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MEASUREMENT OF THE TOTAL ENERGY RADIATED BY 150 GeV
ELECTRONS IN A Ge CRYSTAL

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ABSTRACT

We have measured the radiation emitted by 150 GeV e^- incident along the $\langle 110 \rangle$ axis of Ge crystals. The on-axis total radiated energy is 25 times larger than for non-aligned directions for 0.4 mm thick Ge. The distribution of the radiated energy versus the angle of the electron beam yields a half width much larger than the channeling critical angle. The on-axis results confirm the predictions of the crystal assisted radiation theory. The Born approximation to the coherent bremsstrahlung fits the data at large angles.

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We report on measurements of the emission of radiation by 150 GeV electrons in 0.4 mm and 1.4 mm thick Ge crystals. These experimental results are the first obtained for values of the quantum electrodynamic parameter χ of the order of a few units. For these values of χ the quantum electrodynamic reduction of the classical theory reaches a factor of few tens [1] ($\chi = \gamma \frac{\xi}{\xi_{cr}}$ where γ is the Lorentz factor, ξ the crystal electric field, and $\xi_{cr} = m^2 c^3 / eh = 1.323 \times 10^8 \text{ V/\AA}$ the critical electric field).

The present results are described in terms of the relative energy loss by radiation $\Delta E/E_0$, where E_0 is the energy of the incident electrons. When the electron beam is directed along the $\langle 110 \rangle$ axis of a 0.4 mm crystal, $(\Delta E/E_0)_{\text{Axis}}$ is measured to be 25 times higher than the calculated random value. This on-axis enhancement is compared with the predictions of the crystal assisted radiation (CAR) theory [2]. We have also measured $\Delta E/E_0$ at several incidence angles to the $\langle 110 \rangle$ axis. We compare our results with the coherent bremsstrahlung (CB) calculations. Finally we compare the relative radiation loss $(\Delta E/E_0)$ to the attenuation $(\Delta N/N_0)$ of a photon beam by pair creation in a Ge target [3]. We observe that, in the vicinity of the axis, the ratio $(\Delta E/E_0)/(\Delta N/N_0)$ is an order of magnitude larger than in random conditions.

The experiment was performed at CERN with 150 GeV e^- . At the target position, the beam angular divergence was measured to be $\pm 30 \mu\text{rad}$. For both crystals the intrinsic curvature was measured at room temperature to be $< 10 \mu\text{rad}$.

Figure 1 summarises the experimental set-up. The forward radiation was recorded by a downstream calorimeter consisting of a $10 \times 10 \times 64 \text{ cm}^3$ lead glass (~ 25 radiation lengths) and a $12 \times 12 \times 0.5 \text{ cm}^3$ plastic scintillator S_p , in front of the calorimeter, vetoing the charged particles. After passing through the crystal the electrons were deflected away from the photon detector by a magnet and directed into a $2 \times 40 \text{ cm}^2$ plastic scintillator S_e . The incident electron flux was monitored by a $1.5 \times 1.5 \text{ cm}^2$ thin plastic scintillator S_F . The experimental trigger was $S_F \cdot S_e \cdot \overline{S_p}$. In order to suppress a high energy cut-off of the produced photons, a few runs were taken with $S_F \cdot \overline{S_p}$ only. In Fig. 2 we show the

radiated energy spectra for $\langle 110 \rangle$ -aligned and non-aligned directions (background not subtracted). The non-aligned spectrum (measured at an angle of 40 mrad from the axis, and far from any major plane) is consistent with the amorphous thin-target Bethe Heitler shape. In contrast, the aligned spectrum shows several striking features. In particular, for the 1.4mm crystal, we observed that:

- the spectrum is peaked at ~ 0.9 , which means that, along an axis, an electron radiates nearly its full energy;
- there is an apparent suppression of the background in the low energy region of the spectrum.

These features suggest that each incident electron has a high probability of emitting several photons. To confirm this, a series of attenuation measurements were done with lead sheets of increasing thicknesses (.3, .8, 1.5, 3 and 6 mm) successively inserted between the crystal and S_p . This scintillator vetoes any event in which a pair is created in lead. Fig. 3 shows that the interposition of the lead absorbers leads to a drastic change in the shape of the aligned spectrum, in contrast with what one would expect from a single photon spectrum. This implies a substantial enhancement of the radiation yield for an aligned crystal. Due to the multiphoton process, the measurements do not provide direct information on the energy distribution of single photons. However the experimentally determined distribution of total radiated energy per event can be compared with theory without extracting the photon energy partition within a multiphoton event.

In Table I we give the average energy radiated by 150 GeV electrons in 1.4mm and 0.4mm thick Ge crystals for two temperatures. The large experimental uncertainty in the background measurement prevents precise determination of the radiated energies in random conditions. However, the experimental random value is consistent with the calculated value [4]. The energies radiated for $\langle 110 \rangle$ incidence are much higher and are determined with a much better precision. Consequently we compare them with calculated random values. For the crystal cooled to 100 K we obtain:

$$(\Delta E/E_0)_{\text{Axis}} = (24.7 \pm 2.0) (\Delta E/E_0)_R \quad (0.4\text{mm Crystal})$$

$$(\Delta E/E_0)_{\text{Axis}} = (13.8 \pm 0.4) (\Delta E/E_0)_R \quad (1.4\text{mm Crystal})$$

The finite thickness Δl attenuates considerably the variations of $\Delta E/(E_0 \Delta l)$ when $\Delta E/E_0$ tends to unity, its limit value. Along an axis, the quantity $L_R = \Delta l / \log(1 - \Delta E/E_0)$ is an increasing function of the crystal thickness (in an amorphous target L_R is the well-known radiation length). This fact is directly related to the decrease of the electron energy inside the crystal. Effectively the measured values of $\Delta E/E_0$ for the two crystal thicknesses have shown that in contrast to an amorphous target, the relative radiated energy per unit length $[dE/(E_0 dl)]$ in the crystal is an increasing function of E_0 and a decreasing function of the temperature.

The radiation enhancement effects for ultrarelativistic particles incident parallel to the crystal axis is predicted by CAR, which makes the premise that an aligned crystal is effectively a distribution of uniform transverse electric fields, and describes the charged particles as undergoing synchrotron-like radiation in these fields. The crystal and beam imperfections and dechanneling effects are parameterized by a path length L , over which the transverse field is effectively constant. This theory had so far been tested only with positrons and at lower energies (≤ 17 GeV) [5]. Application of CAR to the present case requires the consideration of thick target yield. This has been done by treating the crystals as a series of thin layers and assuming that no more than one photon is radiated in each layer. The results are shown in figure 3. By using the same set of parameters (equilibrium flux distribution for channeled electrons and $L = 1 \mu m$) one obtains a good agreement with the data for the two targets.

Also measured for the 1.4 mm crystal is the dependance of dE/E_0 on the angle θ between the incident beam and the $\langle 110 \rangle$ axis, and this is shown in fig. 4. We observe that :

- the radiated energy decreases monotonically with increasing θ ;
- the half width of the distribution is much larger than the calculated channeling critical angle $\psi_c = 66 \mu rad$;
- this distribution does not exhibit any particular behaviour around ψ_c . In contrast, theoretical calculations [6] predict a drastic change around ψ_c .

In the same figure we present Born approximation calculations of the CB total radiated energy [7]. The comparison between the results of this calculation (where the finite crystal thickness and the angular beam divergence are taken into account) and the experimental data shows good agreement at large angles. Note that this agreement is obtained without normalization. For small angles ($\theta < 160 \mu\text{rad}$ for Ge) the Born approximation breaks down and this is reflected by the overestimate.

In an associated experiment, we measured the pair production by photons in the vicinity of the $\langle 110 \rangle$ Ge crystal axis, where three processes may contribute: the well known Bethe-Heitler process, the coherent pair production, and a new process called the crystal assisted pair production [3]. In Ge, the attenuation of 100 GeV photons aligned with the $\langle 110 \rangle$ axis is about twice as large as for non-aligned photons. If one compares the pair production and the emission of radiation in the vicinity of the axis (up to a few hundred μrad) one observes that

$$(\Delta E/E_0)_{\text{Axis}} / (\Delta N/N_0)_{\text{Axis}} \approx 13.$$

This ratio is known to be $9/7$ for an amorphous target. It is noteworthy that this ratio is an order of magnitude higher on-axis than in random orientation.

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Thickness	0.4 mm		1.4 mm			Background
Alignment	Random	<110>	Random	<110>	<110>	
Temperature (K)	100	100	100	100	280	
$\Delta E/E_0$	0.014 ± 0.004	0.37 ± 0.03	0.050 ± 0.013	0.72 ± 0.02	0.64 ± 0.02	0.061 ± 0.006

TABLE I: Average relative energies $\Delta E/E_0$ radiated by
150 GeV electrons in 1.4 and 0.4 mm thick Ge crystals.

FIGURE CAPTIONS

- Fig. 1 Experimental set-up. C, iron collimator - I, iron wall - M, magnet - S_F , S_e , S_p plastic scintillator - L.G., lead glass - Pb, removable lead converter - T_x , crystal target system.
- Fig. 2 Radiation spectra from 150 GeV electrons aligned with the $\langle 110 \rangle$ axis of 0.4 mm and 1.4 mm thick Ge crystals at 100K, where x is the radiated energy in units of E_0 . A non-aligned 1.4 mm Ge spectrum is shown for comparison. The ordinate is N_e the number of radiation events per electron in an interval of $\Delta x = 0.02$.
- Fig. 3 Radiation spectra obtained when the $\langle 110 \rangle$ axis of 0.4 mm (a) and 1.4 mm (b) thick Ge crystals is aligned with the beam. The energy cut off at $x = 0.92$ is experimental. The effect of passing the produced photons through 1.5 and 3 mm thick Pb converters and vetoing events in which a pair is created in these converters is shown. The continuous curves are the crystal assisted radiation predictions.
- Fig. 4 Relative radiated energy ($\Delta E/E_0$) in the 1.4 mm thick Ge crystal versus the angle θ between the incident beam and the $\langle 110 \rangle$ axis. The angular scan is made in a plane containing the $\langle 110 \rangle$ axis and making an angle of 0.1 rad with respect to a $(1\bar{1}0)$ plane. The continuous curve is the CB prediction. The curve is dashed in the range where the born approximation is questionable.

FIG.1

FIG. 2

FIG.3

θ mrad

FIG.4