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Effects of Nucleon Charge Exchange on the $(\pi, \pi N)$ Puzzle

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Charge-exchange interactions of the nucleons within the nucleus are shown to account for the observed differences in the ratios of neutron-knockout cross sections for $\pi^{\pm}$ from the impulse-approximation predictions. Also, the energy dependence of the knockout cross sections is obtained from the measured total pion reaction cross sections with a simple model for the threshold behavior.

New measurements[1] of the cross sections $\sigma^{\pm}$ for the removal by $\pi^{\pm}$ of a neutron from a light nucleus have provided information relative to one of the most interesting puzzles in medium-energy nuclear physics. In this Letter we will show that many features of these experiments can be attributed to the final-state charge-exchange interactions of the outgoing nucleons.

For a $Z=N$ nucleus, the impulse approximation implies that the ratio $\mathcal{R}=\sigma^-/\sigma^+$ equals the ratio of free $\pi^{\mp}$ cross sections, which is about 3 in the (3, 3) resonance region from 100 to 300 MeV. However, earlier measurements[2] on ^{12}C, ^{14}N, and ^{16}O all gave $\mathcal{R}\approx 1$ at 180 MeV. In addition to nucleon charge exchange,[3,4] several other mechanisms were proposed to explain the large discrepancy: "quasi-α particles,"[5] excitation of intermediate states of definite isospin,[2,6] Fermi averaging,[7] compound-nucleus effects,[4] formation of nucleon isobars with particular nuclear interactions, etc. The relatively limited data made it difficult to test these suggestions.

Nucleon charge exchange has a large effect on $\mathcal{R}$ because it both increases σ^+ and decreases σ^-. A π^+ has a large cross section for scattering by a proton. If a struck proton charge exchanges before it leaves the nucleus, the net result is a neutron knockout. Similarly, when a π^- strikes a neutron which charge exchanges, the net result is a proton knockout.

The new carbon data (Figs. 1 and 2) show that $\mathcal{R}$ rises steadily with the pion energy T_π in the resonance region, increasing from *less than 1* at 50 MeV to about 1.8 at 290 MeV; at 180 MeV it is about 1.6, considerably more than the old value of 1.0. This gradual approach toward the impulse-approximation prediction for $\mathcal{R}$ is consistent with the fact that the nucleon charge-exchange cross section decreases as the average nucleon energy T_N increases.

To illustrate the nucleon charge-exchange effects, we suppose that the probability for a nu-

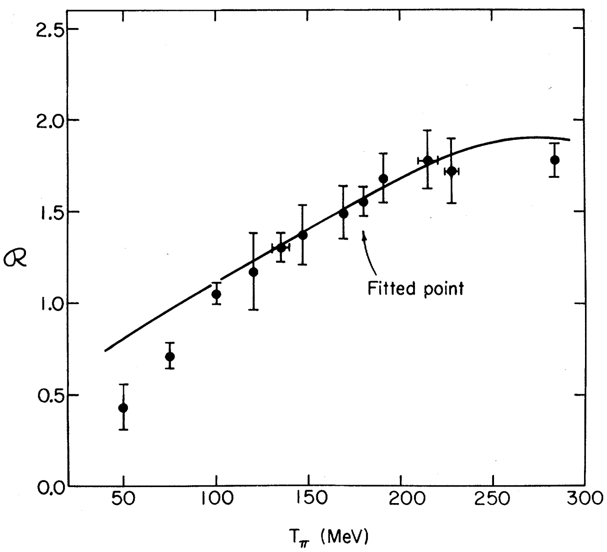

FIG. 1. Energy dependence of the predicted ratio $\mathcal{R}=\sigma^-/\sigma^+$ from Eq. (1). Data taken from Ref. 1.

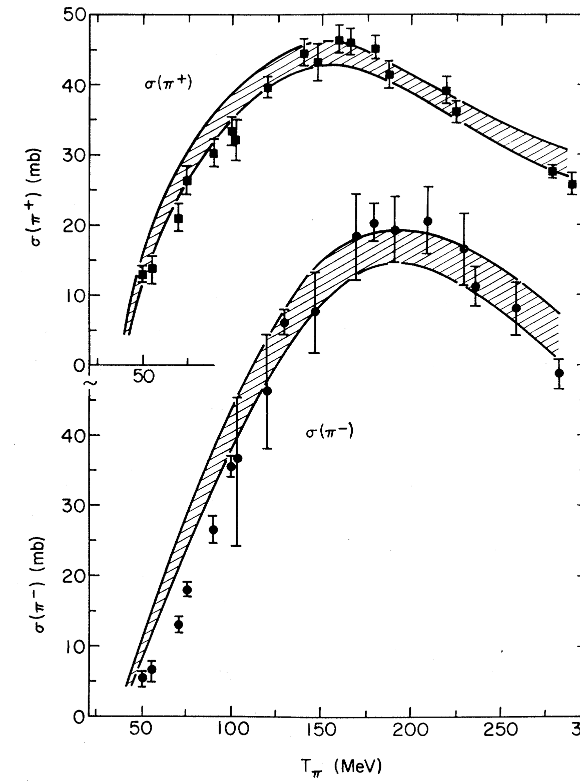

FIG. 2. Energy dependence of $\sigma^\pm$ given by Eq. (4) compared with data of Ref. 1. The width of the theoretical bands reflects the errors in the input reaction cross sections (Ref. 8).

cleon to charge exchange before it leaves the nucleus is P. When a pion scatters on a nucleon and transfers enough energy to eject it from the nucleus, the probability of the nucleon exiting with its original charge state is then $1-P$. For $Z=N$, including these charge-exchange processes changes the impulse-approximation prediction to

$$\mathcal{R}=\frac{\sigma^-}{\sigma^+}=\frac{\sigma_{\pi^-n}(1-P)+\sigma_{\pi^-p\to\pi^-p}P}{\sigma_{\pi^+n}(1-P)+\sigma_{\pi^+p}P}\approx\frac{9-8P}{3+6P}, \qquad (1)$$

where the approximate form includes only the (3, 3) amplitude.[9] Note that when P is zero, $\mathcal{R}$ is 3 as expected. In a very large nucleus, or with very slow nucleons, we might expect the nucleons to completely "forget" their original charge state. In this case $P=\frac{1}{2}$ and $\mathcal{R}=\frac{5}{6}$. Thus even with (3, 3) dominance, charge exchange opens the possibility of obtaining any ratio from 3 down to $\frac{5}{6}$.

The simplest way to estimate the charge-exchange probability P is to apply a semiclassical transport model.[10] This model assumes that πN and NN processes occur in the nucleus much as in free space, except perhaps for minor corrections due to the nuclear medium. It also assumes straight-line propagation up to and from the πN collision. With a uniform nuclear density $\rho=3/(4\pi R^3)$, the result for P is

$$P=\tfrac{1}{2}[1-\exp(-A\rho\sigma_{ex}d)]. \qquad (2)$$

Here σ_{ex} is the cross section for nucleon charge exchange and d is the average distance traveled by a nucleon in the nucleus. Both quantities depend indirectly on T_π.

We may calculate d by assuming that the recoil nucleon travels exactly forward after being struck by the pion. This approximation is best near the resonance. If the mean free path of the pion is λ, then with $x=2R/\lambda$,

$$d=(4R/3)\{1-(3/2x)+(3/x^2)[1-(1+x)\exp(-x)]\} \qquad (3)$$
$$\approx\tfrac{4}{3}R-\lambda \quad (\text{when } x\gg 1).$$

The maximum value of d occurs when λ is a minimum or at the (3, 3) resonance peak.

The charge-exchange cross section σ_{ex} can be estimated from the measured free np backscattering cross sections[11] at the average nucleon recoil energy T_N, which is about $T_\pi/3$; the precise value of T_N as a function of T_π depends on the neutron removal energy of the nucleus (which is 18.7 MeV for ^{12}C). If Pauli-principle corrections are neglected, σ_{ex} is obtained by integrating the backscattering cross section from 180° to the maximum angle which will leave the incident nucleon with insufficient energy to escape from the nucleus. The result is that σ_{ex} varies as $T_N^{-1.9}$ to within required accuracy.

Using a "sharp-edged" Fermi-gas model to estimate the Pauli-principle corrections[12] reduces σ_{ex} by a factor of about 3 but again leads to a $T_N^{-1.9}$ variation. This Pauli reduction factor is undoubtedly too large for nucleons which travel mainly near the edge of the nucleus and which account for many of the actual neutron-knockout events. We have circumvented this difficulty by setting $\sigma_{ex}=\beta T_N^{-1.9}$ and *fitting* β to give the experimental value of $\mathcal{R}$ at $T_\pi = 180$ MeV. The value of β obtained in this way is *between* the free and the Pauli-corrected values.

Our results for $\mathcal{R}$ for ^{12}C obtained using the exact form of Eq. (1) are shown in Fig. 1.[13] The agreement with the data is remarkably good. It is better than one ought to expect from this semiclassical model since the conditions for its applicability are poorly satisfied at best.[14,15]

The model used here can easily be applied to other nuclei as well. The best test of the picture would be the expected A dependence as it enters through the charge-exchange probability. Unfortunately we do not know of any knockout data yet for heavy nuclei. Preliminary results[8] for ^{14}N, ^{16}O, and ^{19}F show more or less the same features as the more extensive and more precise ^{12}C data and can also be understood in our model. Applying Eq. (1) to these nuclei (appropriately extended for $Z \neq N$ in the case of ^{19}F), we obtain curves for $\mathcal{R}$ very similar to that shown in Fig. 1. Here too the fitted β parameters lie between the free and full-Pauli-principle limits and the theoretical curves agree with the data within the present statistical errors.

The semiclassical model can also be used to relate the energy dependence of the knockout cross sections to the total pion-nucleus reaction cross section, σ_R. At pion energies below the particle-knockout threshold, the reaction cross section is due to nuclear excitation and pion absorption. For a pion to knock out a nucleon in a collision, the energy transferred must at least equal the removal energy. Consequently pions above the threshold must scatter through angles greater than some minimum angle $\theta_0(T_\pi)$ to eject nucleons. In carbon the neutron-removal energy is 18.7 MeV, corresponding to the energy transferred by 40-MeV pions scattered through 180°. This agrees with the observed threshold (Fig. 2).

Let us define the threshold factor $f(T_\pi)$ as the ratio of the integral from θ_0 to 180° of $d\sigma(\pi N)/d\Omega$ to the total πN cross section. We might suppose that the cross section for nucleon knockout is a constant fraction of σ_R times the threshold factor. With this assumption and Eq. (1), the (3,3) dominance approximation for the π^+ reaction gives

$$\sigma^+ = c(3+6P)f(T_\pi)\sigma_R(T_\pi), \tag{4}$$

whence $\sigma^- = \sigma^+\mathcal{R}$. Using experimental π^- ^{12}C values[16] for the reaction cross sections and choosing $c=0.0313$ leads to results (Fig. 2) in good agreement with the data. In particular, the downshift of the σ^+ peak from the 160-MeV peak in σ_R and the upshift of the σ^- peak are correctly predicted, as might have been expected from the good fit to $\mathcal{R}$.

To summarize, we have seen that charge exchange of the outgoing nucleons as estimated semiclassically can account for the large differences between the observed neutron-knockout ratios and the impulse-approximation predictions.[17] Whether additional mechanisms are also important here will become clearer when the predictions of this model are tested against proton-knockout data and data from heavier nuclei. More reliable wave-mechanical treatments of the final-state charge-exchange interaction effects would also be in order.

We wish to thank the authors of Refs. 1 and 15 for many stimulating discussions concerning their data.

Note added—We have recently also considered the effects of *pion* charge exchange on $\mathcal{R}$, both before and after the πN knockout reaction. The changes are small ($\leq 4\%$) and $\mathcal{R}(T_\pi)$ is basically unchanged from that shown in Fig. 1. Details will be given in a later publication.

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Measurement and Interpretation of Γ_n/Γ_f for Actinide Nuclei*

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The (^{3}He, *df*) and (^{3}He,*tf*) reactions were used to measure fission probabilities from threshold up to ~12 MeV of excitation energy for a series of actinide nuclei. The data were fitted over the whole range of nuclei and excitation energies with a microscopic model which does not contain an arbitrary normalization for Γ_n/Γ_f. The fits indicate that for most actinide nuclei fission proceeds through a first saddle point that is *not* axially symmetric.

Previous experimental determinations[1] of Γ_n/Γ_f for actinide nuclei have primarily come from calculated total reaction cross sections or from the analysis of high-excitation–energy spallation cross sections. In the first case the results are limited both by the target nuclei available for study and by the accuracy of the calculated total reaction cross sections. In the second case the Γ_n/Γ_f values deduced represent an average over a range of excitation energies and decaying nuclei. In a few cases Γ_n/Γ_f values have been determined using (t,pf) reactions[2] but these measurements were only valid in the energy range up to 2 MeV above the neutron binding energy and they were limited to a relatively few nuclei.

Similarly the variations of Γ_n/Γ_f both with nucleus and with energy are only very schematically understood. Empirical trends with Z and A have been shown by Vandenbosch and Huizenga[1] but these trends or the energy dependence of Γ_n/Γ_f have not been reproduced in any theoretical calculations.

In this Letter we report three new developments which give significant improvements both to the techniques for measuring Γ_n/Γ_f and to a basic theoretical understanding of neutron-to-fission competition in actinide nuclei. These new developments are as follows: (1) The (^{3}He,*df*) and (^{3}He,*tf*) reactions are used to determine experimentally the absolute values of $P_f = \Gamma_f/(\Gamma_f + \Gamma_n + \Gamma_\gamma)$ for excitation energies up to ~12 MeV for a wide variety of nuclei which have not been previously accessible. (2) A theoretical calculation of P_f incorporating collective enhancements[3] to the nuclear level densities and a double-peaked fission barrier is shown to reproduce absolute values of