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e^+-e^- pair creation by 40-150 GeV photons incident near the <110> axis in a germanium crystal

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Abstract

Experimental results are presented on the pair production from high-energy photons (40-150 GeV) incident on a 0.5 mm Ge single crystal around the <110> axis. The observed enhancement increases from around 1 at threshold (40 GeV) to 7 at 150 GeV for photons aligned with the axis. Also the angular dependence and the differential e^+/e^- spectra have been studied. For photons aligned with the axis, the results are in good agreement with calculations based on the constant field approximation.

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The dominant absorption process of high-energy photons in matter is pair creation. The photons turn into e^+/e^- pairs under the influence of the electromagnetic field from the target nuclei and electrons. The presence of an external field is necessary to fulfil energy and momentum conservation in the process. The pair production yield in amorphous material is given by the Bethe-Heitler value, and the photon intensity has an exponential decrease with foil thickness, characterised by the usual energy-independent radiation length.

When photons are incident on single crystals at sufficiently small angles to crystal axes or planes, the pair production probability is enhanced over the value pertaining to an amorphous target due to coherent interaction with many target atoms. The major part of the enhancement is due to coherent interaction with the atoms belonging to a given string or plane. In addition, interference peaks may show up as a result of consecutive crossings of different strings or planes. According to custom, the phrase "Coherent Pair Production" (CPP) will be used solely in the Born limit, where the interaction with the crystal is treated as a perturbation and the charged particles are represented by plane waves[1].

Conversion of photons requires strong fields. Near atomic nuclei (or electrons), the electric field is very large but extends only over distances of the order of one Angstrom. When travelling at a very small angle with respect to, for example, a string of atoms, the field from the individual atoms may in some cases be replaced by an average field, obtained by smearing the atomic charges along the string. In this continuum approximation, which is the back-bone of "channeling", a photon incident at a small angle to the string experiences a high field ($\sim 10^9$ V/m), which is macroscopic in the direction along the string. This leads to an enhanced pair production with respect to the amorphous case[2,3]. For well-aligned photons, the enhanced pair production yield can be calculated in the so-called constant field approximation (CFA). This approach exploits the fact, that the transverse field from the string is essentially constant during the formation time of an e^+/e^- pair. The energy-momentum conservation in the pair production process can be fulfilled for very high energy photons if the electron is bound in the string potential[4]. This leads to a kinematic threshold energy of $2(mc^2)^2/U_0$, where U_0 is the depth of the continuum potential and mc^2 the electron mass. The energy threshold corresponds to a few GeV for e.g. the <110> axis in germanium. Considerably higher energies are, however, required in order to compete with the incoherent pair production. Baier et al.[5] have estimated the energy at which the axial pair production equals the Bethe-Heitler value. In their calculations the threshold is given by $m^3c^4\varrho d/\hbar^2 Z\alpha$. Here ϱ is the thermal vibration amplitude, d the atomic spacing along the string, Z the atomic number and α the fine structure constant. This energy corresponds to 50 GeV for the <110> axis in a Ge crystal cooled to 100K.

The first results[6] on pair production for high energy photons aligned with the <110> axis in Ge showed severe disagreement with theory. This disagreement has later been attributed to experimental effects, and in a recent letter[7] new results, which are in good agreement with calculations, are presented. These experiments used the same technique as in low-energy channeling experiments, where a crystal is tilted in a well-collimated beam. The present experiment, on the other hand, was based on a technique developed during a series of high energy channeling experiments performed at CERN[8]. Here the crystal axis is positioned in a divergent beam, and the angle to the axis of the individual charged projectiles is measured by wire chambers. When tagged photons are produced, the direction of the photon is known from the direction of the electron within ~$1/\gamma$. This method does not depend on accurate alignment of the crystal with the beam, but on accurate off-line determination of the incident angle of the projectiles. Furthermore detailed angular scans within the beam cone can be generated in the off-line analysis.

The experiment was performed at the tagged photon facility in the upgraded West Area at the CERN SPS (Fig. 1). A tertiary electron beam of energy 170 GeV was used to produce tagged photons in the energy range 40-150 GeV. The radiator thickness was 4% of a radiation length, producing only a negligible number of multi-photon events. The angular resolution of the produced photons was approximately 20 μrad horizontally and 25 μrad vertically (RMS). The energy resolution of the tagging system was better than 0.5%. The photons were incident on a Ge crystal mounted in a goniometer. A scintillator in front of the crystal veto´ed pairs produced upstream and a scintillator behind the crystal was used for triggering. Two drift chambers close to the target were used to improve the angular resolution. The energy of the produced pair was determined by the Ω spectrometer and by the large lead/liquid scintillator calorimeter (the Geneva detector). A lead/scintillating fibre detector (plug) was used to detect forward emitted photons.

The target was a 0.5mm Ge crystal with the <110> axis perpendicular to the surface. The crystal was checked off-line for bending by x-ray diffraction. It was mounted in a goniometer with a step angle of 0.01^0 and was cooled to 100 K by liquid nitrogen.

The background of pairs produced without a target corresponds to 30% of the random yield in 0.5 mm Ge. The measured pair production yield in a random direction agreed with the Bethe-Heitler yield to better than 5%.

In fig.2 the pair production yield measured for photons incident within 250 μrad of the <110> axis in Ge is shown as a function of photon energy. The measured yield is normalised to the yield obtained in a random direction with the same crystal. Furthermore, the no-target background has been subtracted. The points are plotted at the centroid energies for the photon energy intervals 40-50, 50-75, 75-100, 100-125 and 125-150 GeV. The measured pair production yield is seen to increase drastically with energy from around 1 at 40 GeV to 7 at 150 GeV. The experimental results have been compared to a CFA calculation. The thermally averaged Doyle-Turner potential[9] is used in the calculation, with a two-dimensional vibration amplitude of 0.074 Å (ref.10), corresponding to a temperature of 100K. The yield calculated from the CFA has been drawn on top of a background of one, representing the incoherent contribution. This incoherent contribution, resulting from thermal diffuse scattering, has not been calculated. A reasonable value to be used in fig.2 is 1, as it amounts to 80-90% of the Bethe-Heitler yield in the Born limit and it accounts for the full yield at axial alignment below threshold. The uncertainty in the total yield introduced by this choice is small. A remarkable agreement between the experimental values and the calculations is seen. The results presented in fig.2 are slightly lower than the results presented in ref.7. Also our computed yield is lower than in ref.7, probably due to the use of a more realistic thermal vibration amplitude.

The angular dependence of the pair production yield is shown in fig.3 for five different photon energy intervals as indicated (the centroid energies are given in parentheses). Each point corresponds to an angular interval of approximately 0.5 mrad. At low photon energies a minimum is observed on the axis, but at high photon energies, a maximum is seen. This results from the more rapid increase with increasing energy of pair production in a constant field compared to normal CPP. In fig.3 the experimental results are also compared to calculations for the photon energies 47, 90 and 138 GeV. At large angles, the angular variation has been calculated using the normal CPP theory[1]. The curves shown have been calculated for an azimuthal angle of 0.2 rad to the (110) plane corresponding to the experimental situation. As shown in ref.11, the CPP theory is applicable for angles to the axis larger than the energy independent angle $\Theta_0=U_0/mc^2$. At high energy, where CPP is appreciable, Θ_0 is larger than Lindhard's critical angle for channeling ψ_1 (= 56 μrad at 150 GeV). For small angles, the angular variation has been calculated in the CFA (including first-order correction)[5]. This approximation is valid up to $\sim\Theta_0$. Good agreement is seen between experimental results and calculations at both small and large angles of incidence. Furthermore, no structure has been seen around ψ_1 in scans with smaller angular steps. This corroborates the present understanding, that the enhanced pair production rate is not dependent on the pair being channeled.

For low photon energies, differential pair production yields peak at $\eta=1/2$. Here η is the ratio of the positron energy and the incident photon energy. For high photon energies the yield peaks at $\eta=0,1$. This behavior is predicted for pairs produced by both the Bethe-Heitler, the CPP and the CFA mechanisms[4]. The relevant photon energies are however very different. At the energies involved in the present investigations, the differential Bethe-Heitler spectrum exhibits a shallow minimum at $\eta=1/2$. This minimum is not expected when photons, with energies close to threshold, are incident along crystal axes[4].

The measured differential pair production yields for photons with incidence angles at 0 and 3 mrad to the axis are shown in fig.4 for 5 photon energy intervals. The spectra are normalized to experimental Bethe-Heitler distributions, which are essentially constant over the major part of the spectrum and the no-target background is subtracted. Due to the strong photon emission by aligned electrons and positrons (ref. 12), fig. 4 only contains events for which the sum of the energies of the electron and positron equals the energy of the incoming photon to within 3%. This reduces the number of events by a factor of 50 and the measured differential spectra have thus been normalized to the measured total pair production yields. Good agreement is found between measured and calculated differential spectra. In particular the distribution is narrower for photon energies near threshold than at high energy, as predicted. Moreover the differential distributions of pairs produced in the constant-field region are considerably narrower than far out in the CPP region (cf. also ref. 4).

The use of the periodic arrangement of atoms in crystals allows the study of high-field electromagnetic processes otherwise inaccessible in the laboratory. This is the case for pair production studied in the present work, but also for bremsstrahlung (see ref. 12). The large angle- and energy-dependent enhancements observed indicate possible applications. In particular the angular and energy dependence of the radiation length allows construction of compact calorimeters with an angular resolution of the order of one mrad. Such calorimeters are well suited for both high-energy physics experiments and γ-ray astronomy.

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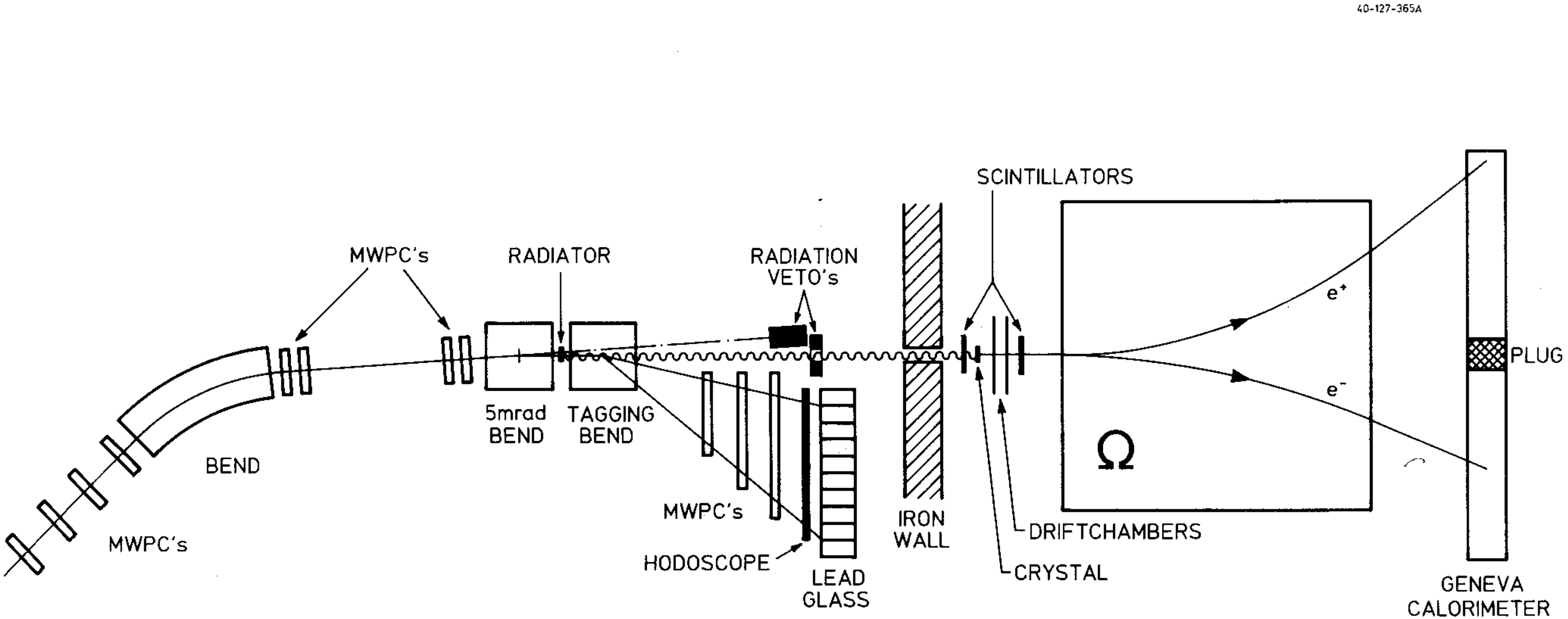
Figure Captions

1) Schematic drawing of the experimental equipment.
2) Measured pair production yield as a function of photon energy for photons incident within 250 μrad of the <110> axis in Ge. The pair production yield is shown relative to the yield obtained in a random direction. The full-drawn curve is calculated using the constant field approximation.
3) Angular dependence of the pair production yield (relative to random) for five different photon energy intervals, as indicated in the legend. The angle is given relative to the <110> axis.
4) Differential pair production spectra for photons (120-140 GeV, 100-120 GeV, 80-100 GeV, 60-80 GeV and 40-60 GeV) aligned to less than 0.25 mrad of the <110> axis (top) and 2.75-3.25 mrad to the axis (bottom).


40-127-365A
MWPC's
RADIATOR
RADIATION VETO's
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e⁺
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BEND
Ω
MWPC's
MWPC's
HODOSCOPE
LEAD GLASS
IRON WALL
DRIFTCHAMBERS
CRYSTAL
GENEVA CALORIMETER

Fig. 1

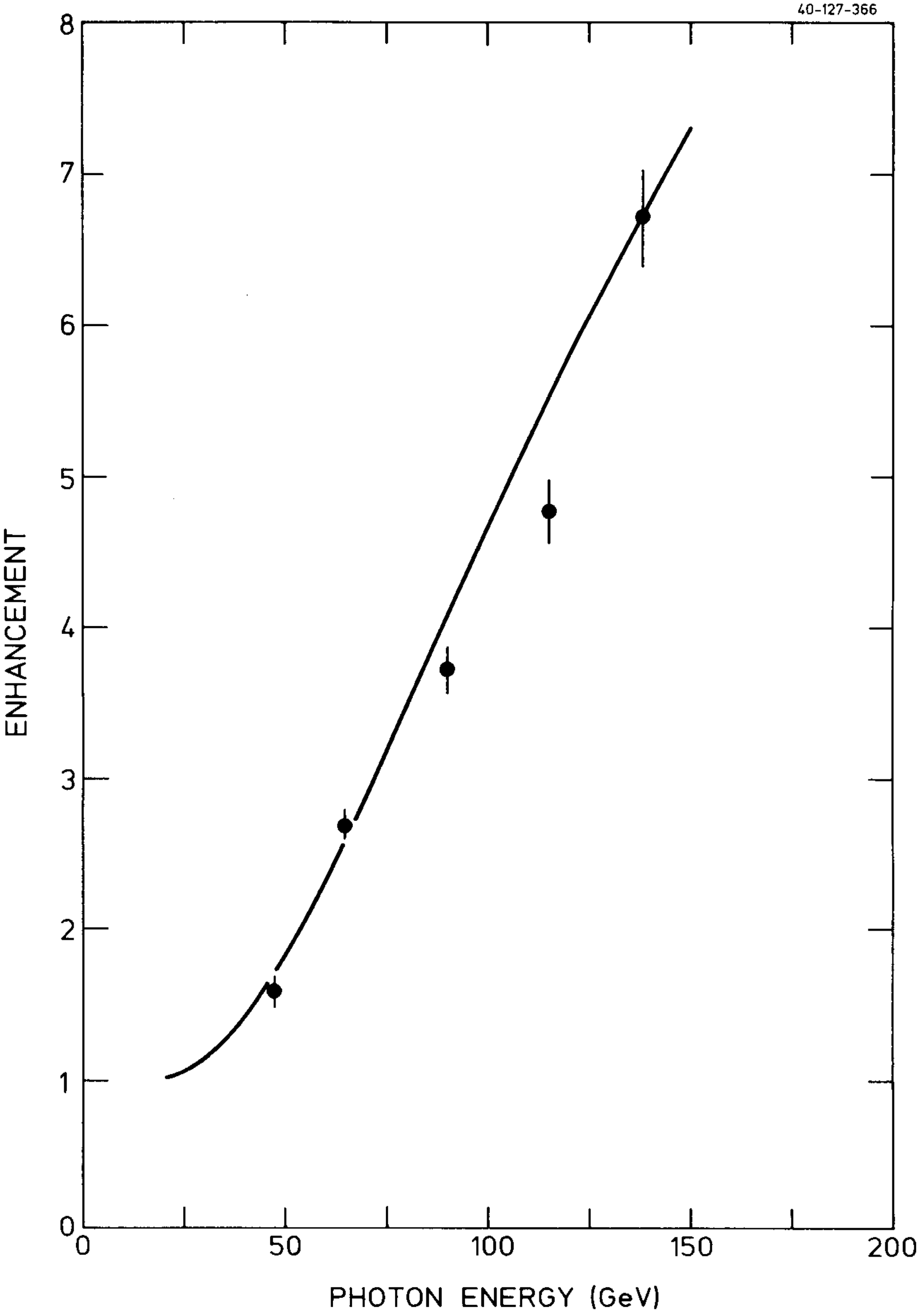
40-127-366
ENHANCEMENT
0
1
2
3
4
5
6
7
8
0
50
100
150
200
PHOTON ENERGY (GeV)

Fig. 2

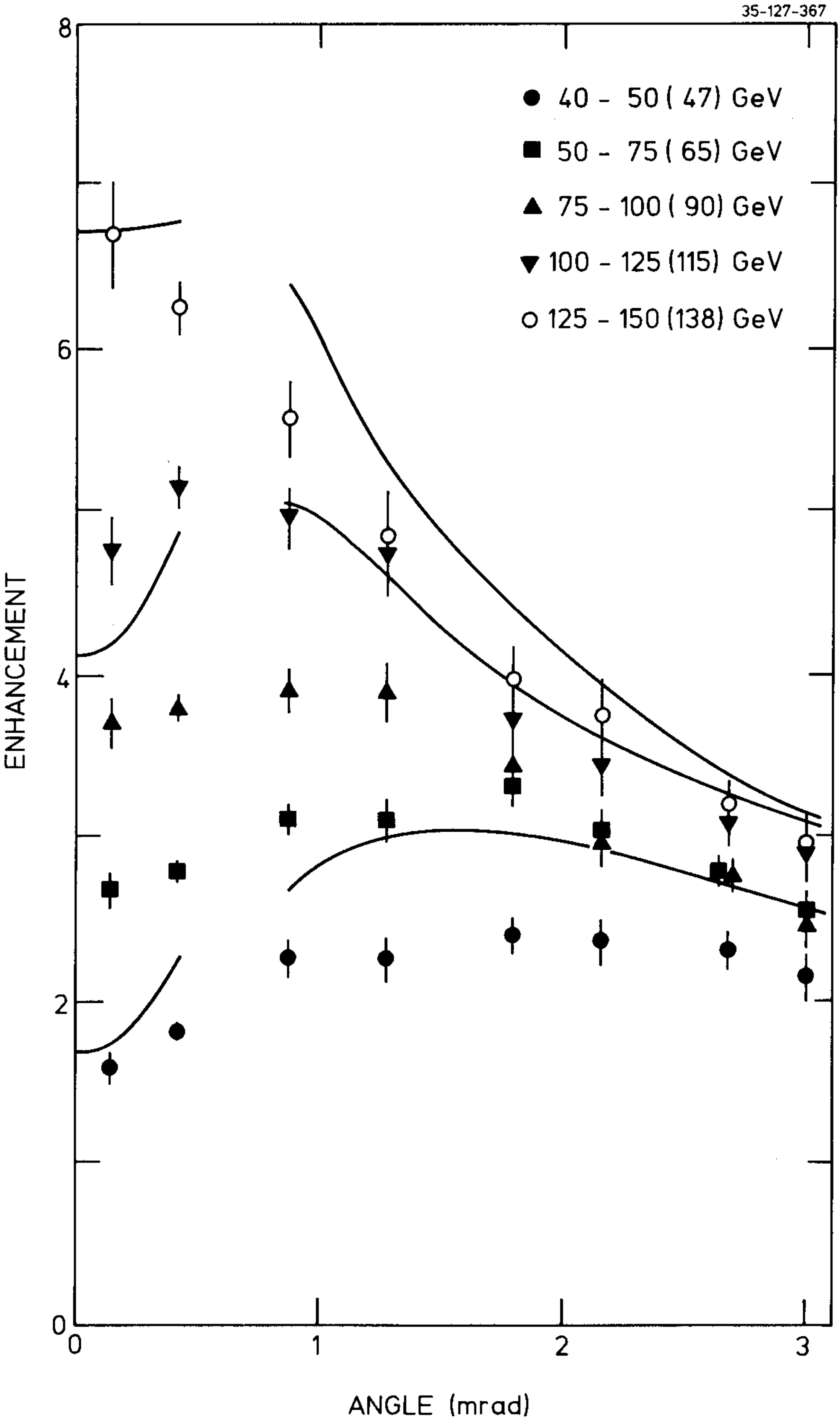
35-127-367
8
6
4
2
0
0
1
2
3
ENHANCEMENT
ANGLE (mrad)
● 40 - 50 (47) GeV
■ 50 - 75 (65) GeV
▲ 75 - 100 (90) GeV
▼ 100 - 125 (115) GeV
○ 125 - 150 (138) GeV

Fig. 3

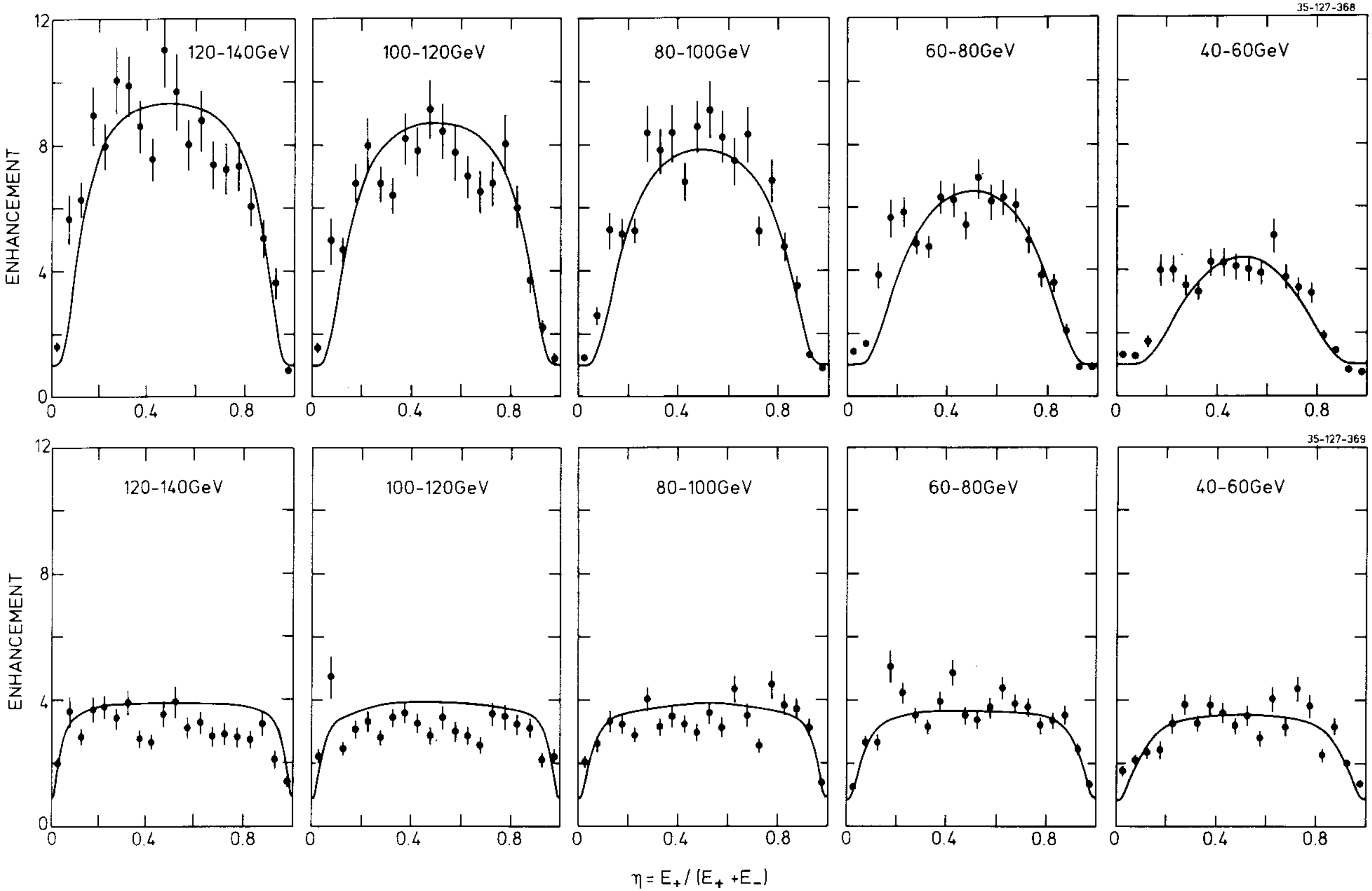
35-127-368
35-127-369
ENHANCEMENT
ENHANCEMENT
120-140GeV
100-120GeV
80-100GeV
60-80GeV
40-60GeV
120-140GeV
100-120GeV
80-100GeV
60-80GeV
40-60GeV
0
4
8
12
0
0.4
0.8
$\eta = E_+/(E_+ + E_-)$

Fig. 4