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Pion-nucleus absorption via the delta-nucleon intermediate state

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The predictions of the intranuclear cascade model for pion-nucleus reactions is reexamined in view of new experimental and theoretical developments that affect the understanding of the true pion absorption process. A strong suppression of pion absorption on $T=1$ nucleon pairs causes only slight differences in the intranuclear cascade predictions since there is an isospin-dependent distance restriction in the model. We have also shown that the data that were interpreted as an indication for double-Δ excitation can be explained also by sequential delta formation prior to absorption.

It has generally been assumed that the major process responsible for pion absorption is the $\pi+2\text{N}\rightarrow\Delta\text{N}\rightarrow\text{NN}$ reaction with the cross sections for the various isospin states in the intermediate and final states determined by the isospin coupling rules.

Recently there have been two developments which affect the above simple picture for the pion absorption process.

(1) An experiment by Ashery *et al.*[1] with resonance-energy pions incident on ^{3,4}He showed that the cross sections for absorption on $T=1$ nucleon pairs are suppressed by more than a factor of 20 compared with what is expected on the basis of the isospin coupling coefficients. Preliminary experiments at other energies[2,3] as well as an experiment with stopped pions[4] also find a sizeable suppression but seem to indicate that it is strongly energy dependent.

(2) Brown *et al.*[5] have proposed an alternative pion absorption mechanism based on a Δ-Δ intermediate state in order to explain the experimental ratio of the proton yield in π^+ vs π^- absorption and the experimental indications that more than two nucleons take part in the pion absorption process.[6]

In a recent paper[7] we have compared the predictions of the intranuclear cascade (INC) model for pion-nucleus reactions with the experimental results for inclusive inelastic scattering, true absorption, and angular correlations for the $(\pi,\pi\text{p})$ and $(\pi^+,2\text{p})$ processes. In general good agreement was obtained between the predictions of the model and the experimental results. It is therefore of interest to reexamine the predictions of the model for pion absorption on a $T=1$ nucleon pair and the experimental data which are cited by Brown *et al.* as indicating the importance of the two-delta mechanism.

The reason for the suppression of pion absorption on $T=1$ nucleon pairs is believed to by dynamical, i.e., dependent on the orbital angular momentum states allowed in the intermediate Δ-N states. An NN pair in a $T=0$ $^3S_1$ state can form a Δ-N intermediate state in a relative S state $(L=0)$, but a $T=1$ $^1S_0$ pair can only form a Δ-N in a P^- or higher orbital angular momentum state $(L>0)$ which is predicted to have a lower probability for the $\Delta\text{N}\rightarrow\text{NN}$ transition.[8]

In nuclei heavier than ^{4}He, $T=1$ nucleon pairs do not have to be in a relative $^1S_0$ state since they may belong to different shells. However, the experimental results[9] indicate that even in Bi the cross-section ratio $(\pi^-,\text{pn})/(\pi^+,2\text{p})$ is only a few percent, indicating that the cross section for pion absorption on nucleons from different major shells is probably quite small.

In view of the experimental evidence for the strong suppression of the pion absorption on a $T=1$ nucleon pair, it is of course of great interest to see how this suppression will affect the predictions of the INC model. For this purpose we have calculated the absorption of 245 MeV pions on ^{12}C with the extreme assumption that pion absorption on a $T=1$ pair is forbidden. This condition was implemented in our model by making the cross section for pion absorption on two protons or two neutrons equal to zero and reducing absorption on a pn pair by 25%. (We assume that two nucleons to be in a relative S state.) In Table I we show the calculated and experimental values for the absorption cross section of positive pions on ^{12}C at a bombarding energy of 245 MeV and the "quasideuteron" fraction of the absorption cross section (i.e., the fraction of the cross section for which there is no rescattering of the pions preceding

TABLE I. Calculated and experimental values for the absorption cross section of positive pions on ^{12}C at a bombarding energy of 245 MeV, the "quasideuteron" fraction of the absorption cross section for the reaction $(\pi^+,2\text{p})$. All cross sections are in mb. For the measurement and calculation of $\sigma_{\text{qd}}(\pi^+,2\text{p})$ a lower limit of $E_{\text{p}}\geq 40$ MeV was used for both protons.

	Experimental results	INC calculation No suppression of $T=1$ absorption	INC calculation Pion absorption on a $T=1$ pion completely forbidden
$\sigma_{\text{abs}(\pi^+)}$	95 ± 32[a]	94.2 ± 0.8	76.6 ± 0.8
$\sigma_{\text{qd}(\pi^+,2\text{p})}$	11.4 ± 2.0[b]	19.2 ± 0.4	12.8 ± 0.4

[a] Results of Ref. 10.

[b] Results of Ref. 11.

TABLE II. Ratio of proton yield from π^+ or π^- absorption on three different nuclei, following from the double-Δ mechanism prediction (Ref. 5), experimental data (Ref. 6), and INC calculation (the numbers in parentheses correspond to INC calculation assuming a complete suppression of $T=1$ absorption). The incoming pion energy is 220 MeV. Only protons above 40 MeV were measured in the experiment (Ref. 6) and were considered in the INC calculation.

$\dfrac{Y_p(\pi^+)}{Y_p(\pi^-)}$	Expt. (Ref. 3)	ΔΔ mechanism	INC calculation	
^{27}Al	3.8 ± 0.8	4.1	4.0	(4.2)
^{58}Ni	3.7 ± 0.7	4.2	3.6	(3.5)
^{181}Ta	3.4 ± 0.6	3.9	3.4	(3.5)

absorption and no final-state interaction of the nucleons following absorption) for the reaction $(\pi^+, 2p)$. Finally, the ratio of the number of protons emitted in π^+ vs π^- absorption on three nuclei is presented in Table II. The calculation was made using a modified version[7] of the INC model of Harp *et al.*[12]

We show in Table I the calculated results assuming (1) no suppression of the pion absorption on $T=1$ nucleon pairs (i.e., the ratio between the cross section on $T=0$ and $T=1$ pairs as given by the isospin coupling constants), (2) complete suppression of $T=1$ absorption as defined above. We see that in general there is good agreement between the experimental and calculated results in Table I. However, the most interesting aspect of the calculated results is the fact that the results with and without absorption on $T=1$ pairs differ only slightly from each other. This is due to the fact that in our model pion absorption on two protons or two neutrons is highly unlikely because of the isospin-dependent distance restriction. This restriction prevents any particle from making two interactions with two protons or two neutrons if the distance between the points of interaction is less than $R_{\min}(r) = [3/4\pi\rho(r)]^{1/3}$ (for details see Ref. 7).

Recently Brown *et al.*[5] suggested that double-delta formation in the intermediate state of pion absorption $[\pi + 4N \rightarrow 2(\Delta + n) \rightarrow 4N]$ as compared to the "conventional" $\pi + 2N \rightarrow \Delta + N \rightarrow 2N$ mechanism (see Fig. 1) may be an important mechanism for pion absroption on heavy nuclei at and above the Δ-resonance region. They showed that this mechanism is able to explain some striking features observed for the proton spectra following pion absorption: the ratio of protons from π^+ vs π^- absorption for pion bombarding energies of 220 MeV is $R = Y_p(\pi^+)/Y_p(\pi^-) = 4.0 \pm 0.6$, independent of the proton angle; and the number of protons emitted in the process is larger than two, independent of the target mass. On the other hand, direct two-nucleon absorption without final-state interactions of the outgoing protons would result in a value of R larger than 10, and only two emitted particles per absorbed pion. They also point out that direct absorption followed by final-state interactions of the protons cannot explain the experimental results.

We wish to point out that absorption via a single Δ-N in-

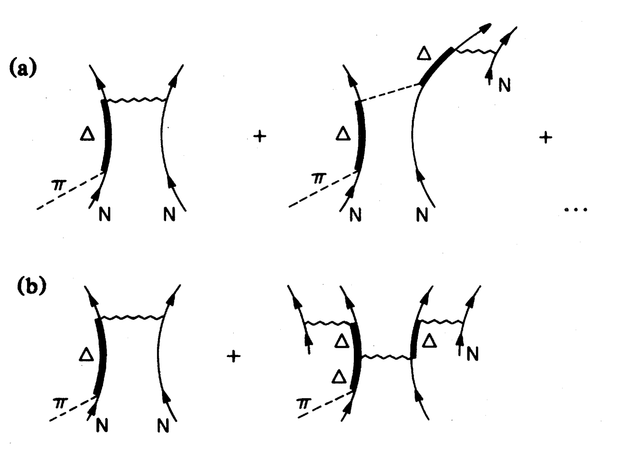

FIG. 1. (a) Absorption through sequential formation and decay of Δ isobars. (b) Absorption through formation of a ΔΔ state (Ref. 5).

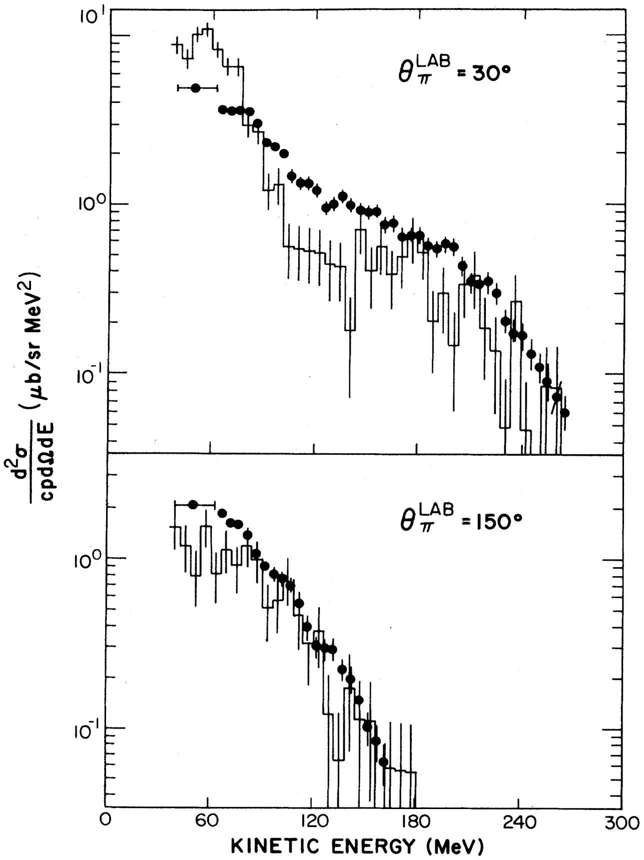

FIG. 2. Comparison of calculated and experimental proton spectra from 160 MeV π^+ on Ni. Solid points are the experimental results (Ref. 6) at 30° and 150°.

termediate state preceded by multiple scattering of the pion with the formation of additional Δ resonances, as shown schematically in Fig. 1, can also explain both the experimental value for *R* and the fact that more than two nucleons seem to participate in the interaction.[6] The difference between this mechanism and that proposed by Brown *et al.* is that they suggest that absorption takes place through the formation of a Δ-Δ intermediate state (two Δ resonances exist simultaneously in the nucleus) while the other mechanism assumes sequential formation of two or more Δ resonances.

To prove our point, we have recently calculated the probability distribution for pion absorption as a function of the number of Δ resonances formed during this process.[7] The calculated distribution is quite broad, approximately angle independent and shows a large probability for the creation of one to three Δ resonances (i.e., two to four participating nucleons) in the absorption. These results are in good agreement with the observed number of nucleons[6] as well as with the optical model calculation of Matusani and Yasaki[13] for 240-MeV pion absorption on ^{16}O.

We show in Table II the ratio *R* of proton emission in the 220-MeV pion absorption on ^{27}Al, ^{58}Ni, and ^{181}Ta together with the experimental results of McKeown *et al.*[6] and the calculated results of Brown *et al.*[5] based on the Δ-Δ model. It is seen that our results, which assume pion absorption to proceed through a single Δ-N intermediate state but allow pion scattering with Δ formation prior to absorption, reproduce the experimental results equally well.

We have also calculated, using the same model, the outgoing proton energy spectra at two angles for 160-MeV π^- absorption on ^{58}Ni. The calculated results are shown together with the experimental results of McKeown *et al.*[6] in Fig. 2. The calculation reproduces reasonably well the shape of the spectra but the absolute magnitude of the calculated results is somewhat lower than the experimental ones, except for the quasielastic peak at ~60 MeV in the 30° spectrum, which is due to π^- scattering rather than absorption. This underestimate was also evident in the previous calculations[7] and may be due to our neglect of the Δ-Δ absorption channel.

In summary, we have shown that a strong suppression of pion absorption on $T=1$ nucleon pairs does not affect strongly the predictions of our INC model since this model already includes a strong suppression of pion absorption on two neutrons or two protons as a result of the isospin-dependent distance restriction. We have also shown that the experimental data discussed by Brown *et al.* do not necessarily imply that double-Δ excitation is the dominant pion absorption mechanism since these experimental features can also be explained by *sequential* rather than *simultaneous* Δ formation prior to absorption. However, we wish to emphasize that we do not claim that the Δ-Δ mechanism is negligible, only that the experimental data cited by Brown *et al.* do not uniquely imply it. In order to determine the relative importance of the Δ-Δ absorption mechanism compared to the "conventional" single-Δ process more experimental information such as the study of the Δ-Δ intermediate state contribution to the $(\pi, 2\pi)$ reaction,[14] as well as more elaborate calculations of the total absorption cross section and its energy and target dependence, are needed.

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