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

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Abstract

A method has been proposed to determine the degree of linear polarization of a coherent bremsstrahlung (CB) based on the analysis of the shape of the photon energy spectrum. This method has been tested by comparison with a direct polarization measurement using an azimuthal asymmetry of incoherent e^+e^- pair production, applied first time for this purpose. 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 spectral shape analysis.

Preprint submitted to Elsevier Science *30 November 2006*

Key words: Analyzing power; Polarimeter; Linear polarization; Bremsstrahlung

PACS: : 14.70.Bh; 24.70.+s; 78.70.-g

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_γ = 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

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carried out with this polarimeter in a CB beam with maximal energy E_γ = 2.55 GeV.

2 Method of polarization measurement

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

$$A = \frac{\sigma_\parallel - \sigma_\perp}{\sigma_\parallel + \sigma_\perp} \ , \tag{1}$$

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.

For cross-sections calculations, analytical expressions of Ref. [8] are used, where the degree of linear polarization is described in the terms of Stokes parameter ξ_3. The values $\xi_3 = +1$, -1 correspond to 100% linear polarization (P_γ =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 related to the measured asymmetry by

$$P_\gamma = A_{exp}/A_{MC} \ , \tag{2}$$

where A_{exp} is the experimental asymmetry and A_{MC} is the Monte-Carlo simulation result, calculated for $P_\gamma = 1$. The simulation includes a detailed model of pair production using differential cross-sections with atomic form-factors [6,9], all experimental conditions and details of polarimeter PS-6. An application of the expression (2) assumes an equality of CB's intensity and polarization spectra for both polarization orientations. 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 depends critically upon the ability of the simulation to account for all experimental factors that can bias the measured value A_{exp}.

3 Layout of the experimental setup

A sketch of the experimental setup on 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 (length 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 a half-angle of 0.12 mr. 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 Wilson quantameter (Q). The polarimeter PS-6 includes a 20 μm aluminum converter (C_2), vertical slit collimator (K_3) which provides angular selection of the emitted e^+e^- pairs, and horizontally bending magnet, instrumented with a six telescopes of scintillating counters, three channels ($N_1 - N_3$) in each arm (see Fig. 2). The telescopes are formed by coincidence of two hodoscopes (three small counters in each), overlapped with a single big counter, located 0.6 m downstream. The left and right telescopes are shifted up and down relative to the median plane, designed to select pairs produced symmetrically with respect to the beam axis.

The vertical slit K_3 made of lead 6 cm thick, 2.6 cm wide and 8 cm high is installed in the vacuum pipe and provides azimuthal angle selection of the emitted e^+e^- pairs within range of $\Delta\varphi = \pm 35°$. The γ- beam profile at that position has dimensions 16×16 mm^2.

The PS-6 hodoscopes are located 19.9 m downstream of the C_2 converter allowing to increase the angular resolution and select pairs with an adjustable range in polar angle. 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 on the collimation precision. The hodoscopes counters are 2.5 cm, 5.0 cm, and 2.5 cm wide, respectively. The vertical movement of the telescopes is performed remotely with a precision of 0.1 mm.

4 Monte-Carlo simulations and polarimeter alignment

The detailed presentation of Monte-Carlo calculations is done in Ref. [6]. Here we are considering an influence of some experimental uncertainties on the analyzing power. Not precise adjustment of PS-6 configuration is one of the main sources of systematic uncertainties, including in particular the positioning of the telescopes vertically (z) and in horizontally (xy- plane) and alignment of K_3 slit on the (x) direction. The mentioned uncertainties may also become a source of differences between Monte-Carlo simulations and experimental data. In this respect a number of calculations has been done to model an expected dependences and elaborate a necessary experimental tests for the geometry control.

The Fig. 3 shows the analyzing power A_{MC}, calculated with Cromer-Waber atomic form-factor [9] and the CB peak energy setting to $E_{\gamma}^{peak} = 1000$ MeV versus the vertical shift (Δz) of the central telescopes (N_{2up}, N_{2down}) relative the median plane with and without K_3 slit inserted. As one may see from figure, the vertical slit has an important impact on the increases of analyzing power, by app. 0.23, due to the restriction of azimuthal angle‘s acceptance. Another consequence of this restriction is the improvement in the energy resolution of PS-6 channels [6].

The z- dependence of analyzing power and its zeroing in the vicinity of $z \approx 0$ in particular, is an important experimental test of the polarimeter performance. As can be seen from Fig. 3, the most optimal value for the z selection is a low gradient flat zone around z =10 mm.

An uncertainty in the z setting may mainly arise from the not precise median plane positioning at the location of telescopes.

A test is proposed to determine the position of the median plane. At the fixed vertical gap Δz between the up and down telescopes, the z- scan around expected position of the median plane is performed (see Section 5). Superimposed curve in Fig. 4 shows the results of Monte-Carlo calculation obtained for $\Delta z = 0$ configuration.

An influence of the beam position uncertainty in the x- direction has been also investigated. The shift of the telescopes toward the x- direction, leads to the change in the A_{MC} asymmetry as is seen in Fig. 5 for the central bin(N_{2up}, N_{2down}). The plot is made for the case of fixed N_{2up} while N_{2down} moves aside from the beam position. For the experimental check of PS-6 detectors symmetry around vertical and horizontal axes (z, x) it is necessary to measure and compare the coincidence rates for the configurations presented in Fig. 6. The full scale Monte-Carlo calculations for these configurations, including a detailed map of analyzing magnet field, gave a compatible results within the limits of statistical uncertainties.

An execution all of the proposed tests allows to determine the actual geometry of the polarimeter and evaluate an expected systematic errors in the values of the measured asymmetry.

5 First measurements and results

The measurements have been carried out on the beam of linearly polarized photons with intensity of $10^8\gamma/s$ at the CB peak energy setting to E_γ =1000 MeV. The spectrum in the peak region was measured and monitored each 5 minutes and peak position controlled using PS-30 pair spectrometer. If the peak position is shifted above $\Delta E_\gamma/E_\gamma = 0.03$ due to beam instability, the data taking with PS-6 was blocked and the relevant crystal angle automatically tuned. Then the spectrum was re-measured to confirm the CB peak position before restart of the data taking. The typical CB spectra measured for the vertical and horizontal beam polarizations are shown in Fig. 7. The photons polarization was calculated according to a Ref. [4,5]. The polarization value at CB peak obtained is equal to $P_\gamma = 0.53 \pm 0.02$.

The energy calibration of PS-6 channels represents the strict test of measured CB shape compatibility with one of PS-30 pair spectrometer. The normalized each to other CB spectra measured by PS-30 (full curve) and PS-6 (points) are shown in Fig. 8. As is seen from the figure, the spectra are quite similar, no noticeable difference is observed in between.

The data on the vertical z- scan at fixed $\Delta z = 0$ are shown in Fig. 4 together with Monte-Carlo simulation results. As can be seen from the figure, Monte-Carlo predictions satisfactorily describe the experimental data. From the Gaussian fit of Monte-Carlo results the mean value error app. 0.1 mm is obtained for the median plane position. As a test of the apparatus systematic uncertainties, coming in particular from the beam, detectors and monitoring system instabilities, the measurements of CB spectra with disoriented crystal (amorphous spectrum) has been carried out. The rate of PS-6 channels for amorphous spectrum was compared to the average of rates for two orthogonal orientations of photons polarization at CB peak setting to $E_\gamma = 1000$ MeV. The difference of those rates, normalized to the number of photons, didn‘t exceed 2-3% (stat.), as it was expected.

Unfortunately the tight time schedule of accelerator didn‘t allow to fulfill the test on the slit positioning, which may become a source of systematical uncertainty in the analyzing power A_{exp}, so the measurements were carried out without it. The configuration of PS-6 telescopes for Δz=10 mm has been chosen. The asymmetry value $A_{exp} = 0.098 \pm 0.011$(stat.) was obtained for the central bin (N_{2up}, N_{2down}) with energy resolution $\sigma_E = 20$ MeV, that is statistically most significant. In the absence of the vertical slit, contributions of other channels is not considered due to the appearance of noticeably overlap with central bin. The systematic error on A_{exp}, coming from uncertainty of PS-6 telescopes adjustment in the (x, z) plane ($\sigma_x = \sigma_z = 1$mm) has been evaluated with Monte-Carlo simulations as app. 0.003 in the absolute value.

With this level of systematic uncertainties and increased statistics one may reach a polarization measurement precision in the level of 0.02- 0.03. The results of two polarimetry methods are compared in Fig. 9 where the polarization, directly measured at $E_\gamma = 1000 \pm 20$ MeV and CB polarization spectrum, calculated within CBSA method [4] are presented. As can be seen from the figure the measured value of polarization $P_\gamma^{exp} = 0.56 \pm 0.06$ (stat.) is agreed well with calculated one.

6 Conclusion

The direct measurements of linear polarization at CB peak energy $E_\gamma =$ 1000 MeV was carried out in the γ-2 beam line of Yerevan Physics Institute's synchrotron at 2.55 GeV energy of electrons, using first time an analyzing power of incoherent pair production on a nuclei for this purpose.

Although the time shortness didn't allow to reach a planned precision of CB polarimetry in the level of 0.02-0.03, an experimental method was reliably tested in many details and expected feasibility confirmed. The polarization at the CB peak was measured to be 0.56±0.06, in good agreement with the value computed from the spectral shape analysis.

This activity will be continued and we hope to carry out a new measurements with full set of the necessary tests.

Acknowledgements

Authors are indebted to the synchrotron staff and his leader Valery Nikogosyan for their efforts of accelerator running, directorate of YERPHI for the support and funding. The support of CRDF grant AP2-2305-YE-02 is also acknowledged.

Figure captions

Fig. 1. Layout of the experimental setup.

Fig. 2. Sketch of the polarimeter PS-6.

Fig. 3. The z- dependence of the A_{MC} asymmetry with and without slit (solid and dashed curves respectively), where $z = (z_{up} - z_{down})/2$ is the half-height of the gap in z between the up and down counters. The energy of CB peak is set to $E_\gamma = 1000$ MeV.

Fig. 4. The z- dependence of calculated and experimental yields of (N_{2up}, N_{2down}) coincidences at fixed $\Delta z = 0$ between up and down telescopes.

Fig. 5. The x- dependence of A_{MC} asymmetry for the central telescopes (N_{2up}, N_{2down}) of PS-6 at fixed $z = 10$ mm for the case of N_{2up} is fixed while N_{2down} moves aside from its symmetry configuration.

Fig. 6. Testing the axial symmetry of PS-6 telescopes configuration
(a) an initial position of the telescopes (N_{2up}, N_{2down})
(b) the final configuration after successive rotations around vertical and horizontal axes.

Fig. 7. An intensity spectra of PS-30 pair spectrometer measured at CB peak energy setting to $E_\gamma^{peak} = 1000$ MeV for both vertical and horizontal orientations of the photon beam polarization.

Fig. 8. An intensity spectra in a CB peak region ($E_\gamma^{peak} = 1000$ MeV) measured simultaneously by PS-30 and PS-6.

Fig. 9. The measured photon beam polarization at $E_\gamma = 1000 \pm 20$ MeV together with calculated curve of polarization by CBSA method [4].

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