X-ray Spec troscopy of Highly Charged Ions at the Tokyo EBIT

Nobuyuki Nakamura*a, Daiji Katoa, Tetsuro Nakahara*b and Shunsuke Ohtani*a,b
aCold Trapped Ions Pro ject, JICOMP, JST, 1-40-2 Fuda, Chofu, Tokyo 182-0024, Japa n
bThe University of Electro-Communications, Chofu, 182-8585 Tokyo, Japan

Recent results and experimental plans in X-ray spectroscopic studies of highly charged ions at the Tokyo EBIT (Electron Beam Ion Trap) are presented. We have been using a flat crystal spectrometer to observe X-ray transitions in the energy range of 3-10 keV. It has been used to investigate the strong configuration mixing in neon-like ions, the electron-impact excitation of highly charged ions, the polariza tion of Ly-α in hydrogen-like Ti, and so on. A Johansson type of spectrometer has been constructed to observe X-ray transitions in the higher energy range, 10-30 keV. It will be used for high-resolution spectrometry of the Lyman series in hydrogen-like medium-Z ions. In particular, an intercomparison method between Ly-α (of In48+) and Ly-β of Rh44+ is proposed to measure the 1s Lamb shift precisely. It will provide a precise test of the QED theory in the strong field regime.

INTRODUCTION

An electron beam ion trap (EBIT) is a versatile device to study highly charged ions (HCIs). It has been used especially for spectroscopic studies, where many remarkable studies have been carried out. Since X-ray radiation is dominant for transitions in HCIs, X-ray spectrometry is very important compared with those of neutral atoms and low charged ions. For instance, the Lamb shift in hydrogen-like ions in creases in proportion to Z while the electronic binding energy in increase only as Z², so that the relative contribution of the Lamb shift in increases as Z. Pre cisely measuring the energy level of the ground state in neon-like ions with Z = 50−56. In this Z region, the order of these three levels changes in the course of the change of the coupling scheme from LS to jj. At the level crossing, strong configuration interaction can be found as avoided crossings. By comparing the experimental results with theoretical calculations, the degree of mixing in the wave functions among the three excited electronic configurations was investigated.

An EBIT is a useful apparatus also to study fundamental electron-HCI collision processes in hot plasmas because trapped HCIs are excited by a monoenergetic, unidirectional electron beam. Recently, electron impact excitation processes of neon-like Xe4+ was studied. Fig. 1 shows X-ray spectra of the two transitions in neon-like Xe4+ taken at the different electron energies, (a) 5.45 keV and (b) 6.73 keV. As seen in the figure, the relative intensity of the line M2 ((2pⁿ 3s J=3/2) → 2p) has strong electron energy dependence. At an electron energy of 5.45 keV, cascades from 2l = 3 to 2p can contribute to the line in ten times of M2 to be the cause the energy is well below the threshold. On the other hand, for Ee = 6.73 keV, cascades from 2l = 4 to 2p can be prominent. Thus it is concluded that the energy dependence of the line M2 is explained by taking the configuration from cascades into account.

RECENT RESULTS

A flat crystal spectrometer has been used so far to observe X-ray transitions in the energy range of 3-10 keV, and the following results were obtained in recent experimental studies.

It is very important to study the atomic structure of neon-like ions because they are expected to be used in applications, such as plasma diagnostics and X-ray lasers. We measured wavelength for the transitions from the three excited levels, (2pⁿ 3s 3/2 J=1, 2pⁿ 3s 1/2 J=1, and (2pˡ 3s J=1), to the ground state in neon-like ions with Z = 50−56. In this Z region, the order of these three levels changes in the course of the change of the coupling scheme from LS to jj. At the level crossing, strong configuration interaction can be found as avoided crossings. By comparing the experimental results with theoretical calculations, the degree of mixing in the wave functions among the three excited electronic configurations was investigated.

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Spectra were also obtained at several other electron energies to study the excitation processes in detail. Theoretical investigation is also ongoing using the collisional radiative model.

An EBIT is also useful to measure the angular distribution and the polarization of radiation because the electron beam is unidirectional. We measured the line intensity ratio between Ly-\(\alpha_1\) and \(\alpha_2\) in hydrogenlike Ti\(^{21+}\) at an observation angle of 90° and obtained the polarization of Ly-\(\alpha_2\) as a function of electron energy.\(^{10}\) This measurement gave the first experimental result for the polarization of Ly-\(\alpha\) in highly charged hydrogenlike ions.

**PLANNED EXPERIMENTAL SUBJECTS**

Up to now, almost all experiments at the Tokyo EBIT have been performed with electron energies of below 100 keV. In the near future, however, it is planned to investigate few-electron systems with electron energies of above 100 keV. One of the planned experiments is an intercomparison between Ly-\(\alpha_1\) of hydrogenlike In\(^{48+}\) and Ly-\(\beta\) of hydrogenlike Rh\(^{44+}\) to study the QED contribution to the 1s binding energy of these ions. Fig. 2 shows the predicted positions of these lines. Within the limits of the relativistic quantum mechanics, the energy level of hydrogenlike ions is given by the solution of the Dirac equation,

\[
E = E_0 \left[ 1 + \frac{\alpha Z}{n - K + \sqrt{K^2 - \alpha^2 Z^2}} \right]^{1/2},
\]

where \(E_0\) is the rest energy \(mc^2\), \(\alpha\) the fine structure constant, and \(K = j + 1/2\). According to the equation (1), the energy difference between Ly-\(\alpha_0\) (2p\(_{1/2}\) \(\rightarrow\) 1s) of hydrogenlike In\(^{48+}\) and Ly-\(\beta_1\) (3p\(_{3/2}\) \(\rightarrow\) 1s) of hydrogenlike Rh\(^{44+}\) is 19 eV. However, by taking the Lamb shift into account, this value is modified to 10 eV, which is almost half of the Dirac value. On the other hand, the Lamb shift contribution to the transition energy of Ly-\(\alpha_1\) of hydrogenlike In\(^{48+}\) is only 0.1%. According ingly, the intercomparison method gives a sensitive test of the QED theory compared with direct absolute measurements of the wavelength of the Lyman transitions.

In order to observe the Lyman transitions in medium-\(Z\) ions, such as In\(^{48+}\) and Rh\(^{44+}\), a Johansson crystal spectrometer has been constructed. The crystal used in this spectrometer is Ge(400) processed for the fixed radius of Rowland circle, \(R = 2900\) mm. The detector is HAMAMATSU V5102UCSI.
which consists of a CsI scintillator and an imager in ten si fier. Fig. 3 shows the spectrum of the Ag K\(\alpha\) obtained with the Johansson spectrometer to examine the characteristics of the crystal. In this measurement, an imaging plate was used as a detector because the image acquisition system for the HAMAMATSU detector is under construction. As seen in the figure, line width of 11 eV FWHM was obtained for K\(\alpha_1\). By taking the natural width (8 eV) into account, resolution which can be obtained by this crystal is considered to be about 7 eV, i.e. \(E/\Delta E = 3,000\) at \(E = 22\) keV. Although the actual resolution is considered to be worse due to the position resolution of the HAMAMATSU detector, the present result indicates that the quality of the present crystal is high enough to study the Lyman series of medium-Z hydrogenlike ions.

Before observation of the Lyman lines of hydrogenlike In\(^{48+}\) and Rh\(^{44+}\), \(n = 2\) to \(1\) transitions of heliumlike In\(^{47+}\) and Rh\(^{43+}\) are planned to be observed. This observation will be performed to examine the spectrometer with the actual EBIT source. However, wavelength measurements of such lines are also important from an atomic physics point of view because there are few high-resolution spectroscopic studies for helium-like ions with \(Z > 36\). In order to produce such ions efficiently, the Tokyo EBIT is on the upgrade to routine operation with a high energy electron beam.

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Key Words

Highly charged ions; Electron beam ion trap; X-ray spectroscopy.

REFERENCES