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**DETAILED INVESTIGATIONS OF SHOWER FORMATION
IN GE - AND W - CRYSTALS TRAVERSED BY 40 TO 287 GEV/C ELECTRONS**

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Abstract

The development of electromagnetic cascades along crystalline directions have for the first time been measured. As compared to random the number of produced particles is enhanced more than 10 times along axial directions in Ge and increasing with particle energy. The critical angle for this strongly enhanced shower formation is around 1 mrad which means that the effect could be harnessed for high-resolution gamma-ray telescopes.

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When high-energy photons ($\hbar\omega \geq 1$ GeV) penetrates an amorphous medium, the process of electron/positron pair production (PP) in the atomic fields is the major interaction process. The inverse process of PP is the emission of bremsstrahlung (BS) from electrons/positrons scattered in the atomic fields. Because of this symmetry, PP and BS are usually treated in parallel in the literature^{1,2} and cross sections only differ owing to the difference in density of states. Through a succession of these energy loss mechanisms an electromagnetic cascade is propagated, until the energies of the charged secondaries have been degraded to the regime dominated by ionization loss. The longitudinal dimension of the cascade can be characterized by the radiation

length L which is given by $L^{-1} \simeq \frac{Nr_0^2 4Z(Z+1)}{137} \log\left(\frac{183}{Z^{1/3}}\right)$ where

Z and N are target atomic number and density, respectively, and r_0 the classical electron radius. For Si, Ge and W $L = 9.4, 2.3$ and 0.35 cm, respectively (for details, see ref. 3).

If, however, the amorphous target is replaced by a single crystal, then the PP and BS spectra can be changed drastically. For certain incident directions to crystal axes or planes, coherence in successive interactions occur - resulting in interference structure of coherent bremsstrahlung (CBS)² and coherent pair production (CPP)². If for charged particles incident directions are nearly parallel to crystal axis/planes then the motion is governed by the lattice continuum potential U obtained by smearing the atomic charges along axial/planar directions - the channeling effect. Here the coherence effects are built into the motion.

In the multi-GeV region PP and BS are enhanced dramatically along axial and planar directions due to the very strong fields from aligned nuclei. These problems have been under inve-

stigations during the last few years. Theoretically different groups considered the subject^{4,5,6}. Recently Baier et al.^{7,8} developed a general theory for PP and BS in oriented crystals, which is valid for any energy and any incident angle θ to the axis. The critical angle θ_0 for this crystal effect is given by $\theta_0 = U_0/m_0 c^2$, where U_0 is the scale of the continuum potential and m_0 the electron rest mass. For $\theta \gg \theta_0$ the general theory transforms into the theory for CPP and CBS. At small incident angles θ ($\theta \ll \theta_0$) PP and BS can be described as processes in constant external fields because the gradient of the potential varies little during the so-called formation time^{5,7}. This model is called the constant field approximation (CFA).

Experimentally two different CERN groups investigated PP and BS in crystals. One experiment used a nearly parallel beam^{9,10} and the other used a broad beam together with drift chambers^{11,12} on the incident side by which a very good angular resolution is obtained. The experimental results are in good agreement with calculations based on CFA. Along crystal axes the intensity of CBS is up to two orders of magnitude higher than in amorphous targets and the CPP is enhanced by more than one order of magnitude. For CPP in axial fields there is a threshold in photon energies $\hbar\omega_{th}$ at which the yields from crystal fields equals that for amorphous foils (the Bethe-Heitler yields). From CFA⁷ it is found for close packed directions in Si, Ge and W that $\hbar\omega_{th} = 120, 50, 15$ GeV, respectively. Below $\hbar\omega_{th}$ the probability of PP in axial fields falls off exponential but the BS is still strongly enhanced.

The influence of crystalline targets on the development of showers (EMC) has been discussed by different groups¹³⁻¹⁵. For particle/photon energies $E \gg \hbar\omega_{th}$ the radiation length along a

crystal axis L_{ch} is reduced (20-50) times as compared to amorphous targets. Further on L_{ch} is energy dependent in contrast to Bethe-Heitler processes where L is constant. For particle/photon energies $E < \hbar\omega_{th}$ only the radiation is strongly enhanced so that a large number of relatively soft photons are emitted and produce a noticeable number of pairs via the Bethe-Heitler mechanism. As a result the enhanced shower development along crystalline directions can be parted up into two groups with respect to incident energies E , namely: the "hard" ones for incident energies $E \gg \hbar\omega_{th}$ and the "soft" ones with energies $E < \hbar\omega_{th}$. For the soft region the radiation lengths are somewhat larger than for the "hard" region. From this it is natural that the total number of photons N_γ in an axial shower is much larger than the total number of charged particles N_e . Baier et al.¹⁴ find that in axial cases and at high energies $N_\gamma/N_e \sim 11$ independent of incident energy so that it should be possible to measure the energy of superhard photons just by detecting the number of charged particles.

Recently we have shown in a preliminary experiment¹⁶ that the number of charged particles N_e produced in axial directions of Si-crystals is enhanced around 15 times in a 50-mm thick crystal ($\sim 1/2 L$) using 205 GeV positrons from a test beam at the CERN SPS. Unfortunately the beam contained muons which gave rise to an extended contamination of the spectra. The present paper shows the first detailed investigations of enhanced shower formation using 40 - 287 GeV/c electrons and for the first time we succeeded in getting nearly perfect W-crystals (mosaic spread $\sim 120 \mu\text{rad}$).

The experiment was performed in the upgraded North Area of the CERN-SPS. A tertiary electron/positron beam was focused to

around $\pm 30 \mu\text{rad}$. Fig. 1 shows a sketch of the experimental set-up. Through bend 1 and bend 2 the background from Dc1 and Sc1 is removed. Drift chambers (DC1, DC2) and scintillators (Sc1, Sc2, Sc3) in the incident beam were used to define the beam. The crystal was mounted in a goniometer. A 0.5 mm thick Si solid-state detector (SSD) was placed 10 cm behind the crystal to detect the charged particles. From the energy deposited in this SSD the average number of transmitted particles M can be obtained because they all deposit 145 keV on the average (the Fermi plateau)¹⁷. A magnet (bend 3) bends the charged particles into the beam dump.

In fig. 2 is shown pulse height spectra from the SSD as a function of deposited energy when 40, 149 and 287 GeV/c electrons are incident on a 10 mm (0.43 L) thick $\langle 110 \rangle$ Ge (a), a 1.7 mm (0.49 L) $\langle 100 \rangle$ W crystal (b) and a 25 mm thick (1.1L) $\langle 110 \rangle$ Ge crystal (c). In the random spectra peaks corresponding to one (the primary) and three particles are prominent. Peaks corresponding to two and four particles are also visible, here an extra δ -ray has been knocked out of the target. Along the $\{110\}$ plane (a) the multiplicity increases because of enhanced radiation emission which in turn produces more pairs through the Bethe-Heitler (BH) cross-section. The even number peaks are also enhanced because the δ -ray yield is increased when GeV electrons are incident along crystal axis or planes¹⁸, but the amount of δ -rays is only a few per cent. In the axial cases the average number of produced charged particles is enhanced dramatically. It should be pointed out that for 287 GeV/c electrons in fig. a there is a change in energy scale. By comparing the data from the 10 mm (a) and the 25 mm (c) Ge crystal it is clear that only for the thicker crystal it is possible to set a discriminator

level for the SSD so that a random direction in the Ge crystal gives practically no signals but in an axial direction nearly all particles are detected. Here it should be noted that with the present projectile energies we are in the "soft" shower region for Ge and for higher particle/photon energies, the distributions for axial alignment would result in even higher multiplicities and give a much better separation between random and aligned spectra. For Ge the maximum enhancement of pair production is around 30 whereas for the present particle energies it is below 10. For W the situation is not expected to be as favourable because here the enhancement of both radiation and pair production is only around 10. This is reflected in the spectra. Although the particle energy is far beyond the threshold energy $\hbar\omega_{th}$ (hard shower) the separation between random and aligned spectra is not obtained. Furtheron there is little difference between the 149 GeV and 287 GeV spectra, which most probable is due to a saturation of the emitted radiation over this energy range. It should be pointed out that the mosaic spread (~ 120 μ rad) is not expected to influence the results very much because the critical angle θ_0 (~ 0.8 mrad) is much larger.

From the SSD-spectra shown in Fig. 2 the average particle multiplicity M can be deduced both for axial (M_{axis}) and random (M_{rand}) directions. In fig. 3a is shown the enhancement of the multiplicity: M_{axis}/M_{rand} as a function of incident particle energy for a 25-mm thick $\langle 111 \rangle$ Ge crystal. Here it is seen that this ratio is increasing with energy as predicted. Hereby it is possible to find the energy of a high-energy photon just by detecting the number of charged particles produced when the incident direction is along a crystal axis.

In order to find the optimum crystal thickness in Ge for

which the multiplicity enhancement is maximum three different crystals were used. The results are shown in Fig. 3b from which it is seen that for Ge around 25 mm - one amorphous radiation length - is optimal and give maximal enhancement of M.

The angular dependence of the axial multiplicity is shown in Fig. 4 for Ge and W for three different particle energies. For Ge the HWHM is 0.5 mrad for 287 GeV/c and increasing with decreasing particle energy. This is in good agreement with the theory by Baier et al. from which the angular dependence should be proportional the characteristic angle $\theta_0 = 0.30$ mrad. For W the experimental HWHM is around 1 mrad and the corresponding $\theta_0 = 0.8$ mrad. For increasing incident energy ($E \gg \hbar\omega_{th}$) the angular width of the enhanced PP is predicted¹⁴ to narrow and thereby narrow the angular width of the enhanced shower formation region.

The present measurement on the dramatic enhancement of shower formation along crystalline directions introduce new and very exiting perspectives. Extrapolating from these measurements, we can envisage (light-weight) calorimeters for very high-energy electrons/positrons and gamma rays with angular acceptance of the order of one mrad. Contrary to a normal calorimeter, where 30 radiation lengths are needed to confine a TeV shower, a coarse energy resolution can be obtained from a multiplicity measurement after approximately one amorphous radiation length of crystalline converter. Such a calorimeter could advantageously be used in future high energy physics experiments¹⁴. Even more promising is perhaps the possibility to construct a compact direction-sensitive electromagnetic calorimeter for gamma-ray astronomy¹⁴. Although such a space-borne detector will have an area (a few m²) much less than the ground-based detectors in use today using either atmospheric Cerenkov light or ex-

tensive air-shower techniques¹⁹ such a detector will allow safe identification of celestial very high energy (≥ 100 GeV) gamma ray sources with significance better than the present 3-5 standard deviations²⁰. This is due to the very good hadron rejection of such a detector. While the electromagnetic-radiation length is reduced by 1-2 orders of magnitude along axial directions, the nuclear-interaction length remains unchanged.

In conclusion, the first studies of electromagnetic showers developing along axial directions in Ge and W single crystals show a drastically reduced radiation length which due to its energy and angular dependence shows interesting options for future high energy electron and photon detectors. A detailed design of such TeV detectors will, however, await new experiments and Monte Carlo calculations based on experiments, since extrapolations to very high energies inaccessible in laboratories are needed for the interpretation of TeV gamma-ray spectra. Detailed investigations of shower formations in Si and diamond crystals would be most interesting because the predicted¹⁴ maximum enhancement of PP is 80 and 160, respectively for close packed axial directions. At the same time the emitted radiation is enhanced around two orders of magnitude along axial directions. So low Z-materials seem to be preferable but only for very high energies because the χ_{th} values are in the region of (90 -150) GeV.

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Figure Captions

Fig. 1. Experimental setup.

Fig. 2. The pulse height spectrum as a function of deposited energy for the solid-state detector (SSD) behind the target. The targets were a) 10 mm thick $\langle 110 \rangle$ Ge, b) 1.7 mm thick $\langle 100 \rangle$ W and c) 25 mm thick $\langle 110 \rangle$ Ge. The incident beam energies are given in the figures. It should be noticed in fig. a that the lower energy scale corresponds to 149 GeV/c axis and the upper one to 40 GeV/c plane and 149 GeV/c random.

Fig. 3. Average number of particles M traversing the solid-state detector (SSD) behind the target. In fig. a is shown $M_{\text{axis}}/M_{\text{random}}$ as a function of beam energy for the 25 mm thick Ge. In fig. b is shown $M_{\text{axis}}/M_{\text{random}}$ for Ge as a function of crystal thickness for two beam energies.

Fig. 4. Average multiplicity M for the 25 mm thick Ge and the 1.7 mm thick W as a function of incident angle to the $\langle 110 \rangle$ axis and $\langle 100 \rangle$ axis, respectively. The beams were 287 GeV/c and 149 GeV/c and 40 GeV/c electrons.

Fig. 1

Fig. 2

Fig. 3

Fig. 4