METHOD OF THE PHOTON BEAM LINEAR POLARIZATION MEASUREMENT USING ASYMMETRY OF THE RECOIL ELECTRONS IN THE TRIPLET PHOTOPRODUCTION PROCESS

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We present a method of the photon beam linear polarization measurement which have been proposed and developed in Kharkov Institute of Physics and Technology and based on the using of the asymmetry of the recoil electrons in reaction $\gamma+e^-\rightarrow e^-+e^++e^-$. It was found that asymmetry of the process has enough big value and weakly depend on photon energy in very wide range. So this method allows to measure the linearly polarization in the wide energy range from some tens MeV and up to TeV photon energies. The schemes of the existing polarimeters and effects distorting the measurement are considered.

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1. INTRODUCTION

Beams of the polarized photons have wide prospects of application in the physics of electromagnetic interactions of nucleus and hadrons. The most of modern experiments in the field of photoproduction of baryon resonances, for example, demand for the restoration of the set of spiral amplitudes of the studied processes an information which can be received only with help of polarized photon beams. In experiments of such type the degree of the photon polarization should be known with high accuracy.

One of the most perspective method for linearly photon polarization measurements have been proposed and developed in Kharkov Institute of Physics and Technology (KIPT) during last thirty years. It have been pointed out that process of the triplet photoproduction

$$\gamma(k)+e^-(p)\rightarrow e^-(p_1)+e^-(p_-)+e^+(p_+) \quad (1)$$

has rather large asymmetry of the recoil electrons yield which furthermore weakly depend on photon energy in very wide energy range. So it was presupposed this process may be used for measuring photon polarization in wide energy interval, from several tens MeV and up to about TeV. Subsequently some photon polarimeters on the base of this method have been constructed in a number of scientific centers.

2. GENERAL CHARACTERISTICS OF THE METHOD

Process of the triplet photoproduction (1) is attractive to use for measurement of the linear polarization of the photons because it is pure electrodynamical process with very convenient for measurement signature. All its characteristics can be calculated with necessary accuracy. In the lowest order of perturbation theory this process with taking into account effects of final electron's identity, is described by 8 Feynman diagrams. For the case of linearly polarized photon it was first theoretically investigated in the Ref. [1,2]. There was shown that differential by azimuthal angle φ_1 cross section of the recoil electron yield has following form

$$2\pi\frac{d\sigma}{d\varphi_1}=\sigma^{(t)}-P\sigma^{(l)}\cos 2\varphi_1= \\ =\sigma^{(t)}(1-P\Lambda\cos 2\varphi_1), \quad (2)$$

where $\sigma^{(t)}$ is the total cross section of the process, $\sigma^{(l)}$ is the part of cross section which depends on polarization, P is degree of photon polarization, $\Lambda=\sigma^{(l)}/\sigma^{(t)}$ is analyzing power of the process.

In Ref. [3,4,5] it was shown that at photon energy $\omega>20\,mc^2$ influence of the identity effects may be neglected and considered process with accuracy better then 2% can be described by two Feynman diagrams. The depending on photon polarization part of the cross section $\sigma^{(l)}$ has been calculated in the [1] for different values of photon energy. Calculations were carried out with using of the technique which has been developed by V.N. Baier et.al. [6] where the total cross sections for different processes of pair production has been considered. It was shown that with increasing the photon energy the total cross section $\sigma^{(t)}$ grows from 1.187 mb at $\omega=20mc^2$ till 8.76 mb at $\omega=1000mc^2$ but asymmetry slowly decreases, respectively, from $\Lambda=0.275$ up to $\Lambda=0.172$ and even at asymptotically high energy of photon $s=(k+p)^2>>m^2c^4$ the azimuthal asymmetry of the yield of recoil electrons is $\Lambda\approx0.14$. These estimations are obtained in the assumption that all recoil electrons can be registered. In the experiment it can be reliably measured only recoil electrons with momentum which exceeds some value $q_0\approx1mc$. The analytical expressions for differential by the value of transferred momentum $X=-q^2=-(p-p_1)^2$ cross section $d\sigma^{(l)}/dX$ and $d\sigma^{(t)}/dX$ has been obtained in the Ref. [2]. By the numerical integration of the obtained expressions for different values of q_0 from $q_0=0.05$ MeV/c till $q_0=1.25$ MeV/c it was shown that introduction of the threshold on registration of the recoil electron momentum q_0 leads to insignificant reduction asymmetry but to the fast decreasing cross section of the process.

Further in KIPT the detailed analysis of the triplet photoproduction process by linearly polarized photons was carried. Results of this analysis were published in review [5]. With the help of helium streamer chamber in KIPT for the first time the linear polarization of the coherent Bremsstruhlung photons with energy 60 MeV has been measured by this method [5,7,8].

3. PECULIARITY OF THE PRACTICAL REALIZATION

The general behavior of the cross section and asymmetry of the process (1) can be characterized as follows: almost in all physical regions of the kinematical variables changing azimuthal asymmetry of the recoil electrons is about $\Lambda\approx0.1$. Near the border of physical region asymmetry sharply grows up to values $\Lambda\approx1$. There are many offered ways of increasing observable azimuthal asymmetry of recoil electrons yield. As it is shown in [9] the selection events of the triplet photoproduction with invariant mass of the pair $\Delta = \sqrt{(p_- + p_+)^2}$ in the vicinity of limiting value $\Delta = 2m$ increases the asymmetry up to value $\Lambda\approx0.95$. Possible design of the polarimeter in which selection of events with $\Delta\approx2m$ would be made with the help of a magnetic spectrometer and the wire chamber has been offered in Ref. [10]. Detecting recoil electrons also would be carried out with the help of the wire chamber.

More simple and effective method of increasing observable asymmetry was proposed by Japanese group [11]. This method is based on observation that for events of triplet photoproduction with opening angle of e^+e^- pair $\theta_\pm\approx5m/\omega$ asymmetry of recoil electron's yield sharply grows. This method is applicable at energy of photons ω less then several GeV because at large energies there are the difficulties connected with too small necessary angles of the e^+e^- pair collimation.

At the very large photon energies the method of increasing observable asymmetry suggested in the Ref. [12] may be used. In this work it was shown that asymmetry of recoil electron's yield is maximal when electron and positron of the e^+e^- pair had identical energies. In the limit of the asymptotically high photon energy azimuthal asymmetry of recoil electron's yield under selection such an event is increased in 1.8 times in comparison with asymmetry without such selection. As selection of events on energy of the components of e^+e^- pairs can be easily realized with the help of a magnetic spectrometer even at very high photon energy this method is perspective at ω> 10 GeV.

Typical arrangement of the polarimeter based on the effect of triplet photoproduction is shown in the Fig. 1. The recoil electrons are detected by the scintillation counters C_2, C_1 is polyethylene plate with some certain thickness. This thickness is defined from condition that electrons with momentum $q<q_0$ will be absorbed in this plate. Background of the charged particles presented in the beam is eliminated by the veto counter V. The pair fragments are detected by the counters P_1 and P_2 in coincidence with a recoil electron. Each of the vertical counters V_1 and V_2 and of horizontal counters H_1 and H_2 subtends azimuthal angles $\pm\Delta\varphi$ around directions $\varphi=0$, $\varphi=\pi$ and $\varphi=\pi/2$, $\varphi=3\pi/2$, accordingly.

In real experiment the photon beam cannot be focused in one point on a target and we shall assume that the density of probability of distribution of photons at crossing a target has Gauss form with dispersion ρ:

$$F(x,y)dxdy = \frac{1}{\pi\rho^2}\exp(-\frac{x^2+y^2}{\rho^2})dxdy. \qquad (3)$$

Let the triplet is created in the point A with polar coordinates *r* and *α* and recoil electron is emitted under azimuthal angle φ_1 and it reaches counter in the point B with coordinates *R*, *φ*. One can see that angles φ_1 and φ are connected as following

$$\cos(2\varphi_1) = \frac{r^2\cos(2\alpha) + R^2\cos(2\varphi) - 2Rr\cos(\varphi+\alpha)}{r^2 + R^2 - 2Rr\cos(\varphi-\alpha)}. \qquad (4)$$

If one substitutes formula (4) into the (2) and averages result with distribution of photons (3) one can obtain

$$\frac{1}{2\pi}\left\langle\frac{d\sigma}{d\varphi}\right\rangle = \sigma^{(t)}\left(1 - P\Lambda\left(1 - \frac{\rho^2}{R^2} + O(\frac{\rho^4}{R^4})\right)\cos(2\varphi)\right). \qquad (5)$$

Thus one con see that for good enough collimated photon beam (*ρ/R<<1*) it is possible to neglect influence of the photon beam's initial size.

Integrating expression (5) on an azimuthal angle φ within the limits of capture of each of detectors H_1, H_2 and V_1, V_2, we shall receive for number N_H of recoil electrons achieved horizontal H_1, H_2 and vertical V_1,V_2 counters:

$$N_H = N_{H1} + N_{H2} = 2C\sigma^t\left(2\Delta\varphi - P\Lambda\sin(2\Delta\varphi)\right),$$
$$N_V = N_{V1} + N_{V2} = 2C\sigma^t\left(2\Delta\varphi + P\Lambda\sin(2\Delta\varphi)\right). \qquad (6)$$

Here *C* is product of the number of electrons corresponding to the unit of the area of a target, on number of photons during time of exposition. Thus, the degree of polarization *P* can be determined from experimentally measured asymmetry as follows:

$$P = \frac{1}{\Lambda\ K(\Delta\varphi)}\frac{N_V - N_H}{N_V + N_H}. \qquad (7)$$

Here $K(\Delta\varphi) = \frac{\sin(2\Delta\varphi)}{2\Delta\varphi}$ is geometrical factor of the device, Λ is theoretically calculated asymmetry at *P*=1. It is easy to see, that the geometrical factor $K(\Delta\varphi)$ increases with reduction of angular capture of counters Δφ. However figure of merit $F(\Delta\varphi) = \Lambda^2\sum N_i$ has a maximum at $2\Delta\varphi\approx66.78^\circ$. Therefore such value Δφ should be used for measurement of polarization of photon beams with low intensity.

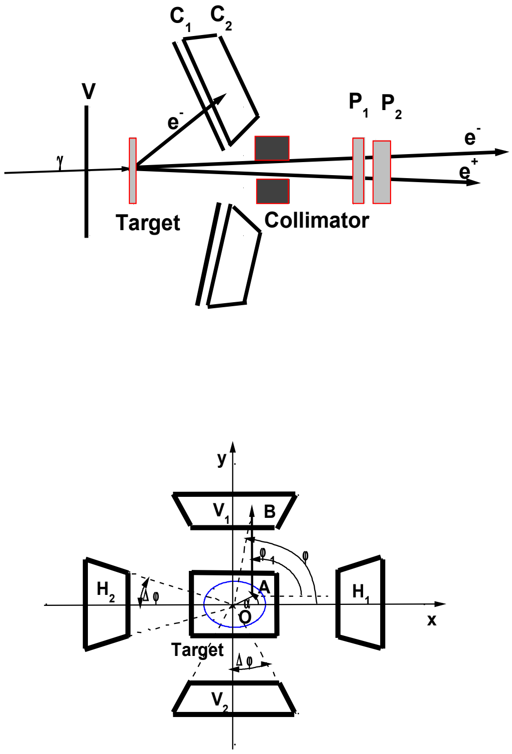

Fig. 1. *Principle scheme of the polarimeter. Side view (top) and view along the beam (bottom)*

In experiment [13] the CBR photon beam with energy 240 … 600 MeV has been used. Asymmetry of recoil electrons for the cases when opening angle of the pair was less then 3.5° and 0.7° has been measured. Analyzing power for these cases has been calculated with taking into account effects of multiple scattering. Expected asymmetry, as the product of this analyzing power and polarization of photon, calculated on the base of Uberall-Diamrini theory was obtained. Experimentally observed asymmetry was in consistence with this value, but statistics was not enough for detailed comparison.

The test experiments [14], which have been carried out by GWU group on the LEGS facility with Compton backscattered photon beam (polarization ~95%), shown that measured asymmetry is less then it is predicted by the theory for pure process of triplet photoproduction. The general reasons of this phenomenon are clear– multiple scattering of low-energy recoil electrons in substance of a target and in an air should reduce observable azimuthal asymmetry of their yield. Besides in considered experiment it is impossible to distinguish process of photoproduction e^+e^- pair on electron and process of photoproduction e^+e^- pair on nuclei with subsequent knocking-on δ-electrons by fast components of created e^+e^- pair. It is obvious that angular distribution of emitting δ-electrons has not any azimuthal asymmetry and contribution of such events leads to reduction observable azimuthal asymmetry.

To receive necessary values of effective cross section Σ_{eff} and effective asymmetry Λ_{eff}, the program of numerical simulation of all electromagnetic processes taking place in experimental installation during measurement of the photon beam of polarization has been developed. This program was created on the basis of the known package GEANT which is directed on numerical simulation of processes taking place in detectors of modern physical facilities. However, there is not code for generation of events of photoproduction e^+e^- pair on electrons in the GEANT. Therefore program GEANT has been modified as follows: case of approach of event of photoproduction e^+e^- pairs among all other possible events was determined in GEANT environment as usually. After an entrance in a code of generation of event of photoproduction e^+e^- pairs on atom with charge Z it is sampled or event of a triplet photoproduction with three final particles (e^+e^- pair and recoil electron), or described in GEANT event of e^+e^-pair photoproduction with two final particles. These events were generated with probability $Z\sigma_{tr}(\omega, q_0)/\sigma_{pair}(\omega, Z)$ and with probability $1 - Z\sigma_{tr}(\omega, q_0)/\sigma_{pair}(\omega, Z)$, accordingly. Here $\sigma_{tr}(\omega, q_0)$ is the total cross section of the triplet production with minimal transferred momentum q_0 by photon with energy ω; $\sigma_{pair}(\omega, Z)$ is total cross section of production e^+e^- pair by photon with energy ω on atom with charge *Z*. Generation of kinematical variables of produced triplet and also calculation of cross section $\sigma_{tr}(\omega, q_0)$ were carried out with help of code BASE/SPRING [14], which takes into account all 8 Feynman diagrams describing this process.

As an illustration of the importance of effects of multiple scattering and of δ-ray knocking on in Fig. 2 the initial momentum-angular distribution of recoil electrons, which are emitted during triplet photoproduction processes in the target is shown. In the Fig. 3 the analogous distribution for all charged particles reached counters V_1, V_2, H_1, H_2 is shown.

One can see that specified effects lead to deformation of initial angular-momentum distribution in the region of measuring. This deformation is especially increasing for region of small momenta of recoil electrons. So to minimize this effect, the recoil counters contain a layer C_1 of a polyethylene film which absorbs electrons with a momentum, less then some q_0.

In order to increase value of the experimental asymmetry it was investigated the possibility to use for this goal the information about spectral characteristics of the particles detected by the recoil counters. Because scintillators have linear dependence between the deposited in them energy of ionizing particles and number of radiated due to scintillations photons, in experiment spectrum of the particles reached detectors can be measured. Therefore the formula (7) for definition of the photon beam polarization degree should be changed as follows:

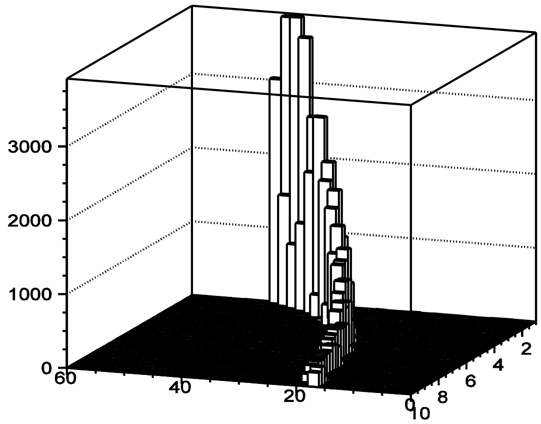

Fig. 2. *Original momentum (1<q<*10MeV/*c) and polar angle (0°<θ <60°) distribution of produced in the target recoil electrons. Photon energy ω=2.5 GeV*

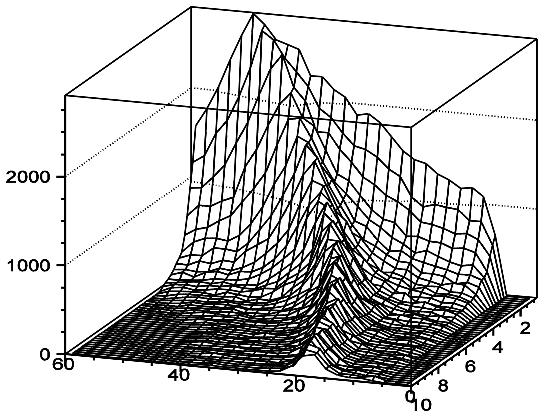

Fig. 3. *Momentum (1<q<10 MeV/c) and polar angle (0°<θ <60°) distribution of charged particles, reached recoil counters. Photon energy ω=2.5 GeV*

$$P = \frac{1}{\Lambda_S K(\Delta\varphi)} \frac{S_V - S_H}{S_V + S_H}, \quad (8)$$

where S_V, S_H are number of counts of vertical and horizontal scintillators with for given value of the deposited in them energy, accordingly, Λ_S is theoretically calculated asymmetry for that case $P = 1, K(\Delta\varphi) = 1$.

Results of the calculations are depicted in Fig. 4. Calculations are carried out for the case of photon energy ω=2.5 GeV and for different values of the collimation angles. Target is a polystyrene with thickness 1 mm. Recoil detectors consist of polyethylene film C_1 of 0.25 mm thickness and scintillation counter C_2 on the base of polystyrene with thickness 3 mm. Histograms (1) correspond to (S_V+S_H) and histograms (2) (S_V-S_H)×5 versus deposited energy *E*. One can see that it is reasonable to consider as observable asymmetry instead of ratio (8) for each channel of deposited energy the following integrated characteristic:

$$\Lambda_S^{obs}(E_0) = \Lambda_S^{int}(E_0) K(\Delta\varphi) = \frac{\int_{E_0}^{E_{max}} dE \left(S_V(E) - S_H(E)\right)}{\int_{E_0}^{E_{max}} dE \left(S_V(E) + S_H(E)\right)}, \quad (9)$$

where integration carried out from given deposited energy E_0 and up to maximal deposited energy E_{max}.

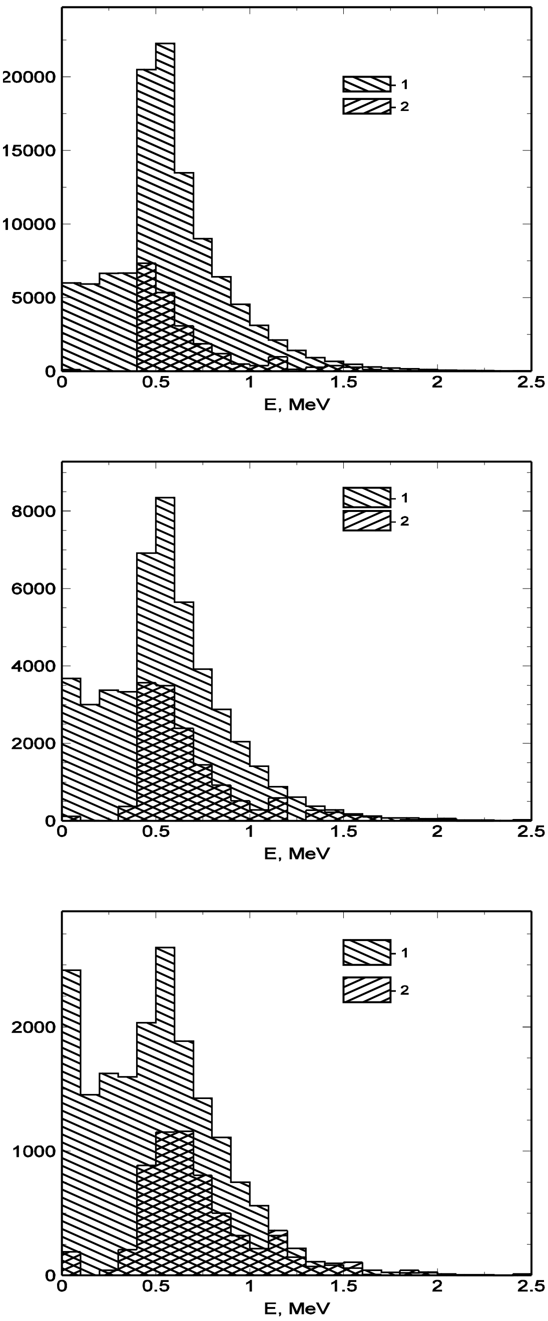

Fig. 4. *Calculated spectra of the particles versus of the deposited energy E (see text). No collimation (top), collimation angle of the e^+e^- pair θ_c=2 mrad (middle), collimation angle θ_c=1 mrad (bottom)*

This characteristic is shown in Fig. 5 for different collimation angles. One can see that background processes (multiple scattering and δ-electrons) decreases the experimentally measured asymmetry in polarimeter of this type up to very small value ~2-5%. Selection on the deposited energy give a chance to increase considerably its value in principle up to 20-30%. But at large values E_0 the statistical errors are too increase and optimal is value E_0≈0.5 MeV, where at the collimation of the e^+e^- pairs in angle ~1 mrad one can obtain asymmetry ~0.1.

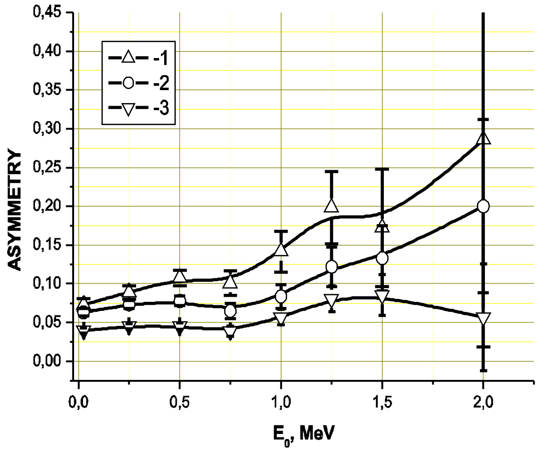

Fig. 5. *The observed asymmetry* $\Lambda_S^{obs}(E_0)$ *for different collimation angles of the* e^+e^- *pairs* θ_c*: 1–* θ_c*=1 mrad; 2-* θ_c*=2 mrad; 3– no collimation*

4. CONCLUSIONS

Thus the carried out consideration shows that method of linear polarization of the high-energy photons measurement based on triplet photoproduction process is the only one from other methods known now, which is suitable in wide region of the photon energies from some tens MeV and up to asymptotically high energies.

The program developed now on the basis of package GEANT takes into account the contribution of all basic electromagnetic processes, which take place in experimental device during measurement, and allows calculate all characteristics of the response of detectors, which are necessary for measurements.

Necessary stage of the method development is realization of a series of test experiments with measurement of linear polarization of photon beams on accelerators, which have photon beams with well-known polarization. Such experiments are planned in the near future by group of University G. Washington, Washington, USA.

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