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# ON THE $\pi^+$ MESON ABSORPTION IN $^4$He

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ABSTRACT

The total cross section of the ($\pi^+$, $^4$He) absorption reaction has been deduced at 120, 145 and 165 MeV. The values are close to those of the $\pi^+ d \rightarrow pp$ reaction cross section and the absorption by a quasi-deuteron is the main mechanism in the non-radiative capture of $\pi^+$ on $^4$He. The $\pi^+$ absorption with emission of p-$^3$He pairs is negligible. The differences between the ($\pi^+$, $^4$He) and the ($\pi^-$, $^4$He) absorption channel are discussed in view of the $\alpha$-clustering effects present in the $\pi^-$ absorption in light nuclei.

## 1. - INTRODUCTION.

Up to now the discussion of primary absorption processes of pions on nuclei appears to be rather controversial. While there exists a general consensus on the existence of the quasi-deuteron process (that is the absorption of pions on n-p pairs), the existence of the quasi-alpha process (that is the absorption of pions $\alpha$-clusters in nuclei) is controversial. In the case of $\pi^-$ absorption the measurements of neutron-triton and neutron-deuteron coincidences on carbon showing pronounced large angle correlations(1) emphasized the importance of $\pi^-$ absorption on $\alpha$-like substructures(2). The measurement of neutron spectra, following the $\pi^-$ absorption in nuclei, could indicate absorption processes on clusters heavier than deuteron(3). In the case of the spectra of the charged particles, emitted following the absorption of stopped negative pions in carbon target, the experimental results(4) give a strong support for the qualitative picture of $\pi^-$ absorption as a primary absorption on quasiparticles with subsequent equilibration by scattering of the primary nucleons on particles and holes. In particular, absorption of $\pi^-$ on $\alpha$-substructures and scattering of primary nucleons on quasi-$\alpha$-particles in the nucleus itself seem to play a noticeable rôle. In the measurements of the A-behaviour of $\pi^+$ and $\pi^-$ absorption cross section at 125 MeV, Navon et al.(5) found that the cross sections vary approximately as $A^{0.7}$, but the $\pi^+$ values are sistematically lower than those measured for the $\pi^-$ absorption. On the other hand, the study of the $\pi^+$ absorption in light nuclei(6) shows a clearly visible effect of two-nucleon capture, but the effects due to capture on larger clusters are not evident.

These experimental results suggest the hypothesis that in the nuclei the $\pi^+$ absorption in quasi-$\alpha$-particles is a channel not so evident as in the case of the $\pi^-$ absorption. However, the study of the $\pi^+$ and $\pi^-$ absorption mechanisms on a free $\alpha$-particle is a prerequisite to any understanding of the clustering effects in the nuclei. In this paper the comparison between the results obtained in the study of the negative pion capture(7) on $^4$He, with those we obtained for the positive pion absorption on $^4$He at $(120 \pm 15)$, $(145 \pm 10)$ and $(165 \pm 10)$ MeV, is performed.

## 2. - EXPERIMENTAL RESULTS AND DISCUSSION.

We studied the interaction of $\pi^+$ on $^4$He with a diffusion cloud chamber in a magnetic field, exposed to the pion beam of Frascati National Laboratories. The experimental set-up, the experimental procedure, the globality of the results we obtained are described in ref.(8). In the present paper the results of the analysis of the absorption events are presented in detail, with all the angular correlations we deduced.

As it is known, the capture of positive pions in $^4$He can lead to three non-radiative final channels:

$$\pi^+ + {}^4\mathrm{He} \longrightarrow \pi^+(n\,{}^3\mathrm{He}) \longrightarrow p + {}^3\mathrm{He}\,, \qquad (1)$$

$$\pi^+(nn) + pp \longrightarrow np + pp\,(3p+n)\,, \qquad (2)$$

$$\pi^+(np) + {}^2\mathrm{H} \longrightarrow 2p + {}^2\mathrm{H}\,. \qquad (3)$$

The events (1) in the photographs appear similar to those of the single charge exchange $\pi^+ + {}^4\mathrm{He} \rightarrow p + {}^3\mathrm{He} + \pi^0$, with the proton and $^3$He tracks always well distinguishible by ionization. On the other hand the deuteron tracks cannot be distinguished from the proton tracks in the case of the reactions (3); the events (3) cannot be distinguished from the $\pi^+ + {}^4\mathrm{He} \rightarrow 3p+n$ events and these last cannot be distinguished from the $\pi^+ + {}^4\mathrm{He} \rightarrow 3p + n + \pi^0$ (or $2p + {}^2\mathrm{H} + \pi^0$) events. However, taking into account the small binding energy of the deuteron, it is possible to assume that the probability of deuteron emission is very small. This assumption is also supported by the experimental data of refs.(9). The 3pn (or 2pd) events appear as stars of three particles, the relatively high energy of the charged particles indicates that the number of reactions $3pn\pi^0$ (or $2pd\pi^0$) is negligible with respect to the number of 3pn events. Fig. 1 shows the distribution of the 3pn (or 2pd) events as a function of the opening angle between the tracks of the two fastest particles, at $E_\pi = 145$ MeV. A strong correlation between the two protons

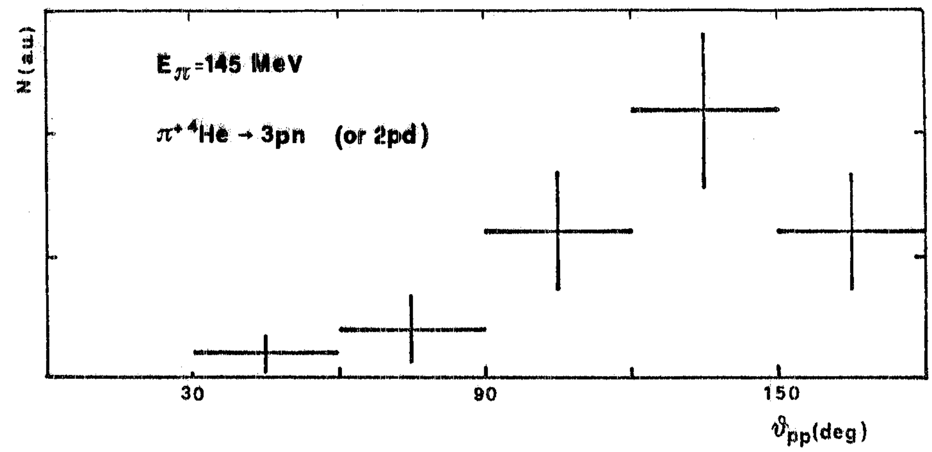


FIG. 1 - Distribution of 3pn (or 2pd) events versus the opening angle between the two fastest protons.

from the $\pi^+$(np) → 2p (quasi-deuteron absorption) is clearly active at large angles, in agreement with the fact that the (np) pairs are twice as abundant as (nn) pairs and a $\pi^+$ yields two protons at large angle when it absorbs on a (np) pair and only one proton from a (nn) pairs. The hystogram contains all the events of the (2) and (3) reactions and the sum of the cross sections of the reactions resulted $(11 \pm 4)$, $(12 \pm 4)$ and $(11 \pm 4)$ mb at 120, 145 and 165 MeV respectively.

Tentatively we measured the angular distributions of the third slower charged particle (spectator) of the 3pn (or 2pd) events. Fig. 2 shows the angular distribution of the spectator particles, at $E_\pi$ = 145 MeV, compared with the phase-space distribution calculated by the FOWL program[10], with the hypothesis that the spectator is a deuteron or a proton from a (np) pair and that the angle between the two tracks of the two fastest particles is larger than 90 degrees. As one can see it is impossible to determine what kind of particle is the spectator.

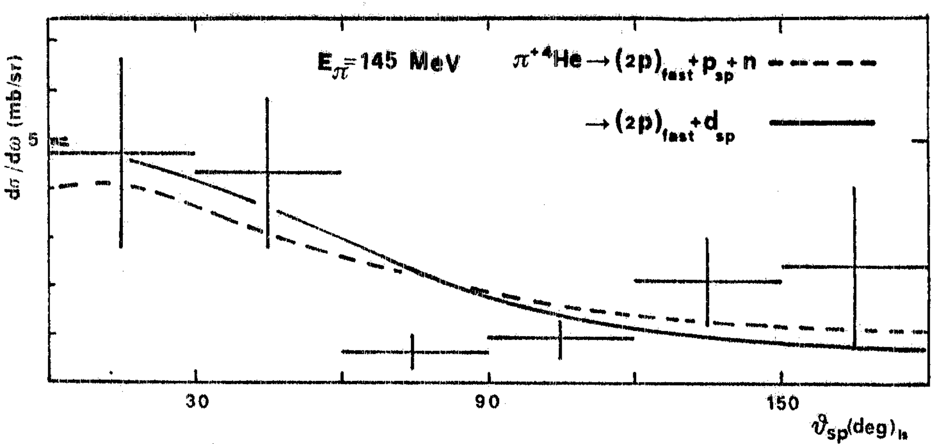


FIG. 2 - $^4$He($\pi^+$, 3pn) differential cross section versus the spectator particle angle, compared with the phase-space distributions obtained with the hypothesis that two protons are emitted with an angle between them larger than 90° and the spectator particle is a $d_{sp}$ (full line) or a proton (dashed line).

There is a group of events which on principle could be confused with the (3pn) events, the multiple scattering events $\pi^+ + {}^4He \rightarrow \pi^+ + 2p + 2n$. As shown in the photographs of ref. (11), it is very difficult to confuse the (3pn) events with the ($\pi^+$2p2n) events because of the large difference between the pion and the proton tracks in diffusion cloud chamber. After several scannings, performed by different people, it has been possible to state that the upper limit of the number of ($\pi^+$2p2n) events, which can be considered doubtful (3pn) events, not exceeds the 10 % of the total. This means that, to the cross section values of the (3pn) reaction, sum of the cross sections of the reactions (2) and (3), it can be added $(3.8^{+0}_{-3.8})$, $(2.8^{+0}_{-2.8})$ and $(2.6^{+0}_{-2.6})$ mb at 120, 145 and 165 MeV, respectively[8].

In order to separate the events (1) from the single charge exchange reaction events $p\,{}^3He\,\pi^0$, we tested the coplanarity of the p and $^3$He tracks and deduced all the kinematic parameters in the phase space for the two- and three-body reactions. Fig. 3 shows the experimental distribution at $E_\pi$ = 145 MeV of all the events with a proton and a $^3$He emitted in the final state, as a function of the opening angle between the two tracks. The data are compared with the phase-space distribution calculated with the FOWL program for the events of the reaction (1).

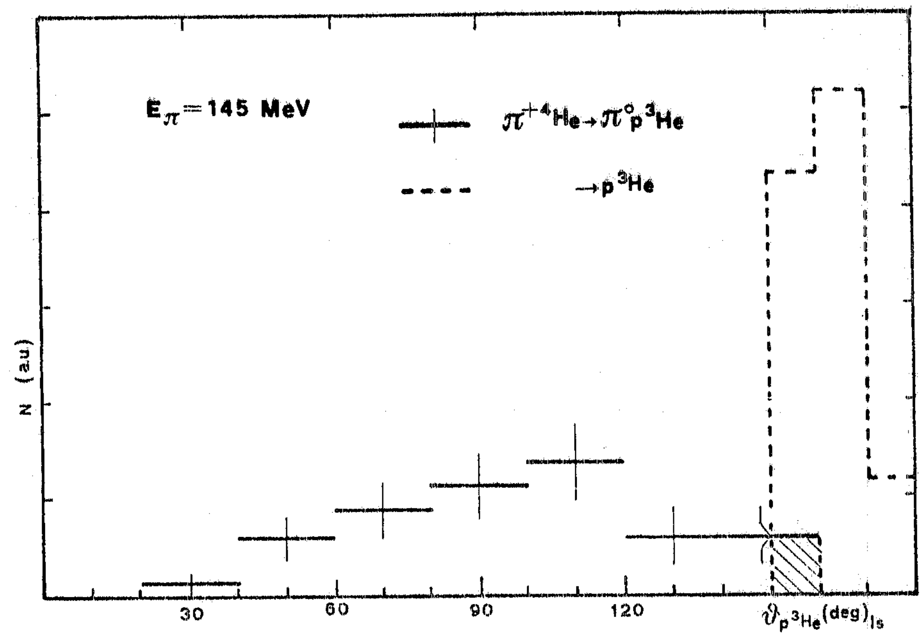


FIG. 3 - Distribution of the events with a p-$^3$He pair in the final state versus the opening angle, compared with the phase-space distribution calculated for the (p, $^3$He) absorption events.

The experimental errors in the angle reconstruction and the energy distribution of the $\pi^+$ beam have been taken into account. This comparison shows that only 3 % of all the ($p^3He$) pairs we measured can be considered as produced by the absorption reaction (1). Moreover, the coplanarity test which also takes into account the experimental uncertainties gave a limit of 10 % for the number of events with p and $^3$He coplanar with the incoming pion. As a consequence the cross section of the (1) channel could be only of few mb in our energy interval(8), that is with an upper limit of about $(2.3^{+0}_{-2.3})$, $(2.8^{+0}_{-2.8})$, $(4.7^{+0}_{-4.7})$ mb at 120, 145 and 165 MeV, respectively. Contemporary to the absorption events, we obtained and measured also the $\pi^+ + {}^4He \rightarrow \pi^+ + n + {}^3He$ reaction events. These two prongs events, with $^3He$ and $\pi^+$ in the final state could (on principle) be confused with the (1) absorption events. Nevertheless the Fig. 4 in which the distribution at $E_\pi$ = 145 MeV of the $(\pi^+ n\, {}^3He)$ events as a function of the angle between the $\pi^+$ and $^3He$ tracks is presented, shows that there is not evidence of events with $\pi^+$ and $^3He$ emitted at large angle between them. These results are in agreement with the data of ref.(6) on the $\pi^+$ absorption in

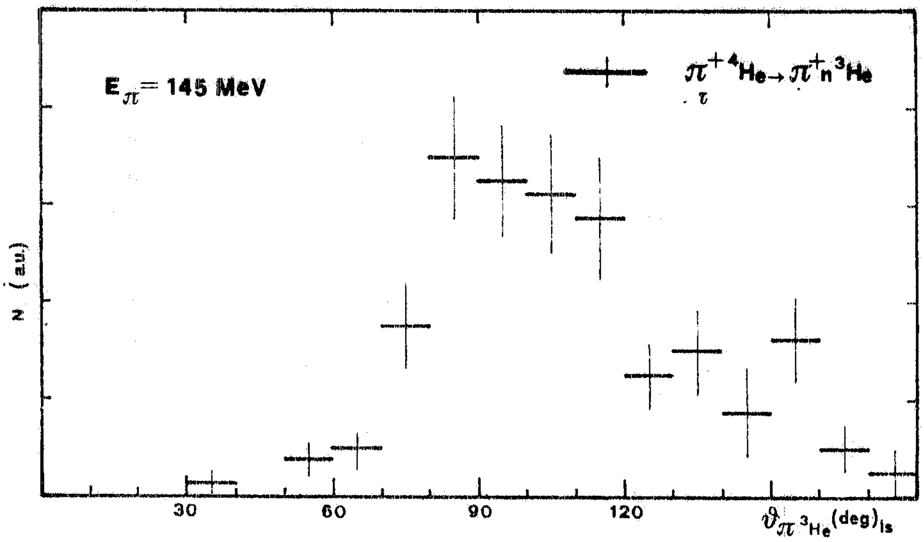


FIG. 4 - Distribution of the $(\pi^+ n\, {}^3He)$ events versus the opening angle between $^+$ and $^3He$.

light nuclei and with those obtained by Kållne et al.[12] in $^4He$, which show the very low probability of emission of p $^3He$ pairs. It is interesting to note that, in the case of the symmetric reaction $\pi^- + {}^4He \rightarrow n + {}^3H$, the cross section is higher[13] than that of the reaction (1) and that the emission of n - $^3H$ pairs has been detected also in the absorption $\pi^-$ in the nuclei[1]. At this point, it is possible to conclude that the pion absorption in $\alpha$-clusters in the nuclei seems to reflect qualitatively the differences between the $\pi^-$ and $\pi^+$ absorption in $^4He$.

Consequently, it is possible to conclude from the present experiment, that in the case of positive pions capture in $^4He$ the more important mechanism (in agreement with ref.(14) results to be the $\pi^+$ absorption on nucleon pairs (in particular in quasi-deuteron). Fig. 5 shows that the values of the sums of the cross sections of the reactions (2) and (3) are a little higher than the values of the $\pi^+$ absorption cross section in free deuterons[15], but these values are lower than the $\pi^+$ capture cross section by nuclear quasi-deuterons in lithium nuclei[16]. It is interesting to note that in the case of quasi-deuteron absorption of photons on $^4He$, the $\gamma + {}^4He \rightarrow (np) + {}^2H$ reaction cross section values are close[17] to the free deuteron photodisintegration cross section for $E_\gamma > 40$ MeV.

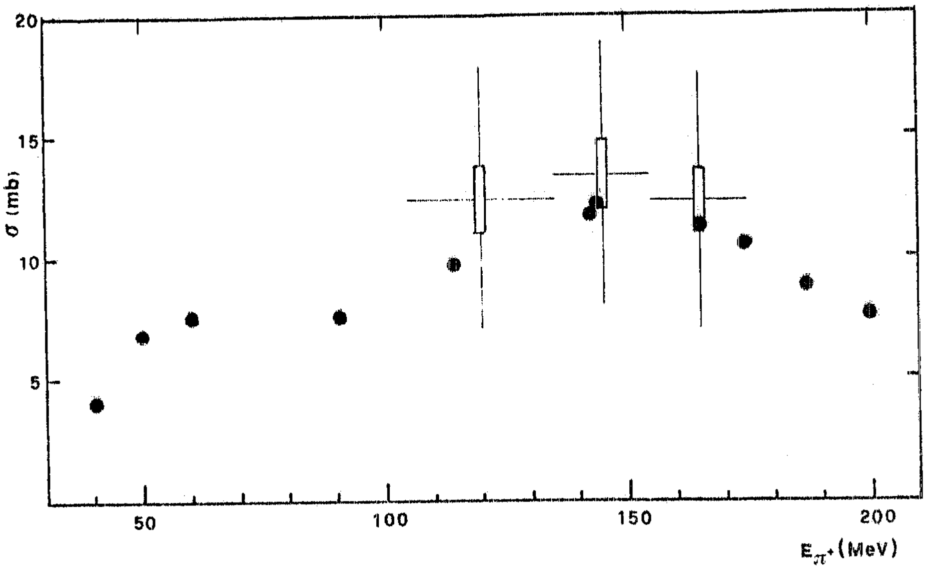


FIG. 5 - $^4He(\pi^+, 3pn)$ cross section versus pion energy compared with the $^2H(\pi^+2p)$ cross section values (full points).

Nevertheless, it must be noted also that the total absorption cross section values we deduced are lower (about for a factor 0.5) than the values deduced by Källne et al.(12) measuring the spectrum of the protons emitted in the $\pi^+$ interactions on $^4He$.

In the case of negative pions capture in $^4He$ there are three non-radiative channels:

$$\pi^- + {}^4He \longrightarrow \pi^-(p\,{}^3H) \longrightarrow n + {}^3H\,, \qquad (4)$$

$$\pi^-(pp) + nn \longrightarrow np + nn(3n+p)\,, \qquad (5)$$

$$\pi^-(np) + {}^2H \longrightarrow 2n + {}^2H\,. \qquad (6)$$

With visualizing detectors it is not possible, because of the complexity and the uncertainties of the identification of the one prong events, to do a good estimation of the reaction cross sections(18) with or without emission of $\pi^0$. The three channels (4), (5) and (6) have been identified in measurements of energy spectra of the emitted particles and studying the correlations of the (np), (nd) and (nt) pairs(7). Nevertheless, the relative branching ratios are not well known, but by charge symmetry the cross sections for the reactions (5) and (6) must be equal to those of the reactions (2) and (3).

It is interesting, at this point, to compare the results we obtained for the $^4He$ with the systematic results deduced by Ashery et al.(5, 19) for the $7 \leq A \leq 209$ nuclei. Fig. 6 shows that both at 125 and 165 MeV all the cross sections of the different $\pi^+$ interaction channels on nuclei are growing with A, monotonically from the hydrogen up to the bismuth ($\sim A^{2/3}$ behaviour). The $(\pi^+, p)$ and $(\pi^-, p)$ data and the $\pi^- + p \longrightarrow \pi^0 + n$ values are from ref. (20); the data on $^2H$ have been deduced from ref. (15); the data on $^4He$ from ref. (8). In the case of the single charge exchange cross section the values are nearly constant in the $1 \leq A \leq 12$ interval and they are grow

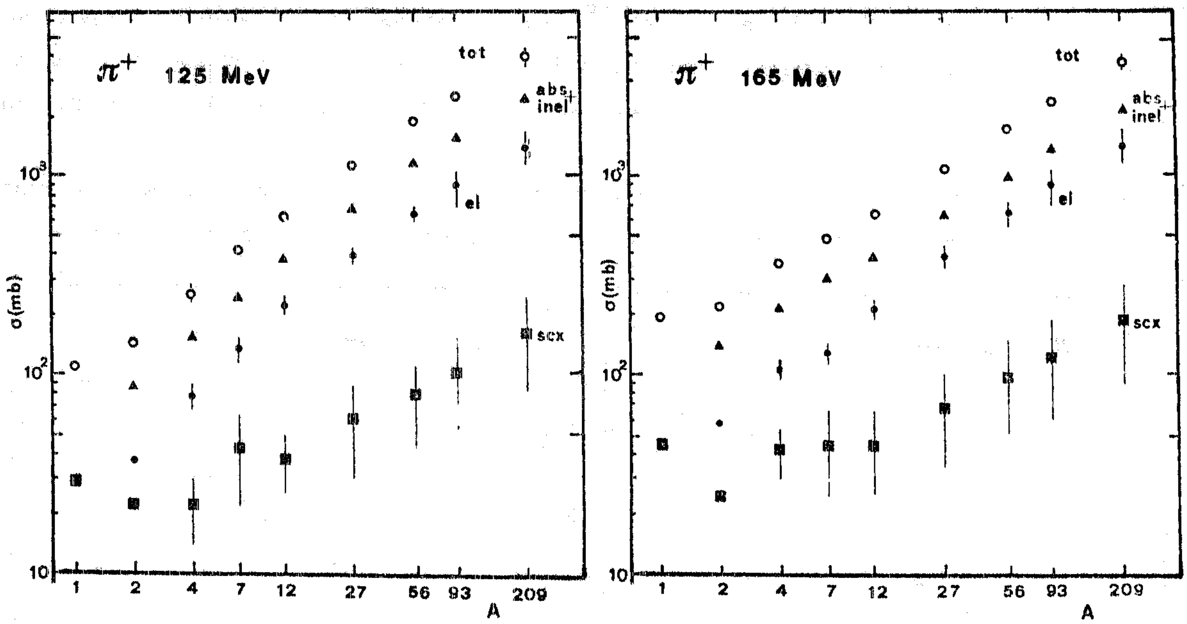


FIG. 6 - Behaviour as a function of A of: the total cross section (open circles); the sum of the absorption and inelastic cross sections (open triangles); the elastic cross section (full points); the single charge exchange cross section (full squares) for $E_\pi$ = 125 and 165 MeV. For A = 1, from ref. (20); for A = 2, from ref. (15); for A ≥ 7, from ref. (5, 19); for A = 4, from ref. (8) at 120 and 165 MeV.

ing for A ≥ 12. It is important to note[19] that for the light and medium nuclei the sum of the absorption cross section and of the charge exchange cross section is systematically higher for the $\pi^-$ than for the $\pi^+$; the $\pi^+$ charge exchange cross section are systematically higher than the $\pi^-$ charge exchange cross sections; consequently the absorption cross section values are systematically higher for the $\pi^-$ than for the $\pi^+$. In Fig. 7 the behaviours at $E_\pi$ = 165 MeV of the sum of the cross sections for absorption and for charge exchange and of the cross section for the single charge exchange as a function of A (both for $\pi^+$ and $\pi^-$) are shown. For A ≥ 7 the data are from ref. (19), for A = 2 from ref. (15), for A = 1 from ref. (20). In the case of the $^4$He, our data are compared with those

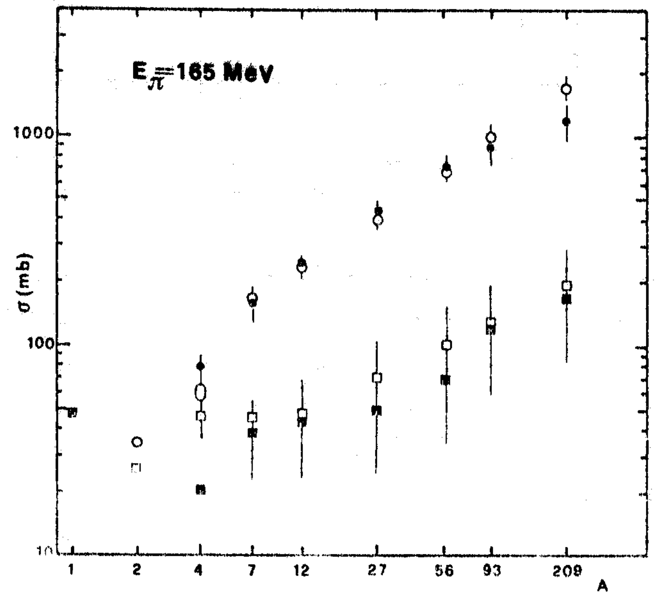


FIG. 7 - Behaviours as a function of A, at E = = 165 MeV, of the sum of the cross sections for absorption and charge exchange ($\pi^+$ open circles; $\pi^-$ full points) and of the cross section for the single charge exchange ($\pi^+$ open squares; $\pi^-$ full squares). For A = 1, from ref. (20); for A=2, from ref. (15); for A ≥ 7, from ref. (5, 19); for A = 4 and $\pi^+$, from ref. (8); for A = 4 and $\pi^-$, from ref. (18) at 153 MeV.

obtained at 153 MeV with $\pi^-$ by Budagov et al.[18]. As one can see, the $\pi^- \rightarrow \pi^0$ charge exchange cross section value (deduced "indicatively" in ref. (18)) is lower than the $\pi^+ \rightarrow \pi^0$ value, but the sum of the cross sections for absorption and for the charge exchange reactions is a little higher for the $\pi^-$ than for the $\pi^+$.

In Fig. 8 the $\pi^+$ absorption cross section values we obtained at 120 and 165 MeV (taking into account also the uncertainties in the separation of the absorption events from the single charge

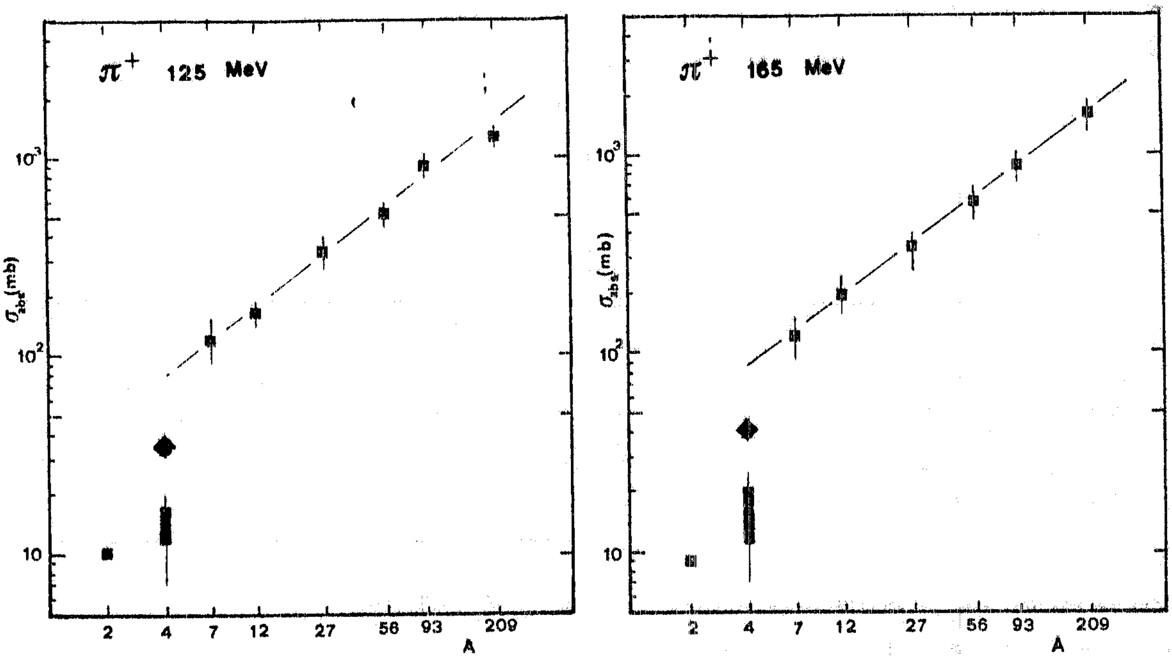


FIG. 8 - Absorption cross section of $\pi^+$ versus A at 125 and 165 MeV. For A = 2, from ref. (15); for A $\geq$ 7, from ref. (5, 19); for A = 4, from ref. (12) (diamond) and present data at 120 and 165 MeV.

exchange events) are compared with the behaviour of the $\pi^+$ absorption cross section values as a function of A obtained by Ashery et al.[19], at 125 and 165 MeV. As one can see the values for the $^4$He are very lower than the trend shown by the A $\geq$ 7 nuclei, also if to the $^4$He absorption cross section values are added the values of the cross section of the quasi-absorption channel $\pi^+ + {}^4He \rightarrow \pi^+ + {}^4He^* \rightarrow \pi^+ + n + {}^3He$, that is about 9 and 22 mb at 120 and 165 MeV respectively[8]. Similar result has been obtained by Schiffer et al.[21] measuring the angular and energy distribution of the protons emitted in the $\pi^+$ absorption on light nuclei.

## 3. - CONCLUSION.

These experimental data could be explained by the importance of the $\pi^+$ absorption on quasi-deuterons[22] relative to other absorption processes, which become dominant as the number of nucleons exceeds four. In the case of $\pi^-$ absorption on $^4$He also the n-$^3$H absorption channel is important, so that the true absorption cross section is higher than in the case of $\pi^+$

absorption. For this reason the absorption of $\pi^-$ on $\alpha$-clusters in nuclei(1, 2, 4) is more evident than in the case(6) of the positive pions.

Recently Germond et al.(23) showed the importante role of the Coulomb barrier in the $\pi^+$ and $\pi^-$ absorption at low energies in heavy nuclei. The $\pi^-$ can probe deeper into the nucleus, but the repulsive Coulomb potential keeps the $\pi^+$ on the edge of the nucleus and it seems likely that a notable fraction of the two-nucleon mode will contribute to the true absorption. It seems realistic that similar mechanism could be extended also to the case of the light nuclei.

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