Coherence effect in the photoproduction of symmetric e^+e^- pairs in germanium and silicon crystals

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A coherence effect of type B has been demonstrated experimentally in the photoproduction of symmetric e^+e^- pairs in a ⟨111⟩ germanium crystal and a ⟨100⟩ silicon crystal.

Coherence effects of type B (in which the γ-ray momentum $\vec{k}$ is parallel to a crystallographic axis) in the photoproduction of e^+e^- pairs in crystals are manifested in the appearance of a distinctive structure (coherence peaks) in a plot of the pair yield against the γ-ray energy ω, as predicted in Refs. 1 and 2. Coherence peaks in the photoproduction of e^+e^- pairs arise when the momentum transferred to the crystal, $\vec{q}$, is equal to one of the reciprocal-lattice vectors $\vec{g}$. Peaks of this sort are common to many processes and occur because the amplitudes for the processes are summed over all the atoms of the crystal, whose periodic arrangement comes into play.

Let us take a brief look at the kinematics of the process. For the photoproduction of symmetric pairs (i.e., the energies of the electron and the positron are the same), in which we are interested here, we can write

$$\omega = \sqrt{\vec{p}_+^{\,2} + m^2} + \sqrt{\vec{p}_-^{\,2} + m^2} = 2\sqrt{\vec{p}^{\,2} + m^2} \tag{1}$$

$$\vec{q} = \vec{k} - (\vec{p}_+ + \vec{p}_-) = \vec{g} \ , \tag{2}$$

where m is the rest mass of the electron (or positron), $\vec{p}_+ (\vec{p}_-)$ is the momentum of the electron (or positron), and $p = |\vec{p}_+| = |\vec{p}_-|$. It follows from (2) that the energy for the occurrence of a coherence effect is at a minimum in the case $\vec{p}_- = \vec{p}_+ = \vec{p}$. Substituting $\vec{p} = (\vec{k} - \vec{g})/2$ from (2) into (1), and using $\vec{k} = \omega\vec{n}$, we find

$$\omega = \sqrt{(\vec{k} - \vec{g}) + 4m^2} + \sqrt{(\omega - g_{\parallel})^2 + g_{\perp}^2 + 4m^2} \ \ , \tag{3}$$

where $\vec{g} = (\vec{g}_{\parallel}, \vec{g}_{\perp})$ and $\vec{g}_{\perp} = 0$ (an effect of type B). It follows that the coherence peaks for a type-B photoproduction of symmetric pairs arise at the γ-ray energies

$$\omega = \omega_n = \frac{4m^2 + g_{\parallel}^2}{2(g_{\parallel})}, \ \ g_{\parallel} = g_n = \frac{2\pi n}{a}, \ \ n = 1, 2, ..., \tag{4}$$

where a is the lattice constant of the crystal. An additional condition is that the structure factor be nonzero (for the given g_n). Since an upper limit ($n \leqslant 8$) is imposed on n by the Debye–Waller factor (thermal vibrations of the crystal atoms), we have $g_n \ll m$, and the positions of the coherence peaks are given by the simple formula

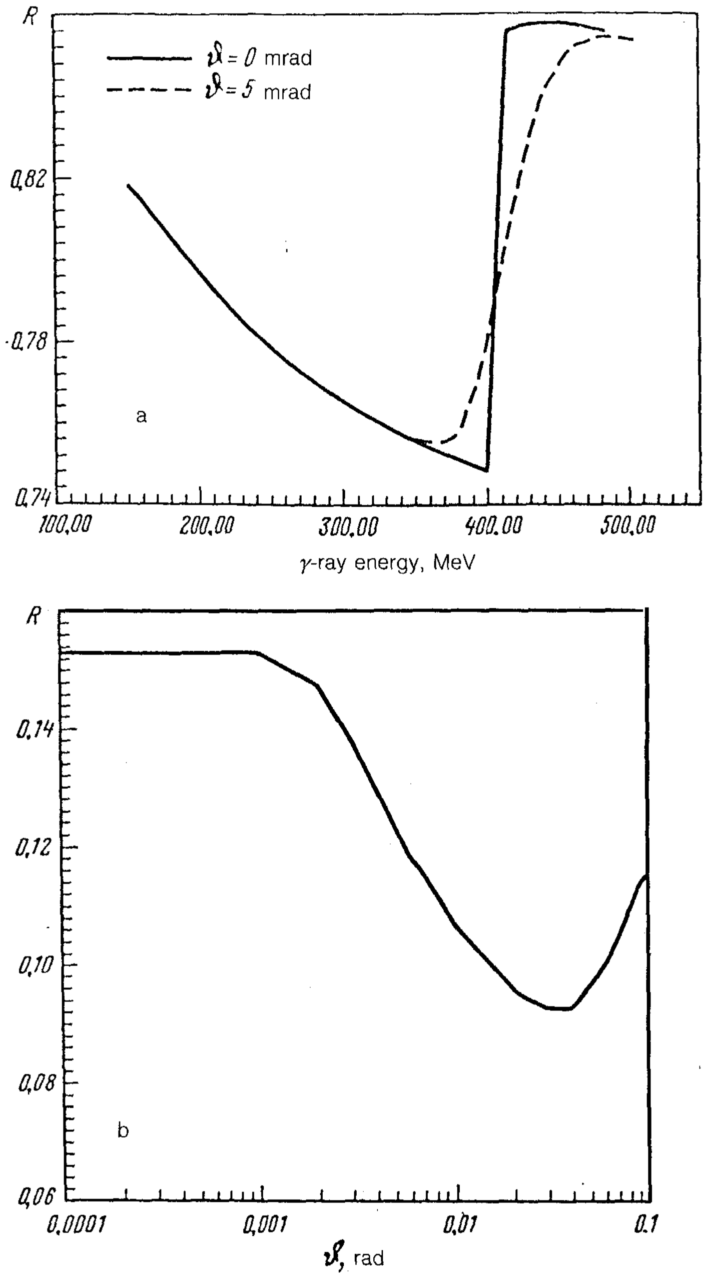

FIG. 1. Theoretical ratio of the cross sections for pair photoproduction in a Ge crystal ($T = 273$ K, $Z = 32$, $a = 5.66$ Å) and in an amorphous target. a—Plot against the γ-ray energy for two orientations, $\vartheta = 0$ mrad and $\vartheta = 5$ mrad; b—orientation dependence for a γ-ray energy $\omega = 430$ MeV.

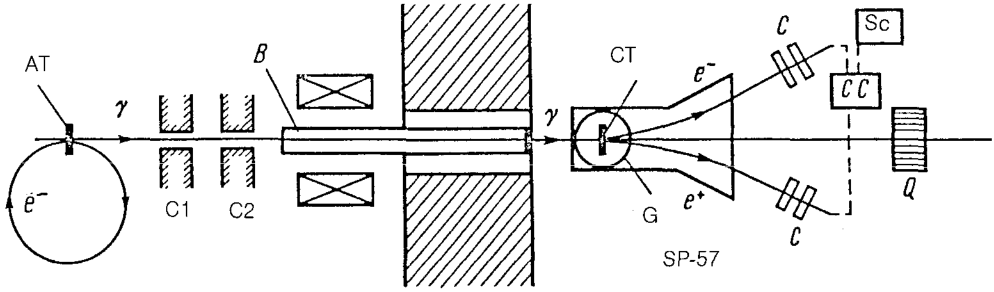

FIG. 2. Experimental layout.

$$\omega = \omega_n \simeq \frac{m^2 a}{\pi n}, \quad n = 1, 2, \ldots. \tag{5}$$

Figure 1a shows the ratio of the cross section for coherent photoproduction of symmetric pairs of type B in a germanium crystal, on the one hand, to the cross section in an amorphous film, on the other, as calculated from the standard equations for coherent pair photoproduction.[3] The positions of the peaks are described well by expression (5). Figure 1b shows the orientation dependence of the same ratio. We conclude from this figure that a coherence effect of type B in e^+e^- photoproduction in a crystal can be observed at angles between the γ ray and the axis up to $\vartheta \sim 100$ mrad.

Figure 2 shows the experimental layout. The electrons were accelerated at the Tomsk synchrotron to an energy $E = 900$ MeV. They collided with an amorphous Ta target (AT) with a thickness of 0.18 mm. After the bremsstrahlung beam passed through collimators C1 and C2, with apertures of 0.2×0.2 mrad, it struck a single crystal (CT). This crystal was mounted on an x, y goniometer (G), between the pole tips of an SP-57 double-focusing magnetic spectrometer. The pairs which were produced were detected by scintillation counters (C). The results were fed to a scalar (Sc). The operation was monitored with a quantometer (Q). The crystal was oriented with a precision on the order of 5×10^{-3} rad. The energy range over which the γ rays were detected was $\omega = 40$–900 MeV. The energy resolution was no worse than 2%. The procedure for orienting the target and the procedure for measuring the yield of e^+e^- pairs were controlled by computer. The apparatus produces a count rate on the order of 50 (symmetric pairs)/s at an electron-beam current $I = 10^{10}$ electron/s.

We selected germanium crystals (0.18 mm thick) and silicon crystals (0.35 mm) to observe the effect. These crystals were oriented with the ⟨111⟩ and ⟨100⟩ axes, respectively, in the working orientation. In the energy range near the theoretical peaks, $\omega \simeq 430$ MeV for Ge and $\omega \simeq 250$ MeV for Si, the double-focusing magnetic spectrometer operated at a high efficiency (98%).

Figure 3 shows the measured ratio of the yield of pairs of equal energy in an oriented Ge crystal to that in a disoriented crystal, as a function of the γ-ray energy. The shape of the plot in Fig. 3 agrees with the calculated results (Fig. 1a), when the precision of the target orientation is taken into account. From the experimental results

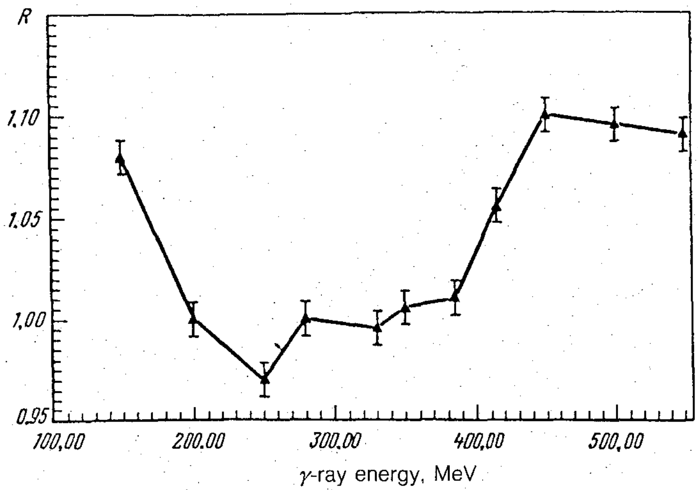

FIG. 3. Measured ratio of the yield of pairs of equal energy in an oriented Ge crystal (the ⟨111⟩ axis) and the yield in the disoriented crystal, as a function of the energy of the incident γ ray.

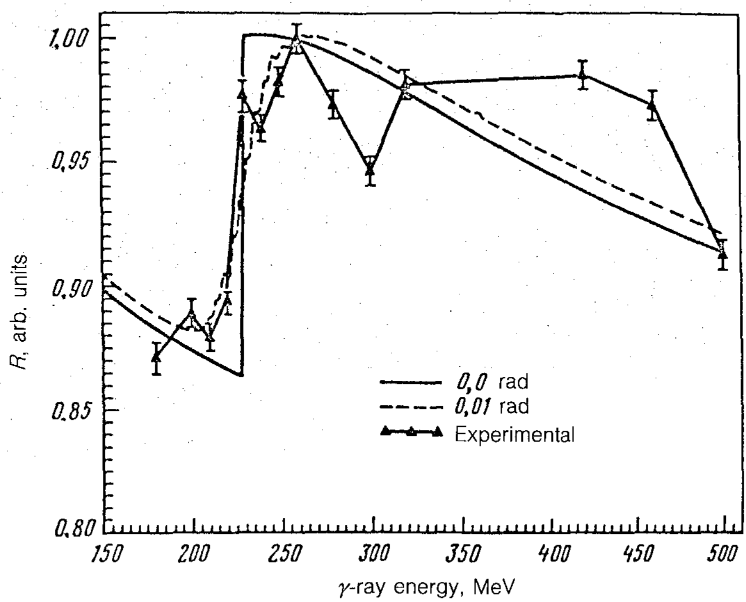

FIG. 4. Experimental and theoretical yield of pairs of equal energy in an oriented ⟨100⟩Si crystal ($T = 273$ K, $Z = 14$, $a = 5.43$ Å) versus the energy of the incident γ ray. The curves are normalized at the maximum. The theoretical curves are shown for the two orientations $\vartheta = 0$ mrad and $\vartheta = 10$ mrad.

we can draw the statistically grounded conclusion that we have experimentally confirmed that a coherence effect of type B occurs in the photoproduction of symmetric pairs in ⟨111⟩ Ge. The position of the peak in the region $\omega \simeq 430$ MeV agrees with expression (4), when we note that the lattice constant for the ⟨111⟩ axis of Ge is $a = 5.66$ Å and that the structure factor of this axis forbids peaks with $n = 2l$, were $l = 1, 3, 5, \ldots$.

The experimental data and the theoretical predictions for the Si crystal are shown in Fig. 4. Here the yield of symmetric e^+e^- pairs for the photoproduction at the ⟨100⟩ axis of Si is plotted against the energy of the γ ray (these curves have been normalized at their maximum). In the pair yield we see a peak (with a relative size $\sim 12\%$) near $\omega \simeq 250$ MeV [the value calculated from (4) is $\omega \simeq 240$ MeV]. This result also agrees with the theoretical predictions[1,2] of the size and position of the peak.

We should mention that orienting a single crystal in a bremsstrahlung beam is a rather tedious procedure. In the first stage of the measurements, we thus contented ourselves with an orientation of the axis within $\vartheta \sim 5 \times 10^{-3}$ rad. In this case we were unable to study the effect of channeling on the process (the critical channeling angle Φ for e^+e^- pairs with an energy 225 MeV in ⟨111⟩ Ge and with an energy of 125 MeV in ⟨100⟩ Si is on the order of 1 mrad). The effect of the interaction of the e^+e^- pairs in the final state with the crystal axes may change the position, size, and shape of the coherence peaks in (5), as was pointed out in Ref. 1. These changes can be seen in Fig. 4.

In future work it would be interesting to carry out an experimental study of coherent photoproduction of e^+e^- pairs in the positronium kinematics ($\vec{p}^+ = \vec{p}^-$), in which resonance effects are more obvious.[4] It would also be interesting to study the photoproduction of asymmetric pairs. Calculations predict that the peaks should shift to higher energies in this case.

Experimental indication of the existence of a coherent photoproduction of e^+e^- pairs was found previously by Avakyan *et al.*[5] in measurements of the total yield of pairs.

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[1]N. Cue and J. C. Kimball, Phys. Lett. A **57**, 1935 (1986).
[2]C. M. Darbinyan *et al.*, Preprint EFI-1007(58)-87, 1987.
[3]M. A. Ter-Mikaélyan, *Effect of the Medium on High-Energy Electromagnetic Processes*, Izd. Akad. Nauk Arm. SSR, Erevan, 1969.
[4]Yu. P. Kunashenko and Yu. L. Pivovarov, Yad. Fiz. **51**, 627 (1990) [Sov. J. Nucl. Phys. **51**, 397 (1990)].
[5]R. O. Avakyan *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **51**, 349 (1990) [JETP Lett. **51**, 396 (1990)].

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