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X-ray spectroscopy of high-Z highly charged ions with the Tokyo EBIT

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Abstract

We have been using the Tokyo electron beam ion trap to investigate the relativistic and the quantum electrodynamical effects on the atomic structure of few electron heavy ions. In this paper, we present 1s binding energy measurement for hydrogen-like rhodium which was performed as one of such systematic studies. It has been obtained by measuring the X-ray transition energy for radiative recombination into the 1s vacancy of bare rhodium and subtracting the electron beam energy from it. For further investigation, a bent crystal spectrometer for hard X-rays is being developed. The design of the new spectrometer and the preliminary result with it are also presented.

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1. Introduction

In the atomic structure of highly charged heavy ions, the contributions from the relativistic and quantum electrodynamical effects are clearly observable compared with that of neutral atoms and low charged ions. For instance, the Lamb shift in hydrogen-like ions increases in proportion to Z^4 while the electronic binding energies increase only as Z^2. Thus, the relative contribution of the Lamb shift is much enhanced at a high Z ionic system. Precise measurement of the energy levels of highly charged heavy ions, thus, gives a test of quantum electrodynamics theory in the strong field regime. The Tokyo electron beam ion trap (EBIT) [1–3] is a suitable device to study such few electron heavy ions because it can produce and trap such ions efficiently with an intense high energy electron beam (300 keV – 300 mA at the maximum). In the course of X-ray spectroscopic studies at the Tokyo EBIT facility, the 1s binding energy in hydrogen-like rhodium has been measured, which is shown in this paper together with the recent development of an hard X-ray spectrometer.

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2. 1s binding energy for hydrogen-like rhodium

In an EBIT, a nearly monoenergetic electron beam with a width of ~50 eV interacts with trapped ions. When the target ion is bare, the beam electron can be captured into the 1s vacancy with emitting a radiative recombination (RR) X-ray whose energy (E_{RR}) is the sum of the electron energy (E_{e}) and the 1s binding energy ($E_{1\mathrm{s}}$) of the recombined hydrogen-like ion:

$$E_{\mathrm{RR}} = E_{\mathrm{e}} + E_{1\mathrm{s}}. \tag{1}$$

Thus, if $E_{1\mathrm{s}}$ is known, E_{e} can be determined by measuring E_{RR}. For example, the 1s energy of hydrogen-like krypton is known with an accuracy of 0.5 eV [4]. Then, by measuring the RR X-ray energy for bare krypton, the electron beam energy can be determined with an accuracy of up to 0.5 eV. Once the electron energy is determined, the 1s binding energy of hydrogen-like heavy ions which are also trapped with krypton ions can be obtained by measuring the RR X-ray energy for those bare ion.

In the present measurement, the RR transitions into the 1s vacancy of bare krypton and rhodium were observed simultaneously:

$$E_{\mathrm{RR}}^{\mathrm{Kr}} = E_{\mathrm{e}} + E_{1\mathrm{s}}^{\mathrm{Kr}}, \tag{2}$$

$$E_{\mathrm{RR}}^{\mathrm{Rh}} = E_{\mathrm{e}} + E_{1\mathrm{s}}^{\mathrm{Rh}}. \tag{3}$$

The difference between the above equations gives

$$E_{\mathrm{RR}}^{\mathrm{Rh}} - E_{\mathrm{RR}}^{\mathrm{Kr}} = E_{1\mathrm{s}}^{\mathrm{Rh}} - E_{1\mathrm{s}}^{\mathrm{Kr}}. \tag{4}$$

Thus, the 1s binding energy of hydrogen-like rhodium ($E_{1\mathrm{s}}^{\mathrm{Rh}}$) can be determined by measuring the difference in RR X-ray energy between rhodium and krypton because $E_{\mathrm{RR}}^{\mathrm{Kr}}$ is accurately known.

The present experimental setup and procedure are similar to those used by Marrs et al. [5] in the measurements of two-electron contributions to the ground state energy of helium-like ions. Highly charged rhodium and krypton were produced and trapped in the Tokyo EBIT. Rhodium was injected from a metal vapor vacuum arc (MEVVA) source [6] installed at the top of the EBIT, while krypton was continuously injected from a gas injector installed at the same level as the middle DT. The injection methods for gas and metal ions are described in detail elsewhere [6].

RR X-rays were observed with a planar germanium detector (Eurisys Mesures EGP500-15) through a beryllium window with a thickness of 1 mm and a radius of 25 mm. The two radioisotopes ^{109}Cd and ^{57}Co were used to calibrate X-ray energy. Radiations from these isotopes were measured simultaneously with the RR X-rays to examine the pulse height drift arising from the output instability of the detector and the electronics. An aluminum foil 0.3 mm thick was placed between the window and the detector to attenuate intense characteristic X-rays from krypton and rhodium ions and prevent the piling up of the signal pulses. The intensity of radiations from the isotopes was adjusted by covering them with an aluminum sheet and by adjusting the distance from the detector.

RR spectra were acquired as follows. After injecting rhodium ions from the MEVVA source, trapping potential was applied to the trap electrodes. Data acquisition was then started after waiting for 1.5–3.5 s for ion production. Observation was continued for 8–12 s, and then the trapped ions were dumped by removing the trapping potential and rhodium ions were injected again. The dumping was needed to avoid the accumulation of contaminants such as Ba and W evaporated from the cathode. One run was terminated after repeating this cycle of 1–1.5 h. More than 10 runs were integrated to obtain the final spectrum. Several runs which were found to show large drift were excluded from the integration. As a result, the drift of each peak was restrained within ±35 eV, which is much small compared to ±200 eV in [5].

In the present measurements, the electron–ion interaction energy for rhodium and krypton ions must be the same. It was thus essentially important to trap and observe rhodium and krypton simultaneously. If rhodium and krypton were observed alternately, the degree of the neutralization of the electron beam must change, where the electron–ion interaction energy would change for each trapped ion. The simultaneous observation is also important to prevent the experimental uncertainty arising from the instability of the electronics and so on. Existence of krypton and rhodium ions in the trap at the same time was confirmed by observing the time evolution of the RR X-rays from both ions.

Measurements were done at two different electron energies 74 and 106 keV to examine systematic uncertainties. The electron beam currents were 155 and 135 mA, respectively.

Fig. 1(a) shows a spectrum obtained at an electron energy of 106 keV. The peak width was mainly determined by the detector resolution, which is ~550 eV full width at half maximum (FWHM). The energy spread of the electron beam (~50 eV) was too small to contribute to the peak width. Although the observation was performed for ~17 h, data showing large drift were excluded from integration to obtain the final spectrum shown in Fig. 1(a). As a result, the practical live time was ~11 h. Two reference lines from ^{57}Co were recorded simultaneously. The value of interest in this experiment is the difference between krypton and rhodium in the X-ray energy for RR into the 1s vacancy of the bare ion, i.e. the difference in the 1s binding energy of the hydrogen-like ion. To determine the center of each peak, the fitting procedure presented by Longoria et al. [7] was used. The solid line in Fig. 1(a) represents the results of the fit, and Fig. 1(b) shows the residuals of the fit. No significant residual is found, suggesting that the peak functions used in the fitting procedure was appropriate. The values of interest obtained are listed in the first column of Table 1. The experimental errors represent the statistical ones.

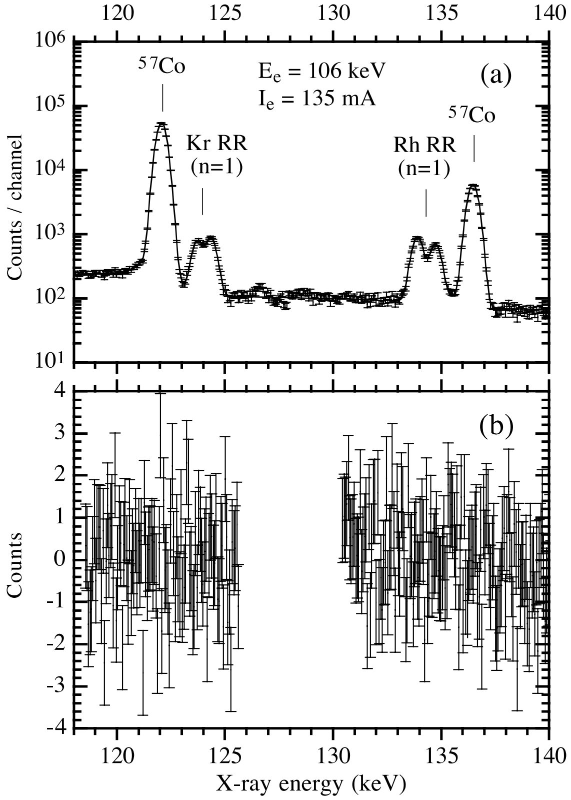

Fig. 1. (a) RR spectra obtained at an electron energy of 106 keV. Peaks around 124 and 134 keV corresponds to RR for krypton and rhodium ions, respectively. There are two peaks for each element; one of them, which appear in the higher energy side, corresponds to RR into the 1s vacancy of the bare ion, and another corresponds to RR into the 1s vacancy of the hydrogen-like ion. Peaks at 122 and 136 keV are the reference lines from the radioisotope ^{57}Co. The solid line is the peak function fitted to the data. (b) Normalized residuals of the fit. The region between 125.7 and 130.4 keV were excluded from the fit procedure.

Similar observation was performed also at an electron energy of 74 keV to examine systematic errors. The experimental spectrum with accumulation time of 13.5 h was fitted by using the similar method. The solid line in Fig. 2(a) represents the result of the final fit, and in Fig. 2(b) the residuals are shown. The values of interest obtained are listed in the second column of Table 1.

Since there is no inconsistency between the two results, the final value was obtained as a weighted mean of the two results as shown in the third column of Table 1.

The energy of the $2p_{3/2}$–1s transition (Lyman-α_1) in hydrogen-like krypton was precisely measured by Tavernier et al. [4] to be $13\,508.95 \pm 0.5$ eV. Taking account of the theoretical $2p_{3/2}$ energy, which was accurately calculated by Johnson and Soff [8] to be -4427.28 eV including the Lamb shift, the 1s binding energy of hydrogen-like krypton is estimated to be $-17\,936.23 \pm 0.5$ eV. Using this value, we determined the 1s binding energy of hydrogen-like rhodium from Eq. (4) to be $-28\,308.4 \pm 3.4$ eV. By subtracting the point-nucleus Dirac eigenvalue, which is 28 337.09 eV including the nonrelativistic reduced mass correction,

Table 1
Difference in X-ray energy for RR into the 1s vacancy of the bare ion between rhodium and krypton

	Present 1	Present 2	Weighted mean
Experiment	10 380.0 ± 7.0	10 369.7 ± 3.9	10 372.1 ± 3.4
Theory [8]			10 375.76
Difference			−3.6 ± 3.4

Results obtained at $E_e = 106$ keV are listed in the column "present 1", and that at $E_e = 74$ keV in "present 2". All values are given in eV. The errors correspond to the 68% confidential limit.

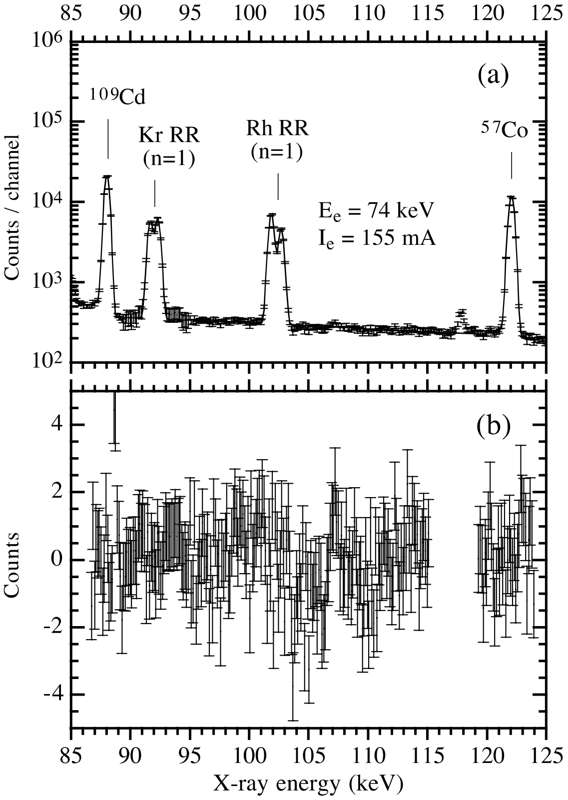

Fig. 2. (a) RR spectra obtained at an electron energy of 74 keV. Peaks around 92 and 102 keV corresponds to RR for krypton and rhodium ions, respectively. Peaks at 88 and 122 keV are the reference lines from the radioisotopes ^{109}Cd and ^{57}Co. (b) Normalized residuals of the fit. The region between 115.2 and 119.1 keV were excluded from the fit procedure.

we have obtained the 1s Lamb shift of hydrogen-like rhodium to be 28.7 ± 3.4 eV. The present results are summarized in Table 2.

In Table 2, a theoretical result obtained with a nonperturbative numerical method by Johnson and Soff [8] is also listed. The difference between the experiment and the theory is slightly larger than the experimental uncertainty. However, considering that the experimental uncertainty represents the 68% confidence limit, it can be concluded that the theoretical value agree well with the experiment. The theoretical uncertainty is estimated to be 0.03 eV including several contributions such as the self energy, the nuclear size effect and so on. Although the experimental uncertainties are not enough to test these theoretical uncertainty, the present measurement demonstrated the new method to measure the 1s Lamb shift with an EBIT. Compared to measurements with an accelerator, the present method using trapped ions has the strong point that the experimental uncertainty is not affected by the Doppler effect, and is limited only by the counting statistics. However, when the accuracy beyond the present measurement is required, it may be needed to develop a detector with higher energy resolution and to develop an EBIT capable of trapping more ions. The present experimental uncertainty is less than 1% of the FWHM of the peak, where it may be difficult to increase the accuracy only by increasing observation time. Novel technical developments for the

Table 2
Present result for the 1s binding energy and the 1s Lamb shift in hydrogen-like rhodium

	Present	Theory [8]	Difference
Rh^{44+} 1s binding energy	28 308.4 ± 3.4	28 311.96 ± 0.03	−3.6 ± 3.4
Rh^{44+} 1s Lamb shift	28.7 ± 3.4	25.13 ± 0.03	3.6 ± 3.4

measurements of the binding energy with high accuracy and high resolution are also needed.

3. Spectroscopy of hard X-rays

The 1s Lamb shift can also be investigated through precise wavelength measurements of the Lyman transitions. For high resolution spectroscopy of such transitions in high-Z highly charged ions, we are developing a bent crystal spectrometer. It consists of a Ge(4 0 0) crystal and an image sensor for hard X-rays. Two crystals are under examination; one is bent in the Johansson geometry while another is bent in the Johann geometry. For both geometries, the radius of the Rowland circle is 2900 mm. The image sensor is HAMAMATSU V5102UCsI, which consists of a CsI scintillator and an image intensifier. The effective area of the sensor is 17.5 mm in diameter and the thickness of the scintillator is 150 μm. The image intensifier has three micro channel plates to have the sufficient gain. The quantum efficiency of the sensor is mainly dominated by the absorption in the scintillator, which is about ~70% for 20 keV. The positions of the crystal and the sensor can be adjusted precisely on goniometers. The size of the goniometer stage is $1.2 \times 1.2\ \mathrm{m}^2$.

The resolution of the spectrometer was examined with the characteristic lines of Ag, which are emitted through interaction of a Ag wire inserted into the EBIT with an electron beam whose current was less than 1 μA. For the Kα line of Ag (~22 keV), a width of 20 eV (FWHM) was obtained including the natural width of about 8 eV. The spectrometer was also examined with X-rays from highly charged ions trapped in the EBIT. Fig. 3 shows the preliminary result obtained for helium-like indium. Although the counting statistics is very low because of the low luminosity of the EBIT source and the low reflectivity of the crystal for hard X-rays, a transition from trapped ions have been successfully observed in a practical accumulation time (10 h). The spectrometer is still under development; the resolution and the efficiency are expected to be improved furthermore.

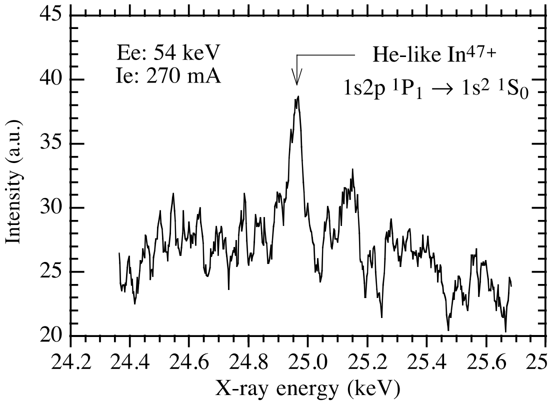

Fig. 3. X-ray spectrum from helium-like indium trapped in the Tokyo EBIT observed with the new bent crystal spectrometer. The observation time was 10 h with a 54 keV – 270 mA electron beam.

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