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LIGHT PARTICLE PRODUCTION IN ^{12}C INDUCED REACTIONS AT CERN SC ENERGIES*)

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*) FROM INVITED TALKS AT THE 4:TH BERGEN WORKSHOP IN NUCLEAR PHYSICS, BERGEN, NORWAY, MARCH 22-24, 1982 AND THE DUBNA CONFERENCE ON NUCLEUS-NUCLEUS COLLISIONS AND NUCLEAR EXCITATIONS, DUBNA, USSR, JUNE 29 - JULY 2, 1982.

IN PART PRESENTED AT THE INT. CONF. ON SELECTED ASPECTS OF HEAVY ION REACTIONS, SACLAY, FRANCE, MAY 3-7, 1982 AND AT THE NORDIC MEETING ON NUCLEAR PHYSICS, FUGLSØ, DENMARK AUG. 16-20, 1982.

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The results from the first generation of experiments at the CERN synchrocyclotron with 30A MeV - 85A MeV ^{12}C beams are beginning to manifest the pattern of heavy ion reactions in the region between the binary low energy side and the "chaotic" high energy side, Results from experiments on the production of p, d and π at these energies are presented.

1. INTRODUCTION

At present two accelerators exist that can provide medium energy (~ 100A MeV) heavy ion beams - the Bevalac with a variety of low intensity (~ 10^7 s^{-1}) beams and the CERN synchrocyclotron with a limited selection of high intensity (~ 10^{11} s^{-1}) beams. The Bevalac experiments on projectile fragmentation /1/ at 90A MeV and 120A MeV have stressed the necessity of introducing low energy corrections (orbital deflections) into high energy descriptions (spectator-participant fragmentation). Experiments on light particle production /2/ have shown a striking difference in the beam energy dependence of the d/p, t/p and ^{4}He/p production ratios which may be a manifestation of the transition from the low energy binary processes with weakly excited residuals to the chaotic high energy region.

At the CERN synchrocyclotron the experimenters have so far mainly used the high quality ^{12}C beam at energies between 30A MeV and 85A MeV. Several investigations /3-7/ have been devoted to the heavy residual fragment(s). All these investigations seem to agree on the fact that the main part of the heavy fragments could be described as evaporation residues from some fast non-equilibrium process (e.g. a cascade process). A limitation of the momentum transfer to about 2 GeV/c seems to be established, particularly from investigations of the opening angle of fission fragments. Very recently a more violent multifragmentation mechanism has been observed in experiments where some kind of trigger for central ^{12}C + Ag collisions have been introduced /8,9/.

In this report we discuss recent results on p, d and π production from CERN SC experiments together with some indications of the multifragmentation process in a 4π experiment. Results from projectile fragmentation experiments are discussed elsewhere /10/.

2. Proton Production

2.1 Inclusive Data

The emission of high energy (E > 40 MeV) protons at large laboratory angles ($\theta_L > 30^o$) was studied with the particle telescope denoted "alt. 1" in Fig. 1. This experiment has been described elsewhere /11/ and we give here only the main features of the results.

i) The absolute cross-sections exhibit a target mass dependence of ~ $A^{2/3}$ while the form of the doubly differential spectra are very similar for all targets with $12 \leq A \leq 197$.

ii) The main part of the emission is described by a thermal (Boltzmann-) source which moves in the laboratory system with about half the beam velocity. The data does not exclude that nucleon-nucleon (NN) scattering may be the main origin of the protons. The apparent temperature of the source is ranging from 11 MeV for a ^{12}C target to 16 MeV for an Au target. For C + Ag reactions the temperature is increasing from 10.6 MeV at 58A MeV beam energy to 15.4 MeV at 85A MeV. These temperatures follow the universal trend of the hot source from 3A MeV to 1000A MeV c.m. energy /12/.

In order to measure complete proton spectra we repeated the experiment for $^{12}C + ^{197}Au$ with the low energy telescope in Fig. 1 and the high energy telescope denoted "alt. 2". The excellent mass resolution in the low energy telescope is evident from the ΔE-E correlations shown in Fig. 1. The rearrangement of the high energy telescope was performed mainly to avoid large multiple scattering corrections in the same proton energy region as in the previous experiment. Very good agreement with the earlier data /11/ was obtained (both form and absolute level) for energies > 60 MeV. Below 60 MeV the new cross-sections are larger which results in a less pronounced peak at ~ 60 MeV in the forward spectra. In Fig. 2 we present the doubly differential ($d^2\sigma/d\Omega dE$) cross-sections for protons with E > 6 MeV.

The expected dominance at low energies of an evaporation source is confirmed in the data. The source moving with about half beam velocity is dominating the high energy part at laboratory angles $\geq 35^o$ while at forward angles it is necessary to introduce the projectile evaporation (fragmentation) source. It should be noticed that the 3^o points are obtained for $^{12}C + ^{12}C$

reactions with a normalisation to C + Au cross-sections as described in the figure caption. Preliminary small angle data for heavier targets does not show any significant difference in the shape of the spectrum close to the projectile energy per nucleon.

From the spectra in Fig. 2 we thus observe in case one wants make the simplest possible description - that of thermal sources - it is not enough to use one single source but rather three sources. Proton spectra obtained both at lower beam energies and higher beam energies are however, sometimes described in terms of one single Boltzmann source /2/ and the reason for this can be understood if we make contour plots of the doubly differential cross-sections in the $p_{\parallel}$ - $p_{\perp}$ plane as is done in Fig. 3. The three contour plots represent the emission from three thermal sources in very assymetric collisions at 10A MeV, 100A MeV and 1A GeV. The 100A MeV contour curves should be realistic since they represent the sources used to fit the data in Fig. 2. The same spacing and strength of the contour curves have been used in the 10A MeV and 1A GeV figures and they should therefore naturally only be regarded as guide figures. At 10A MeV a compound nucleus is of course formed for small impact parameters, but this only means that the simple one peak shape of the doubly-differential cross-sections is even more pronounced. The intermediate velocity source could in some sense be understood as the source of the prompt emission of protons /14/ and we notice that this is the only contribution which may change the simple one-source evaporation shape of the doubly differential cross-sections. At high energies (1A GeV) it is obvious that the doubly differential cross-sections will be very flat especially if one measures the "normal" proton energy region for scintillator telescopes i.e. 20 - 200 MeV.

The 30° $d^2\sigma/d\Omega dE$ spectra of protons in Fig. 4, presented as guide curves for the data points of /13,15/ and our experiment, confirm that the only beam energy region where more than one thermal source is easily observed is the intermediate energy region.

In the spirit of a three-source description we made one leastsquares fit to all data points in the 85A MeV ^{12}C + ^{197}Au spectra (Fig. 2) of a target evaporation distribution + a participant Boltzmann distribution + a projectile evaporation (fragmentation) distribution. The high energy part of the large angle ($\theta \geq 35^{o}$) data is completely dominated by the Boltzmann source moving with half the beam velocity. Here we have noticed that the introduction of a radial collective energy flow /16,17/ gives a substantial improvement of the fit. The transformed cross-section is thus in this case taken to be:

$$\frac{d^2\sigma}{d\Omega dE} = C\sqrt{\frac{E}{S\cdot T\cdot\frac{1}{2}mv_r^2}}\ \sinh\left(\frac{2\sqrt{S\cdot\frac{1}{2}mv_r^2}}{T}\right)\exp\left(-\frac{S+\frac{1}{2}mv_r^2}{T}\right)$$

$$\text{where}\quad S = E+E_s-2\sqrt{E\cdot E_s}\cos\theta\ ; \qquad (1)$$

E_s is the kinetic energy per nucleon of the source in the laboratory system, T is the source temperature and v_r the radial flow velocity. The two evaporation sources are given the expression:

$$\frac{d^2\sigma}{d\Omega dE} = C\cdot\frac{1}{T^2}\sqrt{(E-E_c)\cdot S'}\ \exp\left(-\frac{S'}{T}\right) \qquad (2)$$

$$\text{Where}\quad S' = E-E_c+E_s-2\sqrt{(E-E_c)\cdot E_s}\cos\theta\ ,$$

E_c is the Coulomb barrier which was neglected in (1).

All the temperatures, the normalisation constants (C), the source velocities and the flow velocity are allowed to vary in the fitting procedure, except the projectile source velocity which is taken to be the beam velocity. The parameters which give the smallest χ^2 are given in table 1.

Table 1. Thermal source parameters obtained from the fit described in the text.

Parameter	Target evaporation source		Participant source		Projectile source	
	p	d	p	d	p	d
T (MeV)	6.2	7.6	12.0	12.7	7.0	8.0
β_s	0.03	0.03	0.18	0.19	0.40	0.40
β_r	-	-	0.19	0.13	-	-
Number of protons/event	2.0	0.7	1.2	0.6	1.2	0.5

The parameters seem to be quite reasonable at a first glance. Particularly we want to underline the fact that the flow velocity is close to the first order speed of sound. However, we notice the following difficulties.

i) The angular dependence of the low energy part of the proton emission is not well reproduced.

ii) Although the temperature of the intermediate velocity source is reduced from the inclusion of the collective energy flow, there seems to be a violation of the energy conservation in the participant source since the collective energy per nucleon + the average Boltzmann energy per nucleon is larger than the maximum available energy per nucleon (21 MeV for an equal participation system). Since both these difficulties may be connected with the participant (non-equilibrium) source (also the low energy part of the spectra have non-negligible contributions from this source) we would like to stress the necessity to make calculations where the non-equilibrium phase is treated properly - e.q. cascade calculations, time-dependent mean-field calculations (TDHF), fluid dynamics calculations, time-dependent hot spot calculations etc.

2.2 High Multiplicity Selected Data

In a 4π nuclear emulsion experiment /8/, all protons in each ^{12}C + Ag(Br) event of high multiplicity (the number of charged particles is ≥ 11) were identified. The multiplicity trigger means that 20% of all events are selected and if only the most central collisions are picked out in this way the maximum impact parameter should be about 4 fm and thus very little overlap of low density surface matter is expected. The doubly differential proton spectra (note that it is $d^2N/d\theta dE$) are shown in Fig. 5. When comparing the forward spectra with those obtained in the inclusive measurements (Fig. 2) we notice immediately that the projectile evaporation source is not at all observed and that the target evaporation peak is weaker. It seems as if the intermediate velocity source is dominating the scene completely. Though the low energy isotropic component is weaker it has been pointed out in /8/ that it exists and that it in fact seems to emanate from a source which is moving more slowly in the laboratory system than the source for the average ^{12}C + Au collision.

The fact that the proton emission exhibits a different behaviour in the high multiplicity C + Ag reactions could naturally depend on the selection of central events, but we want to emphasize also that the global (average) available energy per nucleon is 7.9 MeV compared to 4.6 MeV in the C + Au experiment. We will return to other characteristics of the high multiplicity events in the section 5.

3. Deuteron Production

Several experiments both in the 10A MeV region /13/ and at relativistic energies /18/ have shown that the doubly differential cross-sections of light composite particles are strongly correlated to the corresponding proton spectra. In the coalescence model /19/ this phenomenon is expressed in terms of the probability to find more than one nucleon in a small enough volume in momentum-space. Such an approach leads to an invariant $(\frac{1}{p^2}\frac{d^2\sigma}{dpd\Omega})$ cross-section for composite particles (mass number = A) which is proportional to the A:th power of the proton cross-section:

$$\frac{1}{p^2}\frac{d^2\sigma_A}{d\Omega\, dp} = \frac{1}{A!}\left(\frac{4\pi p_0^3}{3\sigma_R}\gamma\right)^{A-1}\left(\frac{d^2\sigma_p}{p^2 d\Omega\, dp}\right)^{A} \qquad (3)$$

Here σ_R denotes the reaction cross-section and σ_p the proton production cross-section. The only adjustable parameter is p_0, the so called coalescence radius which determines the size of the momentum-space sphere for condensation.

In a thermodynamical description the invariant spectrum is ~ exp(-E/T) where E is the total kinetic energy of the composite particle. If these particles emanate from the same thermal source as the protons we could consequently expect a spectrum which is proportional to the A:th power of the proton spectrum. Thus the coalescence condition should be fulfilled. In this case we must however interpret the radius parameter as one which tells us the size of the volume in thermal equilibrium.

In our experiment we have used the low energy telescope to measure spectra of d, t, ^{3}He and ^{4}He in addition to protons. Some preliminary conclusions from this experiment could be drawn although the analyses is still in progress:

i) The coalescence model does not fit very well into the energy region below 30 MeV.

ii) The relative yield of the composite particles are in agreement with the evaporation yields as they are given by Dostrovsky et al. /20/, for excitation energies of 200 - 300 MeV.

In the high energy region we have so far only analysed deuteron spectra in addition to protons. The doubly differential cross-sections are very similar to those of protons concerning the general shape (Fig. 6). An attempt to make the same very general fit to a three-source model, as was done for protons, is presented as solid curves in the figure. The parameters we obtain are given in table 1. We notice that the temperature and the parallel velocity of the "participant" source remains almost the same as for protons while the expansion velocity is somewhat smaller. Since the parameters are similar it it not surprising that a direct coalescence fit with formula (3) also gives a nice agreement with the data. In this case we find a coalescence radius of 190 MeV/c corresponding to a radius of the participant system /21/ of ~ 4.6 fm. This value follows the general tendency of a constant volume for all reactions (at least asymmetric ones) between 25A MeV and 2A GeV/21/.

4. Pion Production

In an exploratory experiment /22/ on π^+ production in 85A MeV ^{12}C induced reactions we found out that a fairly simple plastic scintillator telescope could be used to separate π^+ from protons (E_π > 20 MeV) when the signal from the $\pi^+ \rightarrow \mu^+ \nu^-$ decay (τ = 26 ns) was used as trigger signal. The $\Delta E - E$ correlation plot in Fig. 7 shows a typical pion to proton ratio which can be achieved at fairly large engles ($\theta = 55^{\circ}$) when a 100 ns gate is opened for the delayed signal. In a second experiment we were able to separate π^- and π^+ by using the monoenergetic (4.2 MeV) delayed energy signal for π^+ (Fig. 7) and effective on-line proton rejection conditions. Due to increased efficiencies of π^+ registration and the use of four telescopes of the type shown in Fig. 7 we were able to accept cross sections in the nb/sr region which meant that we could operate with projectile energies as low as 60A MeV and still use relatively thin (~ 50 mg/cm^2) targets.

Fig. 8 contains some of the data for π^+ production at 85A MeV and a comparison of π^+ and π^- cross-sections at 75A MeV. All spectra are falling off smoothly (exponentially) with energy which indicates that we are far from the coherent threshold for pion production where we could expect a resonant behaviour of the kind that has been observed for $^3He + {}^3He$ reactions at 94A MeV /23/.

The fact that the cross-sections in C + C reactions are symmetric in the c.m system (Fig. 9) has been further confirmed in the new measurements and shows that the relative yield at different angles and energies is reliable. A remeasurement of the C + C spectra at 85A MeV in the second experiment (Fig. 8) gave a very good agreement in the absolute cross-sections which makes us believe that the error in them are indeed within the 30% which was given in /22/. The asymmetry which is introduced in the C + Au spectra when looking in the nucleon-nucleon c.m system is also confirmed in the new C + Pb data. However, we believe that this asymmetry does not rule out the possibility of the main production mechanism being inelastic nucleon-nucleon scattering, because the original symmetry in this process may be washed out by the strong reabsorption in the heavy target nucleus.

An attempt to describe the measured cross-sections in an independent nucleon-nucleon scattering model using harmonic oscillator momentum distributions for the light nuclei and Woods-Saxon momentum distributions for the heavy nuclei is reported in /10/. The general conclusion from this kind of approach is that the shape of all $d^2\sigma/d\Omega dE$ distributions are very well reproduced while the absolute level of the cross-sections are overestimated. Due to the small Pauli blocking effect in the $NN \rightarrow d\pi$ channels compared to the $NN \rightarrow NN\pi$ channels the former ones dominate the emission completely. Thus it seems as if the input of free $NN \rightarrow d\pi$ cross-sections according to the available nucleon-nucleon energy distribution in the heavy ion reaction, followed by Pauli blocking for two nucleons in the same momentum cell, results in too high production cross-sections. Calculations within thermodynamic models are in progress /24/.

Some preliminary data, which makes comparisons with models more selective, concerns the beam energy dependence of the cross-sections, the target mass dependence and the π^-/π^+ ratio. Fig. 10 shows an attempt to use Ne + NaFπ^+ production data /25, 26 / at higher beam energies and compare it to our C + C data at 60A MeV, 75A MeV and 85A MeV. Since the integration over angles and energies contains various extrapolations of existing data and the conversion of Ne + Ne cross-sections to C + C cross-sections contains an assumption of an $A^{0.8}$ mass dependence (this was found in our data) we stress that large errors in the points should be expected. We still feel that Fig. 10 gives the right trend in the fall-off of the cross-section with decreasing beam energy. We have observed that the decrease with a factor 20 between 85A MeV and 60A MeV is in agreement with the first nucleon-nucleon scattering approach /10/.

A strong increase in the cross-section for π^+ production at 85A MeV between C + Li and C + C reactions is found (about a factor of 4 different) while an $A^{0.8}$ dependence is found for heavier targets. In a nucleon-nucleon scattering model where the boost from the Fermi energies is necessary for the pion production such a strong mass dependence for light nuclei simply reflects the drastic extension of the tail of the internal momentum distribution when increasing the target mass.

Finally it should be mentioned that we find a significantly larger π^-/π^+ ratio both for a ^{7}Li target and a ^{208}Pb target compared to a ^{12}C target. The question whether this simply reflects the Z/(A-Z) ratio of the target nucleus remains to be answered when all our data is analysed.

5. Multifragmentation

It was mentioned in connection with the proton production that in high multiplicity C + Ag events at intermediate energies (55 - 110A MeV) there is a component of low energy protons which seems to emanate from a very slow source. In this emulsion experiment / 8/ also the heavy fragments were identified either directly if the range is long enough or indirectly from the identification of all other charged products in the event. In general we find in these collisions a very low energy heavy $(Z \approx \frac{Z_{PROJ} + Z_{TARGET}}{2})$ residual nucleus with a velocity in the laboratory system comparable to the proton source velocity, i.e. $\beta \approx 0.01$. At the same time we find, particularly in one fraction of the events, that several medium heavy fragments $(2 \leq Z \leq 30)$ can be emitted from the same collision. Fig. 11 shows the charge distribution in all the central events and in a few violent events individually. The ordinary heavy ion reaction models, which contain a rapid pre-equilibrium process which develops into a slow equilibrium emission of light particles, leaving an evaporation residue behind, could not describe the characteristics of these central collisions.

It is indeed encouraging that multifragmentation descriptions /27,28/ for 100A MeV collisions have been presented lately. The fragment mass distribution in the region $1 \leq A \leq 15$ which comes from the statistical model for the disassembly of nuclear matter /27/ is quite reasonable in comparison with the data. However, we observe also large fragments which hardly could be described as evaporation residues and also an excess of high energy protons (and neutrons) which must come from other processes like nucleon-nucleon scattering or from a nonuniform concentration of energy to particular hot zones in the system /28/.

6. Conclusion

It is obvious that the dramatic increase of the available energy per nucleon of the active system in intermediate energy heavy ion collisions, which contains the passage of the binding energy per nucleon, calls for a large variety of systematic experiments. Many beam-target combinations at several energies have to be studied in detail. Naturally it is not enough to study the inclusive spectra of particles but it is our feeling that there is a better chance in the 100A MeV region, than at relativistic energies to be able learn something about the underlying physics from this kind of data.

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Figure captions

1. The particle telescopes used by the Bergen-CERN-Copenhagen-Grenoble-Lund collaboration in the CERN SC experiments on light particle production. S denotes plastic scintillators and Si denotes fully depleted silicon detectors. The correlations are examples of ΔE-E registrations in the low energy telescope (lower left) and E-time of flight registrations for high energy particles in the telescope denoted "alt. 1".

2. Doubly differential cross sections for protons from C + Au reactions at 85A MeV ($\theta_L \geq 35^\circ$). For $\theta_L = 3^\circ$ the points are obtained for C + C reactions and they are renormalised to the level of the projectile evaporation source which is obtained from the fitting procedure of the three thermal source model described in the text. The solid curves are the results of this fit.

3. A $\frac{1}{p}\frac{d^2\sigma}{d\Omega dE}$ contour plot in the $p_{\parallel} - p_{\perp}$ plane of protons emitted from three thermal sources according to the model described in the text. The thickness of the contour curves describes the absolute cross-sections with a difference of one order of magnitude between each curve. The curves in b are taken from the fit of the model to the 85A MeV data while the curves in a and c should be regarded only as guide figures.

4. Doubly differential cross-sections of protons at $30^\circ \leq \theta_L \leq 35^\circ$ for ^{16}O + ^{197}Au at 8.8, 13.4 and 19.4A MeV /13/, ^{12}C + ^{108}Ag at 58A MeV (this work), ^{12}C + ^{197}Au at 85A MeV (this work), ^{20}Ne + ^{238}U at 241A MeV /15/, ^{20}Ne + ^{197}Au at 393A MeV /15/ and ^{20}Ne + ^{238}U at 1050 and 2100A MeV /15/. Guide curves from the data points have been drawn. The fine structure in the 1050A MeV data is probably due to large statistical errors only.

5. Doubly differential spectra ($d^2N/d\theta dE$) of protons emitted in high multiplicity ^{12}C + Ag(Br) events at energies between 55A MeV and 110A MeV, ($\langle E \rangle$ = 88A MeV).

6. Doubly differential cross-sections of deuterons emitted in ^{12}C + ^{197}Au reactions at 85A MeV.

7. The plastic scintillator telescope used to registrate both π^+ and π^- in the experiment described in section 4. The lower figures show the ΔE-E correlation obtained in scintillator 6 + 7 when the delayed $\pi^+ \rightarrow \mu^+ + \bar{\nu}$ signal is used as trigger signal and the $E_{delay} - E_{prompt}$ correlation obtained in scintillator 7.

8. Examples of $d^2\sigma/d\Omega dE$ spectra of pions from 85A MeV and 75A MeV ^{12}C induced heavy ion reactions. The points denoted $+$ and $\times$ are from the previous experiment /22/.

9. The Lorenz invariant doubtly differential spectra of π^+ from C + C and C + Au collisions in three different coordinate systems. The curves are labelled with the energy in the actual system.

10. The total yield of π^+ in C + C reaction at different beam energies (from /25,26/ and this experiment); The Ne + Ne cross-sections have been multiplied with $(\frac{12}{20})^{1.6}$ to account for a mass dependence of $A^{0.8}$.

11. The charge distribution of all fragments emitted in high multiplicity ^{12}C induced reactions in nuclear emulsion at 55A MeV - 110A MeV. The small figure is the result if all indirectly measured heavy fragments are coming from C + Br collisions and the large figure the corresponding result for C + Ag collisions. The latter one is more realistic since ~ 2/3 of all interactions should be C + Ag.

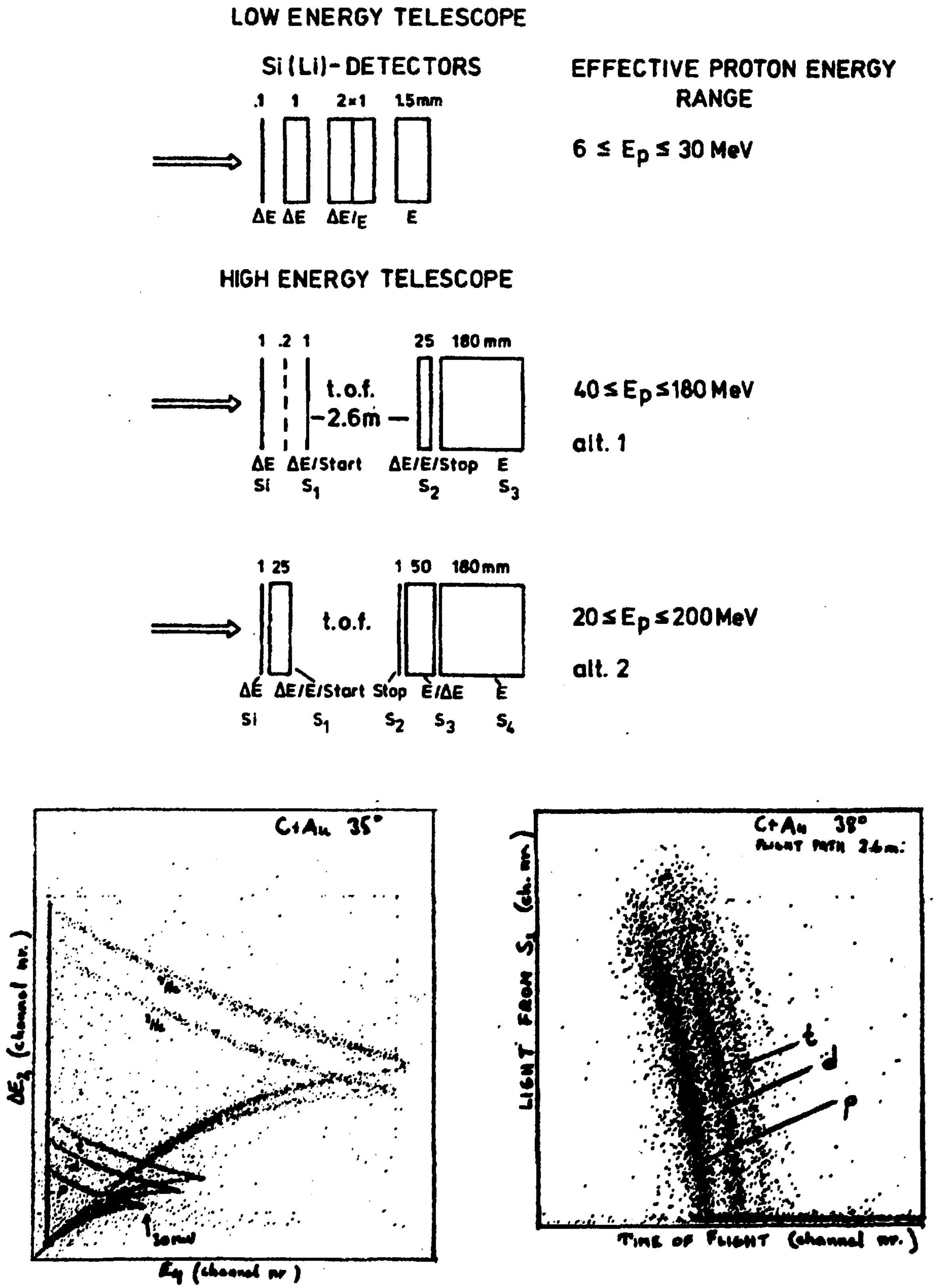

LOW ENERGY TELESCOPE
Si(Li)-DETECTORS
.1
1
2×1
1.5mm
ΔE ΔE ΔE/E E
EFFECTIVE PROTON ENERGY RANGE
6 ≤ E_p ≤ 30 MeV
HIGH ENERGY TELESCOPE
1 .2 1
25 180mm
t.o.f.
-2.6m -
ΔE Si
ΔE/Start S_1
ΔE/E/Stop S_2
E S_3
40 ≤ E_p ≤ 180 MeV
alt. 1
1 25
1 50 180mm
t.o.f.
ΔE Si
ΔE/E/Start S_1
Stop S_2
E/ΔE S_3
E S_4
20 ≤ E_p ≤ 200 MeV
alt. 2
C+Au 35°
^{4}He
^{3}He
30mm
ΔE_3 (channel nr.)
E_4 (channel nr)
C+Au 38°
FLIGHT PATH 2.6m.
t
d
p
LIGHT FROM S_1 (ch. nr.)
TIME OF FLIGHT (channel nr.)

FIG. 1

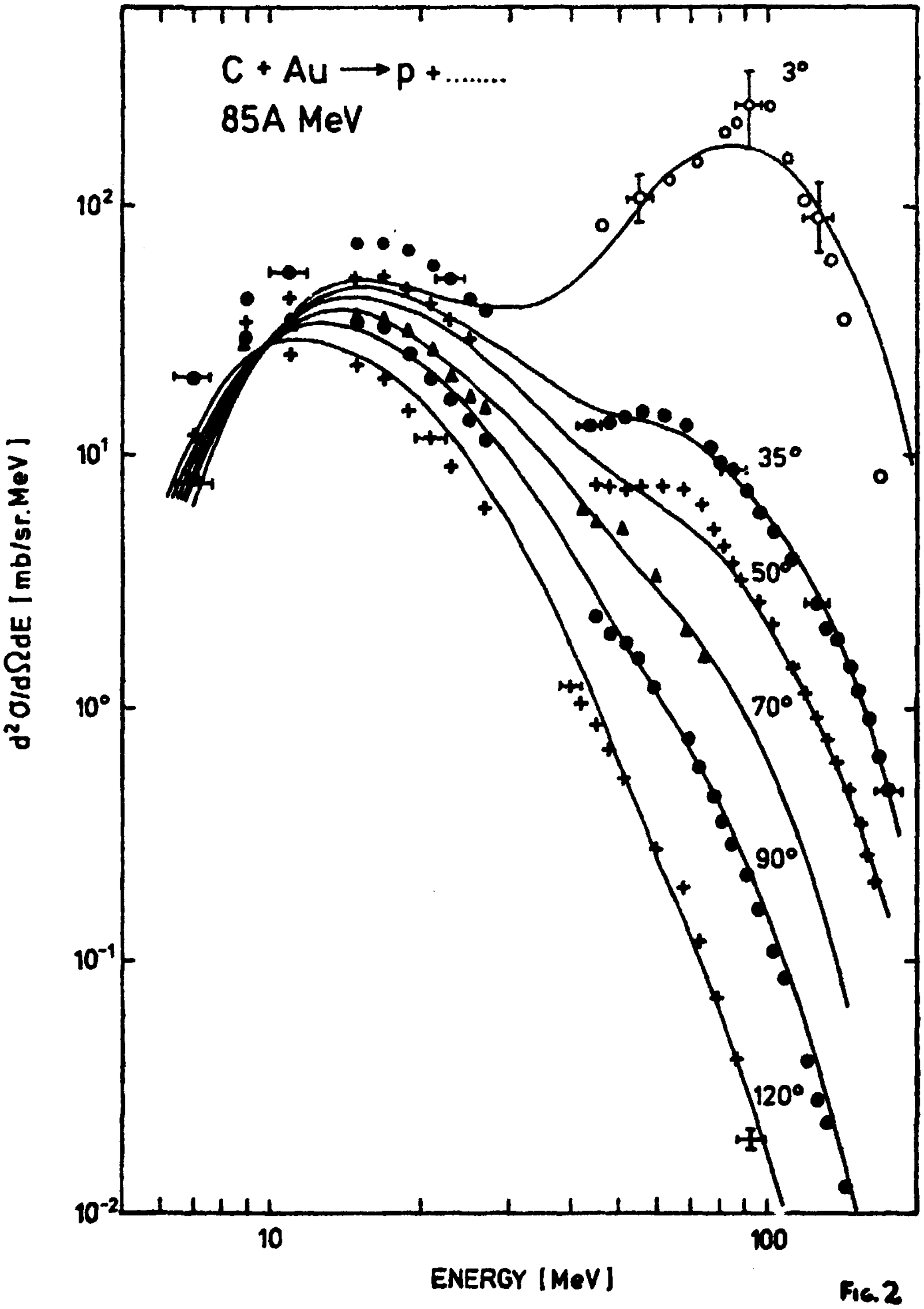

C + Au ⟶ p + ...
85A MeV
3°
35°
50°
70°
90°
120°
10^2
10^1
10^0
10^{-1}
10^{-2}
10
100
$d^2\sigma/d\Omega dE$ [mb/sr.MeV]
ENERGY [MeV]

FIG. 2

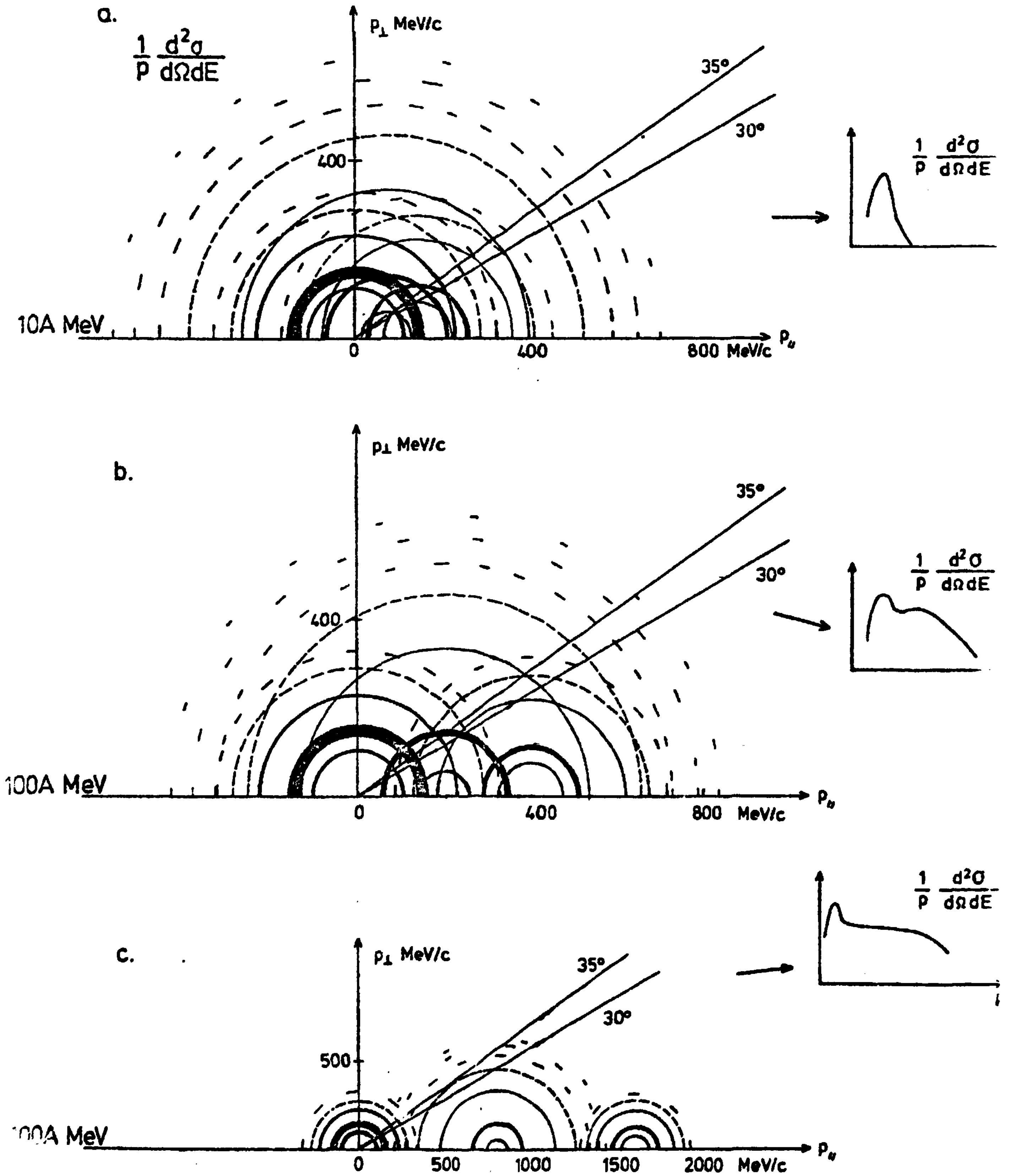

a.
$\frac{1}{p}\frac{d^2\sigma}{d\Omega dE}$
$p_\perp$ MeV/c
35°
30°
400
10A MeV
0
400
800 MeV/c
$p_\parallel$
$\frac{1}{p}\frac{d^2\sigma}{d\Omega dE}$
b.
$p_\perp$ MeV/c
35°
30°
400
100A MeV
0
400
800 MeV/c
$p_\parallel$
$\frac{1}{p}\frac{d^2\sigma}{d\Omega dE}$
c.
$p_\perp$ MeV/c
35°
30°
500
00A MeV
0
500
1000
1500
2000 MeV/c
$p_\parallel$
$\frac{1}{p}\frac{d^2\sigma}{d\Omega dE}$

FIG. 3

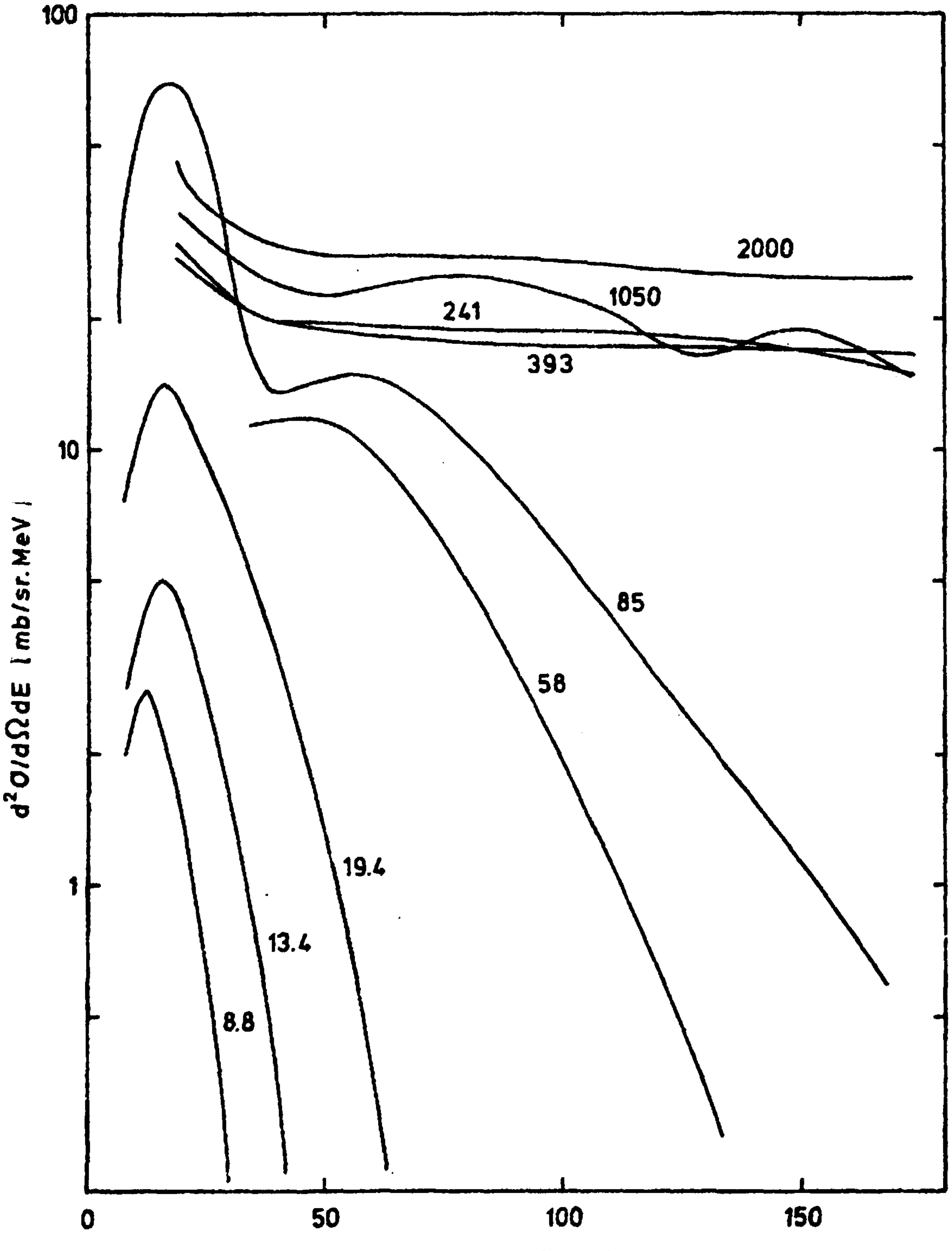

100
10
1
0
50
100
150
ENERGY [MeV]
d²σ/dΩdE [mb/sr.MeV]
2000
1050
241
393
85
58
19.4
13.4
8.8

Fig. 4

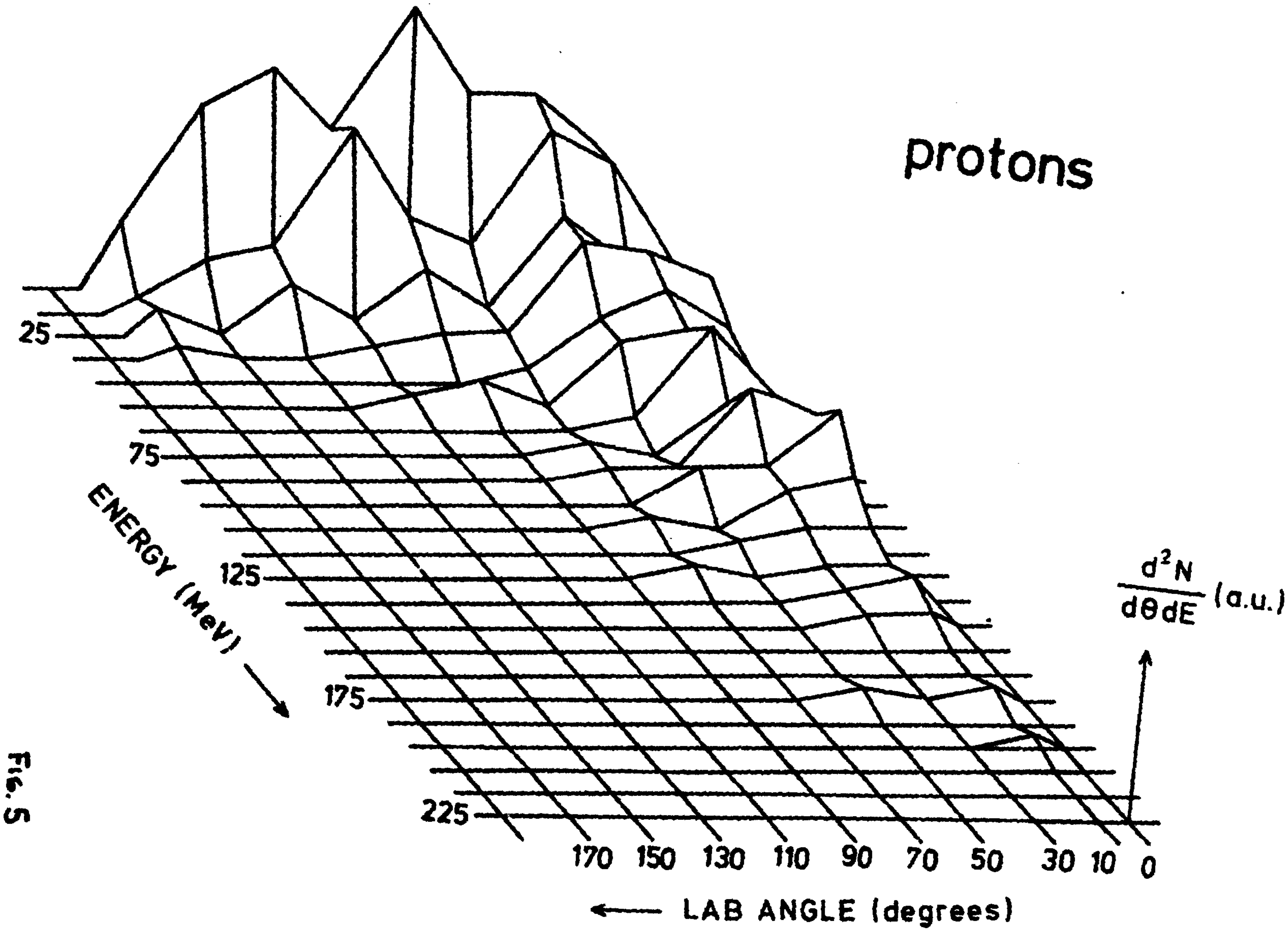

protons
25
75
125
175
225
ENERGY (MeV)
170
150
130
110
90
70
50
30
10
0
LAB ANGLE (degrees)
$\frac{d^2N}{d\theta dE}$ (a.u.)

Fig. 5

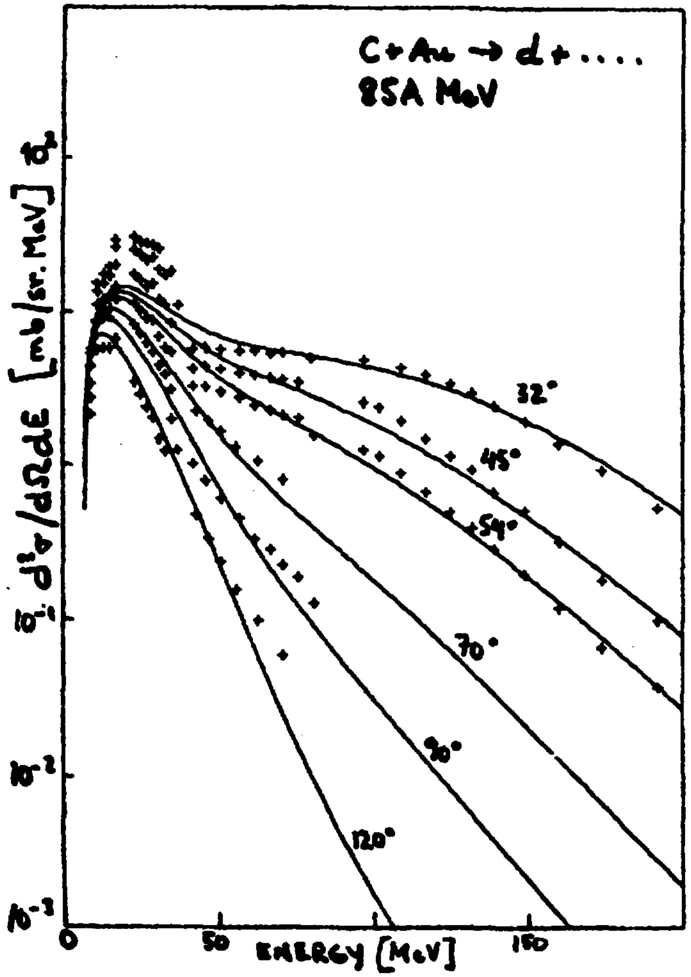

C+Au → d+....
85A MeV
$d^2\sigma/d\Omega dE$ [mb/sr. MeV]
10^2
10^{-1}
10^{-2}
10^{-3}
0
50
ENERGY [MeV]
150
32°
45°
54°
70°
90°
120°

Fig. 6

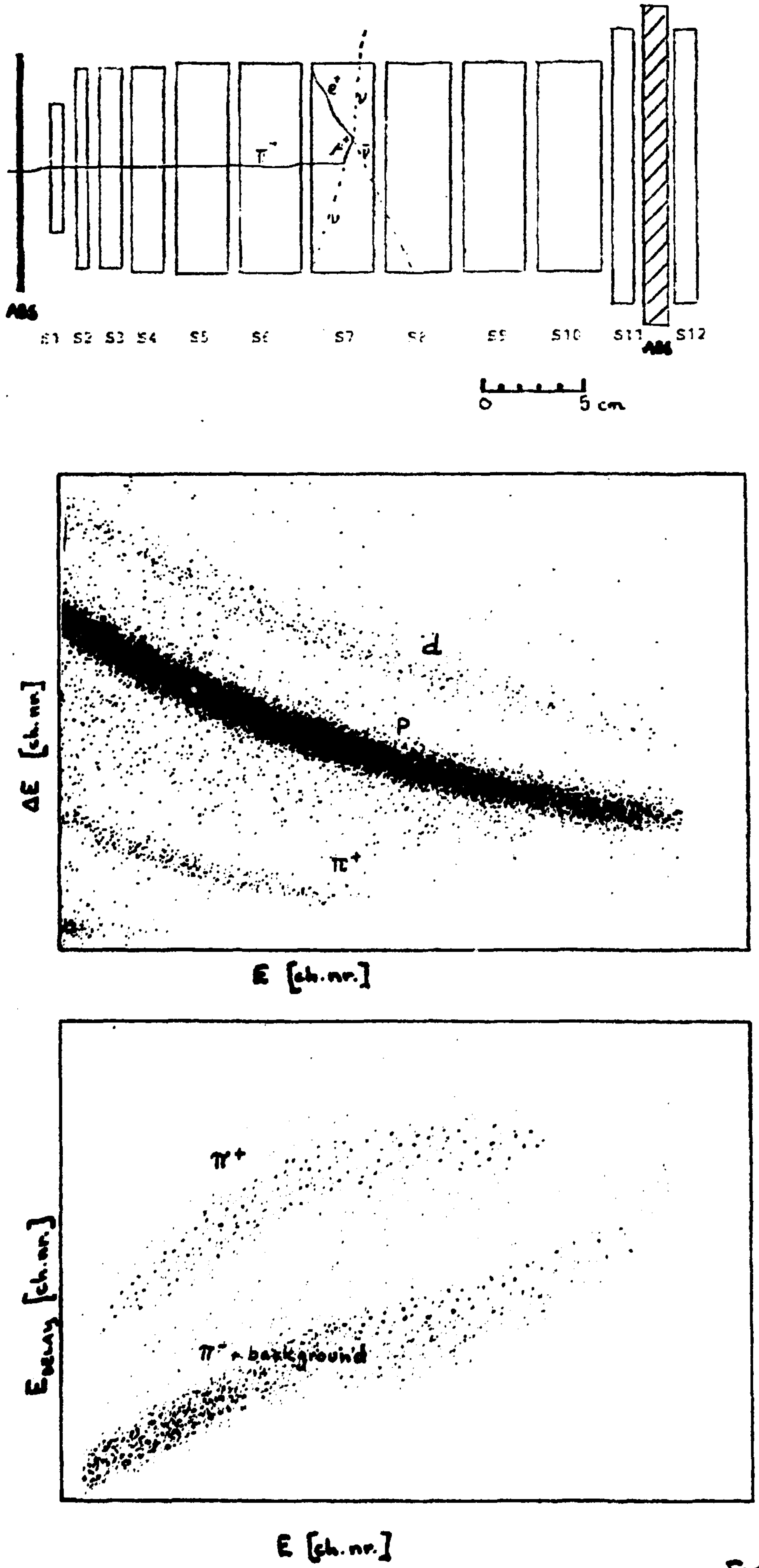

ABS
S1 S2 S3 S4 S5 S6 S7 S8 S9 S10 S11 S12
ABS
π^-
e^+
ν
μ^+
$\bar{\nu}$
ν
0
5 cm
ΔE [ch.nr.]
E [ch.nr.]
d
p
π^+
E_{decay} [ch.nr.]
π^+
π^- + background
E [ch.nr.]

FIG. 7

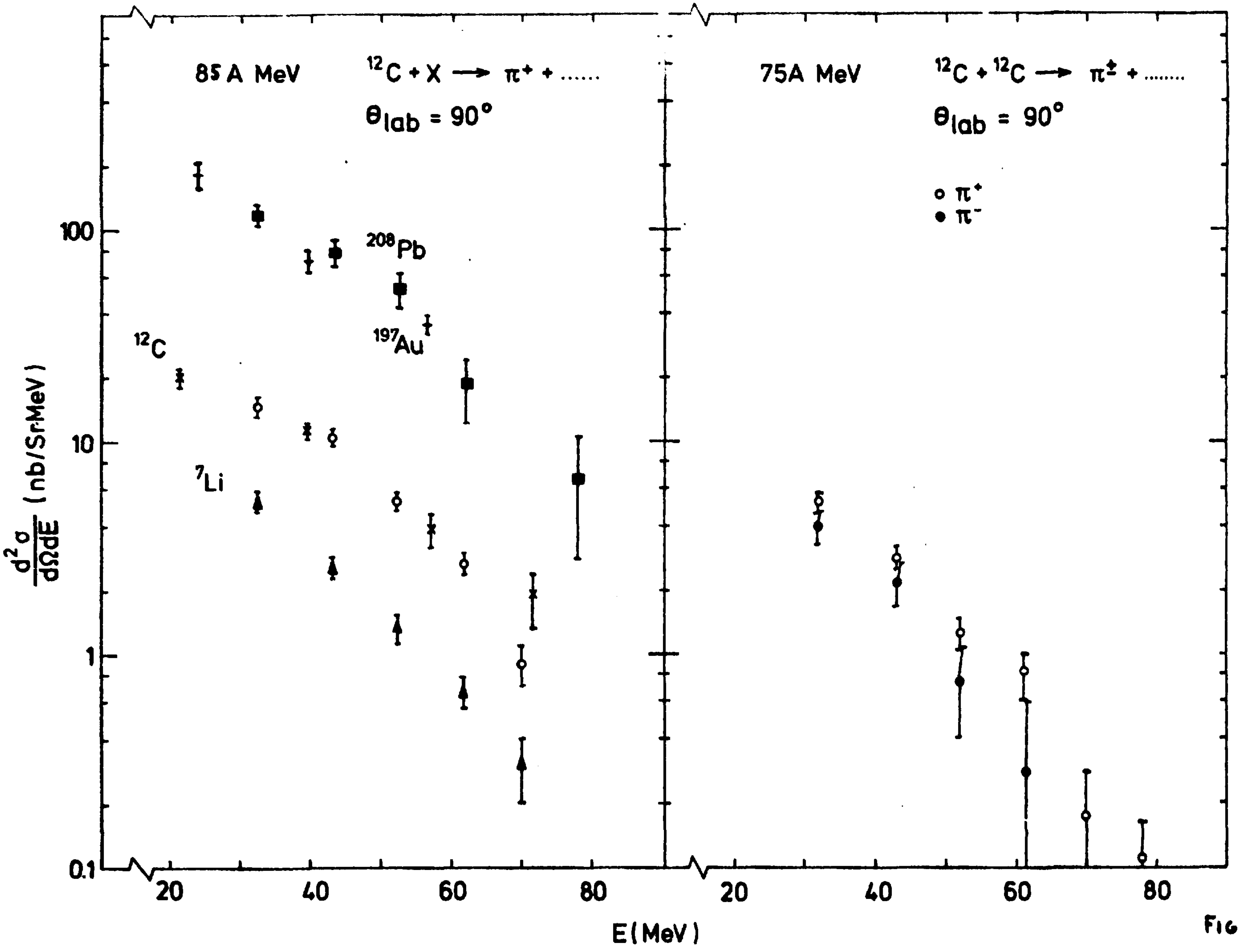
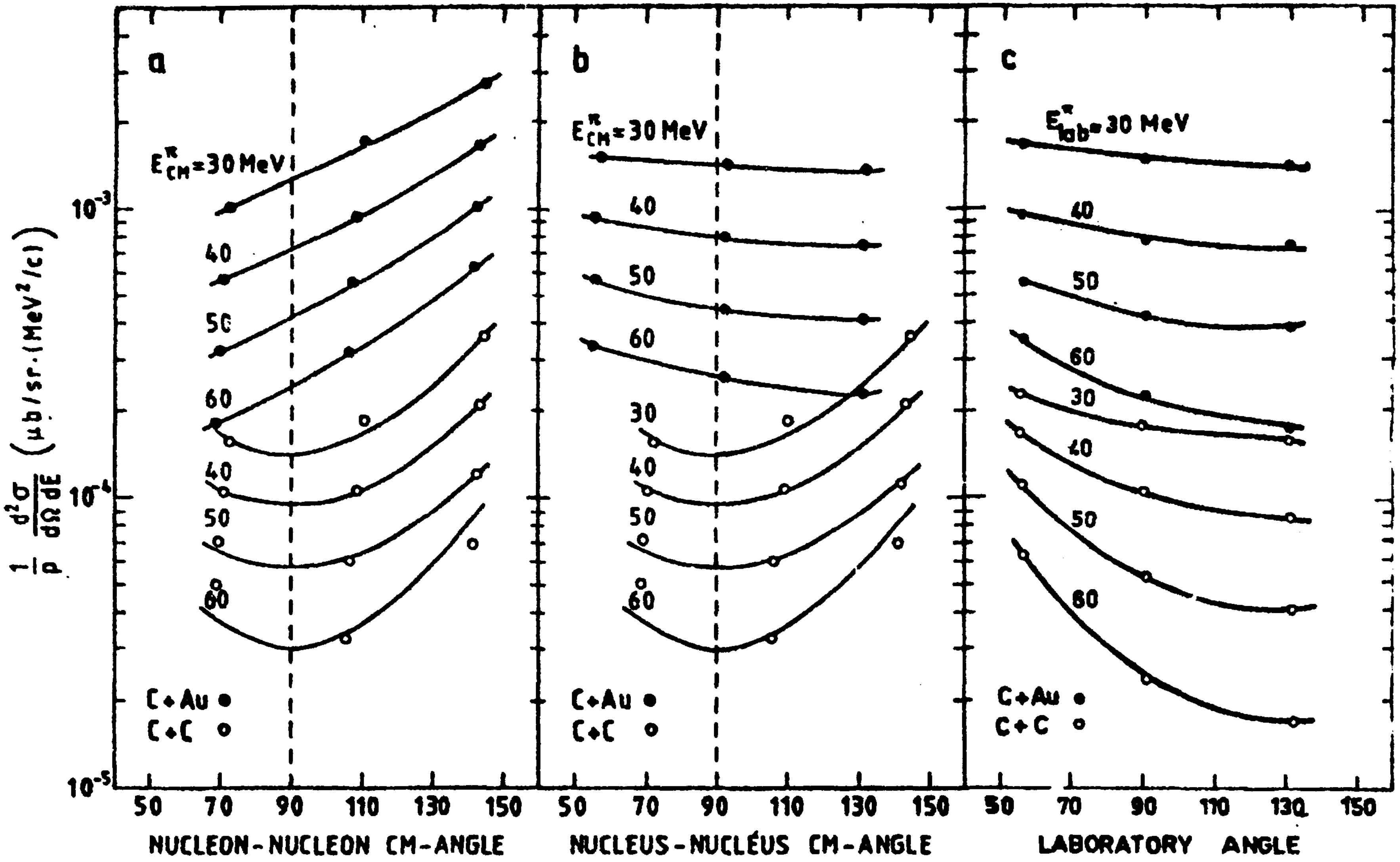

85 A MeV
$^{12}C + X \longrightarrow \pi^+ + \ldots\ldots$
$\theta_{lab} = 90°$
^{208}Pb
^{197}Au
^{12}C
^7Li
75A MeV
$^{12}C + {}^{12}C \longrightarrow \pi^\pm + \ldots\ldots$
$\theta_{lab} = 90°$
○ π^+
● π^-
$\frac{d^2\sigma}{d\Omega dE}$ (nb/Sr·MeV)
100
10
1
0.1
20
40
60
80
20
40
60
80
E(MeV)

Fig. 8



a
b
c
E^{π}_{CM}=30 MeV
E^{π}_{lab}=30 MeV
30
40
50
60
C+Au ●
C+C ○
10^{-3}
10^{-4}
10^{-5}
$\frac{1}{p}\frac{d^2\sigma}{d\Omega\,dE}$ (µb/sr·(MeV²/c))
50
70
90
110
130
150
NUCLEON-NUCLEON CM-ANGLE
NUCLEUS-NUCLEUS CM-ANGLE
LABORATORY ANGLE

FIG. 9

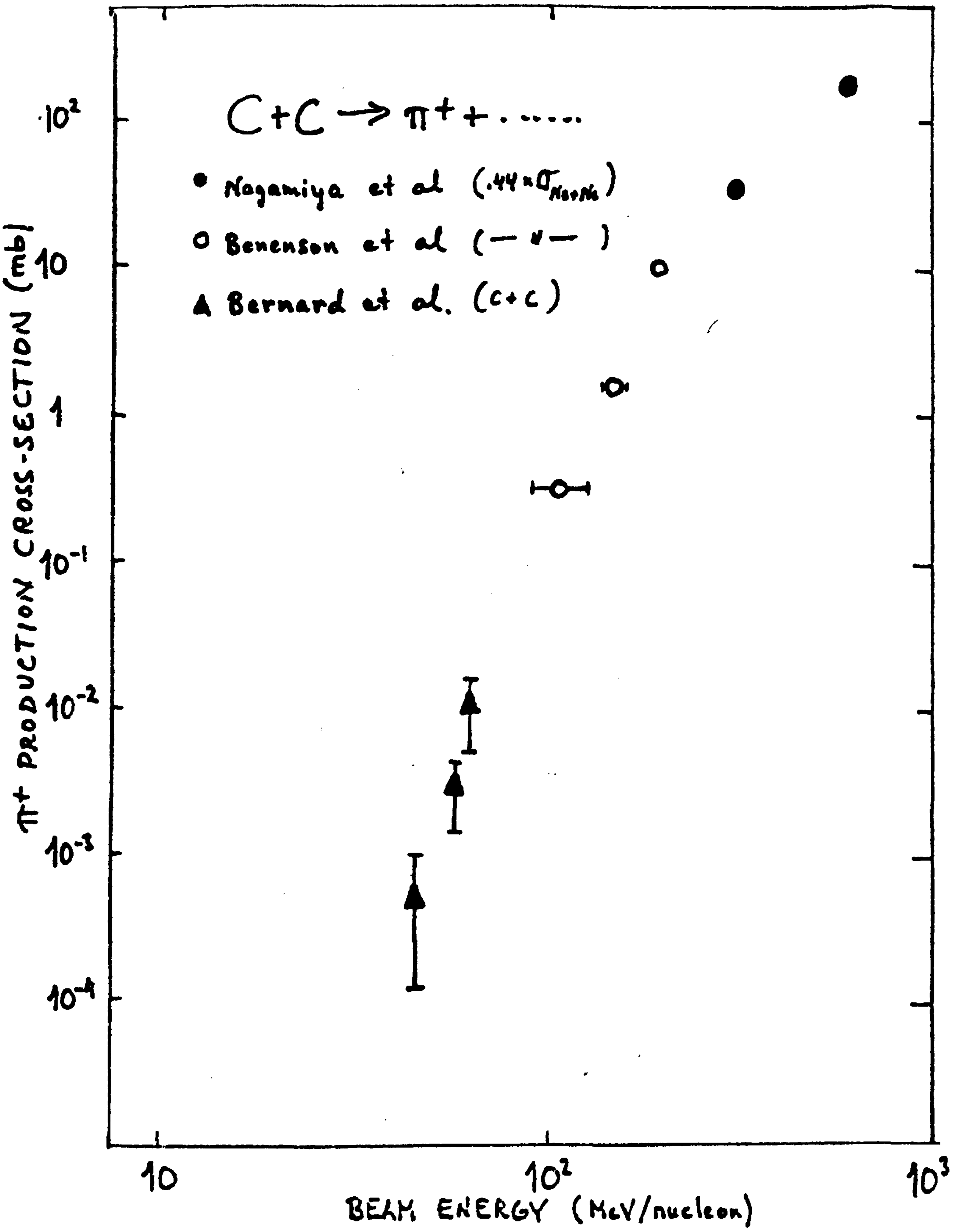

C+C → π+ + ...
● Nagamiya et al (.44×σ Ne+Ne)
○ Benenson et al (— " —)
▲ Bernard et al. (c+c)
π+ PRODUCTION CROSS-SECTION (mb)
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10
10²
10³
BEAM ENERGY (MeV/nucleon)

FIG. 10

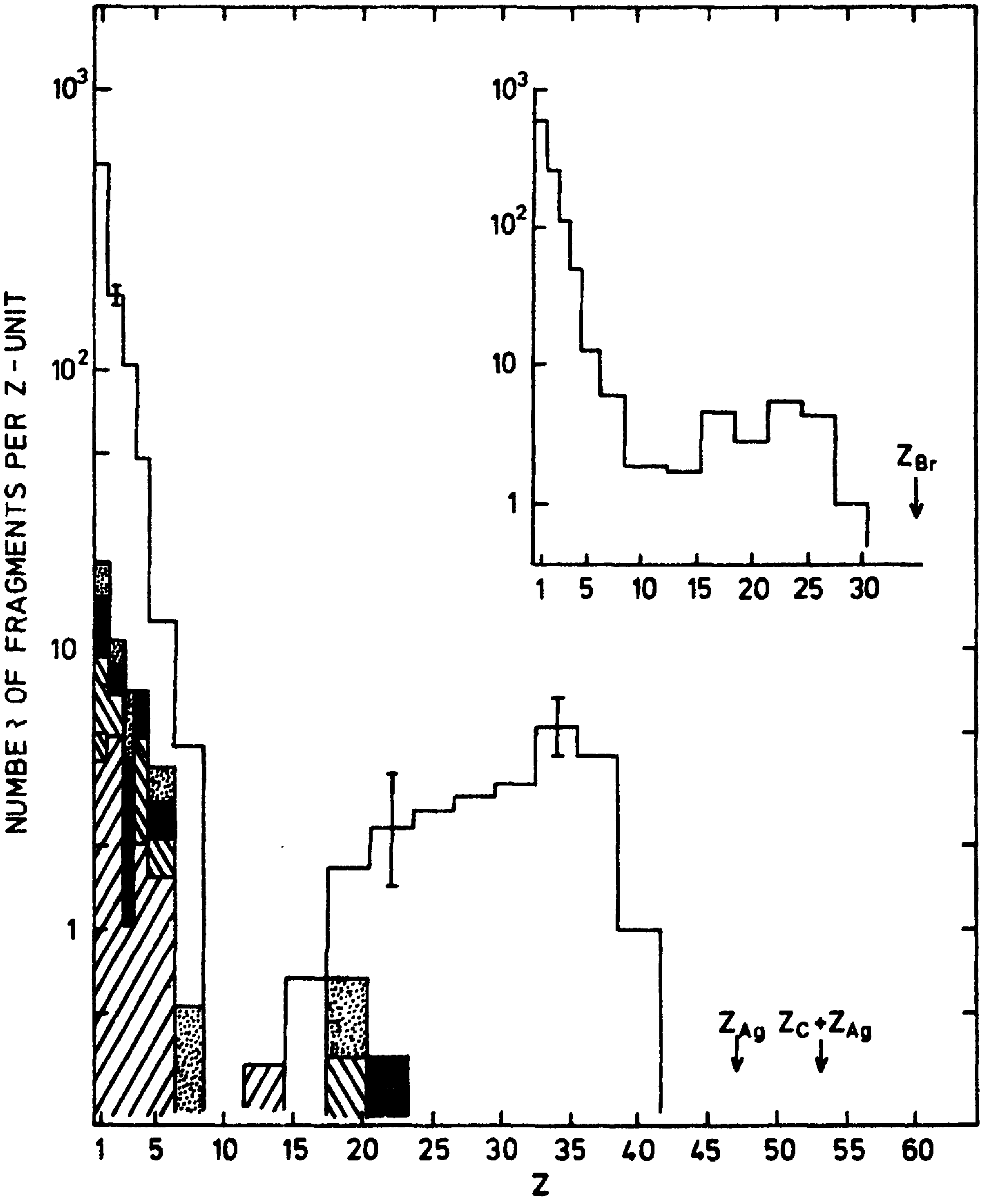

NUMBER OF FRAGMENTS PER Z-UNIT
10^3
10^2
10
1
Z
1
5
10
15
20
25
30
35
40
45
50
55
60
Z_{Ag}
$Z_C + Z_{Ag}$
10^3
10^2
10
1
1
5
10
15
20
25
30
Z_{Br}

Fig. 11

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Referat (sammandrag)

The results from the first generation of experiments at the CERN synchrocyclotron with 30A MeV - 85A MeV ^{12}C beams are beginning to manifest the pattern of heavy ion reactions in the region between the binary low energy side and the "chaotic" high energy side. Results from experiments on the production of p, d and π at these energies are presented.

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