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RADIATION FROM 170 GeV ELECTRONS AND POSITRONS TRAVERSING THIN Si AND Ge CRYSTALS NEAR THE <110> AXIS

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Abstract

The first results from a broad angular beam experiment on emission of high-energy photons from 170 GeV electrons and positrons are presented. The targets were 0.5 mm thick Si and Ge crystals. A dramatic enhancement in the emitted radiation is found for angles of incidence close to the <110> axis. The experimental results are compared to a constant-field cascade calculation.

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When energetic electrons or positrons penetrate single crystals close to axial or planar directions, their motion is governed by correlated scatterings on atoms in the crystal lattice. For particles of energies in the GeV regime, the resulting trajectories can be described by classical relativistic mechanics. The action of the crystal may be represented by an axial or planar continuum potential, obtained by smearing the atomic charges along strings or planes of atoms. The special case of *channeling* appears when the incident beam of particles is aligned with the crystallographic direction under consideration so closely that the flux becomes non-uniform, i.e., positively charged particles are prevented from coming close to target atoms, whereas negatively charged particles are focussed around the nuclei[1-3]. The coherence in the scattering on target atoms results in a strong enhancement of the emitted radiation as compared to the well known one-atom incoherent bremsstrahlung which is described by the Bethe-Heitler formula. The structure of *channeling radiation* is strongly connected to the form of continuum potentials but not directly connected to lattice parameters. This is in contrast to *coherent bremsstrahlung,* by which is conventionally understood the coherently magnified radiation, as obtained in the Born limit[4] and, in turn, pertaining to angles beyond the critical channeling angle. For coherent bremsstrahlung, the spectra from electrons and positrons are equal, which is not the case for channeling radiation.

For particle energies up to 10-20 GeV, the coherent part of the photon spectra only reaches up to about 20% of the particle energy, so the recoil during radiation emission can be neglected. This means that the radiation process can be described classically, and classical electrodynamics can be applied. For 1-10

GeV particles, the agreement between measured and classically calculated spectra is good[5,6]. For an introductory review of channeling and channeling radiation, see ref. 3.

For energies of incidence above 10-20 GeV, the energy of the photons in the coherent part of the spectrum can amount to an appreciable fraction of the primary energy. Consequently, the classical description breaks down and quantum electrodynamics has to be used. At these high impact energies, however, the cumbersome quantum-mechanical calculations can be simplified. For an axially channeled particle, the angular excursion is of the order of the Lindhard critical channeling angle $\psi_1 \propto 1/\sqrt{\gamma}$. This angle is large compared to the range of photon-emission angles relative to the local direction of the charged particle $\Theta \sim 1/\gamma$. Consequently, the derivative of the continuum potential experienced by the projectile varies little during coherent-photon emission, and the entire process appears approximately as in a constant electromagnetic field. This situation is analogous to emission of synchrotron radiation[7]. The ´constant field approximation´ (CFA) essentially applies up to incident angles to a crystal axis of about $\Theta_0 \equiv U_0/mc^2$, where U_0 is the depth of the continuum potential and m the electron rest mass[8]. It should be noted that Θ_0 is independent of particle energy and about 10 times ψ_1 at 100 GeV. Outside Θ_0, the first Born approximation applies (coherent bremsstrahlung)[9]. This is in contrast to the situation for lower particle energies, where the first Born approximation can be applied for angles of incidence down to ψ_1. For small angles of incidence and high energies, we are thus in a situation where the motion of the charged particle through the crystal and the radiation process are decoupled. The radiation spectrum is obtained by averaging the CFA spectrum over the field strengths met by the projectile. For angles of incidence $\psi > \psi_1$, the accessible area in the transverse plane is the entire unit cell. The particle flux is uniform, and electrons and positrons yield identical radiation spectra. On the other hand, for $\psi < \psi_1$, the flux is non-uniform. Electrons are concentrated near the atomic positions, and the radiation intensity and photon energies are higher than for positrons.

Actually, for $0 < \psi \lesssim \Theta_0$, a correction term to the CFA radiation probability has to be added[8B]. This correction, which scales with ψ^2 at each photon energy, strongly suppresses the low-energy part of the spectrum, whereas the high-energy part changes little. Correspondingly, the CFA approach with lowest-order correction is valid for a considerably narrower angular region in the soft than in the hard part of the spectrum where it is applicable to $\sim\Theta_0$.

Recently, the radiation from 150 GeV electrons and positrons traversing 1.4, 0.4, and 0.185 mm Ge around the <110> axis was studied in a parallel-beam experiment[10,11]. An unexpected peak was observed for 150 GeV electrons incident on the 0.185 mm crystal at very small angles ($<\psi_1$) to the <110> axis. This peak has been interpreted as emission of multiple photons from electrons which, due to the photon emissions, lose transverse energy in proportion to their total energy and thus become increasingly better channeled[12]. Multiple scattering is, however, opposing this ´cooling effect´.

In the present paper radiation spectra from 170-GeV electrons and positrons penetrating 0.5 mm thick <110> Si and Ge crystals at an angle of 0.1 mrad to the <110> axis are shown. At this angle, larger than ψ_1, there is no significant ´cooling effect´ as long as the particles are not channeled since the spatial density is uniform and the accessible area is the entire transverse plane. The experimental results can thus be compared in detail to a CFA calculation (with lowest-order correction)[8B], using a uniform particle flux in the transverse plane. This is in contrast to Artru[12B] who erroneously argued from the spatial density in *one* dimension (planar channeling) that there is a ´self-moderation cooling process´ for particles incident close to an axis with $\psi \gtrsim \psi_1$. At 170 GeV, one obtains ψ_1=52 μrad and Θ_0=0.53 mrad for <110> Ge, whereas ψ_1=35 μrad and Θ_0=0.30 mrad for <110> Si, both at 100K.

The experiment was performed at the CERN SPS in the West area. A broad (±0.5 mrad) tertiary electron/positron beam of 170 GeV was used in the experiment. The experimental setup (fig. 1) was used both for pair production[13] and radiation measurements. In the present experiment, there was no excitation of the tag-ging bend, and the Ω magnet was used to bend the projectiles away from the γ detector (PLUG). This detector was a matrix of lead and scintillating fibre blocks with an energy resolution of 10%. The γ detector was calibrated with tagged photons. The angular resolution of the incident charged particles was given by the multiwire and drift chambers and amounts to (20x25) $\mu\mathrm{rad}^2$ (RMS). The crystals were high-purity monocrystalline Si and Ge, with 30-mm diameter, cut perpendicular to the <110> axis. To avoid bending, the crystals were glued at one single point to a copper ring that could be mounted in a goniometer which has an angular step size of 0.01^0. The crystals were cooled to 100K by liquid nitrogen. The mounted crystals were tested for mosaic structure and bending by measuring rocking curves in a double crystal x-ray spectrometer. This procedure ensured a bending of less than 10 μrad. A final check of goniometer stability and crystal bending was performed in the off-line analysis - one of the advantages of using the broad-beam technique. The information for each particle emitting a photon and a fraction of all the incoming particles (normalization events) was stored on magnetic tape for subsequent analysis.

In fig. 2 we present photon spectra, normalized to those obtained in a random direction, for 170 GeV electrons incident on 0.5 mm Si (left) and Ge (right) crystals at angles 90-120 μrad to the <110> axis (full circles). In the case of Ge, also the background spectrum (triangles) and the random spectrum including background (squares) are shown. The background spectra have been subtracted from the aligned and the random spectra before normalization. The random spectra are obtained at an angle of 4.5^0 from the axis far away from the major planes. The error bars in fig. 2 originate from the statistical uncertainties only. Furthermore, there is an overall systematic uncertainty of about 20% on the enhancement, stemming from the statistical errors of the normalization events. This uncertainty, however, does not affect the shape of the spectra. Since the photon detector gives the sum of energies of the photons emitted by each particle, the spectra show the energy lost by the incoming particles rather than the photon spectra. As the crystal thicknesses correspond to 0.5% and 2.1% of the amorphous-radiation length, the enhancements of 40 and 20 for the Si and Ge crystals observed, respectively, imply a non-negligible probability of multiphoton emission. Furthermore, very energetic photons can be emitted, resulting in a significant change of the electron energy between photon emissions. Consequently, the data have been compared to a cascade CFA calculation, taking into account the energy loss of the projectile and emission of more than one photon. The calculation, however, does not take photon-pair creation into account. The dashed lines in fig. 2 represent the calculated CFA yields for infinitely thin crystals (including the first-order correction[8B], corresponding to ψ=0.1 mrad). The thermally averaged Doyle-Turner potential[14] is used in the calculation, with a two-dimensional vibrational amplitude of 0.077 Å for Si and 0.074 Å for Ge (ref. 14), corresponding to a temperature of 100K. The results of the cascade calculation are shown as solid curves in fig. 2. Inclusion of the cascade mainly results in a distribution peaking at a higher energy, and the largest difference between the two curves occurs at low energies, where the number of photons is highest. We see that the total radiated energy measured is about 25% lower than in the cascade calculation in both cases. The shapes of the measured and the calculated spectra also agree reasonably well, especially for Ge. For Si, however, the high-energy part of the experimental spectrum is significantly higher than calculated. This disagreement cannot be accounted for by reasonable changes in the input of the computation of the theoretical spectra since this upper end of the spectrum is very dependent on the energy of the electrons and the maximum electric field encountered by the projectiles. We note, however, that the CFA calculation with first-order correction at an angle of 0.1 mrad to the axis is expected to be less accurate for Si than for Ge due to the smaller value of Θ_0 for Si.

Finally, we compare in fig. 3 photon spectra obtained for 170-GeV positrons incident in the same angular range with the electron data. The positron spectra are identical to the electron spectra within the uncertainties since there is a normalization uncertainty for Ge of 3% and 5% for electrons and positrons, respectively, and about 7% for both electrons and positrons on Si. The fact that the positron data in both cases are higher than the electron data is considered fortuitous. The identical electron and positron spectra are in agreement with our expectations since for $\psi > \psi_1$, both electrons and positrons have a uniform flux distribution in the transverse plane, leading to the same average over the electric fields of the CFA calculation.

In conclusion, first detailed comparisons between experimental photon spectra for 170 GeV electrons and positrons incident on 0.5 mm Si and Ge crystals near the <110> axis and CFA calculations are given. Differences are of the order of 25% in the radiated energy comparable to the uncertainty in the normalization of the data. For Ge, the calculated high-energy edge of the spectrum is in very good agreement with observations, but for Si, an unexplained discrepancy exists. Better agreement has been obtained for the related process of pair production[13]. Combination of the very enhanced pair production and gamma radiation in and above the hundreds-of-GeV region leads to an increased shower formation, which promises well for applications in the construction of compact, direction-sensitive electromagnetic calorimeters for very high-energy physics and gamma-ray astronomy[16].

REFERENCES

1) J. Lindhard, K.Dan.Vidensk.Selsk.Mat.Fys.Medd. 34 No. 14 (1965)

2) E. Uggerhøj, in: *Relativistic Channeling,* eds. R.A. Carrigan, Jr. and J.A. Ellison (Plenum Press, NY, 1987)

3) A.H. Sørensen and E. Uggerhøj, Nature 325, 311 (1987)

4) G. Diambrini Palazzi, Rev.Mod.Phys. 40, 611 (1968)

5) J. Bak, J.A. Ellison, B. Marsh, F.E. Meyer, O. Pedersen, J.B.B. Petersen, E. Uggerhøj, K. Østergaard, S.P. Møller, A.H. Sørensen, and M. Suffert, Nucl.Phys. B254, 491 (1985)

6) J. Bak, J.A. Ellison, B. Marsh, F.E. Meyer, O. Pedersen, J.B.B. Petersen, E. Uggerhøj, S.P. Møller, A.H. Sørensen, and M. Suffert, Nucl.Phys. B302, 525 (1988)

7) V.B. Barestetskii, E.M. Lifschitz, and L.P. Pitaevskii, *Relativistic Quantum Theory,* Part 1 (Pergamon, NY, 1971)

8) ^{A})V.N. Baier, V.M. Katkov, and V.M. Strakhovenko, Phys.Lett. A114, 511 (1986);

^{B})V.N. Baier, V.M. Katkov, and V.M. Strakhovenko, Phys.Lett. A117, 251 (1986)

9) A.H. Sørensen, in: *Relativistic Channeling,* eds. R.A. Carrigan, Jr. and J.A. Ellison (Plenum Press, NY, 1987)

10) A. Belkacem, M. Chevallier, A. Clovvas, M.J. Gaillard, R. Genre, R. Kirsch, J.C. Poizat, J. Remeillieux, G. Bologna, J.P. Peigneux, D. Sillou, M. Spighel, N. Cue, J.C. Kimball, B. Marsh, and C.R. Sun, Phys.Rev.Lett. 54, 2667 (1985)

11) A. Belkacem, G. Bologna, M. Chevallier, N. Cue, M.J. Gaillard, 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. B177, 211 (1986)

12) ^{A})V.V. Tikhomirov, Phys.Lett. A125, 411 (1987);

[B])X. Artru, Phys.Lett. A128, 302 (1988);

[C])V.N. Baier, V.M. Katkov and V.M. Strakhovenko, Novosibirsk preprint 88-17

13) 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. Uggerhøj, and G.W. Wilson, Phys.Lett. B202, 615 (1988)

14) [A])J.U. Andersen, E. Bonderup, E. Lægsgaard, B.B. Marsh, and A.H. Sørensen, Nucl.Instrum.Methods 194, 199 (1982);

[B])P.A. Doyle and P.S. Turner, Acta Crystall. A24, 390 (1968)

15) O.H. Nielsen and W. Weber, J.Phys.C 13, 2449 (1980)

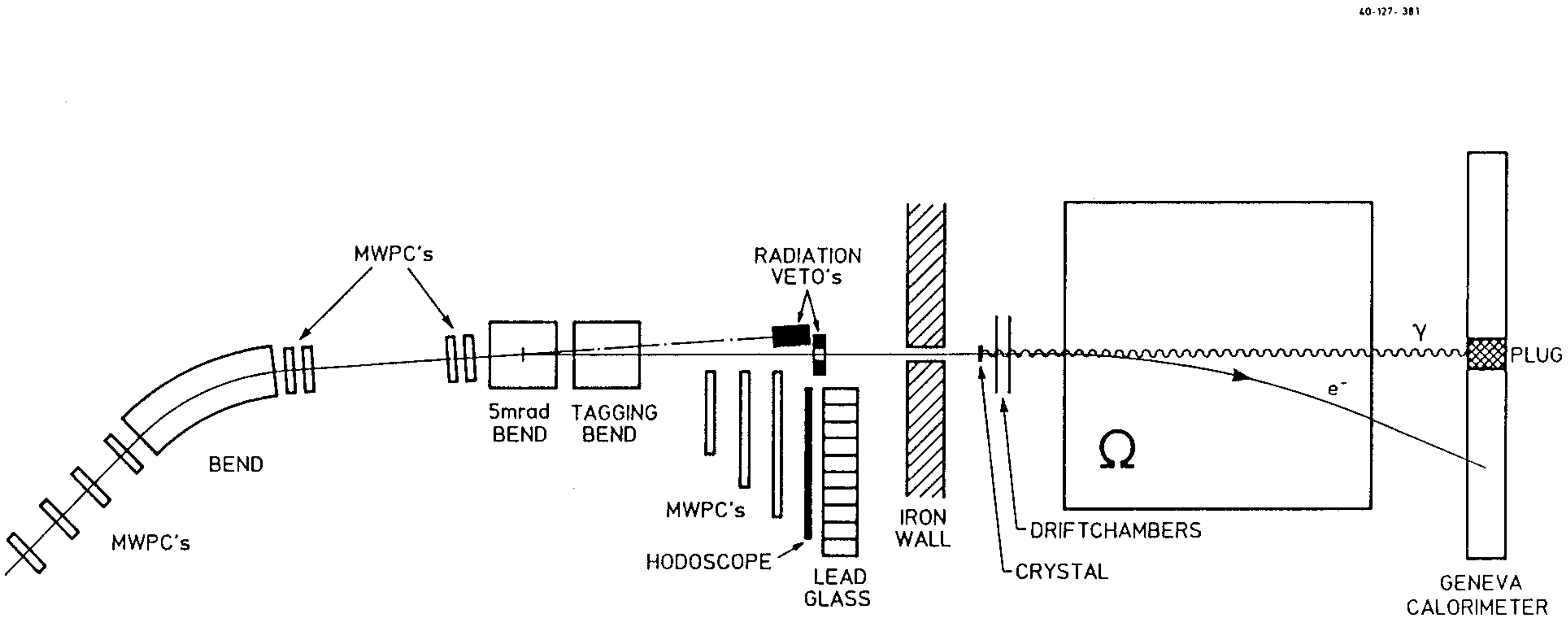
16) K. Elsener, S.P. Møller, J.B.B. Petersen, and E. Uggerhøj, submitted to Phys.Lett.B. CERN EP-preprint 88-65

Figure Captions

Fig. 1. Schematic drawing of the experimental equipment.

Fig. 2. Enhancement, relative-to-random, of gamma radiation for 170 GeV electrons incident in the angular range 90-120 μrad to the <110> axis in 0.5 mm Si and Ge, respectively (full circles). The background (triangles) and the random (squares) spectra observed are shown in the case of Ge. The dashed curves show the result of a CFA calculation valid for infinitely thin crystals, whereas the solid curves are the results of a cascade CFA calculation.

Fig. 3. Comparison of γ-ray spectra for 170-GeV electrons and positrons incident in the angular range 90-120 μrad to the <110> axis in 0.5-mm Si and Ge.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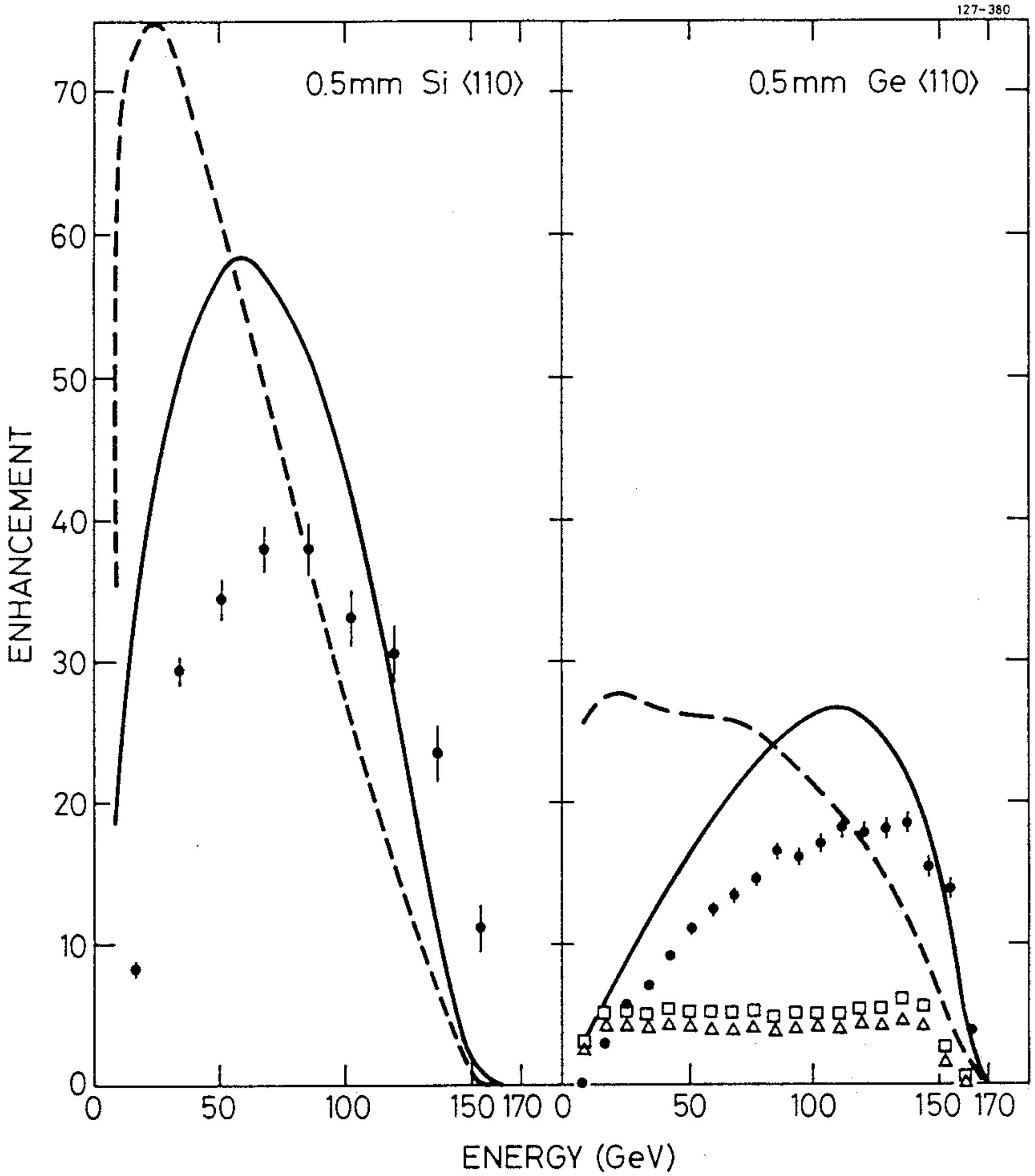
PLUG
GENEVA
CALORIMETER

Fig.1


127-380
0.5mm Si ⟨110⟩
0.5mm Ge ⟨110⟩
ENHANCEMENT
ENERGY (GeV)
0
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20
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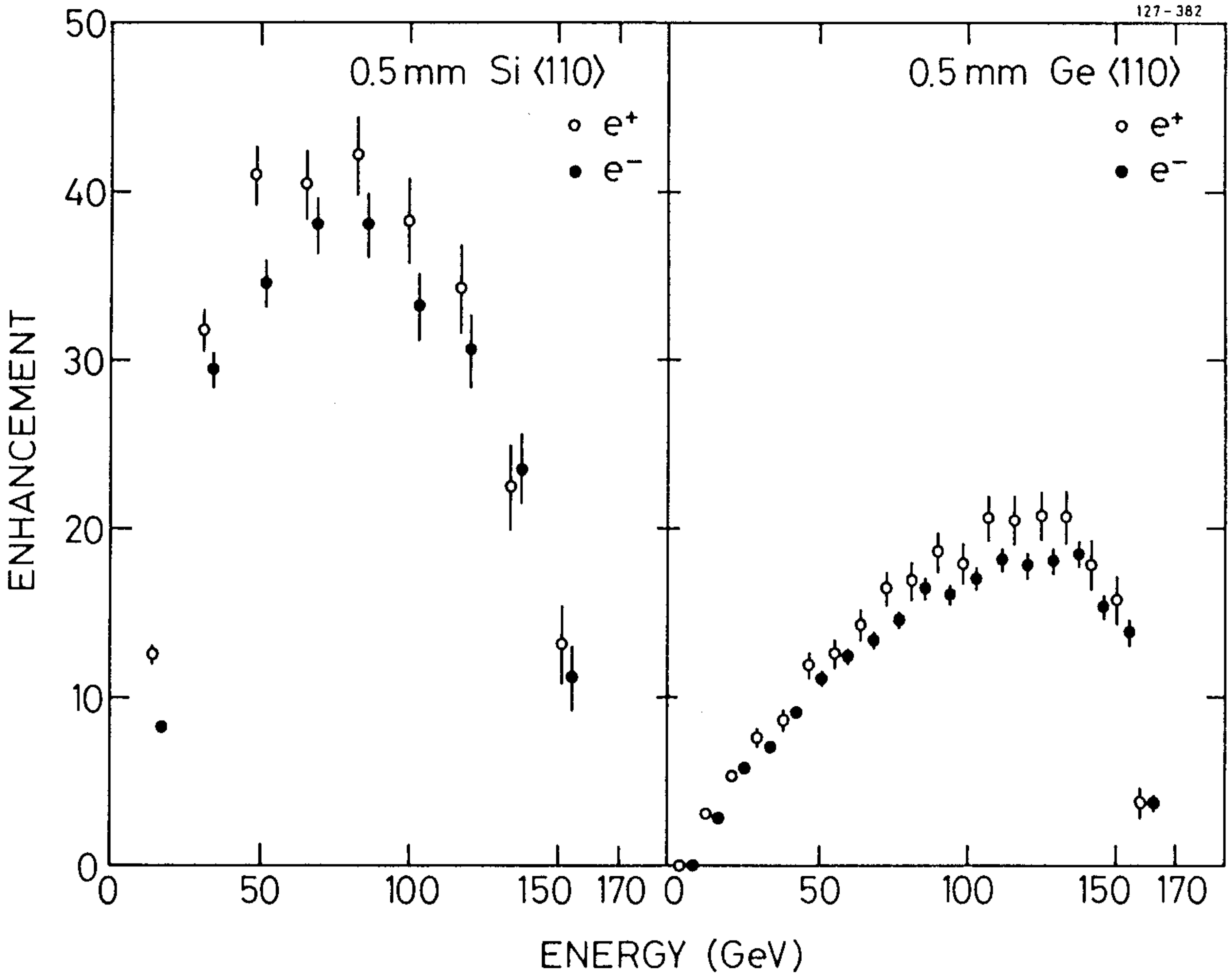
40
50
60
70
0
50
100
150
170
0
50
100
150
170

Fig.2


127-382
0.5 mm Si ⟨110⟩
○ e⁺
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0.5 mm Ge ⟨110⟩
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ENHANCEMENT
0
10
20
30
40
50
ENERGY (GeV)
0
50
100
150
170
0
50
100
150
170

Fig.3