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SEARCH FOR SHOCK WAVE PHENOMENA IN CENTRAL ^{16}O-AgBr INTERACTIONS AT 0.2 AND 2.0 GeV/NUCLEON

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Contents

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Angular distributions of high energy He nuclei, emitted from the target in central ^{16}O-AgBr interactions, are found to be highly forward-peaked at 0.2 GeV/nucleon but almost isotropic at 2 GeV/nucleon. The angular distributions are in qualitative agreement with recent shock wave calculations. However, we observe no narrow peaks either in the angular or in the energy distributions of He nuclei.

1. Introduction

The interest for high energy heavy ion reactions has increased dramatically ever since beams of fully stripped ions became available for experiments at the Bevatron-Bevalac facility in Berkeley in 1971. The first experimental results on the fragmentation of the nuclei in peripheral interactions have been described by various statistical models assuming small correlations among nucleon momenta (1-4). With increasing overlap volume of the nuclei, the reaction process becomes more complex. Hydrodynamic calculations predict the formation and propagation of shock waves when the nuclear sound velocity ($v \sim 0.2$ c) is exceeded. The density perturbation causes the emission of particles from the nuclear surface having a velocity corresponding to the shock-wave propagation velocity. The predicted angular distributions of nuclear matter are different in different shock-wave models. Some models predict comparatively narrow peaks at a straight angle to a conical shock front (5,6) whereas other models predict broad forward peaked distributions (7).

In recent classical microscopic treatments of heavy ion reactions in the hundreds of MeV/nucleon region, conditions for fully developed shock-waves, even for small impact parameters, seem not to be fulfilled (8,9).

The experiments of Schopper et al. (5,10) show comparatively sharp peaks in the $d\sigma/d\Theta$ distributions of particles emitted from high multiplicity reactions in the bombardment of AgCl crystals with ^{4}He, ^{12}C and ^{16}O. The position of the peak is sensitive to the beam velocity. In fact, it is shifting from $\sim 35^{o}$ at 0.25 GeV/nucleon to $\sim 75^{o}$ at 2 GeV/nucleon, and then back to $\sim 50^{o}$ at 4 GeV/nucleon. The authors suggest that these peaks are due to shock-wave emission of high energy He nuclei.

In the inclusive experiment of Poskanzer et al. (11) no narrow peaks are found in the angular spectra of ^{3}He and ^{4}He emitted in ^{16}O bombardment on Ag and U nuclei at 1.05 GeV/nucleon. It has also been shown in an emulsion investigation of ^{16}O-CNO and ^{16}O-AgBr interactions at 2 GeV/nucleon (12) that no statistically significant fine structure peaks are found either in the angular or in the energy distributions of protons or He nuclei, emitted from the target.

In the present experiment we have studied angular distributions of all charged particles with an energy loss larger than that of a proton having an energy of 11 MeV, emitted in central ^{16}O-AgBr interactions at 0.2 and 2.0 GeV/nucleon. Since the main purpose of this investigation is to search for shock-wave phenomena we have studied high energy He nuclei separately.

2. Experimental Techniques

Two stacks of nuclear emulsions, Ilford G5 respectively Ilford K2, were exposed to the 0.25 and 2.1 GeV/nucleon ^{16}O beam of the Berkeley Bevatron. All details concerning exposures and scanning can be found in Refs. 12 and 13. The comparatively low sensitivity of the K2 emulsions allowed us to make a separation in the 2 GeV/nucleon investigation between singly, doubly and multiply charged ($Z \geq 3$) particles in wide energy intervals.

At 0.2 as well as at 2.0 GeV/nucleon we picked out events with a large number of heavy prongs (i.e. target particles with an energy loss larger than 1.4 times the plateau energy loss). These events are normally believed to be central interactions with Ag or Br. Angles of all particles with a restricted energy loss (REL) > 44 MeV/cm (corresponding, for instance, to protons with an energy < 11 MeV) were measured. The multiply charged projectile fragments ($Z \geq 3$), which fall in this energy loss interval, have been identified earlier (12,13) and are excluded here. The composition of the remaining particles is presented in Table 1.

We believe that the frequency of projectile He nuclei with E < 65 MeV/nucleon is negligible for the following reason: Not one single He nucleus has been registered with an energy between 0.4 and 1.1 GeV/nucleon in the 2.0 GeV/nucleon experiment (12). Experimental energy distributions of He nuclei, emitted in heavy ion interactions in the hundreds of MeV/nucleon region, indicate a similar lack of He nuclei emitted in an intermediate energy region (14,15).

3. Experimental Results

3.1. Angular Distribution of Target Particles with REL $\geq$ 44 MeV/cm

Fig. 1 shows angular distributions ($dN/d\theta$) for all particles with REL > 44 MeV/cm. Short-range particles, $R < 10$ µm, are represented by the hatched areas. The dominant part of these particles consists of target recoil nuclei with $Z \geq 3$ (12). It is obviously of little importance whether the short range particles be included in the $dN/d\theta$ distributions or not. Subsequently, the short range particles are omitted.

We have chosen two different N_h intervals for both primary energies in order to observe a possible effect depending on the degree of target disintegration. At 0.2 GeV/nucleon, we chose $N_h \geq 12$ and $N_h \geq 16$. Both these intervals correspond, however, to very central events and it is therefore not surprising that no difference in the $dN/d\theta$ distributions can be observed. At 2 GeV/nucleon, the target nucleus is, on the average, much more disintegrated. We have to choose stars with $N_h \geq 28$ at 2 GeV/nucleon to obtain the same percentage of events as we receive for $N_h \geq 12$ at 0.2 GeV/nucleon. It is important to observe that, at 0.2 GeV/nucleon, N_h includes only very few target protons with $E > 30$ MeV. This indicates that N_h is approximately comparable with the number of charged target fragments registered in the AgCl crystal experiments (5). At 2 GeV/nucleon the frequency of protons with $E > 30$ MeV represents a much larger part of N_h. However, we observe no statistically significant difference between the $dN/d\theta$ distributions for events with $N_h \geq 28$ and for those with $N_b \geq 15$ (N_b = = the number of particles with REL ≥ 6.8 REL_{min}; black prongs). Consequently, it seems to be of small importance whether the N_b or the N_h parameter be used to discriminate against peripheral events.

The most striking feature of Fig. 1 is the shift from the forward peaked $dN/d\theta$ distribution at 0.2 GeV/nucleon to the almost isotropic distribution at 2 GeV/nucleon. No statistically significant narrow peaks can be found in the distributions. This fact is definitely established in Fig. 2 where the $dN/d\Omega$ ($= dN/d\theta \cdot 1/\sin\theta$) representation of these particle samples ($N_h \geq 12$, no target recoils) is shown.

3.2. He Nuclei with $E \gtrsim 7.5$ MeV/nucleon Emitted in Relativistic Interactions

The sensitivity of the K2 emulsion stack was found to be exceptionally favourable for the identification of short--range light particles. The separation between singly, doubly and multiply charged ($Z \geq 3$) particles, mainly by gap density and total bloblength measurements as well as the energy determination, has been discussed in Ref. 12. The sample of particles discussed in the previous section is divided into the following groups:

1. p+d+t, $E < 11$ MeV/nucleon
2. He, $E < 7.5$ MeV/nucleon
3. He, $7.5 \leq E \leq 65$ MeV/nucleon

The admixture of low energy mesons and particles heavier than He nuclei is negligible in all these groups, and subsequently ignored.

The $dN/d\theta$ distribution of the above-mentioned groups of particles in events with $N_h \geq 12$ at 2 GeV/nucleon is shown in Fig. 3. The isotropy of the particles belonging to groups 1 and 2 is expected from the evaporation theory. What is more surprising is the comparatively high degree of isotropy also in the distribution of He nuclei with $E \geq 7.5$ MeV/nucleon. The $dN/d\theta$ distribution of these He nuclei is shown separately in Fig. 4 (solid histogram).

The particles in groups 1 and 2 are generally believed to be emitted almost exclusively through evaporation from an excited nucleus in thermal equilibrium. Therefore, we next examine to what extent an evaporation curve agrees with the low energy "background" here. If the agreement is acceptable, we can use an evaporation calculation for subtracting the background in the 0.2 GeV/nucleon sample where no identification of the target particles has been made.

3.3. Evaporation Calculations

A calculation of the expected $dN/d\theta$ distribution of the low energy particles in groups 1 and 2 from the evaporation theory is presented in Fig. 3 (solid curve). The experimental (p+d+t)/He ratio = 0.66 has been used together with the following evaporation parameters:

Recoil velociey: $\beta_{\parallel} = \beta_{\perp} = 0.022 \Rightarrow \beta_{recoil} = 0.031$

Nuclear temperature: $T = 5$ MeV.

Reduced Coulomb barriers: $V_p = V_d = V_t = 2$ MeV;

$V_{^3He} = V_{\alpha} = 4$ MeV.

The structure of the curve is not very sensitive to reasonable changes in T or V and nor is the inclusion of successive cooling of the excited nucleus very important. On the contrary, a small change in β_{recoil} makes the curve change noticeably. The value $\beta_{recoil} = 0.031$ has been estimated from the momentum distribution of protons emitted with a centre-of-mass energy < 25 MeV (12). It is obvious that a β_{recoil} value closer to 0 would give a better fit. This discrepancy is due to the fact that the emission of He nuclei with E < 7.5 MeV/nucleon is somewhat more isotropic than what is expected from the recoil velocity determined from low energy protons.

In Fig. 4 we compare the result of the dN/dθ distribution after subtracting the calculated evaporation background. (dashed histogram) with the experimental high energy He nuclei distribution. The distributions are noticeably different. This fact reflects the importance of the choice of the β_{recoil} value, and the large statistical fluctuations in the low energy background.

In order to make a correct choice of the β_{recoil} value at 0.2 GeV/nucleon we compare in Fig. 5 energy distributions of He nuclei emitted in central heavy ion events in the GeV/nucleon region and in the hundreds of MeV/nucleon region (14) with predictions from the evaporation theory, using $\beta_{\parallel} = 0.022$ and $\beta_{\parallel} = 0.06$. The value $\beta_{\parallel} = 0.06$ is used since it is often believed that the recoil velocity is much larger at 0.2 GeV/nucleon than in the GeV/nucleon region (5). It is clear that the experimental points below 30 MeV follow the evaporation curve for $\beta_{\parallel} = 0.022$ but scarcely the curve for

$\beta_{\parallel}$ = 0.06. The $\beta_{\parallel}$ value 0.022 is in fact reported for central events in the hundreds of MeV/nucleon region in Ref. 14.

The figure shows that the energy spectra are similar for both incident energies also in the high energy part. The percentage of high energy He nuclei among all particles with REL > > 44 MeV/cm is in fact within the limits of error the same at 2 GeV/nucleon as it is in the hundreds of MeV/nucleon region (23% respectively 19%).

In the 0.2 GeV/nucleon sample, the statistics are more than twice as good as in the 2 GeV/nucleon sample. Therefore, we expect that the statistical fluctuations in the background are comparatively small.

3.4. He Nuclei with E $\geq$ 7.5 MeV/nucleon at 0.2 and 2 GeV/nucleon.

From the above discussions it seems reasonable to assume that the average parallel velocity of the evaporating recoil nucleus (~ 0.022 c), the percentage of protons, low energy He nuclei and high energy He nuclei is the same in the hundreds of MeV/nucleon region as in the GeV/nucleon region. By using the same evaporation parameters as in the 2 GeV/nucleon calculation for the background discrimination at 0.2 GeV/nucleon, we obtain the dN/dΩ distribution of non-evaporated particles shown by the full circles in Fig. 6. The great majority of these particles must be high energy He nuclei. In Fig. 6 we compare this distribution with the experimental dN/dΩ distribution of He nuclei with E > 7.5 MeV/nucleon, obtained at 2 GeV/nucleon (open circles). Since the way of subtracting the evaporation background in the 0.2 GeV/nucleon sample is somewhat uncertain, we also present the dN/dΩ spectrum after a background subtracting where we used $\beta_{\parallel}$ = 0.06 (curve).

The difference between the dN/dΩ distribution at 0.2 and 2 GeV/nucleon is significant, independent of the choice of $\beta_{\parallel}$. The forward-peaked smooth angular spectrum at 0.2 GeV/ /nucleon is shifted to an almost isotropic distribution at 2 GeV/nucleon. In fact, the increasing isotropy of He nuclei with increasing projectile velocity has been pointed out by us once before in an emulsion investigation, where cosmic ray nuclei were used as projectiles (16). At 0.2 GeV/nucleon, we can find no fine structure at all. At 2 GeV/nucleon there may be a local maximum at ~ 70°. This is however not statistically significant.

The only model of heavy ion interactions which at least qualitatively can explain the shift of our dN/dΩ spectrum and especially the existence of high energy He nuclei emitted backwards at 2 GeV/nucleon, is the one presented by Amsden et al. (7). This model is a relativistic hydrodynamical treatment of the heavy ion collision, causing the development of curved shock waves. However, the strong shift in the energy distribution towards higher energies of He nuclei with increasing incident energy, predicted in these calculations, has not been observed in our experiments.

The existence of local maxima in the energy distributions of fragments corresponding to the shock-wave propagation velocity would be a proof of emission from shock fronts. In a plastic detector experiment, Crawford et al. (17) observed possible maxima in the energy spectra of heavy fragments emitted in ^{16}O-Au interactions at 2.1 GeV/nucleon.

The energy spectrum of He nuclei in our experiment at 2 GeV/nucleon, shown in Fig. 5 (open circles), follows the exponential evaporation shape below 30 MeV, subsequently shifting to a less steep power law form, $\sim E^{-\alpha}$, at larger energies. There is no sign of any local maximum in the energy interval $E < 1000$ MeV.

Conclusions

The characteristic shift of the $dN/d\theta$ distribution of He nuclei + low energy protons and deuterons, from a broad forward-peaked shape at 0.2 GeV/nucleon to an almost isotropic distribution at 2 GeV/nucleon, is in qualitative agreement with the results found by Schopper et al. (5,10). The narrow peaks, with positions shifting with the incident energy, as reported from those experiments, have not been observed in our $dN/d\Omega$ distributions. Furthermore, we observe that the difference between the angular distributions in the hundreds of MeV/nucleon region and in the GeV/nucleon region is predominantly due to He nuclei with $E > 30$ MeV. In this energy interval, $E > 30$ MeV, the deviation of the experimental dN/dE spectrum from the exponential evaporation shape becomes noticeable.

On the basis of our present and earlier experimental results, we conclude that the process responsible for the emission of high energy He nuclei causes a very different angular distribution at 0.2 from that at 2 GeV/nucleon, while the energy spectra and the frequency of He nuclei with $E > 30$ MeV are similar.

The forward-peaked $dN/d\Omega$ spectrum of high energy He nuclei in the hundreds of MeV/nucleon region can be explained both by hydrodynamical shock wave calculations and more straight-forward microscopic calculations.

The shift towards a more isotropic distribution at higher incident energy is however harder to explain. So far as we know, the only models in which the combination of high He energies and backward emission in the laboratory system is possible, are the shock wave models.

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Table 1. The experimentally found frequencies of different kinds of particles with REL > 44 MeV/cm in the 2 GeV/nucleon sample.

Particle	Energy	Frequency
p+d+t	$\leq$ 11 MeV/nucleon	37 %
He	$\leq$ 65 MeV/nucleon	54 %
Nuclei with $Z \geq 3$	$\lesssim$ 65 MeV/nucleon	~ 4 %
$\pi^{\pm}$	$\leq$ 1.6 MeV	< 1 %
Target recoils	$\leq$ 0.5 MeV/nucleon	~ 5 %

Figure Captions

1. Angular distributions (dN/dθ) of all particles with REL > 44 MeV/cm obtained in the bombardment of AgBr with ^{16}O ions with an energy of 0.2 GeV/nucleon (events with $N_h \geq 12$ and $N_h \geq 16$) and 2 GeV/nucleon (events with $N_h \geq 12$ and $N_h \geq 28$). The hatched areas represent particles with a range < 10 μm.

2. Angular distributions (dN/dΩ) of all particles with a restricted energy loss > 44 MeV/cm, with the exception of target recoils and projectile fragments, emitted in events with $N_h \geq 12$ at both incident energies (0.2 and 2.0 GeV/nucleon).

3. Angular distributions (dN/dθ) of p+d+t with E < 11 MeV/nucleon (1), He nuclei with E < 7.5 MeV/nucleon (2) and He nuclei with 7.5 ≤ E ≤ 65 MeV/nucleon (3) produced in the bombardment on AgBr with 2 GeV/nucleon ^{16}O ions (events with $N_h \geq 12$). The solid curve shows the result of an evaporation calculation.

4. Angular distributions (dN/dθ) of He nuclei with E ≥ 7.5 MeV/nucleon (solid histogram) emitted in the 2 GeV/nucleon ^{16}O bombardment on AgBr nuclei. The dashed histogram is the result after subtraction of an estimated evaporation distribution from the total distribution of low energy particles (Fig. 3).

5. Energy distributions of He nuclei emitted in the bombardment of 2 GeV/nucleon ^{16}O on AgBr (open circles) respectively in the bombardment of cosmic ray nuclei, $Z \geq 3$, $E > 0.1$ GeV/nucleon, on AgBr. The curves are the result of evaporation calculations, assuming $\beta_{\parallel} = 0.022$ and $\beta_{\parallel} = 0.06$ ($T = 5$ MeV).

6. Angular distributions ($dN/d\Omega$) of non-evaporated He nuclei in the bombardment of ^{16}O ions on AgBr ($N_h \geq 12$). Open circles: He nuclei with $E \geq 7.5$ MeV/nucleon in the 2.0 GeV/nucleon sample. Full circles: remaining $dN/d\Omega$ distribution at 0.2 GeV/nucleon after background subtraction using $\beta_{\parallel} = 0.022$. Curve: The same distribution using $\beta_{\parallel} = 0.06$ in the evaporation background subtraction.

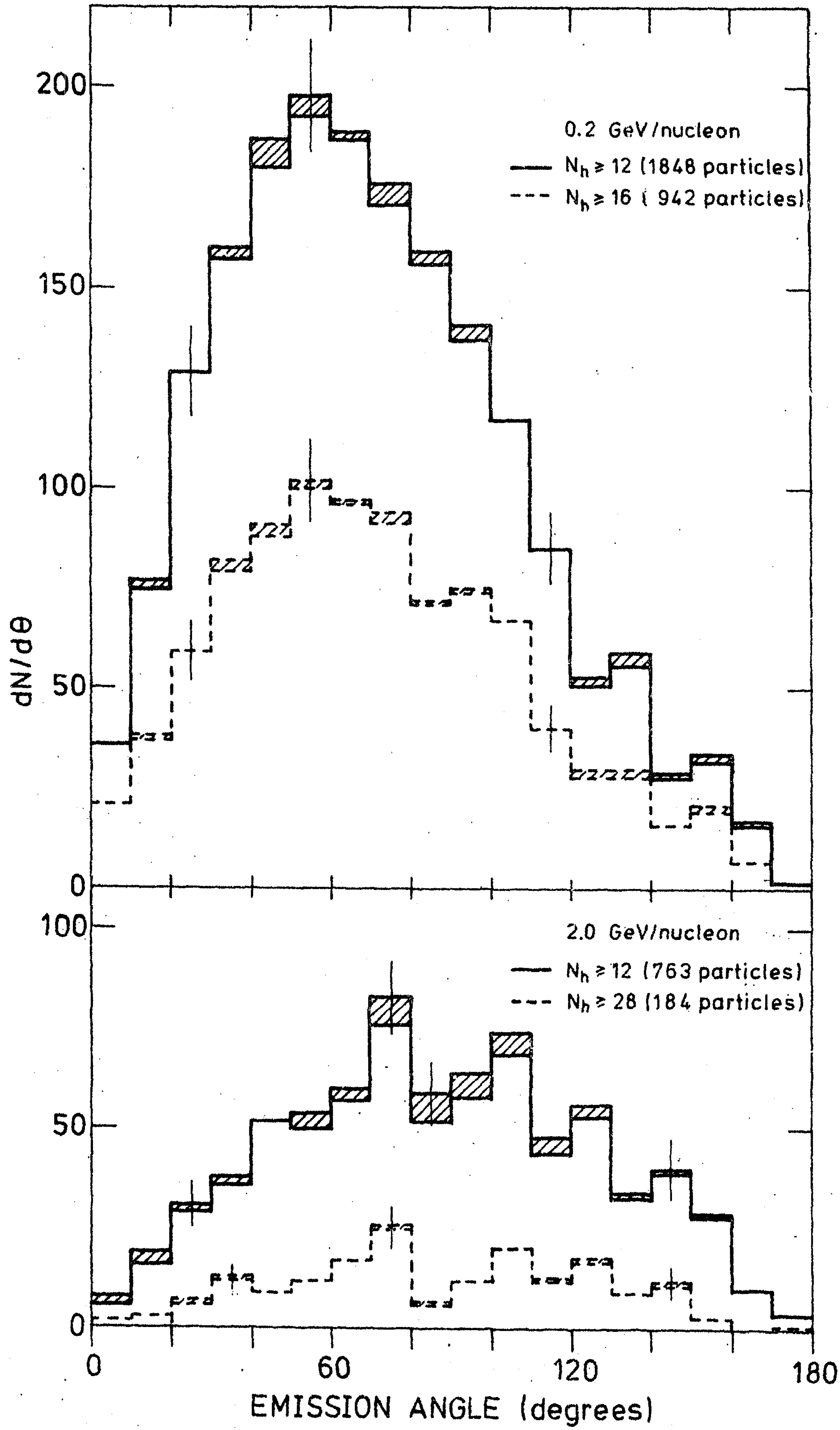
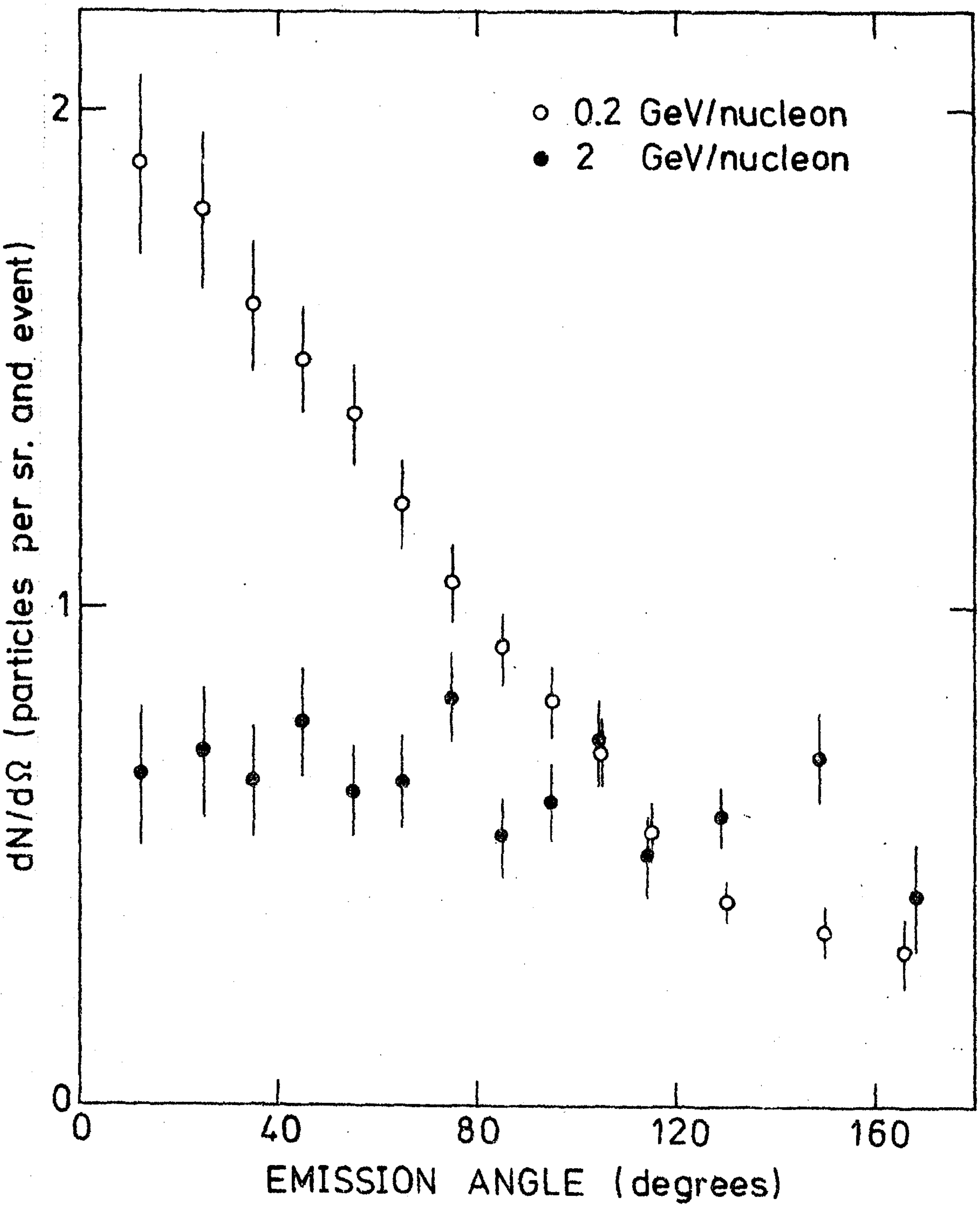

0.2 GeV/nucleon
$N_h \geq 12$ (1848 particles)
$N_h \geq 16$ (942 particles)
2.0 GeV/nucleon
$N_h \geq 12$ (763 particles)
$N_h \geq 28$ (184 particles)
dN/dθ
EMISSION ANGLE (degrees)
0
50
100
150
200
0
60
120
180

Fig. 1



0.2 GeV/nucleon
2 GeV/nucleon
dN/dΩ (particles per sr. and event)
2
1
0
0
40
80
120
160
EMISSION ANGLE (degrees)

Fig. 2

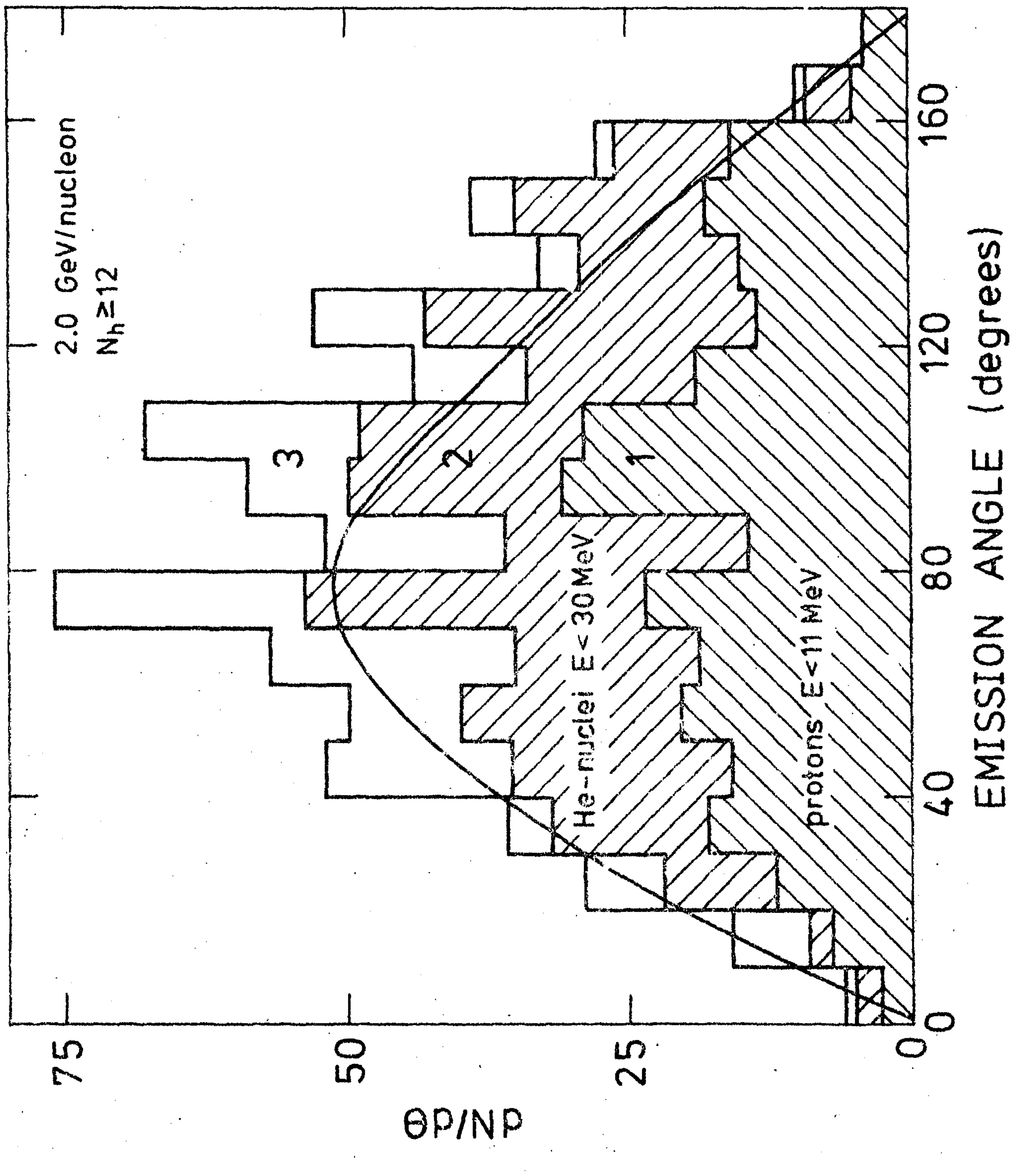
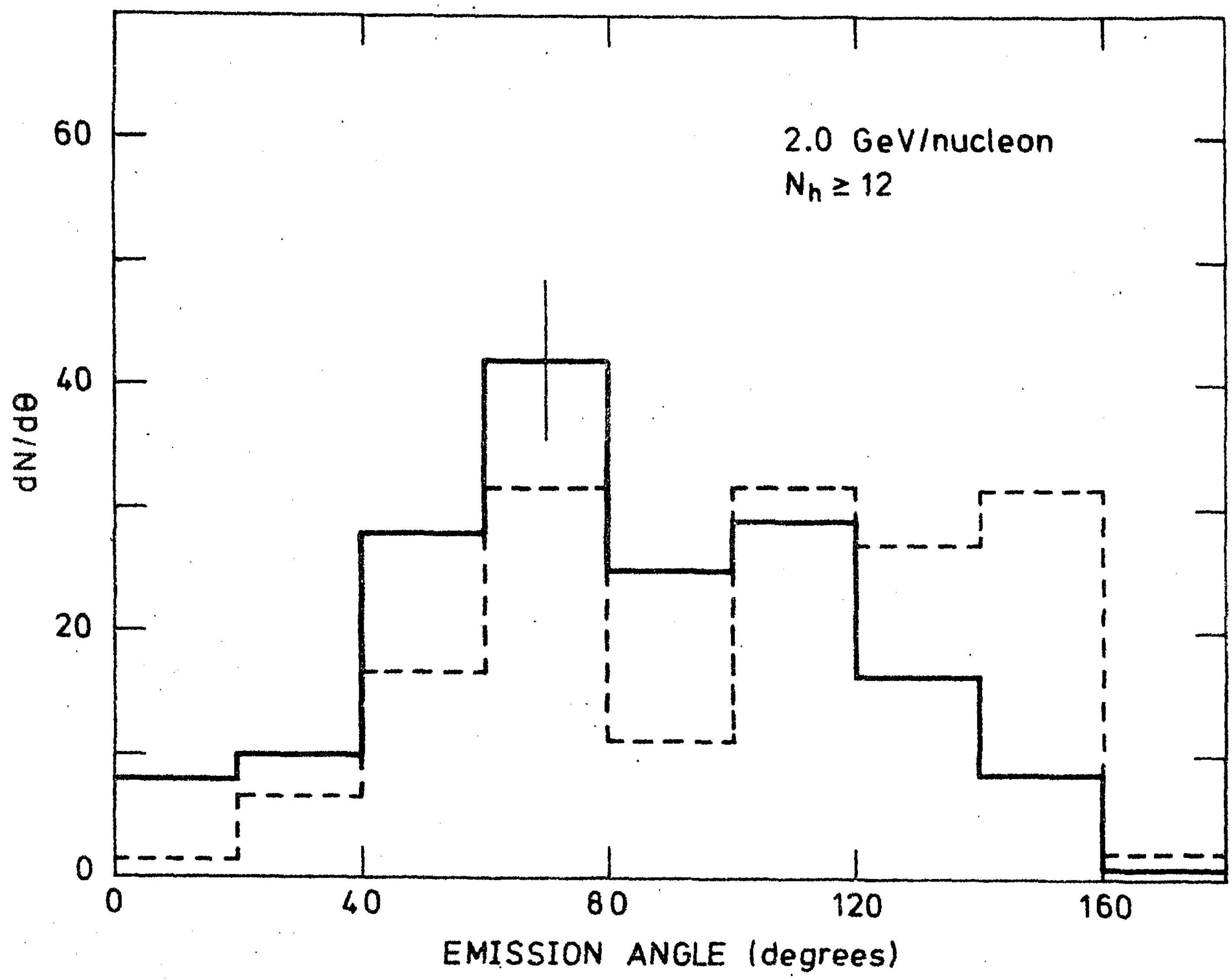
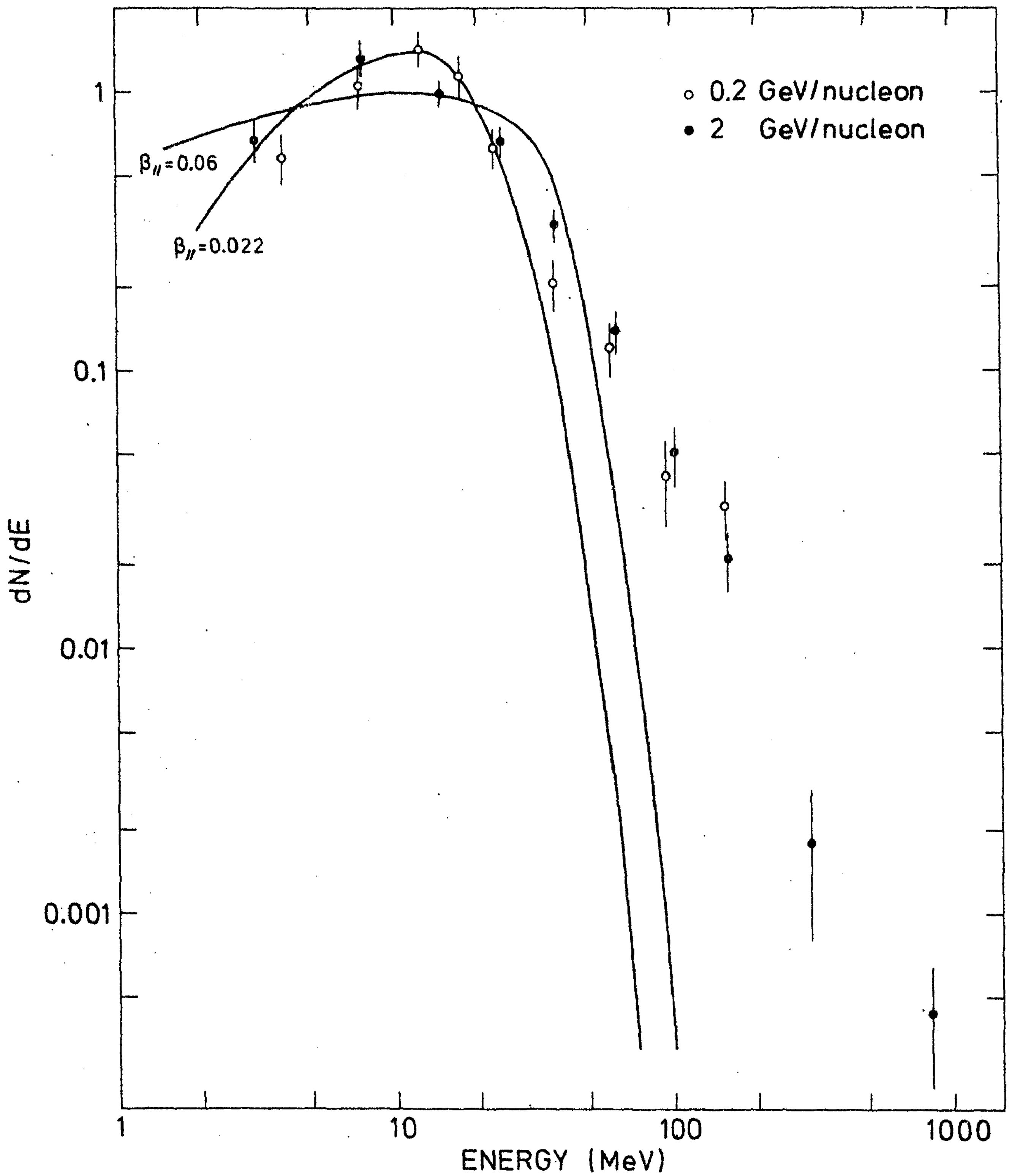

2.0 GeV/nucleon
$N_h \geq 12$
He-nuclei E < 30 MeV
protons E < 11 MeV
1
2
3
dN/dθ
EMISSION ANGLE (degrees)
0
25
50
75
0
40
80
120
160

Fig. 3



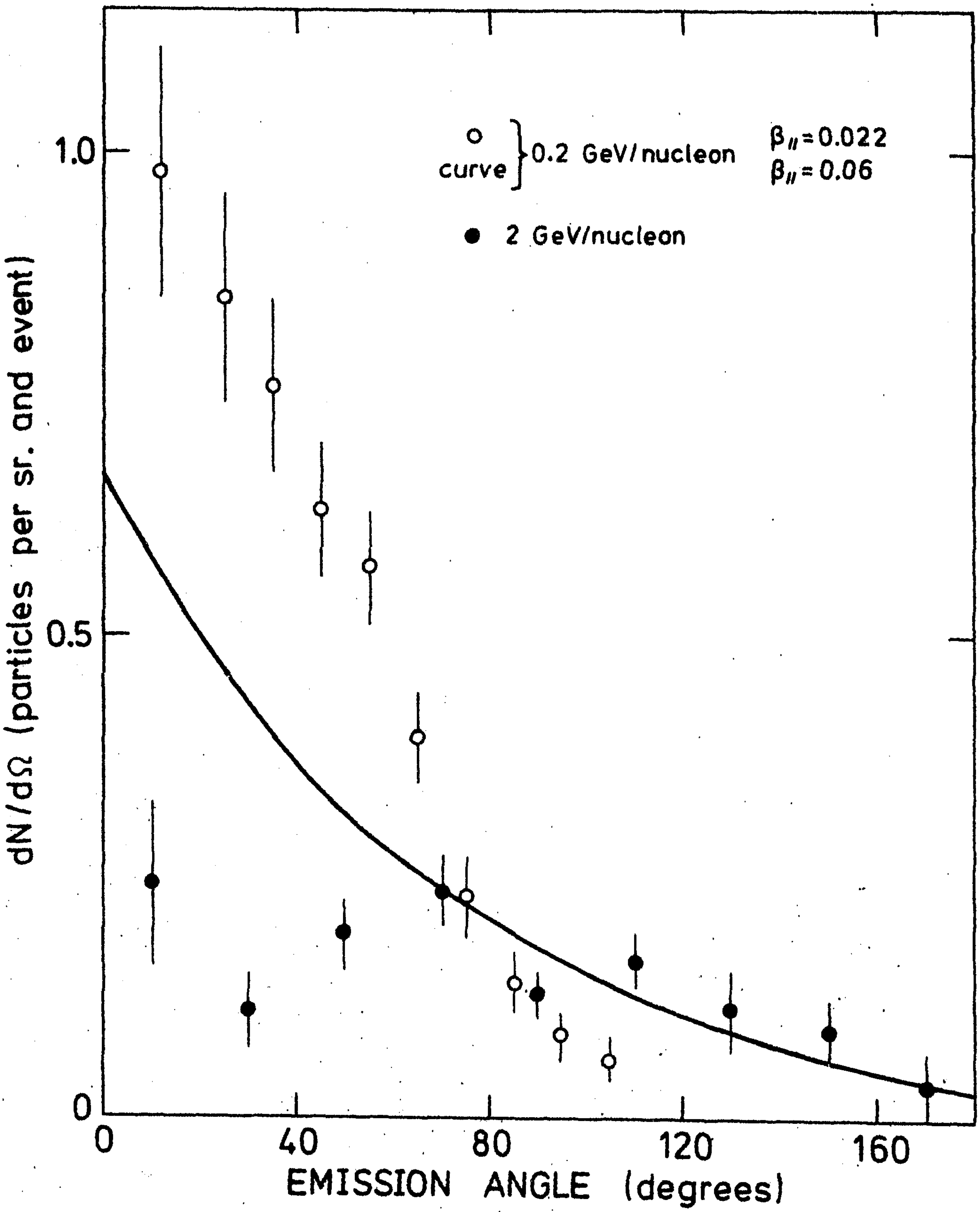
2.0 GeV/nucleon
$N_h \geq 12$
dN/dθ
0
20
40
60
0
40
80
120
160
EMISSION ANGLE (degrees)

Fig. 4



○ 0.2 GeV/nucleon
● 2 GeV/nucleon
β// = 0.06
β// = 0.022
1
0.1
0.01
0.001
dN/dE
1
10
100
1000
ENERGY (MeV)

Fig. 5



1.0
0.5
0
0
40
80
120
160
dN/dΩ (particles per sr. and event)
EMISSION ANGLE (degrees)
○ curve } 0.2 GeV/nucleon
β// = 0.022
β// = 0.06
● 2 GeV/nucleon

Fig. 6