Spin-orbit interaction in bremsstrahlung and its effect on the electron motion in a strong Coulomb field

Oleksiy Kovtun,[1] Valeri Tioukine,[2] Andrey Surzhykov,[3] Vladimir A. Yerokhin,[4] Bo Cederwall,[5] and Stanislav Tashenov[1]

[1]*Physikalisches Institut, Universität Heidelberg, 69120 Heidelberg, Germany*

[2]*Institut für Kernphysik, Johannes Gutenberg Universität Mainz, 55128 Mainz, Germany*

[3]*Helmholtz Institut Jena, 07743 Jena, Germany*

[4]*Center for Advanced Studies, Peter the Great St. Petersburg Polytechnic University, 195251 St. Petersburg, Russia*

[5]*Royal Institute of Technology, 10691 Stockholm, Sweden*

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Linear polarization of bremsstrahlung x rays produced in collisions of longitudinally polarized 2.1-MeV electrons with gold atoms was studied using the Compton scattering technique. We observed that the angle of x-ray polarization is strongly correlated with the incoming electron polarization. This correlation reveals the dominance of the spin-orbit interaction in bremsstrahlung and indicates a striking effect of the electron spin on the electron motion in a strong Coulomb field. The results confirm the validity of the theoretical predictions in a computationally challenging energy regime.

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I. INTRODUCTION

Decelerated motion of an electron in a Coulomb field of an atomic nucleus gives rise to breaking radiation: bremsstrahlung. Its first observation dates back to the discovery of x rays made by Röntgen in 1895 and its spectrum was first interpreted in 1913 by Sommerfeld [1] soon after the discovery of the nucleus itself. Since then, bremsstrahlung has become recognized as one of the most fundamental atomic processes relevant in many branches of physics, most notably astrophysics [2–4] and plasma physics [5,6]. It is used as a source of intense radiation for analytical and medical applications such as imaging [7,8] and cancer radiation therapy and for fundamental research at accelerators [9,10].

The polarization of bremsstrahlung x rays probes the relativistic dynamics of electrons in strong Coulomb fields [11–13]. It is intrinsically connected with the precession of the plane of the electron motion due to the interaction of the electron spin with its orbital momentum with respect to the nucleus. Interestingly, the electron motion in strong Coulomb and laser fields has recently attracted considerable attention in the context of the laser-triggered electron emission from biased nanotips [14,15] and the high-harmonic generation in the x-ray energy band [16]. In the latter case the electron motion is also strongly influenced by relativistic effects, known as the relativistic drift [17], that can suppress generation of higher-order harmonics. Furthermore, interactions of the electron spin with superstrong laser fields were predicted in a number of scenarios [16,18–20].

Bremsstrahlung is a prominent source of x rays and γ rays emitted from extreme sites in the universe where electrons are accelerated to high energies. Those include solar flares [21], supernovae [22], neutron stars [23], and active galactic nuclei [24]. As the plane of bremsstrahlung polarization either contains the direction of the impacting electrons or is oriented perpendicular to it (when unpolarized electrons are involved) polarization reveals the presence of electron beams in these sources [25]. X-ray and γ-ray polarimetry is often the only technique available to gain information on the geometry of spatially unresolved sources [26,27]. Moreover, it was proposed that x-ray polarimetry can be used to test the theory of general relativity predicting a rotation of x-ray polarization in the strong gravitational fields of rotating black holes [28], test quantum electrodynamics (QED) predicting polarization rotation in strong magnetic fields [29], or even provide signatures of axionlike particles [30]. Within this method the plane of x-ray polarization is defined, at the moment of emission, by the symmetry of the source, which is inferred from other observations. General relativity or QED should manifest in the x-ray polarization plane, which is tilted with respect to the symmetry plane of the source. This effect, however, can be masked by the tilt of bremsstrahlung polarization induced by spin-oriented electrons. Such electrons can be produced via the Sokolov–Ternov effect [31,32] or due to a spin interaction with strong magnetic fields [33], which are often present in the vicinities of black holes and neutron stars. Polarized electrons are also emitted in β decays of exotic nuclei produced by supernovae [34]. Although the tilt of bremsstrahlung polarization, caused by polarized electrons, may obscure the effects of QED and general relativity, it can instead be used to identify the presence of polarized electrons in cosmic sources [35]. In a similar way bremsstrahlung x rays produced by spin-oriented electrons can strongly affect the polarization diagnostics of angularly unresolved astrophysical sources. These possibilities call for a better understanding of bremsstrahlung x-ray polarization produced by polarized electrons.

The state-of-the-art theoretical description of bremsstrahlung is based on the partial-wave representation of the continuum Dirac wave functions in the external atomic field [36,37]. It is computationally extensive: At high energies large numbers of partial waves are taken into account to achieve convergence. Thus, reliable predictions for bremsstrahlung polarization produced by spin-oriented electrons were obtained only at collision energies up to around 2 MeV [36,37]. At ultrarelativistic energies, typically higher than 5 MeV, bremsstrahlung could so far only be described by approximate models such as the one of Sommerfeld and Maue [38–40]. However, these models fail at lower energies.

So there appears to be an energy gap around 2–5 MeV where the polarization properties of bremsstrahlung could not yet be reliably described.

Precision measurements of linear polarization of x rays produced by spin-oriented electrons represent nowadays a stringent tests of bremsstrahlung theories. So far this has been done only in two experiments, both performed at a low collision energy of 100 keV where the spin-orbit interaction is weak [11,12,41]. It causes a small tilt of the bremsstrahlung polarization plane, namely, 2.1° for longitudinally polarized electrons, when the x rays are observed at a right angle to the impact direction. On the other hand, this effect should get stronger at higher energies and in this way become important for studies of relativistic electron dynamics in strong Coulomb fields, for astrophysics and for diagnostics of spin-polarized electron beams. In this paper we report the observation of linear polarization of bremsstrahlung x rays produced in collisions of polarized electrons with gold atoms at an energy of 2.1 MeV. The results represent an important benchmark for the full-order relativistic theory in the energy regime where reliable predictions are currently challenging. We find a dramatic enhancement of the spin-orbit interaction that causes a 65° tilt of the polarization plane for longitudinally polarized electrons. This indicates the dominance of the spin in the dynamics of the electron motion in the Coulomb field of the nucleus.

II. EXPERIMENT

The experiment was performed at the Mainzer Microtron MAMI in the Institut für Kernphysik of Johannes Gutenberg Universität Mainz, Germany. Longitudinally polarized electrons were produced by illuminating a GaAsP superlattice strained-layer photocathode with circularly polarized laser light. Transverse polarization within the horizontal plane was achieved using a Wien filter [42]. The electron beam was accelerated to 2.1 MeV and its degree of polarization was measured to be $P_e = 0.80 \pm 0.05$ using a Mott scattering polarimeter [43]. The orientation of the electron spin was changed repeatedly between the collinear and anticollinear directions relative to the beam propagation direction by changing the sign of circular polarization of the laser light. Note that this reversal of the electron spin did not affect any other experimental conditions, such as the beam energy and trajectory. The electrons collided with a 500-nm-thick gold foil. Bremsstrahlung x rays emitted in these collisions at an angle of $90^\circ \pm 5^\circ$ with respect to the electron-beam propagation direction were registered by a planar high-purity germanium (HPGe) detector, see Fig. 1. Some x-ray background was generated by the electrons that elastically scattered in the gold target and hit the stainless steel walls of the beam line, predominantly downstream the target. To suppress this background the detector was shielded in nearly 4π and the x rays were collimated by 15 cm of lead. This collimation necessarily left unshielded a small section of the vacuum chamber allowing a direct view of the gold target. Background, which originated in this section, was reduced by a factor of 43 with the help of a 5-mm-thick beryllium plate that absorbed the electrons elastically scattered in the target. We limited the analysis of the experimental data to the x rays in the energy region of 1.6 MeV $< E <$ 2.1 MeV, where we

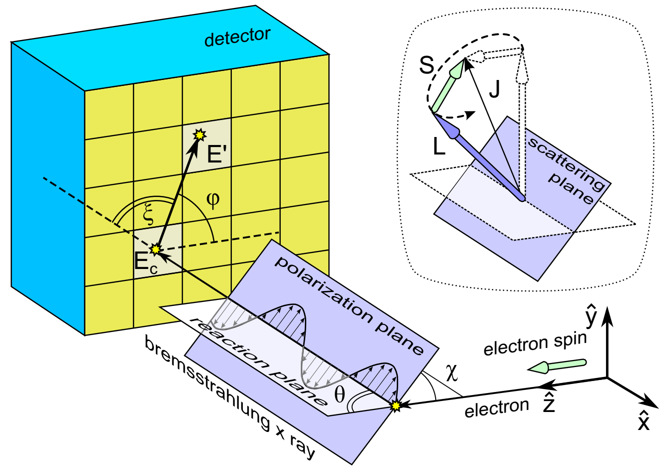

FIG. 1. (Color online) The experiment determines the tilt angle χ of bremsstrahlung linear polarization relative to the reaction plane $(\hat{x},\hat{z})$ defined by the polarized incoming electron $\hat{z}$ and the emitted x-ray propagation directions. The azimuthal distribution of the x rays Compton scattered within the segmented planar HPGe detector was deduced through the coincident detection of the energy depositions E_c and E' in the separate segments. The inset shows the correlated precession of the electron spin **S** and its orbital momentum **L** around the conserved total angular momentum **J**. The orientation of the orbital momentum defines the orientation of the precessing plane of electron motion.

estimated the x-ray background to be negligible. We reduced the unwanted lower-energy x-ray flux on the detector by 20 mm of lead, which efficiently suppressed x rays with energies lower than 500 keV.

The front side of the planar HPGe detector was electrically segmented into a 5×5 matrix of square pixels. Each segment registered an energy deposition in its volume of $10 \times 10 \times 20$ mm^3 with an individual charge-sensitive preamplifier and a sampling analog-to-digital converter. Digitized signals were processed with a moving window deconvolution algorithm [44] to extract the x-ray interaction energies and the arrival times with corresponding resolutions of 4 keV and 100 ns.

III. DATA ANALYSIS

Linear polarization of bremsstrahlung x rays was measured with the Compton scattering technique. It uses the fact that x rays scatter asymmetrically with respect to the plane of polarization according to the angular-differential cross section [11,45]

$$\frac{d\sigma}{d\Omega} \propto \frac{E'}{E}\frac{E}{E'} - \sin^2\xi - P\sin^2\xi\cos 2(\varphi - \chi), \qquad (1)$$

where ξ and φ are the polar and azimuthal scattering angles, χ and P are the angle and the degree of linear polarization, and E and E' are the energies of the incoming and the scattered x rays, respectively (see Fig. 1). The latter energy depends on the polar scattering angle ξ:

$$E' = \frac{E}{1 + E/mc^2(1 - \cos\xi)}, \qquad (2)$$

where $mc^2 = 511$ keV is the rest mass of the electron.

A significant fraction of the bremsstrahlung x rays, emitted in the collisions of the electrons with the gold atoms, were Compton scattered in one segment of the detector and photoabsorbed in another. In such events the first segment measures the energy of the Compton-recoiled electron E_c and the second segment measures the energy of the scattered x ray E'. These energy depositions are detected in time coincidences and their sum is equal to the energy of the bremsstrahlung x ray: $E_c + E' = E$. To distinguish such events from those where two Compton scatterings took place in the two separate detector segments and the second scattered x-ray escaped detection, we imposed the following condition. With the help of Eq. (2) we selected events falling into the interval of forward polar scattering angles $40^\circ < \xi < 85^\circ$. Under this condition we determined a number of x-ray scatterings $X[i,j]$ from one segment i to another segment j, where both i and j span from 1 to 25. The combination $[i,j]$ defines the azimuthal scattering angle φ. Due to a strong dependence of the bremsstrahlung intensity on the x-ray emission angle θ, the detector was illuminated nonuniformly. We compensated for this nonuniformity by a normalization $I[i,j] = X[i,j]/\sum_{j=1,\dots,25} X[i,j]$. The scattering intensities $I[i,j]$ between the segments i and j, which are separated in space by one intermediate segment and represent the same azimuthal scattering angle φ, were combined into an azimuthal scattering distribution $I(\varphi)$. To compensate for the solid angle differences between various combinations of the segments, an intensity ratio

$$J(\varphi) = \frac{I(\varphi + 90^\circ) + I(\varphi + 270^\circ)}{I(\varphi) + I(\varphi + 180^\circ)} \qquad (3)$$

was constructed that exploited the square symmetry of the detector. These normalized distributions $J_{\mathrm{col}}(\varphi)$ and $J_{\mathrm{anticol}}(\varphi)$ of Compton-scattered bremsstrahlung x rays produced by electrons polarized collinearly and anticollinearly relative to the electron-beam propagation direction are shown in Fig. 2. The phase shift between these distributions indicates a strong correlation between the electron-spin orientation and the tilt angle of bremsstrahlung linear polarization.

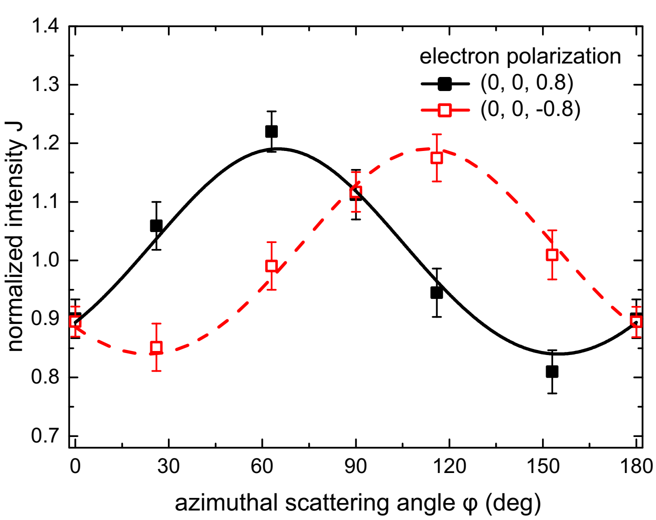

FIG. 2. (Color online) Normalized scattered x-ray angular distributions J_{col} and J_{anticol} in the energy interval 1.7 MeV $< E <$ 2 MeV for the electron-spin orientations collinear and anticollinear to the incoming electron propagation direction. The lines represent the fits of Eq. (4) to the experimental data points. The values in the parentheses represent the components of the electron-beam-spin polarization.

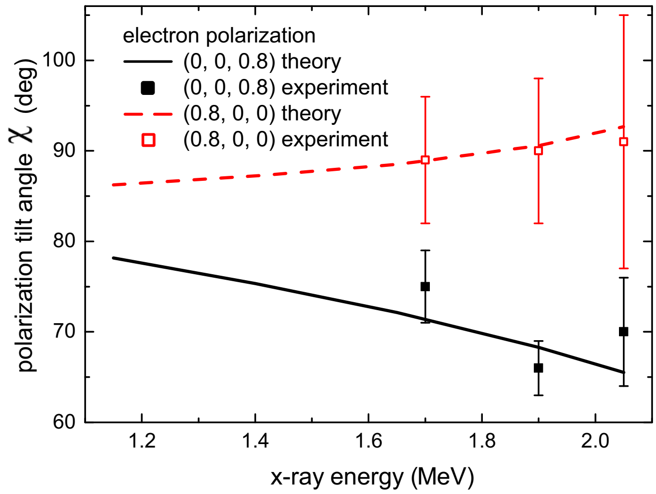

FIG. 3. (Color online) Tilt angles of x-ray polarization produced by 2.1-MeV electrons partially spin polarized along the $\hat{x}$ and $\hat{z}$ axes. The values in the parentheses represent the components of the electron-beam-spin polarization.

To extract the angles of polarization of bremsstrahlung x rays produced by longitudinally polarized electrons we took into account symmetries of the azimuthal angular distributions of the Compton-scattered x rays. The mirror reflection symmetry with respect to the reaction plane reverses the spin of the incoming electron, flips the x-ray polarization plane, and preserves all other parameters. Thus, the normalized Compton-scattering distributions obey the symmetry $J_{\mathrm{col}}(\varphi) = J_{\mathrm{anticol}}(-\varphi)$ [12]. According to Eqs. (1) and (3), we fitted both of these distributions simultaneously with the functions $F(\pm\varphi,\chi,M)$,

$$F(\varphi,\chi,M) = \frac{1 - M\cos 2(\varphi + 90^\circ - \chi)}{1 - M\cos 2(\varphi - \chi)}, \qquad (4)$$

by treating the modulation M and the phase χ as free parameters. The modulation M is related to the degree of linear polarization. Since within this experiment the degree of polarization does not reveal interesting physics, it was not analyzed. The experimental data with transversely polarized electrons were analyzed in the same way. The extracted tilt angles of linear polarization of bremsstrahlung x rays are shown in Fig. 3 as functions of the x-ray energy.

IV. THEORY

Correlations between the electron-spin and bremsstrahlung linear polarization are described theoretically by a set of parameters $P_{1,2}(x,y,z)$ [12,37], where $P_{1,2}$ are the first and second Stokes parameters and (x,y,z) are the projections of the electron-spin-polarization vector on the coordinate axes selected such that $\hat{z}$ axis coincides with the incoming electron propagation direction and $(\hat{x},\hat{z})$ is the reaction plane (see Fig. 1). Note that the degree of the electron-beam polarization $P_e = \sqrt{x^2 + y^2 + z^2}$. These parameters are equivalent to the polarization correlations of Tseng and Pratt [36]: $C_{03} \equiv P_1(0,0,0)$, $C_{31} \equiv P_2(0,0,1)$, and $C_{11} \equiv -P_2(1,0,0)$. The angles χ_z and χ_x of x-ray linear polarization produced respectively by partially longitudinally or transversely polarized electrons can be calculated as [12]

$$\tan 2\chi_z = P_e \frac{P_2(0,0,1)}{P_1(0,0,0)}, \quad \tan 2\chi_x = P_e \frac{P_2(1,0,0)}{P_1(0,0,0)}. \tag{5}$$

The polarization correlations of the x-ray radiation were calculated within the fully relativistic theory based on the partial-wave representation of the Dirac wave functions in an external atomic field. The calculation extends the general approach [37] to the region of higher collision energies. At such energies, convergence of the double partial-wave expansion of the initial- and the final-state Dirac electron wave function becomes extremely slow. The increase of the cutoff parameter of the partial-wave summations leads to a nearly exponential growth of the computational time, which makes calculations rather resource consuming. The key to the success is an effective computation of radial integrals with highly oscillating wave functions. This was accomplished by the method [37] based on the analytical continuation of the Dirac solutions to the complex plane and rotation of the integration contour. Figure 3 shows that the theoretical calculations adequately describe the experimental findings.

V. DISCUSSION

We have observed that the strength of the correlation between the electron-spin orientation and the bremsstrahlung polarization increases dramatically at high collision energies. In particular the tilt angle of x-ray polarization produced by longitudinally polarized electrons increases from 2.1° at 100 keV to 65° at 2.1 MeV (see Fig. 3). However, this correlation is predicted to decrease at further higher energies [39,40]. Thus, our results represent an important benchmark for bremsstrahlung theories at the collision energy where the polarization correlation is nearly at its maximum. Furthermore, in this energy range the radiative corrections of QED were predicted to modify the bremsstrahlung angular distribution at the level of a few percent [46]. Therefore, one may anticipate that polarization will be sensitive to the QED corrections too. Finite-nuclear-size effects [47] may also modify polarization. To date these effects were not considered in calculations of polarization of bremsstrahlung produced by spin-oriented electrons. The experimental accuracy approaches the level where such effects may become pronounced.

The correlation between the electron spin and the tilt angle of bremsstrahlung polarization is explained by the spin-orbit interaction [11,12,35]. The dramatic enhancement of this correlation observed in the present experiment points to the dominant role of the electron spin in bremsstrahlung at a collision energy of 2.1 MeV. It indicates that in this energy regime the trajectory of the electron motion in the field of the nucleus is governed by the interaction of its spin with this field (see Fig. 1). The spin-orbit interaction tilts the plane of the electron motion by a very large angle. This represents a striking example of the relativistic dynamics of a spinning charged particle in a very strong Coulomb field. It is predicted that similar electron-spin dynamics will come into play in future studies of interactions of electrons with extremely high-intensity laser fields [16,18–20]. The observed effect should be also considered in astrophysics. Due to a very strong correlation between the electron-spin and x-ray polarization, even a small fraction of polarized electrons should severely disrupt the x-ray polarization diagnostics of astrophysical sources and identification of the effects of x-ray interactions with strong magnetic and gravitational fields.

In summary, we observed linear polarization of bremsstrahlung x rays produced in collisions of polarized electrons with gold atoms at an energy of 2.1 MeV. Our experiment provides detailed insight into the spin dynamics in a strong field, which is complementary to other spin-related phenomena in energetic atomic collisions [45,48–50]. It motivates further investigations of the effects of the electron-spin- and x-ray polarization correlations in other collision processes. An effect similar to the one investigated here was predicted for radiative recombination, the time-reversed process of photoionization [51,52]. One may expect similar effects to emerge in dielectronic recombination, electron-impact excitation, and ionization. Furthermore, the observed strong polarization correlation in bremsstrahlung positively impacts the recently proposed technique of electron polarimetry [12]. The earlier application of bremsstrahlung for electron-beam polarimetry at 100-keV collision energy was limited by the small magnitude of the correlation [35]. Thus, in the MeV energy range a subpercent accuracy of electron-beam-polarization measurement is feasible. Accurate electron-beam polarimetry is required to search for physics beyond the standard model via studies of parity violation and measurements of the electron electric dipole moment.

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