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LOW- AND INTERMEDIATE-ENERGY PION-NUCLEUS INTERACTIONS IN THE CASCADE-EXCITON MODEL[1]

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1. Introduction

Though pion-nucleus interactions play a special role in the intermediate energy nuclear physics and these reactions have been under investigation during about four decades, an unambiguous interpretation of the observed phenomena has not been found yet [1, 2]. So, up to now there is no common point of view in literature on the question: how many nucleons are involved in pion absorption in nuclei? This problem is still open for both stopped and in-flight pion absorption. Even in the particular 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 for a separate nucleus [3, 4] and as a function of the atomic number A of the target [5, 6]. For in-flight pion absorption there is no sufficient information about the dependence of R on the pion energy and on nucleus-target [2].

Various efforts have been recently made to understand the mechanisms of fast backward nucleon production in the cumulative (i.e., kinematically forbidden for quasi-free intranuclear projectile-nucleon collisions) region (see the last reviews [7]). The role of pion absorption on nucleon pairs of a target in production of a fast backward nucleon is still being under intensive discussion during fifteen years [7, 8, 9]. There is not a common point of view also on the mechanisms of cumulative and subthreshold pion production. The influence of nuclear medium on pion production like the Fermi motion and production on effective targets or clusters with masses larger than the nucleon mass and the importance of Δ intermediate states have recently been discussed by many authors (see, e.g., [10, 11, 12]).

The aim of my talk is to clear up these questions using results obtained in our Cascade-Exciton Model (CEM) of nuclear reactions [13].

2. Basic assumptions of the CEM

A detailed description of the CEM may be found in [13], therefore, only its basic assumptions will be outlined here. The CEM 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. We include the emission of n, p, d, t, ^3He and ^4He at both the pre-equilibrium and the evaporative stages of reaction.

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. Hence the CEM predicts the absolute values for calculated characteristics and does not require any additional data or special normalization of its results.

The cascade stage of the interaction is described by the Dubna version of the intranuclear cascade model [14]. All the cascade calculations are carried out in a three-dimensional geometry. The nuclear matter density is described by a Fermi distribution with the two parameters taken from the analysis of electron-nucleus scattering data. The energy spectrum of nuclear nucleons is estimated in the perfect Fermi gas approximation with the local Fermi energy. For characteristics of the hadron-nucleon interactions we employ the approximations given in [14]. In our calculations all the CEM parameter values are fixed and are the same as in [13].

3. Nucleon-induced reactions

3.1. The role of nuclear pion absorption in production of cumulative nucleons. Let me begin to show our results with a short comment on nucleon-induced cumulative nucleon production. More than fifty different models involving exotic objects in a nucleus (multiquark bags, fluctons, hard core, nucleus – as a quark-gluon system, etc.) have been proposed to interpret the cumulative nucleon production (see the reviews [7]). Note should be made that the majority of these models has been proposed specially to interpret cumulative particle production by means of particular mechanisms and emission of fast backward nucleons from a two-step process of pion-production followed by absorption on nucleon pairs in a target is usually not taken into account. They consider only single-particle scattering processes and neglect the effects of rescattering and final state interaction, nevertheless, they succeeded in fitting shapes of experimental particle spectra.

It is of interest to estimate the contribution of "background" or conventional nuclear mechanisms in the framework of models that are not specially proposed for the description of cumulative particle production. Such a model is our CEM [13] proposed initially to describe nucleon-nucleus reactions at bombarding energies below $\sim$ 100 MeV and developed subsequently [5] for the description of stopped negative pion absorption by nuclei. The CEM has been applied [8] without any modifications to analyze practically all the existing data on proton- and neutron-induced cumulative nucleon production for nuclei from C to Bi in the bombarding energy range from several tens of MeV up to several GeV. It has been found that the energy spectra of inclusive cumulative nucleons as well as their A and angular dependences are qualitatively reproduced by our model. The main aspects of the analysis [8] are the following:

a) Cumulative nucleons arise at the cascade stage mainly from a two-step process, i.e., pion production in collisions of incident or cascade particles with nuclear nucleons

$$(N \text{ or } \pi) + N \to \pi + \cdots, \tag{1}$$

followed by pion absorption on nucleon pairs within this target-nucleus

$$\pi + [NN] \to N' + N'', \tag{2}$$

while multiple elastic scattering of the projectile is found to be unessential for cumulative nucleon emission. (Process (2) has been approximated by using experimental data for absorption cross section of pions on deuterium). This mechanism does not degenerate with the increase of bombarding energy for ejectile energies less than several hundreds of MeV.

b) Only a small number (3-5) of collisions occurs during the cascade development and this number is practically independent of the target mass number A (according to the processes (1) and (2), at least 3 target nucleons must be involved in the cascade process).

c) The pre-equilibrium component contributes essentially to the hard part of backward emission spectra of nucleons and complex particles. For heavy nuclei, the fraction of fast nucleons emitted at the pre-equilibrium stage is comparable with the cascade component (at least for moderate nucleon energies) and the slope of the pre-equilibrium spectrum is close to the experimental one.

Our CEM calculations have shown that statistical mechanisms play an essential role in inclusive cumulative particle production at bombarding energies up to several GeV and for ejectile energies up to $\sim$ 300 MeV. But the inclusive spectra are not sensitive enough to the mechanisms of particle production and analysis of more "delicate" characteristics (e.g., correlations and polarizations) of nuclear reactions are required.

3.2. Pion production above and below the NN threshold. We have applied our CEM to analyze also practically all known data on nucleon-induced pion production for intermediate and heavy nuclei and bombarding energies less than several GeV. As an example, Fig. 1 shows a part of the recent data [10, 11] on neutron-induced inclusive pion production along with our CEM calculation and the prediction of the Intranuclear Cascade Model (ICM) by Cugnon and Lemaire [15] and by Bertini [16].

Pions in our CEM arise only from intranuclear inelastic collisions $NN \rightarrow \pi NN$, $NN \rightarrow \pi_1, \cdots, \pi_i NN$, $\pi N \rightarrow \pi_1, \cdots, \pi_i N$ $(i \geq 2)$ followed (or not) by additional elastic or charge-exchange rescatterings $\pi N \rightarrow \pi N$ during the cascade. In the version used here of the intranuclear cascade model [14] the production of Δ isobars in intermediate states is not taken into account. As one can see from Fig. 1, these conventional mechanisms of pion production can satisfactorily reproduce the shape and absolute value of pion spectra and the π^- to π^+ ratio. This reflects the influence of the nuclear medium by means of the Fermi motion and the CEM doesn't require production on effective targets or clusters with masses larger than the nucleon mass or other specific mechanisms for the description of pion production in these reactions.

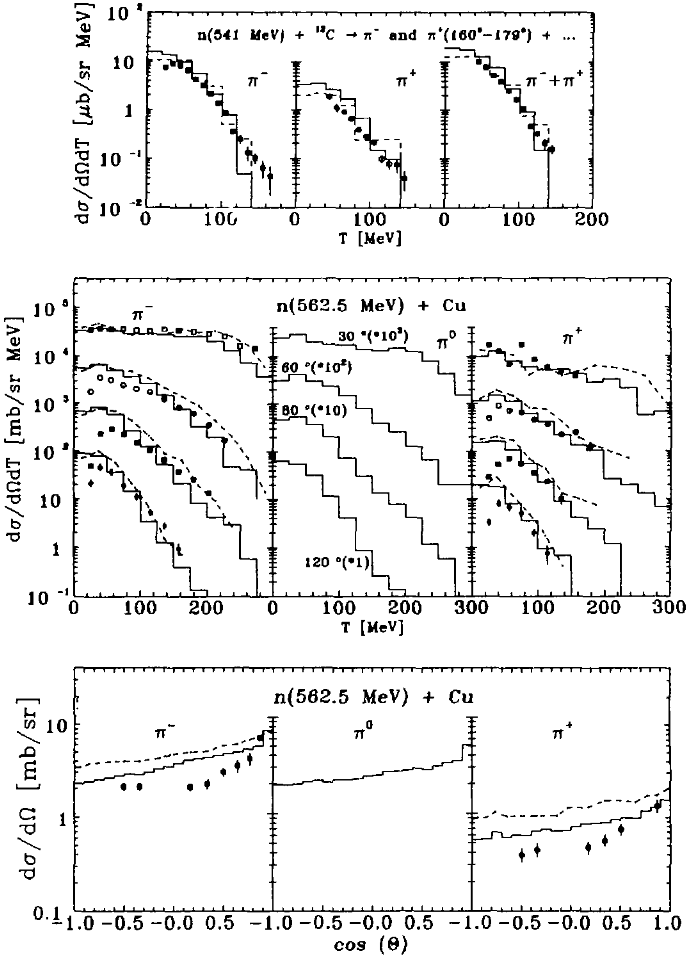

Fig. 1. Inclusive spectra of pions for separate charged states from reactions as indicated. *Upper row:* Points are the experimental data from Ref. [10]. The solid and dashed histograms are our CEM and ICM [15] calculations from Ref. [10], respectively; **middle and upper rows:** double differential cross sections at angles 30°, 60°, 80°, and 120° and angular distributions for pion energies greater than 32.2 MeV of three pion-charge states for 562.5 MeV neutrons on *Cu*, respectively. The points are experimental data [11], the histograms and dashed lines are our CEM and LAHET [16] calculations from Ref. [11], respectively.

The CEM without the Δ in an intermediate state describes the data somewhat better than the Bertini's [16] or Cugnon's and Lemaire's [15] ICM with the Δ as a cascade participant.

The CEM is able to describe also the main part of nucleon-induced subthreshold pion production (see, e.g. [8]). As an example, in Fig. 2 the recent data [12] on subthreshold production of π^+ and π^- from proton-nickel interactions at 201 MeV are compared with our CEM calculations. Though the statistics of our Monte-Carlo simulation is poor, a general agreement between the calculation and the data is observed. This once again reflects the influence of the nuclear medium by means of the Fermi motion.

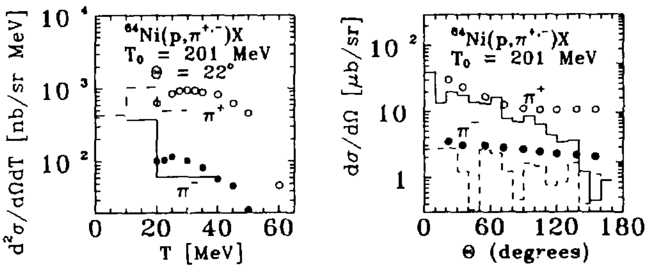

Fig. 2. Double differential cross sections (left graph) and angular distributions (right graph) of the subthreshold production of two pion-charge states from proton-nickel collisions at 201 MeV. The histograms are our CEM calculations, the circles are experimental data [12] as indicated.

4. Pion-induced particle production

4.1. Intermediate bombarding energies. Various measurements of pion-induced reactions have been performed with the purpose to obtain information on different pion absorption mechanisms (see review [2]). So, McKeown et al. have measured inclusive (π, p) cross sections on ^{12}C, ^{27}Al, ^{58}Ni and ^{181}Ta at T_π = 100, 160 and 260 MeV [18]. Assuming that high-energy protons arise only from absorption reactions and neglecting the initial- and final-state interactions, McKeown et al. have analyzed their own 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 resonance in literature: afterwards there were performed many theoretical investigations which demonstrated that McKeown's et al. data may be described by a 2N absorption mechanism, or on the contrary, only by multi-nucleon absorption (see review [2]). Of great interest are also the recent measurements of pion-induced inclusive proton production on copper at 0.6, 0.8 and 1 Gev/c of Golubeva et al. [17]. 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.

We have analyzed, in our CEM, inclusive production of different particles in the incident pion energy range from 100 Mev to 3 GeV (see, e.g., [8]). For our model there is no difference between nucleon- and pion-induced reactions. The first step of the cascade stage of the reaction is simply induced by a pion instead of a nucleon. Let me recall that in the CEM we regard only the 2N absorption mechanism. As an example, in Figs. 3 and 4, a part of Golubeva's et al. [17] and McKeown's et al. [18] data is shown along with our CEM calculations. One can see that both the McKeown's et al. and Golubeva's et al. data may by described satisfactorily in the CEM only by the 2N absorption mechanism. (We obtained similar results for all other known data up to $T_\pi \sim 3$ GeV.) This indicates the importance of initial- and final-state interactions neglected by Golubeva et al. and McKeown et al. in analyzing their data by the "moving-source" representation.

4.2. Stopped pion absorption by nuclei. The CEM have been developed [5] to describe stopped negative pion absorption by intermediate and heavy nuclei. We again take into account only 2N absorption mechanism. The point at which the pion is absorbed in the nucleus was determined from the distribution derived in [20] from calculations on pionic atoms $P_{abs} \sim exp[-(r-c)^2/2\sigma^2]$. The value of constants c and σ were determined by interpolating between the results given in [20] for nearby nuclei.

The particle yield for these reactions in our 2N absorption model is given by

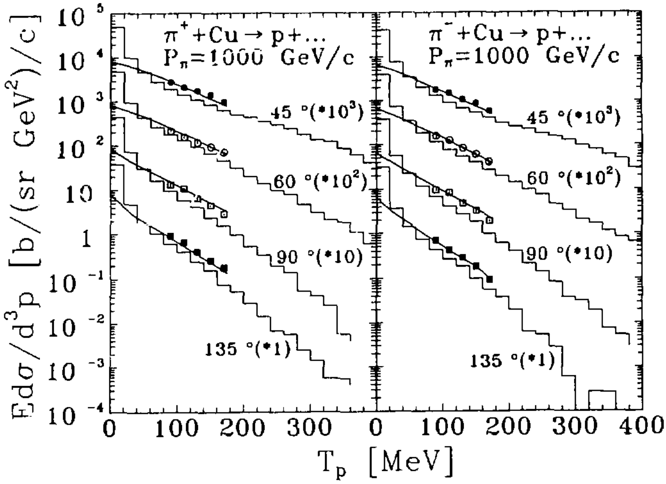

Fig. 3. Measured [17] inclusive proton spectra from π^+ and π^- interactions with copper at 1 Gev/c (symbols), our CEM calculations (histograms) and results of the best fit [17] in the moving-source model (lines). Different emission angles are drawn with symbols as indicated. The histograms are sums of all three CEM (cascade, pre-equilibrium and evaporative) components.

$$Y_{CEM} = (Y_{CEM}^{pp} + R\, Y_{CEM}^{np})/(R+1), \tag{3}$$

where Y_{CEM}^{pp} and Y_{CEM}^{np} are the particle yields accompanying absorption of pp and np pairs, respectively. It is useful to extract from R the statistical factor taking into account the number of np and pp pairs in a nucleus containing N neutrons and Z protons, i.e., $R = [2N/(Z - -1)]R' \equiv R_0 R'$, where R' is the ratio of the absorption widths for the np and pp pairs: $R' = \Gamma(\pi^- np \to nn)/\Gamma(\pi^- pp \to np)$.

A purely theoretical determination of R' is hardly possible at present. The up-to-date experimental data also can not clarify this question (see, e.g., [2, 5]). The interpretation of the value of the R is therefore dual in character. Thus, R can be regarded as a free parameter of the theory that can be used with (3) to normalize the theoretical particle yields to the experimental data. The fact that this normalization is possible is not at all trivial because the physical value of R must be positive, and this occurs only when the experimental yield lies between the theoretical yields calculated for absorption by pp ($R = 0$) and by np ($R = \infty$) pairs. The value of R obtained in this way and, consequently, the value of R' can probably be looked upon as a physical result characterizing the absorption process.

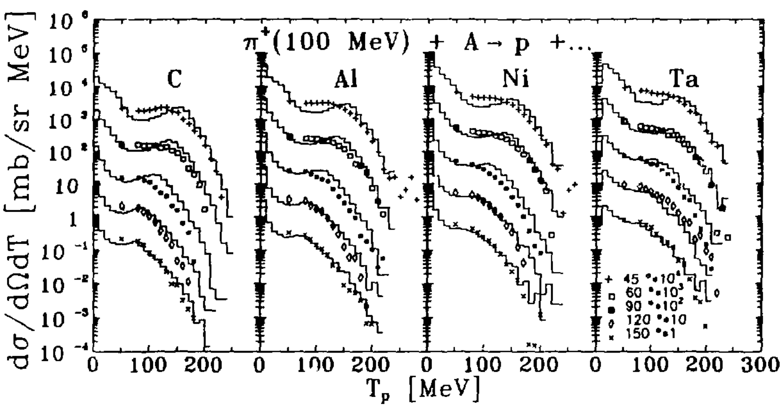

Fig. 4. Measured [18] inclusive proton spectra (symbols) and CEM calculations (histograms). Different emission angles for different target-nuclei are drawn with symbols as indicated. The histograms are sums of all three CEM components.

We have applied (see, e.g., [5, 6, 19, 21]) our model to analyze a large variety of experimental data on stopped negative pion absorption by nuclei from C to Bi: energy spectra and multiplicities of n, p, d, t, ^3He, and ^4He; angular correlations of two secondary particles; spectra of the energy released in the "live" ^{28}Si target on recording protons, deuterons and tritons in the energy range 40-70 MeV, 30-60 MeV and 30-50 MeV, respectively; isotope yields; momentum and angular momentum distributions of residual nuclei, etc. On the whole, the CEM satisfactory reproduces all the analyzed experimental data. This fact indicates that the 2N absorption mechanism is the main one for medium and heavy nuclei. However we have obtained [19] a direct indication on the α-particle absorption mechanism in ^{28}Si from the analysis of spectra of energy released in the target for reactions with emission of tritons.

CEM predicts a noticeable yield of composite particles due to the pre-equilibrium emission mechanism. At the same time, our investigations show that pre-equilibrium emission and evaporation are not the only mechanism of composite particles production. From the differences observed in the experimental and CEM spectra of energy released in the "live" target on recording deuterons and tritons, on the basis of the portion of events with small energy released, we have estimated the contribution of "direct" processes to the formation of composite particles to be at a level of $\sim 20 - 40\%$ for ^{28}Si target [19].

We have shown [5] that emission of particles at the pre-equilibrium stage of reaction is important in the production of high angular and linear momenta of residual nuclei.

Our CEM analysis [5] of the old experimental proton spectra measured for various target 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 et al. experimental data [6, 19] are consistent with the assumption that R' remains constant in a wide range of nuclei from ^{6}Li to ^{209}Bi. The result $R' = 3.5 \pm 1.5$ obtained from our analysis [6, 19] of different characteristics is very close to the value obtained by Blankleider et al. [22] for ^{3}He, i.e., the lightest nucleus for which absorption by both np and pp pairs is possible.

6. Summary and Conclusion

In this talk I have shown that without free parameters our CEM is able to describe the absolute value of various characteristics of pion- and nucleon-induced reactions for medium and heavy target-nuclei and incident energies less than several GeV. In all the considered reactions the main mechanism of pion absorption is a two-nucleon one. The probability for single nucleon absorption does not exceed $10^{-3} - 10^{-4}$ [21].

The problem of the contribution of multi-nucleon absorption is still open for medium and heavy nuclei.

I have demonstrated that McKeown's et al. [18] and Golubeva's et al. [17] data (as well as other known measurements up to $T_\pi \sim 3$ GeV) on pion-induced proton production may be satisfactorily described by the 2N absorption mechanism.

The CEM describes the main part of cumulative and subthreshold pion production data by means of the Fermi motion and does not need production on effective targets or heavy clusters. At intermediate primary energies the CEM without Δ-resonances in intermediate states describes the pion spectra not worse than Bertini's [16] or Cugnon's and Lemaire's [15] ICM with the Δ as a cascade participant.

The two-step mechanism (1+2) determines the main part of production of cumulative nucleons at intermediate incident energies. For ejectile energies less than $\sim$ 100 MeV pre-equilibrium processes contribute also essentially to the fast backward nucleon and complex particle emission.

It was found that pre-equilibrium processes are also of great importance for stopped-pion absorption reactions: they have the greatest effects on the energy spectra of charged complex particles and on the fission probability of the residual nuclei and play a significant part in the production of high angular and linear momenta of residual nuclei.

These results do not imply, of course, that pion- and nucleon-nucleus interaction physics is completely described by the reaction mechanisms considered here. The agreement between experimental 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 and uncertainties of the CEM parameters and from the statistical accuracy of Monte-Carlo calculations. In other words, the CEM calculations explain a major part of particle yields but admit some contributions from other reaction mechanisms.

From my point of view, for medium and heavy nuclei and for ejectile energies less than several hundreds MeV, the conventional mechanisms considered here will contribute to the particle production also at higher bombarding energies (and for other projectiles), as a second stage of the reaction, after specific fast mechanisms involving quark degrees of freedom of nuclei, or even a nucleus being a quark-gluon system. The recent Yuldashev's *et al.* measurements [9] of cumulative proton production in $p+^{20}Ne$ interactions at 300 GeV may serve as a confirmation of this: The authors of this work have found that even at 300 GeV one can produce up to 37% of all protons emitted at $\Theta_{lab} > 90°$ from absorption of pions by quasi-two-nucleon systems in a nucleus. The contribution of specific mechanisms can be estimated as a difference between experimental data and the calculated "background".

I would like to thank the Physics Auxiliary Publication Service of the American Institute of Physics for the kind sending me the AIP document No. PAPS PRVCA-24-211-48 with the tabulations of McKeown's et al. data [18] used here.

It is a great pleasure to thank the Organizers of the Cracow Conference for inviting me to deliver these talk and kind hospitality, as well as for their efforts in maintaining a high standard of the meeting and very pleasant ambience.

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