X-ray Spectroscopy of Highly Charged Ions at the Tokyo EBIT

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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 neonlike ions, the electron-impact excitation of highly charged ions, the polarization of Ly-α in hydrogenlike Ti^{21+}, 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 spectroscopy of the Lyman series in hydrogenlike medium-Z ions. In particular, an intercomparison method between Ly-α of In^{48+} and Ly-β of Rh^{44+} 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)[1,2] is a versatile device to study highly charged ions (HCIs). It was designed especially for spectroscopic studies, where many remarkable studies[3,4] have been carried out. Since X-ray radiation is dominant for transitions in HCIs, X-ray spectroscopy is very important to study the atomic structure of HCIs. In the atomic structure of HCIs, the relativistic and quantum electrodynamics (QED) contributions are very important compared with those of neutral atoms and low charged ions. For instance, the Lamb shift in hydrogenlike ions increases in proportion to Z^4 while the electronic binding energies increase only as Z^2, so that the relative contribution of the Lamb shift increases as Z. Precise measurement of the energy levels of HCIs, then, gives a test of QED theory in the strong field regime.

In recent years, several X-ray spectroscopic studies have been carried out with the Tokyo EBIT.[5,6] In this paper, results of those studies and experimental plans in the near future are presented. A Johansson type of spectrometer is also described that has been constructed for the near future plans.

RECENT RESULTS

A flat crystal spectrometer[7] 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 neonlike ions because they are expected to be used in applications, such as plasma diagnostics and X-ray lasers. We measured wavelengths for the transitions from the three excited levels, $(2p_{3/2}^{-1}3d_{5/2})_{J=1}$, $(2p_{3/2}^{-1}3d_{3/2})_{J=1}$, and $(2p_{1/2}^{-1}3s)_{J=1}$, to the ground state in neonlike 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 crossings, strong configuration interaction can be found as avoided crossings. By comparing the experimental results with theoretical calculations,[8] the degree of mixing in the wavefunctions 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 neonlike Xe^{44+} was studied. Fig. 1 shows X-ray spectra of *n* = 3 to 2 transitions in neonlike Xe^{44+} taken at the different electron energies, (a) 5.54 keV and (b) 6.73 keV. As seen in the figure, relative intensity of the line *M*2 ($(2p_{3/2}^{-1}3s)_{J=2} \rightarrow 2p^6$) has strong electron energy dependence.[9] At an electron energy E_e of 5.54 keV, cascades from $2l^{-1}nl$ ($n \geq 4$) levels can not contribute to the line intensity of *M*2 because the energy is well below the threshold. On the other hand, for E_e = 6.73 keV, cascades from $2l^{-1}nl$ ($n \geq 4$) levels become possible. Thus it is considered that the energy dependence of the line *M*2 is explained by taking the contribution from cascades into account.

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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-α_1 and α_2 in hydrogenlike Ti^{21+} at an observation angle of 90° and obtained the polarization of Ly-α_1 as a function of electron energy.[10] This measurement gave the first experimental result for the polarization of Ly-α 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-α of hydrogenlike In^{48+} and Ly-β of hydrogenlike Rh^{44+} to study the QED contribution to the 1*s* 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,

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

where E_0 is the rest energy mc^2, α the fine structure constant, and $K = j + 1/2$. According to the equation (1), the energy difference between Ly-α_2 ($2p_{1/2} \rightarrow 1s$) of hydrogenlike In^{48+} and Ly-β_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 in the transition energy of Ly-α of hydrogenlike In^{48+} is only 0.1%. Accordingly, 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,

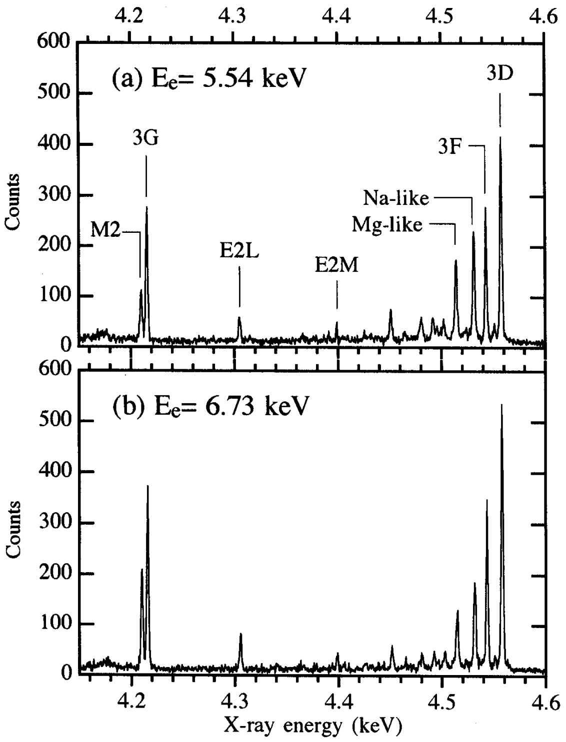

Fig. 1. X-ray spectra from neonlike Xe^{44+} obtained at electron energies E_e of (a) 5.54 keV and (b) 6.73 keV. Notations represent the upper level of the line: M2; $(2p_{3/2}^{-1}3s)_{J=2}$, 3G; $(2p_{3/2}^{-1}3s)_{J=1}$, E2L; $(2p_{3/2}^{-1}3p_{1/2})_{J=2}$, E2M; $(2p_{3/2}^{-1}3p_{3/2})_{J=2}$, 3F; $(2p_{1/2}^{-1}3s)_{J=1}$, 3D; $(2p_{3/2}^{-1}3d_{5/2})_{J=1}$. The final state is the ground state for all lines. The two lines which appear at the left side of the line 3F are lines from sodiumlike Xe^{43+} and magnesiumlike Xe^{42+}.

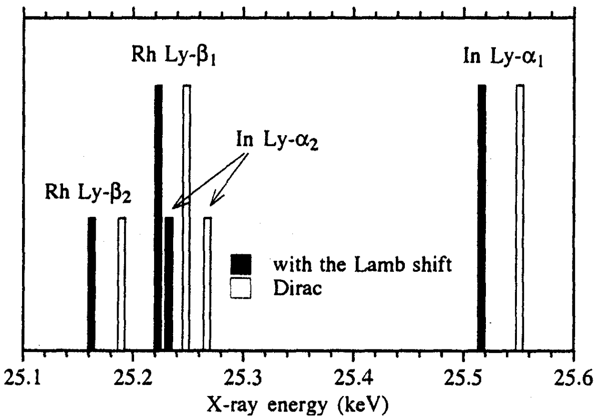

Fig. 2. Predicted line positions of Ly-α of hydrogenlike In^{48+} and Ly-β of hydrogenlike Rh^{44+}. Open lines represent the transition energy calculated from the Dirac equation, and solid lines the transition energy including the Lamb shift.

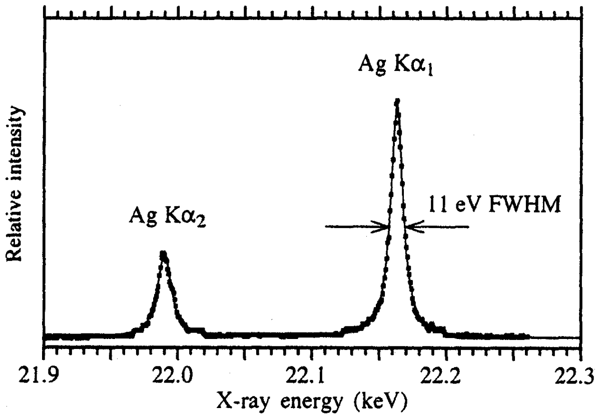

Fig. 3. Spectrum of Ag Kα obtained with the Johansson spectrometer. The line width of $K\alpha_1$ is 11 eV FWHM, which contains the natural width of about 8 eV.

which consists of a CsI scintillator and an image intensifier. 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 heliumlike ions with $Z > 36$. In order to produce such ions efficiently, the Tokyo EBIT is on the upgrade[11] at present toward 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

1. Nakamura, N.; Asada, J.; Currell, F. J.; Fukami, T.; Hirayama, T.; Kato, D.; Motohashi, K.; Nojikawa, E.; Ohtani, S.; Okazaki, K.; Sakurai, M.; Shimizu, H.; Tada, N.; Tsurubuchi, S.; Watanabe, H. *Rev. Sci. Instrum.* **1998**, *69*, 694.
2. Marrs, R. E.; Levine, M. A.; Knapp, D. A., Henderson, J. R. *Phys. Rev. Lett.* **1988**, *60*, 1715.
3. Beiersdorfer, P.; Elliott, S. R.; López-Urrutia, J. C.; Widmann, K. *Nucl. Phys. A* **1997**, *626*, 357c.
4. Widmann, K.; Beiersdorfer, P.; López-Urrutia, J. R. C.; Elliott, S. *Hyperfine Interact.* **1997**, *108*, 73.
5. Currell, F. J.; Asada, J.; Ishii, K.; Minoh, A.; Motohashi, K.; Nakamura, N.; Nishizawa, K.; Ohtani, S.; Okazaki, K.; Sakurai, M.; Shiraishi, H.; Tsurubuchi, S., Watanabe, H. *J. Phys. Soc. Jpn*. **1996**, *65*, 3186.
6. Watanabe, H.; Asada, J.; Currell, F. J.; Fukami, T.; Hirayama, T.; Motohashi, K.; Nakamura, N.; Nojikawa, E.; Ohtani, S.; Okazaki, K.; Sakurai, M.; Shimizu, H.; Tada, N.; Tsurubuchi, S. *J. Phys. Soc. Jpn*. **1997**, *66*, 3795.
7. Nakamura, N. *Rev. Sci. Instrum.* **2000**, *71*, 4065.
8. Kato, D.; Nakamura, N.; Ohtani, S.; Sasaki, A. *Phys. Scr.* **2001**, to be published.
9. Beiersdorfer, P.; Osterheld, A. L.; Chen, M. H.; Henderson, J. R.; Knapp, D. A.; Levine, M. A.; Marrs, R. E.; Reed, K. J.; Schneider, M. B.; Vogel, D. A. *Phys. Rev. Lett*. **1990**, *65*, 1995.
10. Nakamura, N.; Kato, D.; Miura, N.; Nakahara, T.; Ohtani, S. *Phys. Rev. A* **2001**, *63*, 024501.
11. Ohtani, S. *J. Chin. Chem. Soc*. **2001**, in this issue.