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MEASUREMENT OF AXIAL EFFECTS ON THE PAIR CREATION BY 30-150 GeV PHOTONS AND ON THE RADIATION EMITTED BY 150 GeV ELECTRONS AND POSITRONS IN Ge CRYSTALS

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ABSTRACT

Crystal-assisted processes around the < 110 > axis of a Ge crystal cooled to 100 K have been investigated at CERN with 150 GeV e^- and e^+ incident beams and 30-150 GeV incident photons. A large enhancement of the radiation emitted by incident e^+ and e^- is observed. Electrons are found to radiate more than positrons. When the crystal is tilted around < 110 > clear channelling effects are still observed. However the radiation enhancement persists at angles much larger than the channelling critical angle. The total pair creation rate by photons aligned along < 110 > has also been measured: in contrast with the random orientation case, the rate increases sharply with the photon energy. A scan through < 110 > shows that the pair production reaches a maximum at a tilt angle which decreases when the photon energy increases. These measurements indicate that crystal-assisted pair production is not governed by the channelling of the created electrons.

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1. INTRODUCTION

The purpose of this paper is to describe experimental efforts which were developed at CERN in 1984 and 1985 (NA33 Experiment) to investigate crystal-assisted phenomena recently predicted [1-3] and described in the companion paper by J.C. Kimball et al. [4].

The aim of the first experiment run in 1984 was to observe enhancement of the pair production rate when a photon beam is incident along the < 110 > axis of a Ge crystal cooled to 100 K.

The crystal was oriented by measuring the radiation emitted in the crystal by incident 150 GeV electrons. We observed a very large enhancement of the radiation yield for incidence along the < 110 > axis [5]. With a 0.4 mm thick Ge crystal we found that the mean radiated energy is 25 times higher along the axis than in a random orientation. This enhancement persists at angles much larger than the channelling critical angle ($\psi_c \sim 66$ µrad).

When we used a beam of 50-110 GeV tagged photons to look for an enhancement of the pair creation in axial alignment we observed features which proved the existence of this enhancement but which were affected by the high intensity of the radiation emitted by the created electrons and positrons. We improved our set-up and very recently measured the total pair production rate and the yield of the radiation emitted by positrons and electrons in a Ge crystal.

After reviewing the results obtained last year we give a description of the improved set-up and also a preliminary analysis of the data obtained in June 1985.

In this paper we will not discuss the coherence effects which are known to be dominant at large tilt angles and which show up in our experimental data.

2. EXPERIMENTAL

The experimental set-up was originally designed to allow differential measurement of e^+e^- pair creation by incident photons in single crystals. Photon beams are produced by bremsstrahlung of a primary electron beam. The alignment of the crystal was expected to be obtained by detection of planar effects on the radiation emitted in the crystal bombarded with the primary electron beam. Since the enhancement of pair creation around an axis was initially predicted to occur only when the created electron is channelled, the angular resolution of the experimental set-up was required to be much smaller than the channelling critical angle ψ_c. In fact the first experiment, in 1984, revealed that crystal- assisted phenomena are still observable at angles much larger than ψ_c, and that the created $e^\pm$ radiate in the crystal a very large part of their kinetic energy. In 1985, the set-up was improved in order to allow the simultaneous detection of pair creation and of the radiation emitted by the created $e^\pm$. One can easily measure the total energy radiation by a created pair, but may not be able to extract from the data the amount of energy radiated by each member. The radiation of the $e^\pm$ which are created inside the crystal by an aligned photon is probably different from the radiation produced by an aligned $e^\pm$ beam. Nevertheless, it was useful, as a first step, to measure the radiation emitted by electron and positron beams.

A simplified view of the 1985 set-up is sketched in Fig. 1.

2.1 Crystal Target and Goniometer

The Ge crystals used in this experiment were grown and cut by CRISTAL-TEC, Grenoble, France. Single crystals of Ge, of the so-called "zero dislocation etch-pit" quality, were selected and cut in a T-shape profile to facilitate mounting and cooling the sample without distortion. The thin rectangular plate (1.4 x 20 x 25 mm^3) is the part of the sample which was used as target. The thick base (20 x 15 x 5 mm^3) was used to fix the sample on the holder. The surface of the base in contact with the target holder was cut with an accuracy of 1 mrad along the (100) plane. The flatness of this surface allows a good thermal contact between the crystal and the cooled target holder and is also used as an angular reference for the prealignment of the crystal. With this T-shape profile, thermal and mechanical constraints in the thick base do not propagate into the thin plate. Our experiment proved effectively that the overall curvature of the cooled target was less than 10 μrad.

There is no simple laboratory method to measure such small values of the crystal curvature. Nevertheless, we checked with X-rays (double-diffraction method) that the surface curvature was smaller than 25 μrad at room temperature. The in-depth quality of the samples was checked by single γ-diffraction. The curvature integrated over the full depth of the crystal was much smaller than the angular resolution of the γ-diffractometer, namely 47 μrad.

The target crystal was mounted on a two-axis goniometer which could rotate by steps of 1.7 μrad, with a reproducibility of 3 μrad. The goniometer was attached to a high accuracy linear translator which allowed the crystal to be moved in and out of the beam with a reproducibility better than 1 μm in translation and 5 μrad in angle. The goniometer and the translator were manufactured by MICROCONTROLE, Evry, France.

The target holder was linked to a LN2 reservoir by copper braid, and the target was enclosed inside a small box, with cooled walls, to limit thermal radiation. The temperature of the crystal was stabilized at 100 ± 1 K, while the temperature of the goniometer was maintained at 28 ± 2°C.

2.2 The incident $e^{\pm}$ Beams

Secondary electron and positron beams were delivered to us in the North Area of the SPS-Accelerator at CERN. For 70 and 150 GeV $e^{\pm}$ energies, secondary electron beams are produced in two steps from the primary proton beam. In a first step, only the neutral particles (π^0 - γ) emerging from a first target are selected, then, in a second target, the neutral beam produces e^+-e^- pairs which deliver electron or positron beams with a very low contamination rate in hadrons and muons. At 200 GeV the beam intensity obtained by this two-target method would be too low, so the electrons are produced in a single target and separated from hadrons by synchrotron radiation. In a last step, the electron beam is made parallel. The beam parallelism is measured with high accuracy by a "CEDAR" Cerenkov counter, which is removed from the beam line after the measurement. Two collimators select the central part (∿ 1%) of the parallel beam. Finally one obtains 10^4 e^- per burst on the target, where the beam cross-section is $.8cm^2$. The $\Delta p/p$ resolution is 2×10^{-3} and the angular resolution 20-30 μrad. Such beam qualities made it possible to study crystal-assisted phenomena by the method currently used at lower energies in channeling type studies. From measurements using the veto scintillators placed behind the calorimeters we found that the fraction of hadrons and muons was only 1% with electron beams, whereas a large fraction of protons (∿ 25%) contaminates the positron beams.

A doublet of scintillators (B_1, T_1) centered on the beam axis enables rejection of the beam halo. The background radiation measured along the beam axis when the crystal is out of the beam, has to be minimized. In the 1984 set-up, the amount of matter encountered by the incident particles was equivalent to ∿ 1.5mm of Ge. In the 1985 set-up it was reduced to 0.5 mm of Ge by means of additional vacuum pipes along the beam line.

2.3 The Tagged Photon Beam

Tagged photons are produced by bremsstrahlung radiation of the incident electrons in a 0.5 mm lead foil. The choice of the radiator thickness results from a compromise between the need for photon intensity and the necessity of keeping the probability of 2-photon events at a low level. The electrons transmitted through this radiator are separated from the photons and directed into the tagging spectrometer by the magnet M1. The tagging spectrometer contains a thick lead glass calorimeter (21 radiation lengths) and a scintillator (S1). With the three primary electron energies used, 200, 150 and 70 GeV the energy range of the tagged photons was 85-155 GeV, 65-130 GeV and 22-55 GeV respectively.

2.4 The Pair Spectrometer

Two identical lead glass calorimeters (21 radiation lengths) and two scintillators, S2 and S3, form the pair spectrometer.

In the 1984 set-up the two calorimeters touched along the beam line, and thus the energy radiated by the created $e^{\pm}$ in the crystal target was mixed up with the $e^{\pm}$ energies. In the 1985 set-up the two spectrometers were 42 mm apart to allow the simultaneous but separate measurement of the energies of the photons and the $e^{\pm}$ emerging from the crystal target.

It is of importance to note that low energy $e^{\pm}$ miss the bispectrometer. As a consequence, the pair production rate measured in 1984, with the scintillator S2 in the trigger, was only a partial rate (a pair with its positron emerging from the crystal with an energy < 15 GeV was not recorded). In 1985 we used a thin scintillator (B2), located just downstream from the crystal, to measure the total pair creation rate without any cut-off on the energy of the created $e^{\pm}$.

Spectra obtained from the pair spectrometer are now being analyzed and will be published later.

2.5 The Photon Spectrometer

The photon calorimeter, located far away along the beam line, consists of BGO detector (8 radiation lengths) placed in front of a lead glass detector (21 radiation lengths). This combination allows the measurement of photon energies from ∿100 MeV to 200 GeV. A scintillator (V4) is used to reject events in which charged particles enter the photon calorimeter.

2.6 Alignment of the Crystal

We measured the radiation emitted by the primary electron beam in the crystal, which was already preorientated with ± 2 mrad. Clear enhancements of the radiation yield were observed along the major planar directions.

When the axial orientation is found with electrons we observed that it is unchanged, within 10 μrad, with the tagged photon beam (if magnet M1 has been demagnetized before the alignment with the electron beam). It is remarkable that one could change the incident energy (from 70 to 200 GeV), the nature of the incident particle (e^-, e^+ and photon), and remove the goniometer from the beam axis (for background measurement) without changing the beam-crystal orientation.

3. RESULTS

3.1 Radiation by 150 GeV e^- and e^+

We have measured the yield of the radiation emitted by 150 GeV electrons and positrons incident on Ge crystals cooled to 100 K.

Fig. 2 shows photon spectra measured when 1.4 mm and 0.4 mm thick crystals are used. Spectra obtained when the crystal is not aligned are found to be in good agreement with the amorphous thin-target Bethe-Heitler (B.H.) shape. The "random" direction was chosen far away from any major planar or axial direction to avoid coherence effects. When the beam is incident along the < 110 > axis the shape of the radiation spectrum is no longer of the B.H. type and is not the same for the two crystal thicknesses. This means that these crystals, when aligned, do not behave like thin targets.

The change in the shape of the spectra is due to the high probability that each incident electron emits several photons. Since the downstream photon-calorimeter can only measure the total energy of all the photons emitted by a given electron, a multiphoton event is recorded as a high-energy single-photon event. Attenuation measurements using lead sheets (described in Ref. 5) have been made in order to prove that the spectra obtained with aligned crystals are effectively dominated by multiphoton events. The multiphoton process prevents deduction of the thin-target radiation spectrum. However, the total radiated energy per event can be obtained independently of the photon multiplicity and of the photon energy partition inside a multiphoton event.

The mean radiated energy in the 0.4 mm thick crystal is 25 times higher on axis than in random conditions, thus in the limit of a very thin crystal this enhancement should reach a value larger than 25.

Fig. 3 shows the mean radiated energy in a 1.4 mm thick crystal by electrons and positrons for various tilt angles around the < 110 > axis. One observes that:

(i) At angles smaller than the channeling critical angle (ψ_c) electrons radiate more than positrons. On-axis, the mean radiated energy is 108 GeV for electrons and 69 GeV for positrons, whereas in random conditions electrons and positrons radiate an average of only 9.1 GeV.

(ii) The mean radiated energy exceeds the B.H. value over an angular range which is much larger than the channelling critical angle.

(iii) Based on a more recent measurement with a 0.2 mm crystal, the mean radiated energy is found to reach a maximum value along the axis for incident electrons, and at an angle close to ψ_c for incident positrons.

As can be seen in Fig. 3 there are large channelling effects. Indeed we know that the radiation yield increases with the field strength [2,7], thus the difference in the yield of the radiation emitted by electrons and positrons, at incidence angles smaller than ψ_c, reflects the effect of the channelling potential which attracts the electrons toward strong field regions and repels the positrons.

Measurements of the radiation emitted by 150 GeV $e^{\pm}$ in a very thin crystal (0.2 mm) have also been performed. In that case, the number of multiphoton events is very low. The raw data confirm all the above interpretations and channelling effects on the e^- radiation are more clearly seen than in a thick crystal.

3.2 Pair production rate by 30-150 GeV photons

We reported previously [6] the first observation of the enhancement of the pair production rate when a photon beam with an energy higher than 50 GeV is directed along the < 110 > axis of a 1.4 mm thick Ge crystal cooled to 100K. We review first some of these earlier results, obtained from the measured differential yield.

The pair production rate along an axis increases sharply with the incident photon energy, in contrast to the measurements obtained with an amorphous target or a non-aligned crystal. This result is in qualitative good agreement with predictions of the crystal-assisted pair production theory (CAP) [1].

The 1984 data also show the dependence of the pair production rate on the tilt angle of the incident photon beam with the < 110 > axis, featuring a dip at 40 μrad. At first glance this seems to agree with calculations based on final states for which the created electron is channelled [8]. However an instrumental cut-off eliminated all events with a created positron emerging from the crystal with an energy less than 15 GeV (see 2.4). Furthermore, when a created positron loses energy by radiative emission in the crystal, it has a higher probability to emerge with an energy less than this cut-off. The measured pair production is then artificially lowered. The greater the probability that the positron radiates, the more underestimated is the pair production rate. Since we know that the mean radiated energy by positrons is higher around an axis than in random conditions, the pair production rates in Ref. [6] must be considered as lower limits of the total rate. Also, the radiation yield of the positron reaches a maximum around ψ_c (Fig. 3). This leads to less efficient pair detection and may explain the apparent dip at 40 μrad in the pair production rate. These experimental limitations have been rectified in the 1985 experiment in which the total pair creation rate, unaffected by radiation losses, is measured.

We report now the new results which are not yet corrected for the probability that one tagged electron produced two photons in the radiator. Because more analysis is needed to obtain the exact normalization of the measurements, all the reported values are in arbitrary units. The absolute values of the pair-production rate will be published in a forthcoming paper.

Fig. 4 shows the total pair-production rate when the photon beam is incident along the < 110 > axis. The 30-150 GeV energy range of tagged photons was obtained by using successively 70, 150 and 200 GeV primary electrons. There are good overlaps among the measurements performed with the three primary electron energies. These measurements confirm the prediction that the rate increases with the photon energy. With 30 GeV photons the measured rate is about the B.H. value. The rate increases by a factor ∿ 6 for 150 GeV incident photons. These measurements confirm that the results obtained with the 1984 set-up underestimate the total pair production. A quantitative comparison with the theoretical predictions can be done only after a complete analysis of the data, nevertheless the tendency of the raw data is in good agreement with the predictions for high energy photons [4].

Fig. 5 shows the dependence of the total pair production rate versus the angle between the photon beam and the < 110 > axis. Each data point is obtained by integrating the rate over an energy range of the incident photons. Since we used the photons emitted by primary electrons in the radiator, the energy distribution of the photons inside this energy range is given by the usual Bethe-Heitler shape. Contrary to the results obtained in 1984 (with a low energy cut-off), we observe no dip around 40 μrad. This result shows that the enhancement occurs even when the created $e^{\pm}$ are not channeled. The maximum rate is observed off-axis, at an angle which decreases when the photon energy increases. This observation is in good qualitative agreement with a recent calculation of crystal-assisted processes for imperfect alignment [9].

4. CONCLUSION

We have shown that the strong fields that exist in the vicinity of a crystal axis considerably increase the radiation emitted by high energy e^+ and e^-, in good qualitative agreement with recent theoretical predictions. For tilt angles within the critical angle for axial channelling, the radiative emission is influenced by channelling, which can be explained by the fact that the flux distributions are not the same for e^+ and e^- in the strong field regions.

In addition, the total pair production rate was measured for a large range of incident photon energies. For photons incident near an axial direction the production rate increases rapidly with the incident energy above an energy threshold (∿ 30-40 GeV for the < 110 > direction in Ge at 100 K). We prove also that the enhancement of the pair production is not due to the capture in a channelling state of the created electron. This is in agreement with the recent interpretation of the phenomenon in terms of strong field effects. In that sense crystal assisted effects on the pair production should not be called channelling pair production.

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FIGURE CAPTIONS

Fig. 1 Set-up of the CERN-NA33 experiment, see text for details.

Fig. 2 Radiation spectra 150 GeV e^- aligned with the < 110 > axis of 0.4 and 1.4 mm thick Ge crystals at 100 K, where x is the radiated energy in units of the incident energy. A nonaligned 1.4 mm Ge spectrum and the background spectrum are shown for comparison. The ordinate N_e is the number of radiation events per electron in an interval of $\Delta x = 0.02$.

Fig. 3 Variation with the tilt angle from the < 110 > axis of the mean energy radiated by 150 GeV e^+ and e^-, respectively. The angular scan is made in a plane containing the < 110 > axis and making an angle of 0.1 rad with respect to a (110) plane.

Fig. 4 Total pair production rate (in arbitrary units) versus the energy of photons incident along the < 110 > axis. The range of photon energy is obtained from 3 different energies of the primary e^- beam. The data are not corrected for 2-photon events in the radiator.

Fig. 5 Angular scan of the total pair production rate (in arbitrary units) in a plane containing the < 110 > axis and making an angle of 0.1 rad with respect to a (110) plane. Each data point corresponds to an integration of the rate over the indicated photon energy range.

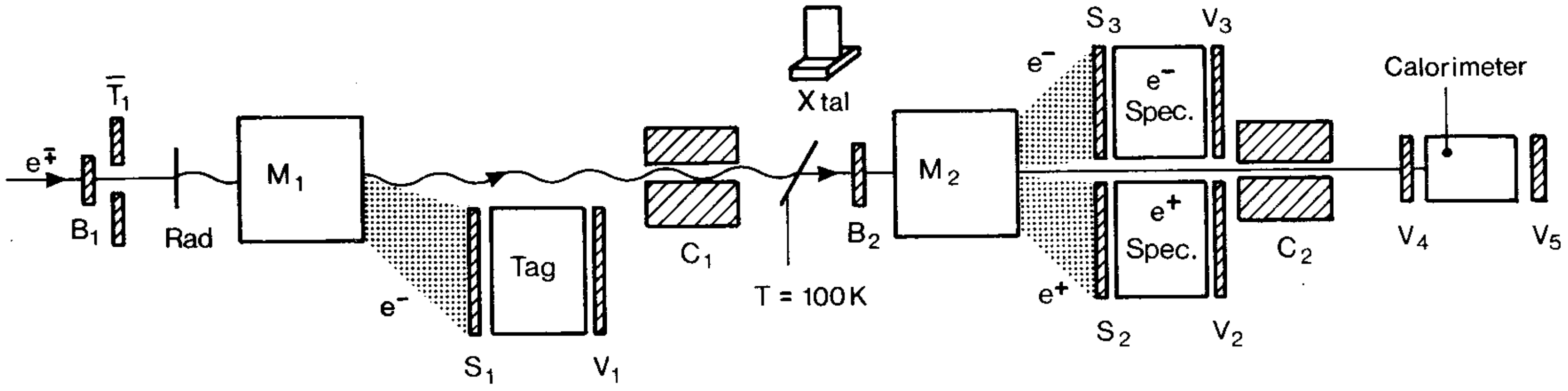
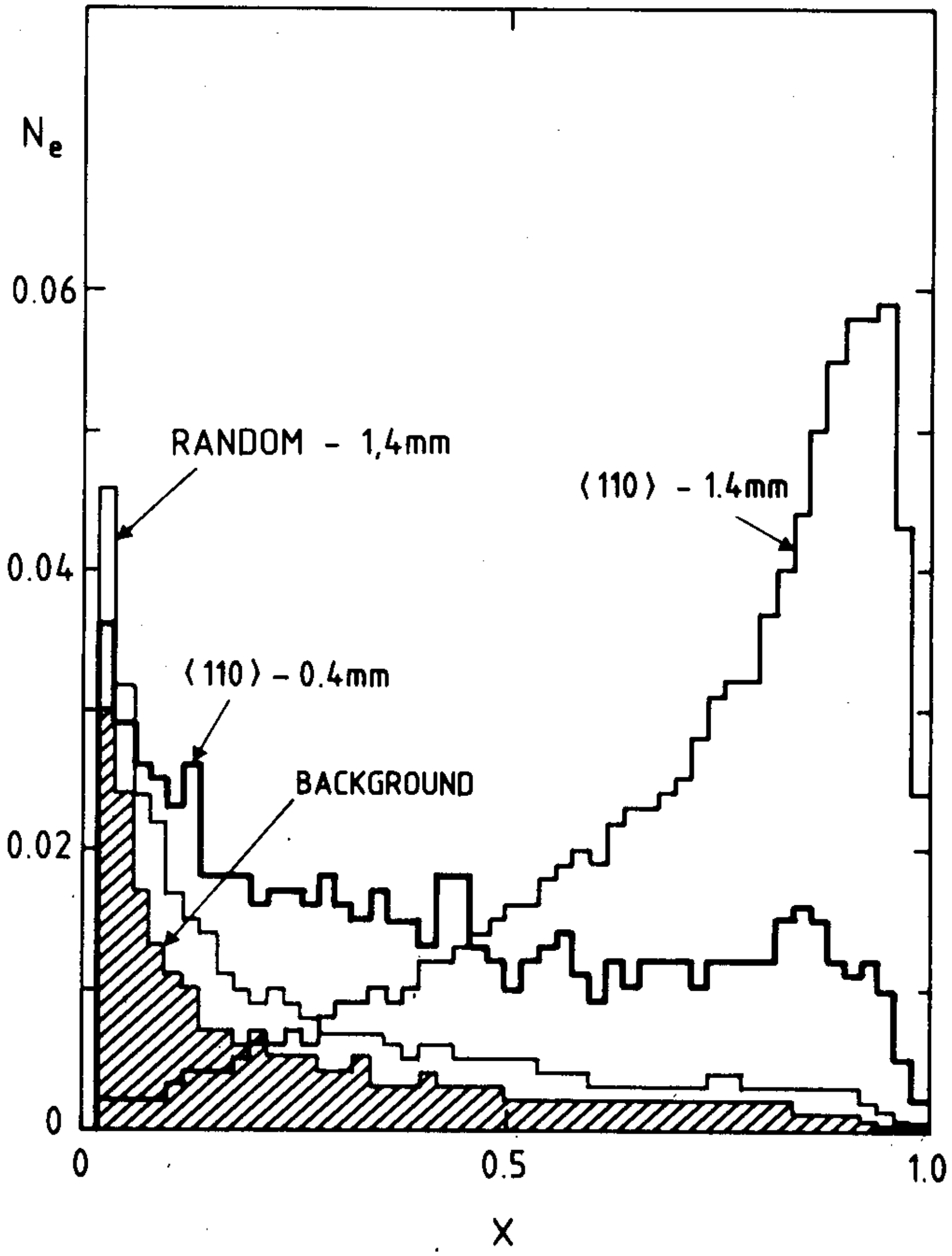

$e^{\mp}$
B_1
$\overline{T}_1$
Rad
M_1
e^-
S_1
Tag
V_1
C_1
X tal
T = 100 K
B_2
M_2
e^-
S_3
e^- Spec.
V_3
e^+
S_2
e^+ Spec.
V_2
C_2
Calorimeter
V_4
V_5

FIG. 1



N_e
0.06
0.04
0.02
0
RANDOM - 1,4mm
(110) - 1.4mm
(110) - 0.4mm
BACKGROUND
0
0.5
1.0
X

FIG. 2

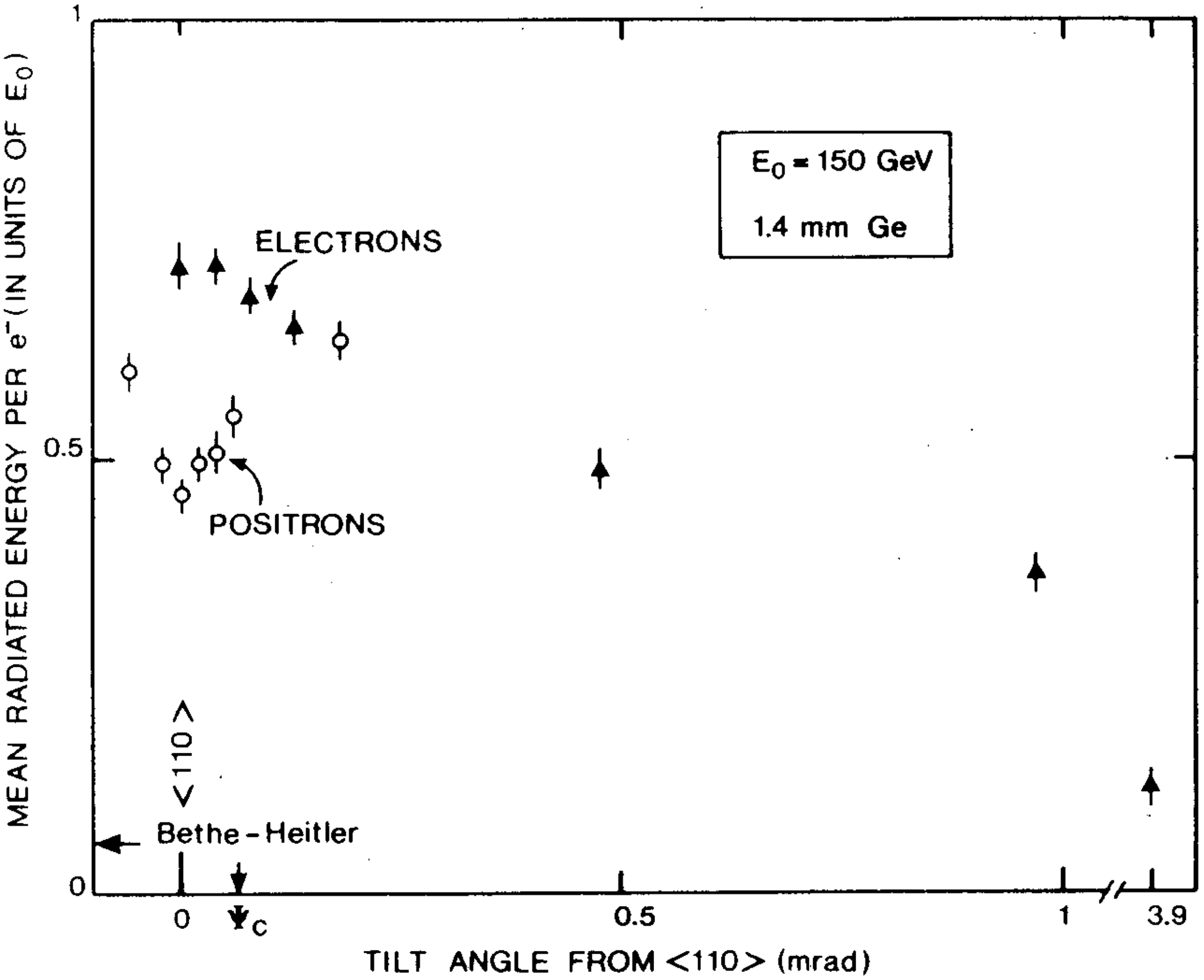

MEAN RADIATED ENERGY PER e⁻ (IN UNITS OF E₀)
1
0.5
0
E₀ = 150 GeV
1.4 mm Ge
ELECTRONS
POSITRONS
<110>
Bethe - Heitler
ψc
0
0.5
1
3.9
TILT ANGLE FROM <110> (mrad)

Fig. 3

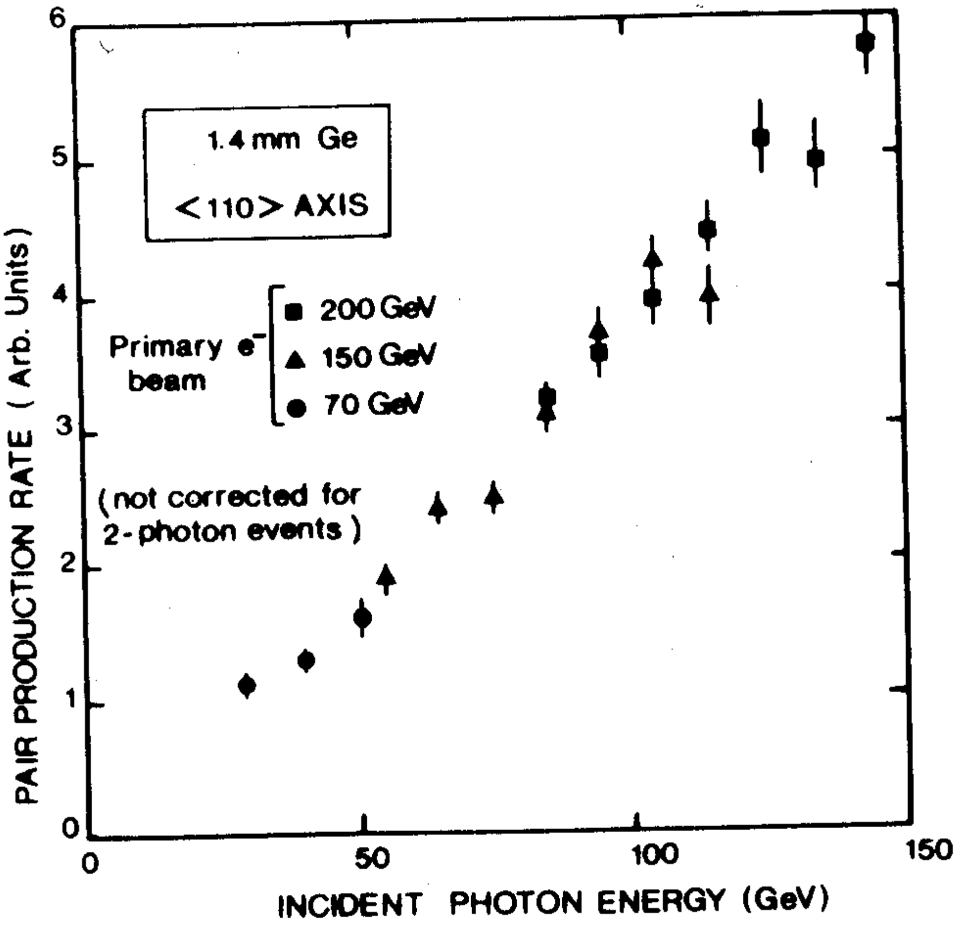

1.4 mm Ge
<110> AXIS
Primary e⁻ beam
■ 200 GeV
▲ 150 GeV
● 70 GeV
(not corrected for 2-photon events)
PAIR PRODUCTION RATE (Arb. Units)
0
1
2
3
4
5
6
0
50
100
150
INCIDENT PHOTON ENERGY (GeV)

FIG. 4

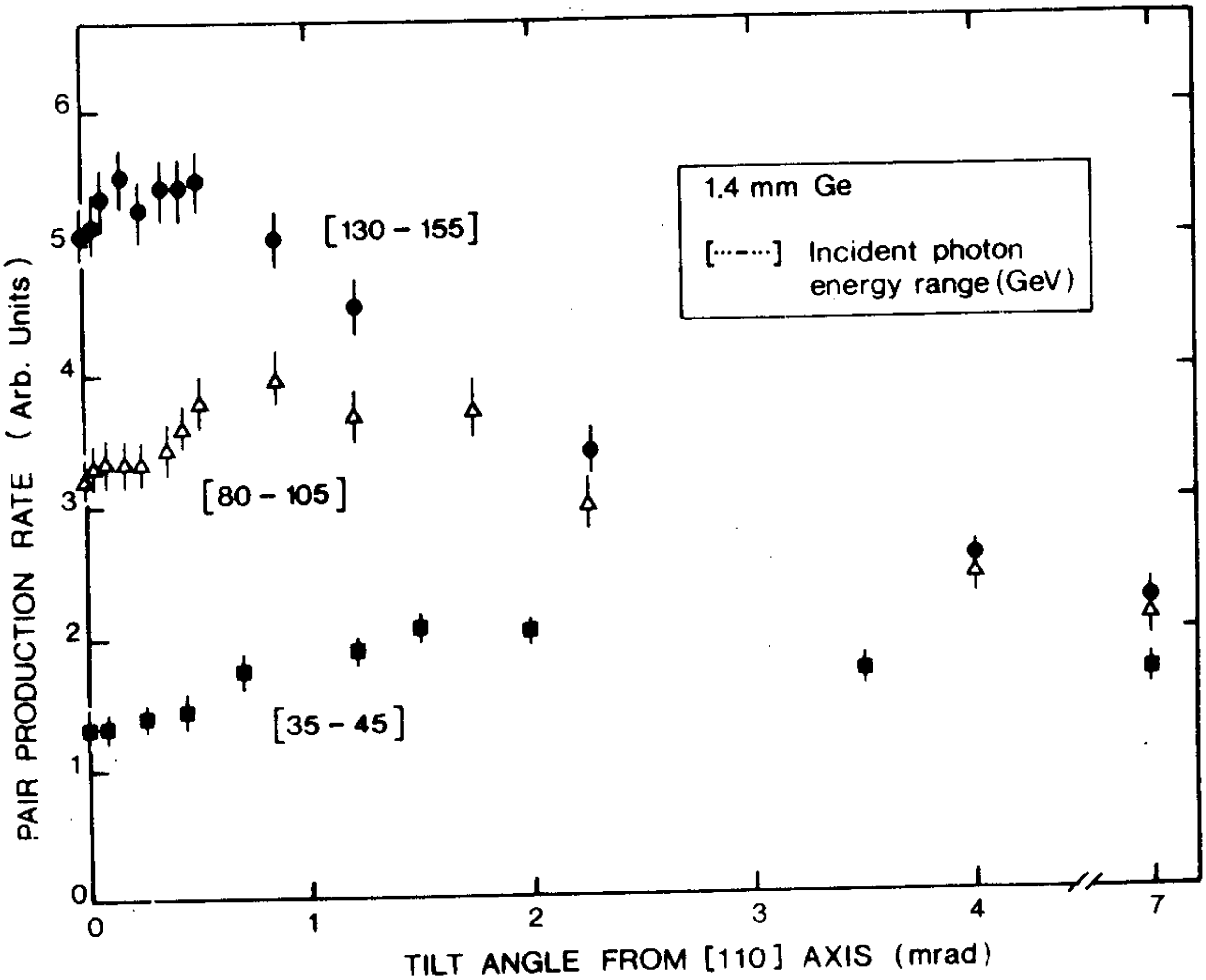

1.4 mm Ge
[·····] Incident photon energy range (GeV)
[130 – 155]
[80 – 105]
[35 – 45]
PAIR PRODUCTION RATE (Arb. Units)
TILT ANGLE FROM [110] AXIS (mrad)
0
1
2
3
4
5
6
0
1
2
3
4
7

FIG. 5