Sequential contribution to nonanalog pion double charge exchange in the Δ_{33} resonance region

R. Gilman
Rutgers University, Piscataway, New Jersey 08855
and Continuous Electron Beam Accelerator Facility, Newport News, Virginia 23606

H. T. Fortune
University of Pennsylvania, Philadelphia, Pennsylvania 19104

M. Kagarlis*
University of Pennsylvania, Philadelphia, Pennsylvania 19104
and Los Alamos National Laboratory, Los Alamos, New Mexico 87545
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In double charge exchange leading to residual nonanalog 0^+ ground states, we examine the relative contribution of sequential charge exchange and delta-nucleon charge exchange. We conclude that the data cannot be quantitatively understood in terms of these two reaction mechanisms.

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I. INTRODUCTION

In principle, pion double charge exchange (DCX) should yield much interesting two-nucleon physics which is otherwise inaccessible. However, extracting clear signals of the underlying physics from the measured data has proven to be difficult, due to difficulties in understanding the reaction mechanism. Recently, we have proposed [1,2] that DCX to residual nonanalog 0^+ ground states is of interest because it results directly from the ΔN charge-exchange interaction, hereafter called DINT [see Fig. 1(a)]. If this view is correct, the data (Refs. [3,4], and references therein) provide clear constraints on the ΔN interaction. This information is otherwise difficult to obtain.

One problem with this view concerns the contribution of sequential charge exchange (SEQ) to the nonanalog residual states. In this paper, we examine the SEQ and DINT contributions to nonanalog DCX, and the state of our understanding of the population of residual 0^+ ground states.

II. HISTORY

The simplest DCX mechanism involves two successive single charge-exchange (SCX) interactions [Fig. 1(b)]. By analogy to the dominance of elastic scattering at forward angles, SEQ cross sections are expected to be largest for the double analog of the target ground state, as it has identical space and spin structure as (and thus a large overlap with) the target.

The earliest measurements [5–7] demonstrated that this expectation was not realized. For targets of ^{16}O and ^{18}O, at an incident energy of 140 MeV, the ratio of (π^+,π^-) ground-state cross sections $\sigma(^{16}\mathrm{O})/\sigma(^{18}\mathrm{O})$ was about 0.5, rather than close to zero, as naively expected.

Calculations by Lee, Kurath, and Zeidman [8], and subsequently by Oset, Strottman, and Brown [9], demonstrated that the use of realistic wave functions for the nuclei could provide ratios as large as 0.5. Calculations by Karapiperis [10] and by us have yielded similar ratios. We also confirmed [11] the relative greater importance of diagonal vs orbit changing transitions in SEQ calculations. There has been no subsequent improvement in our understanding of the relative contribution of SEQ to nonanalog transitions.

The large amount of data that have now been obtained is inconsistent with the idea of SEQ dominance of both

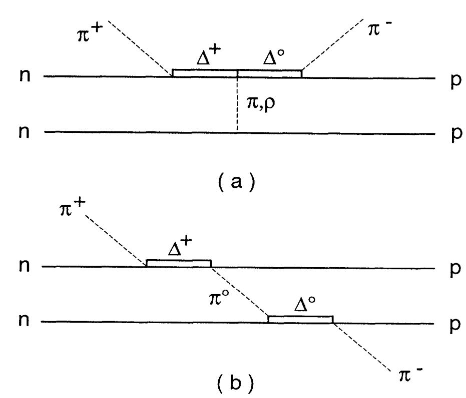

FIG. 1. Two mechanisms for pion double charge exchange: (a) delta-nucleon interaction (DINT) and (b) sequential single charge exchange (SEQ).

*Present address: Niels Bohr Institute, Copenhagen, Denmark.

analog and nonanalog transitions. Nonanalog data, however, do suggest dominance of a single process. On a variety of light nuclei, all nonanalog angular distributions [3,4,12] appear simply diffractive (in contrast to the apparent interference observed [13] for analog states). Excitation functions [3] for nonanalog transitions peak near $T_\pi = 160$ MeV, in contrast to the increase of cross sections with energy observed for the analog transitions. The former suggests a Δ-dominated interaction, while the latter is qualitatively in agreement with the k^2 energy dependence expected for SEQ in a geometric model (k is incident pion momentum). These data, and their simple characteristics, provided the main motivation for developing the DINT model [1,2,14]. However, as we shall see, realistic calculations predict large SEQ contributions to these transitions.

III. DATA AND CALCULATIONS

In Fig. 2, we plot cross sections vs T_π for three light $T = 0$ targets, ^{12}C, ^{16}O, ^{24}Mg, and one $T = 1$ target, ^{18}O. These are the only $T = 0$ targets for which data have been measured at 292 MeV. For each target we exhibit two SEQ calculations. The solid curves use transition densities derived from realistic wave functions [2], but keeping only the $j_{\rm pair} = 0$ components of the transitions. This procedure for ^{18}O results in cross sections larger than the data, and a ratio $\sigma(^{16}\mathrm{O})/\sigma(^{18}\mathrm{O})$ of about 0.5—as noted above. The dashed curves use an identical reaction mechanism, but are further restricted to include only the diagonal (i.e., orbit nonchanging) $j_{\rm pair} = 0$ components of the transition densities.

The dashed curves are closer to the data for both ^{16}O and ^{18}O, but neither calculation is able to predict the different energy dependence observed experimentally. The solid and dashed curves essentially provide upper and lower limits to the SEQ cross sections. The main point of the SEQ calculations is that the SEQ mechanism alone does not describe the nonanalog data.

At the higher energies, where SEQ is believed to be a satisfactory reaction model for analog transitions [15], comparison with ^{18}O data confirms that our reaction mechanism model is satisfactory to within a factor of about 2. (A comparison of the results of different calculational models of DCX leads to the conclusion that theoretical uncertainties are of this order.) Nonanalog SEQ predictions are more uncertain because of the larger contributions from nondiagonal transitions. However, the energy dependence is totally wrong. Experimental ratios of cross sections at 290 and 160 MeV are $\sigma(290\,\mathrm{MeV})/\sigma(160\,\mathrm{MeV}) = 0.10 \pm 0.05$, 0.47 ± 0.12, and 0.04 ± 0.02 for ^{12}C, ^{16}O, and ^{24}Mg, respectively. The calculated SEQ ratios are 1.6, 1.8, and 2.2 for these three nuclei—effectively ruling out any SEQ-only model.

The absolute magnitudes provide a further test. At the higher energies, the SEQ calculations overestimate the data by factors of approximately 16, 1.3, and 40 for ^{12}C, ^{16}O, and ^{24}Mg, respectively. And yet, our ^{18}O calculations are roughly consistent with the data at the higher energies, and with the calculations of others. We are thus faced with a dilemma: How can the SEQ calculations be approximately correct for analog transitions and so wrong for nonanalog? How can the nonanalog data be so much smaller than realistic SEQ predictions? We suggest the interesting possibility that SEQ really is larger than the data and interferes destructively with some other mechanism.

We remark at this point on some results from other π induced reactions. Cross sections for excitation of the isobaric analog state in a single charge exchange are larger than expected, indicating an isovector enhancement to

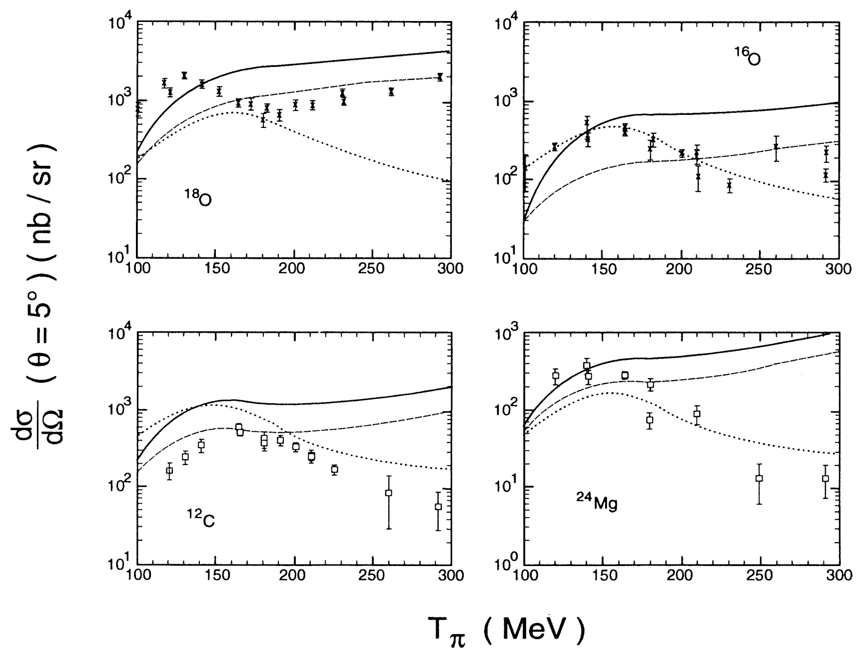

FIG. 2. Pion double charge-exchange g.s. → g.s. cross sections (at 5°) vs T_π for one $T = 1$ and three $T = 0$ nuclei. Solid and dashed curves are $j_{\rm pair} = 0$ SEQ calculations, full and orbit nonchanging, respectively. Dotted curves are DINT calculations.

the πn interaction. Similar results have been obtained from inelastic scattering as well as in various theoretical calculations. This effect has not been included in our SEQ calculations, and would act to increase the results by a factor larger than, but of order, unity. The most strongly populated state in a single charge exchange is probably the giant dipole resonance. This cannot be included in our calculations, but its effects can be studied in coupled channels calculations for analog residual states. This is very difficult for nonanalog DCX, since there may be no experimental way to determine the couplings between the intermediate dipole state and the residual ground state.

Our explanation [1,2,4] of the nonanalog data in terms of a ΔN charge-exchange interaction [14] (DINT) has been described previously. (These are the dotted curves in Fig. 2.) We emphasize that certain features of those calculations are independent of the details of the model. The energy dependence arises from the interplay of two Δ propagators moderated by external distortions. The angular dependence is primarily determined by the nuclear size. (Angular distribution predictions are nearly identical for DINT and SEQ.)

Dependence on target mass results from nuclear size and wave functions [2]. The effect on the predictions of variations in some poorly determined input parameters—such as the π and ρ form factors—is largely to increase or decrease all calculations by a constant factor [1]. Within a factor of about 2, the DINT calculations [1,2,4] reproduce the overall magnitude and energy dependence of the data. Even though the factor of 2 is unsatisfying, we note that no other theoretical model has managed to reproduce the energy or mass dependence of nonanalog DCX.

We now examine whether we can better understand nonanalog DCX as a sum of SEQ and DINT amplitudes. Within our model, the relative phases and amplitudes are fixed; and the results of the calculations are displayed in Fig. 3. For all these, we restrict the calculations to $j_{\text{pair}} = 0$ only.

The solid curves in Fig. 3 result from DINT + SEQ calculations; for the dashed curves the SEQ amplitude contains only diagonal (orbit-nonchanging) terms. Comparison of Figs. 2 and 3 illustrates that the relative phase between SEQ and DINT amplitudes is near 90° at all energies. Hence, the addition of SEQ and DINT simply makes the theoretical cross sections even larger—and further from the data.

Even though it is unrealistic, we also show in Fig. 3 the calculations that result if we arbitrarily set the SEQ-DINT relative phase to 180°. (We emphasize that this cannot be the correct phase if the dominant amplitudes are SEQ and DINT. Their relative phase is set by the calculations and is about 90°.) We note that destructive interference *can* produce a wide range of behaviors. However, even with total destructive interference, the data cannot be fitted by SEQ and DINT alone. Another, as yet undetermined, amplitude appears to be present. If it interferes destructively with ordinary SEQ, agreement with the data may be possible.

There is one alternative to the speculation of an additional amplitude. It is possible that our model for calculation of the SEQ amplitude is reliable only for analog transitions, where the off-diagonal matrix elements are small and diagonal matrix elements dominate the calculation of the cross section. For the nonanalog data discussed here, the off-diagonal components are large. If these off-diagonal components interfere destructively with the diagonal components (in our calculations for ground states, the interference is constructive), then the

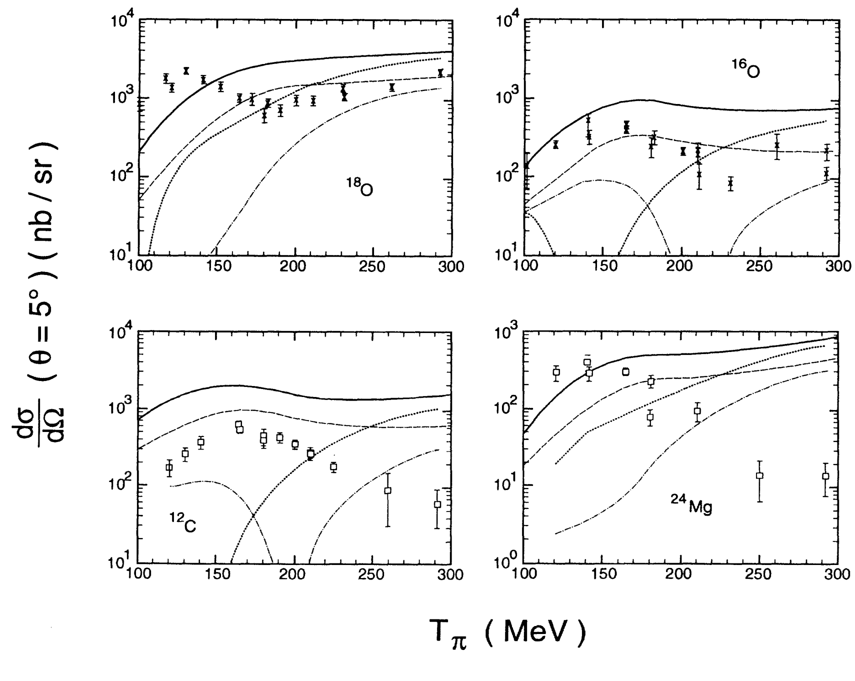

FIG. 3. Data are the same as Fig. 2. Solid and dashed curves result from calculations combining DINT and SEQ contributions from Fig. 2. Dotted and dot-dashed use the same amplitude, but with the DINT-SEQ phase arbitrarily set to 180°.

magnitudes of the nonanalog SEQ calculations presented here are extremely sensitive to the choice of wave function and represent overestimates of the real SEQ magnitude. In this case, our earlier conclusions about the dominance of the DINT mechanism at the Δ resonance may be unaffected.

Our conclusion is that nonanalog DCX is probably more complicated than we had supposed. We speculate that an important contribution to the cross section remains to be identified. At present, we can only speculate about the missing amplitude. An excellent candidate that we are currently investigating is the double spin-flip contribution to the SEQ process, which is not included in the present calculations. Experimentally, it would be beneficial to have a series of excitation functions in the energy range 200–260 MeV, on a set of carefully chosen nuclei. This should enable us to tune the magnitude of the other amplitude, and hence the interference. Of course, these measurements would need somewhat better statistics than most of the 200–260 MeV results quoted herein.

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