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Linear polarization of x-ray transitions due to dielectronic recombination in highly charged ions

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The linear polarization of x rays produced by dielectronic recombination into highly charged xenon ions was measured at an electron beam ion trap using the Compton polarimetry technique. This opens numerous possibilities for diagnostics of anisotropies of hot plasmas. Moreover, it was observed that the polarization of x rays, following the dielectronic capture populating the $[1s2s^22p_{1/2}]_1$ state, is highly sensitive to the Breit interaction. The experimental results for this transition rule out by 5σ calculations not taking the Breit interaction into account.

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I. INTRODUCTION

Dielectronic recombination (DR) is a prominent process in collisions of electrons with highly charged ions (HCIs). In the first step of this process, an electron is captured by an ion under simultaneous excitation of a bound electron, and in the second step, the intermediate excited state decays radiatively [1,2]. Due to the high density of the DR resonances and their high strengths, this process often dominates the recombination rates in a plasma [3,4] and generates intense x rays that effectively cool the plasma [3,5]. Normally, the DR process populates doubly excited states that decay via emission of DR satellite lines which are usually well resolved and have little contribution from other processes. The intensity ratio of a DR satellite line to the main line can be used for diagnostics of the plasma temperature [5,6]. It is also sensitive to the plasma density over a broad range of values [7]. Moreover, an additional, qualitatively different information about the plasma state can be inferred from the linear polarization of the DR satellites, which is highly sensitive to the directionality of the recombining electrons [8–12]. In fact, the directionality of anisotropic plasma electrons not only results in polarized DR lines, but also in anisotropic x-ray emission [13–16]. This can change the observed intensity of x-ray satellite lines and, thus, strongly affect the temperature diagnostics. For these reasons, measurements of the polarization of the DR satellites lines would be beneficial for the diagnostics of anisotropies and temperatures of hot plasmas. Earlier works demonstrated that the satellite lines are polarized [17,18], but no measurement of the degree of polarization of DR transitions was performed. Moreover, a number of experiments that measured the DR cross sections using electron beam ion traps (EBITs) had observed the DR x rays perpendicularly to the electron beam propagation direction [19–25]. The interpretation of such experiments requires knowledge of the DR x-ray anisotropy and, thus, of its polarization. Furthermore, measurements of the x-ray emission anisotropy and polarization can complement each other to access effects beyond the electric-dipole approximation [26].

The interest in polarization of DR x rays arises also from the point of view of understanding the basic electron-electron interaction in strong Coulomb fields of HCIs. This interaction is of fundamental importance for atomic and molecular physics as it defines the level structure as well as the dynamics of the collision processes [27]. The retardation and magnetic corrections to the electron-electron Coulomb repulsion are known as the Breit interaction [28]. While the Breit interaction causes only small shifts in the energy levels in atoms and ions, it was recently predicted that it can significantly affect the linear polarization of DR x rays, and even result, in some cases, in the reversion of the polarization direction [12]. Thus, linear polarization of DR x rays is one of the most sensitive probes of the electron-electron interaction in strong Coulomb fields.

In this paper, we report a measurement of linear polarization of DR x-ray lines. Using an EBIT and the Compton polarimetry technique, we studied the DR resonances populating the states $[1s2s^22p_{1/2}2p_{3/2}]_{5/2,3/2}$, marked Be_2 and Be_3, and $[1s2s^22p_{1/2}]_1$, marked Li_1, in initially berylliumlike and lithiumlike xenon ions. The Be_2 and Be_3 transitions have high resonance strengths, making them ideal candidates for future applications in plasma polarization diagnostics. In the case of the Li_1 resonance, the polarization of the emitted x rays is highly sensitive to the Breit interaction [12]. In all cases, the measured polarization agrees well with the predictions of full-order relativistic calculations. In addition, the experimental results for the Li_1 resonance rule out by 5σ calculations which account only for the Coulomb electron-electron repulsion.

II. EXPERIMENT

The experiment was performed at the Heidelberg EBIT [29–33] at the Max Planck Institute for Nuclear Physics. The principles of EBIT operation are described in detail in a number of publications [34–36]. Briefly, highly charged xenon ions are produced by successive electron impact ionization of xenon atoms using a unidirectional and monoenergetic electron beam; see Fig. 1. The beam is compressed to a diameter of about 50 μm by the magnetic field created by a pair of Helmholtz coils. The ions are trapped within the electron beam by its space charge and by voltages applied to three drift tubes. The electron beam energy, defined by the

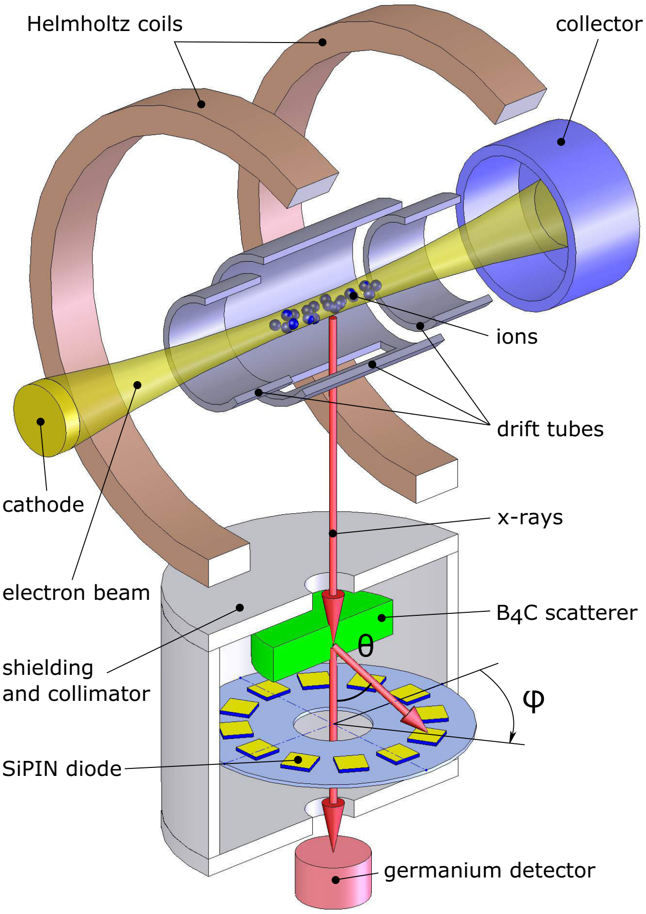

FIG. 1. (Color online) Scheme of the experiment: x rays emitted by the xenon ions, which are produced and trapped in the EBIT, are scattered by a block of boron carbide. The azimuthal distribution of the scattered x rays is measured by an array of SiPIN diodes. A germanium detector registered unscattered x rays.

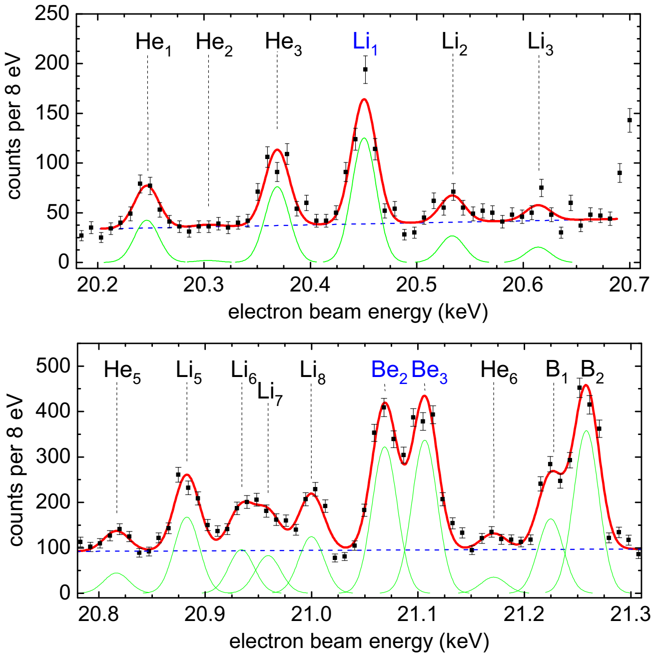

FIG. 2. (Color online) Intensity of the DR x rays registered by the germanium detector as a function of the electron energy. The dashed line represents the RR background, the thin solid lines correspond to the fits of the marked DR resonances, and the thick solid line represents the fit of the complete spectrum. The fractions f_{RR} of the x-ray intensity produced by RR at used collision energies are determined from these fits and used in Eq. (2).

potential difference between the cathode and the central drift tube, was scanned over the region of the *KLL* DR resonances in xenon ions, namely, from 20 to 22.5 keV. In these resonances, the bound electron is excited from the *K* to the *L* shell, while the free electron recombines into the *L* shell. The intensity of the DR x rays registered by the germanium detector as a function of the energy of the electron beam is shown in Fig. 2. The DR resonances appear as peaks on top of a background that is dominated by radiative recombination (RR) into *L*-shell vacancies of xenon HCIs. The trap depth of 50 V and a beam current of 400 mA provided a compromise between the x-ray intensity and a collision energy resolution of 45 eV FWHM, achieved by the evaporative cooling [33,37,38] of the ion plasma component. This resolution was sufficient to observe Li_1, Be_2, Be_3, and a number of other DR resonances, identified with the help of theoretical calculations carried out with the Flexible Atomic Code (FAC) [39,40]. The line centroids and their intensities were fitted with Gaussian functions while keeping their widths fixed to 45 eV.

The polarization of the x rays emitted perpendicularly to the electron beam propagation direction was measured with the Compton polarimetry technique [41,42]. The Compton scattering cross section depends on both the polar θ and the azimuthal φ scattering angles through the well-known Klein-Nishina formula [41],

$$\frac{d\sigma}{d\Omega} \propto \frac{\hbar\omega'}{\hbar\omega} + \frac{\hbar\omega}{\hbar\omega'} - \sin^2\theta - P\sin^2\theta\cos 2(\varphi - \varphi_0), \quad (1)$$

where $\hbar\omega$ and $\hbar\omega'$ are, respectively, the energies of the incoming and the scattered x rays, and P and φ_0 are the degree and the angle of linear polarization with respect to the electron beam propagation direction. Due to symmetry reasons, the latter vanishes: $\varphi_0 = 0$. In this case, the degree of linear polarization is identical to the first Stokes parameter $P = (I_0 - I_{90})/(I_0 + I_{90})$, where I_0 and I_{90} are the intensities of x rays polarized along and perpendicular to the electron beam propagation direction.

For the polarization measurement, the x rays, passing through a round collimation hole in a brass absorber with a diameter of 15 mm, were scattered by a 15-mm-thick block of boron carbide (B_4C); see Fig. 1. The azimuthal angular distribution of the x rays scattered at a polar angle $\theta \approx 45^\circ$ was sampled by 12 SiPIN diodes [43] with dimensions of $9 \times 9 \times 0.38$ mm. They were operated at room temperature and readout using charge-sensitive preamplifiers and 100 MHz sampling analog to digital converters [44], resulting in the energy resolutions between 2.5 and 3.5 keV. In the typical x-ray spectrum, shown in Fig. 3, the peak at ≈31 keV corresponds predominantly to the DR x rays and the broad feature at lower energies is produced by bremsstrahlung.

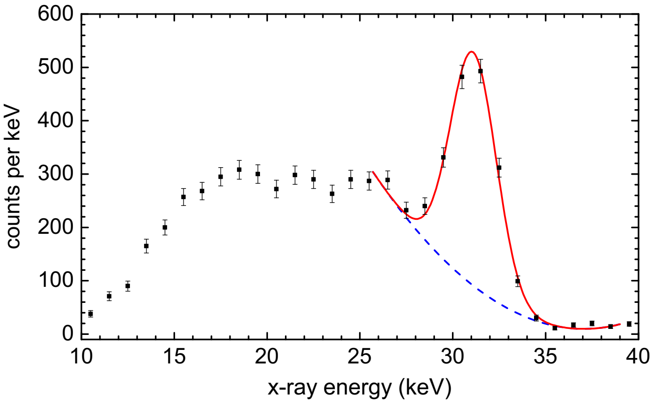

FIG. 3. (Color online) A typical x-ray spectrum observed by a SiPIN diode when the electron beam energy was tuned to the DR resonance Be$_2$. The solid line represents the fitted DR peak with the background, shown as the dashed line.

III. RESULTS

The intensities of the DR lines observed by different SiPIN diodes were extracted by fitting them with Gaussian profiles after subtracting the background, approximated by a second-order polynomial. They are shown in Fig. 4 as a function of the azimuthal scattering angle along with corresponding fits of Eq. (1) that treated the degree P and angle φ_0 of polarization as free parameters. The latter accounted for a possible misalignment of the electron beam and the detector axes. Further corrections to the extracted degree of polarization caused by the finite solid angles covered by individual SiPIN diodes and the finite size of the scatterer were taken into account by Monte Carlo simulations using the GEANT4 framework [45]. The electron cyclotron motion within the electron beam [46–48] was found to have a negligible effect on the x-ray polarization.

As evident from Fig. 2, the contribution of DR to the x-ray intensity cannot be separated from that of RR. Therefore, from Eq. (1), it follows that the degrees of polarization of RR x rays P_{RR} and DR x rays P_{DR} convolve to form the measured degree of polarization P,

$$P = P_{\mathrm{RR}} f_{\mathrm{RR}} + P_{\mathrm{DR}}(1 - f_{\mathrm{RR}}), \tag{2}$$

where f_{RR} is the fraction of the x-ray intensity produced by RR. These fractions for the Li$_1$, Be$_2$, and Be$_3$ lines are $f_{\mathrm{RR}} = 0.20$, $f_{\mathrm{RR}} = 0.24$, and $f_{\mathrm{RR}} = 0.20$, respectively. The theoretical value of $P_{\mathrm{RR}} = 0.50 \pm 0.15$ was obtained with the help of FAC calculations, for RR into the L_3 ionic shell of various HCIs of xenon. The validity of the theoretical predictions for the RR process was previously experimentally verified [41]. The large error bars for P_{RR} are due to the uncertainty of the charge state distribution of xenon ions in the trap. Finally, the polarization P_{DR} could be extracted; the results are summarized in Table I. The experimental errors stem mostly from the fits of Eq. (1); the contributions from the Monte Carlo simulations, f_{RR} and P_{RR}, are negligible.

TABLE I. Measured degrees of polarization of DR x rays for three studied transitions. The corresponding theoretical predictions that took the Breit interaction fully into account are shown along those that included only the Coulomb part of the electron-electron interaction.

Intermediate excited state	Experiment	Theory Coulomb only	Theory Coulomb + Breit
Be$_2$: $[(1s2s^22p_{1/2})_1 2p_{3/2}]_{5/2}$	0.53 ± 0.08	0.50	0.50
Be$_3$: $[(1s2s^22p_{1/2})_0 2p_{3/2}]_{3/2}$	0.43 ± 0.08	0.40	0.40
Li$_1$: $[1s2s^22p_{1/2}]_1$	-0.43 ± 0.10	-0.95	-0.46

To interpret the experimental results, we consider an incoherent nonstatistical population of the unresolved magnetic sublevels σ_m of the intermediate excited state produced by the resonant electron capture, where m is the magnetic quantum number. Since the x rays produced by the decay of individual magnetic sublevels are polarized differently, the measured degree of polarization probes the distribution of σ_m [13,49–51]. Although in some cases the polarization effects beyond the dipole approximation are important [26], for the sake of clarity we limit the discussion to the leading electric-dipole approximation, which is adequate for the experimental accuracy of the present work. It can be shown that the degree of polarization is

$$P(J=1) = \frac{3\alpha_2(\sigma_0 - \sigma_1)}{\sqrt{2} + \alpha_2(\sigma_0 - \sigma_1)}, \tag{3}$$

$$P(J=3/2) = \frac{3\alpha_2(\sigma_{1/2} - \sigma_{3/2})}{1 + \alpha_2(\sigma_{1/2} - \sigma_{3/2})}, \tag{4}$$

$$P(J=5/2) = \frac{3\alpha_2(4\sigma_{1/2} + \sigma_{3/2} - 5\sigma_{5/2})}{\sqrt{14} + \alpha_2(4\sigma_{1/2} + \sigma_{3/2} - 5\sigma_{5/2})}, \tag{5}$$

where J is the total angular momentum of the intermediate excited state and where we assumed that $\sum_m \sigma_m = 1$. In Eqs. (3)–(5), moreover, α_2 is an intrinsic anisotropy parameter which is determined by the total angular momentum of the intermediate state J and the final state J_f [48,52],

$$\alpha_2 = (-1)^{J+J_f-1}\sqrt{\frac{3(2J+1)}{2}}\begin{Bmatrix} 1 & 1 & 2 \\ J & J & J_f \end{Bmatrix}, \tag{6}$$

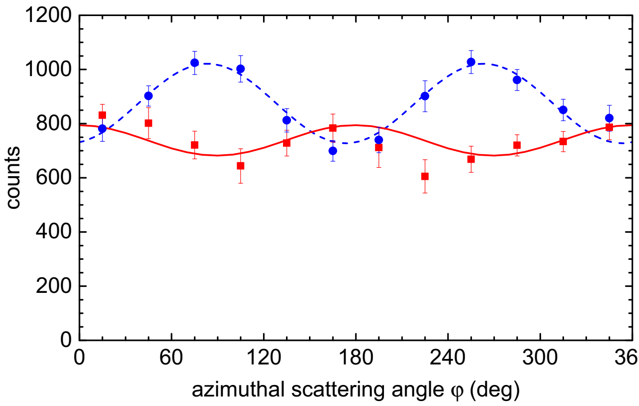

FIG. 4. (Color online) Measured azimuthal distribution of scattered x rays for Li$_1$ (squares) and Be$_2$ (circles) DR resonances. The solid and the dashed lines represent the corresponding fits of Eq. (1) to these distributions.

where the quantity in the large parentheses denotes the Wigner 6-j symbol. The intermediate Li_1 and Be_2 states decay into single final states $[1s^22s^2]_0$ and $[1s^22s^22p_{3/2}]_{3/2}$, whereas the Be_3 state decays into two final states $[1s^22s^22p_{1/2}]_{1/2}$ and $[1s^22s^22p_{3/2}]_{3/2}$. The relative population of magnetic substates of the excited ions σ_m and the degrees of linear polarization of the decay x rays were calculated with the help of the FAC and the RATIP [53] computer codes. In addition to fully accounting for the relativistic electron-electron interaction during resonant electron capture, with the Breit term included, we also performed calculations taking into account only the Coulomb electron-electron repulsion. We found that the Breit interaction plays no role for the formation of Be_2 and Be_3 resonances. Since the electron-electron interaction operator is scalar, it cannot affect the magnetic sublevel population of excited ions if only a single partial wave of a free electron is allowed for the resonant capture transition; see Eq. (2) in [15] and Eq. (6) in [54]. This is exactly the case for the $[1s^22s^2]_0 + e \rightarrow [1s2s^22p_{1/2}2p_{3/2}]_{3/2,5/2}$ processes, in which the total angular momentum of the initial state is zero and, hence, only $d_{3/2,5/2}$ partial electron wave contributes to the capture. We note that the small shifts of the binding energies, caused by the Breit interaction, do not affect the magnetic substate population because of a large experimental spread of the electron collision energies. In contrast, multipole mixing between different allowed partial waves of the incoming electron takes place in the $[1s^22s]_{1/2} + e \rightarrow [1s2s^22p_{1/2}]_1$ transition. Thus the polarization of Li_1 x rays is highly sensitive to the Breit interaction [52,54]. The experimental results rule out by 5σ the calculations that treat the electron-electron interaction purely by the Coulomb force.

IV. DISCUSSION

While measurements of the DR resonant strength [55–57] and the x-ray emission asymmetry [58,59] identified strong contributions of the Breit interaction, especially in heavy gold and uranium ions, the Compton linear polarimetry gives a higher sensitivity to this intrinsically relativistic effect, even in the much lighter xenon ions, where this effect is less pronounced [12]. Moreover, as was demonstrated in the earlier Compton polarimetry work, the sensitivity of this method can be further significantly improved [26,42,60,61], opening a large exploration space, in particular allowing one to access the quantum electrodynamics corrections of the generalized Breit interaction [62,63].

Apart from their fundamental implications, our experimental results open numerous possibilities for polarization diagnostics of hot anisotropic plasmas, which may reveal a presence of energetic directional electrons [64], for instance in relativistic jets of active galactic nuclei [65] and laser-produced plasmas [66]. The significant advantage of DR is a sharp energy sensitivity to plasma electrons, which is in stark contrast to many other processes, which are influenced by a broad energy distribution of the plasma electrons. The plasma x-ray polarization should reveal orientation of magnetic fields [64,67] in solar flares [8,68,69] and magnetically confined fusion plasmas [70], such as those of tokamaks [8,71] and stellarators. Moreover, as mentioned earlier, the polarization measurements may also be necessary for accurate temperature and density diagnostics of such plasmas.

Application of the Compton polarimetry technique provides a significant advantage over the Bragg polarimetry technique, previously used at EBITs [17,48,72–74], by measuring, in addition to the degree of polarization, the angle of polarization [42,61] and by being effective in a broader range of energies [41,75]. Our implementation of the Compton polarimetry is also significantly more accurate [26,41,42,60,61,76] than a similar techniques used in nuclear physics [77–80]. The high polarimetry accuracy allows deep probes of the electron-impact ionization and excitation [48,72–74,81,82], resonant excitation [83], and radiative recombination [26,51,84] by revealing the alignment [51,84,85] of the intermediate excited states.

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