

## UV light from the ground term of Ti-like ytterbium, tungsten, and bismuth

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We have used an electron-beam ion trap to measure the wavelength of the  $J=2-3$  magnetic dipole transition in the  $3d^4$  ground term of Ti-like ytterbium, tungsten, and bismuth. This fills in a gap in previous measurements along this isoelectronic sequence, as well as extending previous work to the highest  $Z$  yet. With the addition of our results, measurements of this line now cover a sufficient range of  $Z$  to allow an interpolation of reliable wavelength estimates for the unmeasured members of the isoelectronic sequence from  $Z=52$  to 83. We provide a table of these wavelengths for each member of the sequence in this range, and compare the measured wavelengths to recent calculations. Our results show that a long-standing discrepancy between prediction and experiment disappears in the high- $Z$  limit.

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Since Feldman, Indelicato, and Sugar made the surprising prediction [1] that a visible-near-uv transition in the ground term of the Ti-like isoelectronic sequence was nearly  $Z$  independent over the upper half of the Periodic Table, several experimental measurements were made to test this calculation [2-4]. The predicted line arises from an  $M1$  transition between the lowest  $J=2$  and 3 levels of the  $3d^4$  ground configuration, and the radiative decay rates are high enough to make the line reasonably strong under most plasma conditions. In addition to being a curiosity (transitions of this sort typically scale as  $Z^4$ ), there is significant interest in these lines because their unexpected weak dependence on  $Z$  makes them potentially important for plasma diagnostics [1-5]. The unusual nature of these lines also makes them useful for testing relatively uncharted aspects of many-body atomic calculations.

The original Dirac-Fock calculations, which included correlations among all  $M$ -shell electrons, disagree with experiment by as much as 5% for  $Z \approx 60$  [3]. This is a surprisingly large discrepancy for such a relativistic calculation of a highly charged ion, the error presumably arising from missing correlation effects. Subsequent calculations [6] for  $54 \leq Z \leq 64$ , which included correlations via excitations to virtual subshells, reduced the discrepancy in this range of  $Z$  to  $\approx 1.5\%$ . In recent years relativistic many-body atomic calculations have improved dramatically [7,8] and it is essential to have high-quality experimental data over as wide a range of  $Z$  as possible to compare with the calculations. Systems like the Ti-like sequence, where many-body effects are very important and the visible transition can be measured accurately, are particularly well suited as tests of the theory. In addition, since the  $J=2-3$  optical transition ( $\Delta E \approx 3$  eV) arises from a small difference between relatively large energies ( $E \approx 80$  eV for tungsten), the Ti-like system serves as a good test of effects which influence the  $J=2$  and 3 states differently. Very recent multiconfiguration Dirac-Fock (MCDF) calculations of this line in the very high- $Z$  ions tungsten and bismuth [9] provide strong motivation for measuring them.

Electron-beam ion traps (EBIT's) are versatile tools for measuring atomic properties over an extremely wide range of charge states. There have been measurements of the  $J=2-3$  line previously reported for five different Ti-like ions:

four in the range from Xe ( $Z=52$ ) to Gd ( $Z=64$ ) [2,3] and a single measurement at Au ( $Z=79$ ) [4]. Some of these measurements were confirmed in subsequent experiments in independent labs [10,11]. Reference [11] also provided an interesting qualitative explanation for the unusually weak  $Z$  dependence of this line. The goal of this study was to measure wavelengths near  $Z=70$  and above  $Z=80$  in order to provide data over the entire region of the isoelectronic sequence where the line exists. The experimental arrangement is similar to that described in previous measurements [3]. Cylindrical high-voltage drift tube electrodes surrounding the trap region provide the accelerating potential for a narrow, intense electron beam which is confined by a 3T magnetic field. A metal vapor vacuum arc (MEVVA) source produces low-charged Yb, W, or Bi ions, which are injected into the EBIT, trapped, and further ionized by the electron beam. The spectrometer we used is a 0.3-m focal length Czerny-Turner scanning monochromator with a linear dispersion of 2.6 nm/mm, coupled to a cooled, blue-sensitive photomultiplier [3]. At the operating temperature of  $-25^\circ\text{C}$ , the background count rate for the photomultiplier was 3 or 4 Hz. The charge state of interest was optimized by adjusting the electron energy to be just below the ionization potentials of the ion, which were calculated to be 4246 eV for  $\text{Yb}^{48+}$ , 4920 eV for  $\text{W}^{52+}$ , and 6662 for  $\text{Bi}^{61+}$  [12]. For the ytterbium and tungsten measurements, nitrogen was introduced into the trap to provide low-mass, low-charged ions for evaporative cooling of the heavy, highly charged ions [13]. During the bismuth measurement, we found that weak lines in some charge state of nitrogen were blended with the Ti-like bismuth line, so argon was used as a cooling gas. In all cases, the gas was expanded into the trap region through a 3.2-mm-diameter hole 16 cm from the trap, from a chamber at  $\sim 1.3 \times 10^{-4}$  Pa.

In these measurements, the identification of the  $J=2-3$  line was aided by the fact that the line disappeared when the MEVVA ion loading was stopped, and that the threshold for observation of the measured lines was at the ionization energy for the production of the ion. (See Fig. 1 for the energy dependence of the tungsten line, and Fig. 2 for the spectra.) Due to the presence of the electron beam, there is a space-charge correction which decreases the actual energy of the

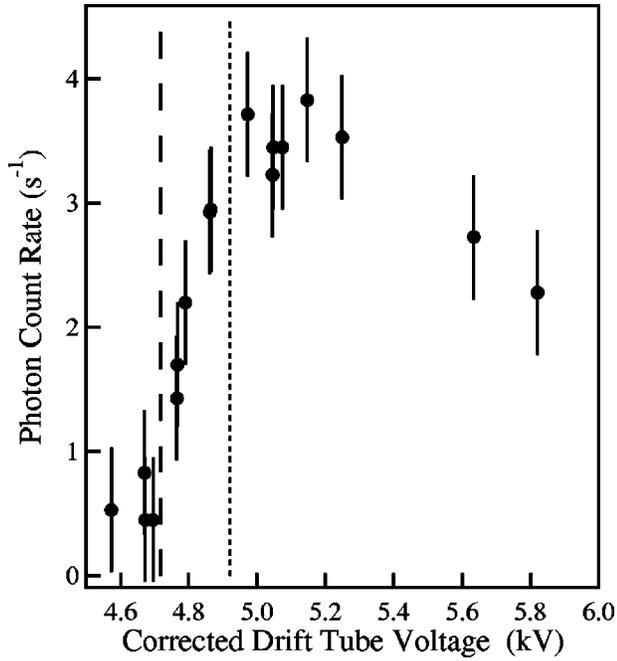


FIG. 1. Plot of the intensity of the observed  $J=2-3$   $M1$  transition in  $W^{52+}$  as a function of electron-beam energy. The drift tube voltage has been corrected for an estimated 220-V space charge shift. The dashed line represents the ionization potential for  $W^{51+}$  (i.e., the threshold for production of  $W^{52+}$ ), and the dotted line represents the ionization potential for the Ti-like state,  $W^{52+}$ .

electrons in the trap region, and this shift in the accelerating potential has been included in the data of Fig. 1. At operating conditions of 90 mA and  $\sim 5$  kV, the space-charge offset is calculated to be  $-220$  V. This estimate does not include the

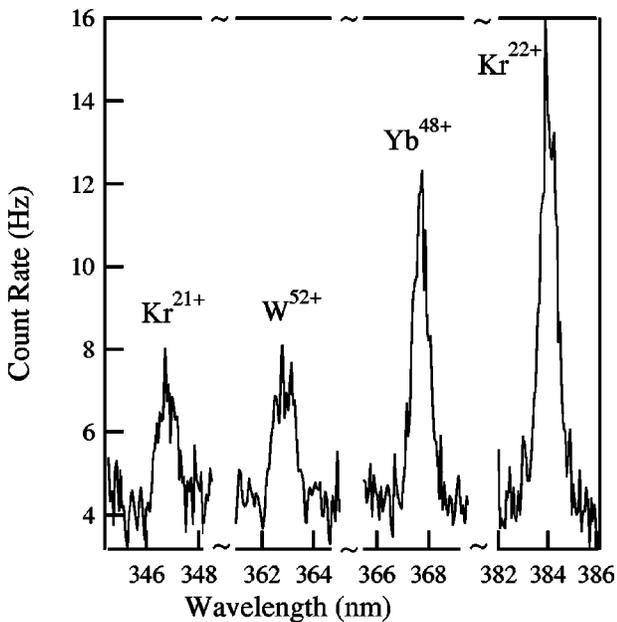


FIG. 2. Selected parts of the observed spectra during the ytterbium, tungsten, and krypton measurements. The spectrometer slits in these measurements were  $300 \mu\text{m}$ , and each peak represents an average of four scans.

partial neutralization of the electron beam by the ions, and therefore the shifted electron energies serve as lower bounds. We note that while the addition of the cooling gas increases the total number of metal ions (Yb, W, or Bi) in the trap, it usually lowers the average charge state at a given beam energy (due to charge exchange with the neutral gas). With the cooling gas, the electron-beam energy which maximizes any given charge state is raised to higher values. This fact can be seen in Fig. 1, where the maximum signal intensity from the  $W^{52+}$  occurs at a beam energy above the ionization potential for the ion. We note that the bismuth line had the correct threshold, and disappeared when the MEVVA ion loading stopped, but the intensity did not decrease even when the beam energy was as high as 10 kV, which is significantly above the ionization potential for Ti-like bismuth. We attribute this behavior to the increased charge exchange cross section for the highly charged  $Bi^{61+}$ , which pushes the charge-state balance to lower charges.

During the ytterbium and tungsten measurements, the calibration of the spectrometer was checked *in situ* against two previously measured lines in Kr which are on either side of the two Ti-like lines that we measured: the  $3s^23p^3\ ^3D_{3/2-2}D_{5/2}$  line in  $Kr^{21+}$  at 346.47(6) nm [14], and the  $3s^23p^2\ ^3P_1-^3P_2$  line in  $Kr^{22+}$  at 384.09(3) nm [15]. All four lines were measured with  $300\text{-}\mu\text{m}$  entrance and exit slits on the spectrometer, but the Yb and the 384-nm Kr lines were also measured with 150 and  $100\text{-}\mu\text{m}$  slits in order to measure slit-dependent systematics. During the tungsten run, the calibration lines indicated a 0.2-nm systematic offset in wavelengths, possibly due to misalignment of the spectrometer. The tungsten data were therefore shifted to correct for this offset. In the bismuth measurement, nearby transitions in  $N^{3+}$  were also used for calibration: the three lines arising from the  $^3S-^3P$  multiplet of the  $3s-3p$  transition array at 347.87, 348.30, and 348.49 nm [16]. The bismuth and calibration spectra were taken with  $250\text{-}\mu\text{m}$  slits in order to be able resolve the closely spaced nitrogen lines.

One interesting aspect of the Ti-like sequence is that the  $J=4$  level, which is the highest energy level of the ground term at low  $Z$ , crosses both the  $J=3$  and 2 levels as  $Z$  is increased. Unfortunately, at high  $Z$  the unobserved UV  $J=4-3$  transition competes with the  $J=2-3$  transition we observe, and at  $Z=74$  (tungsten) the branching ratio to the  $J=2$  level drops to only 16% [17]. With entrance and exit slits of  $300 \mu\text{m}$ , the maximum count rate we observed for the  $J=2-3$  line in  $W^{52+}$  was only 4 Hz, which is more than four times smaller than the rate measured on the same line in  $Gd^{42+}$  under similar conditions [3]. For bismuth ( $Z=83$ ) there is a further factor of 2 decrease in signal, making measurements of this line in such a high charge state even more difficult. The combined standard uncertainty ( $1-\sigma$  level) arising from the calibration, peak fitting and reproducibility considerations are 0.15 nm for  $Yb^{48+}$  and  $Bi^{61+}$  and 0.2 nm for  $W^{52+}$ .

The measured wavelength for the  $3d^4$   $J=2-3$  line in  $Yb^{48+}$ ,  $W^{52+}$ , and  $Bi^{61+}$ , along with previously measured wavelengths for the same transition at different  $Z$ 's, are shown in Fig. 3. We had previously found [3], that a scaling of the electrostatic integrals in the relativistic Cowan code

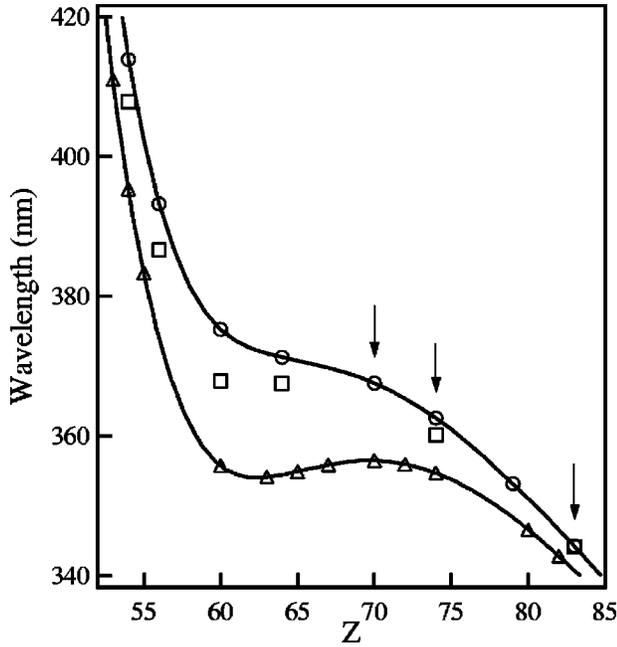


FIG. 3. Plot of the measured wavelengths of the  $J=2-3$   $M1$  transitions in the  $3d^4$  configuration of the Ti-like isoelectronic sequence (circles), including the new measurements of  $\text{Yb}^{48+}$ ,  $\text{W}^{52+}$ , and  $\text{Bi}^{61+}$ , which are indicated by arrows. (The measurements for  $Z \leq 64$  are from Refs. [2,3], and the measurement at  $Z=79$  is from Ref. [4].) The calculations of Refs. [1,17] (triangles) and [6,9] (squares) are also shown. The solid curve through the open circles is a cubic spline of the calculations, and the solid line through the measured points is the estimate described in the text.

[18], which was linear in  $Z$ , described the measured wavelengths for  $Z$  between 52 and 64. Extending this scaling to higher  $Z$  but with the scale factor capped at 1.0, however, failed to provide good agreement, since errors quickly exceeded 5%. In contrast, MCDF calculations improve at higher  $Z$ , as can be seen in Fig. 4, where we have plotted the relative error of the calculations of Indelicato and co-workers [1,17] and of Beck [6,9]. Although the discrepancy between the measurements and theory is not expected to have a simple functional dependence on  $Z$ , it is fairly smooth and the calculations approach experiment at higher  $Z$ . The recent calculation of Beck at  $Z=83$  [9] is in very good agreement with our measurement.

With the addition of the three measurements that we report here, the relatively smooth discrepancy between measurement and calculation can be used as an estimate of the unmeasured wavelengths for  $52 \leq Z \leq 83$ . In the absence of a clear functional dependence for the wavelengths, we used a simple cubic spline interpolation to estimate the difference between the data and the calculated curve shown in Fig. 3; the result is shown in Fig. 4. Using this interpolation, the wavelengths of the other Ti-like ions in this range of  $Z$  were estimated, and the resulting values are given in Table I and shown in Fig. 3. We include two points for  $Z \leq 53$  which involve extrapolations beyond the measured values. It is difficult to estimate robust errors for the interpolation and extrapolation, but we made consistency checks by removing each data point individually from the ensemble and reinter-

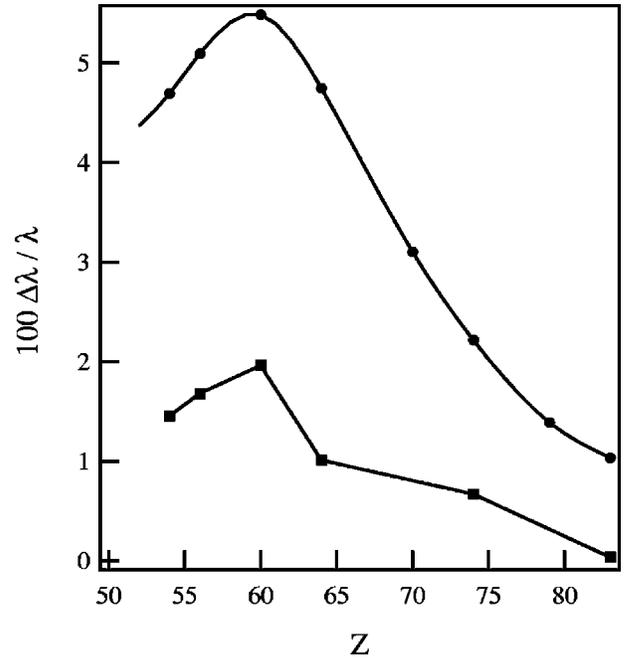


FIG. 4. Plot of the difference between calculated data and measurements (see Fig 3). The circles are from the calculations of Refs. [1,17], and the squares are from the calculations of Refs. [6,9]. The line through the circles is a cubic interpolation constrained to pass through all the measured points.

polating to predict the removed point. With the exception of the measured end points at  $Z=54$  and  $83$  (which become extrapolations once the end data points are removed) and the point of maximum curvature at  $Z=60$ , the estimated values are within 0.1% ( $<0.4$  nm) of the measured values. In all cases (including the extrapolation from  $Z=79$  to  $83$ ) the fits to subsets of the data predict the eliminated points to within 0.2% ( $<0.8$  nm). We expect the estimates to be more ac-

TABLE I. Table of measured and interpolated values for the wavelengths of the  $J=2-3$  transition within the ground term of the Ti-like isoelectronic sequence. A conservative estimate for the uncertainty in the interpolated values is 0.8 nm. (See the discussion in the text.) Measured wavelengths are indicated as (a) Ref. [2], (b) Ref. [3], (c) this work, and (d) Ref. [4].

$Z$	$\lambda$ (nm)	$Z$	$\lambda$ (nm)	$Z$	$\lambda$ (nm)
52	449.4	63	371.9	74(c)	362.6(2)
53	429.6	64(b)	371.3(2)	75	361.0
54(a)	413.9(2)	65	370.8	76	359.2
55	402.2	66	370.3	77	357.4
56(a)	393.2(2)	67	369.8	78	355.3
57	386.5	68	369.2	79(d)	353.2(2)
58	381.4	69	368.5	80	351.1
59	377.8	70(c)	367.64(15)	81	348.9
60(b)	375.3(2)	71	366.5	82	346.6
61	373.6	72	365.3	83(c)	344.29(15)
62	372.6	73	364.0		

curate than this when all the measured points are used (particularly for  $63 < Z < 83$ ), and the uncertainty for most points is likely to be limited by the 0.2-nm uncertainty in the measured wavelengths. Nonetheless, we take 0.8 nm as a conservative estimate for the uncertainty of the entire range studied. Thus the interpolation provides a 0.2% estimate of the lowest Ti-like  $3d^4$   $J=2-3$  transitions for  $52 \leq Z \leq 83$ .

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