X-Ray Spectra from Neon-like Tungsten Ions in the Interaction with Electrons

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X-ray spectra from highly charged tungsten ions have been observed in the interaction with an electron beam at energies ranging from 14 to 1.5 keV by using an electron beam ion trap (EBIT). In this energy range, resonant x-ray transitions at around 9 keV predominantly take place through dielectronic recombination processes. The measured spectra were compared with the theoretical calculation with the Hebrew University Lawrence Livermore Atomic Code (HULLAC).

Keywords: dielectronic recombination, electron beam ion trap (EBIT), resonant process, Ne-like tungsten ion, radiative electron capture

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In the ITER device currently being constructed in Cadarache, France, tungsten is considered to be a material of the plasma facing diverter wall due to the favorable physicochemical properties of this element [1]. For the plasma modeling, it is essential to gain a detailed understanding of the atomic processes of highly charged tungsten ions. Of all others, dielectronic recombination (DR) is the most important atomic process that plays a key role in determining the charge- and energy-balance in a hot plasma [2]. Therefore, an accurate knowledge of DR processes is needed for the development of fusion plasma research.

To date there have been few experimental investigations of DR processes of W ions. As the plasma temperature increases, the dominant charge state for W ions is considered to be changed from Ni-like to Ar-like, and to Ne-like W ions in a plasma with the temperature beyond several keV, which is the most relevant species to the present fusion research. In this report, we show the x-ray spectra due to DR processes ($2s^22p^6 + e \rightarrow (2s^22p^53lnl'$ or $2s2p^63lnl') \rightarrow 2s^22p^63l + h\nu$) of highly charged W ions produced in the Tokyo-EBIT (Electron Beam Ion Trap), in which the Ne-like ions are abundant by controlling the electron beam energy. The Tokyo-EBIT has been partly used to provide useful atomic data for radiative and collisional processes of highly charged ions (HCIs) [3–9] in relation to fusion and astrophysical plasma research.

The EBIT consists of an electron gun, an ion trap and an electron collector. The magnetically compressed electron beam passes through the ion trap region and is collected with the collector. Ions are produced in the trap and further ionized in a stepwise fashion by electron impact until HCIs with a required charge state are produced. Radiation from the excited trapped ions is observed at 90° with respect to the electron beam.

In the present study, the tungsten element is introduced into the trap as a molecular compound gas of $W(CO)_6$ via a nozzle gas injection port, which immediately becomes W ions with high charge-states by electron impact [10]. Ne-like ions are cooked by keeping the beam energy at 14 keV for 90 ms. This cooking energy makes Ne-like W ions the most abundant in the trap, because the ionization energy of Na-like ions is 7.1 keV, while that of Ne-like ions is 14.8 keV. The electron beam energy is ramped linearly from 14 keV to 1.5 keV, which is lower than the lowest DR resonance energy at 2 keV, and returned to the cooking energy to produce Ne-like ions again. This back and forward ramp time is fast (10 ms) enough to preserve the charge balance during the observation. This cooking (90 ms)-observation (10 ms) cycle is repeated until the clear DR x-ray spectrum can be obtained. X-ray spectra are measured with a Ge solid state detector, and recorded as a function of the electron beam energy by a list mode of the data acquisition system.

Figure 1 shows a two-dimensional map of the detected x-ray intensity as a function of the electron energy and x-ray energy. Several L x-rays (x-ray transition to L-shell) are seen along vertical lines at around 9 keV which are transitions to the ground state ($2p^6$) from the upper states of ($2p^{-1}3l$) excited by electron impact. X-ray signals due to radiative recombination (RR) processes are seen along diagonal lines since the RR x-ray energy increases linearly with the electron energy. The strong x-ray signals shown

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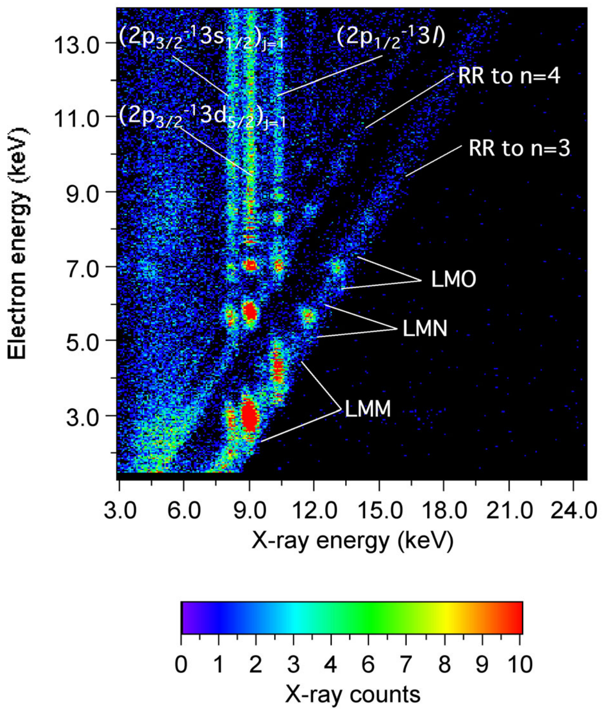

Fig. 1 Two-dimensional x-ray spectrum for Ne-like W ions as a function of electron energy. X-ray counts are shown to increase from black to red.

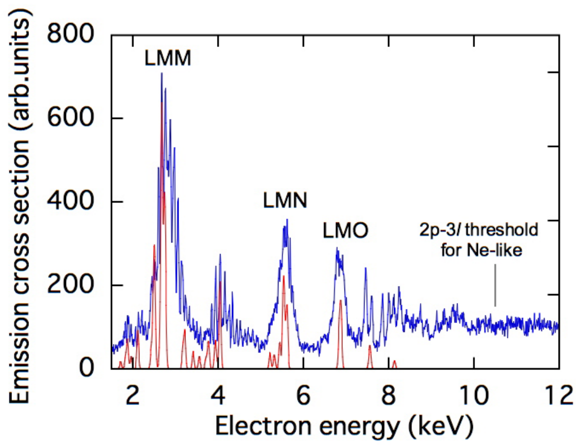

Fig. 2 Relative total x-ray emission cross-sections for highly charged W (dominantly Ne-like) ions as a function of the electron energy. Blue and red lines are the experimental results and data from the calculation by HULLAC for Ne-like ions, respectively.

as red spots are due to LMn(n = M, N, O, $\cdots$) DR resonances. LMn is the notation commonly used to specify DR resonances. For example, LMM refers to the resonant capture of a free electron into the M shell of an ion, at the same time exciting an L shell electron into the M shell. Since the DR processes take place competitively with the RR processes which have similar x-ray energies to those of L x-ray fluorescence, the DR resonances appear at the crossings of vertical and diagonal lines.

When estimating the radiative loss rates from tungsten HCIs which exist in a hot plasma with a temperature of several keV, it is important to know the excitation function for x-ray emissions as a function of the electron interaction energy with a wide range around several keV. Therefore, we derived the energy-dependent emission function of tungsten HCIs from the present observation. Figure 2 shows the relative total x-ray emission cross-sections as a function of the electron energy. The total emission cross-section at a given electron energy is obtained from the integration of x-ray signals with energies ranging from 7.5 keV to 21 keV, which contain the high energy x-ray transitions from the highly excited n level. As shown in Fig. 2, in the total x-ray emission yield spectrum, transitions due to dielectronic recombination processes (LMM, LMN, $\cdots$) have much larger contributions than the L x-rays (L$\alpha,\beta,\cdots$) due to direct excitation by electron impact with threshold energies at around 10.5 keV.

For Ne-like tungsten (W^{64+}), the DR cross-sections were calculated by Behar *et al.* [11] using the multiconfiguration relativistic Hebrew University Lawrence Livermore Atomic Code (HULLAC). In this paper, the total DR cross-sections are presented in the form of 50 eV-wide peaks for individual DR resonances of $2s^22p^53lnl'$ and $2s2p^63lnl'$ (LMn) states, which can be reasonably compared with the present observation, and thus shown in Fig. 2 as red lines. In comparison with the theoretical spectrum, the apparent experimental electron beam energy is shifted to the lower value by 200 eV. This shifted value is due to the potential difference of the actual electron interaction energy with trapped HCIs in the EBIT from the apparent applied voltage at the power supply, which includes the space charge potential lowering.

The experimental DR x-ray spectrum on the whole agrees well with the theoretical one. However, there are non-negligible differences which come from the contribution of x-ray emissions from lower charge-state (q) ions than the Ne-like ions in the trap. When we estimate the q-distribution of trapped ions at the 14 keV cooking energy and add x-ray spectra from these lower q ions to that from Ne-like ions, as we have performed this treatment in the previous investigation [7], there should be better agreement.

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