Measurements and identifications of extreme ultraviolet spectra of highly-charged Sm and Er

Y A Podpaly, J D Gillaspy, J Reader and Yu Ralchenko

National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

E-mail: yuri.podpaly@nist.gov

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Abstract

We report spectroscopic measurements of highly charged samarium and erbium performed at the National Institute of Standards and Technology electron beam ion trap (EBIT). These measurements are in the extreme ultraviolet range, and span electron beam energies from 0.98 keV to 3.00 keV. We observed 71 lines from Kr-like Sm$^{26+}$ to Ni-like Sm$^{34+}$, connecting 83 energy levels, and 64 lines from Rb-like Er$^{32+}$ to Ni-like Er$^{40+}$, connecting 78 energy levels. Of these lines, 64 in Sm and 60 in Er are new. Line identifications are performed using collisional-radiative modeling of the EBIT plasma. All spectral lines are assigned individual uncertainties, most in the $\sim 0.001$ nm range. Energy levels are derived from the wavelength measurements.

Keywords: extreme ultraviolet spectra, electron beam ion trap, samarium, erbium, collisional-radiative modeling

1. Introduction

Spectroscopy of rare earth elements has recently become a subject of active research due to the possible use of gadolinium and terbium as next generation light sources for extreme ultraviolet (EUV) lithography [1, 2]. There are also few available data about transitions of highly charged ions in the lanthanides, which makes this an important area for additional study.

In the National Institute of Standards and Technology (NIST) Atomic Spectra Database [3], erbium and samarium transitions are available primarily for Sm I and II and Er I, II, and III. Fewer data are available for more highly ionized ions. Some transitions have been measured on electron beam ion traps (EBITs) in the EUV and x-ray regimes [4–7]. Much of the available data have been generated from laser produced plasmas [8–16]. Highly charged samarium has also been observed in tokamak plasmas [17–19]. In highly charged erbium, likewise, there are limited available data, including that generated by EBITs [4, 20, 21], laser plasmas [10–12, 22], and tokamaks [17, 18, 23].

In this paper, we report Er and Sm $n = 4-\bar{n} = 4$ transitions in the EUV, continuing our previous studies of Gd [1] and Dy [24]. A full list of identifications, wavelengths, and wavelength uncertainties is generated, and we calculate energy levels with uncertainties for these ions as well. The intent of this research is to expand the number of measured transitions among the rare earth elements near those of interest for EUV light sources and provide a systematic accounting of uncertainties for transitions and energy levels.

2. Experiment

This work was performed at the NIST EBIT [25]. Sm spectra were studied at 12 electron beam energies between 0.98 keV and 2.2 keV, and Er spectra were studied at 12 beam energies between 1.3 keV and 3.0 keV. These energies are sufficient to produce ions between approximately Rb-like and Ni-like ionization stages [3]. Beam currents varied between 15 mA and 86 mA. Plasma confinement was achieved, as usual, through the electrostatic trapping via the electron beam, two drift tubes (at 500 V and 220 V), and a 2.8 T axial magnetic
field. Er and Sm were injected into the trap by using a multichannel metal vapor vacuum arc (MeVVA) [26]. The trap was emptied and new ions were injected from the MeVVA every 10 s. Elements used for calibration were introduced by the MeVVA, by the gas injection system (described in [27]), or were present as intrinsic impurities.

Spectra were recorded with a spectrometer designed for use in the EUV [28]. The spectrometer is a flat-field variable-line spacing type grating spectrometer. Data were collected with a 2048 pixel × 512 pixel (13.5 μm × 13.5 μm pixel dimensions) liquid-nitrogen-cooled charge coupled device (CCD). Spectra were taken as ten one-minute exposures, and a cosmic ray filtering program was used to automatically remove data that were outside of five Poisson standard deviations of the signal, effectively removing the majority of the cosmic rays and aberrant electronic noise. The spectral range for Sm measurements covered approximately 4–20 nm, and for Er approximately 3–17 nm, with the resolving power of λ/Δλ ≈ 400.

Calibration of the samarium spectra was accomplished using 12 lines from Ne4+ through Ne7+, one line of Fe22+, one line of Ba26+, and one line of Ba36+. Spectra of neon were taken at 2 keV and 4 keV, iron was taken at 4 keV, and barium, which is an intrinsic impurity, was taken at 5.8 keV. Calibration of the erbium spectra was performed using 12 lines from Ne4+ through Ne7+, four lines from Xe43+ and Xe42+, one line from Ba45+, one line from O4+, and one line from O5+. Spectra of neon were taken at 2 keV and 4 keV, xenon and barium at 5.8 keV, and oxygen at 1.8 keV. All lines were fit with unweighted Gaussian profiles, and uncertainties were generated for each calibration point. Third order calibration polynomials relating wavelength to detector channel number were calculated, and confidence intervals were generated from which calibration uncertainties were derived. By setting the requirement that the calibration polynomial fit had χ^2 ≈ n − N, where n is the number of calibration points and N is the degrees of freedom of the calibration curve [29], the systematic uncertainty was estimated. For samarium, the systematic uncertainty was found to be 0.00055 nm; for erbium, the systematic uncertainty was found to be 0.0010 nm.

Spectra were recorded at a variety of energies; typical results are shown in figures 1 and 2. The intensities of the experimental spectra are given in the analog-to-digital units of the CCD. Lines were fit with unweighted Gaussians, and statistical, systematic, and calibration confidence interval uncertainties were added in quadrature for each line to generate a total uncertainty.

In order to indicate the second order optical spectral features that are common in diffraction grating spectrometers, we generated artificial second order spectra (gray shifted lines) in the figures. This was performed by doubling the wavelengths, reducing intensities by a factor of three, and vertically shifting the original measured spectra.

3. Collisional-radiative (CR) modeling

The measured spectra were analyzed with the CR modeling that has been extensively described elsewhere (see, e.g., [30–32]), and therefore only the most relevant features will be described below. The line intensities for Er and Sm were calculated with the non-Maxwellian CR code NOMAD [33] utilizing atomic data generated with the flexible atomic code (FAC) [34]. The level energies, radiative transition probabilities (allowed and forbidden), and electron-impact cross sections (excitation, deexcitation, ionization, and radiative recombination) were calculated for 8575 and 8570 levels in Sr-like to Ni-like ions of Er and Sm, respectively. The level energies were improved using an extended calculation taking into account all possible excitations within the n = 4 complex, as described in [31]. The energies of the 3d^4f^l levels in Ni-like ions were taken from a more accurate relativistic many-body perturbation theory (RMBPT) calculation of [35]. The rate of charge exchange between highly-charged ions and neutral atoms in the trap was included as the only free parameter, aside from a small shift in electron beam energy due to space charge as discussed below. A typical calculation of an EBIT spectrum would include 6–7 most populated ionization stages. The calculated bound-bound spectra were then Gaussian-broadened with the instrumental resolution and convolved with the calculated efficiency curve of the EUV spectrometer. Note that the natural widths of spectral lines in
the studied wavelength range are much smaller than the instrumental width.

Examples of agreement between theoretical and experimental spectra of Er are presented in figures 3 and 4. The agreement between theory and experiment for the Sm spectra is practically the same. The second order spectra are shown by the shifted dotted lines. Starting with figure 3, one can see that our CR modeling explains intensities and positions of all strong spectral lines. Note that the theoretical beam energy is lower than the nominal experimental energy; this is due to the space charge effects that are common in EBITs. Although for some lines there is a small shift in wavelength between theory and experiment, a very good match of line intensities allows us to unambiguously identify all prominent lines in the spectrum. For instance, the main groups of spectral lines near 8 nm and 15 nm are due to the $4s_{1/2} - 4p_{3/2}$ and $4s_{1/2} - 4p_{1/2}$, respectively, in Cu-, Zn-, and Ga-like ions of Er.

The theoretical spectrum in figure 4 is also seen to agree well with the measured spectrum. The contributions from different ions are shown by different colors, while the total theoretical spectrum is marked by a black solid line. For this energy, the calculated ion populations are the following: [Kr]: [Br]: [As]: [Se]: [Ge] = 0.015:0.106:0.372:0.439:0.066 (see the inset in figure 4), and the remaining population (<1%) is in the lower ions. Accordingly, the most prominent lines are due to transitions in As-like (blue) and Ge-like (orange) ions. Although a simple visual comparison allows us to identify practically all experimental lines, additional assistance in identification is provided by comparison of the intensity of the lines at the various beam energies. A similar $E_{\text{beam}}$-dependence of line intensities from a particular ionization stage is especially helpful in identification of blended lines.

4. Results

Results of our measurements are shown in tables 1 and 2. Wavelengths calculated by FAC are presented as well. All uncertainties for wavelengths are reported as one standard deviation. The table also presents previous measurements of several spectral lines. If a line has significant blending with another line the letter ‘b’ is appended to the wavelength. For samarium, 71 lines were measured, with 64 of them new.
Table 1. Wavelengths (nm) of highly charged samarium. The numbers in parentheses are the wavelength uncertainties in units of the last significant digit. The numbers in square brackets in column ‘FAC’ are the ordinal numbers for the lower and upper levels. b-blended line.

| Stage | Lower level | Upper level | Wavelength | FAC | Prev. exp. |
|-------|-------------|-------------|-------------|-----|------------|
|       | Conf. | State       | Conf. | State       |             |             |
| 34+ [Ni] | 3d^4p | ((3d^3)_{3/2}, 4p) | 3d^4d | ((3d^3)_{3/2}, 4d) | 6.8494(7) | 6.7384 [9–35] | 6.85(2) |
| 34+ [Ni] | 3d^4p | ((3d^3)_{3/2}, 4p) | 3d^4d | ((3d^3)_{3/2}, 4d) | 7.3563(8) | 7.2344 [12–35] | 7.36(2) |
| 34+ [Ni] | 3d^4p | ((3d^3)_{3/2}, 4p) | 3d^4d | ((3d^3)_{3/2}, 4d) | 10.4908(11) | 10.4800 [10–23] |
| 34+ [Ni] | 3d^4s | ((3d^3)_{3/2}, 4s) | 3d^4p | ((3d^3)_{3/2}, 4p) | 17.6366(17) | 17.5856(7) |
| 34+ [Ni] | 3d^4s | ((3d^3)_{3/2}, 4s) | 3d^4p | ((3d^3)_{3/2}, 4p) | 17.8926(14) | 17.8722 [2–6] |
| 34+ [Ni] | 3d^4s | ((3d^3)_{3/2}, 4s) | 3d^4p | ((3d^3)_{3/2}, 4p) | 17.9864(16) | 17.9661 [3–7] |
| 34+ [Ni] | 3d^4s | ((3d^3)_{3/2}, 4s) | 3d^4p | ((3d^3)_{3/2}, 4p) | 18.1084(20) | 18.0985 [5–8] |
| 34+ [Ni] | 3d^4s | ((3d^3)_{3/2}, 4s) | 3d^4p | ((3d^3)_{3/2}, 4p) | 18.2491(16) | 18.2674 [3–6] |
| 33+ [Cu] | 4p | 4p_ | 4d | 4d_ | 8.2176(7) | 8.2193 [2–4] | 8.2206(15) |
| 33+ [Cu] | 4d | 4d_ | 4f | 4f_ | 10.2238(7) | 10.2183 [5–7] | 10.2249(15) |
| 33+ [Cu] | 4p | 4p_ | 4d | 4d_ | 10.3555(7) | 10.3588 [3–5] | 10.3571(15) |
| 33+ [Cu] | 4s | 4s_ | 4p | 4p_ | 11.3516(7) | 11.1969 [1–3] | 11.3509(15) |
| 33+ [Cu] | 4s | 4s_ | 4p | 4p_ | 17.7416(13) | 17.3523 [1–2] | 17.7450 |
| 32+ [Zn] | 4s4d | (4s_ , 4d_ ) | 4s4f | (4s_ , 4f_ ) | 9.9127(7) | 9.8855 [14–30] |
| 32+ [Zn] | 4s4p | (4s_ , 4p_ ) | 4s4d | (4s_ , 4d_ ) | 10.0851(7) | 10.0602 [5–14] |
| 32+ [Zn] | 4s^2 | 4s4p | (4s^2 ) | 4s4p | 10.9125(6) | 10.8361 [1–5] | 10.911(2) |
| 32+ [Zn] | 4s4p | (4s_ , 4p_ ) | 4p^2 | (4p_ , 4p_ ) | 11.2465(8) | 11.2393 [3–8] |
| 32+ [Zn] | 4s^2 | 4s4p | (4s^2 ) | 4s4p | 18.8153(19) | 18.658 [1–3] |
| 31+ [Ga] | 4p | 4p_ | 4d | 4d_ | 7.7461(8) | 7.7150 [1–11] |
| 31+ [Ga] | 4p | 4p_ | 4s4p | (4s_ , (4p_ )_ ) | 8.9151(7) | 8.1951 [1–9] |
| 31+ [Ga] | 4p | 4p_ | 4d | 4d_ | 10.1294(7) | 10.0619 [2–11] |
| 31+ [Ga] | 4p | 4p_ | 4s4p | (4s_ , (4p_ )_ ) | 10.8203(7) | 10.7701 [1–7] |
| 31+ [Ga] | 4p | 4p_ | 4s4p | (4s_ , (4p_ )_ ) | 11.5749(7) | 11.524 [1–6] |
| 31+ [Ga] | 4p | 4p_ | 4s4p | (4s_ , (4p_ )_ ) | 16.8114(11) | 16.7187 [2–6] |
| 31+ [Ga] | 4p | 4p_ | 4s4p | (4s_ , 4p_ ) | 18.3603(16) | 18.3159 [1–3] |
| 31+ [Ga] | 4p | 4p_ | 4s4p | (4s_ , 4p_ ) | 19.1476(22) | 19.1158 [2–5] |
| 30+ [Ge] | 4p^2 | (4p^2 ) | 4p4d | (4p_ , 4d_ ) | 7.7020(7) | 7.6492 [1–16] |
| 30+ [Ge] | 4p^2 | (4p_ , 4p_ ) | 4p4d | (4p_ , 4d_ ) | 7.9406(7) | 7.9888 [3–23] |
| 30+ [Ge] | 4p^2 | (4p^2 ) | 4s4p | (4s_ , 4p_ , (4p^2 )_ ) | 8.1809(10) | 8.135 [1–13] |
| 30+ [Ge] | 4p^2 | (4p_ , 4p_ ) | 4p4d | (4p_ , 4d_ ) | 9.6994(7) | 9.6032 [2–16] |
| 30+ [Ge] | 4p^2 | (4p_ , 4p_ ) | 4p4d | (4p_ , 4d_ ) | 9.9701(7) | 9.9429 [3–15] |
| 30+ [Ge] | 4p^2 | (4p_ , 4p_ ) | 4s4p | (4s_ , 4p_ , (4p^2 )_ ) | 10.0244(7) | 10.0244 [7–33] |
| 30+ [Ge] | 4p^2 | (4p_ , 4p_ ) | 4s4p | (4s_ , 4p_ ) | 10.6279(8) | 10.6342 [3–14] |
| 30+ [Ge] | 4p^2 | (4p_ , 4p_ ) | 4s4p | (4s_ , 4p_ ) | 10.7648(8) | 10.6784 [3–13] |
| 30+ [Ge] | 4p^2 | (4p_ , 4p_ ) | 4s4p | (4s_ , 4p_ ) | 10.9423(7) | 10.8984 [2–12] |
| 30+ [Ge] | 4p^2 | (4p_ , 4p_ ) | 4s4p | (4s_ , 4p_ ) | 11.1501(7) | 11.1261 [1–7] |
| 29+ [As] | 4p^3 | 4p_ | 4p4d | (4p_ , 4p_ ) | 11.7114(8) | 11.7236 [3–10] |
| 29+ [As] | 4p^3 | 4p_ | 4s4p | (4s_ , 4p_ ) | 12.3270(11) | 12.3630 [3–9] |
| 29+ [As] | 4p^3 | 4p_ | 4s4p | (4s_ , 4p_ ) | 16.5715(9) | 16.5015 [3–7] |
| 29+ [As] | 4p^3 | 4p_ | 4p4d | (4p_ , 4p_ ) | 7.6812(7) | 7.6310 [1–24] |

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lines. For erbium, 64 lines were measured, with 60 of them new lines. In the erbium data, some of the Br-like lines were measured from their second orders and these wavelengths are marked with ’(*2)’.

The level identifications are given in standard notation for relativistic configurations (e.g., 4p, for 4p^j+1/2 and 4d for 4d_{j=1−1/2}). As is customary for the FAC calculations, the electron pairs with total zero angular momentum are omitted. Since only the largest component of a wavefunction is presented, this may result in non-unique labels for some levels. For instance, levels 7 and 9 in As-like Sm are both shown in Table 1 as belonging to the term 4d. of configuration 4p^24d. The calculations show that level 7 is composed of 45.7% of 4p^24d, 45.3% of 4s4p^5 (4s^2, 4p^3), and 3.3% of 4s4p^5 (4s^2, 4p^3), while for level 9 the same relativistic terms have contributions of 49.9%, 34.2% and 5.3%, respectively. Such strong mixing is not uncommon in highly-charged N-shell ions.

The energy levels for samarium and erbium are reported in tables 3 and 4. The conversion factor from eV to cm^-1 was 1 eV = 8065.544 29(18) cm^-1 [36]. The first energy level, the ground level, is taken to have zero energy. In some cases,
Table 2. Wavelengths (nm) of highly charged erbium. The numbers in parentheses are the wavelength uncertainties in units of the last significant digit. The numbers in square brackets in column ‘FAC’ are the ordinal numbers for the lower and upper levels. b-blended line. (*2)-wavelength derived from second order measurement.

| Stage | Lower level | Upper level | Wavelength | FAC | Prev. exp. |
|-------|-------------|-------------|-------------|-----|-----------|
|       | Conf.       | State       | Conf.       | State |           |
| 38+ [Zn] | 4s4p | (4s4p, 4p) | 4s4d | (4s4p, 4d) | 6.7273(12) | 6.2686 [3–10] |
| 38+ [Zn] | 4s4p | (4s4p) | 4s4p | (4s4p) | 8.1312(12) | 8.0900 [1–5] |
| 38+ [Zn] | 4s4p | (4s4p) | 4s4d | (4s4p, 4d) | 8.1732(21) | 8.1548 [5–14] |
| 38+ [Zn] | 4s4p | (4s4p) | 4s4p | (4s4p) | 15.6499(12) | 15.5430 [1–3] |
| 37+ [Ga] | 4p | 4p | 4d | 4d | 6.1755(12) | 6.1626 [1–9] |
| 37+ [Ga] | 4p | 4p | 4s4p | (4s4p, 4p) | 8.0777(14) | 8.0497 [1–7] |
| 37+ [Ga] | 4p | 4p | 4s4p | (4s4p, 4p) | 8.2227(12)b | 8.2190 [1–6] |
| 37+ [Ga] | 4p | 4p | 4s4p | (4s4p, 4p) | 9.3102(12) | 9.3281 [1–4] |
| 37+ [Ga] | 4p | 4p | 4s4p | (4s4p, 4p) | 13.5942(13) | 13.4904 [2–7] |
| 37+ [Ga] | 4p | 4p | 4s4p | (4s4p, 4p) | 14.0226(13) | 13.9493 [2–6] |
| 37+ [Ga] | 4p | 4p | 4s4p | (4s4p, 4p) | 15.1604(12) | 15.1163 [1–3] |
| 37+ [Ga] | 4p | 4p | 4s4p | (4s4p, 4p) | 15.8957(13) | 15.8643 [2–5] |
| 36+ [Ge] | 4p | (4p) | 4d4 | (4p, 4d) | 6.1041(12) | 6.0786 [1–11] |
| 36+ [Ge] | 4p | (4p) | 4s4p | (4s, 4p) | 8.2214(12)b | 8.2014 [1–7] |
| 36+ [Ge] | 4p | (4p) | 4s4p | (4s, 4p) | 13.7334(12) | 13.6693 [3–7] |
| 35+ [As] | 4p | 4p | 4p4d | (4p4d, 4d) | 6.0497(13) | 6.0137 [1–21] |
| 35+ [As] | 4p | 4p | 4p4d | (4p4d, 4d) | 6.0727(23) | 6.0435 [1–20] |
| 35+ [As] | 4p | (4p, 4p) | 4p4d | (4p, 4d) | 8.8392(13) | 8.8433 [3–17] |
| 35+ [As] | 4p | (4p, 4p) | 4p4d | (4p, 4d) | 15.4209(13) | 15.4358 [2–7] |
| 35+ [As] | 4p | (4p, 4p) | 4p4d | (4p, 4p) | 16.3966(13) | 16.4483 [3–7] |
| 35+ [As] | 4p | (4p, 4p) | 4p4d | 4d | 17.1697(15) | 17.1498 [3–6] |
| 34+ [Se] | 4p | (4p) | 4p4d | (4p, 4p) | 5.9929(18) | 5.9580 [1–30] |
| 34+ [Se] | 4p | (4p) | 4p4d | (4p, 4p) | 6.0230(22) | 5.9797 [1–29] |
| 34+ [Se] | 4p | (4p) | 4p4d | 4p | 7.8933(12) | 7.8593 [1–14] |
| 34+ [Se] | 4p | (4p) | 4p4d | 4p | 7.9546(12) | 7.9199 [2–15] |
| 34+ [Se] | 4p | (4p) | 4p4d | 4p | 8.0042(12) | 7.9737 [1–13] |
| 34+ [Se] | 4p | (4p) | 4p4d | 4p | 9.1787(15) | 9.169 [1–9] |
| 33+ [Br] | 4p | (4p) | 4p4d | (4p, 4p) | 5.9479(6)*2 | 5.9049 [1–26] |
| 33+ [Br] | 4p | (4p) | 4p4d | (4p, 4p) | 5.9789(7)*2 | 5.9390 [1–25] |
| 33+ [Br] | 4p | (4p) | 4p4d | (4p, 4p) | 5.9789(7)*2 | 5.9443 [1–24] |
| 33+ [Br] | 4p | (4p) | 4p4d | 4d | 7.7630(12) | 7.7217 [1–14] |
| 33+ [Br] | 4p | (4p) | 4p4d | 4d | 7.8578(10) | 7.8181 [1–13] |
| 33+ [Br] | 4p | (4p) | 4p4d | 4d | 7.8717(13) | 7.8352 [1–12] |
groups of levels are not connected to the ground level by measured radiative transitions, and therefore the energy of a reference level is taken from FAC or, in the case of Ni-like ions, from [35]. These levels are marked in our tables with the symbol + followed by a letter. For those levels with multiple ionizations, the reported results are given as the weighted mean (\alpha 1/\sigma ^2) of the possible derivations. Since none of the derived levels have uncertainties less than 20 cm⁻¹, the results are all rounded to 10 cm⁻¹, unless they are from calculations.

For some lines, their identifications were validated by using the Ritz combination principle. For instance, the Transition between the ground state (level 1) and level 6, is blended by a strong line in the Ge-like ion, and therefore additional confirmation of its wavelength would be helpful. The ground state and the first excited level in this ion are both connected to levels 6 and 7, all four lines having been measured in the present experiment. The energy differences between the two lowest levels calculated from two pairs of measured wavelengths agree within approximately 0.1%, thereby confirming our identifications for all those lines, including the 1–6 transition. Similar analysis was performed for transitions in the Ni-like ions of Sm and Er.

For the spectral range analyzed here, there exist only a handful of other measurements for Sm and Er. Our wavelengths for Ni-like Sm agree very well with the low-resolution measurements from laser-produced plasmas [9]. The high-resolution measurements for Cu-like Sm and Er [10, 14] also agree with our results within experimental uncertainties. Similar level of agreement is observed for other measurements in Zn-like ions [11, 12]. This provides additional confidence in our measured wavelengths and identifications of spectral lines from other ions of Sm and Er for which no previously measured wavelengths are known.

For most cases, the FAC wavelengths deviate from the measured values to within a fraction of one percent. The only exception are the transitions in Ni-like Sm that connect level 35 with quantum numbers 3d⁴4d (3d⁴5s24d⁴_0) with levels 9 and 12. For this J = 0 level the difference between theory and experiment reaches 1.6% for calculations that include double core excitations from n = 3 into n = 4 (value in table 3) and 4% for single 3–4 excitations. The RMBPT results of [35] do not contain J = 0 levels and there is no other recent theoretical work addressing the energy of this particular level. In spite of large differences between calculated and measured wavelengths, the relative line intensities agree very well, thereby confirming our identifications.

5. Conclusions

We report the results of EUV measurements of highly charged ions of samarium and erbium in an EBIT. One
Table 3. Energy levels of highly charged samarium. RMBPT—relativistic many body perturbation theory [35], FAC—flexible atomic code [34], †-weighted average from two transitions, ††-weighted average from three transitions.

| Stage and configuration sequence | Configuration | State | Level number (FAC) | Energy (cm⁻¹) | Unc. (cm⁻¹) |
|---------------------------------|---------------|-------|-------------------|---------------|-------------|
| 34+ [Ni] 3d¹⁰ | (3d⁴⁾⁰⁾ | 1 | 0 | 0 |
| 34+ [Ni] 3d³⁴s | ((3d⁴⁾²⁾, 4s⁺) | 2 | 7 522 190 | +x | RMBPT |
| 34+ [Ni] 3d³⁴s | ((3d⁴⁾²⁾, 4s⁺) | 2 | 7 533 150 | +x | 50† |
| 34+ [Ni] 3d³⁴s | ((3d⁴⁾²⁾, 4s⁺) | 2 | 7 752 539 | +y | RMBPT |
| 34+ [Ni] 3d³⁴p | ((3d⁴⁾²⁾, 4p⁻) | 6 | 8 081 080 | +x | 40 |
| 34+ [Ni] 3d³⁴p | ((3d⁴⁾²⁾, 4p⁻) | 6 | 8 089 190 | +x | 50 |
| 34+ [Ni] 3d³⁴p | ((3d⁴⁾²⁾, 4p⁻) | 6 | 8 304 770 | +y | 60 |
| 34+ [Ni] 3d³⁴p | ((3d⁴⁾²⁾, 4p⁻) | 6 | 8 322 930 | +z | RMBPT |
| 34+ [Ni] 3d³⁴p | ((3d⁴⁾²⁾, 4p⁻) | 6 | 10 404 586 | +a | FAC |
| 34+ [Ni] 3d³⁴p | ((3d⁴⁾²⁾, 4p⁻) | 6 | 10 423 520 | +z | 200 |
| 34+ [Ni] 3d³⁴d | ((3d⁴⁾³⁾, 4d⁻) | 23 | 9 357 800 | +a | 100 |
| 34+ [Ni] 3d³⁴d | ((3d⁴⁾³⁾, 4d⁻) | 23 | 9 782 910 | +z | 150 |
| 33+ [Cu] 3d⁴ | 4s⁺ | 1 | 0 | 0 |
| 33+ [Cu] 3d⁴ | 4p⁻ | 2 | 563 650 | 40 |
| 33+ [Cu] 3d⁴ | 4p⁻ | 2 | 880 940 | 50 |
| 33+ [Cu] 3d⁴ | 4d⁻ | 4 | 1 780 550 | 110 |
| 33+ [Cu] 3d⁴ | 4d⁻ | 5 | 1 846 610 | 80 |
| 33+ [Cu] 3d⁴ | 4f⁺ | 7 | 2 824 720 | 110 |
| 32+ [Zn] 3d² | (4s⁻³⁾²⁾ | 1 | 0 | 0 |
| 32+ [Zn] 3d³⁴p | (4s⁻³⁾²⁾ | 3 | 531 480 | 50 |
| 32+ [Zn] 3d³⁴p | (4s⁻³⁾²⁾ | 3 | 916 380 | 50 |
| 32+ [Zn] 3d³⁴p | (4p⁻³⁾²⁾ | 8 | 1 420 650 | 80 |
| 32+ [Zn] 3d³⁴d | (4s⁻³⁾²⁾ | 14 | 1 907 940 | 90 |
| 32+ [Zn] 3d³⁴d | (4s⁻³⁾²⁾ | 14 | 2 916 740 | 110 |
| 31+ [Ga] 3d³⁴p | 4s⁻³⁾²⁾ | 1 | 0 | 0 |
| 31+ [Ga] 3d³⁴p | 4p⁻³⁾²⁾ | 2 | 303 790 | 50 †† |
| 31+ [Ga] 3d³⁴p | 4p⁻³⁾²⁾ | 2 | 544 650 | 50 |
| 31+ [Ga] 3d³⁴p | (4s⁻³⁾²⁾ | 5 | 826 040 | 80 |
| 31+ [Ga] 3d³⁴p | (4s⁻³⁾²⁾ | 5 | 898 640 | 50 |
| 31+ [Ga] 3d³⁴p | (4p⁻³⁾²⁾ | 7 | 924 190 | 60 |
| 31+ [Ga] 3d³⁴p | (4s⁻³⁾²⁾ | 9 | 1 217 350 | 100 |
| 31+ [Ga] 3d³⁴p | (4s⁻³⁾²⁾ | 9 | 2 900 970 | 130 |
| 30+ [Ge] 3d³⁴p | (4p⁻³⁾²⁾ | 1 | 0 | 0 |
| 30+ [Ge] 3d³⁴p | (4p⁻³⁾²⁾ | 2 | 267 370 | 140 |
| 30+ [Ge] 3d³⁴p | (4p⁻³⁾²⁾ | 2 | 293 400 | 60† |
| 30+ [Ge] 3d³⁴p | (4p⁻³⁾²⁾ | 2 | 896 850 | 50 |
| 30+ [Ge] 3d³⁴p | (4p⁻³⁾²⁾ | 9 | 1 104 630 | 90 |
| 30+ [Ge] 3d³⁴d | (4p⁻³⁾²⁾ | 10 | 1 147 270 | 80 |
| 30+ [Ge] 3d³⁴d | (4p⁻³⁾²⁾ | 12 | 1 181 260 | 160 |
| 30+ [Ge] 3d³⁴d | (4p⁻³⁾²⁾ | 13 | 1 222 350 | 160 |
| 30+ [Ge] 3d³⁴d | (4p⁻³⁾²⁾ | 14 | 1 230 370 | 100 |
| 30+ [Ge] 3d³⁴d | (4p⁻³⁾²⁾ | 15 | 1 296 400 | 90 |
| 30+ [Ge] 3d³⁴d | (4p⁻³⁾²⁾ | 16 | 1 298 360 | 120 |
| 30+ [Ge] 3d³⁴d | (4p⁻³⁾²⁾ | 23 | 1 552 740 | 130 |
| 30+ [Ge] 3d³⁴d | (4p⁻³⁾²⁾ | 33 | 1 892 630 | 900 |
| 29+ [As] 3d³⁴p | (4p⁻³⁾²⁾ | 1 | 0 | 0 |
| 29+ [As] 3d³⁴p | (4p⁻³⁾²⁾ | 2 | 256 210 | 70 |
Table 3. (Continued.)

| Stage and sequence | Configuration State | Level number (FAC) | Energy (cm\(^{-1}\)) | Unc. (cm\(^{-1}\)) |
|--------------------|---------------------|-------------------|-----------------------|-------------------|
| 29+ [As] 4p\(^3\) | \((4p_\gamma, (4p_\gamma^2)_{3/2})\) | 3 | 289 330 | 50† |
| 29+ [As] 4p\(^3\) | \((4p_\gamma, (4p_\gamma^2)_{5/2})\) | 4 | 331 860 | +x |
| 29+ [As] 4s4p\(^4\) | 4d\(_\eta\) | 6 | 799 490 | 50 |
| 29+ [As] 4p\(^4\) | \((4s_\eta, (4p_\gamma^2)_{3/2})\) | 7 | 866 500 | 50 |
| 29+ [As] 4s4p\(^3\) | 4d\(_\eta\) | 8 | 897 600 | +x |
| 29+ [As] 4p\(^4\) | \((4p_\gamma, (4p_\gamma^2)_{5/2})\) | 9 | 943 540 | 60 |
| 29+ [As] 4p\(^4\) | 4d\(_\eta\) | 10 | 1 006 160 | 100 |
| 29+ [As] 4p\(^4\) | \((4p_\gamma, (4p_\gamma^2)_{5/2})_{3/2}, 4d_\eta\) | 21 | 1 263 780 | 120 |
| 29+ [As] 4p\(^4\) | \((4p_\gamma, (4p_\gamma^2)_{5/2})_{3/2}, 4d_\eta\) | 22 | 1 271 620 | 120 |
| 29+ [As] 4p\(^4\) | \((4p_\gamma, (4p_\gamma^2)_{5/2})_{3/2}, 4d_\eta\) | 23 | 1 301 880 b | 120 |
| 29+ [As] 4p\(^4\) | \((4p_\gamma, (4p_\gamma^2)_{5/2})_{3/2}, 4d_\eta\) | 24 | 1 301 880 b | 120 |
| 29+ [As] 4p\(^4\) | \((4p_\gamma, (4p_\gamma^2)_{5/2})_{3/2}, 4d_\eta\) | 28 | 1 356 240 | 120 |
| 28+ [Se] 4p\(^4\) | \((4p_\gamma^2)_{3/2}\), 4d\(_\eta\) | 1 | 0 | 0 |
| 28+ [Se] 4p\(^3\) | \((4p_\gamma^2)_{5/2}\) | 2 | 53 669 | +x |
| 28+ [Se] 4s4p\(^3\) | \((4s_\eta, (4p_\gamma^2)_{3/2})_{5/2}\) | 6 | 823 910 | 50 |
| 28+ [Se] 4p\(^3\) | \((4p_\gamma, 4d_\eta)_{3/2}\) | 7 | 866 050 | 80 |
| 28+ [Se] 4p\(^3\) | \((4p_\gamma, 4d_\eta)_{3/2}\) | 10 | 913 110 | 70 |
| 28+ [Se] 4p\(^3\) | \((4p_\gamma, 4d_\eta)_{3/2}\) | 12 | 964 703 | +y |
| 28+ [Se] 4p\(^3\) | \((4p_\gamma, 4d_\eta)_{3/2}\) | 13 | 1 002 100 | 80 |
| 28+ [Se] 4p\(^3\) | \((4p_\gamma, 4d_\eta)_{3/2}\) | 14 | 1 036 250 | 70 |
| 28+ [Se] 4p\(^3\) | \((4p_\gamma, 4d_\eta)_{3/2}\) | 15 | 1 071 900 | 130 |
| 28+ [Se] 4p\(^3\) | \((4p_\gamma, 4d_\eta)_{3/2}\) | 29 | 1 285 350 | 120 |
| 28+ [Se] 4p\(^3\) | \((4p_\gamma, 4d_\eta)_{3/2}\) | 32 | 1 297 190 | 130 |
| 28+ [Se] 4p\(^3\) | \((4s_\eta, (4p_\gamma^2)_{3/2})_{5/2}, 4d_\eta\) | 65 | 1 922 620 | +y |
| 27+ [Br] 4p\(^5\) | \((4p_\gamma^2)_{3/2}\) | 1 | 0 | 0 |
| 27+ [Br] 4p\(^4\) | \((4p_\gamma^2)_{3/2}, 4d_\eta)_{5/2}\) | 11 | 1 010 100 | 70 |
| 27+ [Br] 4p\(^4\) | \((4p_\gamma^2)_{3/2}, 4d_\eta)_{5/2}\) | 12 | 1 019 100 | 100 |
| 27+ [Br] 4s\(^3\) | 4s\(_\eta\) | 13 | 1 036 490 | 70 |
| 27+ [Br] 4p\(^4\) | \((4p_\gamma^2)_{3/2}, 4d_\eta)_{5/2}\) | 14 | 1 049 090 | 80 |
| 27+ [Br] 4p\(^4\) | \((4p_\gamma^2)_{3/2}, 4d_\eta)_{5/2}\) | 25 | 1 293 300 | 200 |
| 27+ [Br] 4p\(^4\) | \((4p_\gamma^2)_{3/2}, 4d_\eta)_{5/2}\) | 27 | 1 311 620 | 120 |
| 26+ [Kr] 4p\(^6\) | \((4p_\gamma^2)_{5/2}\) | 1 | 0 | 0 |
| 26+ [Kr] 4p\(^4\) | \((4p_\gamma^2)_{3/2}, 4d_\eta)_{5/2}\) | 3 | 887 360 | 70 |
| 26+ [Kr] 4p\(^4\) | \((4p_\gamma^2)_{3/2}, 4d_\eta)_{5/2}\) | 9 | 1 060 100 | 80 |
| 26+ [Kr] 4p\(^4\) | \((4p_\gamma^2)_{3/2}, 4d_\eta)_{5/2}\) | 13 | 1 317 500 | 120 |

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hundred and thirty five lines are measured with individual uncertainties calculated for each line. From these transitions, a total of 161 energy levels were derived and uncertainties were assigned to each value. Overall, the agreement between theory and experiment is excellent with respect to the intensities of the lines and very good for the wavelengths. Our line identifications agree very well with the already known data for Ni-, Cu-, and Zn-like ions.
Table 4. Energy levels of highly charged erbium. RMBPT—relativistic many-body perturbation theory [35], FAC—flexible atomic code [34], †-weighted average from two transitions.

| Stage and Con | Configuration | State | Level number (FAC) | Energy (cm\(^{-1}\)) | Unc. (cm\(^{-1}\)) |
|---------------|---------------|-------|-------------------|------------------------|------------------|
| 40\(^{+}\) [Ni] 3d\(^{10}\) | \((3d^1)^0\)| 1 | 9 391 473 | +x | RMBPT |
| 40\(^{+}\) [Ni] 3d\(^{4}\)4s | \((3d^4)^0, 4s\)| 2 | 9 444 260 | +x | 60† |
| 40\(^{+}\) [Ni] 3d\(^{4}\)4s | \((3d^4)^0, 4s\)| 3 | 10 294 420 | +y | RMBPT |
| 40\(^{+}\) [Ni] 3d\(^{4}\)4p | \((3d^4)^0, 4p\)| 4 | 10 596 630 | +x | 60 |
| 40\(^{+}\) [Ni] 3d\(^{4}\)4p | \((3d^4)^0, 4p\)| 5 | 10 604 920 | +x | 70 |
| 40\(^{+}\) [Ni] 3d\(^{4}\)4p | \((3d^4)^0, 4p\)| 6 | 10 951 450 | +y | 50 |
| 40\(^{+}\) [Ni] 3d\(^{4}\)4p | \((3d^4)^0, 4p\)| 7 | 11 127 857 | +z | FAC |
| 39\(^{+}\) [Cu] 4s | 4s, | 1 | 671 970 | | 60 |
| 39\(^{+}\) [Cu] 4p | 4p, | 2 | 1 193 370 | | 170 |
| 39\(^{+}\) [Cu] 4d | 4d, | 3 | 2 049 480 | | 360 |
| 39\(^{+}\) [Cu] 4d | 4d, | 4 | 2 359 780 | | 230 |
| 38\(^{+}\) [Zn] 4s\(^2\) | \((4s^2)^1\)| 1 | 638 980 | | 50 |
| 38\(^{+}\) [Zn] 4s4p | \((4s^2, 4p)\)| 2 | 1 229 820 | | 180 |
| 38\(^{+}\) [Zn] 4s4d | \((4s^2, 4d)\)| 3 | 2 823 040 | | 310 |
| 38\(^{+}\) [Zn] 4s4d | \((4s^2, 4d)\)| 4 | 2 453 320 | | 370 |
| 37\(^{+}\) [Ga] 4p | 4p, | 1 | 502 760 | | 140† |
| 37\(^{+}\) [Ga] 4p | 4p, | 2 | 659 610 | | 50 |
| 37\(^{+}\) [Ga] 4p\(^2\) | 4p, | 3 | 1 074 090 | | 140 |
| 37\(^{+}\) [Ga] 4p\(^2\) | \((4s^2, 4p)\)| 4 | 1 131 460 | | 240 |
| 37\(^{+}\) [Ga] 4p\(^2\) | \((4s^2, 4p)\)| 5 | 1 216 140 | | 170 |
| 37\(^{+}\) [Ga] 4p\(^2\) | \((4s^2, 4p)\)| 6 | 1 237 970 | | 220 |
| 37\(^{+}\) [Ga] 4d | 4d, | 7 | 1 619 300 | | 320 |
| 36\(^{+}\) [Ge] 4p\(^2\) | \((4p^2)^1\)| 1 | 440 827 | | FAC |
| 36\(^{+}\) [Ge] 4p\(^2\) | \((4p^2)^1\)| 2 | 479 420 | | 70 |
| 36\(^{+}\) [Ge] 4p\(^2\) | \((4p^2)^1\)| 3 | 1 061 840 | | 50 |
| 35\(^{+}\) [As] 4p\(^3\) | \((4p^3)^1\)| 1 | 638 250 | | 330 |
| 35\(^{+}\) [As] 4p\(^3\) | \((4p^3)^1\)| 2 | 1 083 300 | | 90 |
| 35\(^{+}\) [As] 4p\(^3\) | \((4p^3)^1\)| 3 | 1 610 740 | | 170 |
| 35\(^{+}\) [As] 4p\(^3\) | \((4p^3)^1\)| 4 | 1 646 720 | | 310 |
| 35\(^{+}\) [As] 4p\(^3\) | \((4p^3)^1\)| 5 | 1 652 980 | | 370 |
| 34\(^{+}\) [Se] 4p\(^3\) | \((4p^3)^1\)| 1 | 63 215 | | FAC |
| 34\(^{+}\) [Se] 4p\(^3\) | \((4p^3)^1\)| 2 | 1 089 480 | | 180 |
| 34\(^{+}\) [Se] 4p\(^3\) | \((4p^3)^1\)| 3 | 1 249 340 | | 180 |
| 34\(^{+}\) [Se] 4p\(^3\) | \((4p^3)^1\)| 4 | 1 266 900 | | 190 |
| 34\(^{+}\) [Se] 4p\(^3\) | \((4p^3)^1\)| 5 | 1 320 360 | | 190 |
| 34\(^{+}\) [Se] 4p\(^3\) | \((4p^3)^1\)| 6 | 1 660 300 | | 590 |
| Stage and sequence | Configuration | State | Level number (FAC) | Energy (cm⁻¹) | Unc. (cm⁻¹) |
|-------------------|---------------|-------|--------------------|---------------|-------------|
| 34+ [Se]          | 4p⁴3d         | (((4p¹) , (4p²)₂)₃)/₂)₃ | 30              | 1 668 630     | 490         |
| 33+ [Br]          | 4p³           | (4p¹)₃)₃/₂       | 1               | 0             | 0           |
| 33+ [Br]          | 4p⁴3d         | (((4p¹) , (4p²)₂)₃)/₂)₃ | 3               | 1 043 590     | 130         |
| 33+ [Br]          | 4p⁴3d         | (((4p¹) , (4p²)₂)₃)/₂)₃ | 5               | 956 800       | 530         |
| 33+ [Br]          | 4p⁴3d         | (((4p¹) , (4p²)₂)₃)/₂)₃ | 6               | 1 977 240     | 160         |
| 33+ [Br]          | 4p⁴3d         | (((4p¹) , (4p²)₂)₃)/₂)₃ | 12              | 1 270 380     | 210         |
| 33+ [Br]          | 4p⁴3d         | (((4p¹) , (4p²)₂)₃)/₂)₃ | 13              | 1 272 610     | 160         |
| 33+ [Br]          | 4p⁴3d         | (((4p¹) , (4p²)₂)₃)/₂)₃ | 14              | 1 288 160     | 190         |
| 33+ [Br]          | 4p⁴3d         | (((4p¹) , (4p²)₂)₃)/₂)₃ | 24              | 1 672 540     | 190         |
| 33+ [Br]          | 4p⁴3d         | (((4p¹) , (4p²)₂)₃)/₂)₃ | 25              | 1 672 540     | 190         |
| 33+ [Br]          | 4p⁴3d         | (((4p¹) , (4p²)₂)₃)/₂)₃ | 26              | 1 681 280     | 170         |
| 32+ [Kr]          | 4p⁶           | (4p¹)₃h          | 1               | 0             | 0           |
| 32+ [Kr]          | 4p⁴3d         | (((4p¹) , (4p²)₂)₃)/₂)₃ | 3               | 962 370       | 130         |
| 32+ [Kr]          | 4p⁴3d         | (((4p¹) , (4p²)₂)₃)/₂)₃ | 9               | 1 303 010     | 200         |
| 32+ [Kr]          | 4p⁴3d         | (((4p¹) , (4p²)₂)₃)/₂)₃ | 13              | 1 684 740     | 380         |
| 31+ [Rb]          | 4d            | 4d              | 1               | 0             | 0           |
| 31+ [Rb]          | 4d            | 4d              | 2               | 95 819 +x     | FAC         |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 5               | 1 067 570     | 150         |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 6               | 1 082 580     | +x 120      |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 8               | 1 124 800     | 170         |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 11              | 1 158 890     | 160         |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 14              | 1 179 840     | +x 140      |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 16              | 1 207 390     | +x 150      |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 17              | 1 211 910     | 180         |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 21              | 1 255 770     | 200         |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 22              | 1 255 770     | 200         |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 25              | 1 279 690     | 190         |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 28              | 1 341 500     | 210         |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 32              | 1 446 140     | 240         |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 34              | 1 589 690     | 300         |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 40              | 1 674 780     | 510         |
| 31+ [Rb]          | 4p⁴3d²        | (((4p¹) , (4p²)₂)₃)/₂)₃ | 45              | 1 720 010     | 400         |

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