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PARTICLE DISTRIBUTIONS OF MAIN QED AND BACKGROUND PROCESSES CAUSED BY INTERACTION OF HIGH ENERGY PHOTONS WITH MATTER OF PHOTON POLARIMETER TARGET

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The angular and energy distributions of the particles resulted from interaction of the polarized photons of energy 50-3000 MeV with matter of the photon polarimeter target were studied. The optimal kinematical ranges were founded for using the pair and triplet photoproduction processes for photon linear polarization measurement. The pair photoproduction could be used in the range up to 2-3 GeV if the coordinate (microstrip) detector with pitches ~100 mkm is applied for measurement azimuthal distributions of the line segments between electron and positron crosses the detector plane. The angular region $10^0<\theta<40^0$ is more suitable if the triplet photoproduction process is used. The conditions were determined for decreasing contribution of the main background process of δ-electron production which strongly influences on the analyzing power of the triplet photopoduction process. For effective δ-electron background suppression it is desirable to apply the differential thresholds of the recoil electrons registration subject to their angle emission. Such approach can allow one to reduce the δ-electron contribution up to ~10% at the most suitable angular intervals $10\text{-}40^0$ for polarization measurement.
KEY WORDS: photon beam, linear polarization, photon polarimeter, pair and triplet photoproduction, Compton scattering, recoil electrons, δ-electrons.

Linearly polarized photon beams are widely used in researches of nucleon and nuclear structure, mechanisms of the photon interaction with hadrons and nuclei. So problem of the photon polarization determination becomes important for obtaining high data accuracy in these experiments. Most reliable way to get the photon polarization value is its direct measurement. There are various approaches for the linear photon polarization measurement, see, e.g. [1], but using main QED (quantum electrodynamics) processes, such as photoproduction of e^+e^- pairs in a nuclear field, $\gamma+Z\rightarrow Z+e^++e^-$, or in the field of atomic electrons, $\gamma+e^-\rightarrow e^-+e^++e^-$ (triplet photoproduction), are most preferable because, firstly, these processes have sufficiently high analyzing power (azimuthal dependence of the reaction cross section due to photon polarization) which weakly depend on energy in wide range, secondly, the analyzing power can be calculated (in principle) with high precision, thirdly, these processes have large cross section and convenient signature for their identification. But there are some factors which can considerably reduce the analyzing power of these processes. These are (i) experimental conditions and technique of the polarization measurement and (ii) background processes which are initiated in a matter of the polarimeter target by both the initial photons and the charge particles produced in the primary QED processes.

The general relations among the main QED and background processes in photon energy range E_γ~10…1000 MeV were studied for some target materials (plastic (C_6H_6), Al and Si with thicknesses 0.1-0.5 mm) in the previous paper [2] using method of mathematical simulation. As was shown, efficiency of the photon conversion for plastic targets with thickness 0.1-0.5 mm is $\sim10^{-4}\ldots.10^{-5}$, at that total part of secondary (background) processes initiated by the charged particles of the primary QED processes (pair and triplet photoproduction and Compton scattering) is no more than ~5%. The most background process is the δ-electron production resulted, mainly, from electrons and positrons of the pairs. Because production of the e^+e^- pairs is sufficiently larger then the triplet photoproduction, the δ-electron yield can be comparable with the recoil electron's yield from the triplet photoproduction especially under large angles ($\theta\sim40^0\text{-}50^0$) of the electron emission that can sufficiently decrease the analyzing power of the polarimeter based on the triplet photoproduction. So, search of the kinematical conditions where the background contribution is minimal is important for effective photon polarimeter, based on the triplet photoproduction processes. The purpose of the work is to study in more detail the angular and energy distributions of the particles produced in the main QED and background processes and determination the optimal kinematical conditions for background suppression when the pair and triplet photoproduction processes are used for measurement of the photon linear polarization.

SCHEME OF THE SIMULATION

The investigations have been carried out by mathematical simulation method with using computer code developed for simulation of the processes which take place in the polarimeter target when the high energy polarized photon beam passes through the target. The code is based on the GEANT-3 package [3] which was supplemented by some subroutines for calculation of azimuthal angles differential distributions of the final particles produced by the polarized photons at the Compton scattering and pair and triplet photoproduction. For the triplet photoproduction description the BASE/SPRING code [4] was applied.

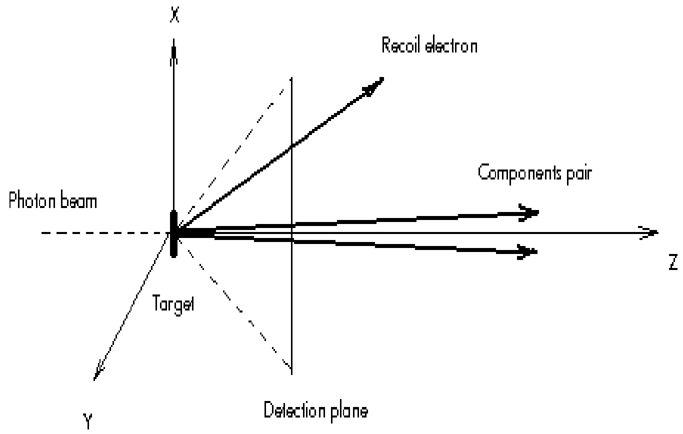


Fig.1. The scheme of the simulation.

The scheme of the simulation is shown in Fig.1. Point like polarized photon beam arrives along Z axis and falls on the polarimeter target. The interaction points along Z axis are determined in a random way. If the interaction has happened the type of process is determined and kinematical characteristics of the reaction products are calculated. Then the way of every particle is tracked from the point of origin up to the target exit and all kinematical parameters and type of the particles flying off in forward direction are fixed on the "detector" plane which was placed at 1.5 cm distance from the target. In such a way large body of the simulation events of the photon interaction with polarimeter target has been accumulated for initial photon energies in the range 10-3000 MeV, the various targets thicknesses and materials. The accumulated data base allows one to study all necessary distributions of the particles produced in the target by polarized photons. Some details of the simulation were presented in Ref. [2].

FEATURES OF THE PARTICLE DISTRIBUTIONS FROM MAIN QED PROCESSES

Pair photoproduction

The e^+e^- pair photoproduction is the most probable QED process which happens in the polarimeter target at photon energies E_γ~50-3000 MeV and it produces also main (δ-electron) background [2] that can hamper the use of the triplet photoproduction reaction for photon polarization measurements.

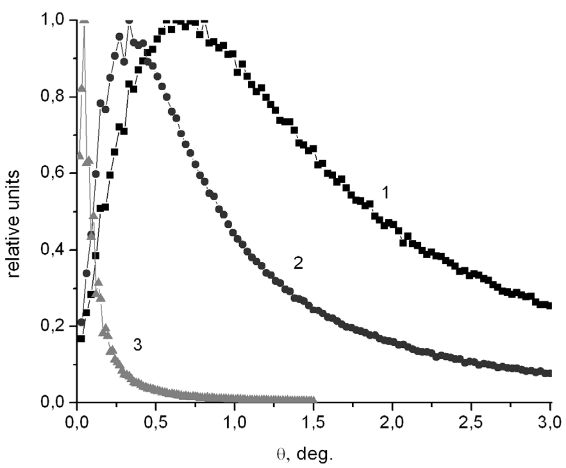


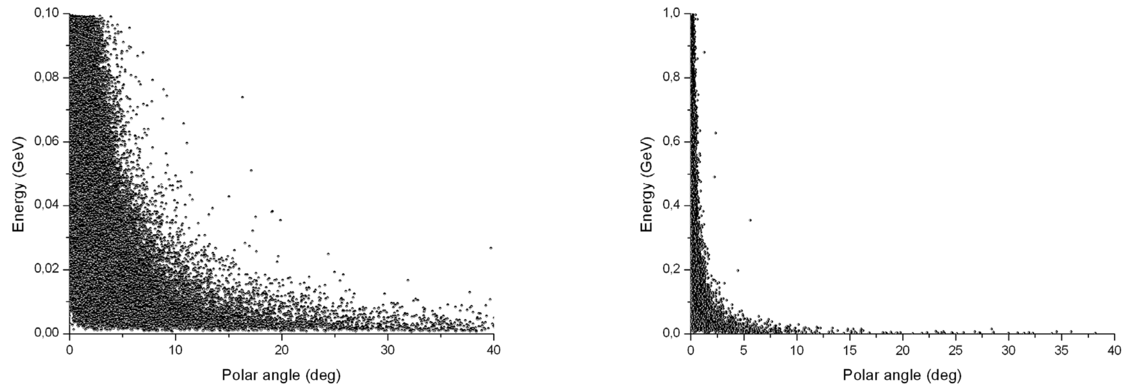
Fig.2. The polar angle distributions of the electrons from pair production on the "detector" plane for photon energies E_γ=50 (squares), 100 (circles) and 1000MeV (triangles).

The kinematical characteristics of the pair photoproduction process are well known. For purpose of the photon polarization measurement it is of interest the angular interval where the pair production yields dominates or comparable with the other QED processes yields. Some simulation results of the angular distributions of the pair electrons produced in the plastic (C_6H_6) target of 0.5mm thickness are presented in Fig.2. The angular distributions are fixed on the "detector" plane, thus influence of the electron multiple scattering is taken into account.

The angular distributions of the pair electrons (and positrons), as it is known, are strongly peaked in forward direction, and full width at half maximum (FWHM) in our conditions changes from ~2^0 up to ~<0.1^0 at photon energy increasing from E_γ~50MeV to E_γ>1000MeV. However, there is a part of the electrons (mainly with low energy, ~<10-20MeV) which are emitted under sufficiently larger angles and can strongly scatter in the target material. As a result, the pair particles angular distributions has a tail which may reach some tens degrees, especially for low initial photon energy, Fig.2. Their number at these angles may be comparable with number of the recoil electrons from triplet photoproduction. Calculations show that interval of polar angles <10^0 is the range where the pair particles yield dominates over other processes yields for photons with energies E_γ>350MeV. For smaller energy this angular interval should be increased up to ~20^0, Fig.3

Distribution of the distances between the electron and positron crossing the detector plane is another important characteristic for the pair polarimeter construction because the azimuthal dependence of the line segments between the points of electron and positron crossing the detector plane correlates with the photon polarization plane and can be used for polarization measurements [5].

This characteristic is very convenient for polarization measurement and expected distributions of these intervals on the distance 100cm from the polarimeter target are shown in Fig. 4 for some photon energies. They have maximum depending on the photon energy, the FWHMs of which are varied from ~7cm for E_γ~50MeV up to ~2-3mm for E_γ~2-3GeV. Such properties of the distributions allow one to measure the line segments azimuthal distributions by coordinate (microstrip) detector with pitches ~100mkm for photon energies up to 2-3GeV [5]. For photons with energy E_γ~<200-300MeV the distributions are wide enough so the detector plane can be placed nearer (~30-50cm) to the polarimeter target.



(a) (b)

Fig.3. Two-dimensional (polar angle – energy) distributions pair electrons. Target is plastic (C_6H_6) of 0.5mm thickness E_γ=350MeV - (a) and E_γ=1000MeV - (b).

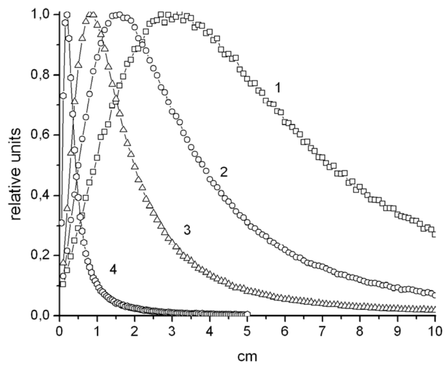


Fig.4. Distribution of the distance between pair electron and positron crosses the detector plane on 100cm distance from the polarimeter target. The photon energy is E_γ=50 - (1), 100 - (2) and 200 - (3) and 1500MeV - (4).

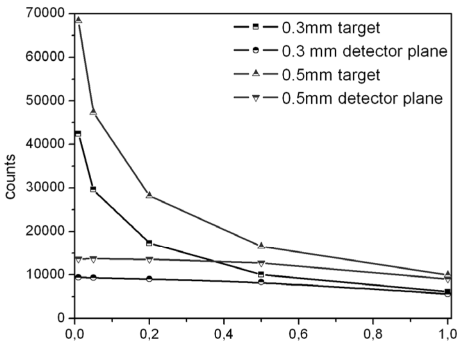


Fig.5. Number of the recoil electrons from the triplet photoproduction born inside the plastic target and fixed on the "detector" plane as a function of the recoil electron momentum q. Photon energy 1000MeV, target thickness is 0.3 and 0.5mm.

Triplet photoproduction

This is another QED process which can be used for linear photon polarization measurement. Such proposition was firstly advanced by Kharkov theorists V.F. Boldyshev and Yu.P. Peresunko in [6] and then it was theoretically studied in details in the following works (see [7,8] and references there). As was shown, the azimuthal distribution of the recoil electrons correlates with direction of the linear photon polarization, so it can be used for polarization measurement. At that the recoil electrons kinematical characteristics are very suitable for registration because (i) recoil electrons are emitted under large angles (up to 80^0), (ii) they have high enough energy for registration (up to ~10-20MeV). The analyzing power of the process is sufficiently large (Λ~0.14) and weakly depends on photon energy up to hundreds GeV, as well as the features of the recoil electrons distributions, that allows in principle to use this process for polarization measurement in very wide energy range.

Cross section of the triplet photoproduction strongly depends on the recoil electron momentum q, in such a way yield of the recoil electrons is considerably increases with q decreasing, Fig.5. But recoil electrons with low energies are emitted under large angles and many of the electrons born inside the target do not exit from it owing to energy losses.

Thus, for plastic target with thickness ~0.3…0.5mm most of the recoil electrons born with q<0.5MeV/c are stopped in the target and so there is practically no increasing of the yield on the "detector" plane of the recoil electrons with momentum q<0.5MeV/c, Fig.5. Thus, in the course of the triplet production simulation we usually fixed the threshold recoil momentum value for triplet events generation at q_0=0.5MeV/c. In this case the triplet yield is ~20-25 times less than the yield of the e^+e^- pairs. Typical energy and angular distributions of the recoil electrons off the triplet photoproduction are shown in Fig.6 for two cases: (i) at the production point that corresponds to theoretical distributions and (ii) on the "detector" plane where the multiple scattering influence reveals itself. As was emphasized above, the recoil electron distribution features practically do not depend on the photon energy in the range under study, E_γ~50-3000MeV. Their yield sharply increased with their energy decreasing, so the overwhelming part of them are at the energies E_r~<15MeV. The recoil yield considerably increases also at large angles of the recoil electron emission. Due to certain kinematical relation between energy and emission angle of the recoil electrons (with the emission angle increasing the recoil energy decreases) the recoil electron generation threshold q_0~0.5-1MeV/c leads to cutting the recoils with the polar outlet angle θ_r~>50-60^0, at that for all photon energies under study. Because the recoil electrons emitted under large angles have low energy (E_r~<2MeV at θ_r >40^0) they are strongly scattered in the target material (up to ~15^0-20^0), thus upper side of the angular distribution is smeared and, firstly, the long tail of low energy scattered electrons appears, and secondly, the maximum of the angular distribution is shifted to angle ~30-40^0, Fig.6. One can suppose that electrons which are fixed on the detector plane at the angles θ_r ~>50^0 are subjected to strong multiple scattering, so they can lose the primary azimuthal asymmetry and turn into low energy electron background.

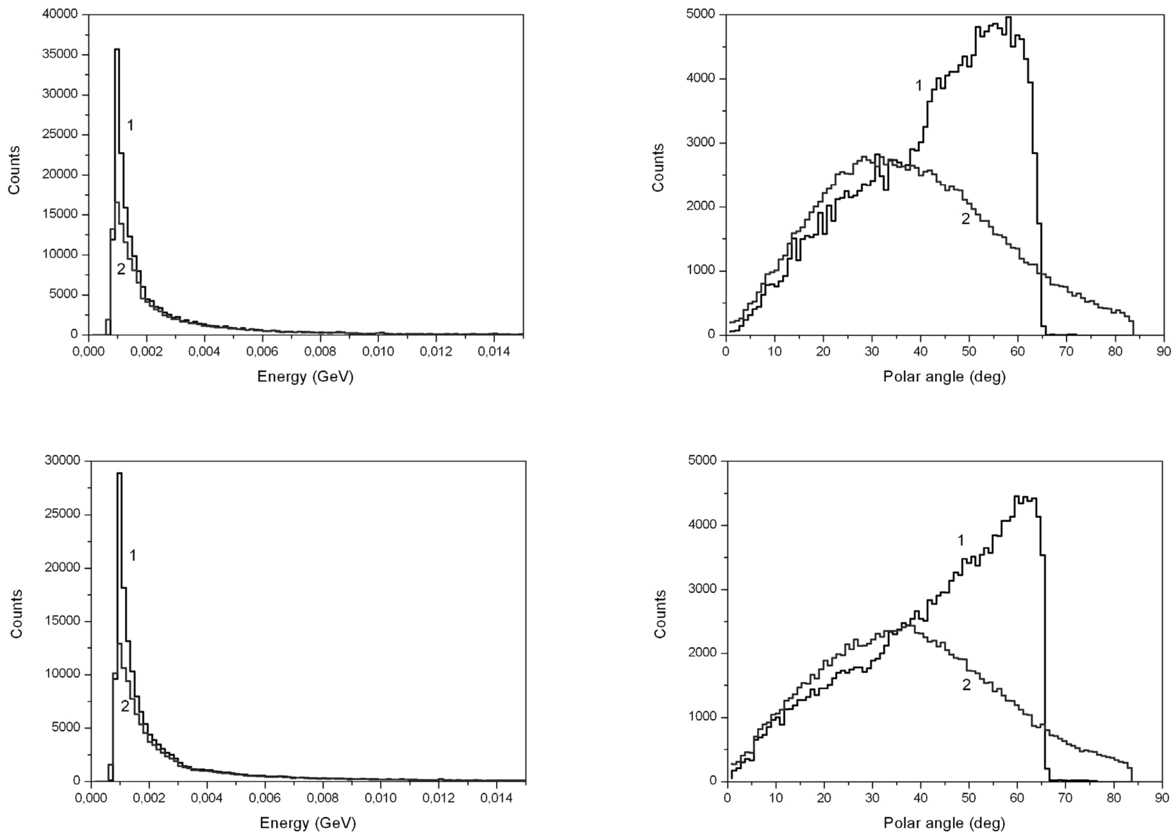


Fig.6. The energy and angular distributions of the recoil electrons from the triplet photoproduction for E_γ=100MeV (upper) and 1000MeV (down) at the polarimeter target - (1) and on the detector plane - (2). Target is plastic with the thickness 0.5mm, q_0=0.5MeV/c.

In more details the relations between energy and angle of the recoil electrons is shown in Fig.7, where two dimensional distributions are plotted for cases (1) and (2) above.

One can see the kinematically allowed physical region for the recoil electrons from the triplet photoproduction

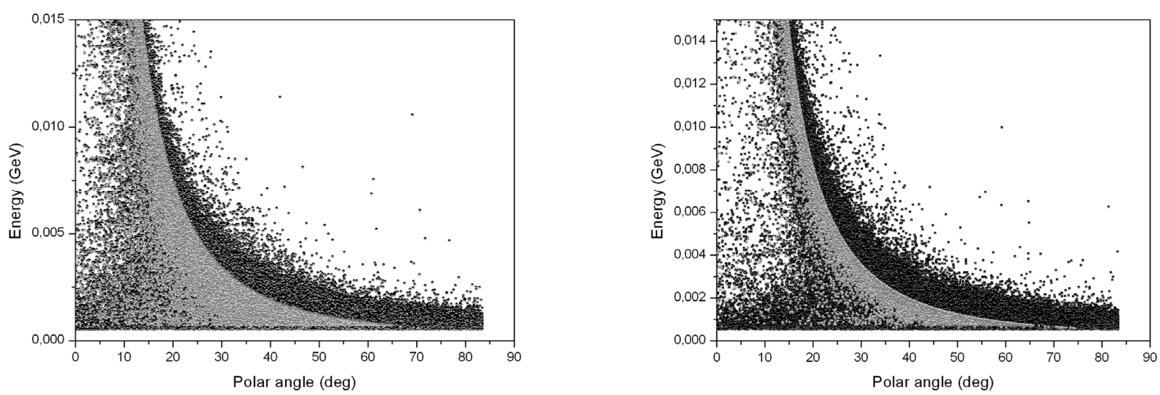


Fig.7. Two dimensional (polar angle-energy) recoil electron distributions in the polarimeter target (gray points) and on the detector plane (black points). Target thickness is 0.5mm plastic, $q>q_0$=0.5 MeV/c, E_γ=100MeV (left), 1000 MeV (right).

which is typical for all photon energies and confined between the two (high and low) kinematical borders: $q_{min}(\theta_r)\leq q\leq q_{max}(\theta_r)$ [6-8]. The upper branch is clearly seen in the recoil electron distributions in the target built at the points of their birth (the case (i)) due to sharp upper edge.

The low border corresponds to electrons with energies E_r<1MeV and it is not clearly seen in the figures due to simulation threshold for triplet production.

The calculations show that the recoil electrons are emitted in the allowed kinematical region and preferably near its borders, and the distributions become narrower with the photon energy increasing. The multiple scattering smears the sharp boundary and makes distribution considerably wider thus low boundary becomes seen in figures. Besides, the long large "electron" tail due to multiple scattering of the low energy electrons appears at angles more than 60^0 for all photon energies. So, in spite of that from statistical point of view it is profitable to decrease threshold of the recoil electron registration, but due to considerable multiple scattering of the low energy electrons it is desirable to restrict the electron angles detection by the value $\theta_r<45^0$ that limits the recoil electron energy E_r~>1MeV.

Compton scattering

Compton scattering is important process for photon polarimetry, especially if the triplet photoproduction is used for polarization measurement, due to two factors. Firstly, the Compton cross section is comparable with the triplet production cross section in the energy range less than E_γ~300-400MeV, and, secondly, scattered Compton electrons and photons have kinematics that practically coincide with the recoil electrons upper branch from the triplet photoproduction, Fig.8.

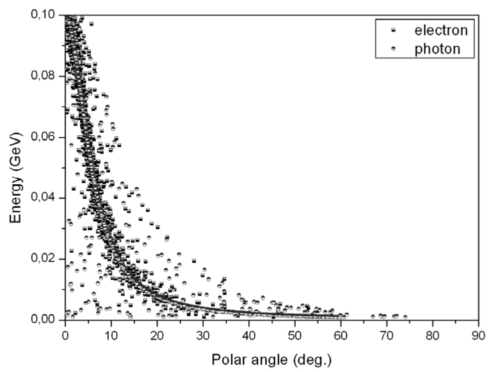


Fig.8. Two-dimensional distributions of the Compton scattered electrons and photons. Photon energy E_γ=100MeV, plastic target 0.5 mm thickness. Electron threshold q_0=1 MeV/c.

Because the angle and energy of the Compton scattered particles are related, their two dimensional distributions are narrow lines, but electron line becomes wider due to multiple scattering, especially for low initial photon energies, E_γ<100MeV. The Compton scattering gives an important part of the background yield especially at forward angles, $\theta<30^0$. As was shown in [2] for E_γ~100MeV at these angles yield of the Compton scattered photons ~3 times more than recoils yield and it contribution stay noticeable at higher photon energies and reaches ~30-50% at E_γ~1000MeV. The Compton electrons contribution is less noticeable. It is equal to recoils for photon energies E_γ~100MeV at angles $\theta_r<30^0$, exceed at less energies and become insignificant at higher energies, E_γ~1000MeV. In any case for decreasing the Compton background contribution one ought to use the trigger conditions based on signature of the reactions.

FEATURES OF THE BACKGROUND PROCESSES PARTICLE DISTRIBUTION

As was shown in [2], the main background contribution results from δ-electrons (δ-rays) which are knocked-out predominantly by the electrons and positrons from e^-e^+ pair photoproduction and also by fast charged particles from other processes.

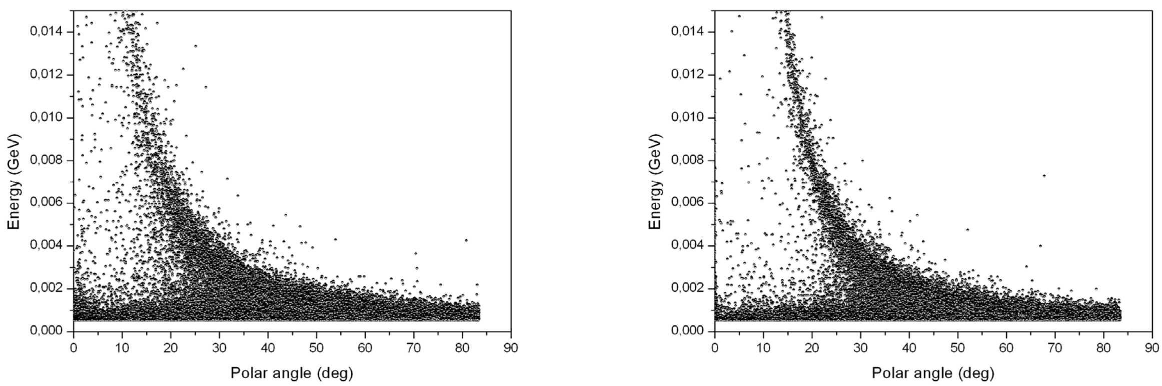


Fig.9. Two dimensional δ-electrons polar angle-energy distributions on the detector plane E_γ=50 MeV (left) and E_γ=3000 MeV (right).

This background can be comparable with the recoil electron yield from the triplet photoproduction, thus it may have a big influence on the analyzing power of the triplet polarimeter.

Two dimensional plots of the δ-electrons polar angle-energy distributions in Fig.9 demonstrate that they are very similar to the recoil electrons distribution, Fig.7. It is clearly seen the δ-electrons concentration along the upper branch of the kinematically allowed physical region for the recoil electrons. There is also significant concentration of low energy electron (with energy <1-1.5MeV) in all angular interval 0-90^0. Thus, the δ-electrons are disseminated in the bulk of the recoil electrons and it is difficult to separate them. But there are some differences between these particle fractions distributions that may allow if not discriminate the δ-electrons in whole but decrease their contribution and influence on the analyzing power of the triplet polarimeter. In Fig.10 the energy and angular distributions of the recoil and δ-electrons are presented in more detail and their detailed comparison could be made.

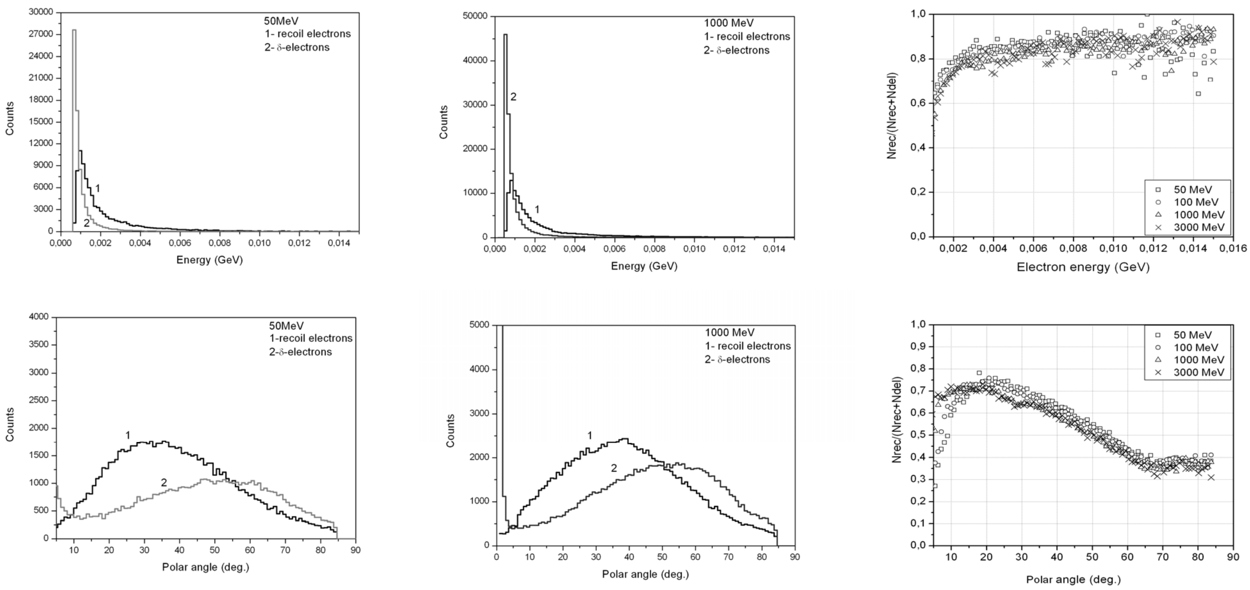


Fig.10. Energy and angular distributions of the recoil and δ-electrons on the detector plane
Left panel – Eγ=50 MeV, middle – 1000 MeV.
Right panel – energy and angular dependence of the relative recoil electrons contribution to the electron yield.

Firstly, both energy and angular distributions of the recoil and δ-electrons are practically independent on the photon energy. They are strongly peaked with the electron energy decreasing. At that, the number of the δ-electrons essentially exceed the number of the recoil electrons at low energies, E_r~<1MeV, but situation becomes opposite at higher energies. The part of the δ-electrons quickly reduces up to ~25% at E_r~2MeV and then smoothly decreases with energy up to ~10% at E_r~15MeV, but as one can see the above, number of the particles at this energy is low. So, the threshold for electron registration ~1-2MeV is needed for essential decreasing the δ-electron's background.

Secondly, there is a difference in the angular dependence behavior of the recoil and δ-electrons. The recoil electron distributions in real situation (when the multiple scattering is taken into account) for all photon energies have maximum at angles θ_r~30^0-40^0 where the yield of the recoil electrons exceed the δ-electrons yield. The δ-electron's distributions smoothly increase with angle increasing and have maximum at larger angles, θ_δ~50^0-60^0 where the yield of the δ-electrons exceeds the recoils yield. The calculation show, that their part reaches 60% at the anglesθ_δ>50^0 but it decreases for smaller angles, up to ~25% at θ_r~15^0-30^0, Fig.10. As a whole, the angular dependence of the relative recoil electron contribution has maximum at angles θ_r~20^0-25^0 for E_γ~50MeV which smoothly shifts to low angles with photon energy increasing, to θ_r~15^0 for E_γ~3000MeV. So, one can see that the mentioned above angular interval ~10^0-40^0 for recoil electron registration is also preferable from the point of view of the δ-ray background contribution. In this angular range the contribution of the δ-electrons does not exceed ~25% for all photon energies under study.

For more detail study of the δ-electron background contribution the energy spectra of the recoil electrons and the δ-rays and their ratio were investigated in certain angular intervals: 10^0-20^0, 20^0-30^0, 30^0-40^0, 40^0-50^0 and 50^0-60^0. Some results are presented in Fig.11. As it was expected, the spectra of the recoil electrons for angular intervals 10^0-40^0 demonstrate two peaks which correspond to two branches of the kinematically allowed physical region for the recoil electrons from the triplet photoproduction. The low energy peak is at energies not more than 1.5-2MeV, and it position does not depend on the photon energy and angular interval. The peak at higher electron energy distinctively reveals in the spectra at the angles 10^0-40^0 and its energy decreases with the angular interval increasing, so at larger angles the peaks are merged.

There are also two peaks in the δ-electron spectra which have the same energy behavior as for the recoil electrons spectra but there is some difference in their intensity. The δ-electrons dominate in the low energy range (the range of the first peak) in all spectra, but at the range of the second peak the recoil electrons yield significantly exceeds the δ-electron yield, especially at the angles 10^0-30^0 where contribution of the δ-electron can be reduced up to ~10%. At angles more 50^0 the δ-electrons become dominate again and there is no difference in the energy dependence between the recoil and δ-electron. So, for suppression of the δ-electron background (and increasing the analyzing power of the triplet polarimeter) it is necessary to use the threshold E_{th}~1-1.5MeV for the electron registration in order to reject all low energy electrons.

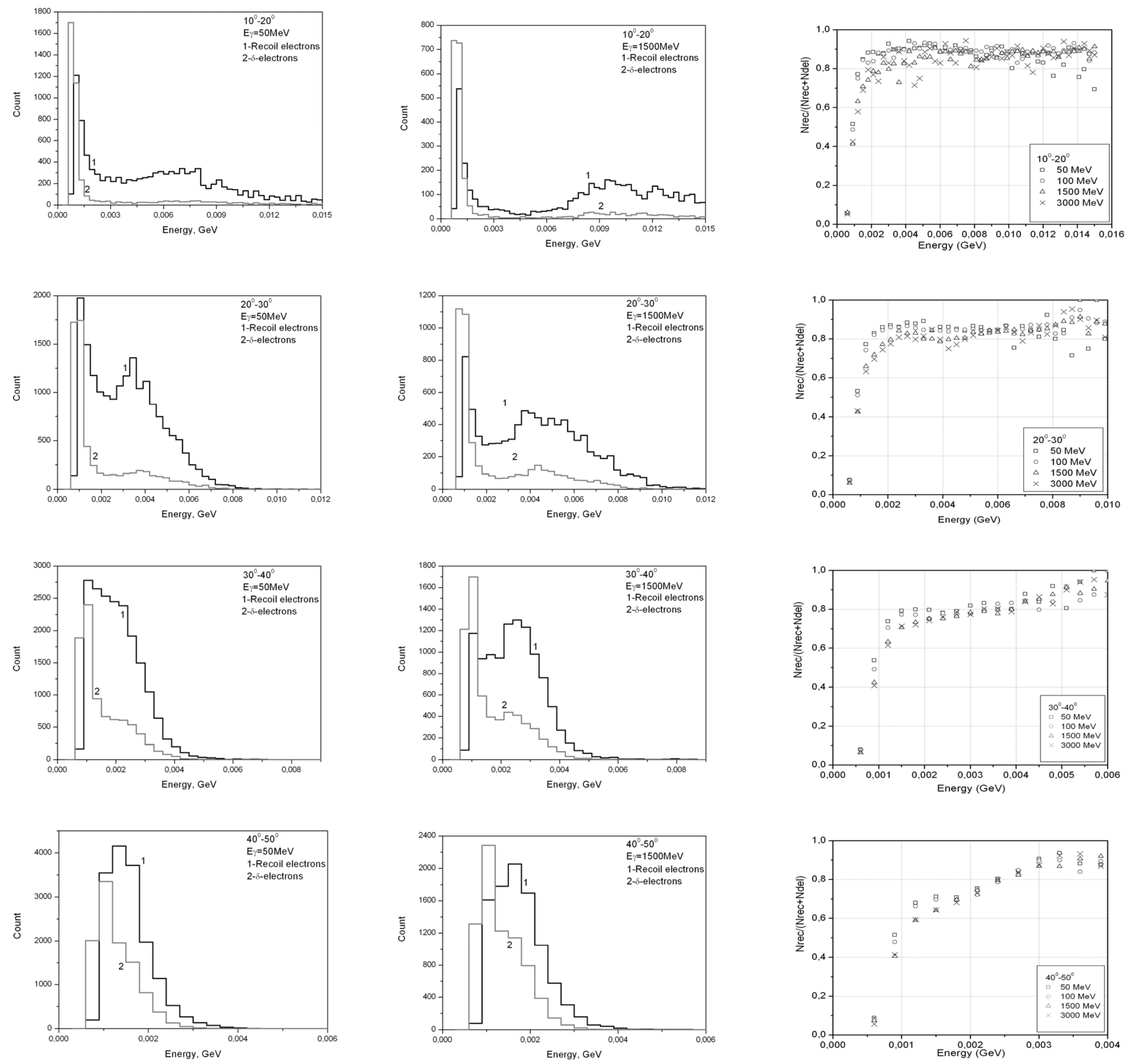


Fig.11. Energy dependence of the recoil and δ-electron yields for electron emission angles 10^0-20^0, 20^0-30^0, 30^0-40^0 and 40^0-50^0 for photon energies 50 (left) and 1500MeV (middle). Right panel: energy dependence of the relative recoil electrons contribution to the electron yield for the emission angles 10^0-20^0, 20^0-30^0, 30^0-40^0 and 40^0-50^0 for photon energies 50, 100, 1500 and 3000MeV.

But for more effective background suppression it is desirable to apply the different thresholds for various angular intervals: E_{th}~4-5MeV for angles 10^0-20^0, E_{th}~2-2.5MeV for angles 20^0-30^0 and ~1.5MeV for angles 30^0-40^0 and larger. In this case it is possible to get the ~90% level of the δ-electron background suppression at more profitable angular interval (20-40^0) for triplet process using for polarization measurements.

CONCLUSIONS

The energy and angular distributions of the all main QED and background processes were considered for photon energy range E_γ~50 - 3000MeV. Although the pair photoproduction is strongly peaked in the forward direction, $\theta<1$-2^0, the angular region up to $\theta\sim10^0$ is the interval where contribution of the electrons and positrons from the pair production exceed the recoil electron yield from the triplet photoproduction and other processes. The Compton scattering gives also essential contribution in this angular interval, especially at low photon energies, E_γ<~300MeV.

The pair photoproduction process could be used for linear photon polarization measurement in the range up to 2-3GeV if the coordinate (microstrip) detector with pitches ~100mkm to apply for measurement the azimuthal distributions of the line segments between electron and positron crosses the detector plane.

The angular region $10^0<\theta<40^0$ is more suitable if the triplet photoproduction process is used for the linear photon polarization measurements. The main background process which decreases the analyzing power of the triplet photoproduction is the δ-electron background produced by the high energy charged particles (mainly from pair production) in the polarimeter target. The recoil and δ-electrons have very similar energy and angular distributions, but δ-electron contamination is enriched by low energy electrons. For effective δ-electron background suppression it is desirable to apply the differential thresholds depending on the angle of the recoil electron emission. Such approach can allow one to reduce the δ-electron contribution up to ~10% at the most suitable angular intervals $10\text{-}40^0$ for polarization measurement.

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РАСПРЕДЕЛЕНИЕ ЧАСТИЦ ОСНОВНЫХ КЭД И ФОНОВЫХ ПРОЦЕССОВ ПРИ ВЗАИМОДЕЙСТВИИ ВЫСОКО-ЭНЕРГЕТИЧЕСКИХ ФОТОНОВ С МАТЕРИАЛОМ МИШЕНИ ФОТОННОГО ПОЛЯРИМЕТРА

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Изучены угловые и энергетические распределения частиц, образующихся при взаимодействии поляризованных фотонов с энергией 50-3000 МэВ с мишенью фотонного поляриметра. Определены оптимальные кинематические условия использования процессов рождения пар и триплетов для измерения линейной поляризации фотонов. Фоторождение пар может быть использовано в диапазоне энергий до 2-3 ГэВ, если координатные микростриповые детекторы с шагом в ~100 мкм позволят измерять азимутальные распределения линии сегментов между электроном и позитроном пары пересекающих детекторную плоскость. Определены условия уменьшения вклада основного фонового процесса рождения δ-электронов, сильно влияющего на эффективность применения процесса фоторождения триплетов. Для эффективного подавления фона в виде δ-электронов целесообразно ввести дифференцированный порог для регистрации электронов отдачи в зависимости от их полярного угла. Такой метод может уменьшить вклад δ-электронов до ~10% в наиболее пригодных для измерения поляризации угловых интервалах $10\text{-}40^0$.

КЛЮЧЕВЫЕ СЛОВА: фотонный пучок, линейная поляризация, фотонный поляриметр, фоторождение пар и триплетов, комптоновское рассеяние, электроны отдачи, δ-электроны.