Pion-nucleus charge-exchange reactions with isobar dynamics

Pervez Hoodbhoy,* Roger A. Freedman,† Gerald A. Miller, and Ernest M. Henley
Institute for Nuclear Theory and Department of Physics, University of Washington, Seattle, Washington 98195
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The angular distribution for elastic pion double charge exchange on ^{18}O at 164 MeV is studied. Delta motion and delta-nucleus charge exchange interactions are included and found to be important, but the cross section is not satisfactorily reproduced. Some of our results are consistent with the single datum point for the single charge exchange reaction on ^{18}O.

[NUCLEAR REACTIONS Elastic (π^+,π^-) and (π^+,π^0) cross sections calculated and compared with experiment: $E_\pi = 164$ MeV.]

The explanation of the $^{18}O(\pi^+,\pi^-)^{18}Ne$ double isobaric analog state (DIAS) angular distribution[1,2] at 164 MeV has presented theorists with several striking features: The first minimum occurs at an angle of 22°; that is smaller by about 18° than typical diffraction model estimates. Further, the large angle cross section is smaller than the 5° cross section by only a factor of about 3. Despite some hints from phenomenology[3–5] there is still no satisfactory microscopic treatment of the double charge exchange reaction.

The simplest reaction mechanism for double charge exchange, called the simple sequential model (SSM) in Ref. 6, is shown in Fig. 1(a). Here a π^+ changes a valence neutron into a proton (via a Δ intermediate state), becomes a π^0, and leaves the nucleus in the analog state of the target. The π^0 then changes another valence neutron into a proton. This process, computed in an approximation in which the motion of the deltas (Δ) through the nucleus is ignored, is moderately successful[6] at a pion energy of 292 MeV but fails (see Ref. 1) to explain the 164 MeV ^{18}O angular distribution.

There are several reasons why the SSM calculation described above should fail. Many processes are ignored and it is known from numerous studies of elastic scattering (e.g. Ref. 7) that both delta motion and delta-nuclear interactions are important at 164 MeV. In this paper we seek to improve charge exchange calculations by including these effects. To complement the usual Δ-nucleus interaction,[7] we include a "Lane potential" term which incorporates the effects of Δ charge exchange as shown in Fig. 1(b). In this way we account for many of the processes absent in the SSM. Another motivation for including this term is that the destructive interference of the two amplitudes of Fig. 1 could lead to a minimum at small angles. Despite this improved treatment and the inclusion of Fig. 1(b), we are unable to reproduce satisfactorily the troublesome angular distribution.

To perform our calculations we use the theory of Refs. 8 and 9. In that work an optical potential formalism was developed in which a Δ produced inside the nucleus propagates as a quantum mechanical particle with a finite lifetime. Effects of Pauli blocking and true meson absorption are included in that formalism by means of a Δ-nucleus interaction. Excellent fits to elastic scattering data for a variety of target nuclei were obtained. In addition, that work is readily extended to allow computations of elastic single and double charge exchange cross sections.

We begin by assuming, as in Ref. 8, that the delta moves in a potential of the form

$$\sum_\Delta(r) = V_0(r) + \vec{t}_\Delta \cdot \vec{T}_{A-1} V_1(r) \ . \tag{1}$$

Here $\vec{t}_\Delta$ and $\vec{T}_{A-1}$ are the isospin operators for the

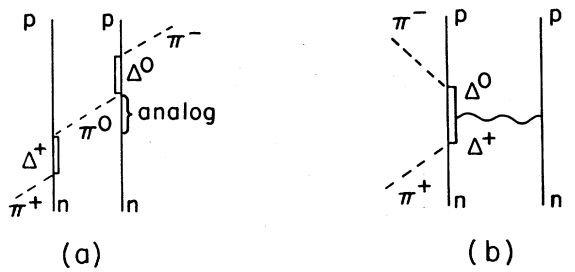

FIG. 1. Reaction mechanisms. Dashed lines are pions and solid lines are nucleons. (a) The simple sequential model. (b) The delta-nucleus charge exchange. The wiggly line indicates the delta-neutron charge exchange interaction.

Δ and residual nucleus. The radial dependence is given by

$$V_0(r)=(V+iW)\rho(r)/\rho(0) \quad (2)$$

and

$$V_1(r)=\frac{(V_1+iW_1)}{N-Z}\left[N\frac{\rho_N(r)}{\rho_N(0)}-Z\frac{\rho_P(r)}{\rho_P(0)}\right], \quad (3)$$

where $\rho_N(r)$ and $\rho_P(r)$ are the neutron and proton densities and

$$\rho(r)=\rho_N(r)+\rho_P(r)$$

is the total nucleon density. The isoscalar parameters V and W, but not the isovector ones, V_1 and W_1, are well determined by elastic scattering data.[8,9] The term $V_1(r)$ allows the process of Fig. 1(b) to occur.

The isospins of the incoming pion and the nucleus can be combined to yield a total isospin $\tau=T_A-1$, T_A, T_A+1 or for ^{18}O, $\tau=0,1,2$. Since the pion-nucleus system is an eigenstate of $\vec{\tau}^2$, it is convenient to work in the isospin representation. Thus, the optical potential of Refs. 8 and 9 must now not only be computed for several partial waves, but also for each of the three isospin values. The contribution of the core nucleons to the optical potential is given as in Eqs. (2.24)–(2.28) of Ref. 9, while the valence contributions are obtained by multiplying the corresponding terms of those equations by a factor:

$$(\tau(\tau+1)-T_A(T_A+1)-2)/2(N-Z)\,,$$

where T_A is the isospin of the target. To work in the isospin representation we replace the term $\vec{t}_\Delta\cdot\vec{T}_{A-1}$ of (1) by $\vec{t}_\pi\cdot\vec{T}_A$, where $\vec{t}_\pi$ is the pion isospin operator. This is merely an alternate representation of the Δ-nuclear interaction, and indeed

$$\vec{t}_\Delta\cdot\vec{T}_{A-1}\approx\vec{t}_\pi\cdot\vec{T}_A\,.$$

The calculation of the optical potentials for each isospin forms the bulk of the computations. From these potentials, the corresponding T matrices are obtained by solving the Lippman-Schwinger equation. A simple unitary transformation from the isospin representation to the usual channel representation gives the T matrix in the latter representation. These T-matrix elements allow the computation of the single and double charge exchange cross sections.

For the nuclear wave function, we use a simple shell model without core polarization. The core proton wave functions are chosen to be s and p shell Gaussian, with parameters chosen to match the experimental ^{18}O charge density.[10] The fit is very good. The sensitivity of the cross section to this wave function choice was not investigated, but is expected to be considerably less than to the valence nucleons. The core neutrons have wave functions identical to those of the protons.

It is known[11–13] that computed double charge exchange cross sections are very sensitive to the choice of valence neutron wave functions. For this reason we use three different forms. The first set is generated by placing the valence neutrons in a square well of radius R and with each neutron bound to the nucleus with the correct binding energy −5.92 MeV. The value of R is adjusted to give a difference between the rms neutron and proton radii of 0.11 fm. The second set has this difference set equal to 0.19 fm. These choices represent numbers within an acceptable range.[14] For the third set, we simply take the radial neutron wave function to be proportional to the square root of the total nucleon density of ^{18}O. The three sets are denoted by I, II, and III, respectively, in all figures.

RESULTS

Our procedure is to vary V_1 and W_1 for each of the wave-function sets, I–III, in order to obtain a fit. It is found that no choice of V_1 and W_1 yields a good description of the data. In Fig. 2 the calcula-

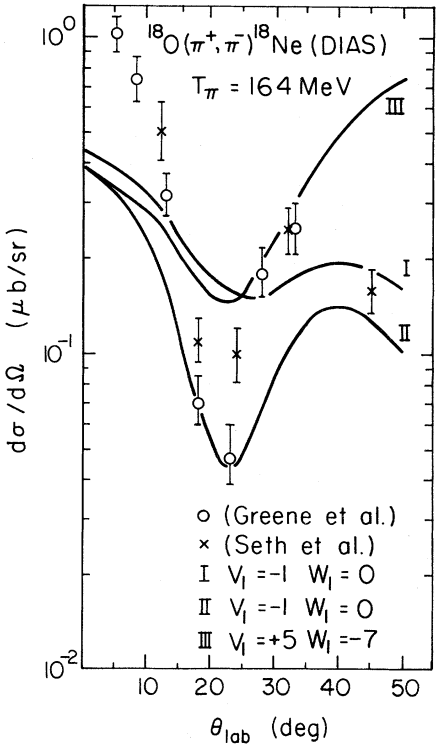

FIG. 2. Double charge exchange angular distributions. The curves labeled I, II, and III use wave functions I, II, and III (see text).

tion closest to the data for each wave function is shown. While V_1 and W_1 can be adjusted so that the minimum is at the correct position, the forward cross section and second maximum are described poorly. In performing these calculations we also determine that the double charge exchange results are not at all sensitive to small variations in V and W about their values as determined in Refs. 8 and 9 from elastic scattering.

By comparing the curves labeled I and II (Fig. 2), which use the same values of V_1 and W_1, one can observe the great sensitivity to the valence neutron wave function.

The effects of including the motion of the Δ are studied in Fig. 3. The dashed curve shows results for a fixed scatterer approximation obtained by replacing the Δ-nucleus Green's function by an isospin-independent Breit-Wigner function. The solid curve gives the corresponding calculation with Δ motion properly included [with $V_1=W_1=0$ and $V=-55$ MeV, $W=-5$ MeV (Refs. 8 and 9)]. There are large differences between the curves, so that a detailed treatment of delta dynamics is a necessary ingredient in performing double-charge exchange calculations.

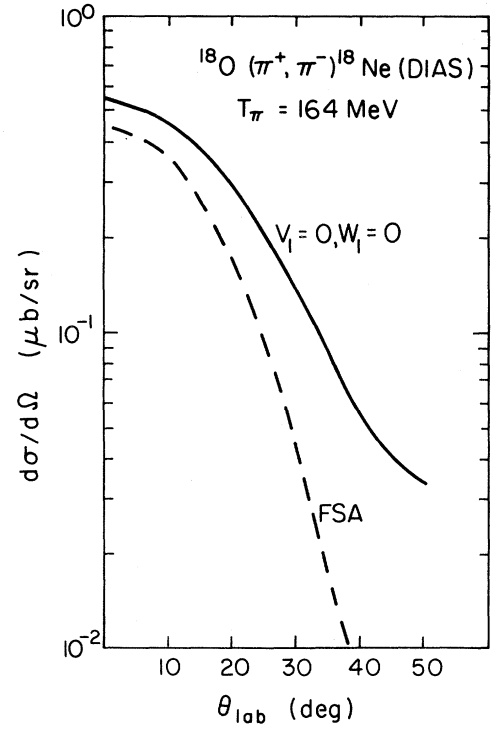

FIG. 3. Double charge exchange angular distributions. The solid curve indicates the inclusion of Δ motion. The dashed curve indicates the fixed scatterer approximation. Wave function III is used.

The importance of including Δ-nucleus charge exchange is indicated in Fig. 4 which shows results for many values of the set (V_1, W_1). By changing from (0,0) to (0, −2) MeV, for example, one can drastically alter the computed angular distribution. Despite this extreme sensitivity, no choice gives a good description of the data. (A reasonable, but not exhaustive search was made.) By comparing with the charge exchange, or Lane term for the nucleon-nucleus interaction of strength $(110/A)$ MeV, we can see that all of the values used in Fig. 4 are reasonable choices.

In contrast with the double charge exchange calculations, some of the single charge exchange results are in good agreement with the solitary data point[15] at 5°. Figure 5 displays results corresponding to the curves labeled I, II, and III of Fig. 2. Despite the disparity between curve I (or II) and III, one cannot conclude that a nonzero value of the difference between the rms neutron and proton radii is necessary to understand the single charge exchange process. This is because of the sensitivity to V_1 and W_1. There are values of these parameters for which the

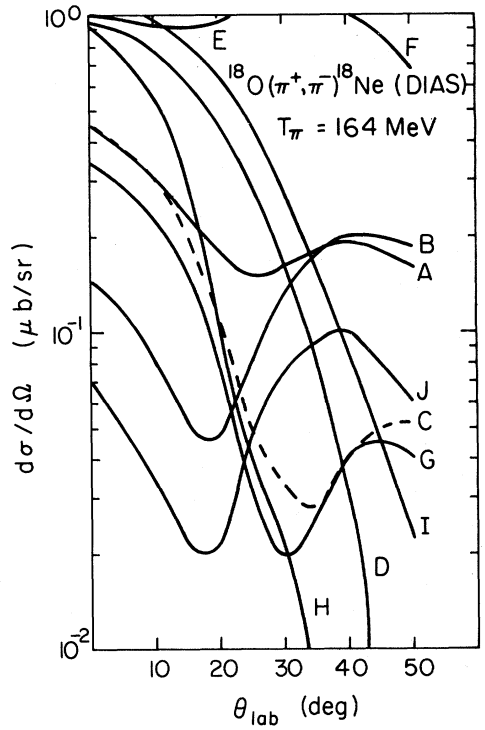

FIG. 4. Double charge exchange angular distributions. Wave function I is used. The curves labeled A–I represent different sets of (V_1, W_1) as follows: $A=(-1,0)$; $B=(-1,-1)$; $C=(0,0)$; $D=(1,1)$; $E=(-3,0)$; $F=(-2,2)$; $G=(1,-1)$; $H=(1,0)$; $I=(-2,1)$; $J=(0,-2)$. The units of V_1 and W_1 are MeV.

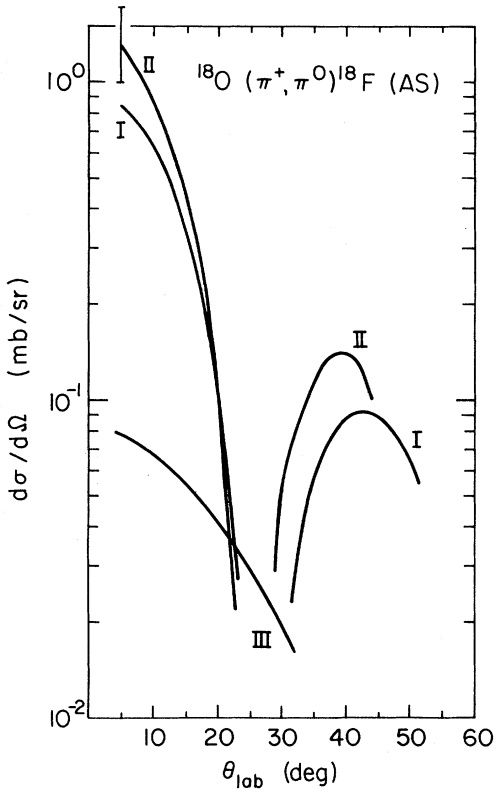

FIG. 5. Single charge exchange reactions curves labeled I, II, and III correspond to the calculations of Fig. 2.

single charge exchange results of I and II are poor but those of III are good. Perhaps a study of a series of nuclei could resolve the parameter ambiguities.

DISCUSSION

The failure of our dynamical isobar model for double charge exchange in explaining the $^{18}O(\pi^+,\pi^-)^{18}Ne$ (DIAS) angular distribution leads to a number of rather interesting conclusions.

The most important inference to be drawn is that the double charge exchange reaction mechanism is not simply that shown in Figs. 1(a) and (b), but must include other effects such as short range correlations,[12] spin-flip terms, core polarization,[5] deltas in the nuclear wave function,[16] etc. Without a detailed calculation the relative importance of such terms cannot be accurately judged. Thus the double charge exchange reaction mechanism continues to remain an enigma.

While a successful microscopic explanation is still to be achieved, the present calculation serves to emphasize some necessary ingredients for such an explanation. First, inclusion of recoil has a crucial effect on the computed angular distribution. Second, charge exchange of the propagating delta also has a very large effect. Lastly, it appears that the high sensitivity to details of the valence neutron wave functions mandates that these wave functions be well determined by some other probe or mechanism before one can claim to understand the double charge exchange mechanism.

The single charge exchange reaction is somewhat easier to understand. However, there are parameter ambiguities. One can describe the data by a variety of sets of (V_1, W_1) and valence neutron wave functions.

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*On leave from the Department of Physics, Quaid-e-Azam University, Islamabad, Pakistan.

†Present address: The Quantum Institute, University of California, Santa Barbara, CA 93106.

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