PHYSICAL REVIEW
LETTERS

VOLUME 16 6 JUNE 1966 NUMBER 23

# POLARIZATION MEASUREMENT OF THE 6-GeV COHERENT BREMSSTRAHLUNG FROM THE HAMBURG ELECTRON SYNCHROTRON

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(Received 9 May 1966)

High-energy bremsstrahlung produced in a suitably oriented monocrystal is expected to be highly polarized.[1-5] We report an experiment in which in agreement with these predictions linear polarizations up to 70% were measured.

The essential parts of the experimental setup were two diamonds, each adjustable in angular orientation by a high-precision goniometer. The first one—inside the synchrotron vacuum chamber—produced the photons from the circulating electron beam. The photon beam was collimated and cleaned of charged particles twice by broom magnets before hitting the second diamond, which converted part into electron pairs. This diamond was mounted with its goniometer inside a spectrometer magnet. Symmetric electron pairs were momentum analyzed with 2% resolution and detected by means of two scintillation-counter telescopes. A Quantameter was used to monitor the photon beam. From the point of view of polarization, the first crystal must be regarded as the polarizer, the second one as the analyzer.

The spectrum produced by the first diamond, as shown in Fig. 1(a), was chosen by adjusting the orientation such that it had one major peak at 2 GeV, the high-energy edge being at 6 GeV. We reported in Ref. 5 that such "one-point" spectra in which the dominating peak is due to the contribution of the lattice plane $(2\bar{2}0)$, defined in Miller indices, are expected to show particularly high polarizations. The orientation of the diamond is best described by giving the position of the electron momentum $\vec{p}_0$, which coincides with the photon beam axis, in the coordinate frame of the crystal axes: [110], [001], [110]. For the spectrum in Fig. 1(a), $\theta_1 = 50.5$ mrad is the angle of $\vec{p}_0$ relative to the polar axis [110], and $\alpha = 49.6$ mrad is the azi-

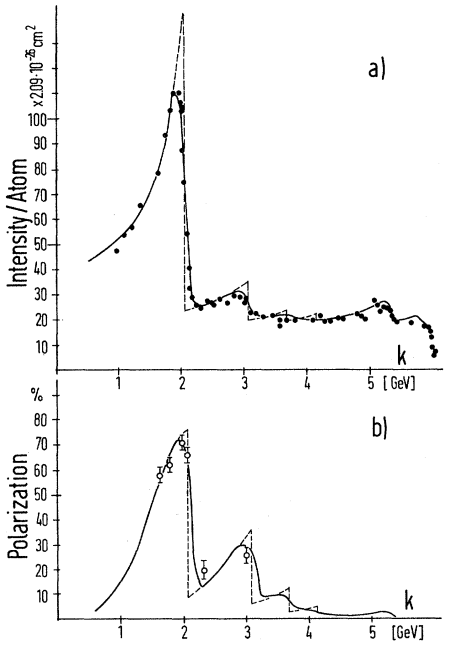


FIG. 1. Spectrum and polarization from a 6-GeV electron beam hitting a diamond crystal at $\theta_1 = 50.5$ mrad, $\alpha_1 = 49.6$ mrad. The bremsstrahlung intensity, $k(d\sigma/dk)$, is given as a multiple of $\bar{\sigma} = (Z^2e^4)/(137m^2c^4) = 2.09 \times 10^{-26}$ cm$^2$.

muthal angle measured from the plane [110], [001]. The experimental points in Fig. 1(a) represent coincident counts of electron pairs converted in a 20-$\mu$ Au foil in which the cross section is independent of polarization. The points were normalized to the theoretical curve —shown as dashed line—at the high-energy end of the spectrum. The solid curve is derived from the theoretical curve by taking into account the angular averaging effects in the same way as described in Ref. 5, the only difference being that a more rigid collimation was used here. The collimation angle as seen from the radiator was only $\pm 0.05$ mrad. This explains why there is little difference between the dashed and the solid curves. The intensity of the collimated photon beam was limited to $2\times 10^9$ effective quanta per minute in order to keep the accidental coincidence counts lower than 10% of the true ones.

Our method of measuring the polarization was first proposed by Barbiellini et al.[6] It is based on the fact that the pair-production cross section in crystals depends on the direction of the polarization vector of the incoming photon on the one hand and the preferred recoil direction of the crystal as given by its specific orientation on the other hand. This circumstance is expressed by the "asymmetry ratio" $R$ of pair production, which is defined for completely polarized photons by

$$R = (J_\perp - J_\parallel)/(J_\perp + J_\parallel), \tag{1}$$

where $J_\perp$, $J_\parallel$ are the cross sections for pair production in diamond from photons with their electric vector perpendicular and parallel, respectively, to some reference plane $\Pi$, which will be defined later. $R$ depends on $k$, the photon energy, and on $\theta_2$ and $\alpha_2$. These angles correspond to $\theta_1$ and $\alpha_1$ if $\vec{p}_0$ is replaced by $\vec{k}$. The asymmetry ratio depends strongly on $\theta_2$ and $\alpha_2$ and has characteristic discontinuities like the bremsstrahlung intensity. $R$ is completely analogous to the polarization $P$ for bremsstrahlung which is given by the definition

$$P = (I_\perp - I_\parallel)/(I_\perp + I_\parallel), \tag{2}$$

where $I_\perp$, $I_\parallel$ denote the photon intensity with electric vector $\vec{\epsilon}$ perpendicular and parallel, respectively, to the plane $\Pi$, for which we choose the plane [110], [001].

In the experiment we observed the number of counts $N_\perp$ with photons of polarization perpendicular to the reference plane $\Pi$, and—after rotating the analyzer crystal around the beam axis $\vec{k}$ by 90°—we observed the counting rate $N_\parallel$. The polarization is now determined by the relation

$$P = (1/R)\cdot(N_\perp - N_\parallel)/(N_\perp + N_\parallel), \tag{3}$$

where $R$ is regarded as known from the theory. It is evident from (3) that the statistical error for $P$ is the smaller the larger $R$ is. Therefore the orientation of the analyzer crystal must be chosen such that $R$ is as large as possible. We found that if we oriented the analyzer crystal to be on the high-intensity edge of the $(02\bar{2})$ discontinuity, already known from the bremsstrahlung spectrum, not only does the asymmetry have the largest value, but also the peak intensity is insensitive to small angular misalignments.[7] It is therefore not difficult to find the peak intensity experimentally. With the help of its goniometer, the analyzer diamond could be rotated around two axes perpendicular to $\vec{k}$, fixing $\theta_2$ and $\alpha_2$. In addition, because the direction of polarization was held fixed, there was a third axis by which the analyzer could be rotated around $\vec{k}$ by 90° without changing $\theta_2$ and $\alpha_2$. The angular accuracy of the goniometer was $\pm 0.1$ mrad.

The experimental points for the polarization are shown in Fig. 1(b). They confirm the expected high polarization of the peak of the spectrum. The dashed line is again calculated for ideal experimental conditions, while the solid curve is the result of averaging exactly with the same angular distribution that had been used for the spectrum above.

The statement that we consider $R$ in Eq. (3) as known deserves some further explanation. One may argue that if $R$ is regarded as known theoretically the same should hold for $P$ because both come out of the same theory. The difference lies, however, in the experimental realization of the theoretical assumptions. There can be imperfections in the crystal such as mosaic structure, and the directions of the particles are smeared out by multiple scattering and beam divergence. These influences result in a reduction of the intensity of bremsstrhlung and its polarization by angular averaging, which cannot be calculated accurately in all cases. The pair production, however, is to a large extent insensitive to such angular averages because the angles of orientation are much larger

than for bremsstrahlung production at comparable energies. Also the photons are not subject to multiple scattering in the target. We have collected experimental evidence that the angular dependence of the pair-production cross section in diamond agrees well within a few percent with the theoretical prediction, by studying it with unpolarized photons. Hence we regard $R$ as well determined in the sense that if there were a source for completely polarized photons one would measure $R$ with good precision. Insofar as this point of view is accepted the measurement yields absolute values of $P$.

Equation (3) shows further that the measurement of a number of points with varying values of $P$ fixes the ratio between them, $P_1:P_2:P_3\cdots$. The experimental points show that the method adopted is consistent with the theoretical expectation. We therefore conclude that (I) the pair production in crystals can be considered a precise tool for the determination of photon polarization, and that (II) in accordance with the theory of coherent bremsstrahlung production, photon beams with a high degree of linear polarization can be obtained.

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## INFLUENCE OF ATOMIC-OXYGEN ABSORPTION-LINE SERIES ON CROSS-SECTION MEASUREMENTS*

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(Received 2 May 1966)

We have recently obtained the absorption spectrum of atomic oxygen in both the afterglow and discharge regions of a flowing helium-oxygen microwave discharge in the 600- to 960-Å wavelength region. From the spectrum, the nine Rydberg series due to allowed transitions from the atomic-oxygen ground state $2s^22p^4\,^3P_{2,1,0}$ were observed.

The upper states of these transitions are as follows:

$$2s^22p^3(^4S^\circ)ns\,^3S^\circ, \quad 2s^22p^3(^2D^\circ)ns'\,^3D^\circ,$$
$$2s^22p^3(^4S^\circ)nd\,^3D^\circ, \quad *2s^22p^3(^2D^\circ)nd'\,^3S^\circ,$$
$$2s^22p^3(^2P^\circ)ns''\,^3P^\circ, \quad 2s^22p^3(^2D^\circ)nd'\,^3P^\circ,$$
$$*2s^22p^3(^2P^\circ)nd''\,^3P^\circ, \quad *2s^22p^3(^2D^\circ)nd'\,^3D^\circ,$$
$$*2s^22p^3(^2P^\circ)nd''\,^3D^\circ.$$

None of these series has been previously observed in absorption in this wavelength region, and the four series marked with asterisks were previously unknown. For two of the remaining five series, only one member was known. A complete analysis of the spectrum and description of the experiment is in progress and will be published in the near future.

In this Letter, we wish to point out the relation between these series lines and the recent absorption cross sections of Cairns and Samson[1] done in the ionization continuum region using a similar afterglow for producing the atomic oxygen. We have compared the wavelengths of the atomic-oxygen absorption lines found in our investigation with the wavelengths of the cross-section measurements. This comparison indicates that there will be appreciable absorption by atomic-oxygen lines for three of the 22 cross-section measurements. These are at the approximate wavelengths 685.5, 725.5, and 735.9 Å. These three cross sections are the largest values found and are the ones which are most different from the recent theoretical cross-section curves of Dalgarno, Henry, and Stewart.[2] We suggest that the large cross sections at these wavelengths are due to absorption by the atomic lines as well as by the ionization continuum.

The atomic-oxygen lines and their relation to the cross-section measurements are shown in Table I. The cross-section and atomic-oxygen-line wavelengths are generally the same within experimental error. This agreement