Angular dependence of the photon linear polarization in the elementary process of atomic-field bremsstrahlung

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In an electron-photon coincidence experiment, the angular dependence of the photon linear polarization in the elementary process of atomic-field bremsstrahlung was measured for a fixed direction of the outgoing electron and for coplanar geometry. An electron beam of 300 keV was used, incident on a carbon target. It has been found that for photon-emission angles with large cross section the radiation is almost completely polarized with the electric vector in the reaction plane. A strong decrease of the polarization caused by electron spin-flip radiation was observed for a photon-emission angle near the minimum of the cross section. Within the experimental errors we find agreement with theoretical calculations.

I. INTRODUCTION

Bremsstrahlung produced by a beam of unpolarized electrons in the Coulomb field of an atomic nucleus exhibits linear polarization properties. Many measurements have already been made to investigate the dependence of the polarization on the photon energy, the photon-emission angle, the initial electron energy, and the atomic number of the target (see for example Refs. 1–3). However, in all these measurements the decelerated outgoing electrons are not observed. Consequently, this polarization is produced by averaging over many elementary bremsstrahlung processes with different directions of the outgoing electrons. Thus, the polarization behavior provides only a very limited amount of information about the elementary bremsstrahlung process with fixed direction of the outgoing electron.

The purpose of the present experiment was to measure the polarization of the photons in the elementary bremsstrahlung process. This was done by combining the polarization analysis with a coincidence observation between photons and outgoing electrons. In this way, it is possible to make a check of the theoretical work in its barest form, with no integrations over the directions of the outgoing electrons to cover up the fundamental behavior of the process.

According to a simple classical picture in which every elementary bremsstrahlung process corresponds to a radiating electric dipole, one would expect the radiation to be always completely linearly polarized in this coincidence experiment.

For nonrelativistic electron energies the electric dipole model should be a good approximation, because the influence of the electron spin is negligible and the radiation is caused mainly by a change of the orbital motion of the electron.[1] Therefore, the bremsstrahlung consists predominantly of electric dipole radiation with the electric vector in the plane containing the vector of the electron acceleration and the direction of emission. The direction of the electron acceleration is given by the difference of the momenta of the incoming and outgoing electron. The direction of the polarization vector is hence closely associated with the direction of the outgoing electron.

At relativistic electron energies, the dependence of the bremsstrahlung linear polarization on the orbital motion of the electron is complicated by the intimate relationship between the spin and momentum of the Dirac electron. In a theoretical analysis Fano, McVoy, and Albers[4] investigate the contributions to the bremsstrahlung coming from a change of orbital motion and a change of spin orientation. They state that when the momenta of the incoming and outgoing electron and the photon all lie in the same plane, the entire contribution of the change of orbital motion is polarized in that plane. We have chosen this clear geometry for the experiment. In this way it is possible to discern the contribution of the spin-flip radiation by a deviation from the complete linear polarization in that plane. This gives a more direct physical insight into the bremsstrahlung process.

We compare our measurements with theoretical calculations of Elwert and Haug.[5,6] For the parameters of the present measurement these predictions are nearly identical with calculations in the Born approximation theory.

II. EXPERIMENTAL METHOD

In order to measure the photon linear polarization of the elementary bremsstrahlung process, the photons are analyzed in a Compton polarimeter and detected in coincidence with outgoing electrons scattered in a particular direction. A schematic

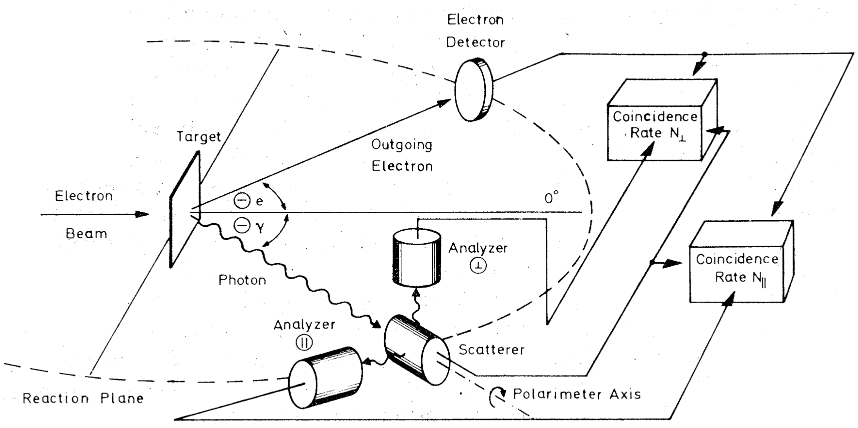

FIG. 1. Schematic view of the experimental arrangement. For the sake of simplicity, only two analyzers are shown instead of the four used.

view of the experimental arrangement is shown in Fig. 1.

A beam of monoenergetic electrons impinges on a thin target. The generated photons and the associated outgoing electrons may be emitted in any direction. We have chosen the coplanar geometry; the momenta of the incoming and outgoing electron and the photon all lie in the same plane, the so-called reaction plane.

By an electron detector, outgoing electrons of a definite energy are selected from the continuous spectrum. Thus, the energy of the coincident photons is given by the difference between the incoming and the detected outgoing electron energies.

The degree of linear polarization is defined by the expression

$$P = (I_\perp - I_\parallel)/(I_\perp + I_\parallel)\,, \qquad (1)$$

where $I_\perp$ and $I_\parallel$ are the bremsstrahlung intensity components with electric vectors perpendicular and parallel, respectively, to the reaction plane. Complete polarization with the electric vector parallel to the emission plane thus corresponds to $P = -1$.

The polarimeter depends on the polarization sensitivity of the Compton process, and consists of a central scatterer and four analyzers to measure the scattered photons in the reaction plane and perpendicular to it (in Fig. 1 only two analyzers are shown). In order to reduce background, a plastic scintillation detector was used instead of a simple scatterer, employed in a previous measurement.[7]

The pulses from the electron detector and the photon detectors are fed to two conventional coincidence systems. Acceptable events were those producing a coincidence between the electron detector, the central scatterer, and either the horizontal or vertical analyzers. The quantity which is measured directly is the ratio of the counting rates of the true coincidences $N_\perp/N_\parallel$. In this case $N_\perp$ and $N_\parallel$ denote the true coincidence counting rates of scattered photons in the direction perpendicular and parallel, respectively, to the reaction plane. To obtain the linear polarization P from the measured data, the asymmetry ratio R of the Compton polarimeter must be known. The ratio of the coincidence rates $N_\perp/N_\parallel$, the asymmetry ratio R, and the polarization P are connected through the relation

$$P = \frac{R+1}{R-1}\,\frac{1 - N_\perp/N_\parallel}{1 + N_\perp/N_\parallel}\,. \qquad (2)$$

The asymmetry ratio R is the ratio of counting rates which one would obtain in the analyzer perpendicular and parallel to the reaction plane for a photon beam completely polarized in this plane. In the present work R was calculated by a Monte Carlo program.

III. APPARATUS AND PROCEDURE

The measurement was performed with an arrangement which we have used for some time to investigate the elementary processes of electron-nucleus bremsstrahlung[8] and electron-electron bremsstrahlung.[9,10] For this work the arrangement had to be completed by a Compton polarimeter. A brief review of the relevant information is given below.

A. General setup

The electron beam from a 300-kV accelerator was focused to a 1-mm-diam spot on target. The beam current amounted to about 1 μA. The targets consisted of self-supporting carbon foils with thicknesses ranging from 37–48 $\mu g/cm^2$.

A magnetic spectrometer selected outgoing electrons of 140 keV (energy width 5.2 keV) and a scattering angle of 20° with respect to the incident electron direction. The electrons were detected with a plastic scintillation counter (NE 102A with photomultiplier 56 DVP). The aperture of the electron detector amounted to 5° in the reaction plane and to 1.5° perpendicular to it.

The bremsstrahlung from the target was collimated and leaves the scattering chamber through a plastic window (50 μm) before entering the polarimeter. Electrons scattered in this direction were deflected by permanent magnets to avoid bremsstrahlung production in the window. The unscattered electron beam was monitored by a Faraday cup for beam-current control. Simultaneously the incident beam current was monitored by observing elastically scattered electrons with a solid-state detector.

B. Polarimeter

In this experiment the polarimeter has to analyze monoenergetic radiation, since the energy of the coincident photons (160 keV) is given by the difference between the incoming (300 keV) and outgoing (140 keV) electron energies. We have constructed a type of Compton polarimeter first described by Metzger and Deutsch[11] and used for a polarization measurement of γ rays.

The polarimeter consists of a central plastic detector as scatterer (NE 102 A) surrounded by four NaI(Tl) scintillators (1.5-in.-diam$\times$1.5-in. crystals with photomultipliers 56 DVP) for the detection of the scattered quanta. A scattering angle of 90° was chosen. The scatterer (40-mm diam$\times$20 mm) was mounted on a light pipe (40-mm diam$\times$ 70 mm) and connected to a photomultiplier (XP 2020). The distance from the target to the scatterer was 640 mm and from the polarimeter axis to the front face of the photon detectors 64 mm. The photon detectors were shielded against background radiation as well as direct radiation from the target.

In order to avoid asymmetries produced by the construction of the polarimeter and by different detector efficiencies, the polarimeter could be rotated around its axis. During one period of measurement each of the four detectors spent equal times in all four positions. In each of these positions, the plane defined by the axis of the scatterer and one of the rotating scintillators made, sequentially, the angles of 0°, 90°, 180° and 270° with the reaction plane. Spectra which were obtained at opposite angles were added. The polarimeter was installed on a table which could be rotated around the center of the scattering chamber. In this way the linear polarization could be measured at different photon-emission angles.

The actual value of the asymmetry ratio R for a given photon energy depends on the geometric construction of the polarimeter. In the present work the asymmetry ratio was calculated by a Monte Carlo program which took into account the geometry of the arrangement and multiple scattering, including the effects of polarization of the scattered photons. The photons might be scattered either within the plastic scintillator or within the light pipe. In order to be detected the photon must transfer a minimum energy to the plastic scintillator. The interactions to be considered were photoelectric effect, coherent scattering, and Compton effect. The absorption coefficients and the scattering coefficient, respectively, were taken from the tables of Veigele.[12] The energy distribution of the incident photons was assumed as in the measurement. The scattering angle and the aximuthal angle were simulated according to the probability distributions derived from the Klein-Nishina formula and the corresponding formula for coherent scattering. For this arrangement of the polarimeter the computed value of the asymmetry ratio was $R = 6.2$. The systematical error was estimated to be 5%. The statistical error could be neglected. In order to simplify the calculation, we neglected the following effects: scattering of bremsstrahlung in the light-tight enclosure of the scatterer (thickness 0.2 mm), backscattering from the walls of the polarimeter, and scattering on the edge of the lead collimators situated between the scatterer and the photon detectors.

C. Electronics

A block diagram of the electronics used in the measurement is given in Fig. 2. The pulses from the detector of the outgoing electrons and the recoil Compton electrons of the scatterer were routed to a time–to–pulse-height converter. The converter output passed a linear gate and was fed to a multichannel analyzer. The gate was opened if two conditions were fulfilled simultaneously. First, there has to be a fast coincidence between recoil electron in the scatterer and the Compton-scattered photon in any one of the four NaI(Tl) scintillators. The coincidence circuit consisted of four time–to–pulse-height converters followed by a single-channel analyzer. In Fig. 2 only one of the four identical circuits is shown. Second, the pulses from the photon detectors must lie in a prescribed pulse-height interval given by the Compton effect.

The linear signals of the photon detectors were preamplified and added. A single-channel analyzer following a spectroscopy amplifier selected the desired pulse height. With a routing unit the timing spectra were stored in four sections of the multichannel analyzer, according to how the

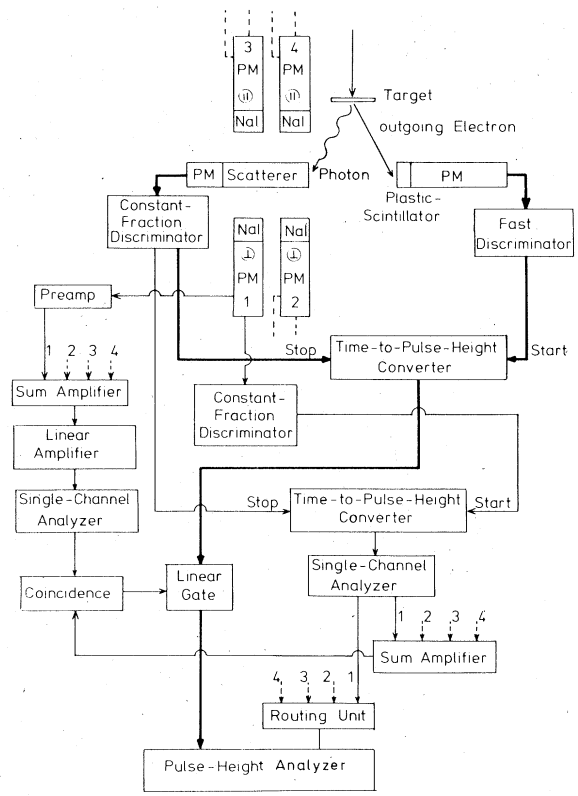

FIG. 2. Simplified block diagram of electronics. Only one of four identical circuits is shown.

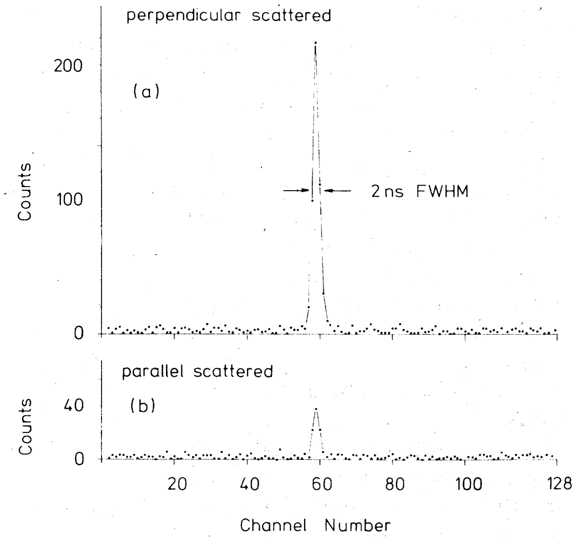

FIG. 3. Electron-photon timing spectra showing the coincidence peaks for photons scattered (a) perpendicular and (b) parallel to the reaction plane (photon emission angle -40°, accumulation time 100 h).

photons were scattered in one of the four NaI(Tl) scintillators. Two equivalent timing spectra at a time were obtained for photons of the elementary process scattered perpendicular or parallel, respectively, to the reaction plane. In this way there was a control of asymmetries between opposite detectors. A typical sum of equivalent timing spectra received during one period of measurement (100 h) is shown in Fig. 3. The numbers of true coincidences $N_{\perp}$ and $N_{\parallel}$ were determined by using a least-squares fit to subtract the background of random coincidences that lie beneath the peak.

IV. RESULTS AND COMPARISON WITH THEORY

The measurement of the photon linear polarization in the elementary bremsstrahlung process was performed at five different photon-emission angles for outgoing electrons of a fixed direction of 20° and energy of 140 keV. The incident electron energy was 300 keV. The results are shown in Fig. 4. According to definition (1) the negative values of the polarization indicate that the radiation is polarized prevalently parallel to the emission plane.

The theoretical curve (solid line) has been calculated for the present experimental situation and may be compared directly with the experimental results. The starting point for the calculation of the curve was the theory of Elwert and Haug[5,6] for the generation of bremsstrahlung in the Coulomb field of an atomic nucleus. Here bremsstrahlung

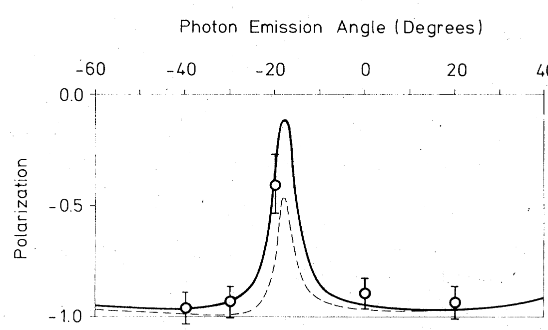

FIG. 4. Linear photon polarization in the elementary bremsstrahlung process as a function of the photon-emission angle for outgoing electrons of +20° and 140 keV. Primary electrons of 300 keV are used, incident on a carbon target. The experimental values are shown by open circles. The theoretical curve (solid line) has been calculated for the present experimental situation with the Elwert-Haug theory.[5,6] The dashed curve shows the theoretical polarization without corrections for the finite solid angles, the finite energy width of the magnetic electron spectrometer, and the electron plural scattering in the target. The correction, however, for a contribution of electron-electron bremsstrahlung has been made (see Sec. IV).

is calculated with the aid of Sommerfeld-Maue eigenfunctions, i.e., under the assumption of a point-Coulomb potential and low atomic numbers Z ($Z/137 \ll 1$). Screening is neglected.

For comparison, a calculation of the polarization in Born approximation was performed and had practically the same results for these parameters. Coulomb effects might thus still play no significant role here.

The polarization, calculated according to the Elwert-Haug theory and first represented without taking corrections into account, is shown in Fig. 5(a) (solid line). From this curve the solid line of Fig. 4 is obtained by making the following corrections.

(a) Corrections were made for the finite solid angles of the photon and electron detector and for the finite energy width of the magnetic spectrometer used in the experiment.

(b) According to the finite thickness of the target there is a certain probability that the radiating electron is scattered elastically before and/or after the bremsstrahlung process. The influence of this plural scattering on the polarization was calculated with a Monte Carlo program.[13]

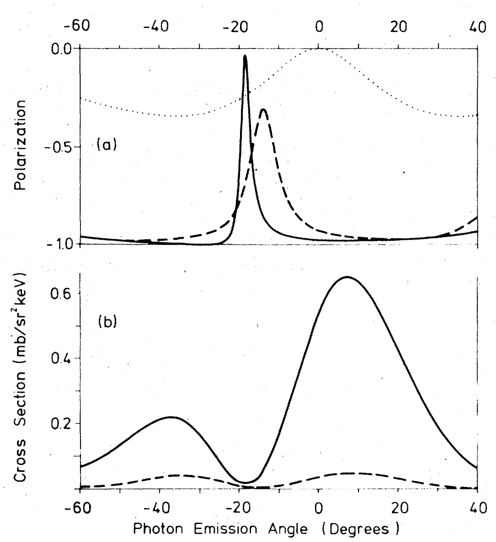

FIG. 5. (a) Theoretical photon linear polarization (uncorrected) in the elementary process of electron-nucleus bremsstrahlung (——) and electron-electron bremsstrahlung (----) as a function of the photon-emission angle, calculated for the experimental parameters. For comparison with the elementary process, the theoretical polarization of electron-nucleus bremsstrahlung is shown, integrated over all directions of motion of the outgoing electron (• • • •). (b) Theoretical triply differential cross section of electron-nucleus bremsstrahlung (——) and electron-electron bremsstrahlung (----) as a function of the photon emission angle, calculated for the experimental parameters and with corrections for the finite solid angles and the finite energy width of the magnetic electron spectrometer. (The cross section of electron-electron bremsstrahlung is multiplied by a factor of 6 according to the number of electrons in the carbon atom).

(c) Correction was made for a contribution of electron-electron (e-e) bremsstrahlung, since an electron passing through matter can produce bremsstrahlung not only in the Coulomb field of a nucleus but also in a collision with an atomic electron. As the energy transfer to the electron is much greater than the binding energy of the carbon electrons, we may neglect the binding energy and treat the problem as a collision between free electrons. In the final state there are two electrons and one photon. The three-body final state is kinematically determined by the coincidence observation between the photon emitted in a definite direction and the outgoing electron of definite energy and direction. The energy of the e-e bremsstrahlung photon is dependent on the emission angle and amounts to 137–111 keV for the angles from $-40°$ to $+20°$. The difference between these energies and that of the electron-nucleus bremsstrahlung of 160 keV is relatively small. Therefore the e-e bremsstrahlung cannot be separated from the electron-nucleus bremsstrahlung with the NaI(Tl) detectors used in the experiment. However, when the cross section of e-e bremsstrahlung was measured in a previous electron-photon coincidence experiment[10] where a Ge(Li) detector was used as photon detector, the two elementary processes could be separated. In this measurement the triply differential cross section of the e-e bremsstrahlung was found to be in good agreement with a theoretical calculation.[14] On the basis of this calculation, the polarization of the elementary process of e-e bremsstrahlung was calculated,[15] yielding the result shown in Fig. 5(a) (dashed line). The corresponding triply differential cross section (for six target electrons) is shown in Fig. 5(b) (dashed line). The polarization resulting from these two elementary processes by taking into account the corresponding cross sections is represented by the dashed curve of Fig. 4. From this curve, with corrections (a) and (b), one obtains the solid line curve of Fig. 4, which must be compared with the measured values.

The error bars include statistical and systematical errors. The statistical error is due to counting statistic. The systematical error (estimated to 5%) comes from the computation of the asymmetry ratio R. The two errors were considered to be independent and were added in quadrature. In spite of a long period of measurement (300 h), the error for the polarization at $-20°$ is relatively large, as the cross section is rather small at this point.

V. DISCUSSION

Looking at the angular dependence of the polarization of the electron-nucleus bremsstrahlung [Fig. 5(a), solid line] and at the corresponding cross section [Fig. 5(b), solid line], one sees that the greatest part of the radiation is almost completely polarized with the electric vector in the reaction plane, containing the momenta of the incoming and outgoing electron and the photon. This is in accordance with the conception of the simple classical model that the radiation emitted in the plane of the orbit of the electron is linearly polarized with its electric vector in this plane. However, such a simple model cannot explain the deviation from the complete polarization, especially the strong decrease of the polarization in the minimum of the cross section.

In a theoretical analysis Fano, McVoy, and Albers[4] investigate the contributions to the bremsstrahlung coming from a change of orbital motion of the electron and a change of spin orientation. They point out that orbital and spin changes are not independent and that the contributions of the change of orbital motion and spin orientation yield, respectively, linearly and circularly polarized bremsstrahlung. Interference effects of both contributions yield observable features even when the incident electron beam is unpolarized, e.g., that the dominant component of the electric vector is perpendicular to the reaction plane. However, when the momenta of the incoming and outgoing electron and the photon all lie in the same plane, the entire contribution of the change of the orbital motion is polarized in that plane. Therefore, deviations from the complete polarization in the reaction plane must be caused by the influence of the spin-flip radiation. The strong decrease of the polarization in the minimum of the cross section shows that here the influence of the spin is particularly strong. We could confirm the decrease of the polarization by a measured value at $-20°$.

Also in the further course of the polarization, as shown in Fig. 5(a), the degree of polarization generally does not reach -1. Only when the momentum transfer to the nucleus is parallel to the photon-emission direction, is the photon completely linearly polarized. This was shown by Olsen[16] in a Born approximation calculation. With the parameters of our experiment, this angle appears at 29°.

The deviations from the complete polarization in the reaction plane should not occur in the radiation process of a spinless particle. To verify this expectation, we have calculated the bremsstrahlung polarization of a hypothetical spinless electron under the same external conditions with a formula[17] which follows from the Duffin-Kemmer equation. For all photon-emission angles the calculation gives a complete polarization with the electric vector in the reaction plane.

For comparison with the polarization in the elementary process, Fig. 5(a) (dotted line) shows the polarization integrated over all directions of motion of the outgoing electron. This curve was calculated in Born approximation[18] and corresponds to a measurement in which the outgoing electron is not observed. Here the radiation in the forward direction (0°) shows a complete absence of linear polarization because of symmetry requirements, whereas the polarization of the elementary process is nearly complete in this direction. The general features of the integral polarization are discussed in terms of orbital motion and spin effects by Motz and Placious.[1]

The calculations of Elwert and Haug[5,6] for the polarization of the elementary bremsstrahlung process show that the decrease of the polarization in the minimum of the cross section diminishes strongly with increasing target atomic number Z. However, $Z\alpha \ll 1$ is required for the calculation.

Measurements of the polarization in the elementary bremsstrahlung process at high Z could show the influence of Coulomb and screening effects in its barest form. For comparison, calculations of the polarization in the elementary process according to the method of Tseng and Pratt[19] would be highly desirable since they calculate the bremsstrahlung process by means of partial-wave expansions, using point Coulomb as well as screened potential.

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