Isospin dependence of pion absorption on nucleon pairs

Richard R. Silbar and E. Piasetzky
Los Alamos National Laboratory, University of California, Los Alamos, New Mexico 87545
(Received 1 July 1983)

The suppressed ratio of (π^-, pn) to (π^+, pp) pion absorption cross sections on ^{3,4}He has an important contribution from NN′ intermediate states, where N′ denotes a P_{11} πN interaction. The order-of-magnitude energy variation of this ratio, from stopped pions to pions above the (3,3) resonance, is reproduced in calculations using a unitary isobar model. We predict a strong asymmetry in the angular distribution of the ratio of higher pion energies.

A recent experiment[1] with resonance-energy pions incident on ^{3,4}He nuclei has discovered that the ratio of cross sections for absorption on $T=1$ and $T=0$ nucleon-nucleon pairs is suppressed by more than a factor of 20 from the isospin symmetry expectation. Preliminary experiments at other energies,[2,3] as well as an experiment with stopped pions,[4] also find this suppression but indicate that the ratio is strongly energy dependent. The reason for the suppression is believed to be dynamical, involving the orbital angular momenta allowed in the NΔ intermediate states which generally dominate the absorption mechanism.[1,5] An absorbing NN pair in a $T=0$ $^3S_1$ state can form an NΔ intermediate state in an s wave $(L'=0)$, but a $T=1$ $^1S_0$ pair must have $L'\geq 1$, which means much smaller amplitudes.

This special kinematical situation which leads to a suppression of the otherwise dominant Δ contribution provides us with a unique opportunity. We can use experimental information on the energy and angle dependence of the $T=1$ to $T=0$ ratio to investigate small effects in the NNπ system that are otherwise masked by the dominant NΔ intermediate states. The ratio is, or will be, a good way to discriminate between various unified, unitary models that have been developed in recent years to describe NN and NNπ interactions.[6]

The first steps in such a program have been taken by Lee and Ohta,[5] who have considered the $L'=1$ NΔ intermediate states in the $T=1$ reaction. They find that the three-body absorption mechanisms contribute negligibly to the kinematical situations investigated to now and that the $T=1$ to $T=0$ ratio at 165 MeV can be explained by the NΔ states. We consider here one of the next logical ingredients, the contribution of the NN′ intermediate state, where N′ denotes an interacting P_{11} πN state. In contrast to Lee and Ohta, we find that the $L'\geq 1$ NΔ intermediate states influence the ratio mainly through their interference with the more important NN′ states. Our calculations, including both NN′ and NΔ channels, are in good agreement with the general features of the order-of-magnitude energy variation of the $T=1$ to $T=0$ ratio. In addition we predict a strong backward peaking in the ratio that could be observed in experiments to be done at higher pion energies.[7]

Our calculations for the two-nucleon absorption process, $\pi+(\mathrm{NN})_{L=0,S,T}\rightarrow \mathrm{NN}$, use time-reversal symmetry and an isobar model[8] for the NN → NNπ reaction. This is a relativistic model which respects two- and three-body unitarity. For details we refer the reader to Ref. 8, but the essence of the calculation is illustrated by the graph in Fig. 1. For pion absorption on a nucleon pair at rest with respect to each other, we simply require the two absorbing nucleons to have the same three-momenta, hence forcing them into a relative s state. Then, using Clebsch-Gordan coefficients, we project out either singlet or triplet spin states ($S=0$ or 1) for this NN pair. The isospin of the pair is therefore also fixed ($T=1$ or 0, respectively) by antisymmetry. The kinematics for this reaction is essentially the same as for pp → dπ^+.

Our isobar model[8] is similar in spirit to that used by Lee and Ohta. Both models have the important feature of unitarity above the inelastic threshold. This can make numerical differences as large as a factor of 3 from Born approximation calculation for the ratio R. The major difference between the models, as far as pion absorption is concerned, is that their model allows only NΔ intermediate states. We have two isobars, Δ and N′.[9] The addition of NN′ intermediate states brings in two new pieces of physics. The NN′ intermediate state can have $L'=0$ when the absorbing pair has $T=1$, in contrast to the $L'\geq 1$ requirement for NΔ states. Also, the final nucleon-nucleon state can now have total isospin $I=0$ as well as $I=1$. Interference of the $I=0$ and $I=1$ amplitudes makes possible an unsymmetric angular distribution of the proton in the overall center of mass.

In this Brief Report we present results of the relative pion absorption cross sections for a $T=1$ or $T=0$ NN pair at rest in the laboratory. For comparison with the data for capture on ^{3,4}He we should also take into account several nuclear corrections. One of these is the effect of Fermi motion, but as far as the cross section ratio is concerned

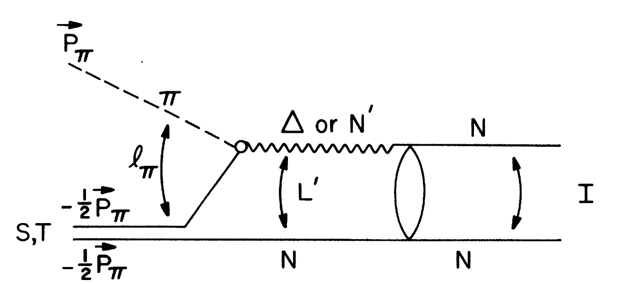

FIG. 1. Form of the graphs calculated for pion absorption on two nucleons, relatively at rest, with total spin S and isospin T. The overall isospin is I, and L' indicates the relative orbital angular momentum between the spectator nucleon N and the πN isobar, either Δ (P_{33}) or N′ (P_{11}). The blob represents the partial wave amplitude (in the LSJ representation) obtained by the unitary isobar model of Ref. 8. The three-momenta of the initial particles are indicated at the left of the diagram.

that should not bring in qualitative differences. Another is the possibility that the pion capture involves more than two nucleons. However, for the situation in which two nucleons are observed "at the free kinematics," as in the experiment of Ref. 1, Lee and Ohta have shown that three-body capture processes make a negligible contribution.[5]

One other point that needs to be made before we present our results is that, given the possibility of $I=0$ final states, the extraction of a "$T=1$ to $T=0$ ratio" is not unambiguous. We have therefore calculated the ratio which corresponds to experiment,

$$R=\frac{\sigma(\pi^-,\mathrm{pn})}{\sigma(\pi^+,\mathrm{pp})}=\frac{N_{T=1}^{\mathrm{pp}}\sigma_3}{N_{T=0}^{\mathrm{np}}\sigma_1+N_{T=1}^{\mathrm{np}}\sigma_2}\ , \qquad (1)$$

$$\sigma_1=\sigma[\pi^+ + (\mathrm{np})_{S=1,T=0}\rightarrow \mathrm{pp}]\ ,$$

$$\sigma_2=\sigma[\pi^+ + (\mathrm{np})_{S=0,T=1}\rightarrow \mathrm{pp}]\ ,$$

$$\sigma_3=\sigma[\pi^- + (\mathrm{pp})_{S=0,T=1}\rightarrow \mathrm{pn}]\ ,$$

where the N's are the numbers of available nucleon pairs with given charge and isospin in the capturing nucleus. For ^{3}He, $N_{T=1}^{\mathrm{pp}}$ $N_{T=0}^{\mathrm{np}}$, and $N_{T=1}^{\mathrm{np}}$ are 1, 1.5, and 0.5, respectively, while for ^{4}He they are 1, 3, and 1. Thus, $R(^3\mathrm{He})=2R(^4\mathrm{He})\equiv R$, allowing us to plot results for both nuclei on the same graph with a simple scaling factor.

Figure 2 shows our calculated results for the cross sections σ_1 and σ_3 (in arbitrary units) and the ratio R (in percent) for three pion laboratory energies, ranging from below to above the (3,3) resonance. The small cross section σ_2, not shown, is comparable in size with σ_3, and thus does not significantly influence the ratio R. The angle θ is the center of mass (c.m.) angle between the pion and the outgoing proton. Calculations with both Δ and N′ isobars present (and interfering) are shown as solid lines, while the separate Δ and N′ contributions are shown as dashed and chained-

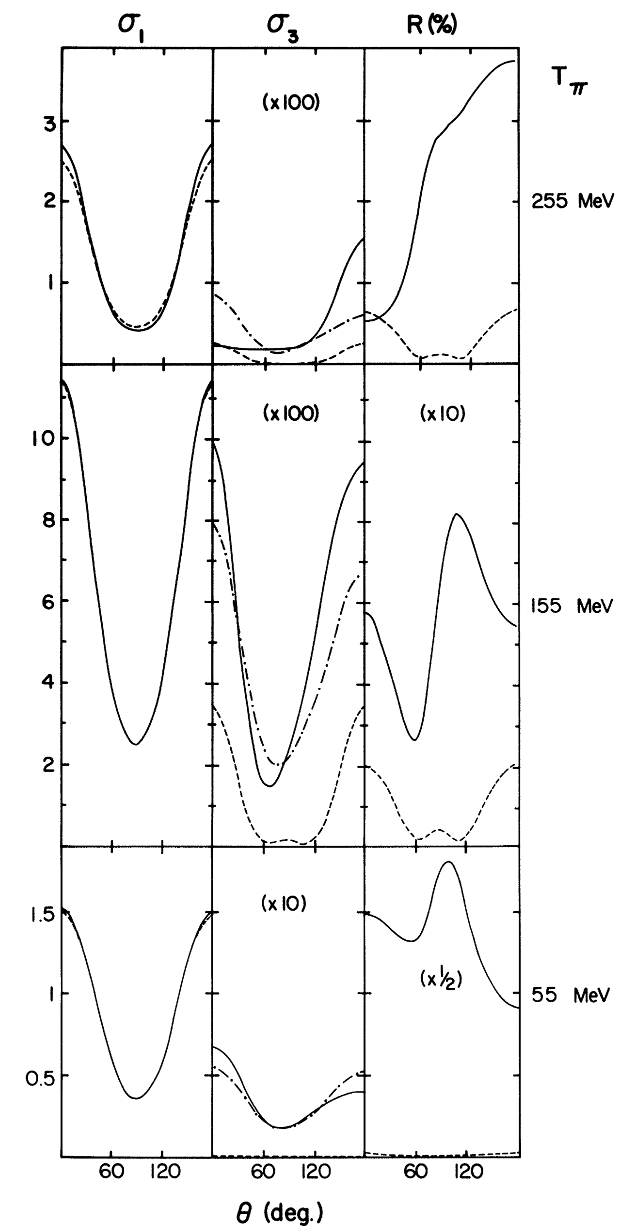

FIG. 2. Predicted cross sections σ_1 and σ_3, in arbitrary units (same for all graphs), and the (π^-,pn) to (π^+,pp) ratio R, in percent, for three incident pion energies. The full calculations with both NN′ and NΔ intermediate states are shown as solid lines, those with NΔ states only as dashed lines, and those with NN′ states only as chained-dot lines. The angle θ is the c.m. angle between the incident pion and the outgoing proton.

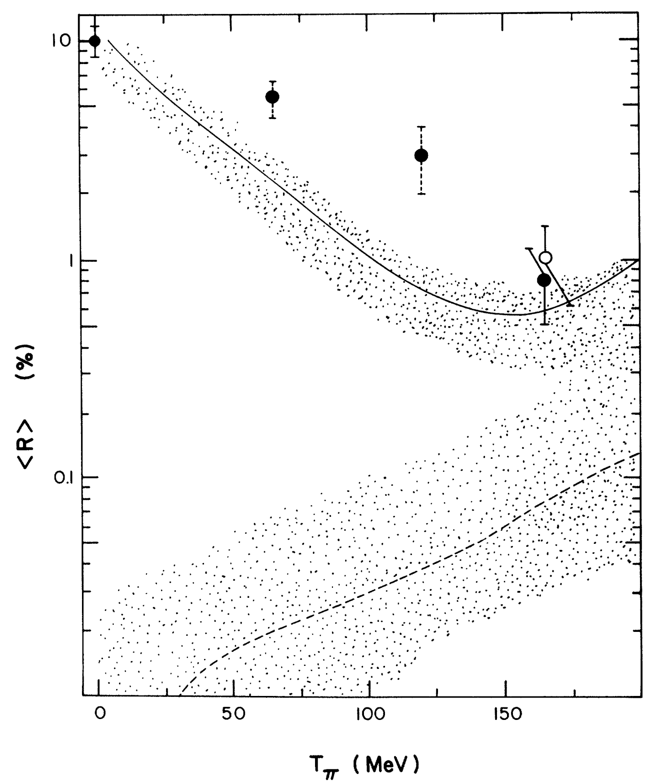

FIG. 3. Angle-averaged (π^-,pn) to (π^+,pp) ratio R (in percent) as a function of incident pion energy, compared with data from Refs. 1–4. The solid curve is the prediction with both NN′ and NΔ intermediate states, while the dashed curve is that for the case of NΔ states only. The dotted areas surrounding the curves indicate the range of variation of $R(\theta)$. Solid data points are from ^{3}He, open circles from ^{4}He; preliminary data points are indicated with dashed error bars.

dot lines, respectively. (The N′-only contribution to σ_1 is negligible and therefore not plotted.) The $T=0$ cross section σ_1, as expected, and the cross section σ_2 are dominated at all energies by the Δ resonance. Both σ_1 and σ_2 have angular distributions like $A+\cos^2\theta$, similar to those for the $\pi^+ d \rightarrow pp$ reaction.

The more interesting graphs are those of σ_3, which show complicated interferences between NΔ intermediate states (with $L' \geqslant 1$) and the somewhat larger NN′ states. It is this interference that gives rise to the striking angular dependence of the ratio R. The pronounced backward peaking at $T_\pi = 255$ MeV is probably most amenable to near-future experimental verification.

To compare these predictions with the available experimental data, we have averaged $R(\theta)$ for ^{3}He over angles. The energy dependence of $\langle R \rangle$ is shown in Fig. 3, along with data from Refs. 1–4. The agreement is surprisingly good, considering that the present model uses a rather simple N′ propagator[10] and it does not include contributions from any of the other "small" πN interactions (e.g., S_{31}) or from NN final state interactions. Note in particular that keeping only NΔ intermediate states, as in Ref. 5, gives R's that are very much smaller than experiment at lower energies.

In this regard, we note that our "NΔ-only" results (dashed curves) are rather smaller than those of Lee and Ohta. One reason for the difference might be that they average over a ^{3}He ground state wave function, while we do not. A more likely reason for the difference, in our opinion, is the different treatment of $NN \rightarrow N\Delta$ amplitudes and Δ propagator. That is, the $T=1$ to $T=0$ absorption ratio appears to be quite sensitive to model details, and for that reason its experimental measurement should be pursued energetically. At the same time we urge other theoreticians to apply their models to calculate this ratio. The comparison with experiment should clarify the physics of the NNπ system which is presently hidden by the dominance of the Δ resonance.

To summarize, we have found that the observed suppression of the $T=1$ to $T=0$ two-nucleon absorption ratio provides a window for examining small effects in the NNπ system that would otherwise be masked by the dominance of the Δ resonance. In particular, the N′ (P_{11} πN) isobar gives important contributions to R. It explains the much larger values of R below the resonance, in good agreement with presently available data, and also predicts a strong backward peaking in $R(\theta)$ at higher energies.

The calculations discussed here were based on a model and computer codes developed in collaboration with J. Dubach and W. M. Kloet. We also thank D. Ashery, T.-S. H. Lee, S. M. Levenson, and M. M. Sternheim for helpful discussions. This work was supported by the U.S. Department of Energy.

[1]D. Ashery *et al.*, Phys. Rev. Lett. 47, 895 (1981).

[2]G. Backenstoss *et al.*, contributed paper to the Symposium on Delta-Nucleus Dynamics, Argonne, Illinois, 1983 (unpublished).

[3]M. A. Moinester *et al.* (unpublished); D. Ashery, invited talk given at the Symposium on Delta-Nucleus Dynamics, Argonne, Illinois, 1983 (unpublished).

[4]D. Gotta *et al.*, Phys. Lett. 112B, 129 (1982).

[5]T. S. H. Lee and K. Ohta, Phys. Rev. Lett. 49, 1079 (1983).

[6]I. R. Afnan, invited talk at the 10th International Conference on Few-Body Problems, Karlsruhe, 1983 (unpublished).

[7]D. Ashery, Experiment Proposal 705, Los Alamos Meson Physics Facility, 1982 (unpublished).

[8]W. M. Kloet and R. R. Silbar, Nucl. Phys. A338, 281 (1980); J. Dubach *et al.*, Phys. Lett. 106B, 29 (1981).

[9]The N′ does not represent a resonance but a P_{11} πN interacting state; its propagator contains a pole, which is the nucleon itself.

[10]More realistic P_{11} πN propagators have been discussed, for example, by Y. Avishai and T. Mizutani, Nucl. Phys. A352, 399 (1981), and by I. R. Afnan and B. Blankleider, Phys. Rev. C 22, 1638 (1980).