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Visible spectra of heavy ions with an open 4f shell

Shunichi Murata[1] | **Marianna S. Safronova**[2,3] | **Ulyana I. Safronova**[4] | **Nobuyuki Nakamura**[1]

[1]Institute for Laser Science, The University of Electro-Communications, Tokyo, Japan
[2]Department of Physics and Astronomy, The University of Delaware, Newark, DE
[3]Joint Quantum Institute, NIST and University of Maryland, College Park, MD
[4]Physics Department, The University of Nevada, Reno, NV

Correspondence
Nobuyuki Nakamura, Institute for Laser Science, The University of Electro-Communications, Tokyo 182-8585, Japan.
Email: n_nakamu@ils.uec.ac.jp

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We present visible to near-infrared spectra of highly charged Yb (the atomic number 70) and W (74) obtained with a compact electron beam ion trap. By observing the dependence on the electron beam energy, the charge state that should be assigned to the observed lines is determined. For In-like Yb^{21+} and W^{25+} and Sn-like W^{24+}, the experimental spectra are compared with theoretical calculations done by the CI+all-order method. In each spectrum, the most prominent line is identified as the magnetic dipole transition from the first excited fine structure level to the ground level in the ground electronic configuration, $4f^3$ for In-like ions and $4f^4$ for Sn-like ions.

1 | INTRODUCTION

Recently, visible transitions in highly charged ions with an open 4f shell attract attention from several applications, for example, spectroscopic diagnostics of the edge plasma in ITER[1] and high-precision frequency metrology that enables sensitive detection of fundamental constant variation.[2] However, the spectra from such ions often show complex features due to dense fine structure levels arising from the coupling of 4f electrons. For example, Ho^{14+}, which is a candidate ion for the metrology application,[3] has nearly 800 fine structure levels arising from the $4f^6 5s$ and $4f^5 5s^2$ configurations near the ground level.[4] It is therefore rather challenging to understand the spectra of such complex ions in detail.

As the first step toward systematic understanding, we have recently studied the simplest 4f open-shell systems, that is, Ag-like ($4d^{10}4f$) and Cd-like ($4d^{10}4f^2$) ions.[5] In that study, several visible transitions in Ag-like and Cd-like ions of Ho (atomic number $Z = 67$), Er (68), and Tm (69) were observed with a compact electron beam ion trap (called CoBIT)[6] and identified through the comparison with theoretical calculations. In this study, we extend the previous study toward systems with more 4f electrons, such as In-like ($4d^{10}4f^3$) and Sn-like ($4d^{10}4f^4$) ions. Spectra of W and Yb ions obtained with CoBIT are presented and compared with theoretical transition probabilities obtained by the CI+all-order method.[7]

2 | EXPERIMENTS

The present experiments were performed using CoBIT.[6] Radiation from the ions produced and trapped in CoBIT[6] in the visible to near-infrared regions was observed with a commercial Czerny–Turner type of spectrometer. A Peltier-cooled charge–coupled device was used as a detector. A vapor of $W(CO)_6$ was introduced from a gas injector for producing W ions, whereas Yb was introduced with an effusion cell.[8] Wavelength calibration was done by using standard lumps placed outside CoBIT. More details of experimental setup and procedure are given in our previous papers.[5,9] It is noted that no sensitivity correction was applied to the observed spectra.

3 | RESULTS AND DISCUSSION

Figure 1 shows the electron energy dependence of highly charged W spectra. The lines indicated by the arrows in the 720-eV spectrum were not observed at 680 eV. Thus, they should be assigned to Sn-like W^{24+} considering that the ionization energy[10] of W^{23+} is 686 eV. When the electron energy was further increased to 770 eV, several lines that were not observed at 720 eV were observed as indicated by the arrows in the 770-eV spectrum. They should be assigned to In-like W^{25+} considering that the ionization energy of W^{24+} is 734 eV. In such a way, the charge state that should be assigned to the observed lines can be determined by observing the electron energy dependence although one must pay attention to the ionization below threshold when metastable excited states have nonnegligible population in the trap.[11,12]

The upper panel of Figure 2 shows the spectrum of W ions obtained at an electron energy of 770 eV. In this wavelength range, we assigned five lines, 1 to 5, as transitions in In-like W^{25+}, whose ground state configuration is $4f^3$. The lower panel shows the calculated transition probabilities for the magnetic dipole (M1) transitions in the $4f^3$ ground configuration.[7] The labels *a* to *g* correspond to the transitions shown in the calculated energy levels (Figure 3). Because an EBIT is a low-density plasma where the coronal plasma condition is well satisfied, transitions to the ground level are dominant in the spectra. Thus, judging from the comparison with the calculation, the most prominent line 2 at around 494 nm in the experimental spectrum should be identified to the transition *d*, that is, the transition from the first excited fine structure level $^4I_{11/2}$ to the ground level $^4I_{9/2}$. Visible spectra of In-like W^{25+} were also observed by the Shanghai EBIT group.[13] Their identification of the 494-nm line is consist with the present identification. We consider that the transition *f*, that is, the transition from the third excited fine structure level $^2I_{13/2}$ to the first excited fine structure level $^4I_{11/2}$, should also be observed with an intensity comparable with that of the transition *d* as it is the transition near the ground level. Thus, line 4 or 5 should correspond to the transition *f*, but we are not sure which of them does, whereas the line at 588 nm was identified as the transition *f* by the Shanghai group.[13]* The other observed lines may correspond to the other transitions (*a*, *b*, *c*, *e*, and *g*). However, they are the transitions between the higher excited levels, for which the intensity should be carefully considered through collisional radiative model calculation for the comparison with the experimental spectrum.

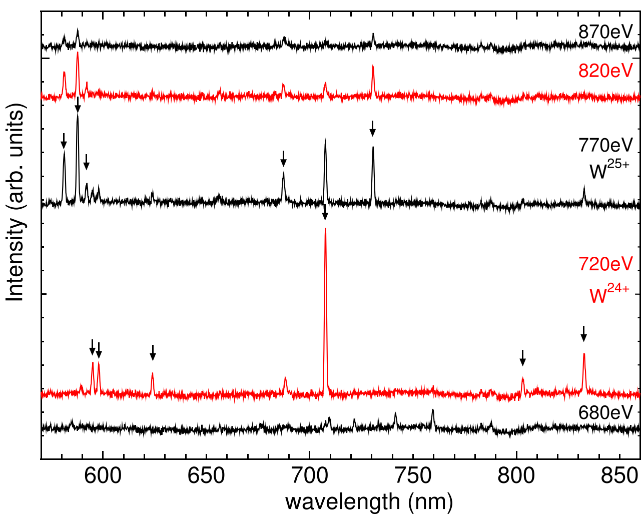

FIGURE 1 Electron energy dependence of visible to near-infrared spectra of highly charged W ions

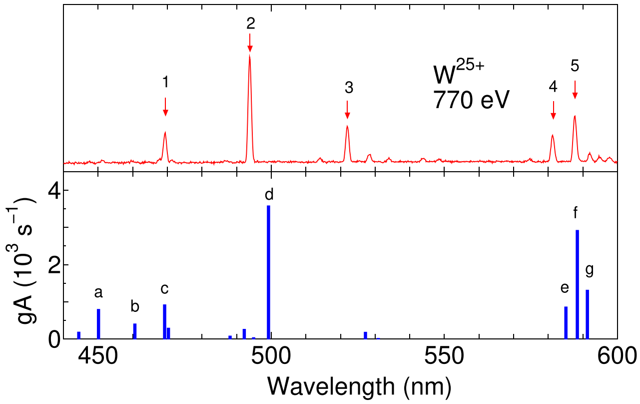

FIGURE 2 Upper panel: Visible spectrum of In-like W^{25+} obtained with CoBIT at an electron energy of 770 eV. Lower panel: Theoretical transition probabilities calculated by the CI+all-order method[7]

The top panel of Figure 4 shows the spectrum of Yb ions obtained at an electron energy of 570 eV. In this wavelength range, the seven lines indicated by the arrows were assigned to In-like Yb^{21+}. In-like Yb^{21+} also has the $4f^3$ ground configuration; thus, its energy levels are similar to those in In-like W^{25+} (Figure 3). The lower panel shows the calculated transition probabilities. Similar to In-like W^{25+} (Figure 2), the most prominent line observed at around 810 nm should be identified as the $^4I_{9/2}$ – $^4I_{11/2}$ transition (corresponding to the transition *d*), which is predicted at 817 nm in the calculation. The line observed at around 887 nm probably corresponds to $^4I_{11/2}$ – $^2I_{13/2}$

*The upper level of the transition *f* (the lowest energy level with the angular momentum $J = 13/2$ is assigned as $^4I_{13/2}$ in Li et al.,[13] whereas it is assigned as $^2I_{13/2}$ in Safronova et al.[7] This inconsistency is considered to be due to the incompleteness of the LS coupling scheme.

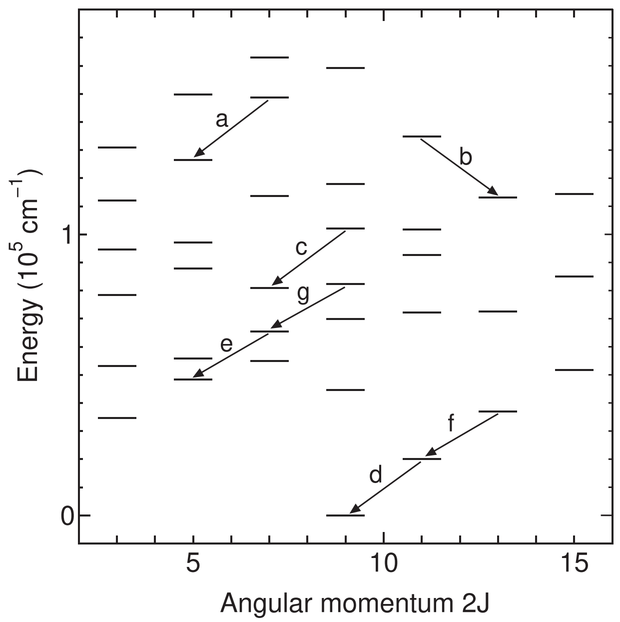

FIGURE 3 Theoretical energy levels of the $4f^3$ ground configuration of In-like W^{25+} calculated by the CI+all-order method[7]

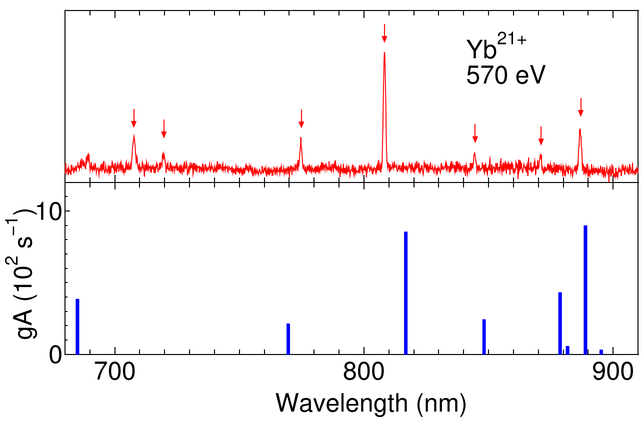

FIGURE 4 Upper panel: Visible to near-infrared spectra of In-like Yb^{21+} obtained with CoBIT at an electron energy of 570 eV. Lower panel: Theoretical transition probabilities

(corresponding to the transition *f*), which is predicted at 889 nm in the calculation. If these identifications are correct, the agreement between the experiment and the calculation in wavelength is much better for the transition *f* than for *d* in In-like Yb^{21+}. Thus, in the spectrum of In-like W^{25+} (Figure 2), line 5 may correspond to the transition *f* rather than line 4 as identified by the Shanghai group.

The upper panel of Figure 5 shows the spectrum of W ions obtained at an electron energy of 720 eV. In this wavelength range, six lines indicated by the arrows were assigned to Sn-like W^{24+}, whose ground state configuration is $4f^4$. The lower panel shows the calculated transition probabilities for the M1 transitions between the fine struc-

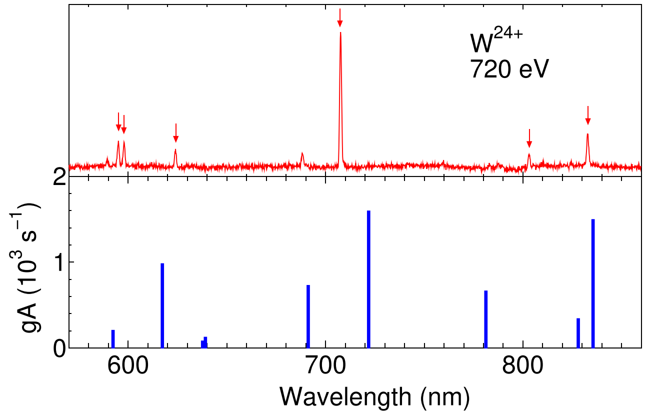

FIGURE 5 Upper panel: Visible to near-infrared spectra of Sn-like W^{24+} obtained with CoBIT at an electron energy of 720 nm. Lower panel: Theoretical transition probabilities[7]

ture levels in the $4f^4$ ground configuration.[7] The most prominent line at around 707 nm in the experimental spectrum probably corresponds to the M1 transition from the fist excited fine structure level $^5I_5$ to the ground level $^5I_4$, which is predicted at 722 nm with a weighted transition probability of 1.6×10^3 s^{-1} in the calculation. The line observed at around 887 nm probably corresponds to the M1 transition from the second excited fine structure level $^5I_6$ to the fist excited fine structure level $^5I_5$, which is predicted at 836 nm with a weighted transition probability of 1.5×10^3 s^{-1}.

In summary, we have observed visible spectra from magnetic dipole transitions in In-like W^{25+} and Yb^{21+} and Sn-like W^{24+} with a compact electron beam ion trap. In each spectrum, the transition from the first excited fine structure level to the ground level has been confirmed as a prominent peak. The transition from the second or third excited fine structure level to the first excited fine structure level has also been identified. In order to identify other observed lines, we need further studies, such as the comparison with collisional radiative model calculations[14] and the systematic studies along the isoelectronic sequence.[5]

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ORCID

Nobuyuki Nakamura https://orcid.org/0000-0002-7009-0799

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