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NEW CHANNELING EFFECTS IN THE RADIATIVE EMISSION OF
150 GeV ELECTRONS IN A THIN GERMANIUM CRYSTAL

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ABSTRACT

We have observed the orientation dependence of the radiative emission of 150 GeV electrons and positrons incident at small angles with respect to the $\langle 110 \rangle$ axial direction of a thin (0.185 mm) Ge crystal. The processes are well understood, except for channeled electrons, which radiate unexpected high energy photons.

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We report on measurements of the radiation emitted by 150 GeV electrons and positrons incident along and around the $\langle 110 \rangle$ axial direction of thin germanium crystals (in this context "thin" means that the crystal thickness is much smaller than the radiation length for random crystal orientation). For axial incidence on a crystal these ultrarelativistic particles experience very strong transverse fields and quantum electrodynamics effects are expected to be important. In these conditions the relevant parameter [1] $\chi = \frac{e\hbar}{m^2 c^3} \gamma \mathcal{E}$, where γ is the Lorentz factor of the incident particle and $\mathcal{E}$ the transverse electric field derived from the continuum potential of the atomic rows, reaches values close to unity. Moreover we know from measurements performed with the same experimental set-up that a new process of e^+e^- pair creation in crystals shows up when photons of this energy range are aligned with an axial direction [2].

We observe large enhancements of the radiated energy, that extend to incidences far from the $\langle 110 \rangle$ direction (several milliradians). Electrons and positrons are seen to radiate the same amount of energy, except in the very narrow region around the $\langle 110 \rangle$ direction where their different behaviours are due to their respective channeling properties. In particular we observe quite new features in the radiative emission of channeled electrons, in conditions that had never been met in past experiments [3-6]. Our observation of an exceptionally large photon creation rate at the highest energies ($\sim 85\%$ of the beam energy) for exact alignment was not predicted by any theory of which we are aware, and then raises new theoretical questions. It could be also of special interest because of its possible application as a new photon source for particle physics.

In a previous study [6], performed with 150 GeV electrons incident on Ge crystals of thicknesses 0.4 and 1.4 mm (chosen in view of the principal aim of the experiment, the electron pair production), we observed a very large enhancement of the radiative emission. However the magnitude of the effect was such that the photon energy spectra were substantially distorted by photon multiplicity, and that most electrons were observed to radiate a very large fraction of their energy when axially aligned. We were thus prevented from observing the intrinsic shape of the photon spectra. Even the measurements of the total radiated energy were biased since successive photons were emitted by a given electron at decreasing energies and since, in contrast with ordinary bremsstrahlung in this energy range, these radiation processes are energy dependent. In brief the crystals we had used cannot be considered to be thin when axially aligned.

We have then modified our experimental set up (fig. 1) in order to make it more suitable for the measurement of large radiated energies and also for a better observation of the photon spectrum produced by a thinner crystal. The incident particles are detected by the scintillator B associated with two photomultipliers B_1 and B_2 . The scintillator T_1 has a circular aperture and is used as a veto counter to eliminate the beam halo. Then the trigger $B_1 B_2 \bar{T}_1$ rejects stray particle events and spurious events due to noise signals of B_1 or B_2 . After passing through the crystal the beam is deflected by a magnet, which allows the detection of the radiation in the photon spectrometer (lead glasses and BGO scintillators coupled to two photomultipliers). Before entering the spectrometer, the photons pass through the scintillator B_3 that is preceded by a 1 mm thick lead sheet and is used for the study of the photon multiplicity as follows : since the pair creation is independent of the photon energy above ~ 1 GeV, the probability of getting a signal in B_3 (due to a created e^+e^- pair) increases with increasing photon multiplicity. This signal can be used to discriminate the corresponding radiation events off line. It can be shown that the bin-by-bin ratio of the spectra obtained without and with the veto is a good approximation of the mean multiplicity in each energy bin.

We used two Ge crystals, the 1.4 mm thick previously used and a 0.185 mm thick crystal (both provided by Crystal-Tec, Grenoble, France). Both were cooled to 100 K. We took advantage of the very good agreement between the previous and the present data obtained with the 1.4 mm crystal to incorporate the earlier data obtained with the 0.4 mm crystal in our analysis. In principle the concept of radiation length is inadequate to characterize an energy dependent process like the energy loss by radiation for axial incidence. If however we convert into radiation lengths the mean relative energy losses $\Delta E/E_0$ (where E_0 is the incident beam energy) measured for 150 GeV electrons, one obtains $L_R = 0.97 \pm 0.03, 0.87 \pm 0.1, 1.15 \pm 0.06$ mm for crystal thicknesses $\ell = 0.185, 0.4$ and 1.4 mm, respectively. The relative constancy of L_R (which contradicts our previous statement [6] based on the 0.4 mm and 1.4 mm crystal data alone) shows that the energy dependence of the process is, at most, moderate and that using radiation lengths is still correct (within 10%). Thus we are relatively confident of our only measurement of the energy dependence of the radiation rate, which has been performed with the 1.4 mm crystal. From measurements with aligned electron beams of 70, 150 and 200 GeV we obtained radiation lengths $L_R = 1.42 \pm 0.06, 1.15 \pm 0.06$ and 1.21 ± 0.06 mm, respectively, whereas the measurements at random incidence yielded a constant value of 23.5 ± 0.4 mm, in perfect agreement with the Bethe-Heitler (BH)

theory. The much small on-axis value decreases significantly between 70 and 150 GeV and then seems to stop decreasing. This is perhaps the first observation of the beginning of the saturation effect corresponding to the maximum of the radiation intensity (minimum L_R) that is expected for values of χ around 3 according to the synchrotron radiation theory [1].

The orientation dependence of $\Delta E/E_0$ with respect to the $\langle 110 \rangle$ direction of the 0.185 mm crystal for 150 GeV electrons and positrons is shown in fig. 2. The tilt angle θ between the beam direction and the $\langle 110 \rangle$ axis has been varied in such a way that the beam direction is kept parallel to the plane making an angle of 0.1 rad with the (001) plane. The angular dependence of $\Delta E/E_0$ is clearly seen to be divided into two distinct parts, on either side of the angle $\theta_c \sim 80 \mu\text{rad}$. For tilt angles larger than θ_c , electrons and positrons radiate the same energy, that decreases so slowly when θ increases that it is still twice the random value for $\theta = 6 \text{ mrad}$. For larger θ values the angular variation of the radiated energy is governed by coherence effects and is well fitted by the Born approximation approach to coherent bremsstrahlung, that is known, however, to apply for sufficiently large θ angles [7]. For smaller angles the radiation intensity is found to be well described by the theory of Belkacem, Cue and Kimball [8] in which synchrotron-like radiation is assumed to be emitted by particles having straight line trajectories in the large transient transverse fields of the crystal atomic rows. The predictions of these two theories are shown in fig. 2.

For θ angles smaller than θ_c it seems reasonable to attribute the markedly different behaviours of electrons and positrons to channeling effects since θ_c is close to the Lindhard critical angle ($\Psi_c = 66 \mu\text{rad}$), in spite of the beam divergence of $\pm 30 \mu\text{rad}$. These features, predicted by Baier et al. [9], are qualitatively understood since electrons and positrons have distinct channeling trajectories. Electrons are attracted by atomic rows into areas where there are strong transverse fields whereas positrons are repelled from these regions. The study of the photon energy spectra will tell more about the channeling effects on the radiation emission.

To this end we show in fig. 3 the most significant spectra obtained with 150 GeV electrons (a) and positrons (b) for various crystal orientations. These are the spectra of radiated energy, which give $x \frac{d^2 N(x)}{d\epsilon dx}$ (where x is the energy in units of E_0), the energy radiated per particle, per unit energy and per unit path-length in the crystal. The width of the energy bins is 3 GeV and the first bin

corresponds to energies between 3 and 6 GeV. It must be noted that the gains of the photomultipliers suffered slight variations ($\sim 5\%$) due to the daily temperature variations. These gain shifts show up mainly in the comparison between e^- and e^+ spectra that have been obtained many hours apart. Note also that the background spectrum (obtained with the crystal out of the beam) has not been subtracted. Doing so would not make sense because of the complication of the photon multiplicity for directions close to the axis. However, as the mean radiated energy is related to the total area under the radiated energy spectrum, it is correct to subtract the background contributions, which we did. The random spectrum, where background contributes for $\sim 80\%$, is very well fitted by the BH theory, which shows that it is not distorted by photon multiplicity. The other spectra present various shapes that we will analyze now.

First, the e^- and e^+ spectra obtained for $\theta > \theta_c$ are quite similar, as shown for $\theta = 96 \mu\text{rad}$. For $\theta < \theta_c$, electrons and positrons are seen to differ also in their energy spectrum. For positrons the axial alignment seems to shift the energy spectrum toward the low energies. This behaviour can be qualitatively explained if one considers that the synchrotron-like radiation emission is reduced by channeling effects both in photon intensity and energy. Recent experiments performed with 4 to 17.5 GeV positrons incident along the $\langle 110 \rangle$ axial direction of a thin diamond crystal by Cue et al. [10] have shown the adequacy of such a theoretical description.

As for electrons, the axial alignment gives rise to a rather sharp peak located at $\sim 0.85 E_0$ that seems to sit on top of the $\theta = 96 \mu\text{rad}$ spectrum. We believe that this feature is, in contrast with the positron case, specifically due to the properties of the axially channeled electrons. In order to prove this we must show that the peak is not just due to the increase of the photon multiplicity resulting from a strong axial enhancement of the radiation (as it was the case with the 1.4 mm crystal [6]).

The multiplicity measurements with B3 show that the mean photon multiplicity in the energy range around $0.85 E_0$ is about 2 for the $\theta = 96 \mu\text{rad}$ spectrum and about 3 for the $\langle 110 \rangle$ spectrum. Moreover the low energy part of the spectra (below $\sim 0.4 E_0$) is very little affected by channeling, as well in intensity as in multiplicity (that stays around 2). Consequently the evolution of the spectrum shapes from $\theta = 96 \mu\text{rad}$ to $\theta = 0$ cannot be explained only by a distortion induced by an increasing multiplicity of the photon emission. Computer simulations have

shown that such a process would not stress but rather wash out the structures of a given spectrum, and would be unable, for instance, to account for the $\theta = 17 \mu\text{rad}$ spectrum where a shallow minimum appears at $\sim 0.6 E_0$.

We remark also that the peak does not shift when the beam incidence is varied within θ_c although its average photon multiplicity is not constant. It is again a strong indication that the peak is not due to multiplicity. The orientation dependences of the multiplicity and of the spectrum shape suggest strongly that the peak is mainly due to a high energy photon emitted by channeled electrons. This new channeling effect cannot be explained by any existing theory.

As channeled electrons are seen to contribute specifically to the radiation emission their radiated energy spectrum can be crudely estimated by subtracting the $\theta = 96 \mu\text{rad}$ spectrum, that may be supposed to represent the contribution of unchanneled electrons. We have observed that 60% of the incident electrons participate in this last spectrum (i.e they radiate more than 3 GeV), whereas this fraction goes up to 65% for the $\langle 110 \rangle$ spectrum. The radiation probability of channeled electrons appears to be much higher than 0.65 since they are only a small fraction of the incident beam. If the radiation probability is taken to be equal to unity, one deduces a channeled fraction of 10-15 %, which is quite reasonable [11] since the angular dispersion of the incident beam is not small compared with the critical angle.

It must be emphasized that the peak at $0.85 E_0$ in the spectrum of the radiated energy, due to the channeled electrons and that sits on the unperturbed contribution of the unchanneled part of the beam, has nothing to do with the peak at $0.9 E_0$ of the photon spectrum previously obtained with the 1.4 mm crystal [6]. In this last case the high energy peak was entirely due to photon multiplicity and was built up at the expense of the low energy part of the spectrum. Although the channeling contribution was much probably present in the spectrum it was overwhelmed by the radiative emission of unchanneled electrons. That explains also why the angular dependence of the radiation emission performed with the 1.4 mm crystal did not reveal any narrow channeling structure. As for positrons, for which the radiation intensity is reduced by channeling, the signature of channeling is still visible in the angular dependence of the radiation emission in this thick crystal [12].

Our main conclusion is that we have observed a very high energy peak ($0.85 E_0$) in the radiated energy spectrum yielded by aligned 150 GeV electrons in a 0.185 mm Ge crystal. The study of the photon multiplicity has shown that the peak

does not result from a pile-up effect, that would lower the low energy part of the spectrum, and the study of the orientation dependence of the spectrum area has shown that this new feature must be attributed to the axial channeling of electrons. It may seem surprising that previous studies of axial electron channeling at lower energies had not revealed this new type of radiation. That could be due to a strong energy dependence of the emission probability or even to a threshold effect and/or to the fact that the spectrometers used in those experiments were not designed to detect photons of energies so close to the incident electron energy. This new high energy channeling radiation is not understood at the moment and is under active theoretical investigation.

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FIGURE CAPTIONS

Figure 1

Schematic drawing of the experimental set-up.

Figure 2

Variation of the mean radiated energy per electron (o) and per positron (o) with the tilt angle θ with respect to the $\langle 110 \rangle$ direction of the 0.185 mm Ge crystal cooled to 100 K. The projectile energy is 150 GeV. Inset : Enlarging of the area around $\langle 110 \rangle$.

Curve 1 : Born approximation based theory of coherent bremsstrahlung.

Curve 2 : Theory of synchrotron-like radiation in strong transverse crystal fields.

Figure 3

Energy radiated per projectile, per unit energy and per unit pathlength for various incidence angles θ with respect to the $\langle 110 \rangle$ direction of the 0.185 mm Ge crystal. The projectiles are 150 GeV electrons (a) and positrons (b). The bin energies are expressed in units of E_0 , the incident energy.

FIG. 1

FIG. 2

FIG. 3