# POLARIZATION OF THE HARD BREMSSTRAHLUNG OF THE RELATIVISTIC ELECTRONS IN A CRYSTAL

***S.V. Kasian, V.L. Morokhovskii****

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

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Results of the polarization measurements of high energy bremsstrahlung in crystals are presented. For analysis of the photon polarization the asymmetry of the yields of the single $\pi$-meson photo-production on proton was used. The asymmetry of the yields of products of $\pi$-meson photo-production on the liquid-hydrogen target are presented for bremsstrahlung photons with energy $E_\gamma = 700\,MeV$ generated by electrons with energy $E_{e^-} = 800\,MeV$ in the $Si$-crystal targets with thickness $120\,\mu m$ and $30\,\mu m$. The properties of the high energy bremsstrahlung in crystals for the cases of electron beam orientations under the small angles respectively to the crystal axis $\langle 111\rangle$ and plane (110) are investigated.

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## 1. INTRODUCTION

As follows from the theory of coherent bremsstrahlung in the first Born approximation [1] the highest photon polarization can be obtained for the lowest photon energies, because minimum momentum transfer to the nucleus $\delta$ ($\delta \approx \frac{mc^2}{2E_0}\frac{x}{1-x}$, where $x = \frac{\hbar\omega}{E_0}$ is the re-lative quantum energy) much less than the period of the reciprocal lattice $b_i = \frac{2\pi}{a_i}$. In this case the recoil momentum $\vec{q}$ of the nuclei are restricted to a very thin disk-shape region perpendicular to $\vec{p}_0$ called "pancake" by Uberall, the lower and sharp boundary being a distance $\delta$ away from the origin. Such kinematic conditions allow to create such crystal orientation respectively to the electron momentum $\vec{p}_0$, when only one point of the reciprocal lattice will be inside the "pancake", and only one quanted recoil momentum $\vec{q} = \vec{g}$ is possible. Selected direction of the recoil momentum is the reason of the bremsstrahlung polarization with high degree.

The intensity and polarization in the coherent maxima fall down rapidly if $x \to 1$. If $x \to 1$, then $\delta$ becomes of order or larger than period of the reciprocal lattice $b$. Very large number of the reciprocal lattice points hits the "pancake", so the spectrum of the recoil momenta becomes practically continuous, and coherent part of the bremsstrahlung intensity becomes negligibly small. In the case $x \sim 1$ the length of the photon creation $\delta$ becomes less than lattice period and therefore only one atom can be inside the sone of the photon creation [1],[2], so the constructive interference of the bremsstrahlung amplitudes from different atoms is absent. The polarization of bremsstrahlung with high relative energy accordingly to the Diambrini's theory must be negligibly small.

However it's known, that if high energy electron beam directed under the small angle respectively the atomic rows or planes of crystal target, then the angular distributions of the multiply scattered electrons characterized by azimuthal asymmetry [3]. Naturally to assume that in the analogous conditions we can obtain the high energy bremsstrahlung with not vanished polarization. It can be stipulated by the distortion of the wave function of the initial electron state due to interaction with string or plane potential. The aim of this experiment is to verify this hypotheses.

## 2. EXPERIMENTAL SETUP AND PROCEDURE

The experiment has been performed on the Kharkov $2\,GeV$ linear accelerator. The experimental setup is shown on the Fig.1.

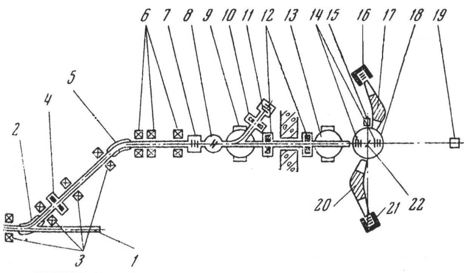


***Fig.1.*** *The experimental setup: 1-beam line of the $2\,GeV$ electron accelerator; 2,5-magnets of parallel beam transfer; 3,6-quadrupolar lenses; 4,10-collimators monochromators; 7,11,14-electron monitors; 8-goniometer and crystal target; 9,13-cleaning magnets; 12-photon collimators; 15-Faraday cup; 17- magnetic spectrometer SP-103; 18-target chamber; 19-quantometer; 20- magnetic spectrometer SP-02; 21- lead-shealding; 22- liquid hydrogen target*

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

Electron beam with energy $800\,MeV$ and a spectral spread of order of $\triangle E/E \approx 1\%$ after the system of parallel beam- transfer (pos.2-5) was focused by the quadrupolar lenses (pos.6) on the $Si$-crystal target (pos.8).

Electron beam on the target has the axial symmetrical distribution with middle cross section of order of $\approx 6mm$ and middle divergence of order of $\approx 2 \cdot 10^{-4}\,rad$. The beam distribution was controlled by scintillator screen¡ which can be placed directly in front of the crystal. Crystal targets were placed into the three-axes goniometer, which provided orientation of the crystal axes respectively to the electron beam direction with precision of order of $5 \cdot 10^{-5}\,rad$. Silicon crystal targets have the form of foils with diametrical dimensions are about the four times larger than the beam spot dimensions and have the thicknesses $t_1 = 120\,\mu m$ and $t_2 = 30\,\mu m$. The platitude of the crystal target coincides with (111) crystallographic plane. Crystals were orientated by using the method, which was described in details in the [4]. Electron beam was deflected by the magnet (pos.9) after passing through the crystal and after crossing the secondary electron monitor (pos.11), which was used for the beam current controlling during the experiment, was dumped in the shielding.

The bremsstrahlung from the crystal target was selected with the help of two couples of collimators (pos.12) in the forward direction. The angle of collimation was $\theta_k = 1/(2\gamma)$, where $\gamma$ is the electron Lorentz factor. Photon beam after the second cleaning magnet was directed to the liquid-hydrogen target with the thickness of $200\,mm$. The photon beam has the transverse dimensions $10 \times 10\,mm^2$ on the liquid-hydrogen target. After the hydrogen target the photon beam intensity was controlled by thin ionization chamber (pos.19) and finally by quantometer (pos.19). Ionization chamber and quantometer are also used for the control of the crystal orientation. Photo-producing of the single $\pi$-meson on the proton is the result of the interaction of the high energy photons with liquid-hydrogen target:

$$\gamma p \to \pi^0 p', \qquad \gamma p \to \pi^+ n. \tag{1}$$

The yields of the products of these reactions: protons $p'$ and mesons $\pi^+$ were measured by magnetic spectrometer equipped with telescope of scintillator detectors and threshold Cherenkov gas detector [5]. Magnetic spectrometer [6] has angular acceptance $\triangle\Omega = 8.2 \cdot 10^{-3}\,sterad$ and momentum acceptance $\triangle p/p \approx 0.1$. Telescope of scintillator detectors was built of three plastic scintillators in the form of rectangular plates with dimensions: $(10\times175\times130)\,mm^3$, $(20 \times 175 \times 150)\,mm^3$, $(20 \times 200 \times 150)\,mm^3$. For connections with photomultipliers the organic glass light-conductor was used. For excluding the electron-positron background the threshold Cherenkov gas detector was used. It was constructed in the form of steel box $(200\times150\times600)\,mm^3$ with $4\,mm$ steel windows and filled by $CO_2$-gas with pressure $6 - 20\,Pa$.

The photo-multiplier supplied with special optic system was used for registration the Cherenkov radiation. Construction and parameters of this device were described in details in [5]. The identification of the products of the photo production, i.e. $\pi^+$-mesons and protons were realized by registration the coincidence of signals in the three scintillations of telescope under the condition of anti-coincidence with signal from Cherenkov gas detector, which was placed behind the telescope. Such scheme allows to reliable registration of the products of photo-production with elimination of the background from relativistic electrons. Parameters of the scintillations, the high voltage on the photomultipliers, the levels of thresholds of pulse discriminators were chosen in such a way that the products of photoproducing were registrated with efficiency about 100%. Anti-coincidence with signals from Cherenkov detector allows us to exclude 99% of the electron background. Analogous equipment was successfully used earlier in the experiments, where coherent bremsstrahlung polarization was measured [7]. Spectrometer was tuned up on the momentum of $539\,MeV/c$ and angle of registration $\theta_L = 49.3^\circ$ respectively to the photon beam direction in the horizontal plane. As a result we have registered $\pi^+$-mesons and protons, which were produced by photons with energies $700 \pm 35\,MeV$. The cross sections of the photo-production have maxima at the energy $700\,MeV$. This condition is the best for using reactions (1) as an analyzer of the photon polarization. The reactions of the photo-production (1) in such conditions have the analyzing abi-lity for photon polarization $\Sigma \approx 0.7$, [8], where analyzing ability determines by the value of asymmetry

$$\Sigma = \frac{d\sigma_\perp - d\sigma_\parallel}{d\sigma_\perp + d\sigma_\parallel}, \tag{2}$$

and $d\sigma_\perp$, $d\sigma_\parallel$ are cross sections of photo-production of $p$ or $\pi^+$ by polarized photons in the plane perpendicular or parallel to the plane of reaction. For the chosen photon energy $\Sigma$ has the same values as for protons, so for $\pi^+$-mesons. The experimental value of the photon beam polarization can be defined as

$$P = \frac{1}{\Sigma} \cdot \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel}, \tag{3}$$

where $N_\perp$, $N_\parallel$ are the sum yields of $p$ and $\pi^+$-mesons in the planes, which are $\perp$ and $\parallel$ to the plane of reaction, respectively. The second multiplier in (3) is the asymmetry of the yields of products of photo-production, which we measured in our experiment.

For the aim of excluding the systematic errors the measurements of yields $N_\perp$ and $N_\parallel$ were performed as a series of measurements with many times changing orientation of the crystal plane respectively to the horizontal plane.

### 3. EXPERIMENTAL RESULTS

1. The asymmetry of the yields of products of $\pi$-meson photo-production on the liquid-hydrogen target

$$\Sigma' = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel}$$

was measured for bremsstrahlung photons with energy $E_\gamma = 700\,MeV$ generated by electrons with energy $E_{e^-} = 800\,MeV$ in the $Si$-crystal targets with thickness $120\,\mu m$ and $30\,\mu m$. The electron beam was directed in the crystal plane (110) under the angle $\theta = 35\,mrad$ respectively to the crystal axis $\langle 111 \rangle$. We performed the yields measurement by many times changing plane (110) orientation parallel and perpendicular to the plane of reaction. Such crystal orientations are shown on the Fig.2.

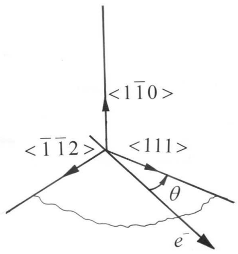


***Fig.2.*** *The crystal orientations, which were used. The first picture shows the crystal plane* (110) *parallel to the plane of photo-production; the second picture shows the position of the plane* (110) *perpendicular to the plane of photo-production*

Analogous results of measurements were performed earlier for the $Si$ crystal target with thickness $120\,\mu m$ and presented in the work [9], [10], [11]. Here we improve the previous result [9], [10], [11] by excluding some systematic errors caused by errors of the crystal orientations and unstability of the electron beam parameters. Besides we presented the new result for the crystal target with thickness of $30\,\mu m$. Experimental results are presented in the Table 1.

***Table 1.***

| Crystal thickness | $30\,\mu m$ | $120\,\mu m$ |
|---|---|---|
| Asymmetry $\Sigma'$ | 0.04 | 0.05 |
| The authenticity | 0.95 | 0.95 |
| The confiding interval | $\pm 0.02$ | $\pm 0.04$ |

2. The asymmetry yields $\Sigma'$ of products of $\pi$-meson photo-production on the liquid-hydrogen target measured for bremsstrahlung photons with energy $E_\gamma = 700\,MeV$ generated by electrons with energy $800\,MeV$ in the $Si$ crystal target with thickness $120\,\mu m$ for the cases of electron beam orientations under the different angles respectively to the crystal axis $\langle 111 \rangle$ in the arbitrary plane, which was far from any crystal plane.

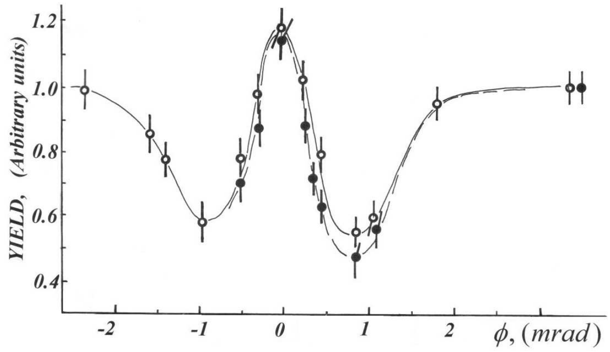


***Fig.3.*** *The yield of the products of $\pi$-meson photo-producing in arbitrary units as a function of the angle $\phi$ between photon beam direction and $< 111 >$ crystal axes (The yield equal unit corresponds to the angle $\phi = 10^{-1}\,rad$). The line with points $\circ$ corresponds to the measurement of the angle $\phi$ in the plane of reaction. The line with points $\bullet$ corresponds to the measurement of the angle $\phi$ in the plane, which is perpendicular to the plane of reaction*

The crystal orientations were chosen by the following way. The yield of photo-producing depends on the crystal orientation, i.e. depends from the angle $\phi$ created by crystal axis $\langle 111 \rangle$ and the electron beam direction. Such dependence correlates with the dependence of the bremsstrahlung intensity from angle $\phi$. It's shown on the Fig.3. The asymmetry was measured in 5 points, which are designed by $\phi_i\,(i = 1; 2; 3; 4; 5)$. The angle $\phi_5 = 10^{-1}\,rad$ corresponds to the case of large angle $\phi$, when the yield of the products of $\pi$-meson photo-producing becomes constant. We should pay attention to the reason of the minimum in the point $\phi_3 = 0.9\,mrad$ of the orientation dependence which is shown on Fig.3. This crystal orientation characterized by the maximum asymmetry of the angular distribution of scattered electrons and radiated photons, which is caused by coherent scattering on the atomic strings. Orientations $\phi_1 = 0\,mrad$ and $\phi_5 = 0.9\,mrad$ characterized by the symmetrical angular distributions as for scattered electrons, so for radiated photons. Our results of measurements of the asymmetry $\Sigma'$ for different angles $\phi_i$ are presented in the Table 2.

***Table 2.***

| Crystal orientation | $\phi_1$ | $\phi_2$ | $\phi_3$ | $\phi_4$ |
|---|---|---|---|---|
| Angle $\phi$ $(mrad)$ | 0 | 0.5 | 0.9 | 1.1 |
| Asymmetry $\Sigma'$ | 0.02 | 0.04 | 0.08 | $-0.08$ |
| The authenticity | 0.95 | 0.95 | 0.95 | 0.95 |
| The confiding interval | $\pm 0.06$ | $\pm 0.06$ | $\pm 0.07$ | $\pm 0.1$ |

One can see, that significant asymmetry observed only at the orientation angle $\phi = 0.9\,mrad$, which corresponds to the minimum of the yield dependence on Fig.2. and it is $\Sigma' = 0.08 \pm 0.07$.

## 4. CONCLUSIONS

Summing up the results of our measurements of asymmetry of the $\pi$-meson photo-production on protons by bremsstrahlung with relative photon energy $x \to 1$, which was created by relativistic electrons in crystal targets, we have the reason to draw the following conclusions.

1. If relativistic electron momentum was directed respectively the crystal axes or plane under the angles, which was essentially larger than the angle of the multiple electron scattering in a crystal target, then the asymmetry of the $\pi$-meson photo-production on protons by high energy bremsstrahlung was not observed. Under conditions of our experiment the theory of the coherent bremsstrahlung in the first Born approximation can be applied. The theoretical value of the bremsstrahlung polarization for the photons with energy 700 $MeV$ created by electrons with energy 800 $MeV$ in the $Si$-crystal is of order of $P \sim 10^{-8}$. The experimental errors overheads this value, and the asymmetry of the $\pi$-meson photo-production was not revealed.

2. In the cases when momentum of the relativistic electron forms small angle with crystal axes or plane the asymmetry of the $\pi$-meson photo-production on protons by high energy bremsstrahlung comes to light. In these cases the experimental errors are less than the observed asymmetry. So the polarization of the high energy bremsstrahlung in this case is much larger than the value predicted in the frame of the first Born approximation. It's necessary to accentuate that the largest asymmetry of the $\pi$-meson photo-production was observed in the case when the maximum asymmetry exists in the angular distribution of the multiply scattered high energy electrons in a crystal. Such correlation points out on the necessity of development more general theory of the coherent bremsstrahlung.

3. The sign of the asymmetry of the $\pi$-meson photo-production $\Sigma'$ " + " means that the plane of photon polarization is perpendicular to the plane of the reaction of the $\pi$-meson photo-production [8]. For the first case of the crystal orientation, which was described above in subsection 3 the plane of photon polarization coincides with the crystal plane, which is shown on the Fig.2. In the axial case described in the subsection 3 in the second part, the plane of the photon polarization is perpendicular to the plane, which is created by the electron beam direction and the crystal axis.

4. For obtaining real spectra of photon energy and polarization it's necessary to take into account the multiple scattering of relativistic electrons in the crystal matter. If electron momentum and atomic row or plane form the angle $\theta$ much larger than middle square angle of multiple scattering, then the spectra averaging over the electron momentum divergence, stipulated by multiple scattering [12] is ordinary used. In the opposite case if angle $\theta$ is smaller than middle square angle of multiple scattering, we must take into account real angular distribution of multiple electron scattering in a crystal target. Apparently the most convenient solution of this problem is to obtain the bremsstrahlung cross section in the high-energy approximation [13] and calculate spectra of photon energy and polarization. In this case the potential may be presented as a single atomic potential in the region of small impact parameters plus averaged string or plane potential in the region of large impact parameters.

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## ПОЛЯРИЗАЦИЯ ЖЕСТКОГО ТОРМОЗНОГО ИЗЛУЧЕНИЯ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОНОВ В КРИСТАЛЛЕ

***С.В. Касьян, В.Л. Мороховский***

Приведены результаты измерения поляризации высокоэнергетичного тормозного излучения релятивистских электронов в кристаллах. Для анализа поляризации фотонов использована асимметрия выхода фоторождения $\pi$-мезонов на протоне. Приведены асимметрии выходов фоторождения $\pi$-мезонов тормозными фотонами с енергией $E_\gamma = 700$ МэВ, генерируемых электронами с энегией $E_{e^-} = 800$ МэВ в кристаллических мишенях $Si$ с толщинами 120 и 30 мкм. Исследованы свойства высокоенергетичного тормозного излучения в кристаллах в случаях, когда пучок электронов ориентирован под малым углом относительно оси кристалла $\langle 111\rangle$ и плоскости кристалла (110).

## ПОЛЯРИЗАЦІЯ ЖОРСТКОГО ГАЛЬМОВОГО ВИПРОМІНЮВАННЯ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОНІВ В КРИСТАЛІ

***С.В. Кас'ян, В.Л. Мороховський***

Приведено дані вимірювання поляризації високоенергетичного гальмового випромінювання релятивістських электронів в кристалах. Для аналізу поляризації фотонів використана асимметрія виходу фотонародження $\pi$-мезонів на протоні. Приведено асиметрії виходів фотонародження $\pi$-мезонів гальмовими фотонами з енергією $E_\gamma = 700$ МеВ, які генеруються електронами з енегією $E_{e^-} = 800$ МеВ в кристалічних мішенях $Si$ з товщиною 120 та 30 мкм. Досліджено властивості високоенергетичного гальмового випромінювання в кристалах у випадках, коли пучок електронів орієнтований під малим кутом відносно вісі кристалу $\langle 111\rangle$ та площини кристалу (110).