RELATIONS BETWEEN MAIN QED AND BACKGROUND PROCESSES AT INTERACTION OF THE PHOTONS WITH THE TARGET OF THE PHOTON POLARIMETER

D.D. Burdeinyi, V.B. Ganenko, Yu.P.Peresun'ko, I.M.Shapoval, G.A. Vashchenko*

National Science Center "Kharkov Institute of Physics and Technology", 61108, Kharkov, Ukraine

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The simulation of the processes which take place at the photon interaction with matter of the polarimeter target has been carried. The relations between main QED and background processes were studied. It was found that δ-electron production is the basic background process for polarimeter based on the triplet photoproduction reaction. Their total contribution is no less $\sim 20-30\%$ even for optimal polarimeter target (plastic with $0.1-0.3\,mm$ thickness).

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1. INTRODUCTION

Polarization investigations play an important role in researches of nucleon and nuclei structure, mechanisms of the photon interaction with hadrons and nuclei. Therefore linearly polarized photon beams have been produced practically at all electron accelerators and at present they are successfully used in leading scientific centers such as MAMI, ELSA and JLAB. There are various methods of the polarized photon beams generation (see for instance [1]) and general problem at the beams using in experiments is an accurate determination of the photon polarization value. The overall tendency of experimental data accuracy increasing brings to increasing requirement to accuracy of the photon polarization determination. At present desirable level of the polarization determination is $\sim 1-2\%$ and most reliable way to get this value is a direct polarization measurement by photon polarimeter.

There are some requirements to efficient photon polarimeter and the basic from them are following. Analyzing power of a process which is applied for the polarization measurement, firstly, has to be high enough in the energy range where the polarization measurements are performed and the energy range has to be as wide as possible; secondly, it has to weakly depend on energy in this range and, thirdly, it has to be determined or calculated with high precision. Various approaches can be used for the linear photon polarization measurement, see, e.g. [1], but QED processes are most preferable because they not only satisfy the above requirements, but in addition they have large cross section and convenient signature for registration.

Thus well studied process of the Compton scattering, $\gamma + e^- \to \gamma + e^-$ can be used for photon polarization measurement but at low photon energies ($E_\gamma < 10-20\,MeV$) owing to rapidly decreasing analyzing power and cross section with increasing the energy (the analyzing power is less 0.04 at $20\,MeV$)[1]. Therefore at higher energies the e^+e^- - pair photoproduction in the field of nuclei, $\gamma + Z \to Z + e^- + e^+$, or in the field of atomic electrons (triplet photoproduction), $\gamma + e^- \to e^- + e^+ + e^-$, can be applied. The proposition to use the pair production process for linear polarization measurement was put forward at 1950th [2, 3]. It was based on the fact that the pair production plane is correlated with the plane of the photon polarization. The azimuthal distribution in this case can be presented as

$$\frac{d\sigma}{d\varphi} = \sigma_0^{pair}[1 + P\Lambda\cos(2\varphi)], \qquad (1)$$

where $\sigma_0^{pair} = \sigma^{pair}(Z, E_\gamma)$ is the cross section of the pair photoproduction with unpolarized photons, P is the degree of the photon polarization, Λ is the analyzing power (or asymmetry) of the process when $P = 1$, the azimuthal angle φ is counted from the photon polarization direction. The value of the analyzing power depends on reaction kinematics and can be ranged in interval $\Lambda \sim 0.1-0.3$. The main experimental difficulty of this process using is small angle between the pair components, which decreases with increasing photon energy, thus the method can be effectively used at energies up to some GeV.

As to the triplet photoproduction using for the photon linear polarization measurement it has firstly been proposed in KIPT by V.F. Boldyshev, Yu.P. Peresunko [4, 5] in early 1970th and then the method has being steadily developed and improved up to now

*Corresponding author. E-mail address: ganenko@kipt.kharkov.ua

[6]. It was shown that besides above correlation of the plane emitted e e pairs with direction of the photon polarization, recoil electrons in the reaction are preferably emitted in the plane orthogonal to the polarization direction. The differential cross section on azimuth angle of the recoil electron can be presented as

$$\frac{d\sigma}{d\varphi} = d\sigma_0^{tr}[1 - P\Lambda\cos(2\varphi)], \quad (2)$$

where $d\sigma_0^{tr} = d\sigma^{tr}(E_\gamma, q_0)$ is the cross section of the triplet photoproduction with unpolarized photons, q is the momentum of the recoil electron. The recoil electrons are emitted under large polar angles (up to 80°) and have energy up to $\sim 10 - 20\,MeV$ that is high enough for and convenient for registration. Theoretical value of the analyzing power is $\Lambda \sim 0.14$ in the case if any selection of the recoils is not produced. The analyzing power can be increased up to $\Lambda \sim 0.2 - 0.3$ by imposing various rules of the events selection, e.g. when the events with nearly equal electron and positron energy are selected. Calculations predict that properties of the recoil electrons and the analyzing power of the process weakly depend on the photon energy up to some hundreds GeV that allows in principle to use this method in a wide energy range for linearly photon polarization measurements.

There were attempts to built photon polarimeter on the base of the triplet photoproduction process by Japan [7] and the SAL groups [10] in which the azimuthal asymmetry of the recoil electrons yields averaged on rather wide ranges of polar and azimuthal angles was measured. The measured value of the analyzing power for both polarimeters was found to be a very low, $\Lambda \sim 0.03$ for SAL and twice as much for Japan polarimeter that was much less than the expected theoretical value $\Lambda \sim 0.14$. It was supposed that the reduction of the analyzing power might be due to multiple scattering and contribution of background from $\delta-$rays production and other processes. These factors are important and their contribution depends also on peculiarities of the polarimeter construction: material and thickness of the target, sizes and displacement of the particles detectors etc. To study the background processes contribution in more detail the method of mathematical modeling was performed.

2. SCHEME OF SIMULATION

The investigations have been carried out with using the developed code for simulation of the processes which take place when the photon beam interacts with the polarimeter target matter. The code is based on the GEANT-3 package [9] which was supplemented by some subroutines because the standard widely used GEANT-3 package is not oriented to taking into account the polarization effects in the processes of e^+e^- pair photoproduction and Compton scattering, so there are no codes for calculation of the azimuthal angles differential distributions of the final particles of these QED processes produced by the polarized initial photons. Furthermore, the GEANT-3 has no code for the triplet photoproduction process as well. Therefore the GEANT-3 code has been modified to take into account effects of the photon linear polarization for the e^+e^- pair photoproduction, the Compton scattering and BASE/SPRING code [10] of the triplet photoproduction process calculation has been added which was modified to apply for our conditions. This code uses techniques of direct numerical calculation of the corresponding processes helicity amplitudes and it is capable to generate momenta of all final particles taking into account the degree and direction of the photon polarization.

At the simulation the triplet production processes take into consideration if momentum of the recoil electron exceeds some minimal momentum, $q > q_0$. After entering into e^+e^--pair photoproduction code of the GEANT, this process may be branched either into the usual e^+e^--pair production on screened nucleus with outgoing electron and positron or into the triplet production with three outgoing particles. This forking is generated randomly with probability $(1 - W)$ and W, respectively. Here $W = Z\sigma^{tr}(E_\gamma, q_0)/\sigma^{pair}(Z, E_\gamma)$ is the ratio of the corresponding total cross sections: $\sigma^{pair}(Z, E_\gamma)$ for the pair production by photon with energy E_{gamma} in the media with charge Z from GEANT code and for the triplet photoproduction $\sigma^{tr}(E_\gamma, q_0)$ with recoil electron's momenta $q > q_0$ from the BASE/SPRING code. The layout of the simulation is shown in Fig.1.

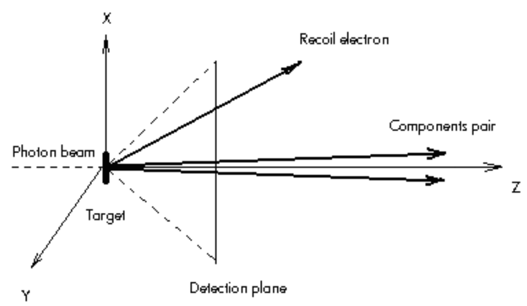

Fig.1. *Layout of the simulation*

Point like polarized photon beam arrives along Z axis and falls on the target. The interaction points along Z axis are determined in a random way. If the photon interaction has happened a type of the process is determined and kinematical characteristics of the reaction products are calculated. Then the way of every particle is tracked up to the target exit. The particles flying off in forward direction are fixed on the "detector" plane. It was placed at some distance from the target ($1.5\,cm$ in this case) and the type and kinematical parameters of the particles are determined at the plane. In such a way the data base was accumulated for certain initial photon energies (in the range $20 - 2000\,MeV$) and the targets thickness ($0.1 - 2\,mm$) and materials (plastic scintillator C_6H_6, Al, Si) which allow us to study all necessary distributions of the particles produced in the target by polarized photons.

3. GENERAL FEATURES OF THE PARTICLES YIELD

Yield of the main QED processes (pairs and triplets photoproduction, Compton scattering) as a function of photon energy are shown in Fig.2 for the plastic target of $1\,mm$ thickness. For the triplet photoproduction events with the recoil electron momentum $q > q_0 = 0.1 MeV/c$ were only taken into account. One can see that in this case the pair production is 6-8 times larger than the triplet production in all energy range. It should be noticed that yield of the triplet photoproduction strongly depends on the recoil electrons momentum q, Fig.3 and considerably increased with q decreasing. But recoil electrons with low energies are mainly emitted under large angles and do not exit from the target. Thus in the simulation we have usually chosen the events with recoil momentum $q > q_0 = 0.5\,MeV/c$. In this case the pair production is $\sim 20 - 25$ times larger than the triplet production. The yield of the Compton scattering becomes equal to the triplet one at $E_\gamma \sim 175\,MeV$ if $q > q_0 = 0.1\,MeV/c$ are taken into account but in the case the triplets selection with $q > q_0 = 0.5\,MeV/c$ they become equal at significantly higher energy, $E_\gamma \sim 600 MeV$.

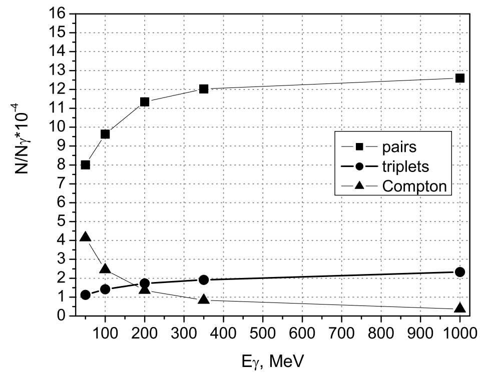

Fig.2. *The yield of the QED processes on 10^4 photons as a function of the photon energy for plastic target of $1\,mm$ thick.The recoil electron momentum $q > q_0 = 0.1\,MeV/c$ were taken into account*

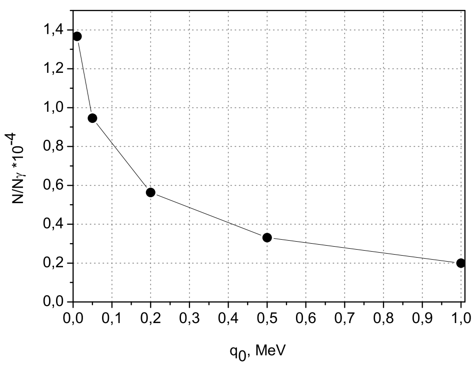

Fig.3. *The yield of the triplet photoproduction as a function of minimal recoil electron momentum q_0*

The reaction products of the main QED processes in their turn produce secondary particles when they pass through the target matter: δ-electrons, bremsstrachlung photons, secondary e^+e^--pairs etc. Some simulation results of the particle's yield initiated by photons with energy $E_\gamma = 100$ and $1000\,MeV$ in the plastic target (C_6H_6) 0.1 and $0.5\,mm$ thickness which were registered on the "detector" plane is plotted in Table 1 for each initial QED process: pairs and triplets photoproduction and Compton scattering.

There are varies combinations of the secondary particles (reaction channels), relative frequency of which depends on the target material and thickness. In the case of the $0.5\,mm$ plastic target just $\sim 95\%$ primary pairs, $\sim 77\%$ triplets and $\sim 86\%$ Compton scattered particles produced in the target, reach the "detector" plane. The rest are involved in the secondary interactions, main from which are the δ-electron production. In general, the portion of the δ-electron production is not large, no more $\sim 3-4\%$ of the primary QED processes but their sum yield may be considerable relatively to triplet one due to δ-rays production by pair particles the number of which is $\sim 6 - 8$ times as many then the triplet one even for selection the triplet events with $q > q_0 = 0.1\,MeV/c$. In the case $q > q_0 = 0.5\,MeV/c$ the part the of δ-electron contribution can reach more high value. It should be noticed that considerable part, ~ 16, of the recoil electrons at triplet photoproduction under condition $q > q_0 = 0.5\,MeV/c$ are absorbed in the $0.5\,mm$ plastic target and do not reach the "detector" plane. Their portion becomes 5 times less for $0.1\,mm$ target thickness.

As a whole the portions of all secondary processes practically do not depend on photon energy in the energy range under study but there is increasing of the portions with the target thickness and atomic number increasing, Table 2. So, part of the δ-electrons produced by the electrons and positrons at the pairs is increased two times more at increasing the plastic target thickness from 0.1 to $0.5\,mm$, at that relative yield of the triplets at the "detector" plane is sufficiently decreased with target thickness and atomic number increasing.

The relation of the total recoil electrons yield to total δ-electron yield from all primary QED processes is plotted in Table 3 for some targets of various thickness and material. One can see that total δ-electrons contribution varies form 30% up to 50% when the plastic target thickness changes from 0.1 to $0.5\,mm$. For Si and Al targets this portion is larger. Because the background processes strongly influence on the analyzing power of the triplet polarimeter, especially the δ-electrons, which has similar signature to triplet process and they practically cannot be separated, decreasing their contribution is very important for the polarimeter scheme where the triplet production is used for polarization measurement. In general, thinner target is more profitable for polarization measurement from point of view of the δ-electron background.

4. ANGULAR DEPENDENCE OF THE BACKGROUND CONTRIBUTION

To decrease the δ-electron contribution influence on the triplet polarimeter analyzing power the search of kinematical conditions was performed where this contribution is less. For this aim the particles angular distributions produced by photons in the polarimeter target were studied. In Fig.4 it is shown the angular dependences of all particles produced by photons with energies 100 and 1000 MeV and registered on the "detector" plane.

Table 1. *QED processes which take place in the polarimeter target and are detected on the "detector" plane,* $q > q_0 = 0.5\,MeV/c$

Material	C_6H_6	C_6H_6	C_6H_6
Thickness, mm	0.5	0.5	0.1
Energy, MeV	100	1000	1000
Pair initial	$N_{pair}/N_\gamma = 6.032 \cdot 10^{-4}$	$N_{pair}/N_\gamma = 8.380 \cdot 10^{-4}$	$N_{pair}/N_\gamma = 2.059 \cdot 10^{-4}$
Channels	N_{ch}/N_{pair}	N_{ch}/N_{pair}	N_{ch}/N_{pair}
$e^+ + e^-$	0.9471	0.9445	0.9423
$e^+ + e^- + e^-$	0.0290	0.0300	0.0158
$e^+ + e^- + \gamma$	0.0092	0.0109	0.0032
$e^+ + e^- + e^- + e^-$	0.0014	0.0015	0.0007
$e^+ + e^- + e^- + \gamma$	$< 10^{-4}$	0.0005	$< 10^{-4}$
Triplet initial	$N_{triplet}/N_\gamma = 2.264 \cdot 10^{-5}$	$N_{triplet}/N_\gamma = 3.301 \cdot 10^{-5}$	$N_{triplet}/N_\gamma = 0.779 \cdot 10^{-5}$
Channels	$N_{ch}/N_{triplet}$	$N_{ch}/N_{triplet}$	$N_{ch}/N_{triplet}$
$e^+ + e^- + e^-$	0.7707	0.7682	0.8950
$e^+ + e^- + \gamma$	0.0038	0.0043	$< 10^{-4}$
$e^+ + e^- + e^- + e^-$	0.0370	0.0359	0.0277
$e^+ + e^- + e^- + \gamma$	0.0120	0.0152	0.0045
$e^+ + e^-$	0.1609	0.1601	0.0337
Compton initial	$N_{compton}/N_\gamma = 1.460 \cdot 10^{-4}$	$N_{compton}/N_\gamma = 2.046 \cdot 10^{-5}$	$N_{compton}/N_\gamma = 0.475 \cdot 10^{-5}$
Channel	$N_{ch}/N_{compton}$	$N_{ch}/N_{compton}$	$N_{ch}/N_{compton}$
$\gamma + e^-$	0.8456	0.8755	0.8652
e^-	0.1182	0.0876	0.0880
γ	0.0010	$< 10^{-4}$	$< 10^{-4}$
$\gamma + e^- + e^-$	0.0125	0.0136	0.0067

Table 2. *Portions of the QED processes which take place in the polarimeter target and are detected on the "detector" plane for various photon energies and target thicknesses and materials,* $q > q_0 = 0.5\,MeV/c$

Material	C_6H_6	C_6H_6	C_6H_6	C_6H_6	C_6H_6	Si	Si	Al	Al
Thickness, mm	0.3	0.5	0.5	0.5	0.5	0.1	0.3	0.1	0.3
Energy, MeV	1000	10	50	350	500	1000	1000	1000	1000
Pair	-	-	-	-	-	-	-	-	-
$e^+ + e^-$	0.9505	0.9306	0.9472	0.9457	0.9451	0.9534	0.9218	0.9526	0.9201
$e^+ + e^- + e^-$	0.0241	0.0257	0.0281	0.0294	0.0298	0.0223	0.0356	0.0230	0.0366
$e^+ + e^- + \gamma$	0.0071	0.0071	0.0086	0.0104	0.0107	0.0104	0.0268	0.0104	0.0273
$e^+ + e^- + e^- + e^-$	0.0011	0.0012	0.0014	0.0014	0.0014	0.0010	0.0016	0.0010	0.0017
$e^+ + e^- + e^- + \gamma$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	0.0016	$< 10^{-4}$	0.0017
Triplet	-	-	-	-	-	-	-	-	-
$e^+ + e^- + e^-$	0.8318	0.7709	0.7725	0.7684	0.7663	0.8363	0.6870	0.8299	0.6772
$e^+ + e^- + \gamma$	0.0017	0.0026	0.0033	0.0040	0.0040	0.0031	0.0144	0.0031	0.0150
$e^+ + e^- + e^- + e^-$	0.0344	0.0345	0.0328	0.0378	0.0365	0.0307	0.0350	0.0314	0.0346
$e^+ + e^- + e^- + \gamma$	0.0102	0.0084	0.0116	0.0135	0.0144	0.0151	0.0342	0.0167	0.0346
$e^+ + e^-$	0.1025	0.1593	0.1579	0.1598	0.1629	0.1005	0.2145	0.1047	0.2236
Compton	-	-	-	-	-	-	-	-	-
$\gamma + e^-$	0.8747	0.7697	0.8304	0.8652	0.8694	0.8824	0.8635	0.8789	0.8626
e^-	0.0897	0.1795	0.1325	0.0978	0.0940	0.0888	0.0857	0.0908	0.0864
γ	0.0010	0.0170	0.0024	$< 10^{-4}$	0.0001	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$
$\gamma + e^- + e^-$	0.0115	0.0120	0.0124	0.0131	0.0128	0.0083	0.0133	0.0097	0.0137

Table 3. *Relation of the recoil electron yield from triplet photoproduction and total contribution of the δ-electrons from all initial QED processes for some polarimeter targets. Photon energy is* $1000\,MeV$, $q > q_0 = 0.5\,MeV/c$

Material	C_6H_6	C_6H_6	C_6H_6	Si	Si	Al	Al
Thickness,mm	0.1	0.3	0.5	0.1	0.3	0.1	0.3
$N_{recoil}/(N_{recoil}+N_\delta)$	0.682	0.574	0.502	0.413	0.261	0.419	0.265

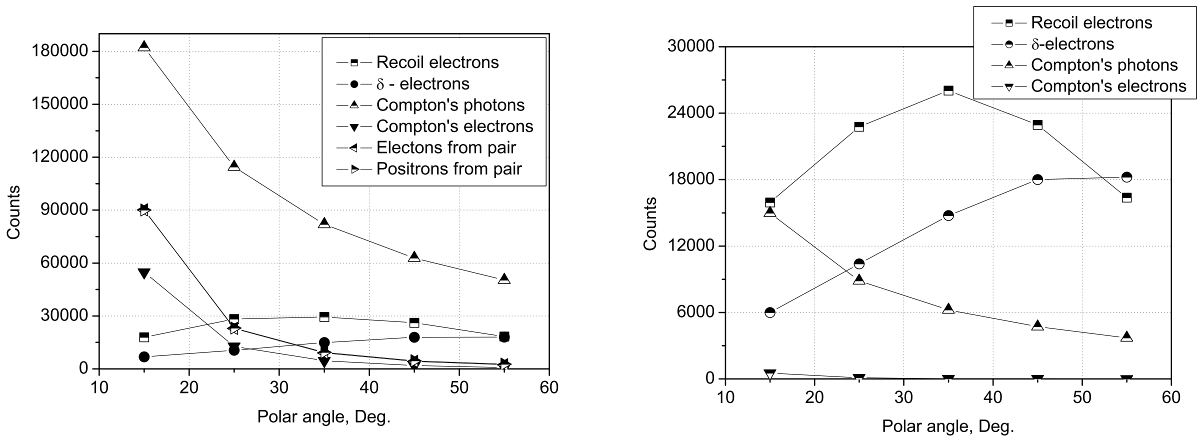

Fig.4. *The angular dependence of the particles yields from main QED processes and the δ-electron production. Photon energy is* $E_\gamma = 100\,MeV$ *(left panel) and* $1000\,MeV$ *(right panel), target is the plastic* $0.5\,mm$. *Number of photons* $5 \cdot 10^9$. *The points present sum of the particles yield of the corresponding processes in the* $\pm 5^0$ *angular intervals*

First of all one can see that number of the Compton scattering photons essentially exceed the rest particles yield in all angular range for photon with energy $E_\gamma < 100\,MeV$.

Their part is also considerable and for higher energies at least for angles $\theta < (20 - 30^0)$. To eliminate their contribution it is needed to use the recoil electron's and pair's detectors with low efficiency for photon registration and special triggers are also have to be applied.

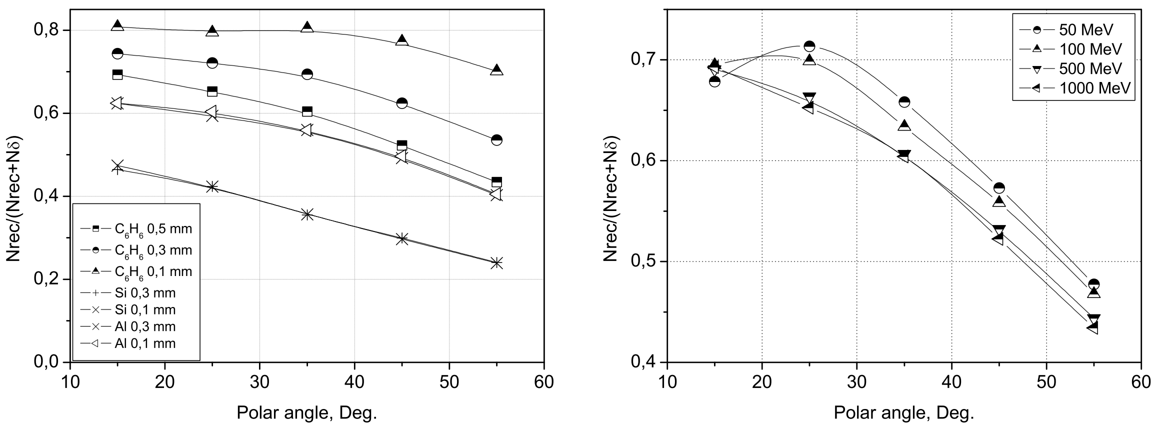

Fig.5. *The angular dependences of the ratio of the recoil's electron yield to the summary of one and δ-electron yield for* $E_\gamma = 100\,MeV$ *and some target thicknesses and materials (left) and for plastic target* $0.5\,mm$ *thickness and some photon energies (right)*

The Compton scattered electrons and pair's components give large contribution under small polar angles, $\theta < (10 - 15^0)$. With increasing the photon energy this angular interval becomes less, but in any case the angles $\theta < (10 - 15^0)$ are very undesirable for the recoil electron detection. So the polar angular range $\theta > 20^0$ is more suitable for recoil electrons detection and main background contribution which will be detected by recoil electron counters comes from secondary particles, practically all of them are δ-electrons produced by fast electrons and positrons from pair production. Because as was pointed above the δ-electrons have kinematical characteristics (energy and angle of emission) practically similar to the recoil electrons from triplet photoproduction it is necessary to find the kinematical conditions where the δ-electrons contribution is less. Their relative contribution as a function of polar angle is shown in Fig. 5, where it is plotted the ratio of the recoil's yield to the summary one of the recoil and δ-electrons

$$R = N_{recoil}/(N_{recoil} + N_{\delta}). \quad (3)$$

One can see that the δ-electrons relative contribution has certain angular dependence, the ratio (3) reach maximal value at the angles $\theta < 40^0$ e.g. $R \sim 0.8$ for thin polarimeter target for plastic with $0.1\,mm$ thickness, and smoothly decreases at more large polar angle. Such tendency is similar for targets from various material and different thickness but the maximal ratio is decreased with the target thickness increasing and becomes $R \sim 0.6 - 0.7$, for example, for plastic $0.5\,mm$. It is seemingly, to use thicker plastic target for the triplet polarimeter it is no expediently. The same one can say about Si and Al targets with the thickness more than $0.1\,mm$.

The partition of the δ-electron practically does not depend on photon energy at the range under study. In general, the results of the simulation show that most profitable angular interval for recoil electrons registration if we will use the triplet photoproduction process for photon linear polarization measurement is ranged from $\theta \sim 20^0$ and up to $30 - 35^0$ and the target from plastic with thickness $\sim 0.3\,mm$ has to be applied. In the case of the targets with large atomic number using the profitable thickness is about $0.1\,mm$, but for triplet polarimeter using the targets from light material it seems is more profitable.

5. CONCLUSIONS

The simulation of the processes which take place at the photon interaction with the photon polarimeter target has been carried out and the data base has been accumulated. The general relations between main QED processes (e^+e^- pairs and triplet photoproduction and Compton scattering) and background and secondary processes initiated by the main QED processes were studied.

All QED processes will give contribution to particles counting rate in the recoil electron detectors at all angular range and essential part of the contribution results from the Compton scattered photons, especially at low photon energies. The pair production along with Compton scattered electrons makes large contribution at small polar angles, $\theta < 10^0$.

The main background process if we will use the triplet photoproduction reaction for linearly photon polarization measurement is the δ-electron production in the target matter by electrons and positrons from pair production. In most preferable angular range $\theta \sim (20 - 30^0)$ the δ-ray's background reaches $\sim (20 - 25\%)$ but it contribution can increase up to 60% with the angles increasing up to $\theta > (40 - 50^0)$.

At higher photon energies the contributions of the Compton scattering and pair production are considerably reduce, the δ-electron contribution remains practically the same.

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СООТНОШЕНИЕ МЕЖДУ ОСНОВНЫМИ И ФОНОВЫМИ ПРОЦЕССАМИ КЭД ПРИ ВЗАИМОДЕЙСТВИИ ФОТОНОВ С МИШЕНЬЮ ФОТОННОГО ПОЛЯРИМЕТРА

Д.Д. Бурдейный, В.Б. Ганенко, Ю.П. Пересунько , И.Н. Шаповал, Г.А. Ващенко

Проведено моделирование процессов, которые имеют место при взаимодействии фотонов с материалом мишени поляриметра. Изучались отношения между основными КЭД и фоновыми процессами. Было найдено, что рождение δ-электронов является основным фоновым процессом для поляриметра, основанного на реакции фоторождения триплетов. Их общий вклад не менее $\sim$ 20-30% даже для оптимальной мишени поляриметра (пластик с толщиной 0.1$-$0.3 мм).

СПІВВІДНОШЕННЯ МІЖ ОСНОВНИМИ ТА ФОНОВИМИ КЕД ПРОЦЕСАМИ ПРИ ВЗАЄМОДІЇ ФОТОНІВ ІЗ МІШЕННЮ ФОТОННОГО ПОЛЯРИМЕТРА

Д.Д. Бурдейний, В.Б. Ганенко, Ю.П. Пересунько , І.М. Шаповал, Г.А. Ващенко

Проведено моделювання процесів, які мають місце при взаємодії фотонів із матеріалом мішені поляриметра. Вивчалися співвідношення між основними КЕД та фоновими процесами. Було знайдено, що народження δ-електронів є основним фоновим процесом для поляриметра, заснованого на реакції фотонародження триплетів. Їх загальний внесок не менш ніж $\sim$ 20-30% навіть для оптимальної мішені поляриметра (пластик з товщиною 0.1$-$0.3 мм).