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INTERACTIONS OF 60 AND 200 A GeV ^{16}O IONS IN NUCLEAR EMULSION

N. Ardito[6], G. Baroni[6], V. Bisi[8], A.C. Breslin[3], D.H. Davis[5], S. Dell'Uomo[6], S. Di Liberto[6], P. Giubellino[8], K. Hoshino[4], K. Kodama[4], A. Marzari-Chiesa[8], M. Masera[8], M.A. Mazzoni[6], F. Meddi[6], A. Montwill[3], M.T. Muciaccia[1], S. Natali[1], K. Niu[4], K. Niwa[4], G. Poulard[2], L. Ramello[8], L. Riccati[8], G. Romano[7], G. Rosa[6], C. Sgarbi[6], S. Simone[1], H. Sletten[2], D.N. Tovee[5], G.R. Vanderhaeghe[2] and C. Wilkin[5]

ABSTRACT

A survey of the interactions of ^{16}O nuclei of energies 60 and 200 A GeV in nuclear emulsions is presented. Correlations between projectile fragments and target evaporation are studied. The electromagnetic dissociation of ^{16}O, mainly ascribed to absorption in the giant resonance region, is found to contribute to a sizeable fraction of the nuclear cross-section, and increases with increasing energy.

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1) Istituto di Fisica dell'Università and INFN, Bari, Italy.
2) CERN, Geneva, Switzerland.
3) Department of Physics, University College, Dublin, Ireland.
4) Department of Physics, Nagoya University, Japan.
5) Department of Physics and Astronomy, University College London, England.
6) Dipartimento di Fisica, Università 'La Sapienza' and INFN, Rome, Italy.
7) Dipartimento di Fisica Teorica e sue Metodologie per le Scienze Applicate, Università di Salerno, and INFN, Rome, Italy.
8) Istituto di Fisica dell'Università and INFN, Turin, Italy.

This letter presents a survey of the interactions of ^{16}O nuclei, of energies 60 and 200 A GeV, with the nuclei present in nuclear emulsions. The survey constitutes the preliminary study of an unbiased sample of ^{16}O-emulsion interactions as a part of a hybrid experiment performed in the HELIOS spectrometer at CERN. The study of such a sample of interactions is, in fact, necessary in order to make a comparison with the interactions collected in HELIOS and selected with suitable triggers, namely a high value of the multiplicity of shower particles and/or of the transverse energy E_T, the aim being to see some signal of the possible formation of a new state of nuclear matter, a quark–gluon plasma.

In particular, the correlation between projectile fragments and target evaporation has been studied as a function of the energy. Moreover, the electromagnetic dissociation of ^{16}O has been found to be an important process, contributing more than 10% to the total visible cross-section at the higher energy.

For the present search, two stacks of Fuji ET7B emulsion, of density 3.60 g/cm^3, were poured and prepared at CERN. Each stack, consisting of 62 pellicles of dimensions 16 cm × 5 cm × 600 μm, was exposed parallel to 200 A GeV ^{16}O ions in the H3 beam line in the West Area at CERN in late 1986, and a further, smaller stack of 8 pellicles, of dimensions 12.5 cm × 4 cm × 600 μm was exposed to the 60 A GeV ^{16}O beam. In order to obtain an unbiased selection of interactions, a line-scanning procedure was adopted. Tracks of beam particles were located 10 mm from the entrance edge of the emulsion stack, and those within the central 80% of the pellicle thickness were followed for a distance of 30 mm or until an interaction point was reached. Since some interactions, particularly those ascribed to the electromagnetic dissociation of the beam nucleus, are not easily detectable at the interaction vertex but only become apparent further downstream, tracks were followed another 10 to 20 mm solely to detect such interactions occurring within the fiducial region. Interaction points were recorded and the following features of each interaction were noted. The numbers of black tracks N_B (if of protons, of kinetic energies $\leq$ 30 MeV) and grey tracks N_G (corresponding to protons in the energy range from 30 to ~ 300 MeV) in the forward and backward hemispheres, the presence of doubly charged and multiply charged fragments of the projectile nucleus proceeding from the interaction essentially undeviated from the beam direction, and the approximate number of near-minimum ionizing (shower) particles were recorded. In order to avoid inclusion, in the sample, of interactions of many instances of fast δ-ray and low-energy pair formation, all events exhibiting merely one or two wide-angle minimum-ionizing particles (> 10 mrad to the beam particle in the case of the 60 A GeV exposure, > 5 mrad for the 200 A GeV one) were rejected. This rejection means, of course, that the few nuclear interactions which also present such topologies have also been removed from the sample.

Some 893 tracks of 60 A GeV ^{16}O nuclei were followed over a total distance of 16.37 m and 145 interactions were observed, leading to a mean free path before interaction of (113 ± 9) mm. The corresponding numbers for the 200 A GeV exposure were 2644 tracks for 69.12 m giving 672 interactions, and a resulting mean free path of (103 ± 4) mm. Leaving out of consideration both the elastic scatters and the electromagnetic dissociations, the mean free paths for nuclear interactions are (125 ± 11) mm and (117 ± 5) mm, respectively. These results are to be compared with a mean free path of 2.1 A GeV ^{16}O ions in emulsion in the range 120 to 130 mm [1].

Table 1 sets out the topological features of the interactions observed. The forward fragments of charge $\geq$ 2 are those making small angles ($\leq$ 1 mrad) with the beam direction and thus likely to represent non-interacting clusters within the incident oxygen nucleus. The distributions of the numbers of target fragments $N_H = (N_B + N_G)$ are given separately in fig. 1, for the 60 and 200 A GeV interactions. The forward–backward asymmetry observed for 'black' prongs is +0.08, consistent with the isotropic evaporation from a slowly forward-moving spallation product, whereas that found for 'grey' tracks, mainly knock-on target protons, is quite positive, +0.42, as expected.

It is noted that a significant fraction of events in the two samples, 30.5% and 29.1%, respectively, exhibit no forward fragment with $Z \geq 2$. These interactions are thought to result predominantly from central collisions in the heavy Ag and Br nuclei of the emulsion since they are generally associated both with a high number of evaporation prongs and large numbers of shower particles. However, the majority of interactions show less — often considerably less — involvement of the projectile nucleus. In fact, as the results presented in table 1 clearly show, the mean N_H values increase significantly the greater the number of projectile nucleons involved in the interaction.

A comparison of the results at 60 and 200 A GeV shows that the fractions of interactions which show no sign of target fragmentation ('white' stars, $N_H = 0$) are high, being greater (18.3%) at 200 A GeV than at 60 A GeV, where it is 12.2%. On the other hand, the mean value of N_H is larger (9.5) for the 60 A GeV interactions than it is for the 200 A GeV ones (7.5). These results would indicate a higher fraction of peripheral processes at the higher energy. It is interesting to note that the fraction of white stars and the mean N_H number observed for 200 GeV proton interactions in emulsion are (17.2 ± 1.1)% and 7.4 ± 0.2, respectively [2].

Whilst at first sight these comparative results appear unexpected, both may be explained, at least partially, by simple geometric arguments [3] which indicate that the probability of oxygen ions interacting with the light emulsion nuclei, especially hydrogen, rather than with the heavy ones is enhanced compared with that for protons. A simple Glauber calculation, which reproduces well the observed mean free paths for both high-energy protons and oxygen ions, confirms this. It predicts the relative occurrence of inelastic processes among the (H):(C,N,O):(Br,Ag) groupings to be (4):(24):(72)% for proton interactions, but (12):(32):(56)% for those of oxygen. On the other hand, the results presented in fig. 1 show that central ion collisions on Ag and Br give rise to larger values of N_H than do those of protons, as expected. It would seem to be by chance that the opposite influence of these two effects results in mean N_H values for ^{16}O and proton interactions which are nearly equal.

A striking feature of the results is the significant fraction of interactions — 6% in the case of those at 60 A GeV, 11% at 200 A GeV — in which all that is observed is the low-energy break-up of the projectile nucleus, the fragments of which proceed in directions confined to within 3 mrad of the original beam direction at 60 A GeV and 1 mrad at 200 A GeV. Such interactions are ascribed to the electromagnetic dissociation of the oxygen nucleus brought about by its interaction with the electric field of a nucleus within the medium [4]. For a given energy transfer the mechanism remains important for large impact parameters as the beam energy is increased. It is also proportional to Z^2, where Z is the charge on the target nucleus, such that the main contributors to this effect in emulsion are the silver ($Z = 47$) and bromine ($Z = 35$) nuclei.

Since very peripheral nuclear interactions provide topologies that simulate electromagnetic dissociation processes, a check was made by means of δ-ray counting on the tracks of both the incoming oxygen nuclei and the resulting forward fragments to ascertain that the sum of charges observed issuing from each process was indeed eight. This procedure also effectively eliminated from the sample those events in which a fast forward-going δ-ray resulted from the passage of an oxygen nucleus through the emulsion thereby simulating an ^{15}Np break-up process, although precision measurements of the resulting tracks over some 3 cm were also, in general, sufficient to show up those due to scattering electrons. These measurements of the angles of the emergent particles are made relative to each other only, and are accurate to $\sim$ 0.05 mrad.

The 81 electromagnetic dissociation events observed, 9 at 60 A GeV and 72 at 200 A GeV, have been assigned to the topological categories shown in table 2.

It should be emphasized that, in this experiment, only the charge on each fragment is determined, so not only are the mass values quoted conjectural but the heavier fragments may well be produced in particle-stable excited states. Moreover, neutrons are not detected, and therefore ^{15}On

disintegrations, expected to be similar to ^{15}Np ones, escape observation, ^{14}Npn disintegrations cannot be distinguished from ^{15}Np ones, and so on.

As an illustration, the relative separation angles of the ^{15}Np category of events at 200 A GeV are plotted in fig. 2, $\Delta\alpha$ being the horizontal component of the ^{15}Np angle, and $\Delta\delta$ the vertical component with respect to the emulsion plane. This plot reveals a 12% loss of events which occur in planes steeply inclined to the plane of the emulsion.

The abrupt cut-off at small angles strongly suggests the electromagnetic nature of these events, the few events at relatively large angles (not shown in fig. 2) being most likely the onset of the nuclear contribution to this topology. On the assumption that the dissociation process has been correctly identified and that the fragments proceed in the forward direction with the energies per nucleon possessed by the original oxygen nucleus, the measured angles relate directly to the transverse momenta $p_\perp$ of the fragments following dissociation. The $p_\perp$ distribution of the protons from the ^{15}Np sample is shown in fig. 3.

Events in the other categories, whose present statistics in the single channels do not allow a similar treatment, are more easily detectable, and the corresponding finding efficiencies will be considered to be close to 100%.

From fig. 3 it is apparent that the great majority, if not all, of the ^{15}Np events may be ascribed to absorption in the giant resonance region ($21 < E < 27$ MeV), where the reaction $^{16}O(\gamma,p)^{15}N^*$ occurs predominantly to the ^{15}N ground state and 6.32 MeV excited state [5]. In fact, in this case one should expect protons in the rest frame of the oxygen nucleus centred around momentum values $p^* = 150$ and 105 MeV/c and, for isotropic emission, $\langle p_\perp \rangle = \frac{1}{4}\pi p^*$.

Using the formula for the flux of virtual quanta [4, 6] and adopting a minimum impact parameter

$$b = \left[1.3\,(A_{\mathrm{target}}^{1/3} + A_{\mathrm{oxygen}}^{1/3}) + 0.4\right] \mathrm{fm}\,,$$

it has been possible to calculate, using both the giant resonance formula and the experimental integrated photodisintegration cross-section [7], the expected mean free path in emulsion. For 200 A GeV incident ^{16}O ions the total mean free path for electromagnetic dissociation is calculated to be 1.3 m, whereas the mean free paths for producing ^{15}Np and Cα are 2.3 m and 48 m, respectively. If it is assumed that ^{15}On disintegrations contribute as ^{15}Np, whereas ^{14}Onn and ^{14}Npn (these detected as ^{15}Np) are like ^{14}Cpp, and taking into account the scanning efficiency, the experimental values on the mean free paths are (0.6 ± 0.1) m for the total electromagnetic dissociation, and (1.6 ± 0.2) m and (7 ± 2) m for the channels ^{15}Np and Cα, respectively. Although the order of magnitude of the total mean free path is the expected one, it is seen that finer details, and in particular the ratio between events in the Cα and Np categories, disagree. Clearly, more experimental data and refined calculations including that of the dissociation produced by strong interaction processes are needed.

Although the statistics for multiparticle break-up are very poor, some of the events (e.g. Li 5p or α 6p) are difficult to ascribe to single-photon absorption processes and suggest the possibility of multiphoton absorption, a new sphere of physics difficult to realize by more conventional means.

The electromagnetic dissociation of projectile nuclei, which already represents a sizeable fraction of the nuclear cross-section in ^{16}O–emulsion interactions at 200 A GeV, is expected to increase with energy and with the charges of both the projectile and the target. It will be then interesting to measure this effect with the forthcoming high-energy ion beams.

It is a pleasure to acknowledge the excellent performance of the CERN PS and SPS, and the enthusiastic work of the related staffs, who succeeded in delivering such a unique oxygen beam.

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Table 1

Topological features of the interactions observed

Energy (GeV/A)	Total inter.	Elastic $^{16}O + p$	Electro-magnetic	Nuclear interact. dissoc.	Forward fragments							Interactions with N_H			
					None	$Z \geq 3$	$Z \geq 3$ no α	$1\alpha + \alpha$	2α	3α	4α	$= 0$	$= 1$	2–8	> 8
60	145	5	9	131 $\langle N_H \rangle$ 9.5	40 30.5% 17.8	35 26.7% 2.8	9 6.9% 5.5	27 20.6% 9.5	14 10.7% 7.6	5 3.8% 5.3	1 0.8% 1.0	16 12.2%	13 9.9%	53 40.5%	49 37.4%
200	672	9	72	591 $\langle N_H \rangle$ 7.5	172 29.1% 13.5	172 29.1% 4.3	42 7.1% 3.9	99 16.8% 9.2	71 12.0% 5.7	35 5.9% 3.0	– – –	108 18.3%	55 9.3%	228 38.6%	200 33.8%

Table 2

Topological categories of the observed electromagnetic dissociations

Category*)	60 A GeV	200 A GeV
^{15}Np	5	44
Cα	–	10
Cpp	3	7
Bαp	–	3
3α2p	–	4
4α	–	2
Li 5p	–	1
α 6p	1	–
Li$\alpha\alpha$p	–	1

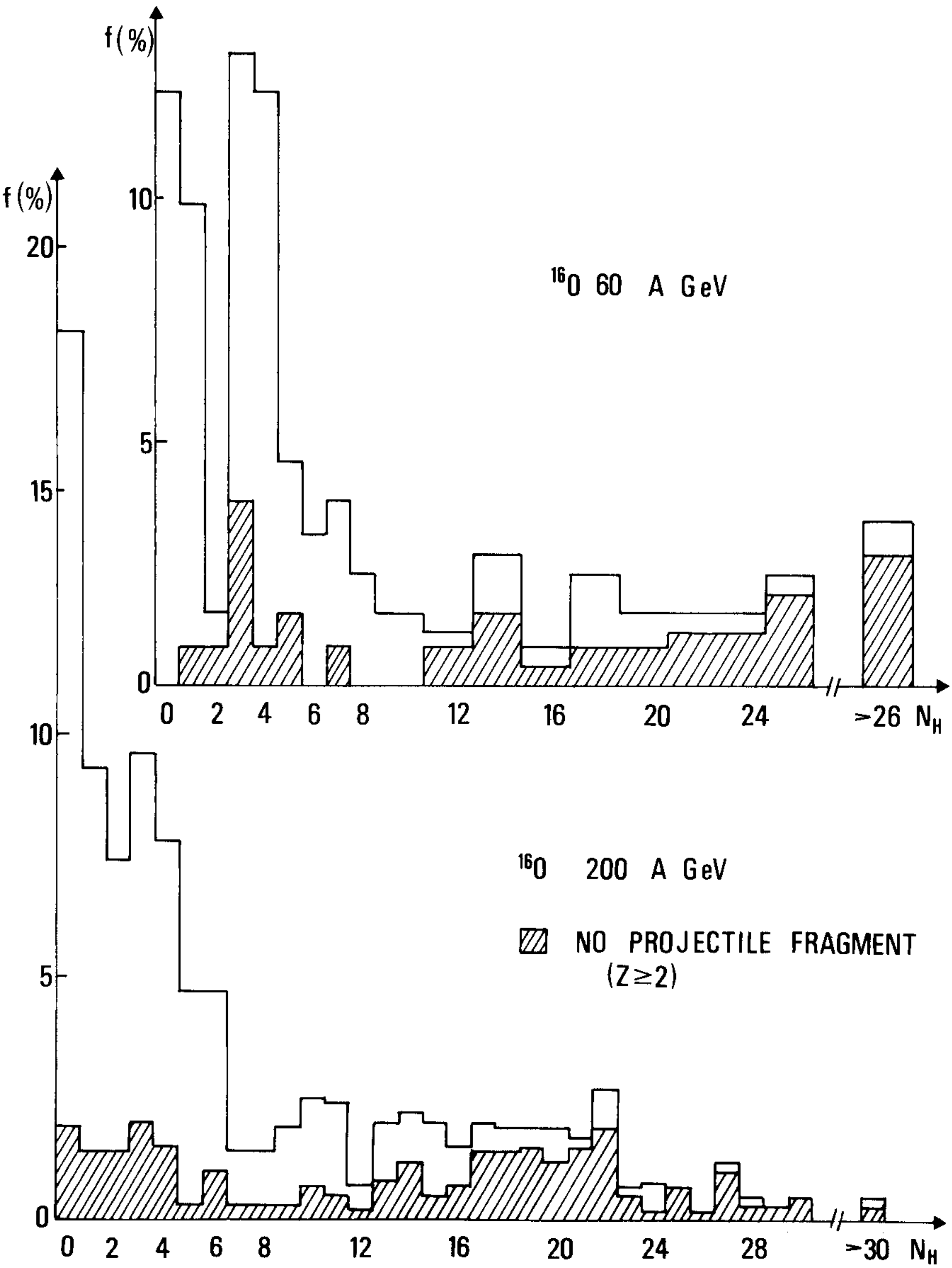
*) The mass assignment is conjectured (see text).

Figure captions

Fig. 1 Distribution of the number of target fragments ($N_H = N_B + N_G$) in ^{16}O–emulsion interactions.

Fig. 2 Vertical ($\Delta\delta$) versus horizontal ($\Delta\alpha$) component of the relative separation angle between p and ^{15}N. This plot reveals a 12% loss of events, i.e. those containing a proton almost superimposed on the N track.

Fig. 3 Transverse momenta ($p_\perp$) distribution of the protons from the ^{15}Np sample, derived from the separation angles.



f(%)
^{16}O 60 A GeV
0
5
10
0 2 4 6 8 12 16 20 24 >26 N_H
f(%)
0
5
10
15
20
^{16}O 200 A GeV
NO PROJECTILE FRAGMENT (Z≥2)
0 2 4 6 8 12 16 20 24 28 >30 N_H

Fig. 1

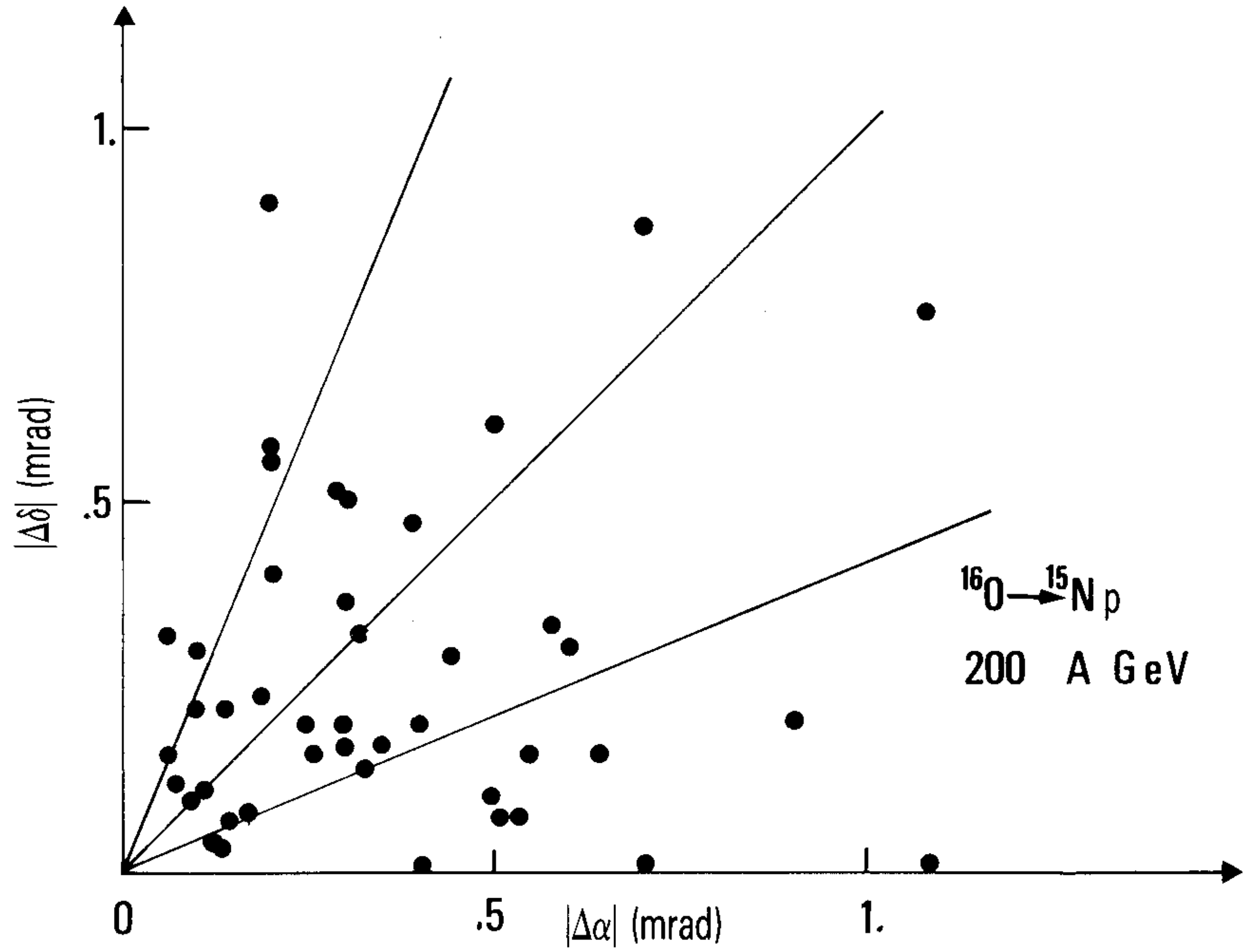

1.
.5
$|\Delta\delta|$ (mrad)
0
.5
$|\Delta\alpha|$ (mrad)
1.
$^{16}O \rightarrow ^{15}N\,p$
200 A GeV

Fig. 2

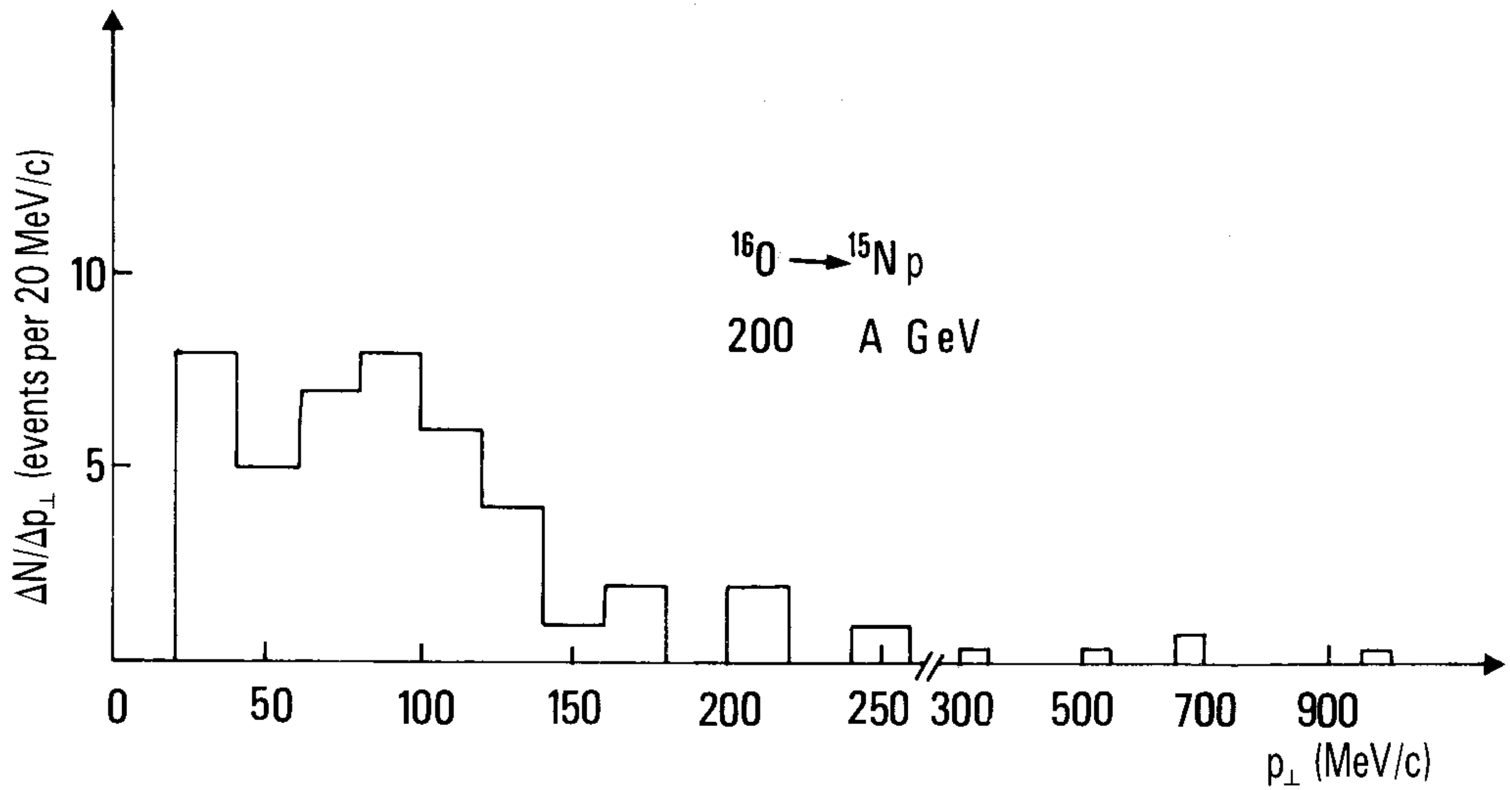

$^{16}O \rightarrow ^{15}N\,p$
200 A GeV
$\Delta N/\Delta p_{\perp}$ (events per 20 MeV/c)
10
5
0
50
100
150
200
250
300
500
700
900
$p_{\perp}$ (MeV/c)

Fig. 3