ISSN 1330–0016
CODEN FIZBE7

LETTER TO THE EDITOR

MEASURING LINEAR POLARIZATION OF REAL PHOTONS

YURIJ P. PERESUN'KO, VALENTIN F. BOLDYSHEV
and EVGENIJ A. VINOKUROV

NSC KIPT, Kharkov, Ukraine

Received 10 February 1999; Accepted 7 July 1999

A survey of known methods of analyzing the linear polarization of high-energy photons is presented. The methods of pair photoproduction in single crystals and in amorphous targets are briefly discussed. The method of measurement of photon linear polarization using azimuthal asymmetry of the recoil electrons from pair photoproduction on electron (triplet photoproduction process) is considered in details. The optimum region of kinematic parameters of emitted particles in which analyzing power increases is discussed. The possibility of using the CEBAF Large Acceptance Spectrometer (CLAS) for the measurement of linear photon polarization by analyzing the recoil-electron distribution in triplet photoproduction process (with the CLAS magnet turned off) is considered.

PACS numbers: 13.88.+e, 29.27.Hj, 29.90.+r UDC 539.122

Keywords: high-energy photons, linear polarization, azimuthal asymmetry of recoil electrons from pair photoproduction, analyzing power

The differential cross-section of all processes with linearly polarized photon has an azimuthal asymmetry and may be written in the form [1]:

$$2\pi \frac{\mathrm{d}\sigma}{\mathrm{d}\phi} = \sigma^{(t)} + P\sigma^{(l)} \cos 2\varphi = \sigma^{(t)}(1 + P\Lambda \cos 2\varphi)\,. \tag{1}$$

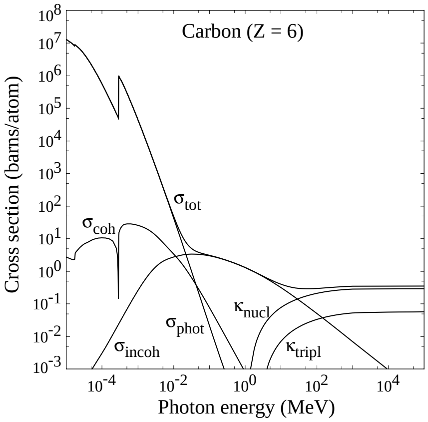
Here, $\sigma^{(t)}$ is the cross-section of the process for unpolarized photons, $\sigma^{(l)}$ is the part of the cross-section due to the photon polarization, P is the degree of linear polarization of the photon beam, $\Lambda = \sigma^{(l)}/\sigma^{(t)}$ is the asymmetry of the yield of the reaction products for $P = 1$ (it is often called the analyzing power of the process) and φ is the azimuthal angle. The relative contributions of the different processes to the cross-section of photon's interactions in carbon [2] are shown in Fig. 1.

One can see that at a photon energy greater than 0.5 GeV, the Compton scattering and other processes have negligible probability in comparison with the e^+e^- photoproduction. Therefore, the methods based on Compton scattering are not appropriate for high-energy photons and will not be considered here. Among the methods of measurement of photon polarization based on the processes of e^+e^- photoproduction, one should consider the following:

1) Methods which use coherent pair photoproduction in single crystals [3]. The analyzing power of this process grows with increasing photon energy ω, and this method may practically be used at $\omega \geq 5$ GeV. The disadvantages of this method are the strong attenuation of the beam on passage through a thick crystal and large and expensive apparatus compared to other methods.

2) Pair photoproduction on nuclei in amorphous target. To analyze the photon polarization, the correlation between the plane of emitted pair fragments and direction of photon polarization is used. In the case when planes of emitted pairs are detected for all pair-production events, the analyzing power, $\Lambda = 0.14$, is nearly independent of photon energy [4,5]. This value may be increased if one would select events of symmetrical pair production with the opening angle near $4m/\omega$. In that case, analyzing power is $\Lambda = 0.33$ [5]. Since the pair fragments are emitted with polar angles $\Theta_-, \Theta_+ \approx m/\omega$, it leads to difficulties when reconstructing the plane in which the pair fragments are emitted. This is the main shortcoming of the method.

3) Method based on the azimuthal asymmetry of the yield of recoil electrons in the process of triplet photoproduction [1], $\gamma(k) + e^-(p) \to e^-(p_1) + e^+(p_+) + e^-(p_-)$. This process is very convenient for the measuring of linear polarization of photon beams in a very wide range of photon energies. The analysis has shown that about 90% of recoil electrons, which can be detected (with a momentum p_1 greater than some minimum detectable momentum $q_0 \approx 1$ mc (m is the electron mass) have a large polar angle Θ_1, which ensures measurements of the azimuthal angle φ_1 and determination of polarization.



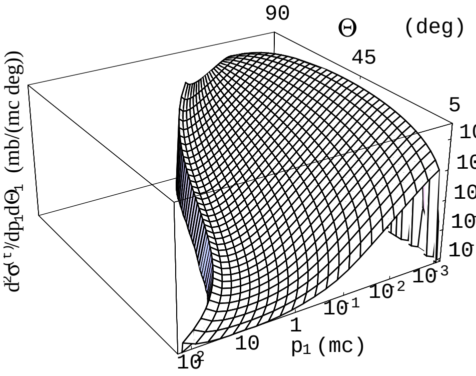
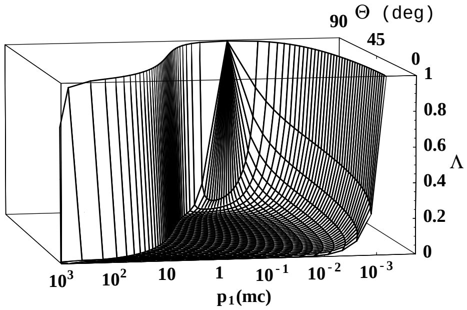


Fig. 1. Photon cross-sections in carbon: atomic photo-effect (σ_{phot}) coherent scattering (σ_{coh}), incoherent scattering (Compton scattering off an electron) (σ_{incoh}), pair production in nuclear field (κ_{nucl}) and pair production in electron field (κ_{tripl}).

Fig. 2 (right). $\sigma^{(t)}$ as a function of p_1 and Θ_1 for $\omega = 3000$ mc).

Figure 2 shows the main characteristics of triplet photoproduction cross-section as a function of recoil electron momentum p_1 and polar angle Θ_1.

From Fig. 3, one can see that near the bound of the physical region, in the most interesting interval of large p_1, the asymmetry Λ extremely quickly increases up to 1. The behaviour of the figures of merit (Fig. 4) also shows that using the recoil electron's momentum and angular distribution for the measuring of polarization assumes very severe conditions on the accuracy of the momentum determination. Therefore, one should use some integral characteristics of the triplet photoproduction process. Figures 5, 6 and 7 show the values of $\sigma^{(t)}(q_0)$, $\Lambda(q_0)$ and the figure of merit $F^2(q_0) = \Lambda^2\sigma^{(t)}$, respectively, integrated over all physical region but with the cutoff at $p_1 > q_0$. One can see



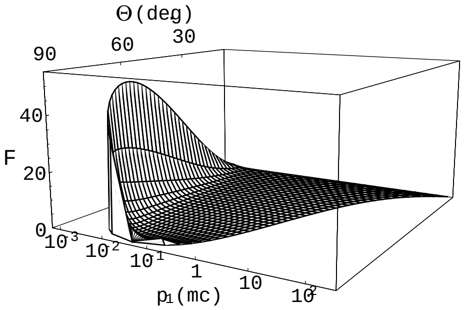
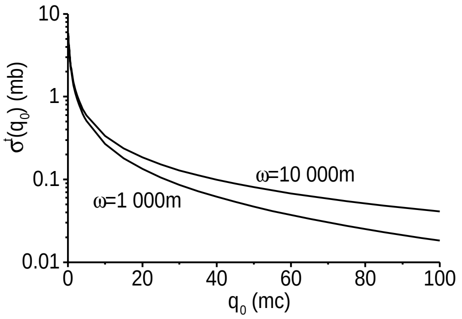


Fig. 3. Asymmetry Λ as function of p_1 and Θ_1 for $\omega = 3000$ mc.

Fig. 4 (right). Square root of the figure of merit, $F = \sqrt{\Lambda^2\sigma^{(t)}}$, as function of p_1 and Θ_1 for $\omega = 3000$ mc (derived using the estimated expected relative error of photon-polarization measurement $\Delta P/P \approx (\Lambda^2\sigma^t)^{-1/2}$).



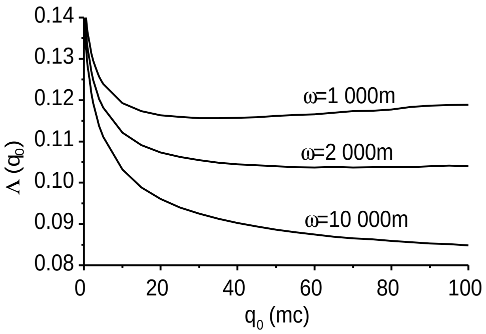


Fig. 5. Integrated values of $\sigma^{(t)}$ as a function of cutoff q_0 for photons of energy 1000 and 10000 mc.

Fig. 6 (right). Integrated values of asymmetry Λ as function of q_0 for photons of energy 1000, 2000 and 10000 mc.

that $\sigma^{(t)}(q_0)$, $\Lambda(q_0)$ and $F(q_0)$ very slowly change with increasing photon energy. $\Lambda(q_0)$ decreases from 0.14 at $q_0 = 0.1\,mc$ to 0.112 at $q_0 = 10\,mc$. The relative error of measurement of polarization is proportional to $F^{-1}(q_0)$ and varies with increasing q_0 slowly when $q_0 > 5\,mc$.

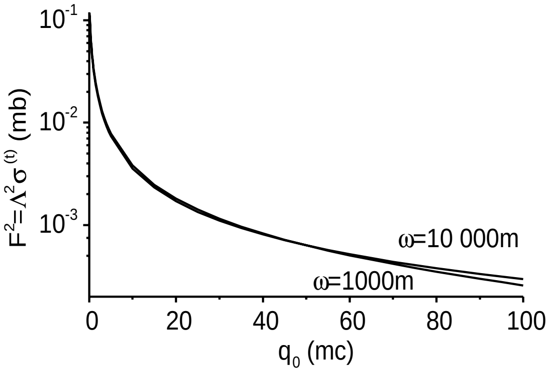


Fig. 7. Integrated values of the square of the figure of merit, $F^2 = \Lambda^2\sigma^{(t)}$*, as function of* q_0 *for photon energy of 1000 and 10000 mc.*

The differential cross-section $d\sigma^{(t)}$ and analyzing power Λ of the process of triplet photoproduction depend on the values of kinematic variables of the final state. One can select events of triplet photoproduction in such a region of these variables where analyzing power and merit increase. The dependence of the considered cross-section $d^2\sigma(q_0)/dx d\varphi_1$ on the fraction x of the energy carried away by the positron was studied in Ref. 6. It has been shown that the asymmetry $\Lambda(q_0, x)$ has a sharp maximum in the vicinity of the point $x = 1/2$. Near the value $x \approx 0.5$, $\Lambda(q_0, x)$ is 1.8 times as large as its average over all x values. Use of a narrow interval near $x = 0.5$ raises the sensitivity of the method by a factor 1.8.

Results in a very convenient form for practical applications are presented in Ref. 7. The dependence of the cross-section on pair opening angle Θ_{+-} was studied. The integration was performed over the experimentally accessible region: $p_1 > q_0 = 0.5$ MeV/c, both the forward going electron and positron should fall within the angular cone with the polar angle $\Theta_0 = 10$ mrad, and polar angle Θ_1 of the recoil electron must be within appropriate region $35° > \Theta_1 > 25°$. It was shown that the detection of events with an opening angle Θ_{+-} around 3 mrad is the optimum condition for the photon energy of 550 MeV. The analyzing power for this case is 0.48.

As far as we know, polarimeters based on triplet photoproduction have been developed in Ukraine, NSC KPTI, Kharkov [1], in Germany, Mainz [8], in Japan, INS, Tokyo [7] and in Canada, SAL [9]. Main features of these devices are similar. They differ by the type of counters for the recoil electron and pair detection. The Japan variant of the device is schematically shown in Fig. 8. Installation of a polarimeter of this type, which is constructed in Canada, SAL, is planned for the Hall B of JLab.

Now, let's discuss the possibility of using the CEBAF Large Acceptance Spectrometer (CLAS) as a polarimeter. This experimental equipment is intended for the study of nuclear processes produced by high-energy photons in a target by observing final-state charged and neutral particles; low-energy electrons are regarded as charged background. The mini-torus (shielding magnet), which is usually present for electron running to reject low-energy electrons, is removed for normal and polarized-photon beam running, and thus will not interfere with our measurements. As we have shown, just the azimuthal asymmetry of low-energy recoil electrons contains important information concerning the photon polarization. The drift chambers situated nearest to the target (named region 1) allow the detection of electrons with polar angles Θ_1 exceeding 5°, and with momentum greater than several MeV/c. The counter, which allows the detection of e^+e^- pairs should be installed somewhere in the exit region of the beam. The events of triplet photoproduction may be unambiguously identified by such a system. The polarization of the photon beam can be determined by the analysis of the azimuthal distribution of low-energy fraction of events. This distribution has to be calculated on the basis of the known distribution of recoil electrons, taking into account absorption of low-energy electrons in the target and in nearby materials. It should be noted that at the photon energy greater than 1 GeV, almost all electrons, which have energy from 1 to the several tens of MeV and are emitted at large polar angles, are produced due to the triplet photoproduction process (see Fig. 1). Therefore, it is possible that for high-energy tagged-photon beams of large intensity, measuring only the azimuthal asymmetry of the yield of electrons in the kinematical region of interest (without

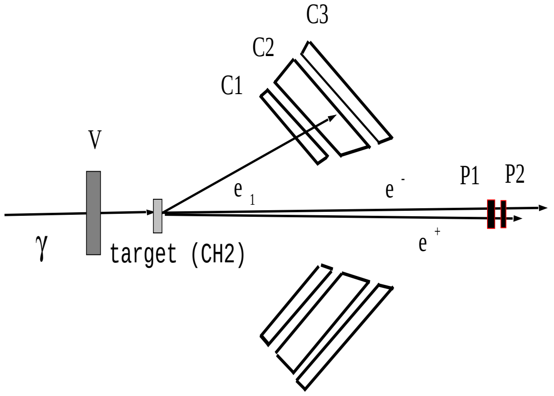


Fig. 8. Triplets are produced in a polyethylene target of 1 mm thickness. The device that detects the recoil electrons with momentum $1.9\ \mathrm{MeV} < p_1 < 10\ \mathrm{MeV}$ *consist of five identical telescopes of scintillation counters, C1, C2 and C3, which cover the intervals of polar angles* $10^\circ < \Theta_1 < 40^\circ$ *and azimuthal angle* $\varphi_1 = \pm 15^\circ$*. The pair fragments are detected in the counters P1 and P2. The results of the investigations showed that cases of triplet production can be unambiguously identified and that this device can be a simple and reliable polarimeter.*

detection of e^+e^- pairs) will be sufficient for the determination of the photon beam polarization.

To estimate the necessary time of exposition, T, let's put that the degree of photon polarization, $P \approx 0.6$, $\Lambda(q_0) \approx 0.12$ and $\sigma^{(t)}(q_0) \approx 0.5$ mb at $q_0 = 1$ MeV/c. Then $\Delta P/P = 1/\Lambda(q_0)P\sqrt{N_e}$, where N_e is the number of detected events. For the case of H_2 liquid target 7.5 cm long and a photon-beam intensity $N_\gamma = 10^8$ s^{-1}, one gets $\Delta P/P \approx 14/\sqrt{N_e} \approx 2.10^3/\sqrt{N_\gamma T} \approx 0.2/T^{-1/2}$ This signifies that to achieve a 1% accuracy, an exposition of about 400 s is necessary. Thereby, it should be possible to get a simple and effective photon polarimeter without a significant change of the device construction.

References

1) V.F.Boldyshev et al., Phys. Part. Nucl. **25** (1994) 292;

2) D. E. Cullen et al., Lawrence Livermore National Laboratory, Report No. UCRL-50400, vol. 6, Rev. 4 (1989) [with extended energy range to 100 GeV], unpublished;

3) H. Uberall. Phys. Rev **103** (1956) 1055; G.Diambrini, Rev. Mod. Phys. **40** (1968) 611; Barbiellini et al., Nuovo Cimento **28** (1963) 435;

4) T. H. Berlin and L. Madansky, Phys. Rev. **78** (1950) 623; G. C. Wick, Phys. Rev. **81** (1951) 623;

5) A. P. Potylitsin, *Polarized High–Energy Photon Beams* (in Rus.), Moscow (1987);

6) E. A. Vinokurov and N. P. Merenkov, Yad. Fiz. **21** (1975) 781;

7) I. Endo et al., Nucl. Instr. Methods A **280** (1989) 144; I. Endo and T. Kobayashi, Nucl. Instr. Methods A **328** (1993) 517;

8) F. Shufer et al., *Gordon Research Conf. Aug. 6-10, 1990*, Tilton School, Tilton, New Hampshire; J. Ahrens, *Workshop on "Polarized Photon Polarimetry"*, June 2-3, 1998, Jeffersob Lab., p.113;

9) R. Pywell and G. Feldman, *ibid.*, p.89.

MJERENJE LINEARNE POLARIZACIJE REALNIH FOTONA

Daje se pregled poznatih metoda za određivanje linearne polarizacije visokoenergijskih fotona. Raspravlja se kratko tvorba parova u monokristalima i amorfnim metama. Podrobno se razmatra metoda mjerenja polarizacije određivanjem azimutalne asimetrije elektrona od fototvorbe na elektronima (trojna fototvorba). Raspravlja se najpovoljnije područje kinematičkih parametara izlaznih čestica. Izlaže se mogućnost primjene CLASa za određivanje linearne polarizacije fotona mjerenjem raspodjele odbijenih elektrona iz trojnog fototvorbenog procesa (za vrijeme mjerenja CLASov magnet bi se isključio).