Visible Transitions in Highly Charged Tungsten Ions: 365 - 475 nm

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Visible transitions of highly charged tungsten W^{q+} have been observed with a compact electron beam ion trap for the charge-state range of q = 8 - 28 and the wavelength range of 365 - 475 nm. More than a hundred previously-unreported lines are presented, and the charge state of the ions emitting the lines is identified from the electron energy dependence of the spectra.

Keywords: tungsten ion, visible spectrum, electron beam ion trap

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Tungsten is considered to be the main impurity in the ITER plasma, and thus spectroscopic data of tungsten ions are necessary to diagnose and control the high temperature plasma in ITER [1]. In particular, there is strong demand in the diagnostics of the edge plasmas for emission lines in the visible range [2]. Until recently, however, only one visible emission line [3] has been reported for tungsten ions with a charge state higher than two. Thus we have been observing visible spectra of tungsten ions with electron beam ion traps (EBITs) [4–6]. In this paper, we present spectra obtained for the wavelength range of 365 - 475 nm and the wavelength of more than a hundred previously unreported lines.

The experimental setup and procedure used in the present study are given in our previous papers [4, 7], they are thus briefly described here. The present experiment was performed with a compact EBIT, called CoBIT [8]. Tungsten was injected into CoBIT as a vapor of $W(CO)_6$ through a gas injection system. Highly charged tungsten ions were produced through successive electron impact ionization by a magnetically-compressed high-density electron beam. The produced ions were trapped by the axial electrostatic well potential applied to three successive cylindrical electrodes and the radial space charge potential of the compressed electron beam. Emission from the trapped ions was observed with a Czerny-Turner spectrometer with a 1200 gr/mm grating blazed at 400 nm. A biconvex lens focused the emissions on the entrance slit of the spectrometer. The diffracted light was detected by a liquid nitrogen cooled CCD. The wavelength was calibrated using emission lines from several standard lamps placed outside CoBIT. The uncertainty of the wavelength calibration was estimated to be 0.06 nm, which was mainly limited by the stability of the system.

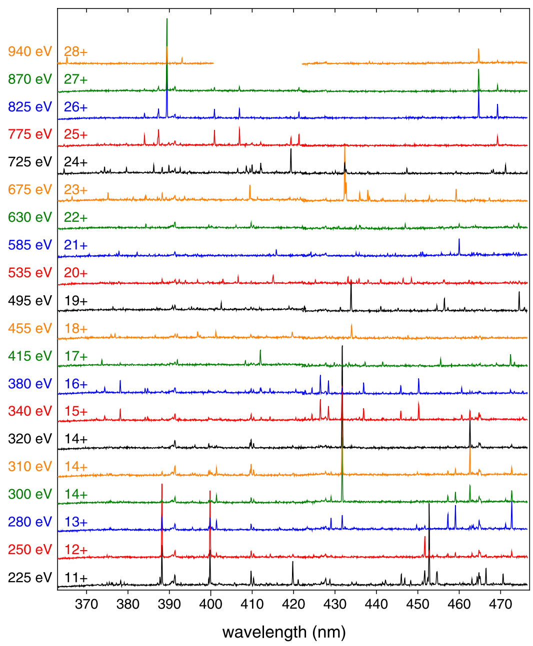

Fig. 1 Visible spectra observed with a compact electron beam ion trap. The electron energy at which the spectrum was obtained and the highest charge state for each electron energy are shown in the left side of each spectrum.

Figure 1 shows the spectra obtained at electron energies 225 to 940 eV. The electron beam current was 10 mA and the central magnetic field was 0.07 - 0.08 T. The data acquisition time was 60 min for each spectrum. The electron energy value was determined only from the output of the power supplies measured with a commercial digital multimeter. The values can thus be different from the real energy due to the space charge potential of the electron

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beam. In addition, the trap potential (30 V in this study) was not a squared well but rather like a "u-shaped" trap, that could result in higher energy components in the trap. Note that sensitivity calibration has not been applied to the spectra, so that the line intensity can not be compared.

As seen in the figure, most lines revealed a distinct appearance energy, from which the responsible ion for each line can be identified. For example, the lines at 389 nm and 464 nm in the 825 eV spectrum can be assigned as the transitions in W^{26+} because their appearance energy (the lowest energy at which the line could be observed) is just above the ionization energy of W^{25+} (784 eV [9]). The charge state for each observed line has been assigned similarly based on the experimental appearance energy and the ionization energy given in Ref. [9]. Such an assignment method has been proved to be reliable through our previous studies [4, 8, 10]. However, the assigned charge states may have an uncertainty of unity especially for weak lines from lower charge state ions, for which the ionization energy interval between adjacent charge states is comparable to the uncertainty in the electron energy.

Table 1 lists the wavelengths of the previously-unreported lines observed in this study, including several lines already reported in our previous papers [4–6] (indicated by asterisks). It is noted that 464.68 nm of W^{26+} is wrongly reported as 464.41 nm in Ref. [6, 11]. The lines at 365.25 and 393.06 nm for W^{28+} are considered to correspond to the lines "c" (365.18(3) nm) and "e" (392.99(3) nm) in Ref. [5], respectively, and it can be confirmed that the present and previous wavelengths are consistent within uncertainties. These lines have been assigned as transitions in W^{28+}, but the possibility of W^{29+} can not be entirely excluded (see Ref. [12] for details).

Since the transitions between different electronic orbitals should have a wavelength much shorter than the visible range, visible transitions are considered to be the magnetic dipole transition between fine structure levels. For W^{26+}, the initial and final fine structure levels were identified as $4d^{10}4f^2$ $^3H_5 \rightarrow {}^3H_4$, $^3H_6 \rightarrow {}^3H_5$, and $^3F_3 \rightarrow {}^3F_2$ for lines at 389.41, 464.68, and 501.08 nm, respectively, through the comparison with theoretical calculation [4,6,11]. Recently we made a calculation for the fine structure splitting between $4d^{10}4f$ $^2F_{7/2} \rightarrow {}^2F_{5/2}$ of Ag-like W^{27+}, and predicted the wavelength to be 343.0 [13] or 339.3 nm [14], which is out of the present observation range. For other lower charge states, however, calculation has not yet been made because the number of the configurations which should be included in the calculation becomes huge as the number of the $4f$ electrons increases. The detailed identification thus remains to be an issue and will be reported elsewhere in future.

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Table 1 Wavelengths (in air) of the observed visible transitions in highly charged tungsten W^{q+}.

q	wavelength (nm)
28	365.25*, 393.06*
26	389.41*, 464.68*, 501.99*
25	383.99*, 387.3*†, 400.88*, 406.92*, 421.28*, 451.15, 467.59, 469.21*, 493.62
24	364.58, 374.34, 375.70, 379.64, 386.23, 389.89, 392.62, 406.49, 408.58, 409.97, 412.2†, 419.35*, 425.17, 447.36, 467.80, 468.22, 471.18
23	366.48, 375.18, 381.25‡, 388.27, 389.19‡, 393.69‡, 409.44*, 411.28‡, 432.32*, 432.66, 437.90, 438.30, 441.52, 449.46, 459.25
22	384.32, 446.95
21	382.21, 385.16‡, 415.83, 424.17, 442.69, 444.58, 450.70, 451.17, 459.99, 463.50, 468.39
20	388.25, 402.91, 406.62, 415.06†, 422.05, 425.27, 433.14, 435.21‡, 435.82, 438.02, 448.47, 462.40
19	376.38‡, 402.52, 418.90‡, 433.89, 441.06, 456.43, 474.49
18	375.90, 376.85, 396.83, 397.42‡, 401.22, 419.68, 434.01
17	373.69, 391.93, 423.65‡
16	455.52‡, 472.39
15	372.41‡, 374.39, 378.14, 384.15, 384.76, 412.17, 414.29, 420.52, 424.45, 426.47, 428.43, 436.92, 450.23
14	462.59‡
13	457.26, 459.08, 472.68
12	401.38, 451.68
11	388.19, 399.81, 428.79‡, 446.04, 452.77, 454.64, 466.48
8	387.15, 405.73

*Reported in our previous paper [4, 6, 11], †blend lines, ‡weak lines.

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