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Nonanalog pion double charge exchange through the Δ_{33}-nucleon interaction

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Numerical results have been obtained for calculations of pion double charge exchange arising from Δ_{33}-mediated processes. Calculations of double-charge-exchange excitation functions and angular distributions are presented for the reaction $^{16}O(\pi^+,\pi^-)^{16}Ne(g.s.)$. The sensitivity of the calculations to quantities specifying the reaction mechanism is shown.

The large cross sections and simple systematics of pion double charge exchange (DCX) on $T=0$ targets[1,2] are among the most surprising features of DCX. The systematics[1] of these $\Delta T=2$, $\Delta J=0$ transitions (excitation functions peaked at Δ_{33} resonance energies, diffractive angular distributions, and an $A^{-4/3}$ mass dependence) were not anticipated and have not been explained in any model. Several calculations of the ratio

$$\frac{d\sigma[^{16}O(\pi^+,\pi^-)^{16}Ne(g.s.)]}{d\sigma[^{18}O(\pi^+,\pi^-)^{18}Ne(g.s.)]}$$

have been performed[3-5] within models in which both transitions proceed via sequential single charge exchanges, but none of these has reproduced the trend of the experimental data with energy and angle. The energy dependence of the nonanalog data[1] strongly suggests a simple Δ-dominated mechanism[6] shown in Fig. 1.

In this Rapid Communication we describe the results of new calculations of nonanalog DCX through this reaction mechanism. In an earlier Letter[6] the contribution of nonsequential charge-exchange processes to the analog reaction, $^{18}O(\pi^+,\pi^-)^{18}Ne(g.s.)$, was examined. The direct Δ_{33}-nucleus interaction process (DINT),[7] displayed in Fig. 1, was found to be of magnitude similar to or larger than the standard sequential charge-exchange mechanism at energies near the Δ_{33} resonance ($T_\pi \sim 180$ MeV). Because it is large and of similar energy dependence to the data, Fig. 1 is assumed to dominate nonanalog DCX; contributions of sequential scattering should be evaluated in the future to verify this. A process involving Δ_{33} components of the initial- and final-state wave functions (DWF) was found to have little effect[6] on the calculated cross sections. Because the theory was described earlier,[6] we present here only a brief description of its main features and concentrate on the modifications between the previous and present works. A full description of the theory will be published in an upcoming article.[8]

DCX cross sections are calculated within a distorted-wave impulse-approximation framework using a version of the code DWPI[9] built around an optical potential of the form given in Ref. 10. The input transition density is constructed microscopically for transitions between specific shell-model configurations. For illustrative purposes we have assumed that ^{16}O is a closed core and that ^{16}Ne is $\nu(p_{1/2})^{-2}\pi(d_{5/2})^2$. Then the $^{16}O(\pi^+,\pi^-)^{16}Ne(g.s.)$ reaction proceeds solely via a $\nu(p_{1/2})^2 \rightarrow \pi(d_{5/2})^2$ transition.

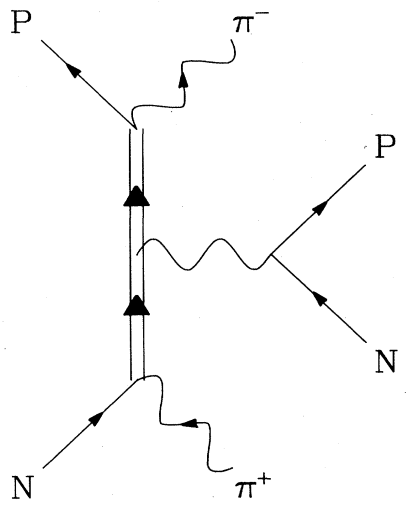

FIG. 1. Feynman diagram for DCX through direct Δ_{33}-nucleus interaction (DINT).

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The DINT process in Fig. 1 is calculated from $\pi+\rho$ exchange interactions. As in Ref. 6 it consists of five tensors M_ν which are contractions of the nucleon spins and the momenta of the mesons. Coefficients of the terms are specified in Ref. 6. Input parameters to the calculations include several coupling constants, e.g., $f_{\pi nn}$, which have been fixed at the values specified in Ref. 6. The π and ρ meson form factors are taken to be $v(k)=(1+k^2/\lambda^2)^{-1}$. Since there are no generally accepted values for λ_π and λ_ρ, we have investigated the effects of variations in these parameters for values near $\lambda_\pi=\lambda_\rho=6.07$ fm^{-1}.

Two of the tensors ($\nu=2$ and 6) lead to transition densities that are scalars in the pion initial and final momenta, $T_0(\hat{\mathbf{k}}',\hat{\mathbf{k}})$. Three ($\nu=4$, 5, and 7) lead to second-rank tensors in the pion momenta, $T_2(\hat{\mathbf{k}}',\hat{\mathbf{k}})$. DINT and DWF have the same tensor terms in k and k', but only DINT has the scalar terms. Since DINT is much larger than DWF, we conclude that the scalar terms dominate, and thus we do not evaluate the tensor pieces. This point, of course, requires further examination.

The most significant difference between the calculation presented here and that in Ref. 6 is in the nuclear structure. We use harmonic-oscillator wave functions coupled to $J=0$ and perform the Moshinsky transformation to relative and center-of-mass (c.m.) coordinates. We define an effective transition density as an integral of Fig. 1 over relative wave functions. This integral extends over the region $r\geq 0.5$ fm to account for short-range, repulsive nuclear correlations. We used the actual effective transition density for our calculations, i.e., we do not make here the reasonable approximation of Ref. 6 that the radial dependence of the effective transition density is proportional to the square of the valence neutron density.

Effective transition densities for ^{16}O$(\pi^+,\pi^-)^{16}$Ne(g.s.) are shown as solid curves in Fig. 2. As we have stated, the scalar transition density has contributions from tensors M_2 and M_6. We show separately the contributions to M_2 from nucleon pairs coupled to $S=L=0$ (the short-dashed curve) and to $S=L=1$ (the long/short-dashed curve). The chain/dot curve is the tensor term M_6 for which the nucleon pairs must be coupled to $S=L=1$. The inclusion of the ρ meson results in a change in the relative magnitude of each term, which depends on the input parameters for λ_π

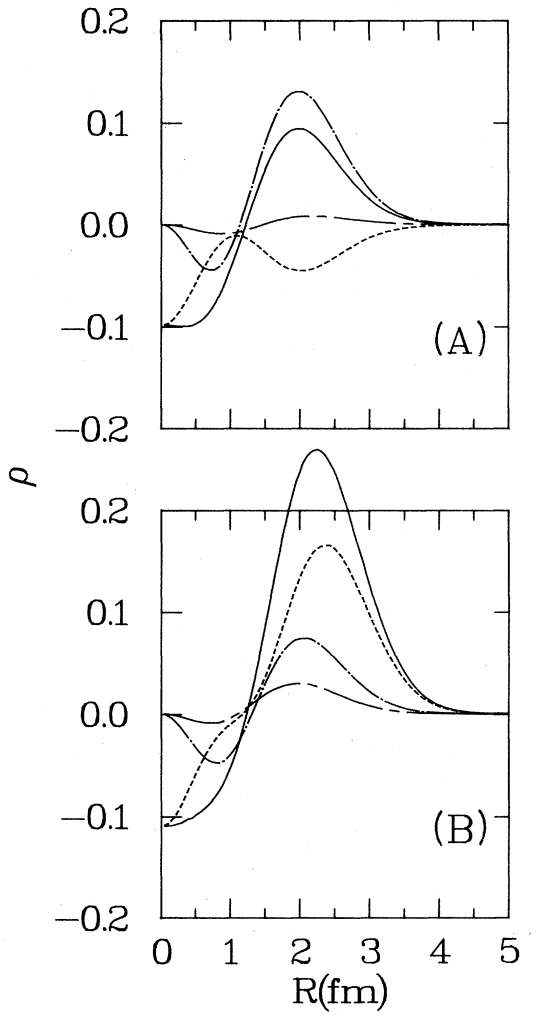

FIG. 2. Effective transition density ρ in arbitrary units for ^{16}O$(\pi^+,\pi^-)^{16}$Ne(g.s.) as a function of the distance R of the neutrons from the center of the nucleus. The assumed transition is $\nu(p_{1/2})^2\rightarrow\pi(d_{5/2})^2$. (A) is calculated assuming only virtual π exchange. (B) is calculated with virtual π and ρ exchange. The π- and ρ-meson form factors used are specified by $\lambda_\pi=\lambda_\rho=6.07$ fm^{-1}. The short-dashed curves denote the contributions to M_2 from nucleon pairs coupled to $S=L=0$ and the long/short-dashed curves for the $S=L=1$ pairs, whereas the chain/dot curves are for the M_6 contributions. The solid curve is the sum of all terms.

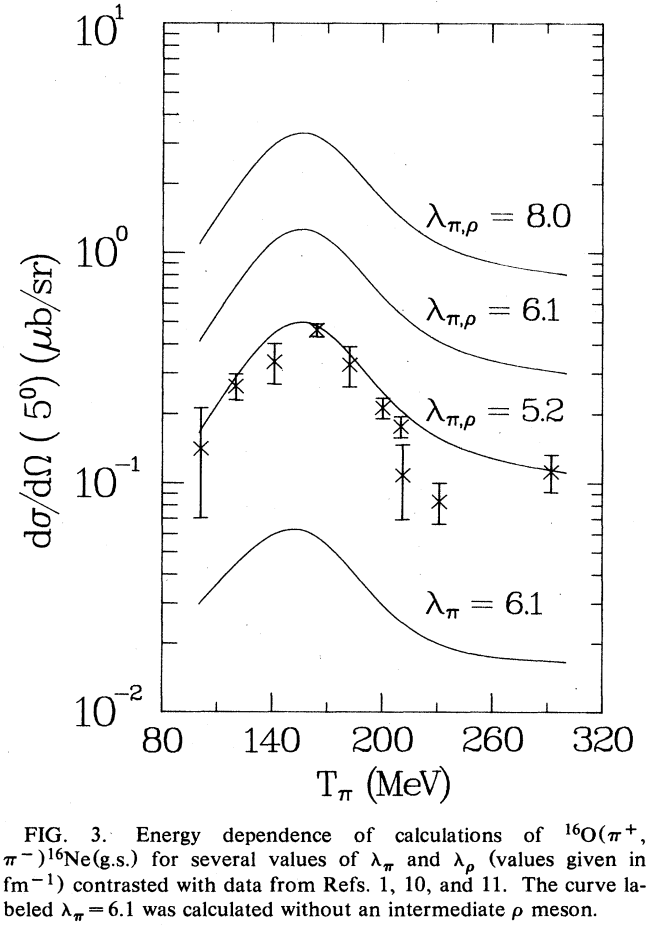

FIG. 3. Energy dependence of calculations of ^{16}O$(\pi^+,\pi^-)^{16}$Ne(g.s.) for several values of λ_π and λ_ρ (values given in fm^{-1}) contrasted with data from Refs. 1, 10, and 11. The curve labeled $\lambda_\pi=6.1$ was calculated without an intermediate ρ meson.

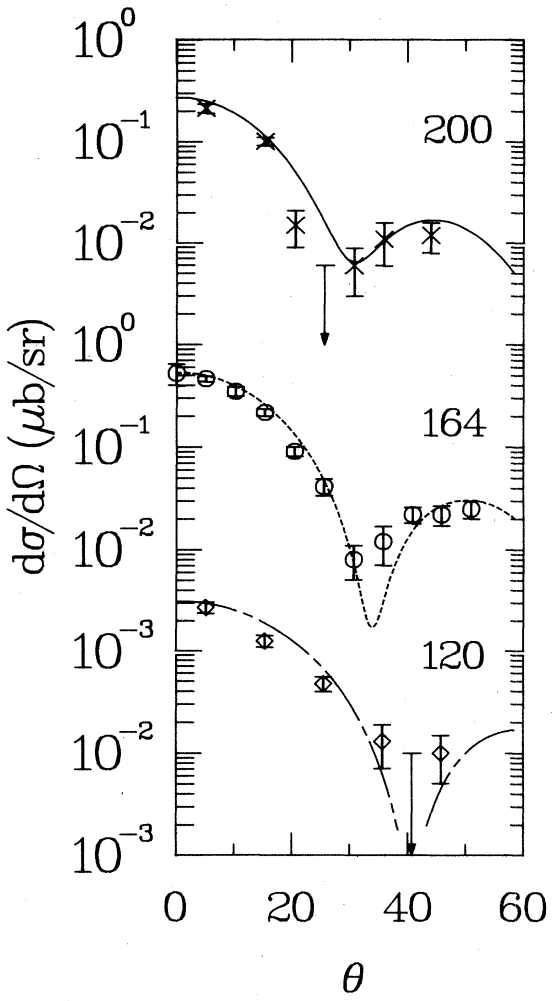

FIG. 4. Angular-distribution calculations of $^{16}O(\pi^+, -\pi^-)$ ^{16}Ne(g.s.) contrasted with angular distributions from Refs. 10 and 12, plotted against $\theta_{c.m.}$ in degrees. The calculations used $\lambda_\pi = \lambda_\rho = 5.2$ fm^{-1}. The incidence pion energy T_π (MeV) is denoted beside each curve.

and λ_ρ. This causes a shift in the position of the peak in the transition density.

In general we find that the calculations are insensitive to the shape of the transition density inside $R \sim 2.5$ fm. We also find (see Fig. 3) that the resulting excitation-function and angular-distribution shapes are insensitive to the parameters λ_π and λ_ρ. The energy dependence is dominated by the intermediate Δ_{33} propagators and the effects of distortions. The angular dependence reflects the nuclear size and the effects of distortions. We emphasize that for wide variations in λ_π and λ_ρ only the absolute magnitude of the calculations is changed. The sensitivity to λ_π and λ_ρ suggests the need for the explicit introduction of a model for the nucleon and Δ_{33} and its coupling to mesons.

Figures 3 and 4 compare calculations with the experimental data[1,11-13] for $^{16}O(\pi^+, \pi^-)^{16}Ne$(g.s.). The agreement in shape of both excitation function and angular distribution is excellent. All experimental nonanalog DCX angular distributions behave as $J_6^2(qR)$, where R is approximately the nuclear size.[1,11,13] That the theory with strong absorption should reproduce these results is not surprising. This is, however, the first calculation to correctly reproduce the energy dependence of nonanalog DCX.

Preliminary indications are that the excitation-function and angular-distribution shapes are also sensitive to the quantum numbers of the specified shell-model transition. Because these features are very similar to the data, we are encouraged to make additional calculations with more realistic nuclear wave functions for several nuclei. This extension will be necessary to compare with the observed $A^{-4/3}$ mass dependence of nonanalog DCX;[1,2] it will be interesting to see whether the same dynamical parameters found for ^{16}O will also produce this A dependence. Calculations are in progress.

In conclusion, calculations of nonanalog DCX through the Δ_{33}-nucleus interaction process reproduce the angular and energy dependence of the data. Both the absolute magnitude and the mass dependence of the calculations require additional investigation. We do, however, appear close to a quantitative explanation of nonanalog DCX.

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