Polarization Transfer of Bremsstrahlung Arising from Spin-Polarized Electrons

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(Received 23 February 2012; published 26 June 2012)

We report on a study of the polarization transfer between transversely polarized incident electrons and the emitted x rays for electron-atom bremsstrahlung. By means of Compton polarimetry we performed for the first time an energy-differential measurement of the complete properties of bremsstrahlung emission related to linear polarization, i.e., the degree of linear polarization as well as the orientation of the polarization axis. For the high-energy end of the bremsstrahlung continuum the experimental results for both observables show a high sensitivity on the initial electron spin polarization and prove that the polarization orientation is virtually independent of the photon energy.

DOI: 10.1103/PhysRevLett.108.264801 PACS numbers: 41.60.−m, 32.30.Rj, 34.80.Nz

Electron bremsstrahlung in the field of the screened Coulomb charge of the atomic nucleus is one of the most important x-ray production processes. This kind of bremsstrahlung mechanism, also referred to as ''ordinary'' or ''electron-atom'' bremsstrahlung, has attracted continuous interest both in basic research as well as in applications during the last decades [1–5]. As for a rigorous probe of bremsstrahlung theory, of special interest is the study of electron-atom bremsstrahlung arising from polarized electrons as it reveals subtle details on the interplay between the polarization properties of charged particles and photons [6,7]. This so-called polarization transfer appears most pronounced for the case of high-Z systems and allows a unique probe of relativistic and even quantum electrodynamic effects in high-energy photon-matter interactions. The underlying polarization correlations have been systematically discussed already in the 1970s by Tseng and Pratt [8] and were later revisited by several theoretical studies [9–11]. While an asymmetry of the bremsstrahlung emission pattern was observed for incident polarized electrons [12], up to the present, however, there was a definite lack of experimental data on the polarization transfer between incident polarized electrons and the emitted x rays. Such measurements were to a large extent hampered by the absence of adequate combinations of x-ray polarimeters and polarized particle sources. Only in the view of recent developments of hard x-ray Compton polarimeters enabling energy-resolved determination of both the degree and direction of the photon linear polarization [13–17], the polarization correlations in atomic bremsstrahlung became fully accessible today for experimental investigations. Along this line, recent measurements were performed to observe a rotation of the photon polarization axis in the case of longitudinal electron polarization when compared to an unpolarized electron beam [18]. However, the observation of the polarization orientation alone still does not provide full knowledge of the polarization transfer in atomic bremsstrahlung. Only simultaneous measurement of the degree and direction of the photon polarization grants complete insight into the polarization correlations, and hence into details of relativistic electron-photon interactions. Beyond the purely scientific interest, there is also practical application, since similar polarization transfer effects were predicted for the radiative recombination process and are currently discussed as a diagnostic method for spin-polarized heavy ion beams [18,19].

In this letter, we report on the first experimental observation of the polarization transfer between transversely polarized incident electrons and bremsstrahlung photons. By using a novel energy and position sensitive Si(Li) Compton polarimeter [17] we were able to determine both the degree of linear polarization as well as the orientation of the polarization axis for different photon energies of the bremsstrahlung spectrum produced by energetic electrons interacting with a thin gold target. While exhibiting a rather different energy dependence with respect to the emitted bremsstrahlung photons, both observables are found to be very sensitive to the spin state of the incident electron. Based on these findings, we conclude that electron-atom bremsstrahlung not only offers unique possibilities for probing strong-field physics but is also well suited as a diagnostic tool for the spin polarization properties of electron beams and more general of charged particle beams. The latter is of considerable interest not only for the field of atomic collisions but also for nuclear, particle, and even solid-state physics [20]. Moreover, when applied to recombination radiation, the presented technique is likely to become a key element for the use of polarized heavy ion beams as it is planned at the future Facility for Antiproton and Ion Research (FAIR) for the realm of fundamental physics [19,21,22].

The experiment has been performed at the source of polarized electrons [23] at Technische Universität Darmstadt. The source, which is based on the illumination of a GaAs photocathode with circularly polarized laser light, provides electrons with a kinetic energy of 100 keV and a high degree of electron spin polarization. Using a Wien filter the electron spin orientation can be rotated up to 180° within one plane. Unpolarized electron beams are also available. In the present measurement a 90 μg/cm^2 thick Au target was bombarded by the electron beam while using two different settings of the electron spin, namely an unpolarized electron beam and a beam being transversely polarized with the spin vector lying within the reaction plane of the bremsstrahlung process. The latter is defined by the incident electron momentum and the direction of the observed bremsstrahlung photons. The degree of electron spin polarization P_e during the measurement was determined to be $76 \pm 5\%$ using a Mott polarimeter. The emitted photons were recorded by the highly efficient Compton polarimeter located at 130° with respect to the beam direction enabling an energy-resolved determination of the bremsstrahlung linear polarization properties. This polarimeter consists of a planar Li-drifted silicon crystal with an active area of 64×64 mm^2 and a thickness of 7 mm. Both, the front and the rear contacts are segmented into 32 strips, one horizontal and one vertical, with a pitch of 2 mm and are read out individually by standard analog electronics, providing both energy and position sensitivity for a registered x-ray event. In particular, coincidences between the individual strips allow for an unambiguous identification of Compton events by registering both the position and energy of the recoil electrons and the Compton x rays, respectively. Therefore, the complete kinematics of any Compton event appearing inside the detector crystal can be reconstructed [14,17]. The linear polarization properties of hard x rays are obtained by means of Compton polarimetry. According to the Klein-Nishina equation [24], which is defined by the polar scattering angle ϑ and the azimuthal angle φ, the Compton scattered photon is preferably emitted perpendicular to the incident photon electric field vector whereas emission in the parallel direction is less probable. Thus, the degree of linear polarization as well as the orientation of the polarization plane of the incident photons can be obtained from the distribution of the Compton scattered photons with respect to the azimuthal scattering angle, see [25] for details. Note that the presented setup is only sensitive to the fraction of linear polarization of the incident photons while circular polarization cannot be distinguished from unpolarized radiation. Fig. 1 shows the energy spectrum of bremsstrahlung together with the characteristic radiation arising from the Au target as recorded by the polarimeter. A stainless steel foil of 225 μm thickness was placed in front of the detector in order to suppress the low energy part of the spectrum. The lower curve represents the Compton events that were reconstructed within the detector crystal for the five energy bins, each having a width of 6 keV. Here, the lower limit at about 70 keV is due to the fact that Compton recoil electrons with energies below 7 keV cannot be distinguished from the electronic noise of the detector. In Fig. 2, the distribution of the Compton scattered bremsstrahlung photons, obtained for an incident photon energy of 92.5 ± 3 keV is presented for the case of unpolarized and transversely polarized electrons, respectively. Here, only Compton events with polar scattering angles $\vartheta = 90° \pm 15°$ were taken into account as they provide the maximum polarization sensitivity [17].

The effect of the polarization transfer can already be clearly seen in Fig. 2, as the data for the spin-polarized electron beam show a clear rotation of the polarization axis in comparison to the reference data obtained with the unpolarized electrons. Moreover, the scattering distribution exhibits a more pronounced anisotropy, indicating a higher degree of linear polarization. Both observations are in agreement with a theoretical analysis of the Stokes parameters P_1 and P_2 which are frequently used to characterize the linear polarization of light (see, e.g., [26,27]). While $P_1 = (W_{0°} - W_{90°})/(W_{0°} + W_{90°})$ describes the (ratio of) probabilities for bremsstrahlung photons to be emitted with the polarization vector oriented along the axes $\phi = 0°$ and 90°, the parameter P_2 is defined by a similar ratio but with $\phi = 45°$ and 135°. Here, the axis

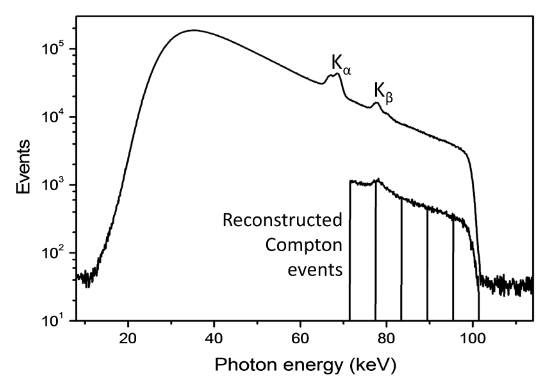

FIG. 1. Bremsstrahlung spectrum resulting from an unpolarized electron beam impinging on a thin Au target. The data were recorded using a Si(Li) Compton polarimeter located under an observation angle of 130° (see text for details).

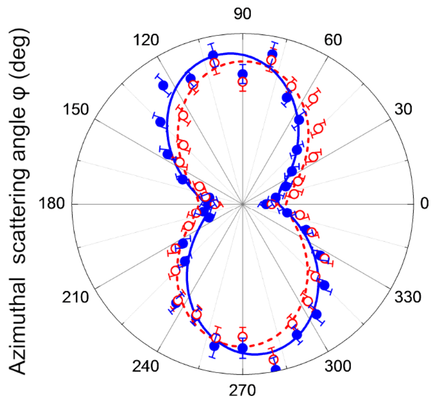

FIG. 2 (color online). Azimuthal distribution of Compton scattered x rays for incident bremsstrahlung photons with an energy of 92.5 ± 3 keV: transversely polarized electrons (filled symbols); unpolarized electrons (open symbols). The solid and dashed lines result from an adjustment of the Klein-Nishina equation to the experimental data.

$\phi = 0°$ is usually chosen to lie parallel to the reaction plane. These two Stokes parameters depend in rather different ways on the incident electron spin polarization P_e. That is, the parameter P_1 is independent from P_e as long as the electron polarization lies initially within the reaction plane (see above). In contrast, P_2 is proportional to the degree of electron polarization and vanishes if $P_e = 0$. These Stokes parameters translate into the experimental observables P_L and χ, i.e., the degree of linear polarization and the polarization rotation angle, by the following relations:

$$P_L = \sqrt{P_1^2 + P_2^2}, \quad (1)$$

$$\chi = \frac{1}{2} \arctan\left(\frac{P_2}{P_1}\right). \quad (2)$$

From these expressions and properties of the Stokes parameters it follows for unpolarized electrons ($P_e = 0$) that the linear polarization of the x rays is oriented within ($\chi = 0°$) or perpendicular ($\chi = 90°$) to the reaction plane. In contrast, a nonvanishing electron polarization ($P_e \neq 0$) leads to an enhancement of the degree of linear polarization ($P_L > |P_1|$) and to a rotation of the polarization vector out of the reaction plane (cf. Fig. 2).

In order to obtain quantitative results for P_L and χ, a modified version of the Klein-Nishina formula was adjusted to the scattering distribution (see, e.g., [13]) for each energy interval using the least squares method, as shown in Fig. 2 (solid line: transversal electron polarization; dashed line: unpolarized electrons). Here, the degree of linear polarization P_L and the rotation of the polarization axis χ to the detector axis are treated as free parameters. The derived values for the degree of linear polarization were corrected for the unpolarized K-β radiation superimposing the bremsstrahlung in the two lowest energy intervals (cf. Fig. 1) and a minor contribution caused by random coincidences. Moreover, the polarimeter quality, defined as the ratio of the reconstructed degree of linear polarization and the real incident photon polarization was evaluated by means of a Monte Carlo simulation based on the EGS5 program package, see [28]. Note that these corrections only affect the anisotropy of the scattering distribution, i.e., the degree of polarization, but not its orientation. To ensure a reliable comparison of experimental results obtained for finite-thick target foils to bremsstrahlung theory assuming single-collision conditions, the effect of multiple electron scattering within the target on the bremsstrahlung characteristics has to be taken into account. One can expect that the linear polarization shows a high sensitivity to the target thickness as the straggling of incident electrons followed by bremsstrahlung emission leads to a superposition of different degrees of polarization and polarization orientations. This results in a decrease of the degree of linear polarization and a rotation of the polarization axis. To quantify this effect, the Monte Carlo code PEBSI was developed for modeling the bremsstrahlung arising from polarized electrons during their passage through matter. This computer code was verified by comparing its predictions with the results of the well-established simulation program PENELOPE and experimental data on polarized electron scattering [29]. By employing the PEBSI program, we found that for our target foil the straggling of the electrons results in a significant reduction up to 25% of both the linear polarization and the rotation of the polarization vector. Thus, the experimental data have been corrected by this additional factor to account for the influence of target thickness.

In Fig. 3, the results for the degree of the linear photon polarization P_L for different energies of the bremsstrahlung photons are displayed for transversely polarized (filled symbols) and for unpolarized (open symbols) electrons. The experimental values, whose error bars reflect the statistical uncertainty only, are compared with relativistic calculations based on the partial-wave expansion of the Dirac wave functions [10]. These theoretical predictions have been obtained assuming unpolarized (solid line), completely (dashed line), and partially (shaded area) polarized electrons. For the latter case, the experimental value of $P_e = 76 \pm 5\%$ for the degree of the incident electron-beam polarization has been employed. As seen from the Fig. 3(a), a nonzero P_e leads to a clearly enhanced P_L. Following the discussion above, such an enhancement can be explained by the contribution of the Stokes parameter P_2 that becomes nonzero for the polarized electron beam. Moreover, the experimental results show a clear reduction of P_L with decreasing photon energy. This energy dependence is confirmed by the theoretical calculations for both, polarized and unpolarized incident electrons, even though a slight systematic deviation outside

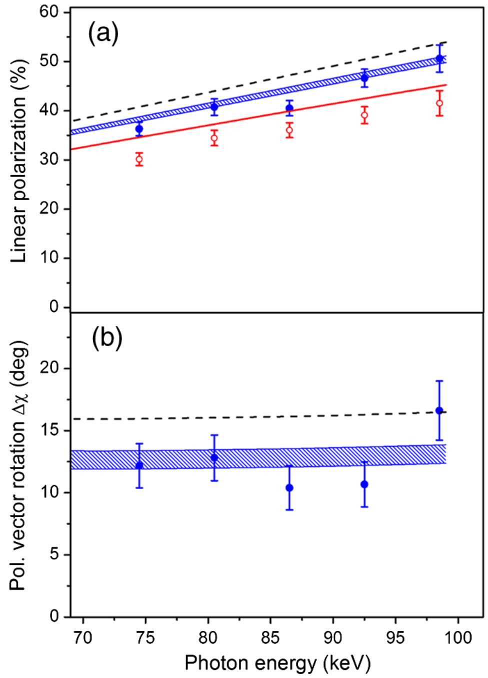

FIG. 3 (color online). (a) Degree of linear polarization of bremsstrahlung arising from transversal polarized (filled symbols) and unpolarized electrons (open symbols) in comparison to theory (shaded area, solid and dashed lines), see text for details. (b) Rotation angle of the bremsstrahlung polarization-axis with respect to the reaction plane.

of the statistical uncertainties is found for the values of P_L in the latter case. However, taking into account the overall systematic uncertainty which is conservatively estimated to amount 5% the agreement is reasonable. This estimate accounts for the effects of stray radiation superimposing the detected bremsstrahlung, minor fluctuations of the electron beam position, the uncertainty of the polarimeter response function and the uncertainty of the presented theoretical results. Fig. 3(b) shows the rotation of the polarization axis with respect to the reaction plane for the five bins of the photon energies. The data are obtained as the angle between the orientation of the scattering distribution arising from transversely polarized and unpolarized electrons, respectively (cf. Fig. 2). As seen, the experimental results for the rotation angle χ are in a good agreement with theory, which is even better than one observes for the degree of linear polarization P_L. This can be attributed to the fact that the orientation of the Compton scattered photon distribution is basically not altered by effects such as contributions due to unpolarized radiation and the polarimeter quality. It is also interesting to note, that in contrast to the degree of polarization the orientation of the polarization axis remains virtually unaltered over the photon energy range from 70 to 100 keV. Such an "invariance" of the angle χ together with the strong energy dependence of the degree P_L reflects the fundamental properties of the bremsstrahlung polarization correlations. Namely, as seen from Eqs. (1) and (2) this behaviour implies an almost equal photon-energy dependence of the Stokes parameters P_1 and P_2, an effect which—until now—has never been observed experimentally nor investigated theoretically.

Besides the fact that the energy differential determination of both observables, i.e., the degree and orientation of the polarization, provides a rigorous probe of the polarization-transfer phenomena, such measurements also deliver an access to the degree of incident electron polarization. In particular, the quasi-constant rotation of the polarization axis enables a robust technique for electron spin polarimetry, as the magnitude of the rotation is dependent to the degree of the incident spin polarization. Entering the experimental χ and the theoretical P_1 in Eq. (2) leads to the parameter P_2 for separate photon energies which contains the information about the incident electron polarization. For each of the five bremsstrahlung energy bins, the ratio of these values and the theoretical P_2 for a completely polarized electron beam delivers the degree of the electron polarization. Taking into account the statistical uncertainty, the mean of the five values is obtained as $P_e = 72 \pm 5\%$, which is in good agreement with the $76 \pm 5\%$ yielded by the standard Mott polarimetry technique. Hence, our findings clearly indicate the potential of the Compton polarimetry as a new method for the spin-diagnostics of charged particles [19,21].

J. E. acknowledges support by DFG through SFB 634 and by the state of Hesse through the LOEWE center HIC for FAIR. A. S. acknowledges support from the HGF and GSI under the project VH-NG-421.

[1] H. W. Koch and J. W. Motz, Rev. Mod. Phys. **31**, 920 (1959).
[2] R. Birch and M. Marshall, Phys. Med. Biol. **24**, 505 (1979).
[3] B. Nordell and A. Brahme, Phys. Med. Biol. **29**, 797 (1984).
[4] J. Nakel, Phys. Rep. **243**, 317 (1994).
[5] C. A. Quarles, Rad. Phys. Chem. **59**, 159 (2000).
[6] U. Fano, K. W. McVoy, and J. R. Albers, Phys. Rev. **116**, 1159 (1959).
[7] R. H. Pratt, R. D. Levee, R. L. Pexton, and W. Aron, Phys. Rev. **134**, A916 (1964).
[8] H. K. Tseng and R. H. Pratt, Phys. Rev. A **7**, 1502 (1973).
[9] C. D. Shaffner, X.-M. Tong, and R. H. Pratt, Phys. Rev. A **53**, 4158 (1996).
[10] V. A. Yerokhin and A. Surzhykov, Phys. Rev. A **82**, 062702 (2010).
[11] D. H. Jakubassa-Amundsen and A. Surzhykov, Eur. Phys. J. D **62**, 177 (2011).
[12] E. Mergl, H.-Th. Prinz, C. D. Schröter, and W. Nakel, Phys. Rev. Lett. **69**, 901 (1992)
[13] S. Tashenov *et al.*, Phys. Rev. Lett. **97**, 223202 (2006).

[14] U. Spillmann, H. Bräuning, S. Hess, H. Beyer, Th. Stöhlker, J.-Cl. Dousse, D. Protic, and T. Krings, Rev. Sci. Instrum. **79**, 083101 (2008).
[15] S. Tashenov, A. Khaplanov, B. Cederwall, and K.-U. Schässburger, Nucl. Instrum. Methods A **600**, 599 (2009).
[16] G. Weber *et al.*, Phys. Rev. Lett. **105**, 243002 (2010).
[17] G. Weber, H. Bräuning, S. Hess, R. Märtin, U. Spillmann, and Th. Stöhlker, JINST **5**, C07010 (2010).
[18] S. Tashenov, T. Bäck, R. Barday, B. Cederwall, J. Enders, A. Khaplanov, Yu. Poltoratska, K.-U. Schässburger, and A. Surzhykov, Phys. Rev. Lett. **107**, 173201 (2011).
[19] A. Surzhykov, S. Fritzsche, Th. Stöhlker, and S. Tashenov, Phys. Rev. Lett. **94**, 203202 (2005).
[20] J. Kessler, *Polarized Electrons* (Springer Verlag, Berlin, 1985).
[21] A. Surzhykov, S. Fritzsche, Th. Stöhlker, and S. Tashenov, Phys. Rev. A **68**, 022710 (2003).
[22] T. Aumann, K. Langanke, K. Peters, and Th. Stöhlker, Eur. Phys. J. Web Conf. **3**, 01006 (2010).
[23] Y. Poltoratska *et al.*, AIP Conf. Proc. **1149**, 983 (2009).
[24] O. Klein and Y. Nishina, Z. Phys. **52**, 853 (1929).
[25] F. Lei, A. J. Dean, and G. L. Hills, Space Sci. Rev. **82**, 309 (1997).
[26] W. H. McMaster, Am. J. Phys. **22**, 351 (1954).
[27] V. V. Balashov, A. N. Grum-Grzhimailo, and N. M. Kabachnik, *Polarization and Correlation Phenomena in Atomic Collisions* (Kluwer Academic/Plenum Publishers, New York, 2000).
[28] G. Weber, H. Bräuning, R. Märtin, U. Spillmann, and Th. Stöhlker, Phys. Scr. **T144**, 014034 (2011).
[29] G. Weber, R. Märtin, A. Surzhykov, M. Yasuda, V. A. Yerokhin, and Th. Stöhlker, Nucl. Instrum. Methods B **279**, 155 (2012).