PROPOSAL

CERN/PSCC/78-13
PSCC/P3
September 14, 1978

Measurement of the Influence of Channeling on Atomic and Nuclear Reaction Yields

Aarhus-CERN-Strasbourg Collaboration

S.Kjær Andersen, H.Nielsen, H.Schiøtt, E.Uggerhøj,
H.Pilkuhn[+], (University of Aarhus)
G.Charpak, G.Petersen, and F.Sauli (CERN)
F.Grob and P.Siffert (Strasbourg)

We propose to study the influence of channeling on close encounter processes, such as nuclear particle production, atomic inner shell excitation, and δ-electron emission in Ge and Si crystals acting as energy-loss detectors. Because of the excellent energy resolution of such solid-state detectors it is also possible to measure cross sections for nuclear elastic scattering.

From previous channeling experiments at PS there are indications of very pronounced directional effects in crystalline materials for processes occurring close to or at the nucleus. If the particles are directed parallel to a crystal axis or plane, the yield compared to the yield in a "random" direction is dramatically reduced for positive particles whereas negative particles show an increase. From variations in the "tails" of the energy-loss distributions of such channeled particles, strong directional effects in δ-electron yield are also expected. A deeper understanding, both theoretically and experimentally, and especially for negative particles, is very desirable but will require more detailed measurements with better statistics.

We ask for a non-separated charged beam operating in the range 2 to $\sim$20 GeV/c together with a standard particle identification Cerenkov system. The detector consists of a set of small-size, high-accuracy drift chambers, a cryogenic crystal holder, and the associated electronics (all already existing).

At least in the beginning the d_{31} beam will meet our demands for test of solid-state detector targets, background, resolution, etc. Estimated running time is around 8 weeks for setting up and data taking. Computer time is estimated to around 25 hours CP time on the CDC 7600.

[+] On visit from University of Karlsruhe
B R D

I. Summary of Old Results

The influence of channeling on the energy loss and scattering phenomena for high-energy particles has been studied for around 4 years at CERN,[1-8], and more recently also in U.S.A.[9-11] and USSR[12]. The CERN experiment has resulted in a series of reports on our measurements with 1-15 GeV/c protons, pions, and kaons incident on Si- and Ge crystals acting as intrinsic solid-state detectors. The results up till now can be summarized under the following three main topics: 1) Energy loss, 2) Anomalous scattering phenomena, and 3) Nuclear reactions.

1) For positive channeled particles it was found that the ionization energy loss is reduced by almost a factor of three for axial and low-index planar directions. The results were compared to the different and conflicting theories and found to be in good agreement with the theory of Esbensen and Golovchenko[13].

Negative well-channeled particles were found to have an increased average energy loss by around 20%.An increase is expected from the qualitative picture of channeling in which the negative channeled particles are focused around the nuclei, whereas the positive particles are kept away. No detailed theory for negative particle channeling exists at present.

Figure 1 shows a typical energy-loss spectrum for 15 GeV/c protons incident on a 0.74 mm <110 > Ge-crystal. The "random" curve is obtained for incident angles far away from any axial or planar direction, in which case the same result is obtained as from an amorphous target of the same thickness. It is seen that the aligned spectrum has a very steep rise and a reduced Landau tail (suppression of close collisions with electrons). Figure 2 shows the Si and Ge results compared to theoretical calculations. The rather strong relativistic rise for <110> Ge should be noticed. In Fig.3 is shown the same energy-loss spectra for 15 GeV/c π^-. Here the aligned case has a strongly increased Landau tail (close collisions with electrons are more favoured).

2) It was found that if a crystal axis (or plane) is close to the incident beam cone($\lesssim$5 mrad for 15 GeV/c), the scattering distributions are drastically changed. For certain incident angles, the multiple scattering is strongly reduced, whereas for other incident angles, it is strongly increased. Figure 4 shows the multiple scattering for 15 GeV/c protons and π^- incident on a 4.2 mm <110 > Ge

crystal. It is clearly seen that the width is strongly dependent on incident angle. The intensity distributions in exit angle space are ring-shaped (doughnuts) with very pronounced minima along the axis. Figures 5 and 6 give examples of doughnuts for protons and π^-. The <110> axis is at the minimum and the incident beam direction is at the point of highest intensity. The wide-angle scattering yield is dramatically reduced for positive channeled particles but increased for negative particles as shown in Figs. 7 and 8 giving results for 15 GeV/c protons and π^- incident on the 4.2 mm Ge crystal.

3) Strong directional effects for nuclear reaction probabilities have been observed when 15 GeV/c protons and pions are incident on the 4.2 mm Ge crystal (see ref.6).

In the random situation our measurements agree with Glauber's theory of diffraction scattering and with published particle-production data. For channeled protons the nuclear reaction probabilities fall off very drastically but in a way which is in agreement with standard channeling theory; negative channeled pions seem to have increased nuclear reaction probability. Figure 9 shows the variation in yield of those particles that have had an energy loss > 5.1 MeV by traversing the 4.2 mm Ge crystal. The average energy loss for this target is 2.3 MeV. Such large energy losses can be shown to be correlated with particle production[6]. Clearly the two cases are very different. Unfortunately bad statistics made it impossible to investigate the increase for negative particles in detail. To get a more detailed insight into the anomalous scattering phenomena mentioned above, a binary collisions Monte Carlo program was run. Figure 10a shows the calculated exit intensity distributions in angle space for 15 GeV/c π^- traversing a 0.3 mm < 110 > Ge crystal and fig.10b shows the measured distribution. In Fig.11 is shown impact parameter distributions for both π^+ and π^- at 15 GeV/c traversing a 40 μ Ge <110> crystal normalized to random. The channeled π^+ is seen to have practically no chance to come close to the nuclei - in good agreement with the wide-angle scattering measurements, whereas the channeled π^- have a strongly increased probability for close collisions, which is in qualitative agreement with measurements on the 4.2 mm crystal. There the increase is not nearly as large but the crystal is also much thicker, giving rise to a considerable dechanneling.

For a 0.3 mm crystal the calculations still give an average increase in the probability of close encounters for the whole crystal by as much as a factor of 4, for incidence along an axis direction.

II. The New Experiments

Based on the preliminary experiments described above and on the binary collisions calculations we propose an extension of the program as an Aarhus-CERN-Strasbourg collaboration with a view to studying the following main subjects

A. Influence of Channeling on Atomic Collision Yields

(1) K-shell x-Ray Production
(2) Simulation of Life-Time Experiment
(3) δ-electron emission

B Influence of Channeling on Nuclear Reaction Yields

(1) Particle Production
(2) Elastic Nuclear Reactions

ad A (1) K-shell X-ray Production

Studies of negative-particle channeling are complicated by the strong scattering of the particles leading to dechanneling. The problem would be solved if one could use very thin crystals, which for experimental reasons is difficult. The difficulty can be overcome by using as the signal the characteristic K x-rays from the target. The absorption of the x-rays in the target itself automatically limits the active target region to a surface layer of thickness of the order of the extinction length. For Ge this length is, for the 11-keV K-x-ray $\sim 50\mu$. K-shell excitation is a close--encounter process for which the Monte Carlo calculations predict an enhancement in yield by a factor of ~ 10 for incidence along an axis direction as compared to random incidence.

Electrons can not be used for this experiment because of the high Bremsstrahlung background. In order to achieve as clean conditions as possible we intend to measure the x-rays emitted from the front of the crystal.

A(2) Simulation of Lifetime Experiment

Another intriguing perspective of the x-ray measurement is related to the relativistic increase of the adiabatic screening distance for K-shell excitations. This means that the possibility of K-shell excitation will vary with the velocity of the projectile. For positive particles this effect may be utilized in a simulation of a blocking lifetime experiment. In a blocking lifetime experiment the unstable particle is formed at a nuclear site, with a velocity component perpencidular to the atomic string $v_\perp$. If the distance $v_\perp \tau \gamma$ has a value in the range of $\sim$0.1 - 1 Å, a study of blocking effects for the emitted decay products gives the lifetime τ .

In the proposed x-ray experiment the effective impact parameter for K-shell excitation will simulate the $v_\perp \tau \gamma$-value. So for a fixed velocity of the projectile,the variation in x-ray yield around an axis direction will simulate the variation in emission yield (around the same axis) for the decay products in a lifetime experiment[14].

A(3) δ-electron Emission

In recent years the possibility of measuring electron densities in single crystals using a very localized process has been discussed. Annihilation in flight of relativistic positrons traversing a single crystal is one such process. Small cross sections and Bremsstrahlung background have made the experiment little attractive but nevertheless this type of experiment has now been started (Livermore[15], Kharkov[16]). We propose to measure electron densities by detecting the variation in δ-electron yield from relativistic protons and pions as a function of incident proton (pion) direction. Today the understanding of channeling for positive particles is so good that a knowledge of energy and incident direction for the particle enables us to calculate the path through the crystal. An advantage of the high energy particles is that all electrons may be considered as free, and that it is possible to obtain δ-electrons of sufficient energy (several MeV) to escape from the crystal. A comparison of the Landau "tails" (close encounters with electrons) in Figs. 1 and 3 show that strong variations in δ-electron yields can be expected when the angle between incident direction and crystal axis (plane) is varied. A general investigation of the δ-electron yield from single crystals will also be of great interest.

ad B

Influence of Channeling on Nuclear Reaction Yield

As mentioned in section I , our earlier experiment and also the Monte Carlo simulation studies indicate that while positive channeled particles are kept away from the nuclei (thus giving rise to a drastic reduction in nuclear reaction yields) the negative channeled particles are focused around the nuclei resulting in (expected) large increase in close encounter processes. Since the possibility of increasing the reaction rates for nuclear processes is very intriguing and since we cannot solve the problem in a decisive way from existing data we find it most important to obtain these data with good statistics, using thin targets where dechanneling is less serious and where the effects we are looking for are expected to be much more pronounced (see Figure 11).

We plan to study the influence of channeling on two types of nuclear reactions, namely (1) Particle Productions and (2) Nuclear Elastic Scattering.

B(1) Particle Production

If the drift chamber DC3 (see section III and especially figure 12) is hit by two or more charged particles simultaneously ("multihits"), it could be signalizing the occurrence of a particle production event in the target but also δ -electron events may cause a multihit. However, since a δ-electron cannot give rise to an appreciable scattering of the beam particle, a small scintillation counter (SC5) in anticoincidence downstream from the target can effectively discriminate against such events. Note also that since we are not planning to identify the outgoing hadrons or to measure the outgoing angles very precisely, we can move DC3 very close to the target ($\sim$15 cm away) thus covering very large outgoing angles ($\sim 60^0$). By this method we are therefore able to detect almost all particle production events and obtain good statistics for a range of incident angle intervals both outside and inside the critical angle ψ_1 .($\sim$0.2 mrad in Ge).

B(2) Nuclear Elastic Scattering

Cross sections for nuclear elastic scattering can be obtained by combining measurements of the angle Θ and the velocity of a single outgoing charged particle with information of the kinetic energy T_R of the recoil$^{17)}$. If the velocity of the outgoing particle is the same as the beam particle velocity and if

$$T_R = \frac{(P\cdot\Theta)^2}{2M_R}$$

where P is the beam momentum and M_R the mass of the target nuclei, then the event is a nuclear elastic scattering event (no particle production and no nuclear breakup). The fraction of these events where the nucleus has been excited may be estimated by employing a large γ-ray detector placed near the target (Fig.12). The recoil kinetic energy can be measured because our target works as an energy-loss detector$^{18,19)}$.

For each individual event, the precision in this measurement is limited by the background ionization caused by the traversing relativistic particles. This ionization energy loss is statistically distributed (Landau distribution) and the shape of the distribution should be exactly the same in the two cases where

1) the beam particles pass through the target without suffering any large deflections (compared to the standard multiple scattering angles),
2) the beam particles are elastically scattered through a certain angle Θ, (large compared to multiple scattering angles),

the only difference being that in case 2) the whole distribution is moved upwards in energy by an amount which is related to the recoil kinetic energy T_R . On the other hand, if the nucleus breaks up during the process or if new particles are produced, then we can expect a changed energy-loss distribution (the right wing will get enhanced).

Thus it is possible - by comparing the observed energy deposit distribution belonging to a particular scattering angle Θ with the distribution obtained in case 1) - to isolate also for heavy nuclei like Ge (or Si) the differential elastic cross section

$$\frac{d\sigma}{dt}(\pi^{\pm}\mathrm{Ge} \rightarrow \pi^{\pm}\mathrm{Ge})$$

in the scattering angle interval

$$\Theta_{\text{mult.scat}} \ll \Theta \lesssim 30 \text{ mrad} ,$$

the high limit being set by the experimental arrangement we have in mind (see Section III). We would like to point out, however, that only a detailed test study of background, etc, will allow us to give a precise estimate of the accuracy with which the elastic cross sections can be obtained.

III. Setup

The experimental setup is nearly identical to the one used in PS channeling experiment (S150). Two small-size high-accuracy drift chambers (DC1 and DC2) separated by a 10-m vacuum pipe define the incoming charged particle, while the scattered track is detected by DC3 (50×50 cm^2). The target box contains a high precision remote controlled goniometer for angular adjustment of the target, which is a cooled ($\sim$90 K) Ge or Si solid-state detector. The emitted δ-electrons and γ-rays are detected by a solid-state annual detector and Na(I) detectors, respectively. For high precision scattering experiments (exp A1, A2, B2), DC3 is separated from the target by a 10-m long vacuum tube, whereas in the particle production experiment which requires a large solid angle, DC3 is placed close to the target. In experiment B2, a standard threshold Cerenkov is needed behind DC3 to determine the velocity of the outgoing particle. All the equipment, associated electronics and data-handling exist already.

IV. Beam and Running Time

A secondary non-separated high-energy charged beam is required, with intensity not exceeding 10^6/pulse in the range 2 - $\sim$20 GeV/c. A standard Cerenkov counter system for particle identification should be provided. The existing d_{31} in South Hall will at first meet our demands for testing the resolution, background, counting rate in the solid-state detectors. Further on we would like to test the possibility of measuring the emitted K-shell x rays and the background caused by δ-electrons. The installation could start in the beginning of 1979. The estimated running time will be around 8 weeks. We

REFERENCES

1) O.Fich et al., Aarhus-CERN-Strasbourg Coll. Channeling of 1.1 GeV/c Protons and Pions. Phys.Letters 57B (1975) 90

2) O.Fich et al. Aarhus-CERN-Strasbourg Coll. Ionization Loss of Channeled 1.35 GeV/c Protons and Pions, Phys.Rev.Letters 36 (1976) 1245

3) H.Esbensen et al. Aarhus-CERN-Strasbourg Coll. Channeling of Protons, Pions, and Deuterons in the GeV Region. Nucl. Phys.B127 (1977) 281

4) H.Esbensen et al. Aarhus-CERN-Strasbourg Coll. Channeling Effects for 15 GeV/c Negative Pions. Phys.Letters 72B (1978) 408

5) H.Esbensen et al. Aarhus-CERN-Strasbourg Coll. Random and Channeled Energy Loss in Thin Germanium and Silicon Crystals for Positive and Negative 2 - 15 GeV/c Pions, Kaons, and Protons. Phys.Rev.B, August 1978

6) S.K.Andersen et al. Aarhus-CERN-Strasbourg Coll. Nuclear Interactions for 15 GeV/c Protons and Pions under Random and Channeling Conditions in Germanium Single Crystals. Nucl.Phys.B (in press)

7) S.K.Andersen et al. Aarhus-CERN-Strasbourg Coll. Influence of Channeling on Scattering Phenomena for 2-15 GeV/c Pions, Kaons, and Protons. In preparation.

8) E.Uggerhøj, High-Energy Channeling, Invited Talk at Int. Conf.on Particle Interactions with Solids, Moscow, Sept.1978

9) D.Allen et al. Observation of Channeling of Negative Pions of 4 GeV/c Momentum. Nuovo Cimento Lett. 15 (1976) 529

10) C.Ankenbrandt et al. Proposal to Study Channeling at Fermilab. Sept.1975

11) D.Gemmell, LAMPF, private communication

12) Tsyganov et al. Proposal to Serpukhov

13) H.Esbensen and J.Golovchenko, Energy Loss of Fast Channeled Particles. Nucl.Phys.A298 (1978) 382

14) J.U.Andersen, J.Golovchenko, H.Nielsen, and E.Uggerhøj, Is it possible to measure elementary particle lifetimes using blocking technique? Submitted to Nucl.Phys.B

15) R.L.Walker et al. Phys.Rev.A11 (1975) 736

16) I.A.Grishaev et al. Zh.Eksp.Teor.Fiz.72 (1977) 437

17) T.Ekelöf, CERN Yellow Report 76-23

18) R.L.Lander et al., Nucl.Instr.Methods 42 (1966) 261
R.L.Lander et al., Nucl.Instr.Methods 67 (1969) 173
G.Bellini et al., Nucl.Instr.Methods 107 (1973) 85

19) J.Lindhard et al., Kgl.Danske Videnskab.Selskab, Mat.-Fys. Medd.33 (1963) No.12

FIGURE CAPTIONS

Fig.1 Energy-loss spectra for 15 GeV/c protons incident on a .74 mm Ge single crystal. The dots correspond to particles channeled along the $\langle 110 \rangle$ axis, and the circles correspond to particles incident in a "random" direction.

Fig.2 Comparison between the Esbensen and Golovchenko theory and experiment for leading edge ($\Delta E_{1/2}$) in random direction and in the $\langle 110 \rangle$ axial direction for both 0.74 mm Ge and 0.9 mm Si crystals.

Fig.3 Energy-loss spectra for 15 GeV/c π^- traversing the 0.74 mm Ge crystal. For the aligned particles, both incident and exit angles to the $\langle 110 \rangle$ axis are small compared to the critical angle for channeling.

Fig.4 Intensity distribution in the forward direction as a function of scattering angle for different incident angles to the $\langle 110 \rangle$. For comparison is plotted the Bohr-Williams (dashed) and the Moliere (solid) curves.

Fig.5 Three-dimensional intensity distribution in exit-angle space of a parallel 15 GeV/c proton beam (beam divergence = 0.05 mrad) transmitted through a Ge crystal.

Fig.6 The same as Fig.5 but for 15 GeV/c π^-.

Fig.7 Variation in wide-angle scattering yield as a function of angle between incident direction and the $\langle 110 \rangle$ axis. The plot is for 15 GeV/c protons scattered on a 4.2 mm Ge crystal.

Fig.8 The same as Fig.7 but for 15 GeV/c π^-.

Fig.9 Percentage of incoming 15 GeV/c protons and π^-, which suffer an extraordinarily large energy loss as a function of incident angle to the $\langle 110 \rangle$ axis. 5.1 MeV was used as the lower limit for large energy loss, which should be compared to the average energy loss of 2.3 MeV.

Fig.10 Comparison between Monte Carlo calculations (left) and experiment. The plot shows the intensity distribution in the exit angle space of 15 GeV/c π^- transmitted through a o.3 mm Ge crystal.

Fig.11 Impact-parameter distribution for 15 GeV/c protons and π^- traversing a 40μ <110> Ge crystal. The distributions are normalized to random.

Fig.12 Experimental setup.

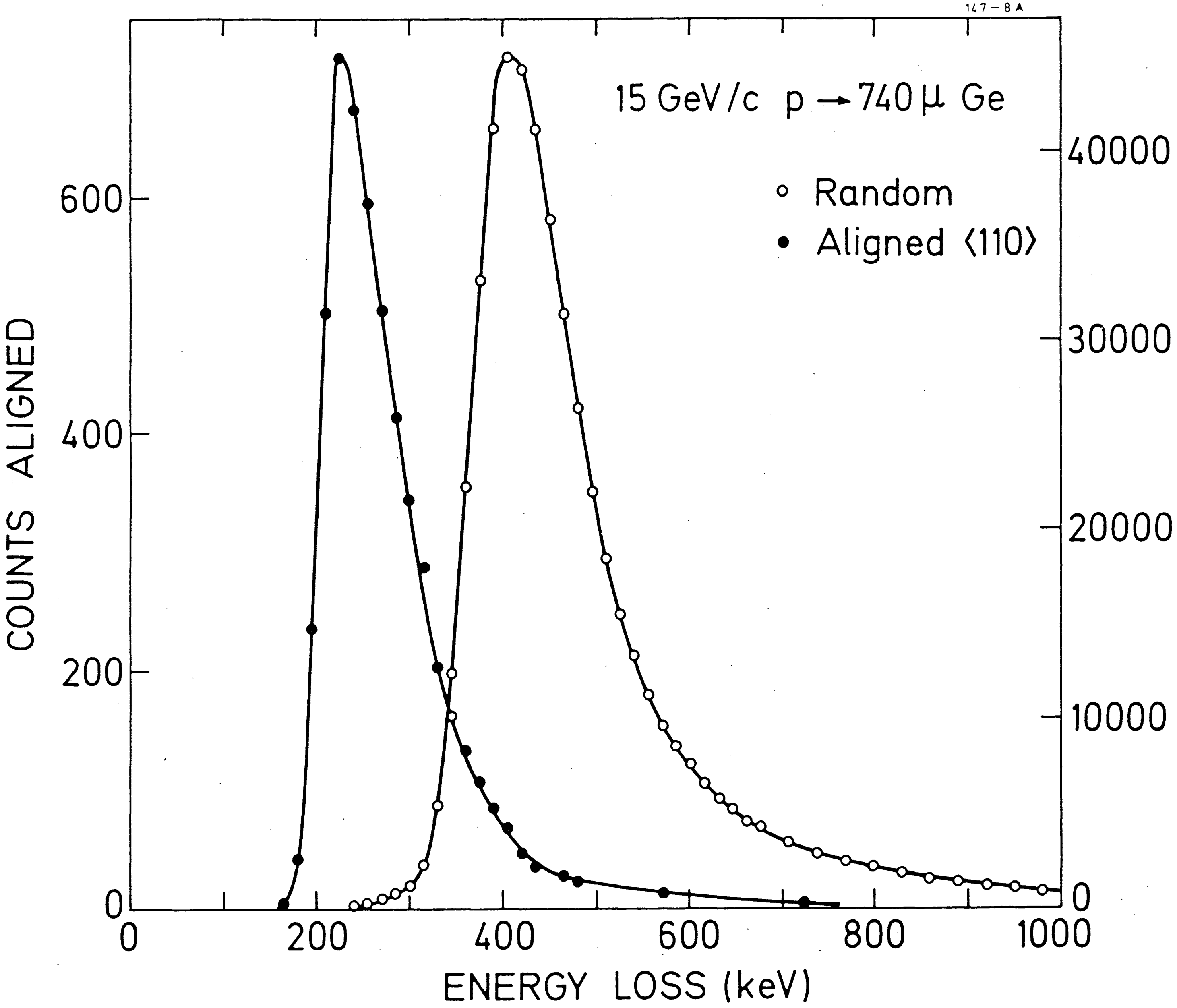
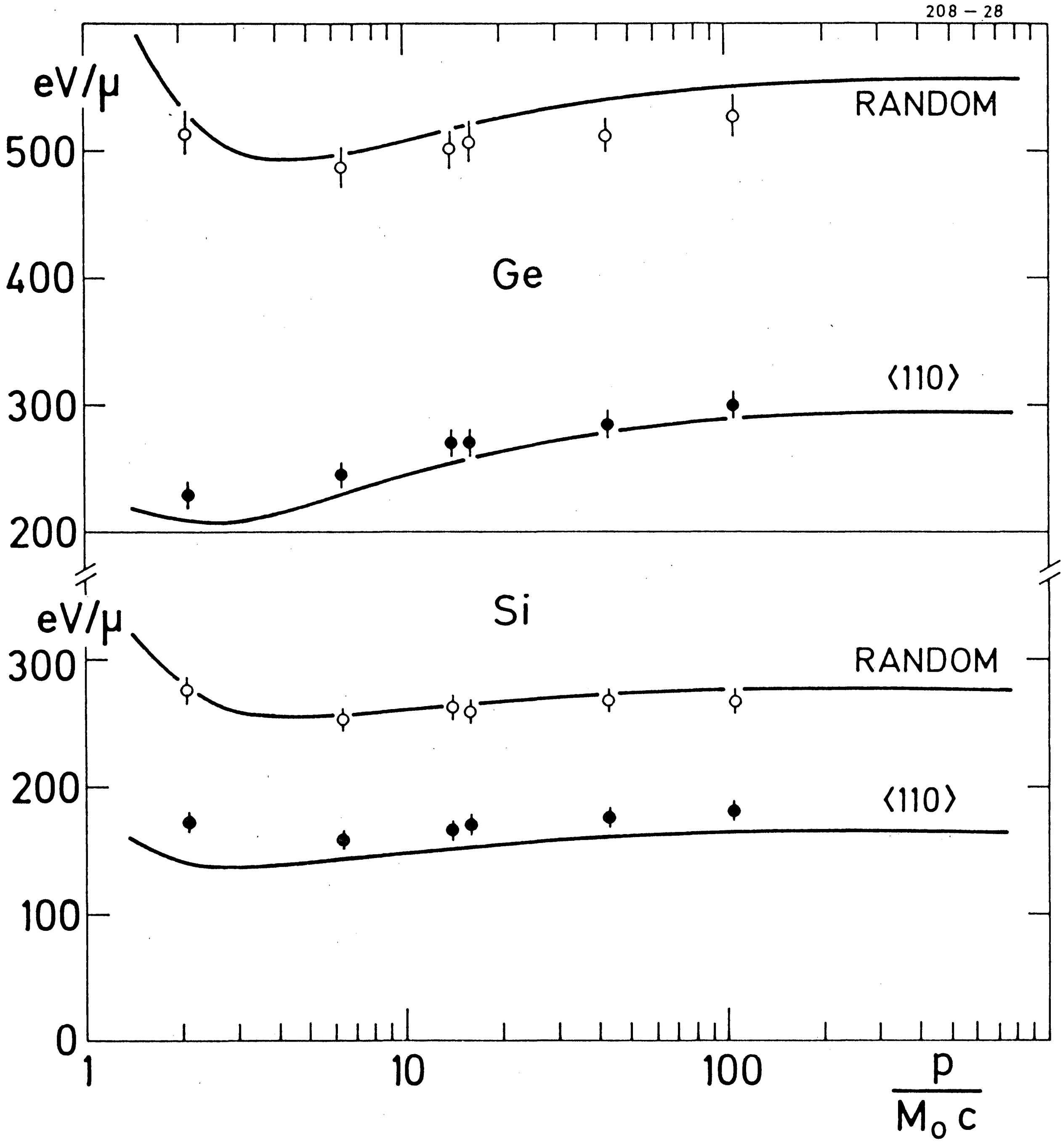

147 – 8A
15 GeV/c p → 740 μ Ge
○ Random
● Aligned ⟨110⟩
COUNTS ALIGNED
0
200
400
600
COUNTS RANDOM
0
10000
20000
30000
40000
0
200
400
600
800
1000
ENERGY LOSS (keV)

Fig 1



208 – 28
eV/μ
500
400
300
200
Ge
RANDOM
⟨110⟩
Si
eV/μ
300
200
100
0
RANDOM
⟨110⟩
1
10
100
p / M₀c

FiG 2

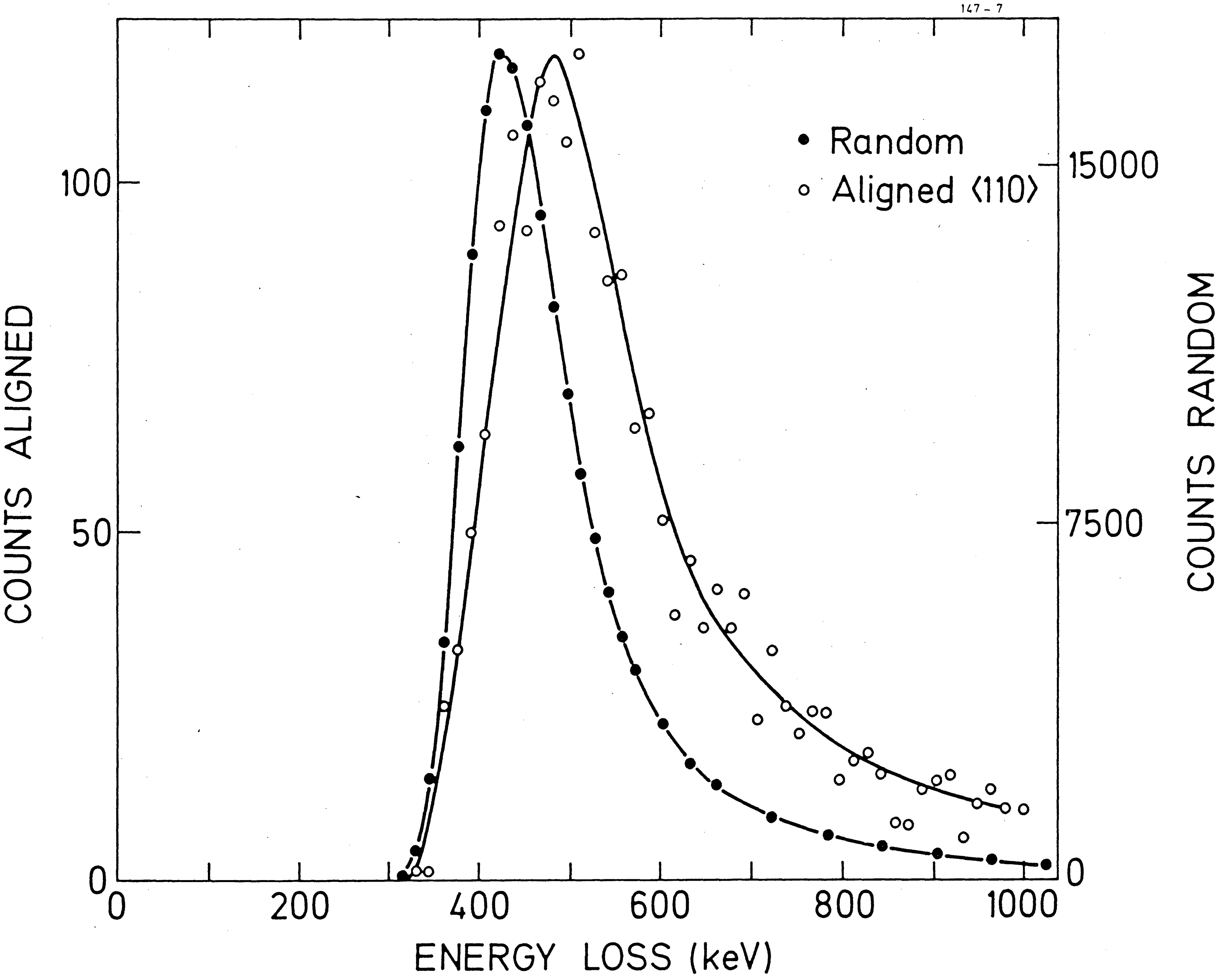

147 – 7
Random
Aligned ⟨110⟩
COUNTS ALIGNED
0
50
100
COUNTS RANDOM
0
7500
15000
ENERGY LOSS (keV)
0
200
400
600
800
1000

FiG 3

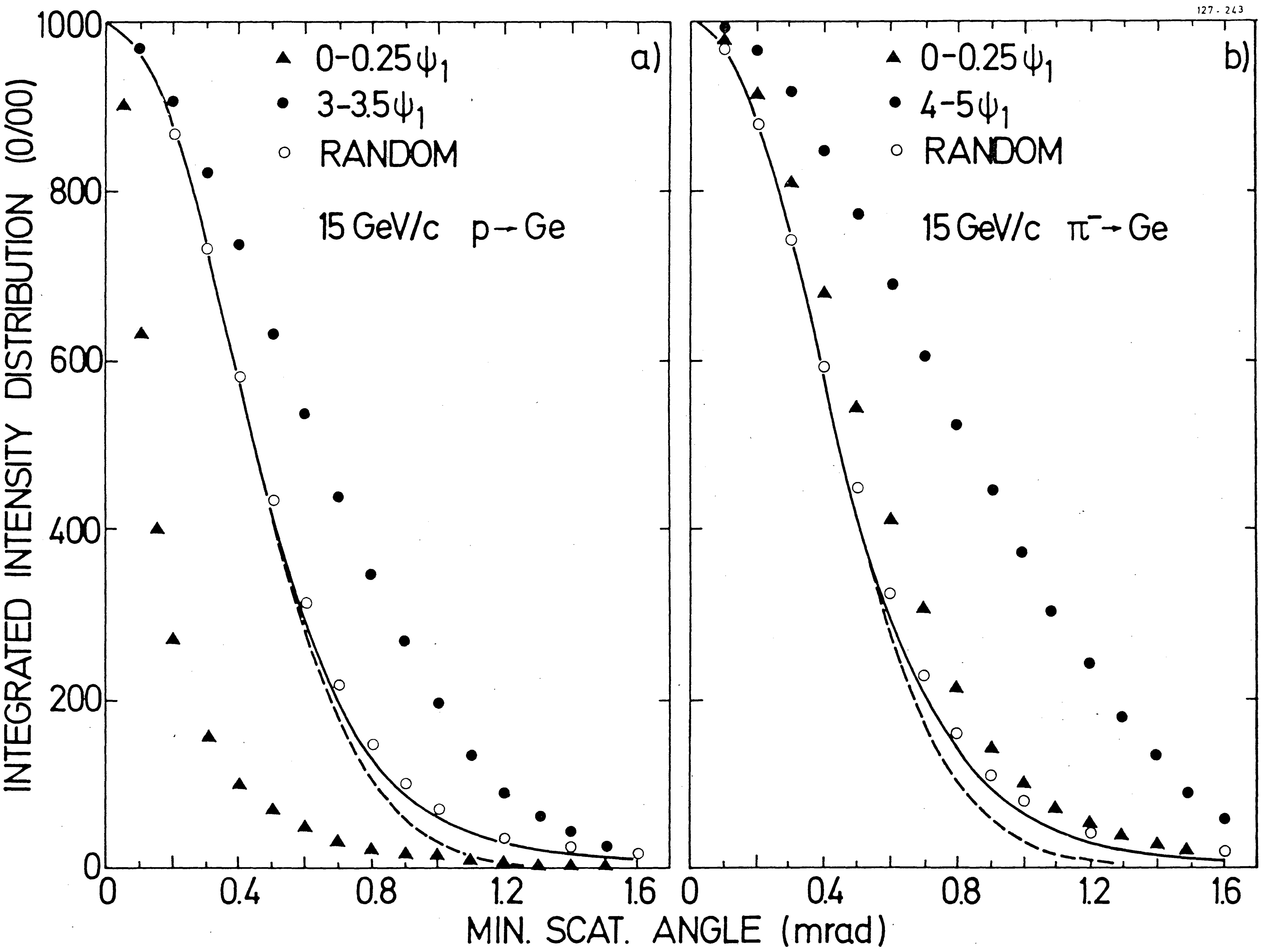

127 - 243
INTEGRATED INTENSITY DISTRIBUTION (0/00)
1000
800
600
400
200
0
a)
▲ 0-0.25ψ_1
● 3-3.5ψ_1
○ RANDOM
15 GeV/c p → Ge
b)
▲ 0-0.25ψ_1
● 4-5ψ_1
○ RANDOM
15 GeV/c π^- → Ge
0
0.4
0.8
1.2
1.6
MIN. SCAT. ANGLE (mrad)

Fig 4

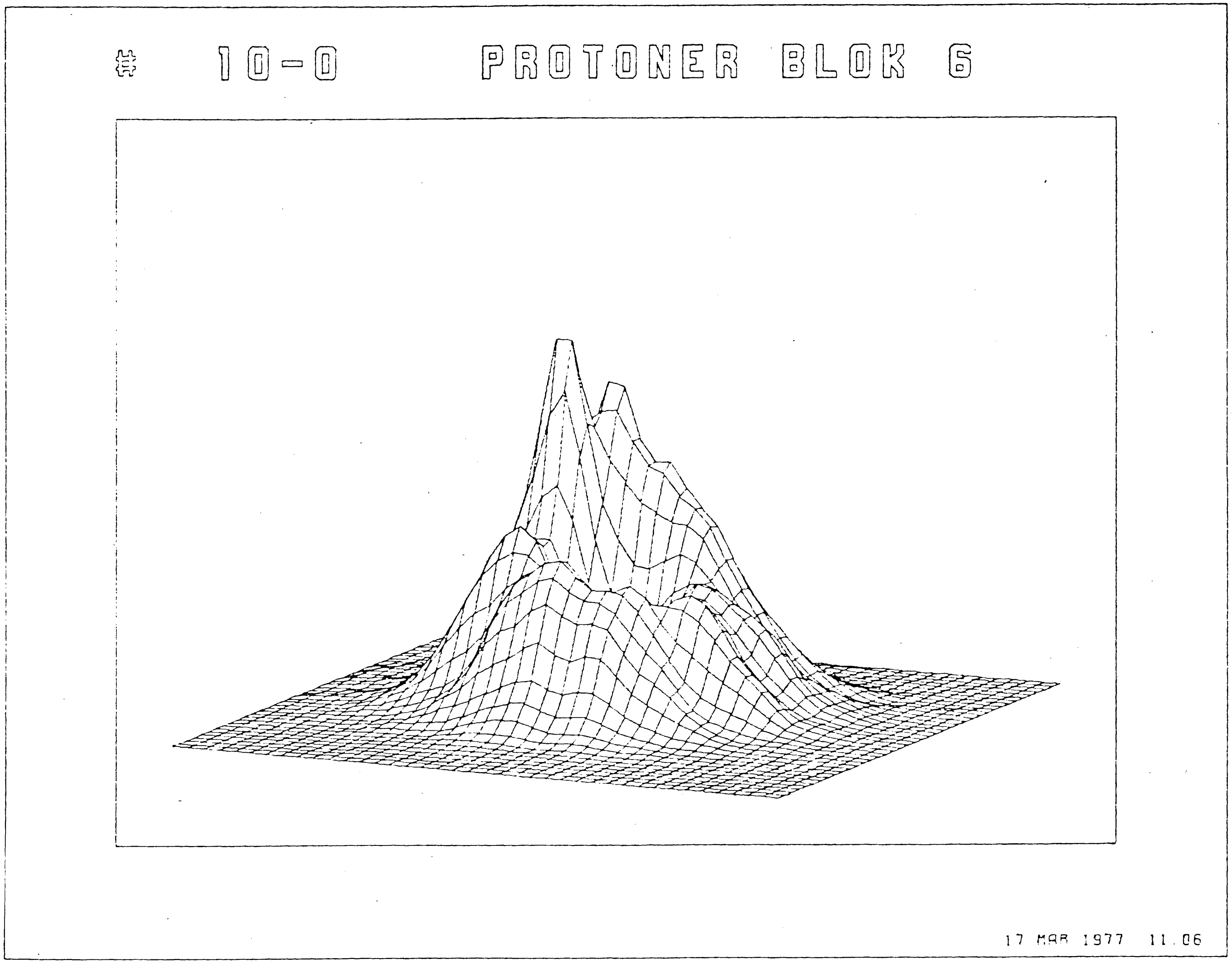


FIG 5

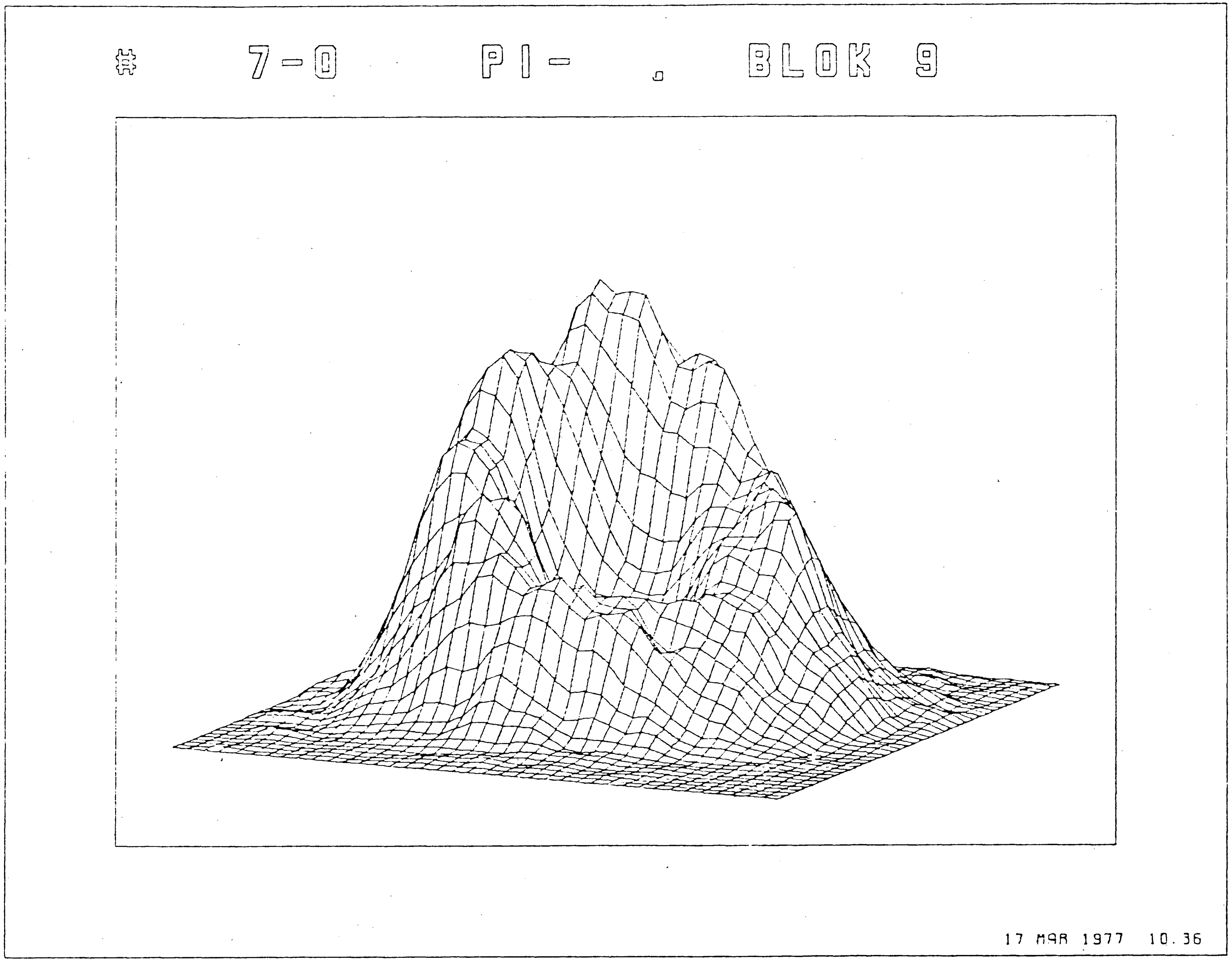


FiG 6

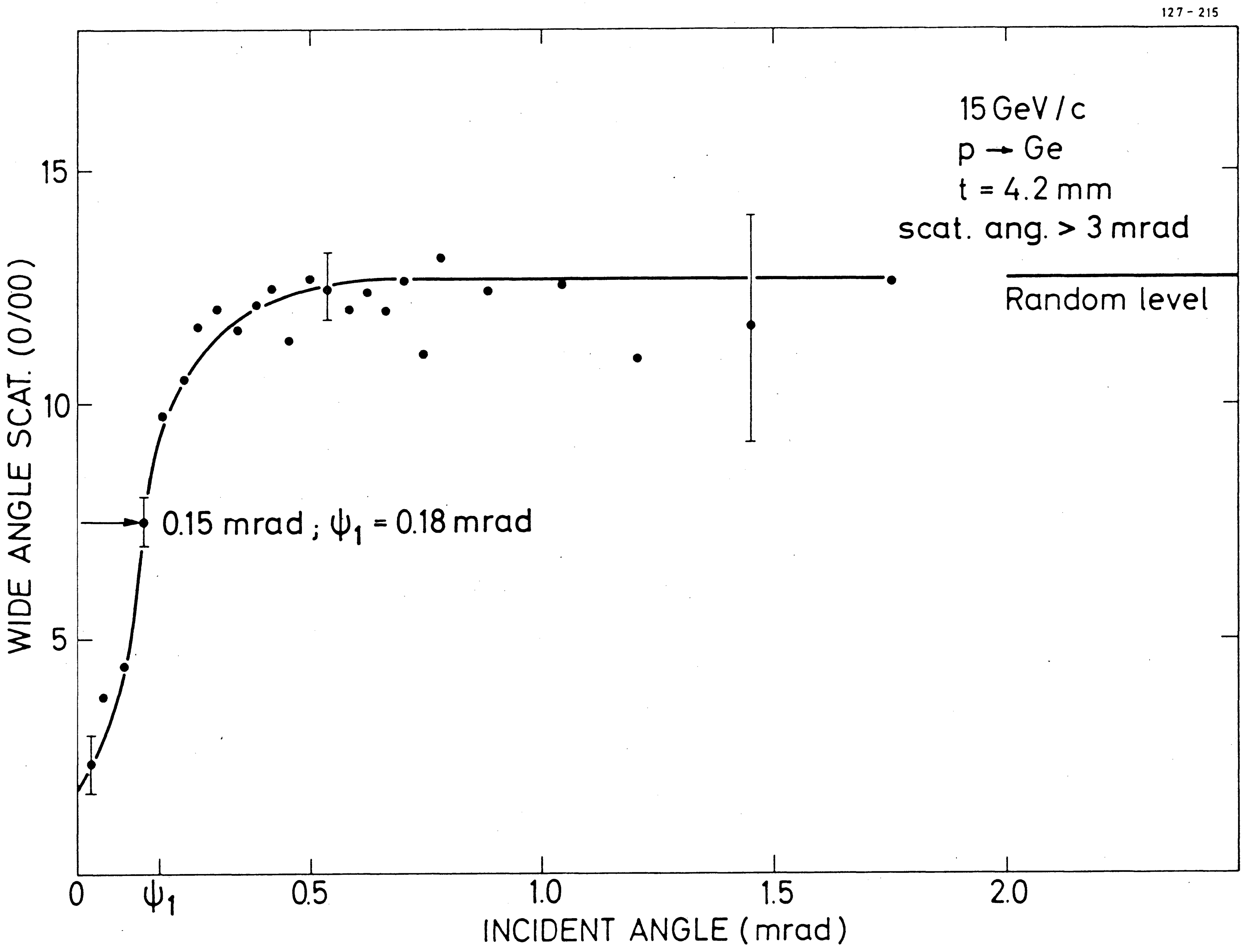

127 - 215
15 GeV / c
p → Ge
t = 4.2 mm
scat. ang. > 3 mrad
Random level
0.15 mrad ; ψ_1 = 0.18 mrad
WIDE ANGLE SCAT. (0/00)
15
10
5
0
ψ_1
0.5
1.0
1.5
2.0
INCIDENT ANGLE (mrad)

FiG 7

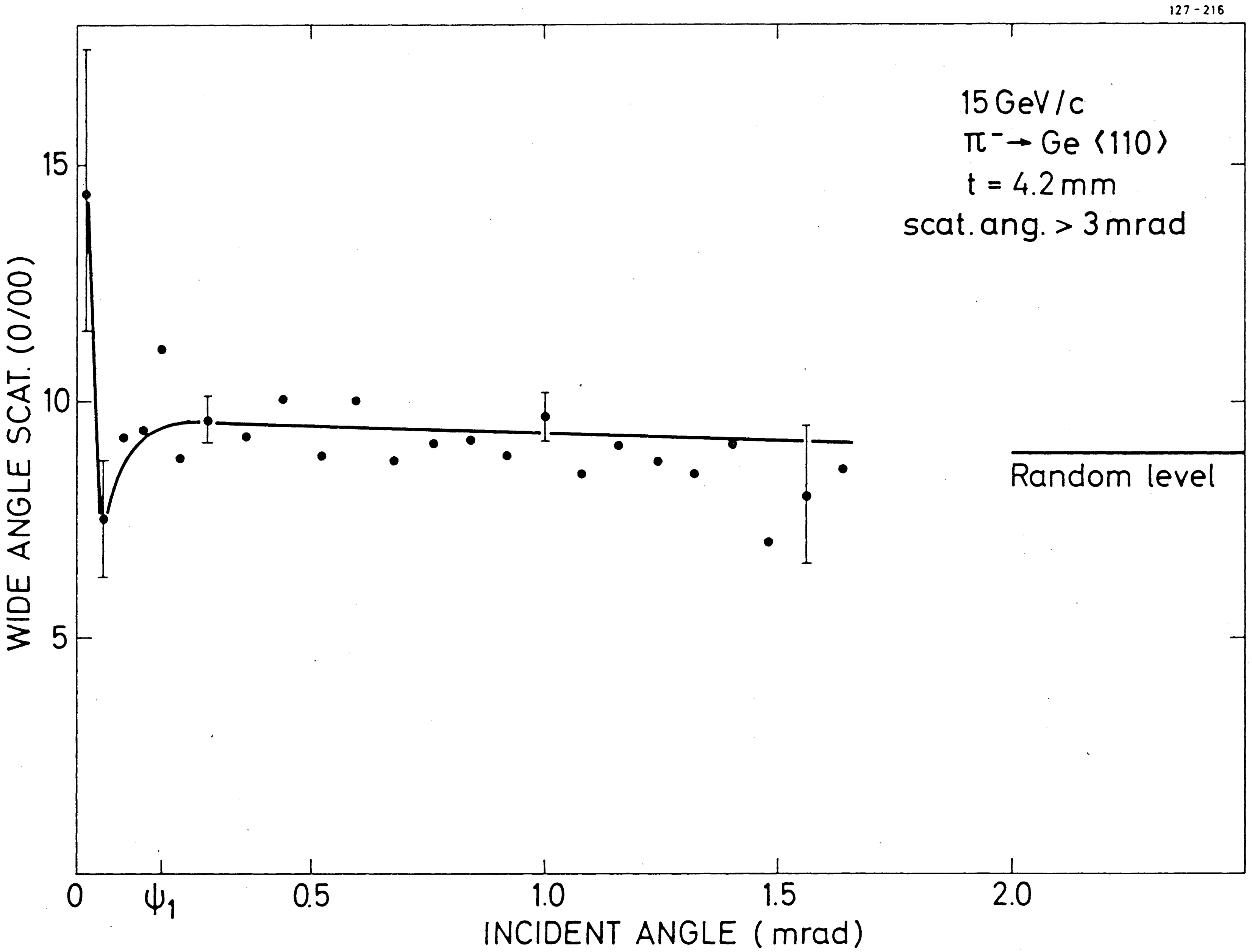

127-216
15 GeV/c
$\pi^- \rightarrow$ Ge ⟨110⟩
t = 4.2 mm
scat. ang. > 3 mrad
Random level
WIDE ANGLE SCAT. (0/00)
15
10
5
0
ψ_1
0.5
1.0
1.5
2.0
INCIDENT ANGLE (mrad)

Fig 8

126 - 67B

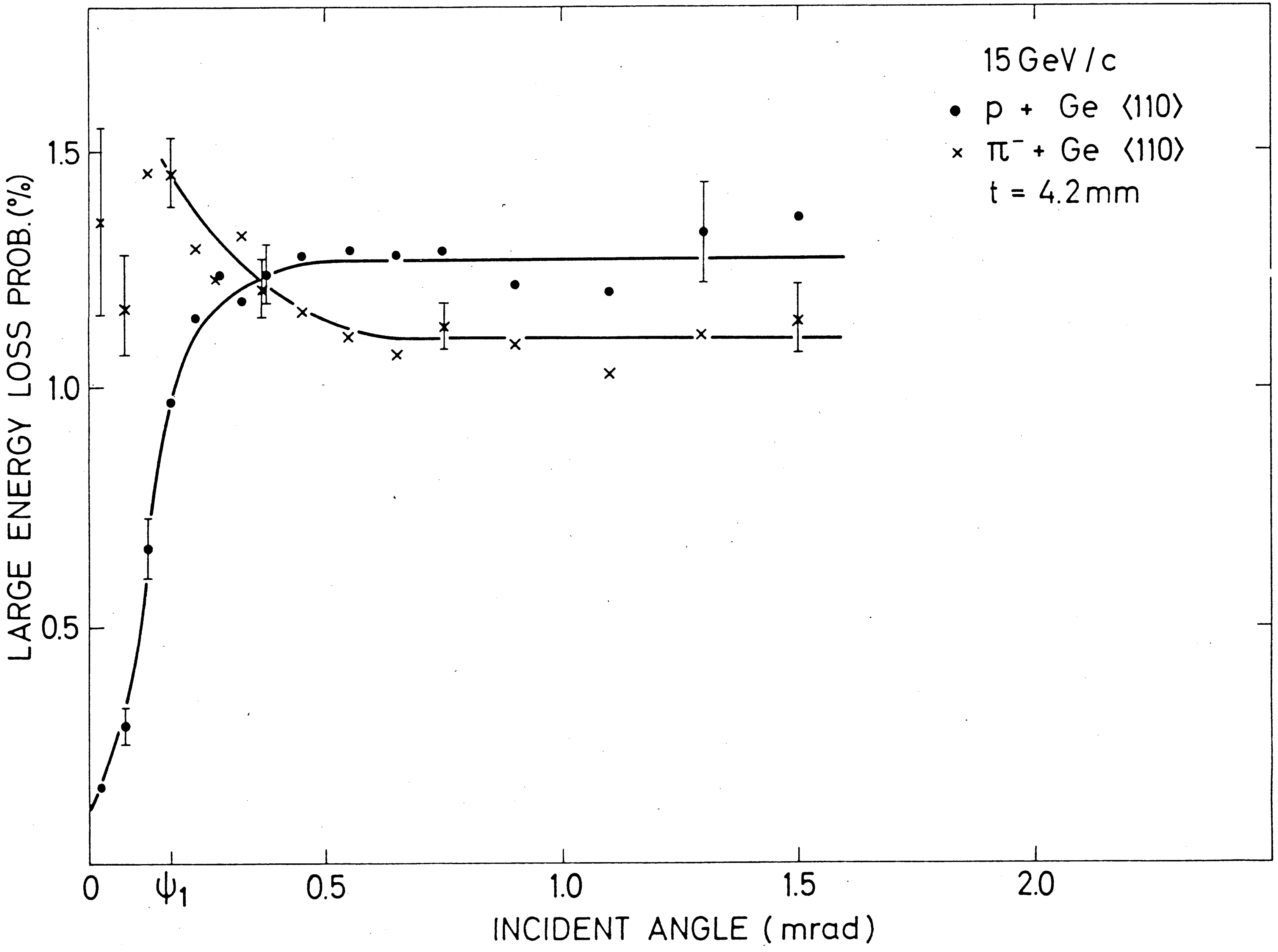

15 GeV / c
● p + Ge ⟨110⟩
× π⁻ + Ge ⟨110⟩
t = 4.2 mm
LARGE ENERGY LOSS PROB. (%)
1.5
1.0
0.5
0
ψ1
0.5
1.0
1.5
2.0
INCIDENT ANGLE (mrad)

FiG 9

15 Gev/c $\pi^- \rightarrow 300\ \mu$ Ge

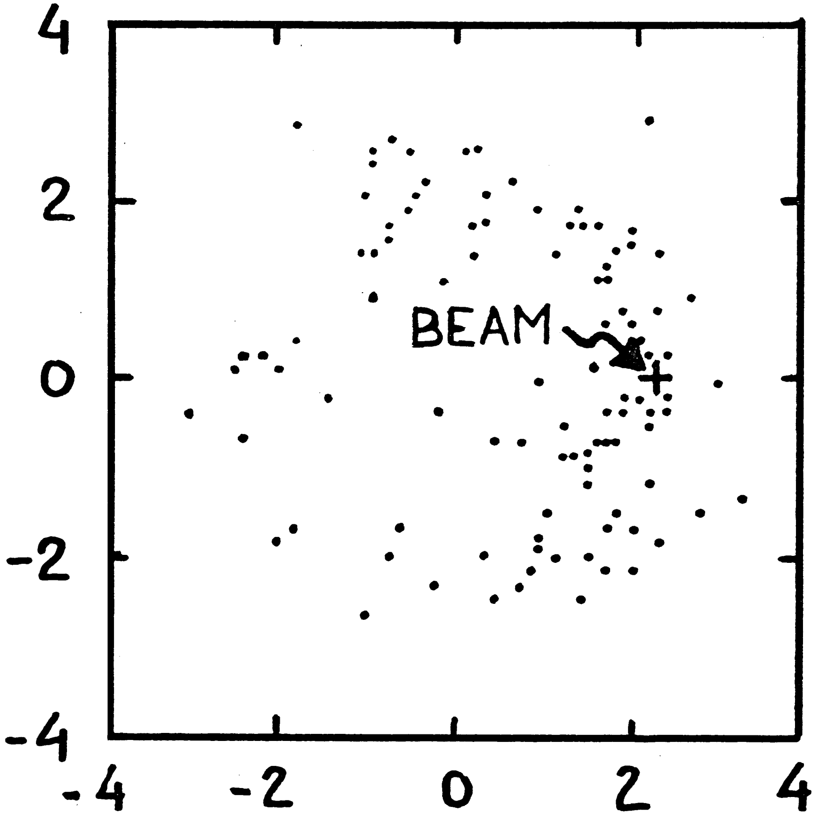


FIG 10 a

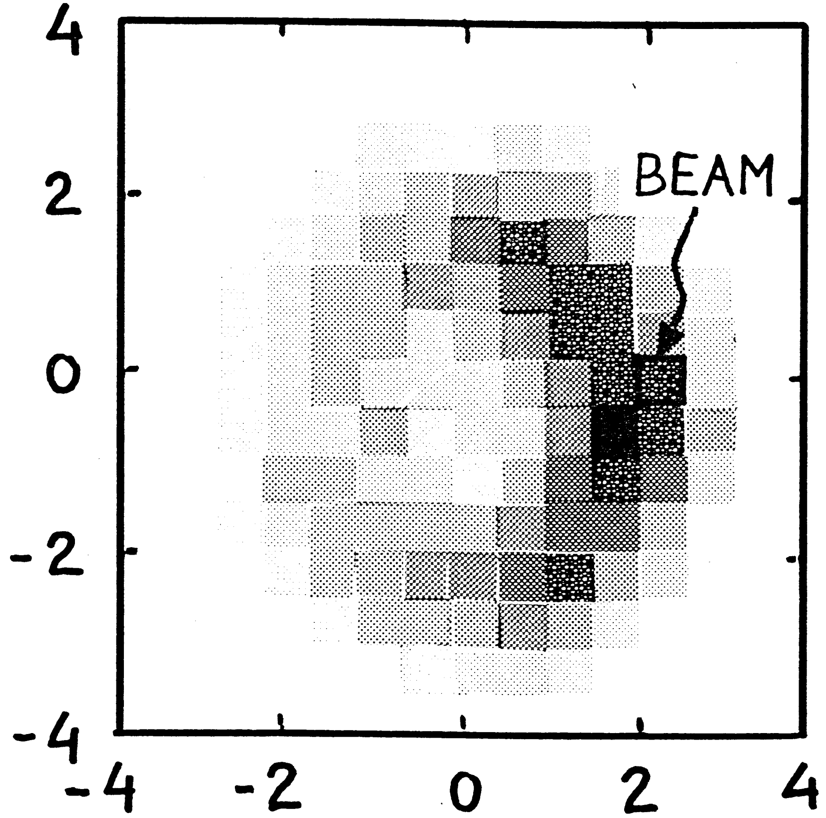


FIG 10 b

EXIT ANGLE RELATIVE TO ⟨110⟩ (UNIT ψ_1)

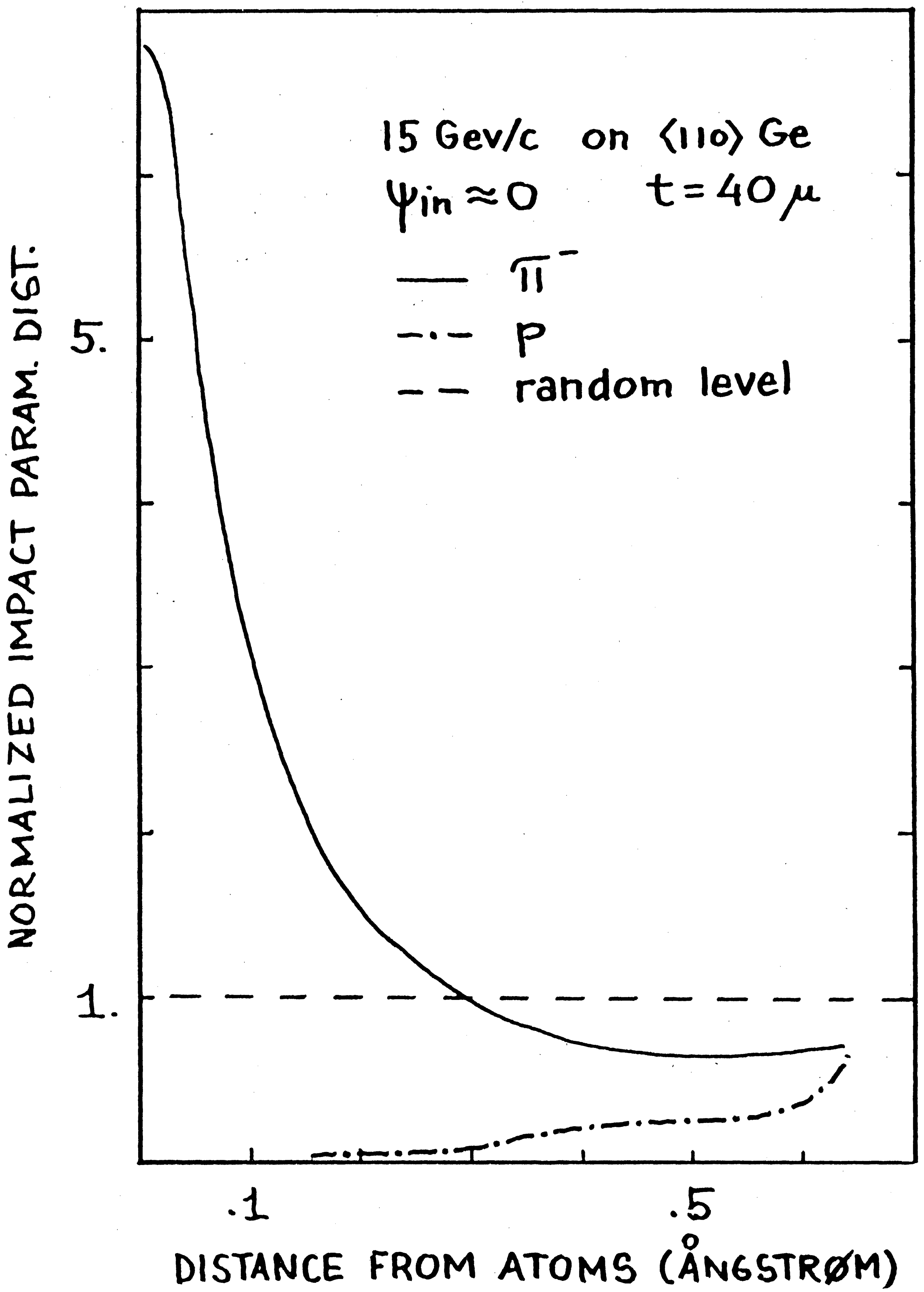

15 Gev/c on ⟨110⟩ Ge
ψin ≈ 0 t = 40 μ
π⁻
p
random level
NORMALIZED IMPACT PARAM. DIST.
5.
1.
.1
.5
DISTANCE FROM ATOMS (ÅNGSTRØM)

FIG 11

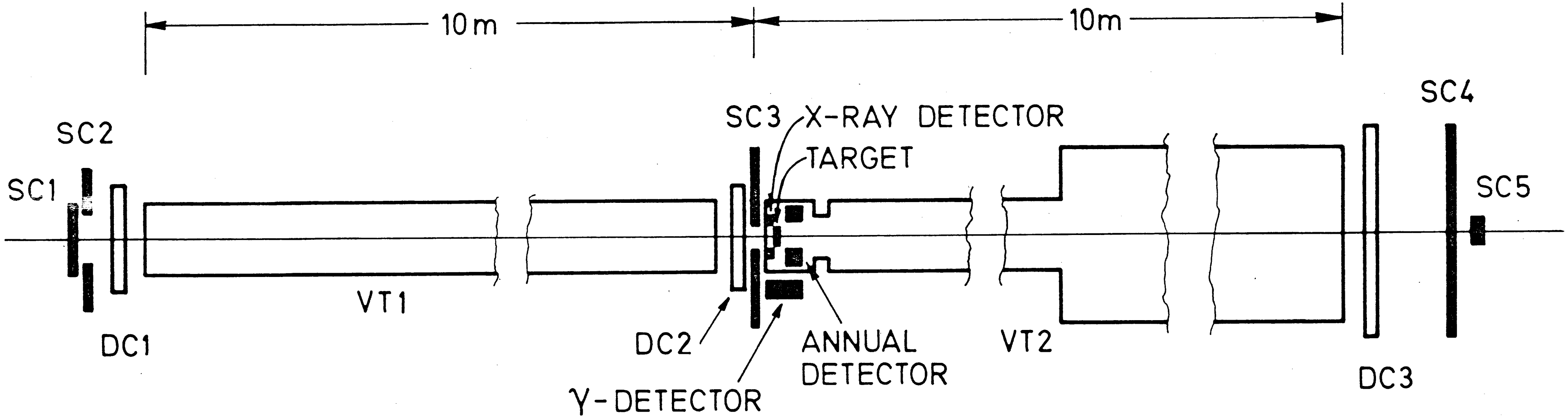

10m
10m
SC1
SC2
DC1
VT1
DC2
γ-DETECTOR
SC3
X-RAY DETECTOR
TARGET
ANNUAL
DETECTOR
VT2
DC3
SC4
SC5

Fig 12