four Eu spectra of present interest fall into the wavelength interval 31 to 34 Å (see Figure 2), just outside of the short-wavelength edge of the range spanned by our four primary carbon calibration lines (C VI Ly_α (n = 1-2) is at 33.735 Å, see Figure 1). This situation with its need for extrapolation implies somewhat larger wavelength uncertainties than any calibration based on interpolation. There also are higher-n members of the C V and C VI spectral line series inside the wavelength interval of interest, but they are, of course, weaker than the lower-n ones. Consequently these potential calibration lines do not stand out among the multitude of weak lines that are seen in the above wavelength interval. Many of the other weak lines are expected to originate from S- and Cl-like ions of Eu, but, given the typical uncertainties of atomic structure computational predictions, the intervals between many of the observed lines are much smaller than the predictive uncertainties. It is therefore not possible to identify with confidence any lines observed here with specific transitions in these two ions of Eu.

The situation is more favourable for P- and Ar-like Eu. Two candidate lines to be identified with 3p-3d transitions of the P-like ion appear in spectra recorded at the higher electron beam energies which have targeted higher-charge state ions and in which the signal has benefited from longer data accumulation times. The lines ($3p^3$ J=3/2 – $3p^2$ 3d, J = 1/2,3/2, 32.671±0.01 Å, $3p^3$ J = 3/2 – $3p^2$ 3d J = 5/2, 33.272±0.01 Å) are partly blended with

unidentified others, but are still seen clearly enough to be of merit.

For Ar-like Eu, FAC predicts 3p-3d lines at 30.816 Å, 31.387 Å, 45.144 Å, and 45.437 Å, of which at least the second and fourth one should be strong enough to be observed. However, the wavelength separation of the two line groups is substantially larger than the wavelength span of our CCD cameras in a given spectrograph setting, rendering a simultaneous observation infeasible. Moreover, the long wavelength lines are in an inconvenient location for practical wavelength calibrations. We therefore shifted the spectrograph setting to include the vicinity of the FAC prediction for the short-wavelength lines while still maintaining our calibration anchors of carbon lines. Of two prominent lines seen in the target range, we take the one at a wavelength of 31.498±0.008 Å to be a viable candidate for Ar-like Eu $3p^6$ $J = 0 - 3p^5$ 3d $J = 1$, while the other line may be from Ca-like Eu (to be corroborated by future research).

Discussion

For the (Na- to Si-like) Eu ions with just a few electrons in the $n = 3$ valence shell, the results of various atomic structure computations on 3s-3p and 3p-3d transitions, respectively, agree with accurate experiments [1] to within 100 ppm in the best cases and to within about 8000 ppm in the poor ones. Among these, FAC, with deviations from 1300 ppm to 3000 ppm, takes a medium rank. For the more complex P- to Ar-like ions, the literature does not offer similar computations, and thus FAC serves as a singularly helpful tool, if one knows about its reliability. With 3p-3d transitions in the present atomic systems, we find a deviation between FAC prediction and our measurement of 2500 to 3500 ppm, with the FAC wavelengths all shorter than what we measure. This corresponds to a systematic wavelength underprediction by about 0.1 Å for most of the Eu ions with an open 3p valence shell.

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