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S.G.Mashnik*

HOW MANY NUCLEONS ARE REQUIRED FOR NUCLEAR PION ABSORPTION?[1]

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*E-mail: MASHNIK@THEOR.JINRC.DUBNA.SU

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1. Introduction

Pion-nucleus interactions occupy a special place in intermediate energy nuclear physics due to touching upon of different fundamental problems of nuclear reactions, hadron interactions and nuclear structure (see, the good reviews [1]-[3]). One of the important modes of the pion-nucleus interaction is pion absorption (no pions in the final state). The cross section of this mode is large, in the Δ resonance region contributes about $\geq 1/3$ of the total pion-nucleus cross section; therefore, this mode affects significantly other pion-nucleus interaction modes [4].

Though good theoretical investigations have been performed in the last fifteen years and many interesting experimental results on pion absorption have been obtained at the meson factories in the USA, Canada and Switzerland, and at JINR, PNPI and CERN, an unambiguous interpretation of the observed phenomena has not been found yet [1]-[3]. So, up to now there is no common point of view in literature on the questions: How many nucleons are involved in nuclear pion absorption? How does the reaction depend on the isospin of the absorbing system and on the energy of the pion?

Today, as many years ago, the only thing we can say with certainty is that the law of energy and momentum conservation forbids the absorption of a pion by a free nucleon. In principle, a pion can be absorbed by an intranuclear nucleon, but for this a momentum of ~ 500 Mev/c is required for the nucleon [3]. As this value is far beyond the Fermi momentum, the reaction will be strongly suppressed. The available measurements and theoretical estimations (see, e.g., [5] and references given therein) give for the single nucleon absorption probability the value $\leq 10^{-3}$. Therefore, pion absorption must involve at least two nucleons.

Recently, reliable experimental indications of the presence of three-nucleon (3N) absorption processes in light nuclei have been obtained (see review [1] and recent works [6]-[8]). However, the questions about its percentage and how does the relative contribution of the 2N, 3N, 4N, etc. absorption depend on the pion energy and nucleus target are still open, especially for medium and heavy nuclei.

This problem is still open for both stopped and in-flight pion absorption. Even in the simplest case of two-nucleon stopped pion absorption by nuclei there is a serious discrepancy between estimates made by different authors for the ratio R of the probabilities of absorption on np and pp pairs, both as a function of the atomic number A of the target [5, 9] and for a separate nucleus [10]. For in-flight pion absorption the situation is much more intricate because besides genuine pion absorption, additional πN scatterings are possible, and the pion energy T_π becomes an additional variable of the reaction.

Up to 1980 the dominance of two-nucleon (2N) genuine pion absorption in these reactions was hypothesized by the majority of authors (see review [1]-[3]). This dominance was strongly questioned by McKeown et al. [11], who have measured inclusive (π^+,p) and (π^-,p) cross sections on ^{12}C, ^{27}Al, ^{58}Ni and ^{181}Ta at $T_\pi = 100$, 160 and 260 MeV. Assuming that high-energy protons arise only from absorption processes and neglecting the initial state interactions (ISI) and final state interactions (FSI), McKeown et al. have analyzed the data in a "hot spot" or a "slowly moving-source" representation and found that the number N_N of nucleons involved in the pion absorption is $N_N \sim 3$ for ^{12}C and increases to $N_N \sim 5.5$ for ^{181}Ta. This work had a large responce in literature: afterwards there were performed theoretical investigations which demonstrated that McKeown's et al. data can be described by 2N absorption mechanism (see, e.g., [12]), or on the contrary, only by multinucleon absorption (see, e.g., [13]), or in the framework of mixed models taking into account both 2N and 3N absorption mechanisms (see, e.g., [14]).

McKeown's et al. results have stimulated also much of the later experimental works (see, e.g., [15] and references given therein). So, in $(\pi^+,2p)$ measurements on nuclei ranging from ^{12}C to ^{209}Bi, at 165 and 245 MeV, Altman et al. [16] found for the 2N component only 10% for ^{12}C and about 2% for ^{209}Bi from the measured absorption cross section. Using intranuclear cascade calculations to correct for the FSI, they estimated that less than 30% of the ^{16}O absorption cross section is due to 2N absorption, thereby implying a dominance of multinucleon ($N_N > 2$) absorption. However, in subsequent measurements also at $T_\pi = 165$ MeV, Hyman et al. [17] have obtained cross sections for ^{16}O, a factor of 2.3 larger than in ref. [16], and after estimation of the FSI they have concluded that at 165 MeV, ~45% of the ^{16}O total reaction

cross section is due to the 2N absorption. In more recent measurements of the reaction $^{16}O(\pi^+,pp)$ at 115 MeV Mack et al. [15] have found a much higher contribution of the 2N absorption: approximately 80% of the total absorption cross section on ^{16}O at 115 MeV proceed via the 2N absorption. Mack et al. did not take into account any contributions from the ISI which could lead to even larger percentages of the 2N absorption at 115 MeV. Taking into account the results by Hyman et al. at 165 MeV [17], Mack et al. have concluded that the 2N absorption fraction decreases with increasing pion energy T_π.

A similar decrease in the 2N absorption fraction with increasing T_π has been also observed in most recent measurements on ^{16}O by Hyman et al. [18] (from $\sim$ 80% at $T_\pi = 115$ MeV, to $\sim$ 50% at $T_\pi = 165$ MeV), and suggested in the theoretical works by Oset et al. [19] and Vicente-Vacas and Hernández [20]. In these models, both the 2N and the 3N absorption mechanisms are taken into account. In ref. [19], the 2N absorption is the dominant one ($\sim$ 90%) at low pion energies, but in the Δ resonance region and beyond, the percentage of the 3N absorption increases and around $T_\pi = 250$–350 MeV tends to stabilize at a level of ~50–55%. Estimates [19] of the 4N absorption gave only a small fraction of the total. The 2N absorption is the dominant one at low T_π ($\sim$ 82% for ^{58}Ni and $\sim$ 78% for ^{12}C at $T_\pi = 85$ MeV) also in the model [20]. In this model, the percentage of the 3N absorption increases with T_π up to $\sim$ 38% for ^{12}C and $\sim$ 31% for ^{58}Ni in the region of the Δ resonance peak. At higher pion energies, the relative role of the 3N absorption decreases, so that the 2N absorption becomes again significantly dominant ($\sim$ 70% for ^{58}Ni and $\sim$ 63% for ^{12}C at $T_\pi = 300$ MeV).

One of the tempting ways to estimate the fraction of the 2N absorption seems to be the measurements of the cross sections for emission of two protons with quasideuteron kinematics from the π^+-induced reaction which are to be compared with the value of the total absorption cross section σ_{abs}. The observed cross sections (see, e.g., the recent Morris's et al. [21] measurements at $T_\pi = 100$ MeV for targets from ^2H to ^{238}U) are typically only a few percent of the σ_{abs} for heavy and medium nuclei. From such measurements one concludes [21] that most of the σ_{abs} on complex nuclei is a results of pion absorption on three or more nucleons ($N_N > 2$). But due to ISI/FSI, especially important for heavy and medium nuclei, only a small fraction of the observed two-proton final states have actually pure unperturbed quasideuteron kinematics. The corrections for ISI/FSI are model dependent; therefore, the interpretation of such measurements is uncertain [22].

It should be noted that in spite of the recent measurements pointing out the importance of the 2N absorption, some authors (see, e.g., the recent work by Mateos and Šimičević [23]) even at present try to describe the pion absorption on light nuclei via only a coherent 3N absorption. At the same time, Vicente-Vacas and Oset [14], by analyzing available data on the (π^+, ppp) reactions (which one could think are just "the" reactions for testing the genuine 3N absorption) have found a strong contribution to this observable of events in which a quasielastic scattering is followed by the 2N absorption. So they have shown that even the description of "the" (π^+, ppp) reactions do not evidently favour the genuine 3N absorption. An indication of the dominance of the 2N absorption in (π^+, ppp) reactions has been recently obtained by Tacik et al. [24]. By analyzing their own measurements of emission of tree correlated protons from the $\pi^+ + C$ interactions with phase space calculations which simulate quasifree three-nucleon and four-nucleon absorption mechanisms, Tacik et al. have found that the contribution to the measured (π^+, ppp) yields from the 3N absorption is about only 4.6%, 11.1% and 18.6% at $T_\pi = 130$, 180 and 228 MeV, respectively, and from the 4N absorption is much smaller.

A large responce in literature (see, e.g., [1]) in connection with the problem of pion absorption mechanisms has also been caused by the recent measurements of pion-induced inclusive proton production on copper at 0.6, 0.8 and 1 GeV/c by Golubeva et al. [25, 26]. By analyzing their own data and measurements by other authors in a "moving-source" representation, Golubeva et al. have found that the number of nucleons involved in pion absorption increases monotonically with pion energy from $N_N \sim 4$ at $T_\pi = 260$ MeV to $N_N \sim 18$ at $T_\pi = 4$ Gev.

The aim of the present work is to analyze McKeown's et al. [11] and Golubeva's et al. [25, 26] data in the framework of our Cascade-Exciton Model (CEM) of nuclear reactions [27], and to review our previous results on pion-nucleus interactions, in the hope of learning more about the absorption mechanisms.

2. The main concepts of the model

A detailed description of the CEM may be found in [27]; therefore, only its basic assumptions will be outlined here. The CEM uses the Monte Carlo simulation method and assumes that the reactions occur in three stages. The first stage is the intranuclear cascade in which primary particles can be rescattered several times prior to absorption by, or escape from the nucleus. The excited residual nucleus remaining after the emission of the cascade particles determines the particle-hole configuration that is the starting point for the second, pre-equilibrium stage of the reaction. The subsequent relaxation of the nuclear excitation is treated in terms of the exciton model of pre-equilibrium decay which includes the description of the equilibrium evaporative third stage of the reaction. So, in a general case, the three components may contribute to any experimentally measured quantity. In particular, for the inclusive particle spectrum to be discussed later, we have

$$\sigma(\mathbf{p})d\mathbf{p} = \sigma_{in}[N^{cas}(\mathbf{p}) + N^{prq}(\mathbf{p}) + N^{eq}(\mathbf{p})]d\mathbf{p}.$$

The inelastic cross section σ_{in} is not taken from the experimental data or independent optical model calculations, but it is calculated within the cascade model itself.

We include the emission of n, p, d, t, ^3He and ^4He at both the pre-equilibrium and the evaporative stages of reaction. The corresponding emission rates into the continuum are estimated according to the detailed balance principle.

The CEM predicts forward peaked in the laboratory system angular distributions for secondary particles. Firstly, this is due to high asymmetry of the cascade component. A possibility for forward peaked distributions of nucleons and composite particles emitted during the pre-equilibrium interaction stage is related to retention of some memory of the projectile direction. In addition to energy conservation we need to take into account conservation of linear momentum $\mathbf{P}$ at each step as a nuclear state evolves. In a phenomenological approach, this can be realized in different ways [27]. The simplest way used here consists in sharing the momentum $\mathbf{P_0}$ (similarly to energy E_0^*) between an ever increasing number of excitons n involved in the interaction in the course of equilibration of the nuclear system. In other words, the momentum $\mathbf{P}_0$ should be attributed only to n excitons rather than to all A nucleons. Then, particle emission will be symmetric in the proper n-exciton system but some forward peaking will arise in both the laboratory and center-of-mass reference frame.

The cascade stage of the interaction is described by the Dubna version of the intranuclear cascade model (ICM) [28]. All the cascade calculations are carried out in a three-dimensional geometry. The nuclear matter density $\rho(r)$ is described by the Fermi distribution with two parameters taken from the analysis of electron-nucleus scattering. Practically, the nucleus target is divided by concentric spheres into seven zones in which the nuclear density is considered to be constant. The energy spectrum of nuclear nucleons is estimated in the perfect Fermi gas approximation with the local Fermi energy $T_F(r) = \hbar^2[3\pi^2\rho(r)]^{2/3}/(2m)$, where m is the nucleon mass. The influence of intranuclear nucleons on the incoming projectile is taken into account by adding to its laboratory kinetic energy an effective real potential V. For incident nucleons $V \equiv V_N(r) = T_F(r) + \epsilon$ where $T_F(r)$ is the corresponding Fermi energy and ϵ is the mean binding energy of the nucleons ($\epsilon \simeq 7$ MeV [28]). For pions, in the Dubna ICM one usually uses [28] a square-well potential with the depth $V_\pi \simeq 25$ MeV, independently of the nucleus and pion energy. The interaction of the incident particle with the nucleus comes to a series of successive quasifree collisions of the fast cascade particles (π or N) with intranuclear nucleons:

$$NN \to NN, \quad NN \to \pi NN, \quad NN \to \pi_1, \cdots, \pi_i NN$$
$$\pi N \to \pi N, \quad \pi N \to \pi_1, \cdots, \pi_i N \quad (i \geq 2). \qquad (1)$$

To describe these elementary collisions, one uses the experimental cross sections for the free πN and NN interactions approximated by special polynomial expressions with energy-dependent coefficients [28] and one takes into account the Pauli principle.

The Pauli exclusion principle at the cascade stage of the reaction is handled in the following way: one assumes that nucleons of the target occupy all the energy levels up to the Fermi energy. Each simulated elastic or inelastic interaction of the projectile (or of a cascade particle) with a nucleon of the target is considered forbidden if the "secondary" nucleons have energies smaller than the Fermi energy. If so, the trajectory of the particle is traced further from the forbidden point and

a new interaction point, a new partner and a new interaction mode are simulated for the projectile (or the traced cascade particle), and so on, until the Pauli principle is kept or the traced particle leaves the nucleus.

The Dubna ICM is described in detail in the monograph [28]. Let us briefly mention here some more questions related to pion absorption. Besides the elementary processes (1), the Dubna ICM takes into account also pion absorption on the nuclear pairs $\pi NN \to NN$. The momenta of two nucleons participating in the absorption are chosen randomly from the Fermi distribution, and the pion energy is distributed equally between these nucleons in the center-of-mass system of the pion and nucleons participating in the absorption. The direction of motion of the resultant nucleons in this system is taken as isotropically distributed in space. The effective cross section for absorption (let us speak below, for concreteness, e.g., about minus pions π^-)* is estimated from the experimental cross-section of pion absorption by deuterons

$$\sigma(\pi^- + \text{“}np\text{”} \to nn) = W \cdot \sigma(\pi^- + d \to nn) . \qquad (2)$$

W may be a complex function on: T_π**, nucleus-target, the point where the pion is absorbed, and on the spin-isospin states of absorbing pairs. Concrete calculations have shown [28] that one obtains an overall satisfactory description of the data for a large range of pion energies and nuclei-targets using an "effective" approximation $W \simeq const = 4$. It is interesting to note that just the same value was obtained by McKeown et al. [11] and other authors (see review [1]) in measurements of pion absorption on ^4He for the ratio

$$R_\pi = [(d\sigma/d\Omega)(\pi + \text{“}np\text{”} \to NN)]/[(d\sigma/d\Omega)(\pi + d \to NN)] .$$

We use here the approximation $W = 4$, as usually in the Dubna ICM [28].

*The corresponding formulae for π^+ absorption may be easily obtained by simple replacements $\pi^- \to \pi^+$, $n \to p$, $p \to n$, $N \to Z$ and $Z \to N$.

**The cross section of the π^+ absorption on ^{16}O at $T_\pi = 115$ and 165 MeV from the genuine 2N absorption has been recently estimated by Hyman et al. [18] and for the first time it has been shown that it falls faster with energy than the cross section of the $\pi^+ d \to pp$ reaction. In our approach this means that W decreases with increasing T_π

It is useful to extract from the ratio R the statistical factor taking into account the number of np and pp pairs in a nucleus containing N neutrons and Z protons. When the radial distribution of neutrons and protons in the nucleus is the same, i.e., $\rho_n(r)/\rho_p(r) = N/Z$, we have

$$R = [2N/(Z-1)]R' \equiv R_0 R' , \qquad (3)$$

where R' is the ratio of the absorption widths for the np and pp pairs: $R' = \Gamma(\pi^- np \to nn)/\Gamma(\pi^- pp \to np)$. R' is a complex function on: T_π, nucleus target and on spins of absorbing pairs. Since the dynamic of pion absorption by nucleon pairs in a particular spin-isospin state is not well understood, a purely theoretical determination of R' is hardly possible at present [1]. What is more, in a classical ICM calculation we do not deal with the spins of absorbing pairs, in principle. The up-to-date experimental data cannot clarify this question as well [1].

As has been mentioned in the introduction, even in the simplest case of stopped pion absorption this question is still open. Our CEM analysis [5] of most of the experimental proton spectra measured for various targets by different authors has shown that either R' is sensitive enough to the nuclear structure of targets, or there are significant contradictions between the absolute normalization of proton spectra measured in different experiments. The recent Gornov's et al. experimental data [9, 29] are consistent with the assumption that R' remains constant in a wide range of nuclei from ^6Li to ^{209}Bi. The result $R' = 3.5 \pm 1.5$ obtained from our analysis [9, 29] of different characteristics is very close to the value obtained by Blankleider et al. [30] for ^3He, i.e., the lightest nucleus for which absorption by both the np and pp pairs is possible.

For the in-flight pion absorption, the question about the value of R, and especially its dependence on T_π is more or less clarified only for very light ^3He, ^3H and ^4He targets, for which kinematically complete experiments have recently been performed [6]-[8]. For all these light targets it has been found that the value of R for in-flight pions is higher than for stopped pion absorption. The T_π dependence of R' for the ^3He targets has been recently measured by Weber et al. [6]. They found that $R'(^3He)$ increases with T_π from ~ 4 at $T_\pi = 0$ to some maximum in the Δ resonance region ($R'(^3He) \sim 14$ at $T_\pi = 162$ MeV) and then again decreases for higher T_π ($R'(^3He) \sim 7$ at $T_\pi = 206$ MeV).

For heavier targets, this question is even more intricate. So, the majority of measurements on complex targets show that the value of R' in the Δ resonances region is higher in comparison with the stopped pion absorption case (see review [1]). At higher pion energies, R' seems to decrease: the recent measurements by Fukuda et al. [31] on the π^+ absorption on ^4He and ^{12}C at 1 GeV/c has shown that the yield ratio of (π^+,pp) to (π^+,np) events is of the order of one (i.e., $R \sim 1$). At the same time, some experiments at T_π below the peak of the Δ resonance indicate very small values of R. So, in the recent measurements of 60-MeV π^+ absorption on Ag and Br nuclei by the nuclear photoemulsion method, Lantsev et al. [32] have found the values $R(C,N,O) \simeq 1.11$, and $R'(C,N,O) \simeq 0.28$ for the group of light nuclei of emulsion C, N and O. For heavy nuclei of emulsion Ag and Br, they found unexpectedly small values $R(Ag,Br) \simeq 0.47$ and $R'(Ag,Br) \simeq 0.18$. Lantsev et al. indicated [32] that such small values of R for heavy nuclei may be explained by a neutron enhancement of their periphery.

So in this intricate case, R can be regarded as a free parameter of the theory. The Dubna version of the ICM was developed by using $R = R_0$, i.e., $R' = 1$ [28]. To our knowledge, the majority of the Dubna ICM calculations of the in-flight pion absorption were performed by different authors with $R = R_0$ (as a rule, the authors do not stress this question in their papers). We use here, as a first approximation, $R = R_0$ independently of the pion energy and of targets. Our experience of many years of the ICM application shows that in the case of the in-flight pion absorption, due to ISI/FSI, the ICM results are not very sensitive to the value of R used. This may serve as a justification of the $R = R_0$ used.

In the version of the ICM used here [28], the production of Δ isobars in the intermediate states (as cascade participants) is not taken into account (we take into account resonances only nonexplicitly through the experimental cross sections of the processes (1) and $\pi + d \to NN$). Different authors have shown [26, 33, 34] that inclusive spectra of ejected particles calculated in the framework of the ICM with Δ resonances as cascade participants are very close to those calculated in the ICM without intermediate Δ states. As we analyze here only inclusive proton spectra, we may use the ICM [28] without Δ as cascade participants.

In our calculations, all the CEM parameter values are fixed and are the same as in [27].

3. Results and Discussion

Using the CEM we have analyzed the entire set of McKeown's et al. [11] and Golubeva's et al. [25, 26] data. As measured and calculated spectra show a fundamental similarity, we confine ourselves to the discussion of some exemplary results. As an example, Fig. 1 shows measured [11] inclusive proton spectra from the π^+-induced reactions at 100 and 220 MeV on C, Al, Ni and Ta along with our CEM calculation. Similar agreement of calculated spectra with the data have been obtained also at incident energy $T_\pi = 160$ MeV and for π^--induced reactions.

The CEM reproduces correctly the change in the spectrum shape with increasing emission angle and in passing from light to heavy targets, providing correct absolute values for the proton yield for all incident energies.

To illustrate the relative role of different proton production mechanisms, for the spectra at 150° from Ni the cascade, pre-equilibrium and the evaporative components of calculated spectra are shown separately. One can see that the main contribution of slow protons to the spectra comes from the evaporation from compound nuclei while with increasing ejectile energy the emission at the cascade and pre-equilibrium stages becomes dominant. For $T_p > 80$ MeV, the cascade component describes almost the entire measured spectra while the contribution of pre-equilibrium emission is one order of magnitude lower.

The CEM describes satisfactorily all proton spectra measured by McKeown et al. [11], taking into account that no normalization was applied to adjust the calculations performed without any free parameters. However, our model overestimates systematically the high energy tails of proton spectra which are formed basically by "primary" protons from elementary processes of the genuine pion absorption. Such overestimations may be motivated by three reasons: First, this may be an indication on the presence of the genuine pion absorption on heavier "clusters" omitted in our calculations.

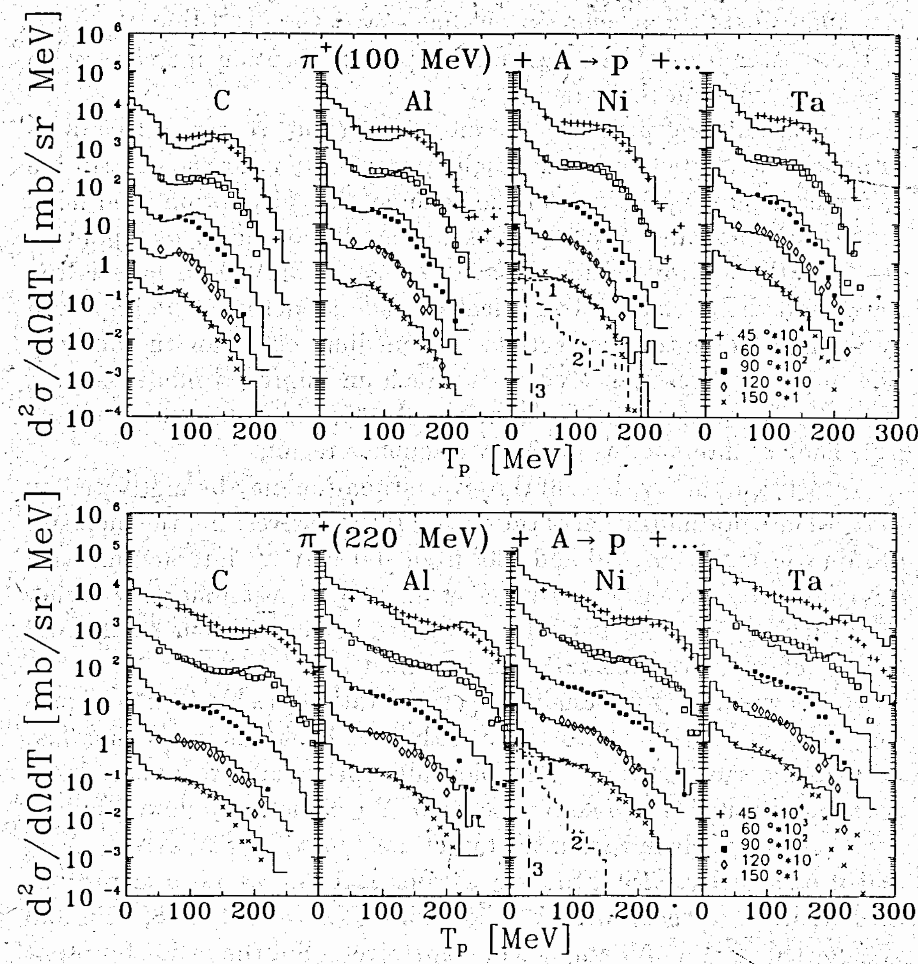

Fig. 1. Measured [11] inclusive proton spectra (symbols) from π^+-induced reactions at 100 and 220 MeV and CEM calculations (histograms). Different emission angles for different target-nuclei are drawn with symbols as indicated. The solid histograms are sums of all three CEM (cascade, pre-equilibrium and evaporative) components. For the spectra at 150° from Ni, dashed histograms 1, 2 and 3 show separately the contributions of cascade, pre-equilibrium and evaporative components, respectively.

At the same time, one can see that the CEM overestimates the hard proton emission equally from light, medium and heavy nuclei. This fact contradicts the conclusion by McKeown et al. [11] that the mass of the cluster involved in the genuine pion absorption increases with the atomic mass of the target.

The second, and probably the most important, reason of this overestimation is related with our rough approximation for the description of the elementary processes of the genuine pion absorption used here: $W \approx const = 4$ and $R = R_0$. Besides, as it was shown by Iljinov et al. [35], the approximation $V_\pi \approx const = 25$ MeV used here is too rough and the classical intranuclear cascade model must be improved by including quantum corrections and medium effect for the description of pions of resonance energies. Such an improved model is, e.g., the optical-cascade model by Iljinov et al. [35] which describes well the pion-nucleus interactions in the Δ resonance region.

At last, the third reason of this overestimation may be motivated by the absolute normalization of the data [11] themselves. So, the inclusive proton spectra at 30°, 75° and 130° from 160 MeV π^+ interactions with ^{58}Ni measured recently by Burger et al. [36] lie systematically higher than McKeown's et al. data [11] and agree better with our results and the calculations by Vicente-Vacas and Oset [14].

McKeown et al. have analyzed [11] the ratio $d\sigma(\pi^+)/d\sigma(\pi^-)$ of proton yields seen with π^+ to those with π^-. If one assumes that fast protons are emitted only from pion absorption on two uncorrelated nucleons through a two-step process of Δ production followed by absorption on a nucleon within the target, i.e., via $\pi N \to \Delta$; $\Delta N \to NN$, and if one neglects ISI/FSI, one obtains [11] for the ratio of protons seen with π^+ to those with π^- the values $R_{2N} = 13.0$, 12.8, 12.6 and 17.2 for ^{12}C, ^{27}Al, ^{58}Ni and ^{181}Ta, respectively. For the ratio of protons emitted from quasifree πN scatterings, using the Clebsch-Gordan coefficients, one obtains [11] $R_{\pi N} = 11.0$, 11.2, 11.2 and 12.0 for ^{12}C, ^{27}Al, ^{58}Ni and ^{181}Ta, respectively. The measured ratios $d\sigma(\pi^+)/d\sigma(\pi^-)$ are lower for proton energies expected both from πN scatterings and from $\pi + 2N \to NN$ (see Fig. 2). Taking this into account, McKeown et al. have concluded [11] that the pure unperturbed $\pi + 2N \to NN$ process is not dominant and that nucleons from quasifree πN scatterings are not cleanly observed.

However, the ISI/FSI, particularly by charge exchange of both the

incoming pions and produced protons, reduce significantly the ratio $d\sigma(\pi^+)/d\sigma(\pi^-)$ in comparison with R_{2N} and $R_{\pi N}$. Similar influence of ISI/FSI was observed also in other nuclear reactions, in particular, for the ratio of π^- to π^+ production from neutron-induced reactions at intermediate energies [37, 38].

The experimental and calculated here ratios $d\sigma(\pi^+)/d\sigma(\pi^-)$ for protons emitted at 30°, 90° and 150° from interactions of 220 MeV pions with C, Al, Ni and Ta are shown in Fig. 2. One can see that both experimental and theoretical $d\sigma(\pi^+)/d\sigma(\pi^-)$ are significantly lower than R_{2N} and $R_{\pi N}$. For small proton energies $T_p \sim 50$ MeV the calculated ratios agree completely with the experimental ones. The measured $d\sigma(\pi^+)/d\sigma(\pi^-)$ increase with proton energies due to the energy dependence of elementary πN cross sections and to the dominance of absorption of pions on isoscalar nucleon pairs ($R >> 1$). The calculated ratios increase with T_p slower and for hard protons the prediction of the CEM lies a factor of two lower than the experimental data. This is a result of using the value $R = R_0$ for the ratio (3).

One should note that by fitting the value of R, it is possible to obtain in our approach an excellent description of both the measured ratios $d\sigma(\pi^+)/d\sigma(\pi^-)$ and the proton spectra themselves. For this, it is necessary to perform for every reaction two sets of independent calculations by taking into account the absorption of π^- mesons only on np pairs ($R' = \infty$) and, respectively, only on pp pairs ($R' = 0$). Then, the particle yields in our model are given by

$$Y_{CEM} = (Y^{pp}_{CEM} + RY^{np}_{CEM})/(R+1).$$

By fitting the value of R, it is possible to "place" the calculated yields Y_{CEM} exactly on the experimental data. We have successfully used such a procedure to describe the reactions of stopped pion absorption by nuclei [5, 9, 29] for which we found $R' \simeq 3.5$.

A part of Golubeva's et al. data [25, 26] are presented in Figs. 3 and 4 along with our CEM calculations and results of the best fit [25, 26] in the moving-source model. For comparison, for proton spectra from 600 MeV/c π^+ interactions with Cu the results of the ICM calculation with the Δ isobar production in the intermediate states from ref. [26] are shown in Fig. 3.

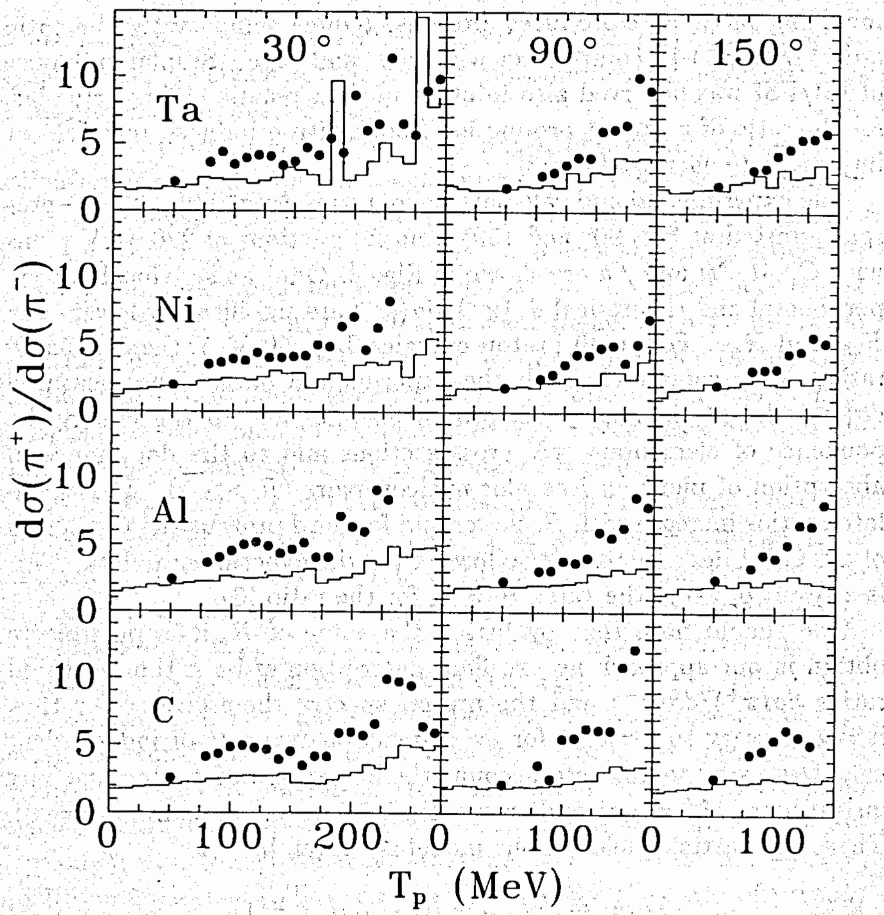

Fig. 2. Ratio of proton yields seen with π^+ to those with π^- at $T_\pi = 220$ MeV from C, Al, Ni and Ta targets. Points are the experimental values calculated here from the measured proton spectra tabulated in the AIP document No. PAPS PRVC-24-211-48 (see [11]). Histograms are the present CEM calculations.

One can see that both our CEM and the ICM equally satisfactorily describe the data by taking into account only the 2N pion absorption. A small systematic underestimation of about 30% of all Golubeva's et al. data by both our CEM and the ICM is not clear for us. The inclusion in our approaches of the pion absorption on heavier "clusters"

will only increase it, and we do not exclude that this is connected with the absolute normalization of the experimental data [25, 26].

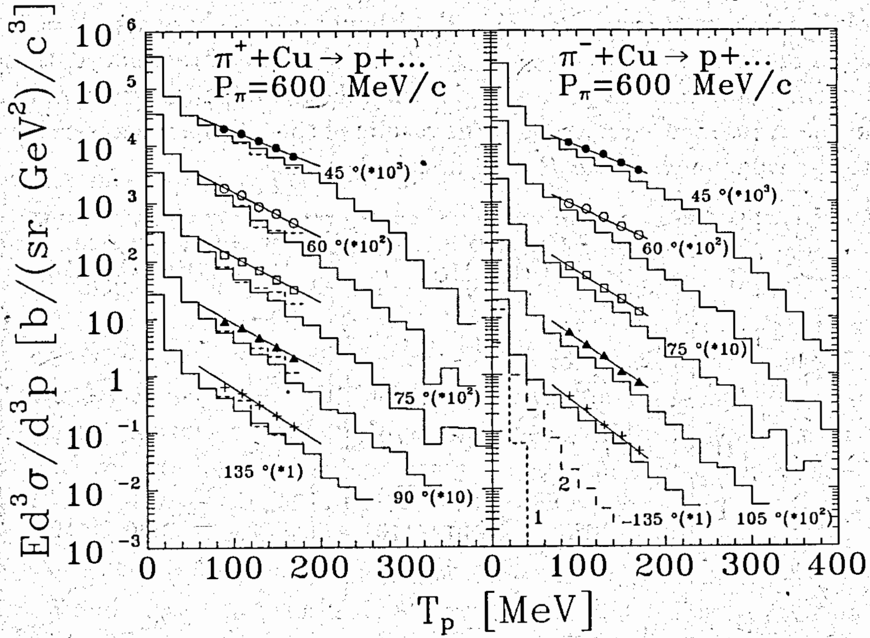

Fig. 3. Measured [25] inclusive proton spectra from π^+ and π^- interactions with copper at 600 MeV/c (symbols), our CEM calculations (solid histograms are sums of all three CEM components), the results of the best fit [25] in the moving-source model (lines) and the calculations with the Dubna ICM with Δ as cascade participants (dashed histograms on the left graph) from Ref. [26]. Different emission angles are drawn with symbols as indicated. The dashed histograms 1 and 2 on the right graph show the CEM evaporative and pre-equilibrium components for the angle 135°, respectively.

As an example, for spectra at 135°, the CEM pre-equilibrium and evaporative components are shown separately in Figs. 3 and 4. One can see that even at these relatively high incident energies the pre-equilibrium processes contribute to intermediate energy proton emission. But for $T_p > 80$ MeV the emission of cascade protons becomes dominant, and the pre-equilibrium components lie one order of magnitude lower than the data.

We see from Figs. 3 and 4 that the CEM equally well describes the proton spectra seen from π^+- and π^--inducted reactions, i.e., describes the ratio $d\sigma(\pi^+)/d\sigma(\pi^-)$ for Golubeva's et al. data better than for McKeown's et al. ones (see Fig. 2), although we use here also $R = R_0$, as in analysis of McKeown's et al. data. This indicates that at these intermediate incident pion energies the role of ISI/FSI is greater than in the Δ resonance region, and the results of the CEM are less sensitive to the value of the ratio R used in calculations.

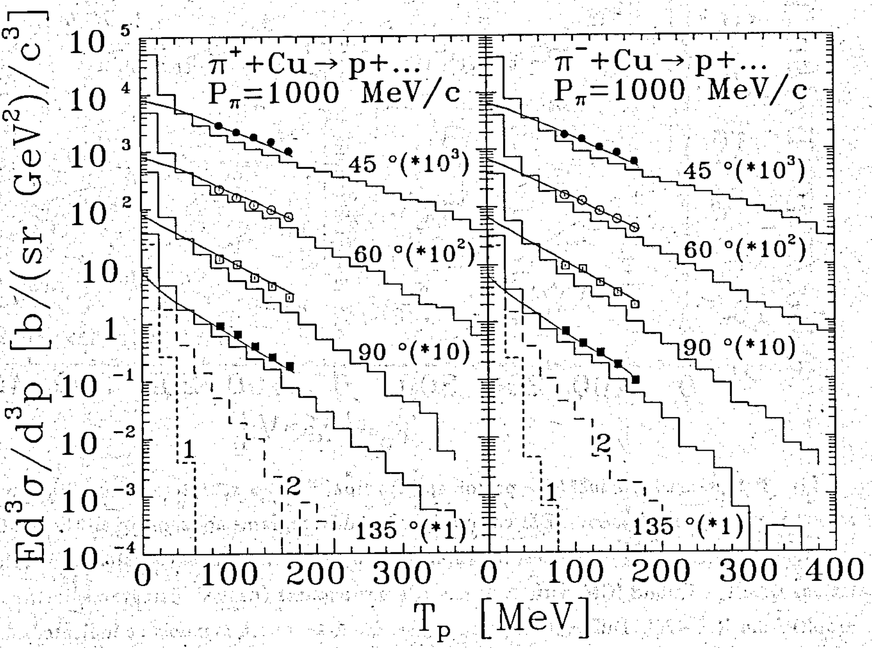

Fig. 4. Measured [26] inclusive proton spectra from π^+ and π^- interactions with copper at 1 GeV/c (symbols), our CEM calculations (histograms) and results of the best fit [26] in the moving-source model (lines). The rest notation is the same as in Fig. 3.

4. Summary and Conclusion

In this work we have shown that both McKeown's et al. [11] and Golubeva's et al. [25, 26] data may be satisfactorily described by the 2N absorption mechanism. The CEM is able to describe these data in the absolute value without any free parameters and does not need to increase the mass of "clusters" absorbing pions with atomic mass of the targets or with incident pion energy.

In our previous works (see [38] and references given therein) we have described satisfactorily with the CEM, taking into account only the 2N pion absorption, pion-induced particle production at higher energies (up to $T_\pi \sim 3$ GeV), as well as nucleon inducted pion (and other ejectiles) production for incident energies up to ~ 3 GeV. We have described satisfactorily in the CEM practically all available by now measurements on stopped pion absorption on C and heavier targets (see [5, 9, 29] and references given therein). One should note that the CEM describes quite well various characteristics of different nuclear reactions at intermediate energies. The recent International Code and Model Intercomparison for Intermediate Energy Reactions organized by OECD Nuclear Energy Agency, France [39] have shown that at intermediate energies the CEM has one of the best predictive powers as compared to other available modern models. All these facts allow us to conclude that for medium and heavy targets the main mechanism of pion absorption is the 2N one. We do not extrapolate this conclusion for very light nuclei for which the CEM cannot be applied. However, the recent kinematically complete measurements on pion absorption on $A = 3$ and $A = 4$ targets [6, 7, 8] have shown that this statement in valid also for light nuclei.

These results do not imply, of course, that nuclear pion absorption is completely described by the 2N mechanism considered here. We point out that the agreement between experimental data and present CEM calculations does not claim to be better than about 50%. The accuracy of the calculated cross section is about 40%, originating from the limited accuracy of the pion absorption probability, uncertainties of other CEM parameters and from the statistical accuracy of the Monte-Carlo calculations. In other words, the CEM explains a major part of particle yields by taking into account only the 2N absorption but does not exclude some contributions from pion absorption on heavier "clusters". Moreover, by analyzing Gornov's et al. data on complex particle production from stopped pion absorption by C, Si, Cu and Ge nuclei [29], we have obtained a direct indication of deuteron and triton emission from absorption of pions on heavier "clusters" on the level of $\sim 30\%$.

To describe better the pion-nucleus interactions in the Δ resonance region, the CEM must be improved by including the dependence of V_π on pion momentum and on radius, a more proper description of the cross sections of elementary processes (2) of the genuine pion absorption by nucleon pairs and taking into account the dependence of the ratio R on T_π and nucleus-target, and by including in our classical approach quantum corrections and medium effect by analogy with ref. [35]. Such a work is in progress at present.

To our knowledge, there are no measurements of neutron spectra from pion-inducted reactions at intermediate energies by now. The measurements with a good energy resolution and statistics of neutron spectra simultaneously with those of protons in the same experiment for different targets and in a large pion incident energy range would be useful, as they will shed light on the question about the role of the 2N absorption mechanism, and particularly, on the still open at present question about the dependences of the function W and ratio R on pion energy and nucleus-target.

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Машник С.Г. E2-93-470
Сколько нуклонов требуется для ядерного поглощения пионов?

В рамках каскадно-экситонной модели ядерных реакций анализируются инклюзивные спектры протонов, испущенных в пион-ядерных взаимодействиях с различными ядрами при энергиях от 100 МэВ до 1 ГэВ. Обсуждается вклад различных механизмов поглощения пионов ядрами и относительная роль различных механизмов образования частиц в этих реакциях. Результаты, полученные здесь, а также выполненный нами ранее анализ разнообразных экспериментальных данных по пион-ядерным реакциям в интервале энергий 0—3 ГэВ подтверждают вывод о том, что двухнуклонный механизм поглощения пионов ядрами является основным. Показано, что, если должным образом учитывать взаимодействия в начальном и конечном состояниях, можно удовлетворительно описать широко обсуждаемые в литературе данные по инклюзивному рождению протонов пионами на основе лишь двухнуклонного механизма поглощения.

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Mashnik S.G. E2-93-470
How Many Nucleons are Required for Nuclear Pion Absorption?

Inclusive proton spectra from π^+ and π^- interactions with different nuclei at incident pion energy from 100 MeV to 1 GeV are analyzed with the Cascade-Exciton Model of nuclear reactions. The contributions of different pion absorption mechanisms and the relative role of different particle production mechanisms in these reactions are discussed. The results obtained here, as well as our previous analysis of a large variety of experimental data on pion-nucleus reactions in the bombarding energy range of 0—3 GeV confirm the conclusion that the main absorption mechanism is a two-nucleon one. It is shown that data on pion-induced inclusive proton production, intensively discussed in literature, can be satisfactory described by the 2N absorption mechanism if the initial- and final-state interactions are taken into account properly.

The investigation has been performed at the Bogoliubov Laboratory of Theoretical Physics, JINR

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