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Experimental study of photon beam polarimetry based on nuclear e^+e^- pair production in an amorphous target

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Abstract

The degree of linear polarization of a coherent bremsstrahlung (CB) was measured using an azimuthal asymmetry of incoherent e^+e^- pair production. The measurement was carried out in the γ-2 photon beam line of the Yerevan synchrotron, using a 2.55 GeV electron beam and a diamond radiator oriented to position the primary coherent peak in the interval 0.9–1.1 GeV. The polarization at the peak was measured to be 0.56 ± 0.06, in good agreement with the value computed from CB spectral shape analysis.

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1. Introduction

Direct methods for determining the linear polarization of a coherent bremsstrahlung (CB) photon beam are based upon the azimuthal dependence of the pair conversion process. These include using an oriented crystal as the pair converter and measuring the conversion rate as a function of crystal azimuthal orientation [1], and measuring the azimuthal asymmetry of e^+e^- pairs from nuclear pair production [2] or of the recoil electron from triplet production [3] in an amorphous target. Alternatively, the polarization may be computed from the basic CB process for an ideal beam and crystal, and then corrected for real experimental conditions based on analyzing the shape of the CB beam energy spectrum [4,5]. The latter method is of great practical utility to experiments using CB beams because the beam spectrum is measured more easily than is the polarization.

In a recent article [6], a CB polarimeter is described which exploits the azimuthal dependence of incoherent e^+e^- nuclear pair production within narrow ranges in both polar $\Delta\theta$ and azimuthal $\Delta\varphi$ angles [7]. Monte Carlo simulations of this polarimeter operating in the energy range $E_\gamma = 0.9$–1.1 GeV have shown that it is capable of measuring beam polarization at the level of $\sigma_p = 0.02$ if symmetric e^+e^- pairs are selected. This polarimeter has recently been constructed and installed on the γ-2 beam line of the YERPHI electron synchrotron. In this paper we present results from experimental measurements carried out with this polarimeter in a CB beam with maximal energy $E_\gamma = 2.55$ GeV.

2. Method of polarization measurement

Direct determination of photon beam polarization involves the measurement of the asymmetry in the scattering rates for some process between the two orthogonal states of the beam, and its interpretation as the product of the beam polarization and the analyzing power.

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The analyzing power or azimuthal asymmetry of incoherent e^+e^- pair production is defined as

$$A = \frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}} \quad (1)$$

where $\sigma_{\parallel}$ and $\sigma_{\perp}$ are the differential cross-sections for pairs with their production plane parallel and perpendicular to the plane of photon polarization, respectively.

These cross-sections are computed using the analytical expressions found in Ref. [8], where the degree of linear polarization is described in the terms of the Stokes parameter ξ_3. The values $\xi_3 = +1, -1$ correspond to 100% linear polarization ($P_\gamma = 1$) for the polarization orientation perpendicular (+1) and parallel (−1) to the production plane. An experimental measurement of asymmetry necessarily includes a finite aperture around the parallel and perpendicular directions. This is taken into account using a Monte Carlo simulation that incorporates the details of the setup. The simulation is used to produce the asymmetry A_{MC} that would result if the polarization of the beam were 100%.

The CB photon beam linear polarization ($P_\gamma < 1$) is extracted from the measured asymmetry as

$$P_\gamma = A_{exp}/A_{MC} \quad (2)$$

where A_{exp} is the experimental asymmetry and A_{MC} is the Monte Carlo simulation result from Eq. (1), calculated for $P_\gamma = 1$. The simulation includes a detailed model of pair production using differential cross-sections with accurate atomic form factors [6,9] and incorporating the detailed geometry and magnetic fields of the beam line and PS-6 polarimeter. The use of Eq. (2) implicitly assumes that measuring the counting rate difference in A_{exp} involves only switching the state of the beam polarization axis, and that all other beam conditions such as the energy spectrum and especially the absolute degree of linear polarization remain unchanged during the measurement. The precision of P_γ depends on the statistical and systematic uncertainties on the values of both A_{exp} and A_{MC}. Controlling systematic errors depend both upon the ability to limit variations in the beam operating conditions during the measurement of A_{exp} and upon the ability of the simulation to estimate the sensitivity to any residual variations which may bias the measurement.

3. Layout of the experimental setup

A sketch of the experimental setup in the γ-2 beam line is shown in Fig. 1. The beam of linearly polarized photons [10], generated by 2.55 GeV electrons incident on a diamond crystal (height 8 mm, width 2 mm, thickness 0.072 mm), is collimated and cleaned by the set of collimators K_1, K_2 and sweeping magnets SM_1, SM_2 to an angular divergence half-angle of 0.12 mrad. It then passes through a 10 μm Mylar converter (C_1) located at the entrance to the PS-30 pair spectrometer. The pair spectrometer measures the CB intensity spectrum simultaneously in 30 energy bins with energy resolution $\delta E_\gamma/E_\gamma = 0.02$ [11]. The integral intensity of the photon beam is measured by the Wilson quantameter (Q) located at the end of the beam line. The polarimeter PS-6 includes a 20 μm aluminum converter (C_2), a vertical slit collimator (K_3) and the PS-6 dipole spectrometer. The slit K_3 and PS-6 hodoscopes are located 15.8 and 19.9 m downstream of the C_2 converter, respectively. These distances are sufficient to allow the particles in pairs to be separated far enough to define a reasonably sharp boundary in the angular acceptance. The vertical slit K_3 is made of lead 6 cm thick, 2.6 cm wide and 8 cm high and installed in the beam vacuum pipe to the entrance of the dipole magnet. It provides azimuthal selection of e^+e^- pairs by passing only those whose pair-production plane is close to the vertical within range $\Delta\varphi = \pm 35°$. After the pairs have been dispersed in the dipole field of the spectrometer, they are detected in scintillating counters arranged to form six telescopes, with three channels on each side of the beam. Each telescope consists of one small scintillator in front which defines the energy channel for that telescope, overlapped with a larger counter located 60 cm behind it. As shown in Fig. 2, the telescopes are on either side of the beam, numbered $N_1 - N_3$ in order of decreasing energy. The front scintillators for channels N_1 and N_3 are 2.5 cm

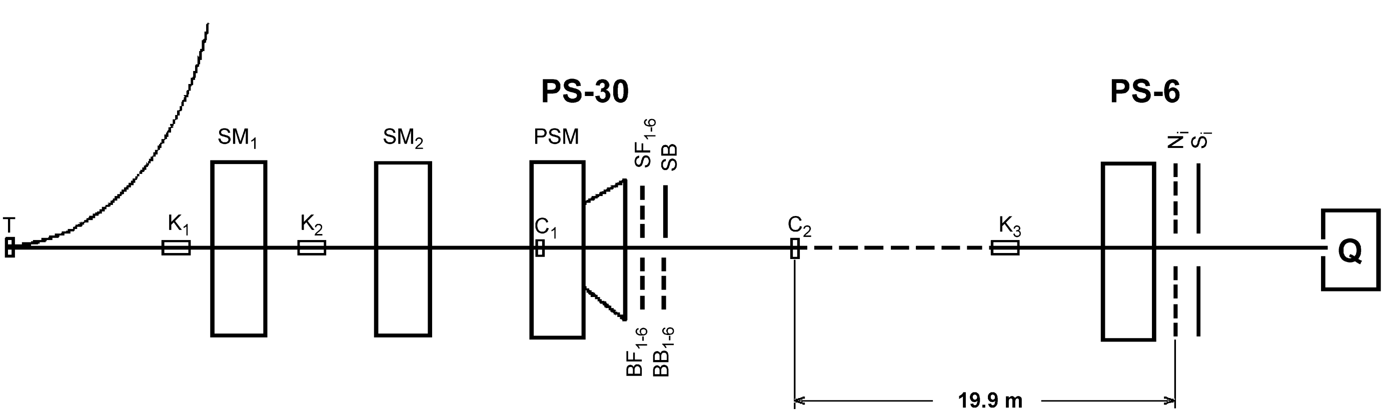

Fig. 1. Layout of the experimental setup, from the bremsstrahlung radiator (T) to the beam stop quantameter (Q). The two pair spectrometers PS-30 and PS-6 are the primary instruments used in this experiment.

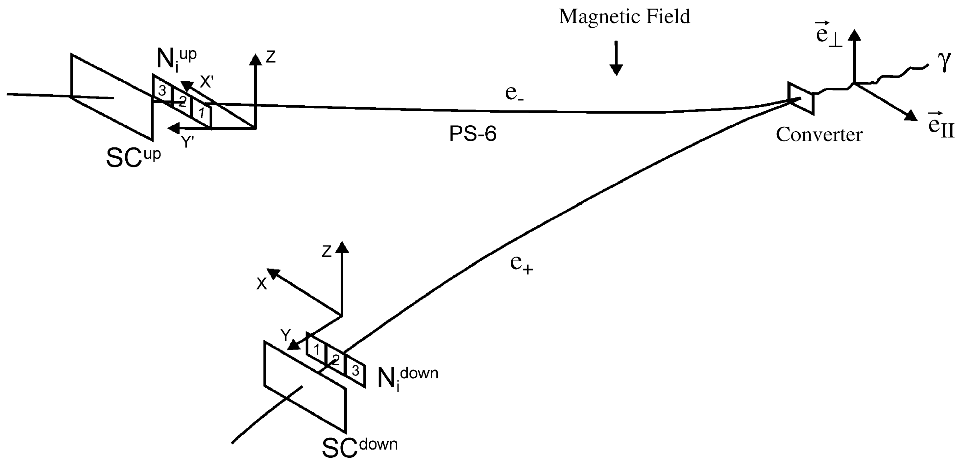

Fig. 2. Sketch of the pair trajectories inside the polarimeter PS-6. The numbered squares on each arm indicate the numbering scheme of the telescope channels (the hodoscopes are marked as $N_1 - N_3$ and the scintillator counters as SC).

wide, while the middle channel N_2 has a larger width of 5 cm. As depicted in Fig. 2, the left and right telescopes are alternately displaced above and below the horizontal mid-plane of the spectrometer. In combination with the azimuthal selection provided by K_3, the vertical displacement of the detector telescopes in PS-6 provides selection of pairs within a well-defined aperture in both polar and azimuthal pair-production angles. The vertical movement of the telescopes is performed remotely with a precision of 0.1 mm.

The transverse profile of the photon beam projected forward to the K_3 position from collimators K_1 and K_2 has a square shape of dimensions $16 \times 16\,\text{mm}^2$. The full beam line between the collimator K_2 and the exit of PS-6 is vacuum pumped, which diminishes the effects of multiple scattering.

4. Monte Carlo simulations and polarimeter alignment

A detailed description of Monte Carlo simulation is found in Ref. [6]. We have used these Monte Carlo tools to investigate the influence of several important experimental uncertainties in the value of A_{MC}. The first of these is the uncertainty in the relative alignment of the components of PS-6, including in particular the positioning of the telescopes vertically (z) and horizontally (x, y), and the alignment of the K_3 slit in the x direction. These uncertainties contribute to the systematic error only to the degree that their actual values are not correctly represented in the simulation. In order to minimize these uncertainties, a considerable fraction of the available beam time was devoted to commissioning the polarimeter with measurements designed to allow the alignment offsets to be determined empirically.

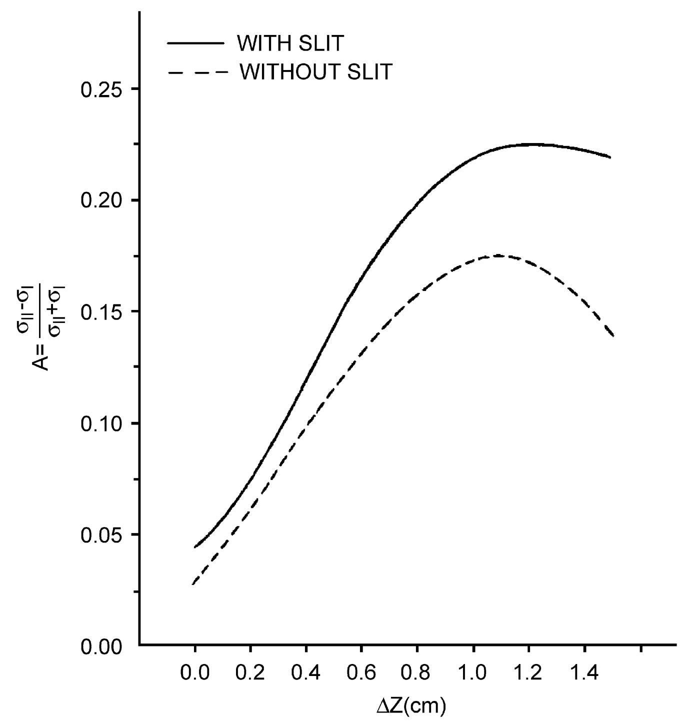

Fig. 3. The analyzing power A_{MC} of the polarimeter as a function of the separation distance $\Delta z = (z_{\text{up}} - z_{\text{down}})/2$ between the spectrometer mid-plane and the inner edge of the telescope acceptance. The curves are Monte Carlo results with (solid) and without (dashed) the K_3 slit in place, evaluated at the CB peak energy of 1000 MeV.

Fig. 3 shows the analyzing power A_{MC}, calculated from Monte Carlo using the Cromer–Waber atomic form factor [9], for the CB peak setting at 1000 MeV. The analyzing power is computed as the normalized counting rate difference (see Eq. (1)) in the coincidence rate of the two central telescopes $N_{2\text{up}}$ and $N_{2\text{down}}$ between the two beam polarization states, as a function of the vertical displacement Δz of the telescopes from the mid-plane of the spectrometer. The analyzing power is very small at $\Delta z = 0$. In order to reach larger values of the asymmetry, it is essential to exclude the region of small θ. This is achieved by increasing the value of Δz, as shown in the plot. The simulation shows that an optimum is obtained around $\Delta z = 1.0$ cm. Fig. 3 also shows the enhancement in A_{MC}

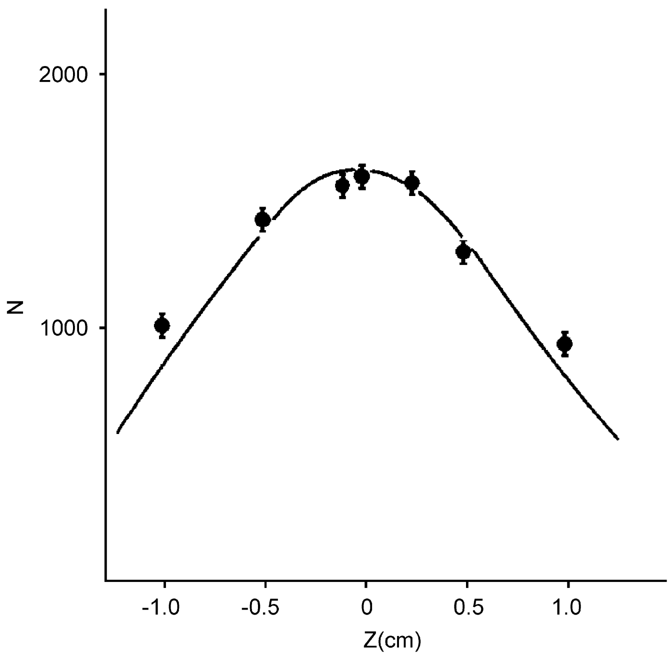

Fig. 4. The dependence of coincidence rate ($N_{2up} \cdot N_{2down}$) on the $z = (z_{up} + z_{down})/2$ of the telescopes from the mid-plane of the spectrometer, at the fixed offset $\Delta z = 0$. The curve is the expected dependence based on Monte Carlo. The data points are actual measurements taken by scanning the telescopes in z while holding $\Delta z = 0$.

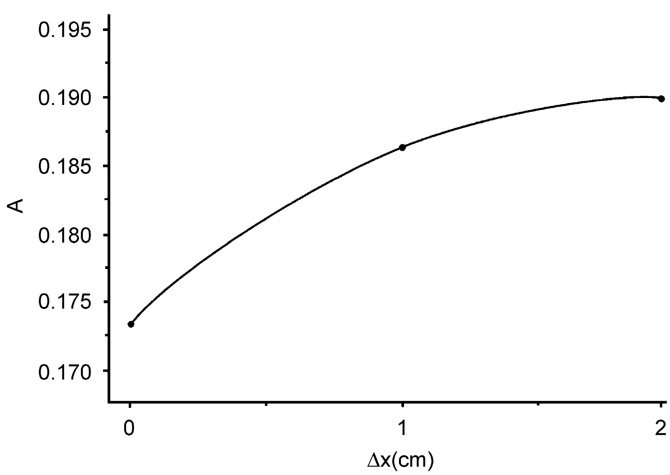

Fig. 5. Dependence of the Monte Carlo analyzing power A_{MC} on the misalignment parameter x which measures the horizontal displacement of telescope N_{2down} from its nominal x position, while telescope N_{2up} is held fixed at its nominal position. The points are Monte Carlo results for the coincidence channel ($N_{2up} \cdot N_{2down}$) and the curve is a smooth interpolation between the points.

that is obtained when the vertical slit K_3 is inserted to restrict the range in $\Delta\varphi$ of pairs accepted. Another consequence of this restriction is the improvement in the energy resolution of the PS-6 channels [6].

The uncertainty in the z setting arises mainly from our imprecise knowledge of the exact height of the spectrometer mid-plane in the position of the telescopes. A test was carried out to determine the position of the median plane. While keeping the vertical gap Δz constant between the left and right telescopes, the z-scan of this configuration around the expected median plane was performed, while monitoring the coincidence rate ($N_{2up} \cdot N_{2down}$) (see Section 5 for results). The curve in Fig. 4 shows the Monte Carlo dependence of the left–right coincidence rate on the z offset with $\Delta z = 0$.

The sensitivity of A_{MC} to an offset of the beam from its nominal axis in the x direction has also been investigated. The effect of displacements of the telescopes along the horizontal x-axis was also considered. A series of Monte Carlo runs were carried out with the electron-arm telescope held fixed in its nominal position and the positron-arm telescope shifted further to the right along the x-axis. The effect of this shift is mainly to select pairs with slightly less than nominal energy, but it also makes the polar angle acceptance windows asymmetric between the two arms. The Monte Carlo results are shown in Fig. 5. Although a 2 cm offset is large compared to what one might expect for the uncertainty in Δx, the figure shows that the value of A_{MC} is sensitive to this alignment parameter. For the experimental check of PS-6 detector symmetry around vertical and horizontal axes (z, x), it was necessary to measure and compare the coincidence rates for the two configurations depicted in Fig. 6. Full-scale Monte Carlo calculations for these configurations, including a detailed map of the analyzing magnetic field, showed compatible results within the limits of statistical uncertainties. The execution of the proposed tests allows to determine the actual geometry of the polarimeter and evaluate the expected systematic errors for the measured asymmetry.

5. First measurements and results

The experimental measurements were carried out in the γ-2 beam line of the Yerevan Physics Institute electron synchrotron working at an electron energy of 2.55 GeV. The CB photon beam generated through the orientation of (2 2 0) diamond crystal planes had a maximum intensity at

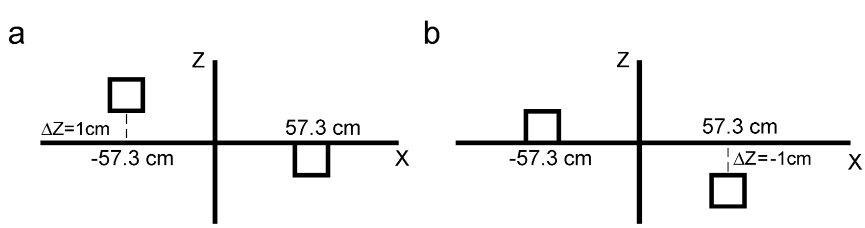

Fig. 6. Configurations used for testing the symmetry and alignment of the PS-6 telescopes: (a) the initial position of channels N_{2up} and N_{2down}, and (b) the final configuration reached by successive rotations around the x- and z-axes.

$E_\gamma = 1000\,\mathrm{MeV}$. The intensity of the photon beam was 10^8 photons per second for the full CB energy range while the coincidence rate was ~1 Hz for the central PS-6 telescope ($N_{2up} \cdot N_{2down}$). The polarization of the CB photons in the coherent peak was switched between horizontal and vertical by rotating the crystal, which required a few minutes each time. During the asymmetry measurements the spectrum in the peak region was measured and controlled every 5 min with the PS-30 pair spectrometer. If the CB peak position in the intensity spectrum was shifted by more than $\Delta E_\gamma/E_\gamma = 0.03$ due to a beam instability, the data taking of PS-6 was blocked and the crystal angle automatically adjusted to compensate for the shift. The spectrum was then re-measured to confirm the CB peak position before the resumption of the data taking. Typical CB spectra measured for the vertical and horizontal beam polarizations are shown in Fig. 7. The good agreement between the spectral shapes represented in the figure by open triangles and circles, each obtained by combining measurements taken at multiple PS-30 field settings, shows the high degree of reproducibility in the beam conditions between runs of opposite polarization. The photon polarization was calculated according to a CB shape analysis method described in Refs. [4,5]. The result of this calculation is represented by the open circle data points in Fig. 9. For the central energy bin ($E_\gamma = 1000 \pm 20\,\mathrm{MeV}$) the polarization value $P_\gamma = 0.53 \pm 0.02$ is obtained.

As another check of the overall consistency of the data, Fig. 8 shows a comparison between the spectral shapes measured in PS-30 (black curve) and PS-6 (data points). The overall normalization of the two spectra has been scaled to be equal at the peak data point. As is seen from the figure, these spectra are in a very good agreement. This serves as a strict test of the relative energy calibration between the two spectrometers. The data points shown in Fig. 4 show the results of an alignment scan of the coincidence rate ($N_{2up} \cdot N_{2down}$) taken versus the z offset of the two telescopes, while keeping $\Delta z = 0$ constant. As can be seen from the figure, the Monte Carlo prediction satisfactorily describes the experimental data. A least-squares fit to the data using an offset to the Monte Carlo curve as the single fit parameter results in an alignment offset of 0.1 mm for the PS-6 median plane.

A further check of the overall consistency of the measurement was made possible by comparing the rates

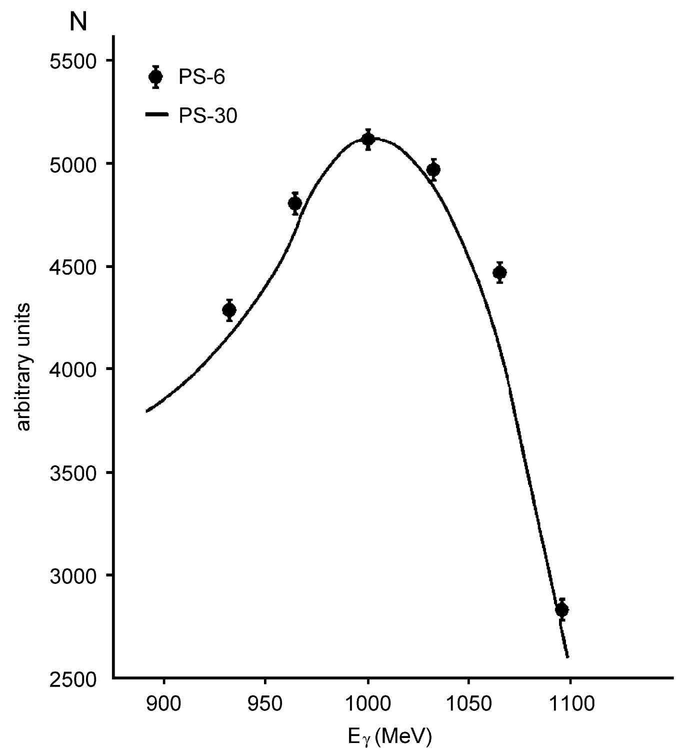

Fig. 8. Comparison between photon beam intensity spectra measured with PS-30 (curve) and PS-6 (data points). The data points were renormalized to match the curve at point 3.

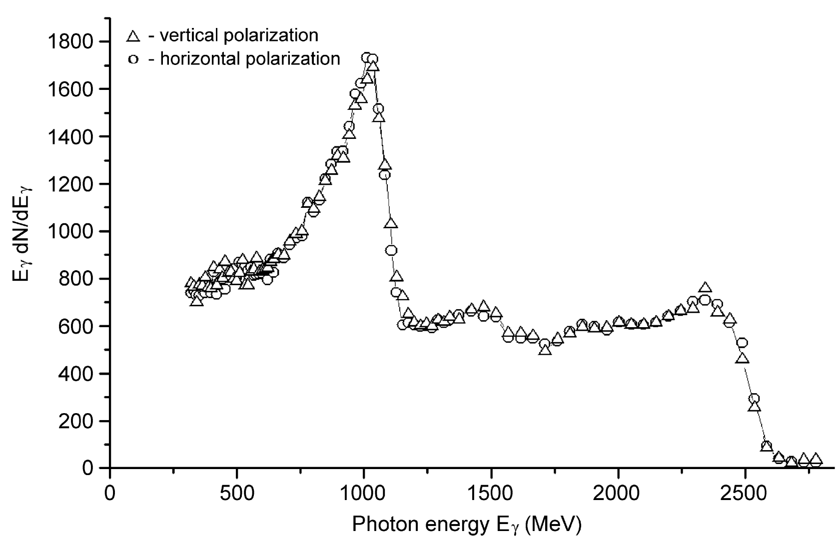

Fig. 7. CB photon beam intensity spectra measured using the PS-30 pair spectrometer with the diamond radiator configured for vertical (open triangles) and horizontal (open circles) polarizations, with the primary peak centered at 1000 MeV.

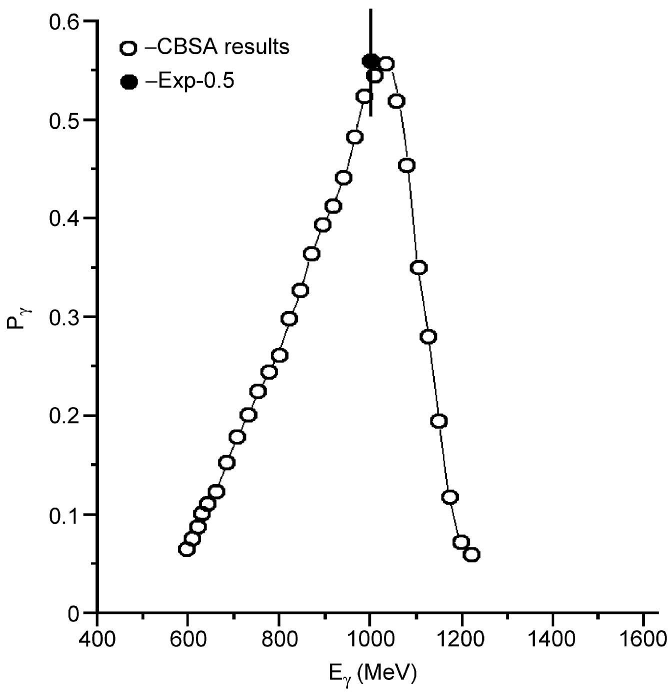

Fig. 9. The polarization of the CB photon beam in the region of the coherent peak at $E_\gamma = 1000$ MeV derived from analysis of the beam intensity spectrum (open circles) and from the PS-6 polarimeter (solid data point). The data point applies to an energy bin that extends ±20 MeV on either side of the displayed error bar.

observed using a diamond crystal radiator with those obtained using an amorphous radiator. The amorphous radiator produces an unpolarized bremsstrahlung beam without any peaks in its intensity spectrum. When normalized to the beam intensity seen in PS-30, the rates observed in PS-6 with an amorphous radiator should equal the average of those seen in the horizontal and vertical polarization orientations using a crystal radiator. This check was carried out with PS-6 set to a pair energy of $E_\gamma = 1000$ MeV. The average rates seen with the crystalline and amorphous radiators were in agreement within statistical errors of 3%.

Unfortunately, the tight time schedule of accelerator did not permit systematic studies of the dependence of the measured asymmetry on the collimator K_3 slit settings. Although the use of the slit improves the analyzing power by as much as 25% (see Fig. 3), it was decided to proceed with the measurement with the K_3 slits pulled back out of the beam in order to avoid uncontrolled systematic errors. The configuration of PS-6 telescopes with $\Delta z = 10$ mm has been chosen. The asymmetry value $A_{exp} = 0.098 \pm 0.011$ (stat.) was obtained for the central coincidence channel ($N_{2up} \cdot N_{2down}$). This channel was chosen because it has the largest sample statistics. Without the K_3 slits restricting the range in x of the tracks at the entrance to the spectrometer, the energy resolution of pairs in PS-6 is comparable to the 20 MeV energy width of the central bin. Because of the limited statistics in the side bins and the significant overlap of their resolution functions with the central bin, it was not possible to extract independent polarization values for more than one energy bin from these data. The systematic error in A_{MC}, coming from the uncertainty of the PS-6 telescopes offsets in the (x, z) plane has been evaluated with Monte Carlo simulations. Starting with conservative estimates of 1 mm for the uncertainties in both x and z offsets, the absolute value of the systematic uncertainty in A_{MC} obtained is approximately 0.003. With this level of the uncertainty, completed with the results of proposed tests and increased statistics, one may reach a precision of CB polarimetry at the level of 0.02–0.03. The results of the direct and indirect polarimetry methods are compared in Fig. 9. As can be seen from the figure, the measured value of $P_\gamma^{exp} = 0.56 \pm 0.06$ (stat.) agrees well with the polarization derived from the shape of the intensity spectrum.

6. Conclusion

A direct measurement of the linear polarization of a CB photon beam at a peak energy $E_\gamma = 1000$ MeV was carried out in the γ-2 beam line of the Yerevan Physics Institute's electron synchrotron operating at 2.55 GeV energy using an analyzing power of incoherent pair production on nuclei for this purpose. The polarization at the CB peak was measured to be 0.56 ± 0.06 (stat.), in good agreement with the value derived from analysis of the shape of the beam energy spectrum. Although the shortness of time did not allow to reach a planned precision of CB polarimetry at the level of 0.02–0.03, the experimental method was reliably tested in many details and the expected feasibility confirmed.

Acknowledgments

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