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ENHANCED SHOWER FORMATION FOR 205 GeV POSITRONS
INCIDENT NEAR CRYSTALLINE AXES IN Ge AND Si

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Abstract

The formation of electromagnetic showers in single crystals has been investigated experimentally. The multiplicity of charged particles in the shower is deduced from the energy deposited in a semiconductor detector. The showers are found to develop much faster along axial directions than far from axes. Based on this effect, the construction of compact electromagnetic calorimeters for very high energy γ rays, using aligned single crystals as converters, is suggested.

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Electromagnetic calorimeters are widely used for detecting the energy of high-energy electrons, positrons and gamma rays. These detectors are based on the following two related processes¹: (1) High-energy electrons/positrons emit photons (bremsstrahlung) when accelerated in an external field. (2) Inversely energetic photons may convert into electron-positron pairs in such a field. The field is supplied by the atoms in the material under consideration.

These two processes combine to produce showers or cascades of electrons, positrons and gamma rays. The length scale entering this process is the so-called radiation length L_0 , given by $L_0^{-1} \approx 4Z(Z+1)Nr_0^2 \log(183Z^{-1/3})/137$, where Z and N is the atomic number and density, respectively, and r_0 the classical electron radius. As examples, we quote $L_0 = 9.4, 2.3$ and 0.35 cm for Si, Ge and W, respectively. On the average, an electron loses its energy by bremsstrahlung exponentially with depth (in units of L_0). The spectrum of the bremsstrahlung photons is in the main a ω^{-1} spectrum, where ω is the photon energy. This means that the actual energy loss fluctuates widely from the average value. Correspondingly, gamma rays have a mean-free path for conversion into electron-positron pairs which is $(9/7)L_0$. The differential pair-production probability is roughly constant so that the energy splitting between the electron and the positron can be in any ratio. In a shower, the number of charged particles will increase as a function of depth x , approximately as $\exp(x/L_0)$, until the shower maximum, where energy starts to dissipate by other processes, primarily ionization and Compton effect. Symmetry and conservation of momentum gives the shower an axis

in the direction of the primary projectile, and the shower spreads much less laterally than longitudinally. These properties about showers in amorphous materials are well known and form the basis for calorimeter design¹.

Recently, it has been demonstrated experimentally that the radiation length connected with bremsstrahlung² and pair production³ at very high energies is drastically reduced along crystal axes. The possibility of coherent action of the atoms in an aligned crystal has been known for a long time⁴. The resulting enhancement of the bremsstrahlung and pair production is primarily due to the coherent interaction with the atoms belonging to a given string/plane of atoms. It is dependent on the angle to the string or plane and the atomic density in the string or plane. According to custom, the expressions "Coherent Pair Production" and "Coherent Bremsstrahlung" will be used solely for the Born limit, where the interaction with the crystal is treated as a perturbation⁴. The new development is concerned with small angles of incidence, where the perturbation theory breaks down. When the projectile is travelling at a very small angle with respect to, for example, a string of atoms, the field from the individual atoms may, for the purpose of calculating the bremsstrahlung or the pair production, be replaced by an average field obtained by smearing the atomic charges along the string. In this continuum approximation, a particle incident at a small angle to the string experiences a very strong field (10^{11} - 10^{12} V/cm) which is macroscopic in the direction along the string. This leads to a very enhanced pair production and bremsstrahlung, as compared to amorphous targets. The enhanced yield can

furthermore be calculated in the constant field approximation (CFA). This approach exploits the fact that the transverse continuum field encountered by the projectile is essentially constant during the formation time of a produced electron/positron pair or photon. The enhanced pair production sets in abruptly near 120 and 50 GeV for, respectively, Si and Ge<110> crystals and increases to a maximum enhancement of 80 and 30 at an energy of 12 and 4 TeV for the two crystals⁵. Bremsstrahlung, on the other hand, is also enhanced at much lower energies, especially for photon energies which are small compared to the projectile energy. The characteristic angle for the constant field bremsstrahlung and pair creation is $\sim \theta_0 = V_0/mc^2$, where V_0 is the depth of potential well and m the electron rest mass. Note that this angle is energy-independent. For the Si<111> and Ge<110> axes at room temperature, θ_0 equals 0.24 mrad and 0.42 mrad, respectively. The characteristic angles in the pair production and bremsstrahlung processes are of the order of mc^2/E , which is much smaller than θ_0 . Here E is the energy of the primary photon or electron. A very high energy electron, positron or photon with an angle of incidence to the crystal axis less than θ_0 will thus develop a shower over a length much smaller than in an amorphous medium⁵. In Ref. 6, directional effects on high-energy electrons and positrons showering into a silicon crystal were seen, but the observations were interpreted as stemming from the Born-limit coherent processes.

We have investigated the shower formation in 50, 25, and 10 mm Si<111> and 10 and 5 mm Ge<110> crystals, using a beam of 205 GeV positrons with a divergence less than 0.1 mrad. The beam was

contaminated with ~30% muons, which were rejected with an electromagnetic lead-glass calorimeter. The crystals, which had a diameter of 30 and 50 mm for the Ge and Si crystals, respectively, were mounted in a remotely controlled goniometer with an angular step size of $0.01^\circ = 0.175$ mrad. In front of the crystals, a 150- μm thick Si detector of area 50 mm^2 was mounted as a beam-defining coincidence. Behind the crystals was mounted a 530- μm thick Si detector of area 450 mm^2 . This detector was used as a charged-particle multiplicity detector, as described below. The experiment was made in the H2 beam in the North Hall at the SPS at CERN.

The energy-loss spectrum of 205 GeV positrons measured with the multiplicity detector without a crystal mounted is seen in fig. 1a. The average deposited energy loss of an ultrarelativistic (minimum ionizing) particle in 1 mm silicon is around 0.36 MeV, but the most probable energy loss is only around 0.30 MeV. The energy-loss distribution is well described by the Landau distribution, an asymmetrical distribution with a tail towards large energy losses. The energy-loss distribution in fig. 1a is mainly a one-charged particle distribution, but with a small peak corresponding to three charged particles. This peak is attributed to the incident particle and a pair from a converted bremsstrahlung photon. Furthermore, there is a small background at the low energies. This background could originate from low-energy radiation in the beam or beam particles hitting the edge of the multiplicity detector.

In figs. 1b and c, the multiplicity spectra with a 5- and 10-mm Ge<110> crystal are shown. For both crystals, we present a

spectrum for 205-GeV positrons aligned with the $\langle 110 \rangle$ axis and a spectrum far (4 mrad) from the axis. The two spectra are normalized to have the same content. We note here that the spectra 4 mrad from the axis are not "true random" spectra since there is still a small influence of the crystal lattice at this angle. The horizontal scale, representing the energy deposited in the multiplicity detector, has been converted into a multiplicity scale, the deposited energy for one charged particle being known from fig. 1a. In the two "random" spectra, Landau peaks from 1, 3, 5, and even 7 charged particles are clearly resolved. This corresponds to the incoming positron and 1, 2, and 3 e^+/e^- pairs from converted photons. For higher multiplicities, the Landau distributions merge into a continuum caused by the linearly increasing width of the Landau distribution with multiplicity. We also see a small peak, corresponding to two charged particles, i.e., the primary positron and one δ ray. The background discussed above is also present. These "random" spectra correspond to average multiplicities of 2.2 and 4.2 for the 5 and 10 mm crystals, respectively. The aligned spectra in figs. 1b and c also exhibit Landau peaks for the low multiplicities, but the distributions extend to much higher multiplicities than the random spectra. The average multiplicities for the two spectra are 4.8 and 13.3, respectively. For the 10-mm Ge crystal, we see a minimum around a multiplicity of 5, indicating that the multiplicity distribution at this thickness starts to separate from the low energy background. Part of the one charged-particle Landau peak could be due to muons evading the trigger logics. Although the average multiplicity is obtained correctly from the

energy deposited in the multiplicity detector, the multiplicity distribution is not easily deduced due to the very long tail of the Landau distribution.

Summarizing all the experimental results in fig. 2, the average multiplicity for the different crystals as function of the angle to the axis are shown. The observed behavior reflects a fast decrease of the multiplicity over an angular scale of a fraction of a mrad and a slow decrease on an angular scale of a few mrad. The small angle is interpreted as the characteristic limiting angle for the constant field approach, θ_0 , whereas the large angle reflects the "normal" coherent process. It is seen that the axial multiplicity relative to the multiplicity far from the axis is larger, the thicker the crystal. This is in accordance with the exponential development of a shower before the shower maximum. The increased shower formation observed at the present energy (205 GeV) is almost entirely due to the increased bremsstrahlung along axial directions since the threshold for the increased pair production is relatively high. The measured charged-particle multiplicities along crystal axes have been compared to multiplicities obtained from a Monte-Carlo cascade program^{5,7}. Only for the 5-mm Ge<110> axis is reasonable agreement obtained, whereas for the other crystals, the calculated multiplicities are up to a factor of two higher than the experimental findings.

Random spectra are independent of the energy of the incoming particle since, as mentioned in the introduction, the shower development is energy-independent before the shower maximum. The average multiplicity in the aligned spectra is, however, in-

creasing with energy⁵ so that higher aligned-to-random multiplicity ratios can be expected for primaries with higher energy. Also thicker crystals will give higher axial-to-random multiplicity ratios because of the exponential increase in the number of particles in the shower before the shower maximum. A high axial-to-random multiplicity ratio can also be obtained from the present data by accepting only events with a high multiplicity signal. If, for example, we require for the 10-mm Ge crystal a signal in the multiplicity detector corresponding to a multiplicity larger than 19, we get a much steeper decrease with angle, as seen in fig. 3. This also results in a much higher axial-to-random multiplicity ratio of 160, but at the expense of the efficiency since only 25% of the aligned showers have a multiplicity larger than 19.

In the preceding paragraphs, we have reported on the increased shower formation of 205-GeV positrons incident on 10-50% amorphous-radiation lengths thick Si and Ge crystals. Extrapolating from these measurements, we can envisage compact (light-weight) calorimeters for very high-energy electrons/positrons and gamma rays with an angular acceptance of the order of one mrad. Contrary to a normal calorimeter, where 25-30 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 experiments⁸. Even more promising is perhaps the possibility to construct a compact direction-sensitive electromagnetic calorimeter for gamma-ray astronomy⁸. Al-

though such a space-borne detector will have an area (a few m^2) much less than the ground-based detectors in use today⁹, using either atmospheric Cerenkov light or extensive air-shower techniques, such a detector will allow safe identification of celestial very high energy (≥ 100 GeV) γ -ray sources better than the present 3-5 standard deviations. 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 Si single crystals show a drastically reduced radiation length which, due to its energy and angle dependence, shows interesting options for future high-energy electron and photon detectors. A detailed design of such TeV detectors will, however, await new experiments¹⁰ and Monte-Carlo programs, in accordance with experiments, since extrapolations to very high energies inaccessible in laboratories are needed for the interpretation of TeV gamma-ray spectra.

References

- 1) B. Rossi, *High Energy Particles*, Englewood Cliffs: Prentice-Hall, 1952, Chap.2.
- 2) A. Belkacem, G. Bologna, M. Chevallier, N. Cue, M.J. Gail-
lard, R. Genre, J.C. Kimball, R. Kirsch, B. Marsh, J.P.
Peigneux, J.C. Poizat, J. Remeillieux, D. Sillou, M. Spighel
and C.R. Sun, *Phys.Lett.B* 177 (1986) 211;
J.F. Bak, D. Barberis, T.J. Brodbeck, A.T. Doyle, R.J. El-
lison, K. Elsener, R.E. Hughes-Jones, S.D. Kolya, D. Mercer,
S.P. Møller, D. Newton, P.J. Ottewell, J.B.B. Petersen, P.
Siffert, A.H. Sørensen, R.J. Thompson, E. Uggerhøj and G.W.
Wilson, *Phys.Lett.B* 202 (1988) 615.
- 3) A. Belkacem, G. Bologna, M. Chevallier, N. Cue, M.J. Gail-
lard, R. Genre, J.C. Kimball, R. Kirsch, B. Marsh, J.P.
Peigneux, J.C. Poizat, J. Remeillieux, D. Sillou, M. Spighel
and C.R. Sun, *Phys.Rev.Lett.*58 (1987) 1196;
J.F. Bak, D. Barberis, T.J. Brodbeck, A.T. Doyle, R.J.
Ellison, K. Elsener, R.E. Hughes-Jones, S.D. Kolya, D.
Mercer, S.P. Møller, D. Newton, P.J. Ottewell, J.B.B.
Petersen, P. Siffert, A.H. Sørensen, R.J. Thompson, E. Ug-
gerhøj and G.W. Wilson, in preparation.
- 4) G. Diambrini Palazzi, *Rev.Mod.Phys.*40 (1968) 611.
- 5) V.N. Baier, V.M. Katkov and V.M. Strakhovenko, *Nucl. In-
strum. Meth.Phys.Research B* 27 (1987) 360.
- 6) R. Del Fabbro and P.G.Murtas, *Physica Scripta* 23 (1981) 690.
- 7) V.M. Strakhovenko, private communication, 1988.

- 8) V.N. Baier, V.M. Katkov and V.M. Strakhovenko, Nucl.Instrum. Meth.Phys.Research A 250 (1986) 514.
- 9) T.C. Weekes, Phys.Rep. 160 (1988) 1.
- 10) Proposal CERN/SPSC/P234, experiment NA43 (scheduled for August 1988)

Figure Captions

- Fig. 1. Deposited energy spectra in the multiplicity detector for 205-GeV positrons. Figure a is without a target, b is with a 10-mm, and c with a 5-mm Ge<110> target. In b and c are shown both a "random" spectrum (4 mrad from the axis) and a spectrum for positrons aligned with the <110> axis.
- Fig. 2. Measured average charged-particle multiplicity as a function of angle to the axis of the five crystals used. The curves are drawn to guide the eye.
- Fig. 3. Relative angular dependence of the average multiplicity for 205-GeV positrons traversing a 10-mm <110> Ge crystal. The distribution is shown for all events (triangles) and for events where a cut in the multiplicity distribution at 19 has been made (squares). The curves are drawn to guide the eye.

Fig. 1

Fig. 2

Fig. 3