A Theory of Low-Energy Pion Double Charge Exchange

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We propose a theory of sequential charge exchange that describes, for the first time, the general features of the excitation function and the angular distributions of charge exchange on a ^{14}C target to the isobaric and double isobaric analog states for pion kinetic energies up to 80 MeV. Our theory consists of conventional coupled-channel scattering through important low-lying states. We conclude that exotic contributions to the double charge exchange process must make a relatively small contribution (less than a factor of 2), effectively ruling out a prominent role for dibaryon resonances recently suggested as an explanation for the data.

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It has been long recognized that sequential scattering, a two-nucleon process in which a pion first undergoes a charge exchange scattering from one nucleon, propagates with the resulting nucleus in its ground or excited states, and then undergoes another charge exchange scattering from a second nucleon, is an important contribution to pion double charge exchange (DCX); see, e.g., Refs. [1,2]. Over the years, more exotic processes involving two nucleons, including short-range correlations and heavy mesons, exchange currents, the delta-nucleon interaction, absorption, and quarks, have been shown to make contributions (see, for example, Ref. [3] and references contained therein). One has hoped that DCX would provide a unique opportunity to study these aspects of hadron dynamics, which have been difficult to identify in more traditional experiments because they are masked by large scattering from single nucleons.

All the available measurements of DCX excitation functions to either the double isobaric analog state (DIAS) or the ground state of the residual nucleus feature a peak in the region $T_\pi = 30$–50 MeV. The apparent failure of conventional theory to explain this low-energy behavior has prompted recent speculation that a dibaryon resonance may be the cause of the observed peak [4] and has renewed interest in hadron dynamics.

The difficulty of identifying exotic mechanisms stems in part from their competition with the sequential scattering background. Calculations of this background, while straightforward in principle, are quite involved in practice, as they touch upon a large number of issues. These include, in addition to details of nuclear structure and conventional multiple scattering, the fact that the nuclear medium has a large and generally poorly understood influence on the dynamics. To facilitate further progress in identifying the contribution from exotic processes, a more powerful and systematic approach to sequential scattering has become necessary. Motivated by this realization, we recently proposed [5] a coupled-channel theory in configuration space, as described below. Our model simultaneously addresses elastic, inelastic, single, and double charge exchange scattering, thus providing the capability of a check of consistency with data at intermediate stages of calculation. All the necessary features of the theory have been incorporated in the computer program $\mu\pi$ (MICROPI) [5].

Because we are using coupled channels, we are able to avoid the closure approximation, which is a feature of most of the recent attempts to explain the low-energy data [6–11] but which is of questionable applicability where the pion kinetic energies are becoming comparable to the nuclear excitation energies. Our model naturally includes the excitation energies; threshold energy effects; distorted waves on initial, intermediate, and final states; medium effects on transition operators; and isospin breaking effects such as the Coulomb interaction, differences in the shapes of neutron and proton densities, and pion mass differences. Some, but not all of these have been included in previous work.

In the present work we use this theory to calculate the sequential-scattering contribution to the low-energy excitation function for the reaction $^{14}\mathrm{C}(\pi^+,\pi^-)^{14}\mathrm{O}$ (DIAS). The choice of reaction and energy range were motivated by the following considerations: (a) Extensive elastic scattering data sets exist, and these have been fit to the low-energy optical potentials [12–14] that we use in our calculation, as explained in Ref. [5]. (b) Data are available for the DIAS [8], as well as for the intermediate isobaric analog state (IAS) in ^{14}N reached via $^{14}\mathrm{C}(\pi^+,\pi^0)^{14}\mathrm{N}$ (IAS) [15,16] at energies below 80 MeV. And (c) intermediate "nonanalog" states that contribute to the DIAS cross section in addition to the IAS [17] will be measured in forthcoming experiments on the high-resolution neutral meson spectrometer [18] at the Los Alamos Meson Physics Facility.

Our theory enables us to calculate the contribution of the intermediate steps using a microscopic transition density $\delta\rho$ built by summing particle-hole density matrix elements obtained from shell-model calculations. It also

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includes an exact treatment of spin flip in the interaction, as well as the contributions due to the Fermi motion of the nucleons in the nucleus in the lowest-order interaction. Both of these improvements have been demonstrated [5] to be important for describing DCX particularly at low energy. The nuclear orbital wave functions are obtained from Hartree-Fock calculations using the Skyrme III interaction [19]. To the microscopic lowest-order potential, whose strengths are related to the free pion-nucleon phase shifts [20] in the usual manner, we have added phenomenological medium modifications [13] that provide excellent descriptions of elastic scattering data [14]. In the spin-independent part of the transition potential, we include a medium modification of the form $\lambda_1^{(2)}\rho\delta\rho/\rho_0$, where the coefficient $\lambda_1^{(2)}$ has been shown [12] to be well described at 50 MeV in terms of Pauli blocking, the Lorentz-Lorenz effect, and the ρ meson exchange. We confirm this description below for all energies up to 80 MeV. However, we include no medium modifications on the spin-dependent components of the optical potential. Although theoretical models of these can be constructed, we adopt a conservative approach in the absence of data necessary to confirm the choice of a particular one.

Let us now turn to the discussion of the results of our calculations. The particle-hole densities used for ^{14}C, ^{14}N, and ^{14}O were obtained from the program OXBASH using the Cohen-Kurath interaction [21]. In the corresponding model space, ten states are available as intermediate states of ^{14}N after the first single charge exchange (SCX) scattering $^{14}\mathrm{C}(\pi^+,\pi^0)^{14}\mathrm{N}$ has occurred. Four of the intermediate transitions have SCX cross sections of comparable strength, and roughly 1 order of magnitude larger than the remaining six. Thus, we show calculations including only the four most important intermediate states, which have quantum numbers (J^π,T) and calculated excitation energies relative to the IAS as follows: $(0^+,1)$ IAS, $(1^+,0)$ E_x = 0.927 MeV, $(2^+,0)$ E_x = 4.302 MeV, and $(2^+,1)$ E_x = 6.842 MeV. The cross section calculated for the DIAS including all ten intermediate states is essentially identical to that including only the four most important ones.

All the available measurements of angular distributions for the IAS up to T_π = 100 MeV, with the corresponding calculations, are shown in Fig. 1. We have determined $\lambda_1^{(2)}$ by adjusting it to obtain the agreement shown there. The empirical values of $\lambda_1^{(2)}$, and the corresponding values calculated using the theory of Ref. [12], are shown in Table I for each energy. To obtain it at other energies, we have interpolated on these numbers. Although the data cannot be described without $\lambda_1^{(2)}$, the differences between the theoretical and empirical values seen in the table are not significant given the limited data set. Since data are not yet available for states other than the IAS, the same values of $\lambda_1^{(2)}$ are used for all transitions at a given energy, except for the state (J^π,T) = $(1^+,0)$. No isovector medium correction has been added for this state

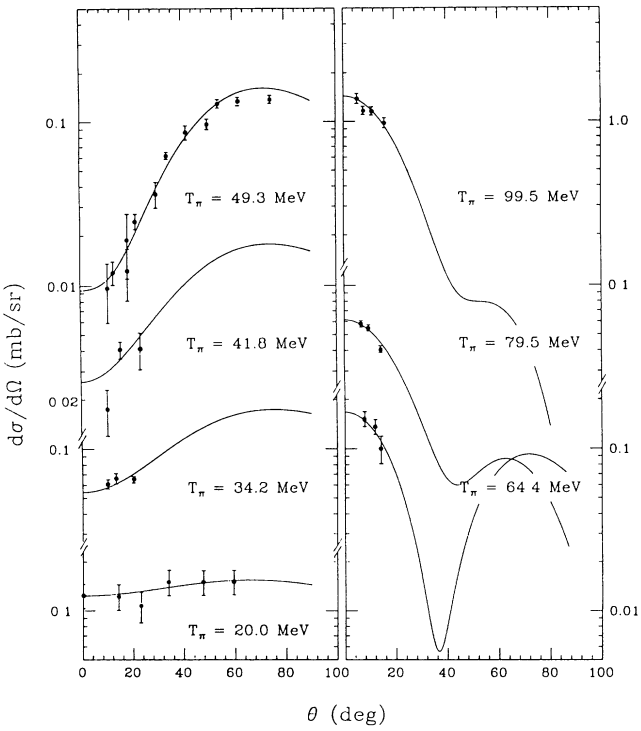

FIG. 1. IAS angular distributions with data from Refs. [15,16]. The lines are corresponding calculations as discussed in the text.

for reasons discussed above. The excitation functions for the DIAS and the contributing SCX states, and angular distributions at T_π = 50 MeV, are shown in Figs. 2 and 3.

Our success in reproducing the features of the DIAS excitation function can be attributed to an intricate interplay among essentially all the ingredients of our calculation. Their influence on the cross section is magnified by a strong interference between double spin flip and non-spin-flip DCX amplitudes. (In our final result, double spin flip reduces the non-spin-flip part of the cross section by about a factor of 2 at 20 MeV, and by a factor of 10 at 80 MeV.) Generally, the correct (convex) shape of the excitation function is the result of the rescattering of

TABLE I. Energy dependence of the parameter $\lambda_1^{(2)}$. Theoretial values are shown in parentheses.

T_π (MeV)	Re($\lambda_1^{(2)}$)	Im($\lambda_1^{(2)}$)
20.0	-8.0 (-5.6)	-1.0 (-0.6)
34.2	-6.5 (-6.5)	-1.0 (-1.7)
41.8	-6.5 (-6.8)	-1.5 (-2.5)
49.3	-6.5 (-7.1)	-1.9 (-3.2)
64.4	-6.0 (-7.3)	-5.5 (-5.2)
79.5	-3.0 (-7.1)	-4.5 (-7.8)
99.5	1.0	0.0

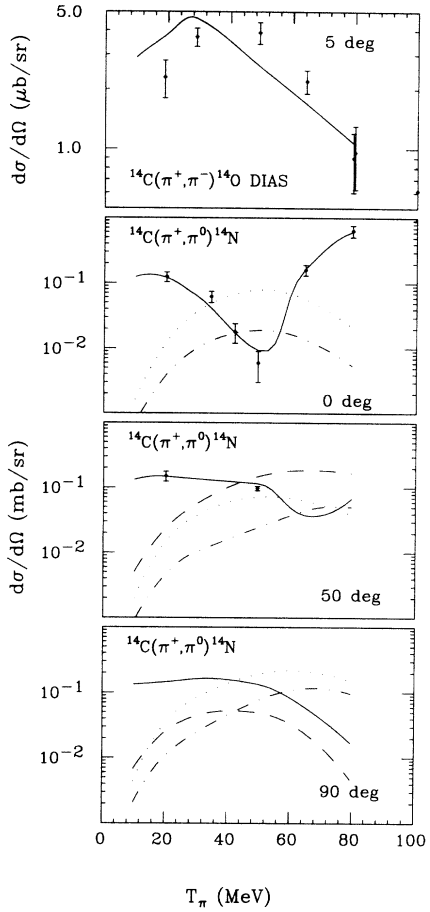

FIG. 2. Calculated excitation functions for the DIAS at 5° (top) with data from Ref. [8], and for the SCX states (bottom), as discussed in the text, at three angles. The solid, dashed, chained, and dotted lines represent the states $(J^\pi, T) = (0^+,1)$, $(1^+,0)$, $(2^+,0)$, and $(2^+,1)$. The second SCX state vanishes at zero degrees.

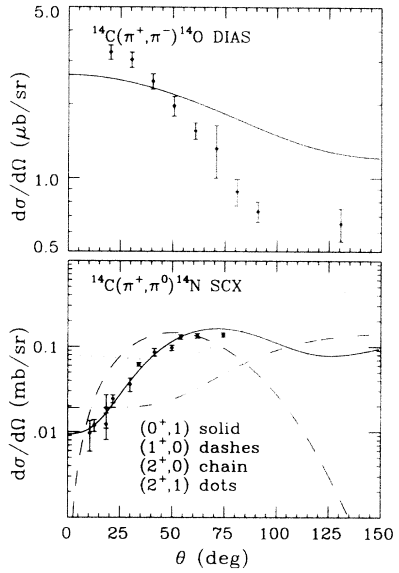

FIG. 3. Calculated angular distributions at $T_\pi = 50$ MeV for the DIAS (top) with data from Ref. [8], and the SCX states (bottom).

the $\pi^\pm$ by the nucleus before and after the double charge exchange has occurred (external distortions). We found the replacement of harmonic oscillator by Hartree-Fock wave functions to be a relatively small effect. However, the rescattering of the intermediate π^0 (internal distortions), medium corrections to the SCX transition operator, and the corrections to closure can amount individually to factors of 2. We believe that the theoretical error on sequential is comparable to the uncertainty arising from medium corrections to the intermediate nonanalog state transitions, and therefore also a factor of 2.

Our predictions for SCX angular distributions and excitation functions to the excited states in ^{14}N provide a stringent test of our model. The test is furthermore practically realizable, since a SCX experiment for the reaction $^{14}C(\pi^+,\pi^0)^{14}N$ is scheduled to run at Los Alamos next summer [22] using the new high-resolution neutral meson spectrometer [18], at precisely the energy range of interest. Once our theory of sequential DCX is confirmed, it should make the study of exotic medium effects in DCX possible at a higher level of quantitative certainty than before.

In summary, we have presented a comprehensive theory of sequential pion double charge exchange. In this theory, the dynamics of the DCX process is entirely determined by theoretical considerations, elastic, and single charge exchange data. The application presented here points to a conventional explanation of low-energy DCX on ^{14}C, leaving little room for exotic mechanisms such as dibaryon resonances.

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