Polarized photon beam polarimeter on the base of e^+e^- pairs photoproduction on nuclei in amorphous target

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Abstract

To directly measure the linear polarization of a coherent bremsstrahlung (CB) photons with a peak energy of 1 GeV at Yerevan Synchrotron, a simple polarimeter is proposed on the base of a bending magnet equipped with two hodoscopes of the scintillating counters positioned above and below of the median plane, allowing to register the symmetric pairs produced in a amorphous target. The Monte-Carlo calculations show that the use of a vertical slit collimation at the entrance of the magnet allows to improve both the analyzing power and the energy resolution. The obtained values of the analyzing power for various atomic form factors of the target (the 20 μm thick Al-converter) reaches a 0.25 - 0.3 with expected yields of useful events on the level of a few Hz.

Key words: analyzing power, polarimeter, linear polarization, bremsstrahlung

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1 Introduction

The linearly polarized coherent bremsstrahlung (CB) photon beams are widely used in the study of photonuclear reactions. At present to carry out experiments with CB beams, it is necessary to know their polarization with a high accuracy. Photon beams linear polarization is mainly determined by means of the calculation methods exploiting the theoretical description of CB spectra [1–3] and measured photon intensity spectra accounting an influence of the experimental factors [4–6].

Among the direct methods of a CB polarization measurements up to 10 GeV, the most efficient is the use of the incoherent e^+e^- pairs photoproduction process on a amorphous target [7–10] as compared to the one, on a crystals [1,2] or on the atomic electrons [11]. In the case of amorphous target the correlation between the plane of emitted pair's fragments and direction of photon polarization is exploited.

The experiments carried out so far [7–10] and references therein, exploited a semi-differential configuration in the e^+e^- pair phase space, where one branch pair's parameters, namely the energy, polar and azimutal angles (f.e. E_+, θ_+, φ_+) were fixed, while the integration over the energy and polar angle in the second one was realized by means of the appropriate acceptance choice, leading to a relatively low analyzing power (app.0.1). The work on the mapping of intensity, analyzing power and figure of the merit in the incoherent photoproduction of e^+e^- pairs was done in the ref. [12]. On a base of the analysis, mainly made for the projection angles up to 1.5 $m/E_\pm$, authors recommended the use of a non coplanar pairs detection configuration, leading to the high analyzing power but rather low figure of merit. In the ref. [13] on the base

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of developed method in work [12] was proposed the use micro strip detectors for measurement of angle correlation in e^+e^- pairs photoproduction from an amorphous target. In the work [14] the suggestion to exploit a symmetric differential configuration: $E_+ \approx E_-$, $\theta_+ \approx \theta_-$, $\varphi_+ \approx \varphi_-$ (wedge and ring method) was proposed, allowing to obtain an effective analyzing power up to 0.3, motivated by the numerical calculations within the formalism, developed in [9].

The aim of the presented work is CB direct polarimetry method development, its Monte-Carlo study on the base of e^+e^- pairs photoproduction on a nuclei in amorphous target and its feasibility for 1 GeV energy range at the Yerevan Synchrotron, a comparison with the calculation method of photon beam polarization, exploiting a CB-spectra measured simultaneously by a multichannel pair spectrometer is also considered.

2 Method of e^+e^- pair's incoherent production on nuclei in the amorphous target for photons' beam linear polarization measurement.

To measure linear polarization of high energy photons in refs. [7] it was for the first time proposed to use $Z(\gamma, e^+e^-)$ pairs production process on nuclei in the amorphous target. The azimuthal asymmetry of e^+e^- pair distribution with momentum $\mathbf{P_{e^+}}$ and $\mathbf{P_{e^-}}$, polar θ_+, θ_- and azimuthal φ_+, φ_- angles are used to analyze the photon polarization with 4 momenta $k(\mathbf{k}, E_\gamma)$ and polarization vector $\mathbf{P}$ (fig. 1). This method exploits the angular correlation between photon beam polarization plane, involving polarization vectors $\mathbf{P}$ and k, and the plane of emitted lepton (electron or positron), having its momentum $\mathbf{P_{e^-}}(\mathbf{P_{e^+}})$ and $\mathbf{k}$.

Azimuthal asymmetry or analyzing power is defined as a:

$$A = \frac{\sigma_{||} - \sigma_{\perp}}{\sigma_{||} + \sigma_{\perp}} \ , \qquad (1)$$

where $\sigma_{||}$- cross section to emit pair into the plane parallel to polarization plane and $\sigma_{\perp}$- into perpendicular one. This ratio has a large value, when $\varphi_{-} - \varphi_{+} \sim \pi$ (complanar pairs). L. Maximon and H. Olsen [9] showed that it is possible to reach a large values of analyzing power (1) by selecting $(e^{+}e^{-})$ pairs over narrow angular range $\Delta\phi$ around the complanar direction (nearly complanar pairs).

Orientation of emitted pair's plane in respect to the photon polarization plane and the analysing power strongly depends on the experiment's geometry. As is shown ref. [14] the high analyzing power may be obtained if symmetric $e^{+}e^{-}$ pairs are selected combining both narrow angular range $\Delta\phi$ and $\Delta\theta$. This method allowed us to develop on the base of a bending magnet a simple polarimeter with analyzing power up to A=0.3 for the energy range of 1 GeV.

To calculate the $e^{+}e^{-}$ pairs yield by linearly polarized photons in amorphous target we used analytical expressions of differential cross section from ref. [14] which depend on the target material through the atomic form factor $F(q)$:

$$d^5\sigma = \frac{\sigma_0}{\pi^2}\, y(y-1)\, \frac{[1-F(q)]^2}{q^4}\, (X_{unp} - \xi_3 X_{pol}) dy\, du_{-}^2 du_{+}^2 d\varphi_{-} d\varphi_{+} \ , \qquad (2)$$

where $\sigma_0 = Z^2 r^2 \alpha$, Z- nuclear charge, r- classical electron radius, $\alpha = 1/137$, $y = E_{\pm}/E_{\gamma}$, $u_{\pm} = E_{\pm}\theta_{\pm}/m$- Stocks parameter, determining the linear polarization ($\xi_3 = +1, -1$) in the case, when the polarization vector $\mathbf{P}$ is parallel or perpendicular to Z- axe direction (fig. 1). In formula (2) the following notations are presented:

$$q^2 = \frac{\delta^2}{m^2} + u_{+}^2 + u_{-}^2 + 2u_{+}u_{-}\cos(\varphi_{+} - \varphi_{-}) \qquad (3)$$

$$X_{unp} = (\xi_+ - \xi_-)^2 + \frac{1}{2}\varphi(y)\xi_+\xi_-[u_+^2 + u_-^2 + 2u_+u_- \cos(\varphi_+ - \varphi_-)] \tag{4}$$
$$X_{pol} = \xi_+^2 u_+^2 \cos 2\varphi_+ + \xi_-^2 u_-^2 \cos 2\varphi_- + 2\xi_+\xi_- u_+ u_- \cos(\varphi_+ + \varphi_-) \tag{5}$$

where q^2 is the square of momentum transfer, $\varphi(y) = y/(1-y) + (1-y)/y$, $\xi_\pm = 1/(1+u_\pm^2)$, $\delta = m^2/2E_\gamma y(1-y)$, - minimum momentum transfer. For investigation the influence of various atomic form factors on the pair production cross section we used $F(q)$ in expression (2), as:

$$F(q) = 1/[1 + (111qZ^{-1/3})^2] \tag{6}$$

for case of complete screening [9] and for form factor Cromer-Waber (CW) we use parameters from [15]

$$F(q) = \frac{1}{Z}(\sum_{i=1}^{4} a_i e^{-b_i q^2} + c) \tag{7}$$

The choice of CW is connected to an opportunity of more reliable description of real atomic form factor [19].

Let's note also that the 5-dimensional differential cross section (2) can be presented in Lab system as dependent on energy and angular variables of pairs' fragments $(E_+, \theta_\pm, \varphi_\pm)$:

$$\frac{d^5\sigma}{dydu_-^2 du_+^2 d\varphi_+ d\varphi_-} = \frac{E_\gamma m^4}{4E_+^2 E_-^2} \frac{d^5\sigma}{dE_+ d\Omega_+ d\Omega_-} \tag{8}$$

3 Yerevan Synchrotron experimental conditions and CB polarimeter for photon linear polarization measurement.

At the beginning of 70-s a linearly polarized photon beam was obtained at the Yerevan synchrotron [16] and many polarization experiments were carried out. To determine the photon beam polarization several calculation methods were used on the base of measured CB intensity spectrum. In ref.[17,18] a methods of linear polarization calculation were proposed on the base of intensity spectra measurement with evaluated accuracy 0.01 in the working region of CB $\Delta E_\gamma/E_\gamma^{peak}$ = 15-20%. Calculations of polarization P_γ showed an independency of atomic form factors choice, giving a coinciding results within accuracy 0.02 in the mentioned energy range [19].

Starting from that we may cross-check a consistency of calculation methods and of direct polarimetry one, extracting as well the correct type of an atomic form-factor.

It is known that photon beam linear polarization P_γ measured by direct method can be defined from formula (9):

$$P_\gamma = A^{exp}/A^{cal} \tag{9}$$

where A^{exp} is the experimental asymmetry cross section of e^+e^- pair production, which also is a function of the real atomic form factor of the used target $F(q)_{real}$. A^{cal} is determined from the formula (1) for $P_\gamma = 1$, on the base of Monte-Carlo calculations using atomic form factor of the target $F(q)$ from [12,13,15] (see formula (6),(7)).

A^{exp} is defined as

$$A^{exp} = (N_1 - N_2)/(N_1 + N_2) \tag{10}$$

where N_1 and N_2 are the number of e^+e^- produced pairs by the linearly polarized incident photon beam (energy E_γ) for two perpendicular orientation of the polarization vector. The degree of polarization for these two perpendicular orientations is the same and equal to $P_\gamma < 1$.

In this conditions, the uncertainties of experimental measurement of the photon beam linear polarization P_γ will consist of statistical accuracy of determination experimental and calculated on the base of Monte-Carlo method asymmetries A^{exp} and A^{cal} and also from systematic uncertainties coming from possible differences between experimental kinematic parameters (energy of primary photons E_γ, energy of e^+e^- pair particles, angular and momentum intervals for registered particles) and these same parameters used in the calculation of A^{cal}. The sensibility of A^{cal} to the kinematics parameters can be studied by Monte-Carlo method.

For minimization of systematic uncertainties it is required: the CB intensity spectrum for the two orientations of polarization vector (and corresponding calculated [19] photon beam polarization) will be controlled in parallel by the 30 channel pair spectrometer PS-30, providing energy resolution of $\sigma_{E_\gamma}/E_\gamma =$ (1.5-2)% [20], the incident CB photon beam intensity spectrum on the target of the polarimeter PS-6 (see fig. 2) measured by the pair spectrometer PS-30 should be identical to the CB spectrum measured (at the same time) by the polarimeter PS-6. It is also expected to provide exact geodesy (with accuracy not worse than 1 mm) at the polarimeter assembly.

In the energy range E_γ = 900-1100 MeV our estimations have shown that accuracy of photon beam polarization measurement is expected up to 0.02.

As mentioned above, the knowledge of the incident photon beam polarization by calculation method P_γ^{cal} [19], and the direct measurement of this quantity P_γ^{exp} (9) as a function of $F(q)$, gives the possibility to determine with known accuracy the value of atomic form factor of the used target $F(q)_{real}$.

The polarimeter PS-6, with the knowledge of the target form factor $F(q)_{real}$, can be used for the measurement of polarization P_γ for strongly collimated CB photon beam [21]. In this case, direct measurement of P_γ may be necessary to check the method of determination CB photon beam polarization by shape analysis of measurement intensity spectrum [19].

A scheme of the experimental set up with polarimeter is presented at fig.

2. A linearly polarized photons beam is collimated to 0.17 mrad upon passing through the collimators K_1, K_2 and sweeping magnets SM1 and SM2 and strikes thin 10 μm lavsan converter C_1 at the entrance of the pair spectrometer (PS-30).

The polarimeter is located downstream of the beam just after pair spectrometer and consists of an amorphous converter (C_2), 20 μm thick Al, a collimator (K_3) - vertical slit with 2.0 cm width providing necessary azimuthal selection of pair fragments and bending magnet (PS-6) with hodoscopes of scintillating counters positioned above and below the median plane for registering e^+e^- symmetric pairs (fig. 3). Distance from converter C_2 to collimator (K_3) is 15.8 m and to telescope counters -19.9 m. The tracing of e^+e^- pair will be realized in the vacuum of the beam pipe and vacuum chamber of polarimeter. No influence of C_1 converter is expected as a possible source of charged background.

4 Monte-Carlo simulation of proposed polarimeter for photon linear polarization measurement and calculation results.

In order to optimize the polarimeter's geometry, including sizes of hodoscopes counters, collimator (K_3) and their positions, Monte-Carlo calculations of luminosity, energy resolution and analyzing power were carried out.

Calculations accounted all experimental conditions, including shape of CB spectrum, sizes of the beam in converter, multiple scattering, topography of PS-6 magnetic field et al.

Simulation of e^+e^- pair production was carried out using analytical expressions of differential cross section (2) by Neumann's method [22].

The calculation of e^+e^- pairs trajectory in PS-6 was performed by Runge-

Kutt method for the system of equations for particle movement [23].

$$\frac{dP}{dt} = \frac{e}{c}[V \times H] \tag{11}$$

Simulation of (e^+e^-) pair tracing included multiple scattering in C_2 according to ref. [22] and accounted for corresponding energy losses [24].

Algorithm of Monte-Carlo code is following - for each event were played:

- the energy E_γ of primary photon,
- the coordinates (x, y, z) of an interaction point in converter C_2,
- the electron momenta P_{e^-}, pair particles polar (θ_-, θ_+) and azimuthal (φ_-, φ_+) angles by the given differential cross section (8).

On the base of obtained (P_{e^-}, P_{e^+}, θ_- θ_+, φ_-, φ_+) values, the components of pair (P_x, P_y, P_z) momenta were calculated in order to trace them in the magnetic field of PS-6 taking into account the energy losses and multiple scattering. At first, aimed to find the optimal polarimeter geometry with required energy resolution $\sigma_{E_\gamma}/E_\gamma$ and analyzing power A, as well as acceptable e^+e^- pair yields, the counters' vertical position (Z) relative the median plane was studied. In fact this position corresponds to lower limit of registered polar angles range. In fig. 4 and fig. 5 the dependences of analyzing power A (curve a) and Figure of merit F (curve b) of Z_{min} (vertical shifting of counters) is presented for complete screening and for form factor Cromer-Waber (CW) respectively. As it is seen the most acceptable value is $Z_{min} = 1.2$ cm, which corresponds to polar angle ($\theta_{min} = 0.4$ mrad) for registered particles in the momentum interval $P = 460$ - 550 MeV/c.

As γ- beam energy is continuous, pairs are widely distributed both in momentum and azimuthal angles which doesn't allows to obtain the good resolution after magnetic analysis. As an illustration of this effect, fig. 6(a) shows the energy distributions of symmetric e^+e^- pairs registered in hodoscopes with a width of 2.5 cm in the momentum interval P = 460-550 MeV/c, where the analyzed data are fitted by Gaussian distribution. As it is seen, pair's energy distributions are overlaped and their separation with good resolution is not possible.

However it was found (see fig. 6(b)), that resolution is improved with restriction of pair's the azimuthal angles' range $\Delta\varphi$ using collimator with vertical slit. Fig. 7(a) shows the primary angular distribution of e^+e^- pair (polar and azimuthal angles) without collimation (0.3 mrad $< \theta_{e^+e^-} <$ 3.8 mrad and $\Delta\varphi = \pm 80°$). In the case of collimation (fig. 7b) with slit width of $|\Delta x| \leq 1$ cm, the azimuthal distribution of pair is narrower ($\Delta\varphi = \pm 45°$) and the upper limit of polar angles is slightly cutted (0.3 mrad $< \theta_{e^+e^-} <$ 2.5 mrad). As is seen from fig.6 (b), the energy resolutions of symmetric pairs are no worse than $\sigma_{E_\gamma}/E_\gamma = 1.2\%$. So, for symmetric pairs registration using 3 hodoscope elements in e^+ and e^- arms of polarimeter (6 in total), a good energy resolution (σ_{E_γ} = 12 MeV) may be obtained in the photon energy range E_γ = 900-1100 MeV. In the fig.6(c) for the case of E_γ^{peak} = 1 GeV and $\Delta E_\gamma/E_\gamma$ = 20% the cross section of collimator with 2 cm width and 8 cm height is presented. The inside square with 1.4×1.4 cm^2 corresponds to γ- beam profile in the place of its location and shaded areas (0.9 cm $\leq |Z_c| \leq$ 4 cm) to ranges of registered pairs in counters positioned at $Z_{min} = \pm$ 1.2 cm distance from median plane of PS-6. As Monte-Carlo calculations confirmed the symmetric pairs registration will be realized in "cross" geometry: "up" - electron, "down" - positron or the contrary.

In the case of aluminum target the dependence of analyzing power A from the converter (C_2) thickness is presented in fig. 8. As it is seen from figure, an increase of converter's thickness from 20 μm to 50 μm leads to analyzing power decrease app.1.5 times. Using Monte-Carlo calculation data, the expected experimental yields of symmetric e^+e^- pairs has been estimated at photon beam intensity of 10^9 eq.photon/sec and aluminum target's thickness of 20 μm on the level of a few Hz.

5 Conclusion

On the base of Monte-Carlo calculations a simple CB polarimeter for direct measuring the linear polarization of photon beam with accuracy 0.02 in the energy range of 1 GeV has been developed by method of incoherent pairs production in amorphous target. It is shown that using hodoscopes of scintillating counters vertical shifted from the polarimeter‘s median plane and the collimator with vertical slit allows to create polarimeter with analyzing power reaches a 0.25-0.3 with expected yields of useful events on the level of a few Hz in the case of 20 μm thick Al-converter and having good energy resolution in the photon energy range E_γ = 900-1100 MeV.

Starting from experimental measurements of polarized photon beam polarization it is possible to cross-check a consistency of calculation methods as well extract the correct type of an atomic form factor.

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Figures captions

Fig. 1. Kinematics of the process $Z(\gamma, e^+e^-)$.

Fig. 2. Scheme of the experimental setup.

Fig. 3. Sketch of the polarimeter PS-6.

Fig. 4. Dependence of analyzing power A (curve a) and Figure of merit F (curve b) from Z_{min} (vertical shifting of counters from the polarimeter's median plane) in the case of complete screening for E_γ^{peak} =1 GeV.

Fig. 5. Dependence of analyzing power A (curve a) and Figure of merit F (curve b) from Z_{min} (vertical shifting of counters from the polarimeter's median plane) in the case of form factor Cromer-Waber (CW) for E_γ^{peak} =1 GeV.

Fig. 6. Energy distributions of symmetric e^+e^- pairs registered in hodoscopes of polarimeter PS-6 with a width of 2.5 cm in the momentum interval P = 460-550 MeV/c:

a) without a collimator

b) with a collimator - vertical slit with $\Delta X \leq 1$ cm

c) the cross section of collimator.

Fig. 7. Polar and azimuthal angular distributions of (e^+, e^-) pairs:

a) without a collimator

b) with a collimator $\Delta X \leq 1$ cm.

Fig. 8. The dependence of analyzing power (A) on the converter (C_2) thickness in the case of aluminum target.