# Photon Emission Asymmetry in the Elementary Process of Bremsstrahlung from Transversely Polarized Electrons

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By using an electron-photon coincidence method the photon emission asymmetry in the elementary process of bremsstrahlung from transversely polarized electrons was measured for fixed directions of the outgoing electrons and coplanar geometry. For an electron beam of 300 keV incident on a gold target, emission asymmetries up to 35% were found. Even in the case of no deflection of the decelerated outgoing electrons a nonzero photon emission asymmetry was observed. The measurements are a proper test for theories going beyond the first Born approximation.

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Bremsstrahlung emitted by an electron scattered in the Coulomb field of an atomic nucleus is a process suitable to study the coupling of radiation with matter. The aim of our experiment is to investigate the role of spin-orbit interaction in this fundamental radiation process. An important observable is the angular asymmetry of bremsstrahlung emitted by a transversely polarized electron beam where the spin direction is perpendicular to the photon emission plane, defined by the momenta of the incoming electron and the emitted photon. Disregarding the decelerated outgoing electrons such left-right photon emission asymmetries have been measured by several groups [1,2] and recently in our laboratory [3] in order to clear up discrepancies with calculations which appeared in previous work [2]. We found good agreement with the theoretical predictions of a partial wave calculation of Tseng and Pratt [4]. However, since in all these experiments only the emitted photons have been observed, the results are necessarily averaged over all electron scattering angles. Therefore the test of theoretical predictions is not as strong as it could be. To get detailed information on the *elementary* collision process we performed a coincidence measurement between outgoing electrons and photons emitted by a transversely polarized beam. The results of the measurement are presented in this Letter.

Using unpolarized electrons such an electron-photon coincidence experiment was first performed in our laboratory in 1966 [5]. Its continuation and the work of other groups were reviewed by Nakel [6]. In all these (coplanar) coincidence measurements it proved that there is a strong angular correlation with the photons being predominantly emitted on the same side relative to the primary beam as the decelerated electrons. This feature can be used to illustrate in a very simple way the photon emission asymmetry from transversely polarized electrons observed in noncoincidence experiments by additionally taking into account the asymmetric scattering of the radiating electrons due to spin-orbit coupling (analogous to Mott scattering). However, to interpret the results of our present electron-photon coincidence experiment revealing the structure of the elementary bremsstrahlung process, the simple picture does not suffice. This becomes particularly clear in the special case where the electron detector is put into the 0° position, i.e., in the direction of the primary beam. Here the outgoing decelerated electrons are not deflected, nevertheless we did find a left-right bremsstrahlung emission asymmetry.

A sketch of the experimental arrangement is shown in Fig. 1. The source for the polarized electron beam (described in detail elsewhere [7]) used the photoemission of electrons from a GaAsP crystal irradiated by circularly polarized light of a helium-neon laser. The source is contained in a high voltage terminal of a 300-kV accelerator tube and produces a continuous transversely polarized beam with a polarization degree in the range of 35% to 40%. The degree of spin polarization was measured by a Mott analyzer put into the beam line in front of the entrance of the scattering chamber. In the Mott analyzer the electrons scattered through 120° by a gold foil were detected by a pair of ion-implanted silicon detectors. The beam was focused to a 1-mm-diam spot on the target foil placed at the center of a vacuum chamber. The targets consisted of evaporated films of gold on carbon backing with thicknesses typically 50 $\mu g/cm^2$, for which plural scattering had been found to be small in previous cross-section measurements. Since the target foil consisted of

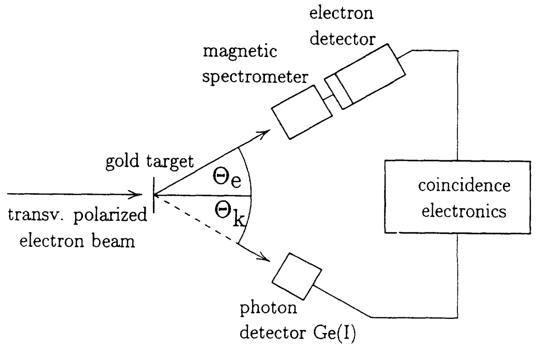

FIG. 1. Sketch of the coplanar electron-photon coincidence experiment. The spin direction of the primary electron beam is perpendicular to the emission plane.

gold the electron polarization could be monitored simultaneously with the bremsstrahlung asymmetry measurements using a second pair of electron detectors, located inside the scattering chamber at 120°.

The bremsstrahlung photons from the target leave the chamber through a thin plastic window before entering a high-purity germanium detector. The electron detector system consisted of a magnetic spectrometer for the energy analysis combined with a plastic scintillation detector (NE 102 A). The magnet is located inside the chamber and mounted on the lid, and the photomultiplier is mounted outside on top of the lid. The angular position can be changed by rotating the lid (under atmospheric-pressure conditions). The magnet is a doubly focusing homogeneous sector field shaped by an iron core with a deflection angle of 137°. Its medium plane is perpendicular to the scattering plane. The fast signals from the electron and photon detectors were fed into a time-to-amplitude converter (TAC) via constant fraction discriminators. The TAC was gated by slow pulses of the photon detector (corresponding to the energy split chosen). There are two experimental ways of obtaining spin-dependent bremsstrahlung emission asymmetry: (1) by measuring the relative, triply differential cross sections for fixed photon and electron detector positions but for two opposite orientations of the primary electron spin; (2) by measuring them for fixed spin orientation but changing the angular position of both the photon and the electron detector symmetric to the direction of the primary beam. We used the first method as the arrangement allows us to easily change the orientation of the electron spin by changing the helicity of the circularly polarized light. In this way many possible instrumental asymmetries do not enter.

Balancing ranges of prime interest for the predicted asymmetry against economy on measuring time, typically several hundred hours, leads to the following choice of parameters: At electron scattering angles $\Theta_e$ of 20° and 45° (with respect to the incident electron direction) the magnetic spectrometer selected outgoing electrons of 200 keV (energy width 10 keV). In a measurement for the electron scattering angle 0°, for which the spectrometer had to be turned into the direction of the incident beam, the background conditions depend strongly on the selected energy. We got minimal background at an energy of 160 keV.

The quantity measured directly is the counting rate of the true coincidences alternately for spin-up and spin-down electrons of the primary beam. We got the asymmetry coefficient $C_{200}$ as the ratio

$$C = A/P\,, \tag{1}$$

where $P$ is the polarization of the beam and, for spin-up and spin-down counting rates $n\uparrow$ and $n\downarrow$, respectively,

$$A = (n\uparrow - n\downarrow)/(n\uparrow + n\downarrow)\,. \tag{2}$$

The indices of $C_{200}$ were chosen corresponding to a classification scheme of bremsstrahlung-polarization correlations introduced by Tseng and Pratt [4]. The meaning of the three indices is as follows (from left to right): the primary electron beam is transversely polarized with the spin perpendicular to the emission plane, the polarization of the photon is not measured, and the polarization of the outgoing electron is not measured. The results of the measurements of $C_{200}$ as a function of the photon emission angle $\Theta_k$ for fixed outgoing electron angles $\Theta_e$ of 20° and 45° are shown in Figs. 2 and 3, respectively. The full curves are calculations of Haug [8], and the dashed curves are the pertinent triply differential cross sections for unpolarized primary electrons from the theory of Elwert and Haug [9].

Theoretical predictions of the process of bremsstrahlung production (reviewed by Pratt and Feng [10]) require calculations of the probability that the incident electron will make a transition to a different electronic continuum state with a photon emitted while in the Coulomb field of an atom. The perturbation causing this transition is the interaction of the electron with the Coulomb field and the radiation field. Whereas presently the interaction of electrons with the radiation field can be treated only by perturbation theory, their interaction with the Coulomb field of the atom can, in principle, be handled exactly. In the latter case one has to use exact wave functions, which describe an electron in a screened nuclear Coulomb field. This is particularly important when the field is strong, i.e., for high atomic numbers $Z$ as in the present case. It is, however, not possible to solve the

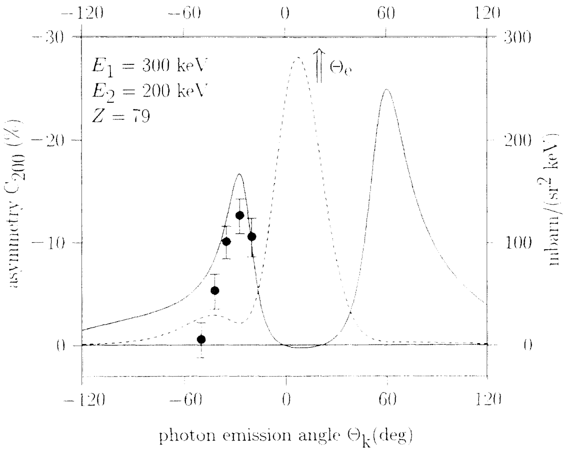

FIG. 2. Photon emission asymmetry $C_{200}$ (full circles) as a function of the photon emission angle $\Theta_k$ for outgoing electrons of scattering angle $\Theta_e = 20°$ and an energy of $E_2 = 200$ keV. The solid line is a calculation of the emission asymmetry from the theory of Haug [8], and the broken line the pertinent triply differential cross section for unpolarized primary electrons [9]. The error bars represent the standard deviations only; the systematic error of the asymmetry scale was estimated to be ±2%.

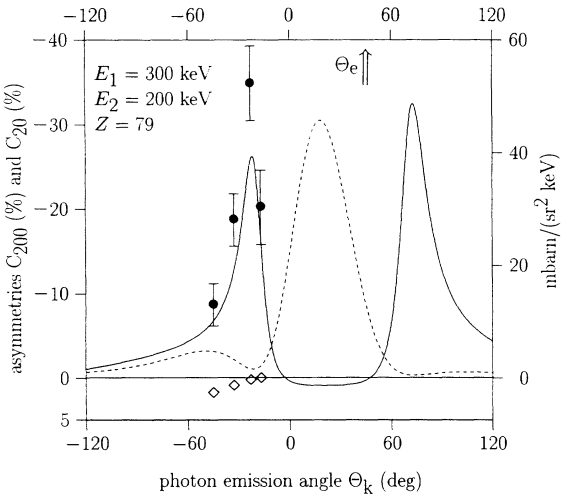

FIG. 3. Photon emission asymmetry $C_{200}$ (full circles) as a function of the photon emission angle $\Theta_k$ for outgoing electrons of scattering angle $\Theta_e = 45°$ and an energy of $E_2 = 200$ keV. The solid line is a calculation of the emission asymmetry from the theory of Haug [8], and the broken line the pertinent triply differential cross section for unpolarized primary electrons [9]. The error bars represent the standard deviations only; the systematic error of the asymmetry scale was estimated to be ±2%. The open diamonds give the noncoincident photon asymmetry coefficients $C_{20}$ measured simultaneously.

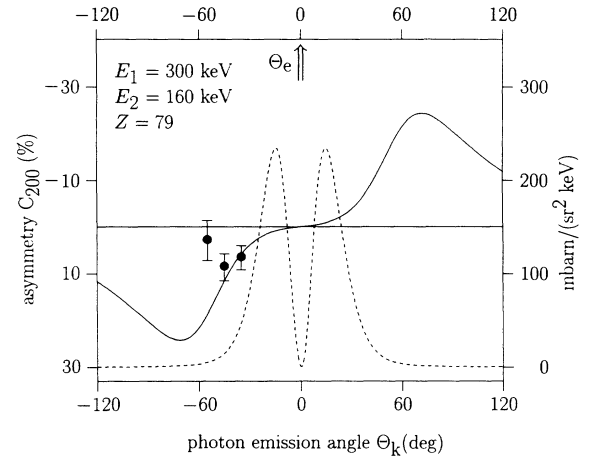

FIG. 4. Photon emission asymmetry $C_{200}$ (full circles) as a function of the photon emission angle $\Theta_k$ for outgoing electrons of scattering angle $\Theta_e = 0°$ and an energy of $E_2 = 160$ keV. The solid line is a calculation of the emission asymmetry from the theory of Haug [8], and the broken line the pertinent triply differential cross section for unpolarized primary electrons [9]. The error bars represent the standard deviations only; the systematic error of the asymmetry scale was estimated to be ±2%.

Dirac wave equation in closed form for a free electron in a Coulomb field, let alone in a screened nuclear field. Therefore only approximations with various assumptions had been available before 1971, when Tseng and Pratt [4] obtained an exact calculation of the bremsstrahlung process. They solved the Dirac equation numerically by means of partial wave expansion using a relativistic local self-consistent screened central potential. This theory, the best currently available for bremsstrahlung, yields *doubly* differential cross sections we used for comparison with our *noncoincident* asymmetry measurements [3]. However, this theory does not yet yield numerical results for the *triply* differential cross section needed for electron-photon coincidence experiments. Therefore we can compare our measurements only with approximate calculations. Calculations in the first-order Born approximation (classical Bethe-Heitler formula [11]) give zero emission asymmetry. Measurements of the asymmetry, therefore, are a proper test for theories going beyond the first Born approximation. In the theory of Elwert and Haug [9], Sommerfeld-Maue wave functions were used to solve the Dirac equation. On the basis of this theory Haug [8] calculated the bremsstrahlung emission asymmetry for transversely polarized electrons. The region of validity can be expressed by $Z\alpha \ll 1$ ($\alpha = \frac{1}{137}$). Although this condition is not fulfilled for gold ($Z = 79$), the measurements for the outgoing electron angles $\Theta_e$ of 20° (Fig. 2) and 45° (Fig. 3) are in qualitative agreement with the calculations. Comparison of the calculated triply differential cross sections with the pertinent photon emission asymmetries shows that high asymmetries occur in regions of small cross sections, whereas in the region of the large lobe the asymmetry is very small. Notice in this context the open diamonds in Fig. 3, giving noncoincident photon asymmetries $C_{20}$ measured simultaneously. The values of $C_{20}$ are very small compared to $C_{200}$ (and have the opposite sign), as this particular measurement integrates over all angles of the outgoing electrons. Thus small asymmetries associated with large cross sections mask the large asymmetries with small cross sections. In comparison with it, the results of the coincidence experiment yield very detailed information on the elementary collision process.

Finally we have studied the interesting special case of the electron detector being placed in the direction of the primary beam to detect outgoing decelerated electrons with deflection angle $\Theta_e = 0°$. Then, for an unpolarized primary beam the corresponding photon angular distribution has to be symmetric about the beam (see, e.g., [12]). For a transversely polarized beam, however, we did find an emission asymmetry. The measured values of $C_{200}$ in dependence of the photon emission angle are shown in Fig. 4. The full curve is the calculation of Haug [8], and the dashed curve the pertinent triply differential cross section from the theory of Elwert and Haug [9] for unpolarized primary electrons. Since the Haug theory does not claim to be valid for high atomic numbers, calculations according to the theory of Tseng and Pratt [4] are highly desirable. After the analysis of Sobolak and

Stehle [13] the sign of the asymmetry is dependent on whether or not the electron spin flips in the bremsstrahlung emission process. If for primary electrons with spin up the radiation is more right than left—which is the case in our experiment—the spin-flip processes should be dominant. These authors also give a classical argument for the origin of the asymmetry considering the force on a magnetic dipole moving in the Coulomb field of an atomic nucleus.

In conclusion, our measurements show the electron-photon coincidence technique combined with a polarized electron beam to be a very sensitive method for testing the bremsstrahlung theory. We mention in passing the only further experiment on polarization correlations associated with the triply differential cross section: linear polarization of bremsstrahlung photons observed in coincidence with outgoing electrons by Behncke and Nakel [14] and by Bleier and Nakel [15]. Here, however, only an unpolarized primary beam was used corresponding to the correlation coefficient $C_{030}$. One might conceive of a future "perfect" scattering experiment with a polarized primary beam and detectors sensitive to polarization of the photons and of the outgoing electrons.

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[1] K. Güthner, Z. Phys. **182**, 278 (1965); P. E. Pencynski and H. L. Wehner, Z. Phys. **237**, 75 (1970); A. Aehlig, Z. Phys. A **294**, 291 (1980).

[2] H. R. Schaefer, W. von Drachenfels, and W. Paul, Z. Phys. A **305**, 213 (1982).

[3] E. Mergl and W. Nakel, Z. Phys. D **17**, 271 (1990).

[4] H. K. Tseng and R. H. Pratt, Phys. Rev. A **7**, 1502 (1973).

[5] W. Nakel, Phys. Lett. **22**, 614 (1966).

[6] W. Nakel, in *Coherence and Correlations in Atomic Collisions*, edited by H. Kleinpoppen and J. F. Williams (Plenum, New York, 1980), p. 187; W. Nakel, in *X-Ray and Atomic Inner-Shell Physics*, edited by B. Crasemann, AIP Conf. Proc. No. 94 (AIP, New York, 1982), p. 389.

[7] E. Mergl, E. Geisenhofer, and W. Nakel, Rev. Sci. Instrum. **62**, 2318 (1991).

[8] E. Haug (private communication) (cf. Ref. [9]).

[9] G. Elwert and E. Haug, Phys. Rev. **183**, 90 (1969).

[10] R. H. Pratt and I. J. Feng, in *Atomic Inner-Shell Physics*, edited by B. Crasemann (Plenum, New York, 1985), p. 533.

[11] H. Bethe and W. Heitler, Proc. R. Soc. London A **146**, 83 (1934).

[12] W. Nakel, Phys. Lett. **25A**, 569 (1967).

[13] E. S. Sobolak and P. Stehle, Phys. Rev. **129**, 403 (1963).

[14] H-H. Behncke and W. Nakel, Phys. Rev. A **17**, 1679 (1978).

[15] W. Bleier and W. Nakel, Phys. Rev. A **30**, 607 (1984); **30**, 661 (1984).