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# COHERENT TYPE-B $e^+e$   PAIR PRODUCTION BY PHOTONS IN A CRYSTAL

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*An overview of theoretical and experimental studies of the coherent type-B $e^+e^-$-pair production by photons in aligned crystals performed at Nuclear Physics Institute at Tomsk Polytechnic University is given.*

## INTRODUCTION

When relativistic particles interact with aligned crystals, most of the physical processes acquire new features compared to amorphous targets. This is caused by the periodic arrangement of crystal atoms. One of manifestations of these features is the occurrence of coherent effects in the course of interaction of high-energy photons and charged particles with crystal targets, which is caused by quantization of the momentum transferred to the crystal. This results in coherent peaks in the cross-section, as a consequence of summation of pair production amplitudes on individual atoms with regard to the periodic ordering of the crystal lattice, which is common for such processes.

At present, coherent processes are classified into two groups: types A and B. This classification was introduced by Saenz and Uberall [1]. A type-A process develops when the angle between the initial particle momentum and the crystallographic axis is quite large and the particle moves at a small angle with respect to the crystallographic planes. In this case, the contribution comes from the reciprocal lattice vectors lying in the plane virtually normal to the direction of particle incidence. A type-B coherent effect occurs when the initial particle momentum is parallel to the crystal axis. In the latter case, it is the reciprocal lattice vectors parallel to the axis, which contribute to the process.

Coherent type-A ptotoproduction of $e^+e^-$ pairs in a crystal was predicted comparatively long ago [2, 3] and was experimentally observed for the total (integral over the electron and positron outgoing angles) yield of $e^+e^-$ pairs [4]. Within recent years, the interest in coherent photoproduction of electron and positron pairs in crystals is focused on type-B photoproduction (CPP-B). It results when the initial photon momentum is parallel to the crystal axis [5, 6] and is manifested in a number of coherent peaks in the dependence of the $e^+e^-$ production cross section on the initial photon energy and the produced electron and positron emission angles. Coherent Type-B pair production occurs at the photon energies up to 1 GeV.

CPP-B was theoretically predicted in [5, 6]. The first experimental indication of the existence of a type-B process was obtained in Yerevan [7] for the total yield of $e^+e^-$ pairs (integral over the electron and positron emission angles and the positron energy). A team of Tomsk researchers [17] measured the photoproduction of symmetrical e+e- pairs (with the energy of the resulting electron being equal to that of a positron). In 1998, a group of collaborators from NPI at TPU , Hiroshima University, and the Institute for Nuclear Research (Tokyo) working at the Tokyo synchrotron measured the yield of "narrow" (strongly collimated) $e^+e^-$ pairs from a silicon crystal oriented along the <100> axis [9, 10] using a bremsstrahlung photon beam. The experiment clearly demonstrated an increase in the coherent peak brilliance up to 200%, which qualitatively agrees with our predictions [11, 12, 21].

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Comparing the experiments on the studies of CPP-B conducted in Yerevan, Tomsk and Tokyo, we may conclude that in the former two cases the enhancement of the coherent peak with respect to the incoherent background was on the order of 10%, while in the latter it was as high as 200%.

It is worthy of mention that when a photon enters a crystal parallel to the axis, a different mechanism of $e^+e^-$ pair production is possible, i.e., their production by photons in a continuous crystallographic axis potential [14–16], whose theory was designed in a quasiclassical approximation [16]. It is critical to emphasize that this process occurs at the photon energies $\omega \geqslant 10$ GeV, which is by far higher than the energies under consideration.

In what follows, we discuss the experiments on CPP-B performed at the Tomsk synchrotron "SIRIUS" [8] and new theoretical results of our team [11, 12, 21].

## 1. TOTAL CROSS SECTION OF COHERENT TYPE-B PHOTOPRODUCTION OF SYMMETRICAL $e^+e^-$ PAIRS FROM CRYSTALS

The differential cross section of a coherent process in a crystal is represented as a sum of the coherent $d\sigma_{\text{coh}}$ and incoherent $d\sigma_{\text{incoh}}$ contributions [2, 3]

$$d\sigma = d\sigma_{\text{coh}} + d\sigma_{\text{incoh}}. \tag{1}$$

The coherent contribution into the cross section is given as follows:

$$d\sigma_{\text{coh}} = d\sigma_1 \exp(-q^2\bar{u}^2)|S(q_\parallel)|^2 I(q_\parallel). \tag{2}$$

(Use is made of the $\hbar = c = 1$ units). Here, $d\sigma_1$ is the differential cross section of photoproduction of an $e^+e^-$ pair on and individual crystal atom, $\exp(-q^2\bar{u}^2)$ is the Debye–Waller factor including thermal vibrations of crystal atoms, $\boldsymbol{q}$ is the momentum transferred to the crystal, $q^2$ is the squared transferred momentum, $q_\parallel$ is a component of the transferred momentum parallel to the crystal axis, $\bar{u}^2$ is the r.m.s. amplitude of thermal vibrations of atoms with respect to the equilibrium positions, $S(q_\parallel)$ is the structure factor of a crystal, and $I(q_\parallel)$ is the interference multiplier responsible for coherent effects. The appearance of the interference multiplier is a consequence of summation of the amplitudes from individual atoms, taking into account the periodic arrangement of atoms in a crystal, common for all coherent processes. This is due to the fact that as the photon energy is increased, $q_\parallel$ is decreased and, therefore, larger longitudinal distances $l_\parallel = 1/q_\parallel$ contribute to the process cross section.

The incoherent contribution to the cross section has the form

$$d\sigma_{\text{incoh}} = d\sigma_1 N\left[1 - \exp(-q^2\bar{u}^2)\right]. \tag{3}$$

Let us consider the kinematics of CPP-B in a crystal. In the case of symmetrical $e^+e^-$ pairs (the energy of the resulting positron is equal to that of an electron), the law of energy conservation may be written as

$$\omega = \sqrt{(\boldsymbol{p}_+)^2 + m^2} + \sqrt{(\boldsymbol{p}_-)^2 + m^2} = 2\sqrt{p^2 + m^2}. \tag{4}$$

Here $\omega$ is the photon energy, $m$ is the mass of electron at rest, $\boldsymbol{p}_+$ ($\boldsymbol{p}_-$) is the momentum of the positron (electron) produced, with $p = |\boldsymbol{p}_+| = |\boldsymbol{p}_-|$. The momentum transferred to the crystal will be given by

$$\boldsymbol{q} = \boldsymbol{k} - (\boldsymbol{p}_+ + \boldsymbol{p}_-) = \boldsymbol{g}, \tag{5}$$

where $\boldsymbol{g}$ is the reciprocal crystal lattice vector. Upon simple rearrangements, from Eqs. (4) and (5) we find the photon energy at which a coherent peak results

$$\omega = \sqrt{(\boldsymbol{k} - \boldsymbol{g})^2 + 4m^2} = \sqrt{\left(\omega - g_\parallel\right)^2 + g_\perp^2 + 4m^2}. \tag{6}$$

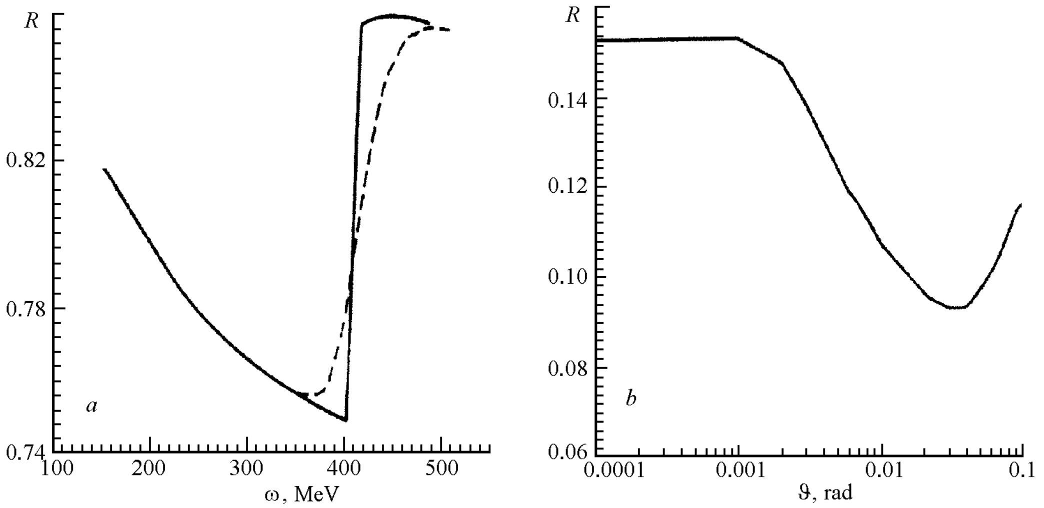

Fig. 1. Coherent effect for $e^+e^-$-pair production in a Ge crystal.

Considering that the transverse component of the reciprocal lattice vector $\boldsymbol{g}_\perp$ becomes zero (coherent type-B process), after simple rearrangements we obtain an expression for the photon energy at which a coherent maximum results

$$\omega = \omega_n = \frac{4m^2 + g_\parallel^2}{2g_\parallel}, \qquad g_\parallel = g_n = \frac{2\pi n}{d}, \qquad n = 1, 2, 3, \ldots \tag{7}$$

Here $d$ is the lattice constant for the crystal axis (crystallographic axis has a certain structure where one can identify a "unit cell" whose replication gives us the entire axis). In what follows we will refer to the size of this cell as the lattice constant of the crystal axis. Due to the presence of the Debye–Waller factor including thermal vibrations of the lattice atoms into consideration, the value of $n$ has an upper bound, $n \leqslant 8{-}10$, hence $g_n \ll m$. In this case Eq. (7) takes the form

$$\omega = \omega_n = \frac{md}{\pi n}, \quad n = 1, 2, 3, \ldots \tag{8}$$

Integrating the differential cross section with respect to $d\sigma$ over the electron and positron outgoing angles, we may arrive at the differential cross section $d\sigma/d\varepsilon_+$. This manipulation results in a standard formula cited in a monograph by Ter-Mikaelyan [2], where it is suffice to assume the incident photon angle with respect to the crystal axis to be zero, $\vartheta = 0$.

For the preparation of experiments on coherent photoproduction of $e^+e^-$ pairs from germanium and silicon crystals and interpretation of the data obtained at the Tomsk synchrotron "SIRIUS" [17], a number of numerical calculations have been carried out whose results are presented below. Figure 1,$a$ shows the cross section of coherent photoproduction (differential with respect to the resulting positron energy) of symmetrical $e^+e^-$ pairs in a germanium crystal, oriented along the <111> axis with respect to the photon beam at an angle $\vartheta$, versus that in an amorphous target of the same thickness ($\varepsilon_- = \varepsilon_+ = \omega/2$, $\vartheta = 0$ is shown by the solid line, and $\vartheta = 5$ mrad – by the dashed line)

$$R = \frac{d\sigma/d\varepsilon_+}{N\sigma_1/d\varepsilon_+} = \frac{d\sigma_{\rm coh}/d\varepsilon_+ + d\sigma_{\rm incoh}/d\varepsilon_+}{N\, d\sigma_1/d\varepsilon_+}.$$

The position of the maximum in the energy dependence of the cross section is described by Eq. (8).

In order to observe the effect experimentally, it is necessary to pre-estimate the requirements on the crystal alignment precision. To this end, we performed the calculations of the orientation dependence (OD) of the ratio of the coherent contribution to photoproduction of $e^+e^-$ pairs in a crystal to that in an amorphous target of an

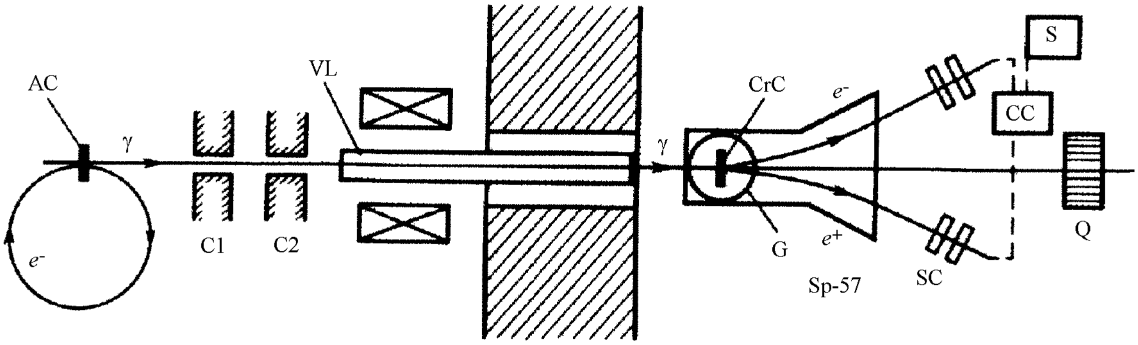

Fig. 2. Layout of the experiment.

equivalent thickness on the incident photon angle $\vartheta$

$$R_1(\vartheta) = \frac{d\sigma_{\text{coh}}/d\varepsilon_+}{N\, d\sigma_1/d\varepsilon_+}.$$

The calculations results for the germanium crystal <111> at the photon energy $\omega = 400$ MeV in the vicinity of the coherent peak $n = 1$ are presented in Fig. 1,*b*. It is evident from the figure that the coherent effect may be observed in a wide range of incoming photon angles with respect to the crystal axis. The precision of alignment should be no worse than $\Delta\vartheta \sim 10$ mrad.

## 2. EXPERIMENT

To measure the CPP-B cross section of symmetrical $e^+e^-$-pairs in silicon and germanium crystals, an experimental setup was designed on the basis of the SIRIUS synchrotron at NPI, TPU, Tomsk.

The experimental layout is given in Fig. 2. The electrons were accelerated to the energy $E = 900$ MeV and were incident on an amorphous Ta converter (AC) 0.88 mm in thickness. The beam of bremsstrahlung, after passing through two collimators (C1 and C2) with the aperture $0.2 \times 0.2$ mrad collided with a crystal converter (CrC). The crystal was fixed in a two-coordinate goniometer (G) located between the poles of a pair magnetic spectrometer Sp-57. The pairs thus produced were detected by the telescope of a scintillation counter (SC) and then fed into a set of coincidence counter (CC) and a scaler (S). It should be underlined that the procedure of crystal alignment on the photon beam is a time-consuming process. This is due to a large width and monotonic character of the orientation dependence of the $e^+e^-$-pair yield on the angle $\vartheta$ (see Fig. 1,*b*). At this stage of measurements we, therefore, restricted ourselves to the crystal-axis alignment with respect to the photon-beam direction to an accuracy of $\Delta\vartheta \sim 5$ mrad using optical methods. The energy range of the detected gamma-quanta was $\omega = 40{-}900$ MeV. The energy resolution was as high as 2%. The results of the $e^+e^-$-pair yield measurements were normalized against the quantometer (Q) readings. The setup allowed a count of approximately 50 symmetrical pairs per second at the e-beam current $I = 10^{10}$ e/s.

The experiment resulted in the relation $R_{\text{exp}} = Y_{111}/Y_{\text{r}}$ being determined, where $Y_{111}$ ($Y_r$) is the $e^+e^-$-pair yield from an aligned crystal (misaligned by the angle 2.5°). The relation $R_{\text{exp}}$ measured [17] for the<111> Ge crystal is presented in Fig. 3,*a*. The thickness of the Ge crystal used in the experiment was 0.18 mm, and the alignment precision was about 5 mrad. The results of the experiment agree qualitatively with the theory (considering the precision of the target alignment and the energy resolution of the experimental setup) and are indicative of the existence of the coherent type-B effect for photoproduction of symmetrical $e^+e^-$-pairs in the crystal. The position of the energy maximum of the photoproduction cross section agrees with the calculation $\omega_{\max} \simeq 400$ MeV.

We also conducted an experiment [17] on detection of the coherent type-B effect in a silicon crystal oriented

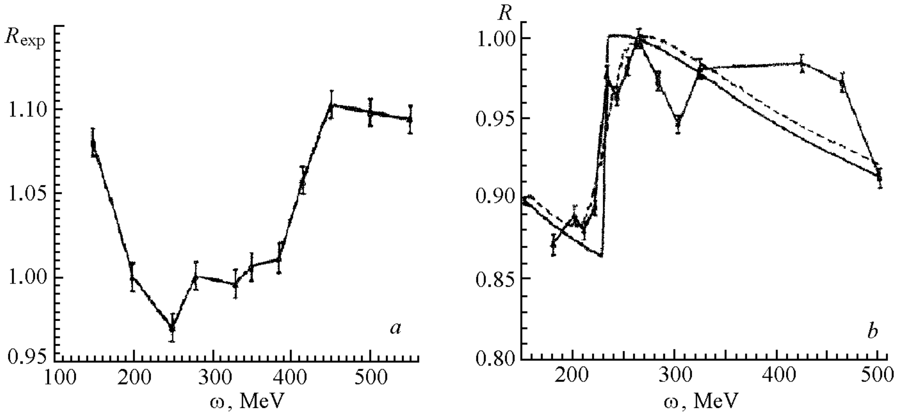

Fig. 3. Ratio of the Ge <111> (*a*) and Si <100> (*b*) cross-sections to that of an equivalent amorphous target versus photon energy.

by the <100> axis. The silicon crystal thickness was 0.35 mm and the precision of alignment was the same as in the previous experiment.

The results of the experiment and the theoretical calculations are shown in Fig. 3,*b*, presenting the relation R versus photon energy. The theoretical curves were calculated for two orientations of the crystal: $\vartheta = 0$ and 5 mrad. The experimentally measured value of the photon energy, at which a coherent peak is observed, was $\omega_{\max} \simeq 250$ MeV, which agrees with the theoretical value $\omega_{\max} \simeq 240$ MeV (Eq. (8)) to an accuracy of 4–5%.

## 3. INCREASING THE COHERENT-PEAK BRILLIANCE UNDER STRONG COLLIMATON OF THE PRODUCED ELECTRON AND POSITRON

It was shown in the previous section that the value of the coherent effect with respect to the total CPP-B cross section was small and found to be on the order of 10%. We, therefore, tried to identify the conditions under which the coherent effect for CPP-B would be most pronounced. As shown in [11, 12], the coherent-peak brilliance (the coherent peak-to-incoherent substrate ratio) appreciably increases if we measure the $e^+e^-$-pair yield under strong collimation of the produced particles (“narrow pairs”).

Let us consider the differential CPP-B cross section under a separate crystallographic axis approximation (1D-model). The position of the coherent maximum for CPP-B in this model is determined by the formula

$$q_{\|} = \omega - p_{\|}^{+} - p_{\|}^{-} = g_n, \qquad n = 1, 2, 3, \ldots, \tag{9}$$

where $\omega = |\boldsymbol{k}|$ is the photon energy, $p_{\|}^{+}$ ($p_{\|}^{-}$) is the positron (electron) momentum projection on the crystallographic axis, $g_n = g_0 n$ ($g_0 = 2\pi/d$) is the one-dimensional reciprocal lattice vector (the component of the crystal lattice reciprocal vector, parallel to the crystal axis).

In the relativistic limit (($\omega \gg m$)), where the electron and positron emission angles are small ($\Theta_+, \Theta_- \sim m/\omega \ll 1$), Eq. (9) acquires the following form:

$$\omega - p^{+}(1 - \Theta_+^2/2) - p^{-}(1 - \Theta_-^2/2) = g_n, \qquad n = 1, 2, 3, \ldots, \tag{10}$$

where $\Theta_{\pm}$ is the electron (positron) emission angle with respect to the crystal axis. It follows from Eq. (10) that it is possible to select such values of $\omega$, $\Theta_+$, and $\Theta_-$ (or, by identifying $p^+\Theta_+$, we may obtain $\omega$ and $p^+\Theta_-$, *etc.*) at which the interference multiplier $I(q_{\|}) = N^2$ and, therefore, the differential cross section would have a sharp coherent peak.

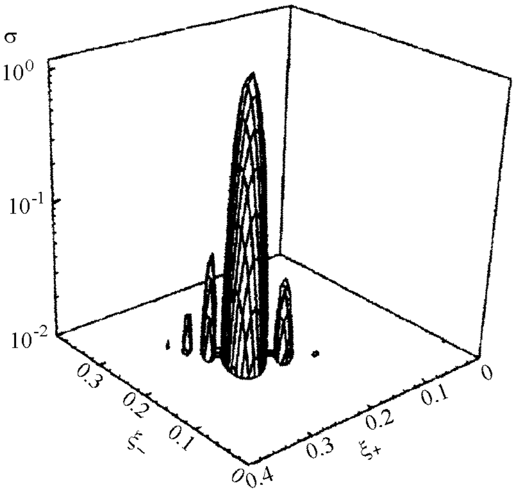

Fig. 4. Dependence of the differential cross section of coherent type-B photoproduction of $e^+e^-$-pairs in crystal on $\xi_+ = \gamma_+\Theta_+$ and $\xi_- = \gamma_-\Theta_-$ near the first coherent peak $n = 1$, $\omega = 240$ MeV. Si <100>, $N = 10^2$, $T = 273$ K, and $\gamma_+ = \gamma_- = \omega/2m$.

In order to illustrate the coherent effect in the crystal, Fig. 4 shows the dependence of the CPP-B differential cross section

$$\frac{d\sigma}{d\Theta_- d\Theta_+ d\varepsilon_+} = \frac{d\sigma_{\text{coh}}}{d\Theta_- d\Theta_+ d\varepsilon_+} + \frac{d\sigma_{\text{incoh}}}{d\Theta_- d\Theta_+ d\varepsilon_+}$$

on the electron and positron emission angles with respect to the crystal axis ($\xi_+ = \gamma_+\Theta_+$, $\xi_- = \gamma_-\Theta_-$)) integrated over the angle $\varphi$ between the electron and positron momenta $\boldsymbol{p}^+$ and $\boldsymbol{p}^-$ in the plane normal to the photon momentum. The calculation parameters were the following: crystal axis containing $N = 10^2$ atoms, symmetrical $e^+e^-$-pairs ($x = \varepsilon_+/\omega = 0.5$), Si crystal oriented along <100>, and photon energy near the first coherent peak $n = 1$ ($\omega = 240$MeV). Since the cross section is assumed to be parallel to the axis $\Theta_+ = \Theta_-$, the figure shows only the region of angles $\Theta_+ \leqslant \Theta_-$. The cross section is normalized with respect to the maximum and contains sharp peaks in accordance with Eqs. (9) and (10). Figure 4 also shows that the differential cross section of the coherent photoproduction of $e^+e^-$-pairs in a crystal may considerably exceed that on $N$ atoms in an amorphous target for a certain region of electron and positron emission angles.

In a real experiment, we may only more or less approach the conditions of Eq. (10) due to a limited angular and energy resolution of the experimental setup, which smears the sharp coherent peaks. One of the simplest ways of approximating the conditions shown in Fig. 4 may be detection of the $e^+e^-$-pairs with predetermined values $x = \varepsilon_+/\omega$ emitted at the angles smaller than a certain fixed angle $\Theta_{\text{m}}$ (collimation or correlation of the $e^+e^-$-pair momenta in the final state).

To this end, the differential cross section of CPP-B was integrated with respect to the electron and positron emission angles $\Theta_+, \Theta_- \leqslant \Theta_{\text{m}}$. The calculation results demonstrated that a more severe collimation of the resulting the $e^+e^-$-pairs (smaller $\Theta_{\text{m}}$) gives rise to a considerable (manifold ) increase in the coherent peak brilliance (the coherent peak-to-incoherent substrate ratio) compared to the yield of non-collimated $e^+e^-$-pairs.

Figure 5 shows the cross section of coherent photoproduction of symmetrical (x = 0.5) and non- symmetrical ($x = 0.5$) $e^+e^-$-pairs in Si crystal <100> with the collimation angle $\Theta_{\text{m}} = 2.0$ mrad. It is evident from the figure that when non-symmetrical "narrow" $e^+e^-$-pairs are produced, the coherent peak is shifted to the region of hard energies. It should be noted that with the constant collimation angle, $\Theta_{\text{m}} = \text{const}$, the width of the coherent peak is decreased with the decrease in the photon energy (see Fig. 5). This is accounted for by the fact that at lower

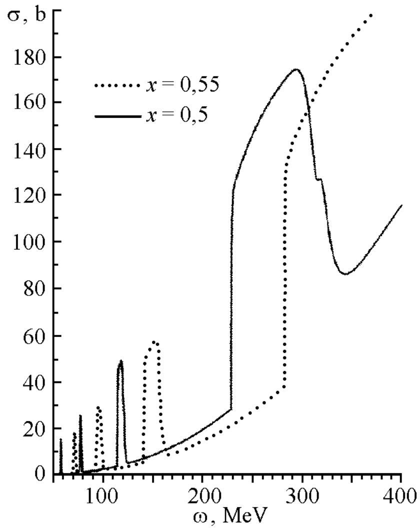

Fig. 5. Cross section of CPP-B for symmetrical ($x = 0.5$) and non-symmetrical ($x = 0.55$) $e^+e^-$-pairs in Si <100> crystal ($T = 293$ K), *versus* photon energy. $N = 10^3$, $\Theta_\mathrm{m} = 2.0$ mrad.

energies, the electron and positron are emitted at larger angles ($\Theta_\pm \sim 1/\gamma$) and, therefore, this is the case of strong collimation of secondary particles.

The total yield of $e^+e^-$-pairs, with the decreasing collimation angle, is also decreased mostly due to suppression of the incoherent part of the cross section. A smaller yield of $e^+e^-$-pairs at low collimation angles may be compensated for by an increased intensity of the initial photon beam.

## SUMMARY

The experiments conducted at the SIRIUS synchrotron at NPI, TPU have demonstrated the coherent type-B photoproduction of $e^+e^-$-pairs. Their value, however, hardly exceeded the experimental error. This ambiguous circumstance prompted us to look for the conditions, where CPP-B would be more pronounced. Based on the theoretical calculations, it has been shown [11, 12, 21] that an introduction of stronger collimation of the resulting electron and positron should give rise to an appreciable increase in the coherent peak brilliance. Further experimental studies performed on the Tokyo synchrotron [9, 10] by a joint team from Nuclear Physics Institute at Tomsk Polytechnic University, the University of Hiroshima, and Institute for Nuclear Research (Tokyo) unambiguously supported our theoretical predictions.

The limiting case of collimation of the resulting electron and positron is a coherent photo- and electroproduction of a positronium atom [18–22] (the bound state of the produced electron and positron moving in the same direction). We believe that, given the positronium atom formation, the coherent effect would be more vividly pronounced.

In [25], the authors also report a theoretical investigation of the temperature effect for CPP-B and the coherent type-B photoproduction of a positronium atom consisting in an increased brilliance of the coherent peak with a decrease in the crystal temperature.

Another line of our research is related to the theoretical study of the interaction effects between the produced electron and positron accompanied by CPP-B and in the continuos crystal axis potential. It turned out that this interaction could give rise to changing of the shape and position of the coherent peak [12, 23, and 24].

From our standpoint, a further theoretical and precision experimental investigation of the photoproduction of $e^+e^-$-pairs in matter, starting from the photoproduction threshold to hundreds of megaelectron-volts, is a very promising scope of research.

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