Possibility of observing radiative self-polarization and the production of polarized e^+e^- pairs in crystals at accessible energies

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If $e^\pm$'s and γ rays are incident on curved crystals at small angles from crystallographic axes, and if the $e^\pm$'s move under planar channeling conditions, it is possible to observe a radiative self-polarization and the production of polarized e^+e^- pairs by γ rays at accessible $e^\pm$ and γ-ray energies.

Magnetobremsstrahlung and pair production in curved crystals should be accompanied by spin effects such as radiative self-polarization and the production of polarized e^+e^- pairs by γ rays.[1–5] For a long time, it was believed that the conditions for observing these effects would be best during planar channeling. However, the average field of crystal planes is not strong enough for such observations, so some corresponding experiments on quantum magnetobremsstrahlung processes at CERN were carried out in the axial case.[6] In the axial case it was not possible to observe a radiative self-polarization or the production of polarized e^+e^- pairs by γ rays.

Just recently, research on radiation processes and pair production has been undertaken at CERN[7] (see also Refs. 8 and 9) in a geometry in which the e^+ and the e^- are moving at small angles from the crystallographic axes under planar-channeling conditions (Fig. 1). In this letter we show that this geometry makes it possible to lower the $e^\pm$ and γ-ray energies required for observing spin effects in curved crystals, to levels attainable today at CERN. This lowering of the required energy is achieved by means of the strong fields of crystal axes; the planar-channeling conditions make it possible to distinguish $e^\pm$ which are polarized along the normal to the plane of their motion under channeling conditions.

We direct the Cartesian z axis along a selected family of axes at the entrance surface of the crystal, while the x and y axes are perpendicular and parallel to a family of crystallographic planes which pass through this axis [in accordance with the experimental conditions of Ref. 7 we will discuss the $\langle 100 \rangle$ axis and the (110) plane]. If channeled motion is to be achieved, the angle θ_x, at which the $e^\pm$ are incident on a plane, must not be greater than the characteristic angle for planar channeling. If the channeled motion is to be stable, the angle θ_y, at which the $e^\pm$ are incident on the axis, must be at least several times the axial-channeling angle. The precision required in the determination of the direction of the $e^\pm$ momentum and the orientation of the crystal was achieved in the experiments of Ref. 7.

The interference of the amplitudes for processes in fields of different crystallographic axes has attracted much interest.[7–9] In order to study a wide range of the angle θ_y, including the region in which this interference becomes important, it is necessary

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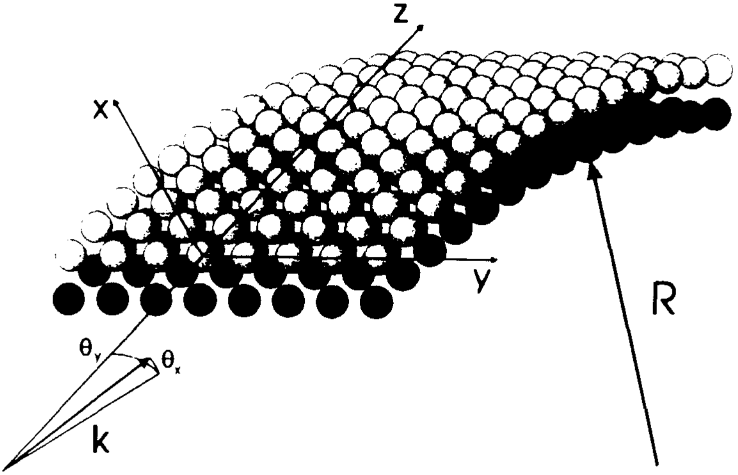

FIG. 1. Geometry of the incidence of the $e^{\pm}$ and γ ray on curved crystallographic axes and plane. In this geometry, it is possible to observe a radiative self-polarization and the production of polarized e^+e^- pairs by γ rays at accessible energies. At the end face of the crystal, the crystal axis is parallel to the z axis, and the crystal plane is parallel to the yz plane. The angle $\theta_x(\theta_y)$ is the angle at which the $e^{\pm}$ or γ with a momentum **k** is incident on the plane (axis). When the crystal is curved in the xz plane, the polarization of the channeled $e^{\pm}$ is normal to the plane parallel to the x axis and the vector **k**.

to carry out calculations from the general semiclassical equations for the probabilities for radiation and pair-production processes.[10] We have developed an effective method for carrying out such calculations.

To demonstrate the possibility of observing radiative self-polarization, we consider the emission of channeled e^+'s with an energy $\epsilon_+ = 150$ GeV. We start with the probabilities for emission with and without a flip of the projection of the e^+ spin onto the normal to the plane of its motion under planar-channeling conditions. We integrate these probabilities over the momentum directions of the photons. We calculate the spectral variation of the polarization of the e^+ after the emission of a photon of energy ω (we are setting $\hbar = 1$) and that of the emission intensity (Fig. 2). This calculation is carried out for the cases in which the e^+ is incident in the (100) plane on the Ge $\langle 100 \rangle$ axis at angles of 100 and 300 μrad at $T = 100$ K. The radius of curvature R of the crystal in the xz plane, normal to this family of planes, is 50 cm. The interference of the emission amplitudes in the fields of different crystallographic axes with $\theta_y = 0.3$ mrad and $\omega \simeq (0.6\text{–}0.9)\epsilon$ reduces the effectiveness of the production of polarized positrons in comparison with the case $\theta_y = 0.1$ mrad, in which the emission is not yet greatly different from magnetobremsstrahlung in the field of individual crystallographic axes.

The dechanneling of the e^-'s makes the self-polarization efficiency significantly lower than in the e^+ case. An alternative method for producing polarized $e^{\pm}$'s, through production by γ rays in a curved crystal, makes it possible to produce polarized e^-'s with essentially the same efficiency as in the e^+ case. Let us consider the

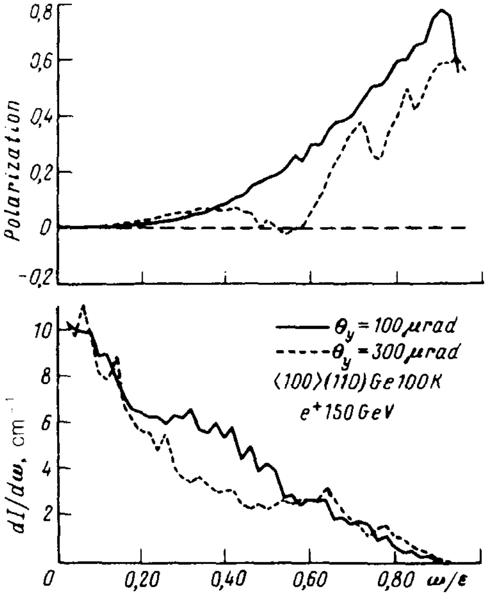

FIG. 2. Spectra of the radiation intensity and the polarization acquired during the emission of one photon by $e^{\pm}$'s incident at angles $\theta_y = 0.1$ mrad (curve 1) and 0.3 mrad (curve 2) on the $\langle 100 \rangle$ axis of Ge at $T = 100$ K.

production of channeled e^+'s with $\epsilon_+ = \omega/2$. We set the energy of the photons equal to the energy of the CERN γ-ray beam:[6] $\omega = 150$ GeV. We start from the semiclassical expression for the differential probability for pair production by an unpolarized γ ray, summed over the polarization of the e^- and integrated over its momentum[10] ($\hbar = c = 1$):

$$dW_\zeta = \frac{\alpha d^3\mathbf{p}_+}{16\pi^2\omega\epsilon_-^2} \int dt_1 \int dt_2 \{\omega^2/\gamma^2 + (\epsilon_+^2 + \epsilon_-^2)\mathbf{v}_{1\perp}\,\mathbf{v}_{2\perp} - i\omega\epsilon_-\zeta[(\mathbf{v}(t_2)$$

$$-\mathbf{v}(t_1))]/\gamma,\mathbf{n}\}\exp\left[-i(\omega\epsilon_+/2\epsilon_-)\int_{t_1}^{t_2}(\gamma^{-2} + v_\perp^2)\,dt\right]. \qquad (1)$$

Here $\mathbf{v}(t)$, $\gamma = \epsilon_+/m$, and ζ are the velocity, Lorentz factor, and polarization vector of the e^+ ($|\zeta| = 1$); $\mathbf{n}$ is the direction of the γ-ray momentum $\mathbf{k} = \mathbf{n}\omega$; $\mathbf{v}_\perp$ is the component of the e^+ velocity normal to the latter direction; and $\epsilon_- = \omega - \epsilon_+$ is the energy of the e^-. The integration is over the entire length of the e^+ trajectory.

Integrating over the e^+ emission direction, and averaging over the direction at which the γ ray is incident on the crystallographic plane, we calculate the polarization and the differential probability for the production of a channeled e^+ as a function of the angle θ_y, at which the photon is incident on the crystallographic axis. The results are shown in Fig. 3. We quickly see that the interference of the amplitudes for pair production in the fields of different axes leads to a decrease and a change in the sign of the e^+ polarization (and also of the e^- produced in a pair with it; more on this below) in the region $\theta_y > 0.7$ mrad. Although at large values of this angle the polarization rises again to 60%, the probability for pair production remains very small. This

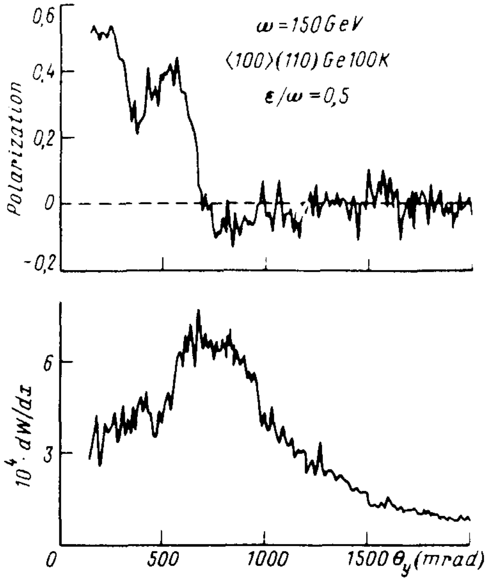

FIG. 3. Polarization and differential probability dW/dx, $x=\epsilon_+/\omega=0.5$, for the production, by a 150-GeV γ ray, of a channeled e^+ and of an e^- produced along with it in a pair. The independent variable is the angle at which the photon is incident on the ⟨100⟩ axis of Ge at $T=100$ K.

circumstance is explained on the basis that at these angles the magnetobremsstrahlung mechanism for pair production is operating in the field of the planes. Since this field is weak, there is an exponential suppression of the pair-production probability at the energies under consideration. Although the motion of the e^+ in the transition region $\theta_y \sim 0.5$–5 mrad can be described well by the average potential of the planes, the pair production (and the hard radiation) in this region are initiated primarily by oscillations of the velocity in the fields of axes (cf. Ref. 8).

The instability of the e^- motion under channeling conditions and the unfavorable shape of the potential well[1,5] make it difficult to use e^- channeling to produce polarized beams of these particles. However, this difficulty can easily be overcome by selecting e^-'s (not necessarily channeled) on the basis of the production of channeled e^+'s paired with them. In this manner one obtains polarized e^- beams with essentially the same polarization and intensity as those of the beams of channeled e^+'s.[5]

The possibility of carrying out an efficient selection of polarized $e^\pm$'s on the basis of the production of a channeled e^+'s means that wide-band γ-ray beams of fairly large divergence can be used.[5] According to Fig. 2, the magnitude of this divergence in the plane of incidence of the γ beam on the crystallographic axis can be up to 0.3–0.4 mrad. The divergence in the plane of curvature of the crystal, on the other hand, is determined exclusively by the angle of this curvature; it reaches 1 mrad even over a distance on the order of a millimeter at a radius of curvature of 1 m. Some experiments carried out at CERN[6] have used "tagged" γ-ray beams with an energy of 150 GeV and a total divergence of $2\times(20$–$30)$ μrad. Since the intensity of broad-band beams is much higher than that of tagged beams,[11] the ability to use them makes it possible to produce sufficiently intense polarized $e^\pm$ beams even at a yield $\sim 10^{-3}$ $e^\pm/\gamma$ (Fig. 3). At $\omega = 1$ TeV the yield of polarized $e^\pm$ reaches 10^{-2} $e^\pm/\gamma$, remaining in the axial case

($\theta_y < 0.1$ mrad) three times that in the planar case ($\theta_y > 0.5$ mrad). We also note that the small crystal thickness required here, which means only a negligible attenuation of the γ beam, raises the possibility of making further use of this beam in other experiments or of producting polarized $e^{\pm}$ particles in several crystals.

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