Polarization measurement of *L*-shell radiative recombination x rays from highly charged bismuth ions

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We report a polarization measurement of *L*-shell radiative recombination (RR) x rays emitted from He- to F-like bismuth ions. The polarization feature was obtained from the azimuthal angular distribution of the Compton-scattered RR x rays detected with a recently developed state-of-the-art Compton polarimeter installed on an electron beam ion trap. This is one of a very few polarization measurements of RR x rays ever conducted and the first one with bismuth ions. We derived the degree of linear polarization averaged over the charge states to be 0.666 ± 0.014. By contrast, a theoretical estimation of the degree of polarization with the Flexible Atomic Code (FAC) yields 0.716 ± 0.023. The discrepancy between the observed and theoretical values is likely to be due to the electron correlation effects.

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I. INTRODUCTION

Radiative recombination (RR) is one of the major physical processes in the collisions of highly charged ions with electrons. In RR, a free electron is captured into an unoccupied orbital of an ion and simultaneously a photon is emitted, carrying an energy equivalent to the sum of the incident electron energy and the binding energy of the recombined level. RR processes are important for a variety of applications, such as plasma diagnostics, and have thus been extensively studied theoretically and in experiments [1,2].

A process called radiative electron capture (REC) in relativistic ion-atom collisions has also been studied for the same reason. In REC, an electron bound to an atom or molecule is captured into a highly charged ion, where a photon is emitted, carrying the excess energy and momentum. When an electron is loosely bound to a neutral target, REC can thus be regarded as the RR of a free electron with a momentum distribution.

RR and REC into inner-shells of highly charged heavy ions, such as *K* and *L* shells, can emit x rays with energies greater than about 10 keV, namely in hard the x-ray range. It is well known that these hard x rays are, in general, strongly polarized [3,4]. This polarization feature is useful for diagnostics of polarized particle beams for experimental verification of the standard model [5,6]. Moreover, hard x-ray polarization also gives us insight into relativistic effects, such as the Breit interaction [7]. Hence, systematic studies of polarized hard x rays from RR and REC are important. Over the last few decades, theoretical calculations of RR and REC x-ray polarizations have been performed [8–10]. By contrast, only a few experiments have been reported to date, primarily because of the technical difficulties in the polarimetry of hard x rays [4,11].

The first experiment for this purpose was performed in 2006 at the GSI Helmholtzzentrum für Schwerionenforschung, where the polarization of *K*-shell REC x rays was measured for bare uranium ions using a position-sensitive germanium pixel detector [12]. More recently, in 2015, the first experiment to measure the polarization of RR x rays was performed with a Si-PIN diode array installed on an electron-beam ion trap (EBIT) at the Max Planck Institute [11]. In their experiment, the degree of the linear polarization of the *L*-shell RR x rays emitted from highly charged Kr ions was measured, but the result was not consistent with the calculated result with the Flexible Atomic Code (FAC) [13]. The reason for the discrepancy has remained unresolved. More systematic

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experimental studies of heavier elements and multi-electron systems are essential to test the theory of relativistic quantum calculations.

Recently, we developed a Compton polarimeter for studying polarization of hard x rays from highly charged ions in the EBIT [14]. It is based on the state-of-the-art Si/CdTe semiconductor Compton camera originally developed for astronomical x-ray observations with the satellite Hitomi [15–19]. The polarimeter, named the EBIT-CC, was demonstrated to work as expected through polarization measurements of K-shell RR x rays emitted from H-like and bare Kr ions [14]. The EBIT-CC employs multilayered Si pixel detectors as scatterers and CdTe pixel detectors as absorbers. It is capable of determining the direction of scattering photons by reconstructing the three-dimensional position of interactions in the camera, and therefore, the degree of polarization of the incoming photons can be determined more precisely than previous instruments.

In this paper, we report an application of the EBIT-CC to the linear-polarization measurement of L-shell RR x rays emitted from He- to F-like Bi ions. The measured degree of linear polarization is compared with a theoretical estimation performed with the FAC.

II. EXPERIMENTS

We observed RR x rays from highly charged Bi ions and measured the degree of linear polarization of the L-shell RR x rays.

The experiment was conducted with the Tokyo-EBIT at the University of Electro-Communications. The detail of the device was described in our previous paper [20]. Here we present its concise summary and the configuration of the experiments. Highly charged Bi ions were generated in the EBIT, the main parts of which are an electron gun, an ion trap surrounded by a superconducting magnet, and an electron collector. The ion trap is composed of three parts and both ends were biased at 50 V for axial confinement of the ions. An electron beam was generated in the electron gun, compressed by a magnetic field of 4 T, and was accelerated to 51.10 keV. The current was approximately 115 mA. The generated electron beam passed through the center of the ion trap and ionized targets on impact. The space charge potential of the beam confined the ions in the radial direction. The typical beam radius was 30 μm and the height of the emission region was smaller than 10 mm. An effusion cell was used for Bi injection into the ion trap [21]. The temperature of its crucible was kept at 580° C during the experiment. A vapor of Bi injected into the trapping region was ionized by successive electron impacts up to a charge state of 81+ (He-like Bi ion). Table I lists the parameters used in the present experiment.

Highly charged Bi ions confined in the trap captured electrons and emitted x rays through RR. The emitted RR x rays were simultaneously observed with a high-purity Ge solid-state detector and the EBIT-CC. These detectors were installed immediately adjacent to the Tokyo-EBIT in the direction perpendicular to the electron beam axis and at distances of about 450 and 500 mm, respectively, from, and in the mutually opposite sides to, the center of the ion trap (Fig. 1).

The Ge detector used in the present experiment was ORTEC GLP-36360/13, whose energy resolution in the specification is 585 eV (in full-width at half-maximum: FWHM) at 122 keV. The resolution in the present experimental circumstance was 553 eV at 81 keV. A beryllium window with an effective diameter of 25 mm was placed in front of the detector.

TABLE I. Experimental parameters.

Parameter	Value
Electron beam energy	51.10 keV
Electron beam current	115 mA
Magnetic field	4 T
Effusion cell temperature	580°C
Trapping potential	50 V
Measurement time	154.4 h
Electron beam radius	30 μm

The EBIT-CC contained two types of detectors: Si detectors, which mainly worked as a scatterer, and CdTe detectors, which mainly worked as an absorber. The Si detectors were stacked in 32 layers, each of which was pixelized into 16 × 16. Two layers of CdTe detectors surrounded the Si-detector layers on all four sides, and eight layers of CdTe detectors were placed at the bottom. The side and bottom layers of the CdTe detectors were pixelized into 16 × 24 and 16 × 16, respectively. The size of each pixel was 3.2 × 3.2 mm^2 for both the Si and CdTe layers. The Compton-scattered position of an incident photon and the photoabsorbed position of the scattered photon were detected with the pixelized detectors, while the energy deposits on the scatterer and absorber of each event were also recorded. For photons with the energy below 100 keV, most of the Compton-scattered photons should be absorbed in the Si or CdTe-side part, and therefore the trigger for the CdTe-bottom part was disabled in the present measurement [14].

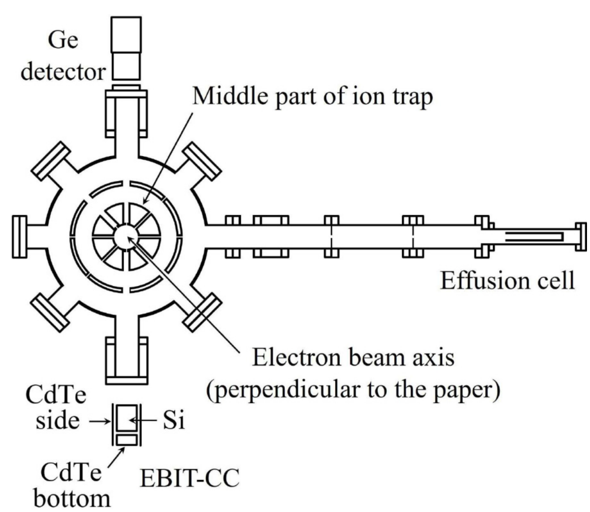

FIG. 1. Schematic drawing of the experimental apparatus. The EBIT-CC and the Ge detector are installed perpendicular to the electron beam axis and at distances of about 450 and 500 mm, respectively, from the center of the ion trap. Details of the EBIT-CC are described in [14,17].

III. THEORETICAL CALCULATIONS

The differential cross sections of the *L*-shell RR with He- to F-like Bi ions are required for estimation of the charge-state abundances of the ions, which is required to determine the degree of linear polarization.

We obtain the fine-structure-resolved total RR cross sections by FAC using the distorted-wave approximation [13], taking into account the electronic dipole operator. The wave functions of continuum and bound orbitals are obtained by solving the single-electron Dirac equations with a spherical model potential based on the self consistent Dirac-Fock-Slater calculation. In the computations, the ground and singly excited states up to $n = 5$ shells of recombining and recombined ions are considered; for instance, the configurations of $1s^2$, $1snl$, and $1s^2nl$ ($n = 2$–5, $l = 0$–4) are considered in the computation of the transition energies and cross sections for RR with He-like Bi ions. The total RR cross section ($\sigma_{\rm RRT}$) for each fine-structure level is computed using the function RRTABLE in the FAC, whereas the differential cross sections and the polarization are computed using the function ASYMMETRY, which gives the total RR cross sections ($\sigma_{\rm asym}$) and differential RR cross sections at 90° ($d\sigma_{\rm asym}/d\Omega$) both with respect to the electron beam for a single nl_j orbital. We thus obtained the differential RR cross section for each fine structure level according to the formula

$$\frac{d\sigma}{d\Omega} = \sigma_{\rm RRT}\frac{d\sigma_{\rm asym}/d\Omega}{\sigma_{\rm asym}}. \tag{1}$$

The function ASYMMETRY also gives the ratios of the 90° cross sections for the RR photons polarized in the directions perpendicular and parallel to the electron beam direction ($\sigma_\perp/\sigma_\parallel$). The degree of linear polarization of the RR x rays was obtained by substituting the calculated $\sigma_\perp/\sigma_\parallel$ into $P = (1 - \sigma_\perp/\sigma_\parallel)/(1 + \sigma_\perp/\sigma_\parallel)$. In the present calculations, only the electric dipole transitions were taken into account, and the other multipole transitions were not considered.

To estimate the charge-state abundances of the Bi ions, we fitted the calculated differential RR cross sections convoluted with the spectral width to *L*-shell RR x-ray spectrum observed with the Ge detector. In the fitting, the relative intensity of the RR x rays from the ions in the same charge state and the relative position of the RR resonance were fixed to the calculated values with the FAC, whereas the charge-state abundance, spectral width, and energy offset were allowed to vary.

IV. EBIT-CC DATA ANALYSIS

The azimuthal angular distribution $\Phi^{(P)}(\phi)$ of the count rate of the x-ray photons having the degree of linear polarization P can be represented with the linear combination of $\Phi^{(0)}(\phi)$ and $\Phi^{(1)}(\phi)$ for the unpolarized and fully polarized photons, respectively, as

$$\Phi^{(P)}(\phi) = P\Phi^{(1)}(\phi) + (1 - P)\Phi^{(0)}(\phi). \tag{2}$$

The degree of polarization was obtained by fitting this function to the experimentally obtained distribution with P as a fitting parameter. Specifically, in this study, $\Phi^{(0)}(\phi)$ and $\Phi^{(1)}(\phi)$ were obtained through Monte Carlo simulations.

We measured the azimuthal distribution of the Compton scattered x rays, using the EBIT-CC. Here, we selected only the two-hit events detected at the Si–Si or Si–CdTe parts of the detector. The total energy of the energy deposits of the two-hit events were restricted to the expected energy range of 68–80 keV for the x rays from *L*-shell RR with He- to F-like Bi ions. We filtered out the events of which the total energy is out of the energy range above, regarding them as the background, i.e., the events that did not satisfy the expected Compton kinematics. The resultant azimuthal angular distribution of the x-ray count rate is a function of the azimuthal Compton-scattering angle of the incident photon, which reflects the polarization characteristics of the photons. Finally, we obtained the degree of linear polarization for the incident RR x rays through the quantitative analysis of the obtained azimuthal distribution in a way described in [14].

The degree of linear polarization was obtained by fitting the azimuthal angular distribution calculated with Monte Carlo simulations to that obtained with the EBIT-CC. The Monte Carlo simulations were performed using the COMPTONSOFT simulation toolkit [22], which is based on the GEANT4 simulation framework [23,24]. In the simulations, photons with the energy distribution that was calculated with FAC simulations from the x-ray energy spectrum obtained in the Ge detector. These photons were also assumed to be emitted from a point source placed at the center of the Tokyo-EBIT. The tracks of the incident x-ray photons in the detector were simulated, where the detector geometry, physical processes in the detector, and data processing system were taken into account. Details about the simulations of the EBIT-CC were given in our previous paper [14]. The azimuthal angular distributions $\Phi^{(0)}(\phi)$ and $\Phi^{(1)}(\phi)$ were then obtained from the simulations for the unpolarized and fully polarized photons, respectively. Note that the distribution of the unpolarized x rays represents the detector response function. Finally, we divided the azimuthal distribution obtained with the EBIT-CC by the simulated $\Phi^{(0)}(\phi)$ and derived a curve with sinusoidal modulation, of which the amplitude represents the degree of polarization of the x rays.

V. RESULTS AND DISCUSSION

In this section, we first estimate the theoretical degree of linear polarization of the *L*-shell RR x rays from the energy spectrum observed with the Ge detector, using the FAC. Then, to verify the application of the EBIT-CC to the present measurement, we compare the energy spectra obtained with the EBIT-CC and the simulation. Finally, the degree of linear polarization of *L*-shell RR is determined from the azimuthal angular distributions obtained with the EBIT-CC and the simulations.

The charge-state abundances of the He- to F-like Bi ions confined in the EBIT are needed to obtain the charge-state-averaged degree of linear polarization. To estimate the abundances, we used the measured and calculated results with the Ge detector and FAC, respectively. We successfully observed the x rays emitted from the RR into the $n = 2$–5 shells of highly charged Bi ions. Figure 2 shows an x-ray energy spectrum measured with the Ge detector. In the spectrum, the *L*-shell RR components are separated into two peaks at

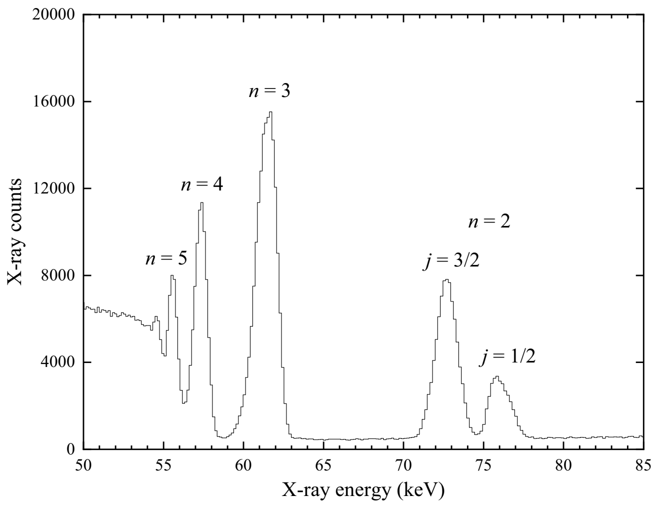

FIG. 2. Energy spectrum of the RR x rays measured with the Ge detector for an electron energy of 51.10 keV. Spectral features due to the RR into the $n = 2$–5 shells were observed in an energy range of 55–80 keV. The L-shell RR was divided into two according to the angular momenta j of 1/2 and 3/2.

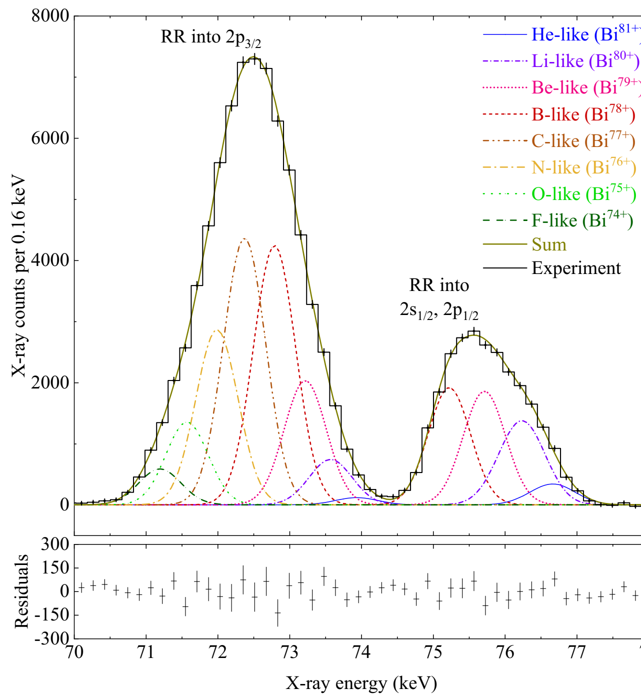

FIG. 3. Observed energy spectrum of L-shell RR x rays in the energy range of 70–78 keV overlaid with the best-fit result and its subcomponents, i.e., the contributions of the L-shell RR x rays from He- to F-like Bi ions (see text for the fitting model). The error bars indicate 1 σ statistical errors. Lower panel shows the residuals of the fit.

~73 and ~76 keV as expected, which correspond to the two different values of the angular momentum j, specifically the RR into the $2p_{3/2}$ subshell and into the $2s_{1/2}$ and $2p_{1/2}$ subshells, respectively. These spectral features are composed of the L-shell RR x rays in several charge states reflecting the charge-state distribution of the He- to F-like Bi ions in the trap.

We performed the spectral fitting by using the theoretical values as tabulated in Table II and the background-subtracted L-shell RR x-ray spectrum measured with the Ge detector. We obtained the acceptable fitting result with χ^2/d.o.f of 55/63 and with no systematic trend in the residuals. Figure 3 shows the observed spectrum with the best-fit model along with its sub-components from the ions of each charge state. The FWHM of the spectral width was determined to be

TABLE II. List of calculated parameters and fitting result about the L-shell RR for He- to F-like Bi ions. $2l_j$, J, E, $d\sigma/d\Omega$, and P indicate the electron capture level, total angular momentum, energy of the RR x ray, differential RR cross section at 90° with respect to the electron beam direction, and the degree of linear polarization of the RR x ray, respectively. The abundance ratio of Bi ions corresponding to the measured L-shell RR spectrum is also listed.

Initial ion	RR to $2l_j$	$2J$	E (keV)	$d\sigma/d\Omega$ (10^{-24} cm^2/sr)	Abundance ratio (%)	P
$Bi^{81+}(1s^2)$	$2s_{1/2}$	1	76.77	3.632	0.55 ± 0.06	0.9665
	$2p_{1/2}$	1	76.53	1.489		0.6624
	$2p_{3/2}$	3	73.97	1.653		0.7098
$Bi^{80+}(1s^2 2s)$	$2s_{1/2}$	0	76.38	1.781	3.51 ± 0.11	0.9667
	$2p_{1/2}$	0	76.17	0.371		0.6632
		2	76.13	1.112		
	$2p_{3/2}$	4	73.65	1.029		0.7106
		2	73.54	0.614		
$Bi^{79+}(1s^2 2s^2)$	$2p_{1/2}$	1	75.75	1.486	9.60 ± 0.27	0.6640
	$2p_{3/2}$	3	73.26	1.625		0.7117
$Bi^{78+}(1s^2 2s^2 2p)$	$2p_{1/2}$	0	75.26	0.739	19.92 ± 0.42	0.6647
	$2p_{3/2}$	2	72.84	0.613		0.7129
		4	72.82	1.021		
$Bi^{77+}(1s^2 2s^2 2p^2)$	$2p_{3/2}$	3	72.41	1.625	20.62 ± 0.46	0.7136
$Bi^{76+}(1s^2 2s^2 2p^3)$	$2p_{3/2}$	4	72.03	1.013	21.67 ± 0.87	0.7144
$Bi^{75+}(1s^2 2s^2 2p^4)$	$2p_{3/2}$	3	71.61	0.806	12.89 ± 0.64	0.7153
$Bi^{74+}(1s^2 2s^2 2p^5)$	$2p_{3/2}$	0	71.23	0.401	11.24 ± 0.85	0.7160

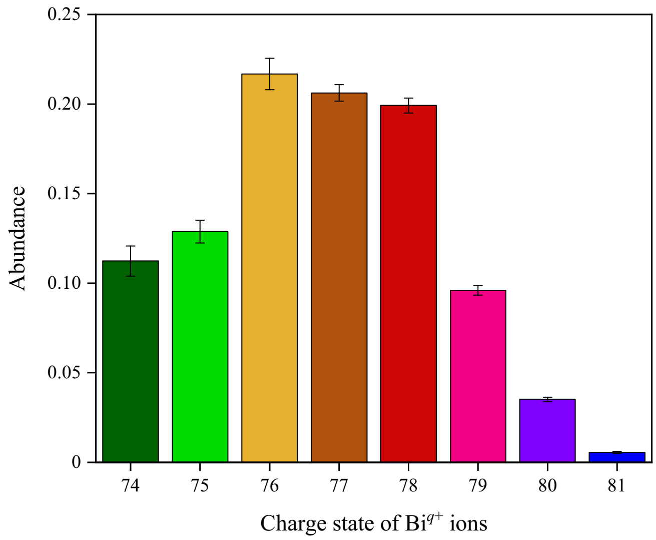

FIG. 4. Charge-state abundance distribution obtained from the spectral fit (see Fig. 3). The histogram shows the abundance of Bi^{q+} ions produced with the electron beam with an energy of 51.10 keV. The error bars indicate the 1σ statistical errors of the fitting.

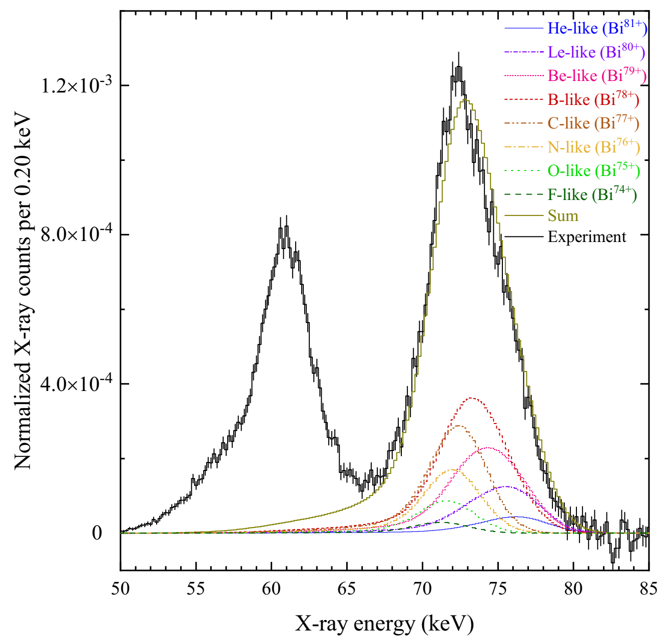

FIG. 5. Histogram with 1-σ error bars shows the background-subtracted data measured with the EBIT-CC, and the others show the Monte Carlo simulated data, where both the measurement and simulation are limited to the two features derived from *L*- and *M*-shell RR.

692 ± 13 eV, which is a combination of the detector resolution and the energy width of the electron beam. The charge-state abundances of He- to F-like Bi ions obtained from the spectral fit are shown in Fig. 4 and listed in Table II.

We derived the theoretical degrees of linear polarization of the *L*-shell RR x rays in this experimental setup to be 0.716 ± 0.023 (1σ statistical error obtained from the abundance fitting), averaging those for each orbital of each charge-state listed in Table II, weighting them with the obtained abundances and theoretical differential cross sections. Theoretically, the RR processes into the $2s_{1/2}$ subshells have the largest cross sections and degrees of linear polarization. However, in the present experimental condition, their contributions to the total polarization are relatively small because of the small abundances of He- and Li-like Bi ions. Similarly, the contributions of the RR into the $2p_{1/2}$ subshells are also relatively small. The averaged degree of polarization of the *L*-shell RR x rays is thus predominantly determined by the RR into the $2p_{3/2}$ subshells in the present case.

The energy spectra obtained with the EBIT-CC and the Monte Carlo simulation are shown in Fig. 5. The two spectra were found to be in agreement, the fact of which confirms the validity of the simulation of the unpolarized and fully polarized cases used to derive the observed degree of polarization. In the measured spectrum with the EBIT-CC, two broad peaks were observed at around 61 and 72 keV, which correspond to *M*- and *L*-shell RR, respectively. The energy resolution of the EBIT-CC was 4.7 keV in FWHM at 81 keV, which is not sufficient to separate the RR peaks for the $2l_{1/2}$ and $2l_{3/2}$ subshells in the observed spectrum. The low-energy tail apparent in the spectrum is characteristic of the EBIT-CC, which is due to the inefficient charge collection in the CdTe semiconductor [22] and is well reproduced in our simulation.

We derived the degree of linear polarization of the measured *L*-shell RR x rays to be $P = 0.666 \pm 0.010$ by fitting the $\Phi^{(P)}(\phi)$ function to the experimental azimuthal angular distribution. Figure 6 shows the modulation curves for the *L*-shell RR x ray obtained from the EBIT-CC measurement and the best-fit result of the simulation. The comparison between the experimentally determined degree of linear polarization and the theoretical one (0.716 ± 0.023) implies that the FAC calculation overestimates the RR polarization or that our experiment suffered depolarization. Here we discuss four possible sources of the discrepancy between the experiment and the theory: electron spiraling, the angular distribution of the degree of polarization, uncertainty in the charge-abundance-estimation, and multipole effects.

Since an electron beam in a strong magnetic field spirals around magnetic field lines, a velocity vector of the beam electrons deviates from the beam-propagation direction, i.e., the central axis of the EBIT. The spiral motion thus causes the depolarization of the emitted x rays. Gu *et al.* [25,26] formulated the degree of the reduction of the polarization as a function of the pitch angle between the magnetic field line and the velocity vector of electrons. Herrmann [27] established a relation between the transverse velocity and radius of the electron beam compressed by a magnetic field. Using these, we estimate the degree of the depolarization to be 0.6% for the pitch angle of about 4° in the present experimental condition.

In general, the degree of linear polarization has an angular distribution, which peaks at 90° and equals 0 at 0° with respect to the quantization axis (the electron beam in the present experiment). The finite acceptance angle due to the finite area of the polarimeter should thus result in depolarization. However, the depolarization effect is calculated to be about 0.1% at the maximum acceptance angle ($90 \pm 3°$). The effect should be much smaller for the degree of polarization integrated over the acceptance angle.

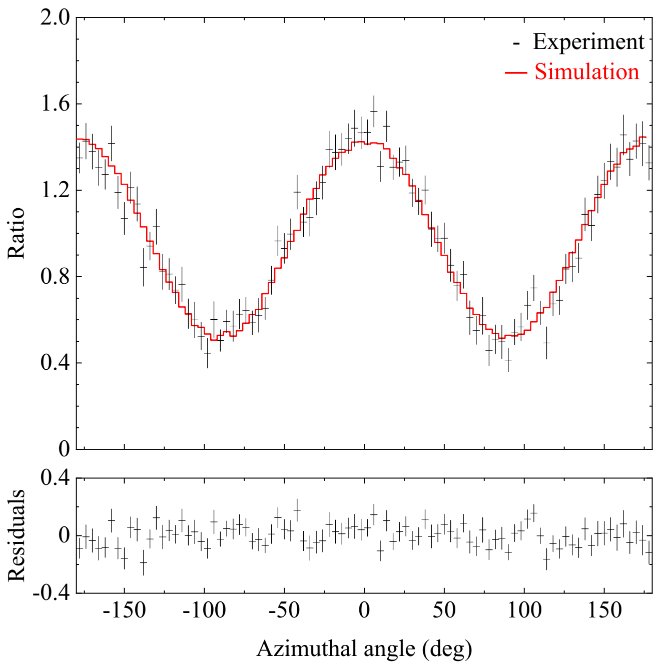

FIG. 6. Modulation curves for the L-shell RR x rays emitted from highly charged Bi ions (see text for detail). The vertical axis indicates the ratios of the azimuthal angular distribution obtained with the EBIT-CC measurement and the best-fit result of the simulation to the simulated distribution for unpolarized photons. Points with 1-σ statistical error bars show the background-subtracted data obtained with the experiments. Histogram shows the best-fit data of the simulation. Lower panel indicates the residuals of the two data.

The charge-state abundance in the EBIT plasma was estimated from the spectral fitting based on the calculated differential RR cross sections. The estimated abundance has some systematic uncertainty, which may affect the resultant estimation of the polarization and may lead to the discrepancy between the above-mentioned theoretical and experimental degrees of linear polarization. To assess the effect of the systematic uncertainty of the charge-state abundance, we estimate the theoretical degree of linear polarization using the trial abundances whose average charge states differ from that of the estimated abundance by $+1$ and -1 and find that they lead to differences of only about 0.5 and 1.5%, respectively. This is presumably because the RR into the $2p_{3/2}$ subshell is always the main component of the L-shell RR regardless of the charge-state abundance.

It is also known that multipole transitions can contribute to the polarization properties of radiations from highly charged ions [8,28]. In the present case, the theoretical value increases by about 0.02 by including magnetic dipole and electric quadrupole transitions, which makes the disagreement with the experiment larger.

Consequently, the four possible sources mentioned above cannot explain the discrepancy and we cannot think of any other major potential sources. Therefore, we conclude that the calculation overestimates the degrees of polarization of RR x rays.

The function ASYMMETRY in the FAC may compute the degree of linear polarization for each subshell in the hydrogenic approximation, where the potential optimized for a certain set of configurations is used. In contrast, using density matrix theory with perturbative calculations, Surzhykov *et al.* theoretically investigated K-shell RR of H-like heavy ions and demonstrated that the inter-electronic interaction effects significantly influence the polarization properties of the recombination x rays [29]. Hence, the electron correlation effects that are not considered in the computation can be one of the main possible reasons for the overestimation. More rigorous theoretical studies are required to clarify the difference.

The electron correlation may affect the differential RR cross sections [10] that were used in the analysis. In the present case, however, this effect on the charge-state-averaged degree of polarization should be negligible because the charge distribution derived from the differential RR cross sections hardly affects the polarization as described above.

VI. CONCLUSION

We determined the degree of linear polarization for the L-shell radiative recombination x rays emitted from highly charged Bi ions on the basis of the measured azimuthal angular distribution of the Compton-scattered events. By using the EBIT-CC, which is based on a multilayered Si/CdTe semiconductor Compton camera, installed in the Tokyo-EBIT, we succeeded in measuring the degree of linear polarization with the quite small uncertainty of 0.010 (statistical) + 0.004 (systematic) for 0.666. We compared the experimental result with the theoretical value calculated with the FAC and found that they are not in agreement; the latter seems to overestimate the degree of linear polarization. The discrepancy suggests the importance of the electron correlation effects.

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