

Dielectronic and Radiative Recombination of Si- to N-like Tungsten Ions

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Abstract. We have performed x-ray spectroscopic measurements of the dielectronic recombination resonance strength for the LMn ($n=3, \dots, 10$) series of Si-like W^{60+} to N-like W^{67+} tungsten ions. Highly charged tungsten ions were produced, stored and excited with the Berlin electron beam ion trap and the emitted radiation was analyzed with a solid state detector. Information on the charge state abundance in the trap was extracted from a fit of the theoretical radiative recombination intensity to measured values. The fit procedure was only feasible when the fine structure, angular momentum of the recombination channels is taken into account. Our measurement of x-rays from $n=2-3$, $2-4$ and higher DR resonance transitions was compared to relativistic calculations of the DR cross sections and rate coefficients calculated with the Hebrew University Lawrence Livermore Atomic Code (HULLAC). The previous theoretical predictions for Ne-like tungsten (W^{64+}) [3] were extended with calculations for ions in adjacent charge states and compare well with the observed DR resonance structure.

1. Introduction

Dielectronic recombination (DR) is an important recombination process for high-temperature laboratory and astrophysical plasmas. DR is the resonant electron capture of a free electron, where simultaneously a bound electron of the ion is excited. The resulting doubly excited intermediate state stabilizes by photon emission. Spectroscopy gathers detailed information on these signatures and allows conclusions on the specific conditions of excitation in the plasma.

Present and future fusion devices are and will be armored with the heavy element tungsten as wall material made possible by the excellent thermal properties and long erosion lifetime to withstand high power fluxes of reactor plasmas [1]. In spite of these advantages tungsten may be sputtered and ionized by the high temperature plasma. The resulting radiative transitions, as for example from DR processes, contribute to the radiation energy loss in fusion plasma, change the charge state balance and satellite lines can alter line shapes, widths and intensities of parent transitions. However, understanding the radiation pattern of highly-charged heavy element ions can provide profound diagnostics of high-temperature plasma conditions and test atomic structure calculations [2].

Calculations of DR cross sections and rate coefficients for Ne-like W⁶⁴⁺ tungsten have been published by Behar et al. [3] and observation is mentioned briefly from the Tokyo EBIT [4]. At the Berlin EBIT we have investigated the DR of W⁶⁰⁺ to W⁶⁷⁺ in detail and compared the spectroscopic information to relativistic predictions applying the HULLAC suite of codes.

2. Experiment

Highly charged tungsten ions are produced, stored and excited using the Berlin EBIT [2]. Electrons extracted from a heated cathode are accelerated to 20 keV, compressed by the 3-Tesla magnetic field generating a space-charge well for radial ion confinement and forming an electron beam with 32 eV energy width. The sectioned drift-tube assembly to which the accelerating potential is applied, provides axial trapping. Tungsten is introduced as W(CO)₆ vapor and ionized by successive electron impact. After breeding for 500 ms to ionize and trap highly charged W^{60+ - 67+} ions the beam energy is rapidly ramped within 15 ms between 1.6 keV and 8 keV to excite and probe the ion ensemble. X radiation emitted from the ions is registered with a Ge-solid state detector. The ionization/DR-probe cycle is repeated many times recording the x-ray energy and the electron beam energy.

3. Radiative Recombination

One specific feature of EBIT-x-ray spectra is the appearance of the Radiative Recombination (RR) process manifested as distinct lines. Fig. 1 shows the detail of the n=3 RR x-ray spectrum from highly charged tungsten ions at a fixed beam energy of 20 keV during the last 100 ms of ionization period before starting the fast DR ramp. The x-ray energy of the registered RR-feature is given by the well-defined electron beam energy and the binding energy of the capture state of the recombining ion. For each tungsten ion the fine structure is taken into account by calculating the binding energy for each n=3 subshell (angular momentum state), the RR cross section [5] to determine the 3l relative contribution for each ion and the electron beam properties (geometry and emission characteristic) to derive a relative theoretical RR intensity distribution. The colored lines in Fig. 1 present the contributions for the individual tungsten ions. A fit of the theoretical distribution for all relevant ions states to the experimental RR-spectrum yields the charge state abundance. The charge state distribution is displayed in Fig. 3.

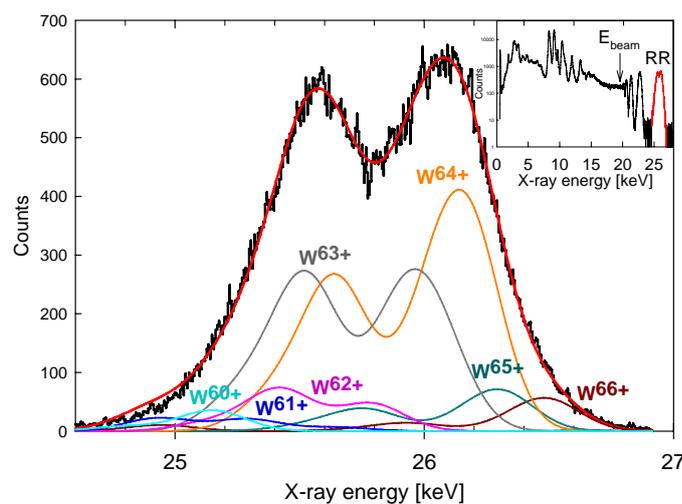


Figure 1: X-ray spectrum showing the detail of n=3 radiative recombination of highly charged tungsten ions. The black quivering line marks the observed intensity and is fitted by the *nl* contribution of W⁶⁰⁺ to W⁶⁷⁺ ions (colored lines) which sum up to the red line and gives the charge state distribution. The inset presents the wide range spectrum produced in EBIT at 20 keV electron beam energy with a logarithmic intensity scale. The spectrum is dominated by n=2-3 direct excitation lines between 8 and 13 keV rising above the Bremsstrahlung background.

4. Dielectronic recombination

Another characteristic target of EBIT investigation is the process of dielectronic recombination. The measurement of DR ramps records the x-ray emission energy as function of the electron beam energy. This information can be displayed as scatter plot (see e.g. [4]) or, emphasizing a particular DR detail,

as excitation function of x-ray emission plotted against the electron interaction energy shown in Fig. 2 for the LMM DR resonance. Fig. 2 presents the excitation function for the case when an L shell electron is excited to the M shell leaving a $2p_{3/2}^{-1}$ hole in the $(2s2p)$ configuration complex simultaneous to the resonant recombination of a free electron to the M shell followed by the emission of a 9.11 keV x-ray during the relaxation of the intermediate doubly-excited state by a $2p_{3/2} - 3d_{5/2}$ transition. Another possible LMM DR channel is the excitation leaving a $2p_{1/2}^{-1}$ hole in the L-shell and relaxation of the $(2s2p)^7 3l 3d_{3/2}$ doubly-excited state (here noted for Na-like W^{63+}) by a 11.8 keV photon originating from a $2p_{1/2} - 3d_{3/2}$ transition. In this manner the excitation function for many other LMn ($n=3$ up to 10) DR resonances have been recorded in the experiment. Apart from the relaxation of the doubly excited intermediate state, x-rays from the deexcitation of the singly excited spectator electron are detected. The observed resonance structure is compared to theoretical predictions from multiconfiguration relativistic calculations using the Hebrew University Lawrence Livermore Atomic Code [3], which is based on the parametric potential and the isolated-resonance, distorted wave approximations [6]. Extensive level-by-level computation found that the population of the $(2s2p)^7 3l 3l'$ doubly excited configuration complex is the dominating DR channel. The original calculations of DR resonance strengths and rate coefficients for Ne-like W^{64+} [3] have now been extended to the adjacent charge states ranging from Si-like W^{60+} to N-like W^{67+} LMn DR. All doubly-excited $2p^5 3l' 3l' nl''$ configurations with $n=3, 4$ were included in the computation for the DR of Na-like through Si-like W ($x=1-4$) and all of the $2p^x 3l nl'$ configurations with $n=3,4$ were included for the DR of N-like through Ne-like W ($x=2-5$). Configuration mixing, which alters the atomic structure and can appreciably affect the DR rates was taken into account. The lower plot of Fig. 2 reveals how the contributions of the different charge states of tungsten ions to the LMM DR cross section shift with decreasing charge state to larger excitation energy. Cross sections are obtained by folding the calculated resonance strength with a 32-eV-wide Gaussian profile of the experimental electron-beam energy. Weighing the cross section of the relevant tungsten ions with the charge state abundance determined by the $n=3$ RR measurement results in the solid line overlaying the experimental data points in upper part of Fig. 2. The detailed structure of the excitation function can be explained by contributions of individual resonances from certain highly charged tungsten ions.

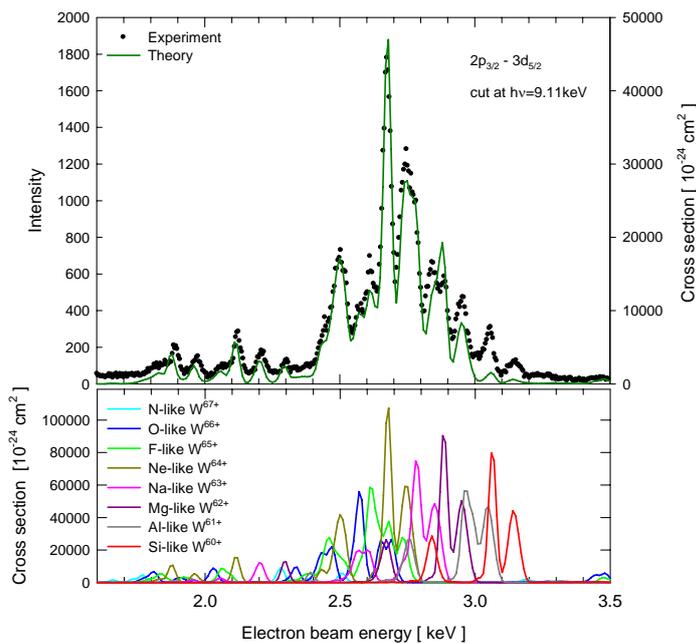


Figure 2. Comparison of measured and calculated LMM dielectronic recombination resonance cross section of highly charged tungsten ions ($q=60+$ to $67+$). Shown here is the part of the LMM DR process during which a $2p_{3/2}$ -electron is excited to $3l$, while a free electron recombines to $3l'$. The doubly excited state relaxes by emission of an x-ray following a $2p_{3/2} - 3d_{5/2}$ transition.

5. Charge state abundance

To interpret the x-ray emission of EBIT it is necessary to gain information on the charge state abundance of the trapped ions. In section 3 we have demonstrated one possible estimation of the charge state distribution by fitting theoretical RR spectrum including the fine structure of the recombination states to the measured RR x-ray intensity. Similarly to this method we can exploit the good resolution of the measured DR emission pattern and fit the theoretical DR cross section to it. The resulting charge state distribution is plotted in Fig. 3. The shift of the distribution to lower charge states reflects the fact that the process of dielectronic recombination changes the ion balance of a plasma.

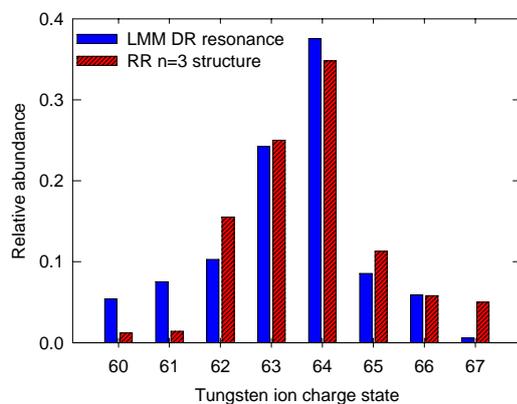


Figure 3: Charge state abundance of tungsten ions determined from the measured radiative recombination intensity at 20 keV, 100 ms before the DR ramp (red, hatched) and from a fit of the theoretical resonance strength to the observed LMM DR intensity.

References

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