EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ENERGY DEPENDENCE OF THE QUASI-FREE $(\pi^+,2p)$ REACTIONS AND EVIDENCE FOR THE REACTION $\pi^+ + (2N) \rightarrow \pi + p + p$ IN NUCLEI

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ABSTRACT

The cross-sections of the $(\pi^+,2p)$ reactions in nuclei, leading to low-lying excited states, exhibit a resonance near 150 MeV incident energy, in close similarity to the free reaction $\pi^+ + d \rightarrow p + p$. This confirms that they proceed by a quasi-free mechanism. The missing-mass spectra show a rise at high mass values, which indicates a quasi-free process in nuclei, corresponding to the free non-peripheral reaction of the type $\pi^+ + d \rightarrow \pi^0 + + p + p$.

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The emission of two fast nucleons following the absorption of pions in nuclei has recently been investigated in detail$^{1-4)}$. The experiments, and their comparison with theory, have produced conclusive evidence for the quasi-free nature of the reaction in the case when the residual nuclei are left in low-lying excited states. The pions seem to be absorbed in closely correlated nucleon-nucleon pairs ("quasi-deuterons") which are ejected, whilst the rest of the nucleus is hardly perturbed. As a consequence, hopes for the exploitation of the reaction for nuclear spectroscopy seem justified, and first attempts in this direction have been made$^{5)}$.

The experiments have shown, in particular, that the quasi-deuterons in the nucleus have centre-of-mass velocities of the order of one-tenth the velocity of light. Since the cross-section for the free reaction $\pi^+ + d \to p + p$ has a pronounced resonance at about 150 MeV laboratory kinetic energy, where the pion velocity is 88% of the velocity of light, one should expect that the corresponding quasi-free reactions in nuclei should exhibit very similar resonance behaviour. The ratio between the quasi-free and the free reaction would indeed be expected to be nearly constant or, at worst, to go through a shallow maximum and a shallow minimum near the resonance energy.

In a recent experiment, Allardyce et al.$^{6)}$ have measured the ^{16}N activity induced in ^{18}O by the impact of positive and negative pions of various energies. The ratio of the ^{16}N production cross-section to the total cross-section for the reaction $\pi^+ + d \to p + p$, is nearly constant up to about 180 MeV. However, beyond that energy it starts growing rapidly, as seen in Fig. 1. This indicates that either the reaction (π,2N) in ^{18}O is not dominated by a direct mechanism, or that the production of ^{16}N is at least partly due to a competing process. The knock-out of one nucleon by the incident pion followed by the evaporation of another nucleon would be the most obvious candidate for such a competing process if it were not for the fact that it should itself exhibit a resonance at about 150 MeV. Instead, the reaction which is called for should preferably be strongly endothermic so that its rapid growth as a function of incident energy could compensate for the decrease in the cross-section of the direct (π,2N) reaction above the resonance.

We believe that we have shed some light on the problem by investigating the energy dependence of the $(\pi^+,2p)$ reaction in several nuclei. The experimental technique has been described previously[7]. Briefly, it consists of measuring the angles of the incident pion and the two outgoing protons by film-less spark chambers. The energy of the pion is determined by magnetic analysis, whilst the energies of the protons are inferred from range measurements. Only protons with kinetic energies higher than 40 MeV and lower than 230 MeV are accepted. The two proton detectors are placed symmetrically with respect to the beam at angles of 79° for the measurements below 100 MeV incident energy and of 74° for the higher energies. These values were chosen to be close to the maximum of the strong angular correlation between the two protons in the case of ground-state transitions. The proton detectors subtend angles, both horizontally and vertically, which decrease linearly with increasing proton range and are ±15° for 40 MeV protons and ±10° for 230 MeV protons. An experimental problem which becomes the more serious the higher the incident energy and, therefore, the higher energies of the outgoing protons, is nuclear absorption of protons in the range-measuring arrays of scintillators. The dE/dx of each proton is determined by pulse-height measurements in an 8 mm thick scintillator in front of the range array, and events for which the range of one or both detected protons is inconsistent with the respective dE/dx value are rejected in the final analysis. As a consequence of the relatively poor resolution in the dE/dx measurements, the resulting cleaning of the energy spectra is not perfect and some background remains to be subtracted. This introduces uncertainties in the determination of cross-sections and precludes precision measurements. In Fig. 1 the measured yields for the production of low-lying states of several residual nuclei are plotted in units of the measured yield of the elementary reaction $\pi^+ + d \rightarrow p + p$, for various incident energies. In spite of the large errors due to the background uncertainty and, in some cases, to poor statistics, it is clear that the energy dependence of yields is strikingly different from that determined by ^{16}N activity measurements, and is qualitatively consistent with the expected behaviour of the direct $(\pi,2N)$ reaction.

The missing-mass spectra behave in a very systematic way as the incident energy is increased. The shape of their low-energy part does not change appreciably. A higher energy tail grows progressively. Finally, when the region of large missing masses becomes accessible, the spectrum exhibits a rise, which is cut off at the high-mass end by the lower limit of 40 MeV on the individual proton energies. As an example, Fig. 2 shows the missing-mass spectra obtained with the target ^{6}Li for different incident energies. The rise at missing masses more than 140 MeV above the mass of ^{4}He is definitely physical, since in this region the background elimination is most reliable. By plotting the spectra as a function of the limits on the acceptable dE/dx values, we convinced ourselves that even the tail beyond the two low-mass peaks contains only a small ($\lesssim$20%) contribution of degraded protons.

The fact that the spectrum starts rising at missing-mass values above the sum of the masses of ^{4}He and a pion, is a strong indication that one is observing a reaction with a free pion in the final state. Then the residual nucleus may often be left in a low-lying state. The angular and energy distributions and correlations of the observed events in the interesting region of the spectrum are consistent with such an assumption. In particular, the rise is relatively stronger if one selects events with smaller angles between the incident pion and outgoing protons. This shows that the yield of the reaction with a free pion in the final state is increasing with decreasing proton angle, and when integrated over all angles it may well be of the same order of magnitude, or larger than the yield of the direct (π,2N) reaction leading to low excitation energies. This would explain the results of Allardyce et al.$^{6)}$. In order to obtain a quantitative estimate of the yield in the interesting region of the excitation energy spectrum, we assume that the tail extends smoothly from below 140 MeV into the region beyond 140 MeV. After subtracting its contribution, we find the yield of the reaction with a free pion in the final state. The results for several nuclei are presented in Table 1.

Questions about the mechanism of the observed reaction are more difficult to answer. The high energies of the observed protons obviously exclude an evaporation process. It is also unlikely that one is seeing the products of an uncorrelated cascade initiated in the nucleus by the incident pion. The large amount of Fermi motion needed to impart high momenta to cascade protons at large angles seems inconsistent with the high measured yield.

In our opinion it is most likely that we are observing the nuclear manifestation of a phenomenon which has often been seen in deuterium[9]. Attempts to analyse events in deuterium bubble chambers in terms of purely peripheral processes, with one of the nucleons playing the role of a spectator, have been unsuccessful. The momentum spectrum of the "spectator" nucleon, defined as the lowest energy nucleon in each event, exhibits a substantial high-energy tail, completely inconsistent with accepted deuteron wave functions.

Unfortunately, to our knowledge, the mechanism of the reaction in deuterium has not been investigated in detail. One attractive possibility for the mechanism in question is $\pi + d \rightarrow N + N^*$, N^* signifying one of the nucleon isobars. Such a hypothesis could explain why the yield of the analogous reaction in nuclei seems to rise quickly only beyond about 180 MeV, as indicated by the results of Allardyce et al.[6]. Unfortunately our results, though consistent with such a hypothesis, are rather insensitive to the reaction mechanism.

If the reaction observed in nuclei is indeed closely connected with the elementary reaction in deuterium, and regardless of the mechanism of the latter, it is quite remarkable how nearly the quasi-deuterons in nuclei behave as real deuterons. Also, the idea that the contribution of pion-quasi-deuteron interactions in nuclei may be comparable to the contribution of pion-nucleon interactions, as put forward in the letter of Chivers et al.[10], is receiving added support.

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Table 1

Observed cross-sections of the reaction $(\pi^+,\pi pp)$, for various target nuclei, integrated over the experimentally accepted angles and energies. The cross-sections are normalized to the corresponding cross-section of the reaction $\pi^+ + d \rightarrow p + p$. The absolute value of the latter has been taken from Ref. 8 and integrated over the accepted region with the result:

$$\int \frac{d\sigma}{d\Omega} (\pi^+ + d \rightarrow p + p) = 25.9 \ \mu b$$

^4He : 22 ± 8 μb

^6Li : 57 ± 11 μb

^7Li : 67 ± 13 μb

^{16}O : 86 ± 30 μb

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Figure captions

Fig. 1 : Yields of the (π^+,2p) reaction leading to low-lying excited states of the residual nucleus, for different target nuclei and different incident energies, relative to the corresponding yields of the free reaction $\pi^+ + d \rightarrow p + p$:

a) reaction $\pi^+ + {}^6Li \rightarrow {}^4He + p + p$, with ${}^4He$ excited between threshold for particle break-up and 50 MeV;

b) reaction $\pi^+ + {}^6Li \rightarrow {}^4He$ (ground state) $+ p + p$;

c) reaction $\pi^+ + {}^{16}O \rightarrow {}^{14}N + p + p$ with ${}^{14}N$ excited between 0 and 30 MeV.

These yields are integrated over our experimental acceptance.

d) reaction $\pi^+ + {}^{18}O \rightarrow {}^{16}N$ (particle bound states) + ... , determined by activity measurements$^{6)}$, relative to the total cross-section of the free reaction$^{8)}$.

Fig. 2 : Missing-mass spectra of the reaction (π^+,2p) on ${}^6Li$, for different laboratory kinetic energies T_{π^+} of the incident pion.

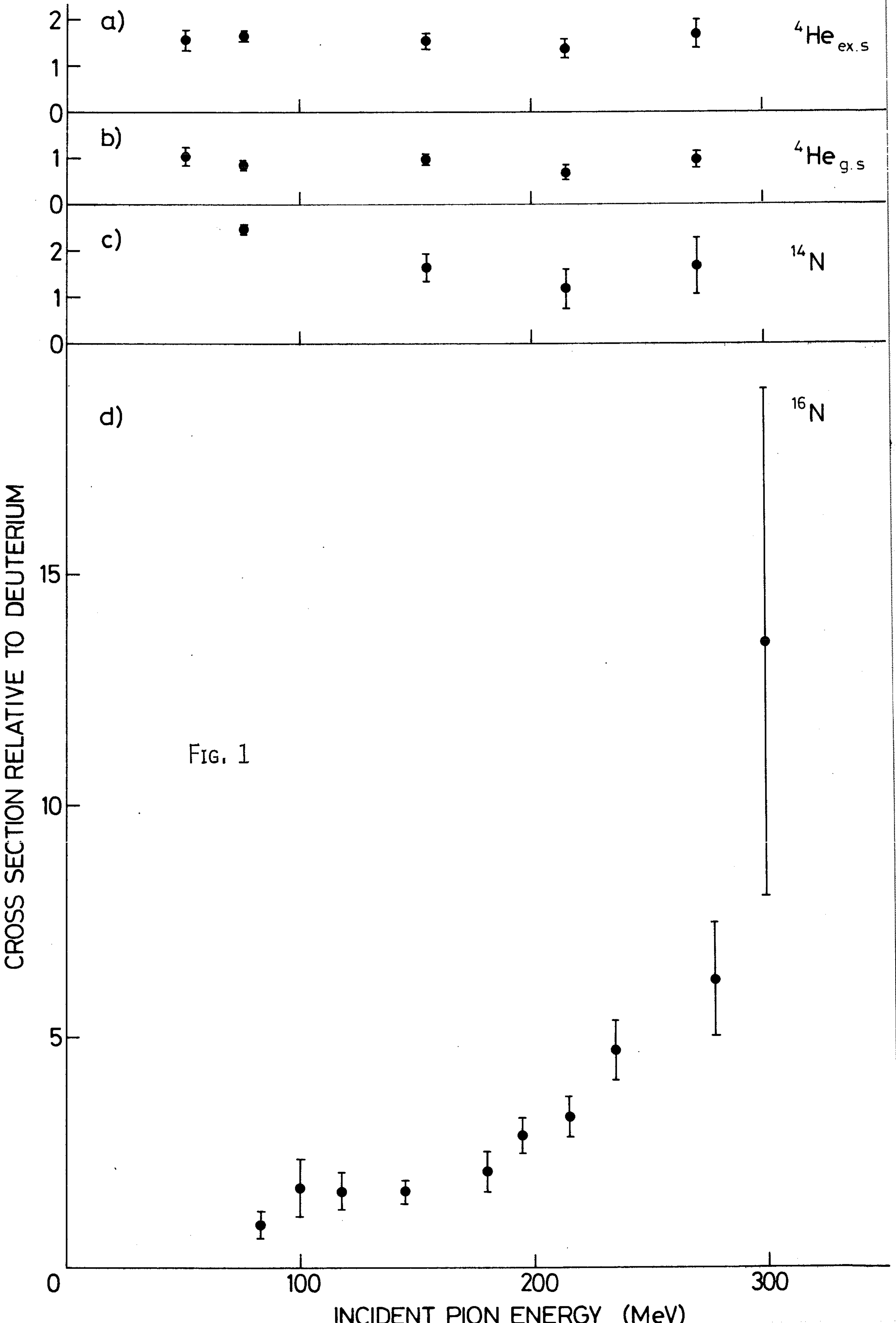
a)
$^4He_{ex.s}$
b)
$^4He_{g.s}$
c)
^{14}N
d)
^{16}N
0
1
2
15
10
5
0
100
200
300
CROSS SECTION RELATIVE TO DEUTERIUM
INCIDENT PION ENERGY (MeV)

FIG. 1

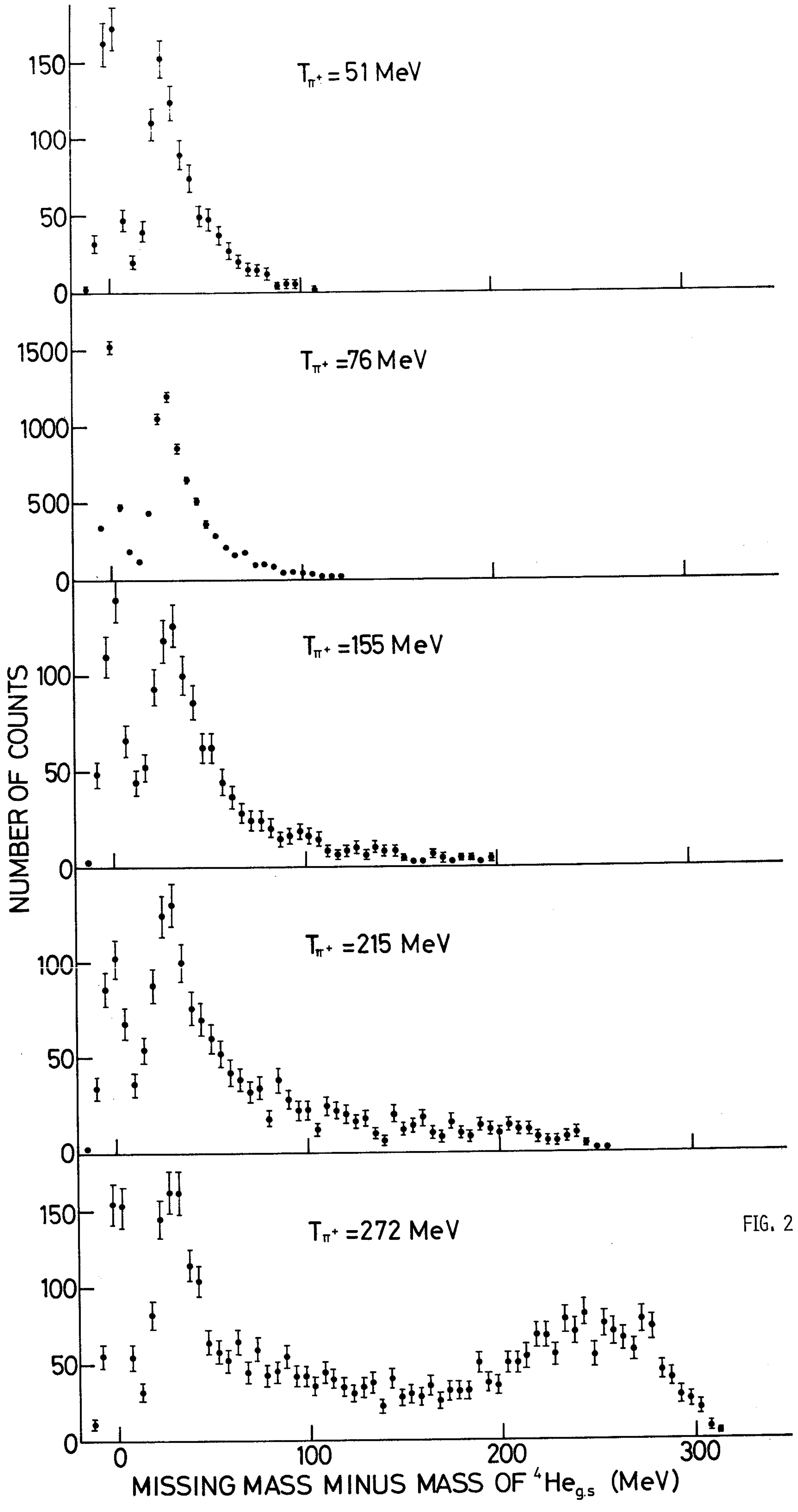
$T_{\pi^+} = 51$ MeV
$T_{\pi^+} = 76$ MeV
$T_{\pi^+} = 155$ MeV
$T_{\pi^+} = 215$ MeV
$T_{\pi^+} = 272$ MeV
NUMBER OF COUNTS
0
50
100
150
500
1000
1500
200
300
MISSING MASS MINUS MASS OF $^4He_{g.s}$ (MeV)

FIG. 2