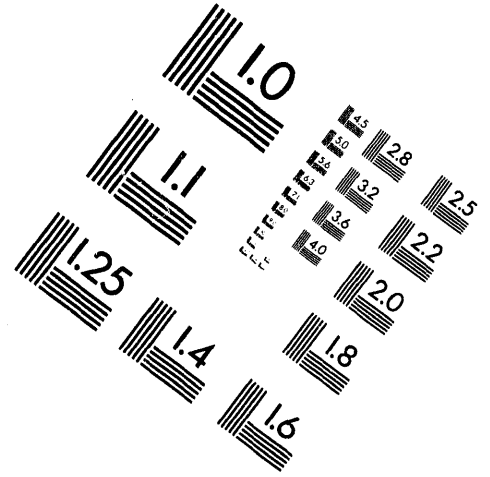
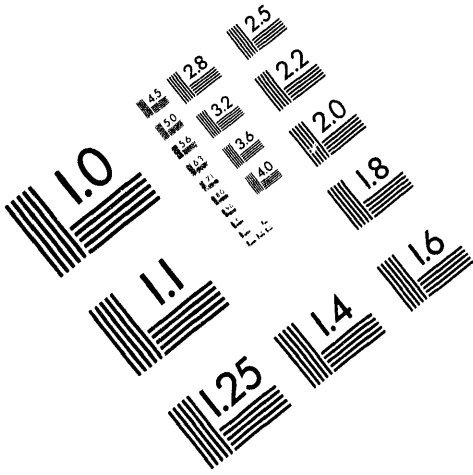




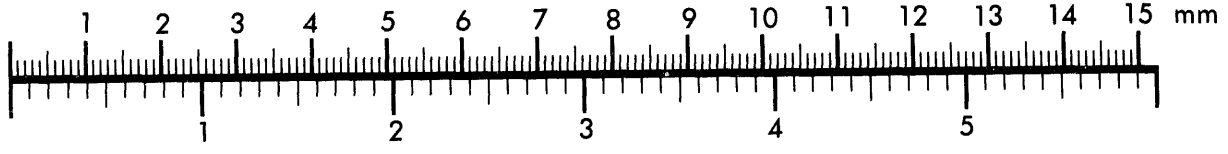
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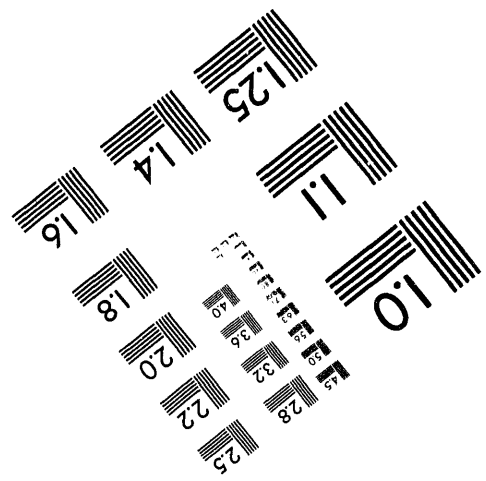
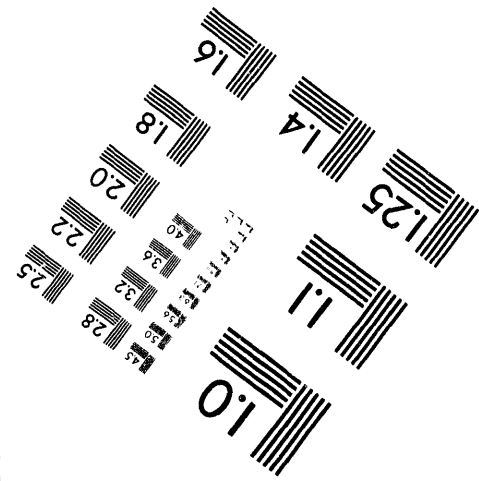
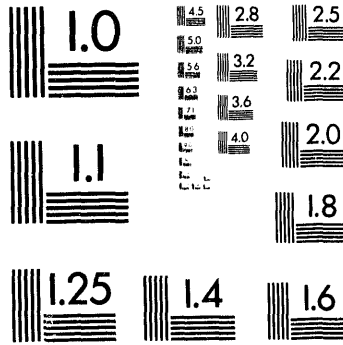
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# THEORY OF PION SINGLE AND DOUBLE CHARGE EXCHANGE

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## ABSTRACT

Pion single and double charge exchange are being understood as an interplay between nuclear structure, hadron dynamics, and multiple scattering. Examples are given from work carried out in the last few years, and prospects for future development is given.

I have been asked to review the theory of pion single charge exchange (SCX) and double charge exchange (DCX). As for all reactions on nuclear targets, the outcome of a charge exchange experiment with pions depends upon the interplay among hadron dynamics, nuclear structure, and multiple scattering. Theory must of course take these considerations into account in interpreting the data to test models. Exactly how this interplay occurs and what one can learn from the current status of it forms the focus of this talk.

The reactions of pions are unique in nuclear physics. The pion is the only probe we currently have for which (1) DCX is possible, and (2) the structure of the probe plays no role in the reaction. Point (1) means that the reaction requires at least two interactions of the pion with the nucleus, so that in leading order the reaction carries information about two-nucleon processes in the target nucleus. Point (2) is important, because it means that the structure of the pion probe plays no complicating role in interpreting the reaction, in contrast to the situation with other nuclear probes.

I won't have much time to discuss SCX. As you may know, there is just recently developed at LAMPF a neutral meson spectrometer (NMS) capable of resolution of about 0.5 MeV. A rather exciting program of measurements has been proposed for it. This includes both nuclear structure as well as reaction dynamics. I will highlight aspects of it that are closely related to DCX.

Under many circumstances, the most likely process of DCX is the double-scattering process indicated in Fig. 1a. Viewed in this way, DCX is simply two SCX scatterings, often called sequential (SEQ) DCX. A nucleon that undergoes charge exchange may be scattered out of the nucleus, as in continuum DCX, or may stay behind inside the nucleus, as in DCX to discrete states. Both types of measurements have been carried out, but I will focus on the latter here. June Matthews and Anna Krutenkova will discuss continuum DCX in the parallel session.

Is this all there is to DCX? The answer is of course no, and a number of the processes that have been studied theoretically is shown in the remainder of the

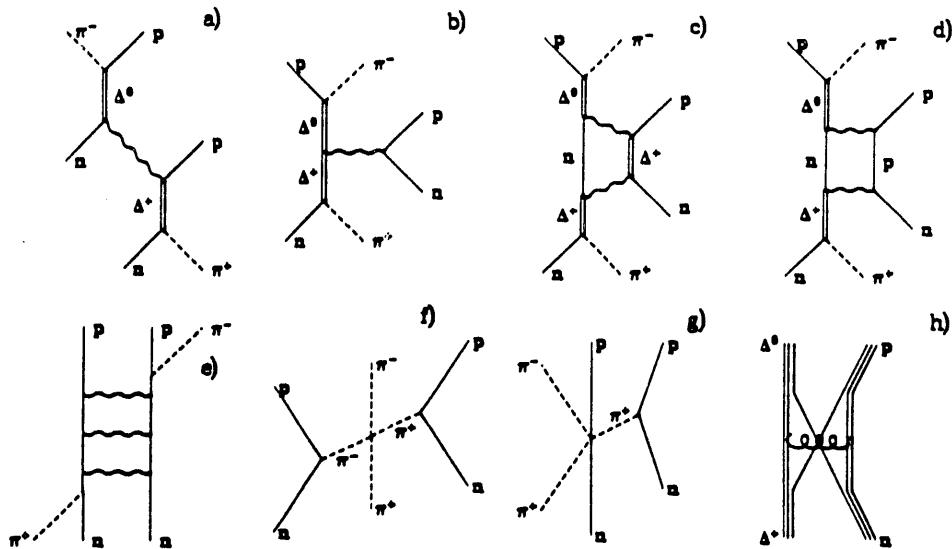


Figure 1: Illustrating contributions to DCX from hadron dynamics: (a) sequential scattering; (b)–(d) delta-nucleon interaction; (d,e) absorption; (f,g) exchange currents; and (h) quarks.

figure. These mechanisms are referred to in this talk as hadron dynamics in order to distinguish them from the nuclear dynamics that dominate SEQ. Processes such as those illustrated in Fig. 1 have also been studied in, and appear to be required for, other pion reactions such as elastic scattering<sup>1</sup>. Specific models of hadron dynamics are discussed later in the talk. These models are often of interest in other contexts besides pion physics.

In order to see experimentally what else is there, one would like to suppress the sequential background. In scattering to discrete states, one may try to use the nucleus as a spin/isospin filter for this purpose. To see how this might work, refer to Fig. 2, where SEQ is illustrated for two different types of transitions, the double isobaric analog state (DIAS) transition, and the nonanalog state transition. In the latter, the nucleons must change their orbits and SEQ is found to be relatively suppressed. In scattering to the continuum, one may suppress sequential by imposing kinematic cuts as discussed by Chris Morris in his talk at this conference.

Double-charge-exchange cross sections have been calculated using some version of multiple-scattering theory<sup>2</sup>. Most of the calculations made before the detection of the DIAS<sup>3</sup> were based on very simple approximations, but since then more sophisticated approaches have been used, including the optical model and its generalizations (i.e. coupled-channel approaches), which stress the propagation of the pion, and the isobar-hole model, which stresses the propagation of the Delta(3-3) resonance. Kargalis, in the parallel session, will discuss a state-of-the-art coupled channel theory.

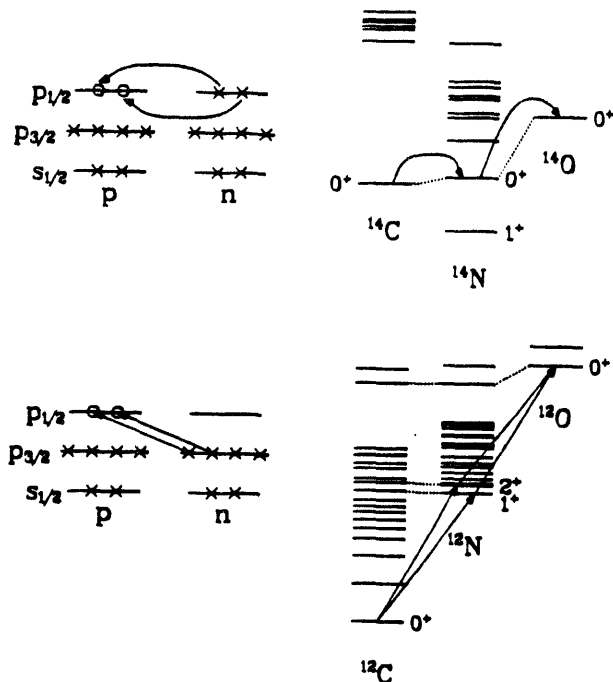


Figure 2: Illustrating sequential double charge exchange (DCX) for analog (upper panel) and nonanalog (lower panel) transitions. Dotted lines connect states that are analogs of one another, i.e., related (ideally) by rotations in isospin space. DCX through the intermediate IAS (analog of the ground state) is known as the "analog route," and DCX through any other intermediate state is called a "nonanalog" route.

It has also proved useful to formulate DCX using various approximations to these approaches, such as the impulse approximation or semi-classical scattering theory.

Because SEQ is so important, all theories build this in from the outset. Although some may regard the nonsequential physics to be of more general interest, SEQ is of considerable importance because it needs to be understood in order to get at the rest. It represents a part of the reaction that is completely known in principle, since it depends only on nuclear structure, the pion-nucleon scattering amplitude, and well-known principles of multiple scattering. Having said this, I should hasten to point out that SEQ is notoriously difficult to calculate confidently, and the more we learn about it, the more the various ingredients are seen to have an intricate interplay among themselves. The sequential scattering background is the main source of theoretical uncertainty standing in the way of testing models of hadron dynamics.

Some of the early attempts to explain DCX were made using coupled channels, see the work by Koren<sup>4</sup> and Miller and Spencer<sup>5</sup>. They retained only "elastic" channels, meaning that, of the many states shown in Fig. 2, only the three states of the isotopic multiplet that include the ground state were explicitly treated. This is of

the same form as the theory put forth earlier by Ericson and Ericson<sup>6</sup> for low-energy pion-nucleus interactions. In order to take into account certain nonelastic contributions, they showed that corresponding "isotensor" terms can be added to the optical potential. The isotensor potential carries the burden of including the excited-state routes in Fig. 2, as well as the hadron dynamics of Fig. 1. The formulation of elastic DCX in the absence of an isotensor interaction is often referred to as the simple sequential model (SSM).

The coupled-channels calculations are actually simplified considerably by taking advantage of the (approximate) isospin invariance of the strong interaction<sup>7-9</sup>, which is sometimes called the isospin invariant model. Subsequent calculations of Liu and collaborators<sup>10-12</sup> and of Johnson, Siciliano, and collaborators<sup>13, 14</sup> using a similar formalism included additional sources of isotensor interaction. Careful phenomenological applications of models such as these to the data collected at the meson factories since 1977 have clearly established the inadequacy of the SSM and stimulated further theoretical and experimental searches for the underlying issues.

Various simple approximations to coupled-channel calculations have been developed to represent scattering both near the Delta(3-3) resonance<sup>7</sup>, where the nucleus is rather black to pions, and at low energy, where it is believed to be more transparent. These approximations provide insights into the reaction that are not easily obtained from the more exact but more numerically intensive approaches. Such models have developed differently for low-energy pions and for resonance-energy pions because of the different strengths of the interaction in these regions.

Double charge exchange was formulated in the isobar-hole model by Karapiperis, et al<sup>15-17</sup>. The first clear indication of the importance of the intermediate nonanalog nuclear excitations of Fig. 2 in low-energy DCX was shown by this group. Once the importance of intermediate nonanalog states was established, formulations of DCX in the impulse approximation<sup>18-25</sup> were vigorously pursued.

The impulse approximation is simplest and most transparent when multiple scattering (or the "distorted wave" effect) can be neglected, an assumption that often gives a good description of pion-scattering data at low energy. Powerful results are obtained when all intermediate states are included using "closure". One such result<sup>26</sup> uses seniority to obtain the explicit dependence on  $n$  ( $n = N - Z$ ), the number of active (or valence) nucleons. Seniority<sup>27</sup> takes advantage of the observation that the long-range part of the effective interaction between nucleons in states of  $T = 1$  and total angular momentum  $J = 0$  is attractive and causes nucleons to tend to group together into pairs having these quantum numbers. For nuclei with a single pair of valence neutrons, this pairing leads to maximal spatial correlations for the pair. However, as more valence pairs are added, their effect is weakened by the Pauli exclusion principle, giving rise to a characteristic nuclear dependence of observables. For the case of DCX to a DIAS, the result is

$$F(\text{DIAS}) = [n(n-1)]^{1/2}[\alpha + \beta/(n-1)] \quad (1)$$



where  $\alpha$  and  $\beta$  depend on angle and energy. The term alpha comes entirely from long-range pieces of the transition operator, encompassing the amplitude of the SSM; beta depends only on its short-range part and on spin<sup>28</sup>. Nuclei that are believed to be well represented by seniority include the calcium, nickel, and tin isotopes<sup>28, 29</sup>. Refinements of this equation<sup>20</sup> have been applied to DCX data in the vicinity of Ca, and good results have been obtained<sup>30</sup>.

**Results, Resonance-Energy Scattering:** A large amount of resonance-energy DIAS data is explained phenomenologically in terms of the isospin invariant model<sup>13</sup> with medium modifications (described with just a few parameters). The failure of the SSM, which describes DCX as two SEQ scatterings through the isobaric analog state and is one of the main results of this analysis, could not have been definitively established without the availability of the SCX data. The other accomplishment of the phenomenology is the successful description of the data in terms of just a few parameters characterizing the isotensor interaction. Having said this, one must hasten to point out that the origin of the phenomenological isotensor interaction is really not understood microscopically, even today after much experience with the role hadron dynamics in DCX. A closely related point is that the shape of the angular distributions of DCX for DIAS at resonance is not at all understood. This continues to represent the most outstanding theoretical problem of DCX.

There is also a large amount of resonance-energy nonanalog data, and this is well described microscopically in terms of the delta-nucleon interaction. Figure 3 shows the results of a restricted model-space calculation of SEQ using the coupled-channel theory of Ref. 31, along with the results of a calculation of the delta-nucleon interaction mechanism that is described in more detail in the discussion of hadron dynamics. Quite good systematic descriptions of the data is obtained. This example illustrates the use of the nucleus as a filter against SEQ and a striking example of the importance of hadron dynamics in DCX.

**Results, Low-Energy Scattering:** With the first low-energy data on <sup>14</sup>C, it was seen that the 50 MeV cross sections were nearly as large as those at resonance<sup>32</sup>. This came as a surprise. It was recognized soon after the first low-energy data was obtained that two SCX scatterings through large angles, allowed because of the transparency of the nucleus to the pion at low energy, provides a means to obtain a larger DIAS cross section than that provided by the SSM<sup>15, 33</sup>. As a result, the nucleus can be excited to low-lying states in the intermediate stages of the reaction in this process, and the intermediate 2<sup>+</sup> state was found to be particularly important<sup>14</sup>.

Tests of scaling implied by the relationship in Eq. 1 have been attempted for f<sub>7/2</sub> shell nuclei at several energies, from which one obtains values for the  $\alpha$  and  $\beta$  parameters of Eq. 1. The results at 35 MeV<sup>30, 34</sup> and at 50 MeV support the seniority-based scaling. In these and other applications to the data, a slightly different parameterization is used<sup>26</sup>. It is expressed in terms of the parameters  $A$  and  $B$ , linearly related to  $\alpha$  and  $\beta$ . The values for the  $A/B$  ratio at 35 MeV is

$$|A/B| = 3.5 \pm 0.8, \cos \phi = 0.55 \pm 0.3 \quad (2)$$

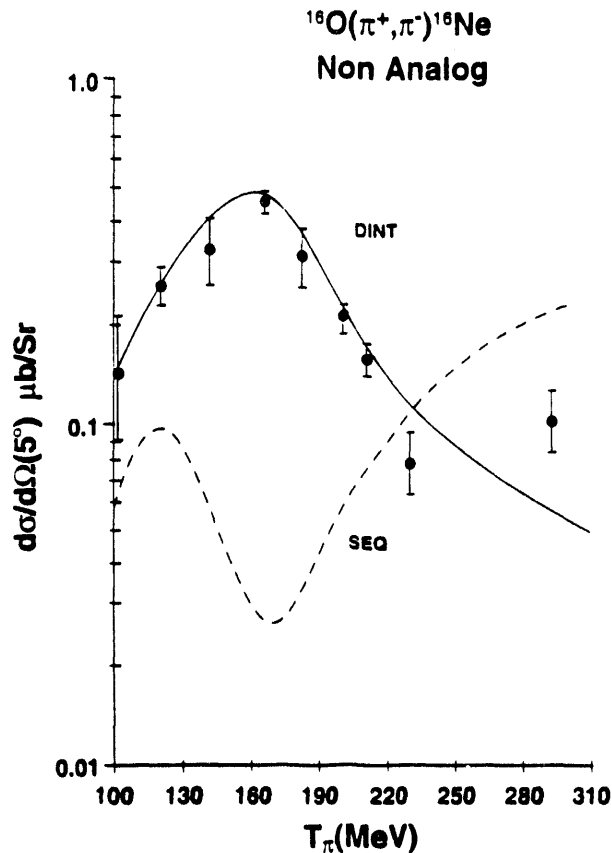


Figure 3: Excitation function of  $(\pi^+, \pi^-)$  forward-angle cross section for orbit-changing nonanalog transition on a  $T = 0$  nucleus. The dashed line shows the SEQ background according to Ref. 31 and the solid line the contribution of the  $\Delta N$  interaction.

where  $\phi$  is the relative phase of  $A$  and  $B$ . These values will be used to assess several theoretical models below. The extension to a wider set of data, including some nonanalog states, has been made by introducing generalized seniority by Ginocchio<sup>35</sup>.

The  $|A/B|$  separation is a second way that one may use the properties of the nucleus to "filter" out hadron dynamics of interest. Since the long-range pieces of the reaction are the less interesting pieces of SEQ (actually, they are just the physics of the SSM that one is not interested in), application of the model to the data enables one to extract the short-range pieces, which carry information about the hadron dynamics in Fig. 1.

In spite of the successful description of a fair amount of data in terms of the scaling based on Eq. 1 and its generalizations, there remains an outstanding problem that indicates that all the elements of the theory of low-energy DCX are not yet in place. In particular, the energy dependence of DCX data at low energy has not been reproduced in the impulse approximation, whether or not distorted pion waves are utilized. This is illustrated in connection with Fig. 4, below. There is some reason to believe that this problem is related to the calculation of SEQ.

Theoretical tools are being developed with which one hopes to overcome the problems SEQ, and two of these are being discussed in the parallel session. One of these, discussed by Khankhasayev<sup>36</sup> and Sarafian<sup>37</sup>, generalizes the isospin invariant model by introducing explicitly a term in the isotensor interaction that sums, using closure, over all excited states reached after the first SCX in Fig. 2. This method should be particularly useful for heavier nuclei, where the excited-state spectrum is very dense. The other, discussed by Kagarlis<sup>38</sup>, sums over these states explicitly using the full coupled-channel theory. This theory should be most useful for the lighter nuclei where only a few low-lying excited states are relevant. With the progress that is being made in these approaches, it should be possible to develop a theoretical model that is sufficiently quantitative to describe the SEQ background in essentially all situations. This is essential for settling the question of how much of the reaction must be attributed to hadron dynamics.

Stimulated in part by the failures of the SSM the various nonnuclear contributions to DCX illustrated in Fig. 1 have been proposed as possible explanations of the data. One means of distinguishing them in the data is by their energy dependence, e.g., the resonance-mediated processes (Figs. 1a - 1d) dominate in the Delta(3-3) region but are expected to decrease in size above and below the resonance, where a rather large number of different processes (Figs. 1e - 1h) take over. Additionally, one may use nuclear states as "filters" to suppress the large background contribution from the SEQ. Two examples of this already encountered are (a) scattering to nonanalog ground states, which suppresses the sequential in the vicinity of the Delta(3-3) resonance; and (b) the use of the  $n$  dependence in scattering to multiplets that are well described by the seniority model to isolate the short-distance part of the DCX amplitude. We now discuss various pieces of Fig. 1 in some detail.

**Short-range correlations:** The short-range repulsion in the nucleon-nucleon (NN) interaction affects the terms shown in Fig. 1. Its effects are assessed by using the corresponding short-range correlation function to suppress contributions to DCX when nucleons approach each other within the healing distance of the correlation function. Such correlation functions have been inferred from microscopic nuclear structure studies. Substantial effects on SEQ were demonstrated in the early calculations of Miller and Spencer<sup>5</sup>. An important piece of short-distance interaction in meson exchange models is provided by the  $\rho$  meson, which can contribute to DCX as the intermediate meson in Fig. 1a<sup>22</sup>. The intermediate meson in SEQ has also been taken to be an  $\eta$  meson<sup>39</sup> at higher energies.

We compare values of the effect of short-range correlations and the  $\rho$  meson to the extracted values of  $A$  and  $B$  (Eq. 2) for the Ca isotopes at 35 MeV in Table 1<sup>40</sup>. The first row gives the sequential process (Fig. 1a) without short-range correlations. In the second and third rows, we add successively the short-range correlations and the  $\rho$  meson. It is clear that these are substantial effects, both suppressing the  $|A/B|$  ratio and hence giving the cross section a stronger dependence on  $n$ .

**Delta-nucleon Interaction:** The terms in Figs. 1b to 1d are the one- and two-

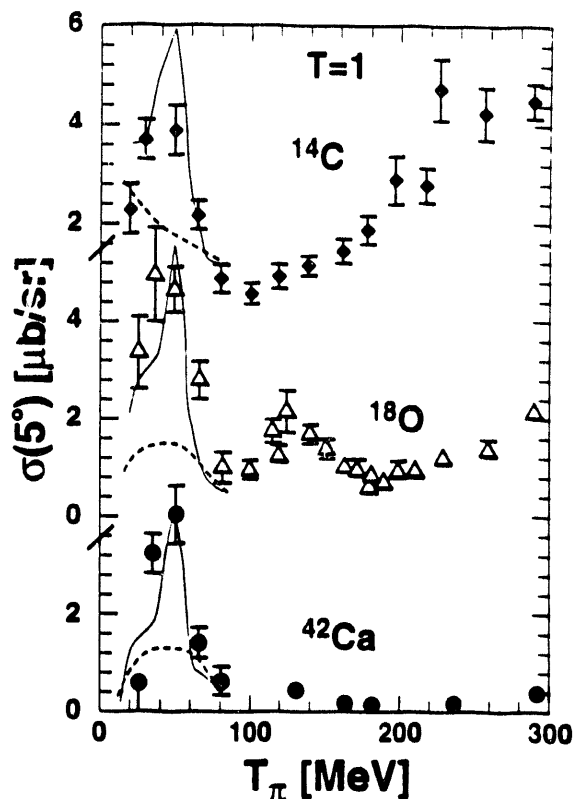


Figure 4: Excitation functions of  $(\pi^+, \pi^-)$  forward-angle cross sections for the DIAS in  $T = 1$  nuclei. The dashed lines are the SEQ background according to Ref. 62, and the solid lines include the  $d'$  dibaryon resonance.

meson contributions to the delta-nucleon interaction. The delta-nucleon interaction is interesting because very little is known about the coupling of the  $\pi$  and  $\rho$  mesons directly to the delta from other sources. Double charge exchange involves only the isovector piece of the delta-nucleon interaction, since a net charge is exchanged by the mesons. The same model<sup>34-46</sup> fits very nicely the systematics of essentially all the nonanalog DCX data and results in specific values for the coupling parameters. The role of the delta-nucleon interaction is relatively small in DIAS transitions<sup>41, 46</sup>. It also has a relatively small effect at low energy<sup>22, 40</sup>, as might be expected and is seen by comparing the third and fourth lines in Table 1.

Absorption: In addition to the excitation of discrete states shown in Fig. 2, intermediate continuum states may contribute to DCX. Several examples of this are shown in Figs. 1c to 1e. The processes in Fig. 1c and 1d are contributions from

Table 1: Values of  $|B/A|$  and  $\cos \phi$  at  $T_\pi = 35$ .<sup>a</sup>

Case	$ B/A $	$\cos \phi$	$\chi^2/N$
SEQ $\pi$	7.2	0.23	23
SEQ $\pi$ + SRC	5.0	0.11	6
SEQ $\pi$ + SRC + $\rho$	3.6	0.05	3
SEQ $\pi$ + SRC + $\rho$ + DINT	4.0	0.03	3
SEQ $\pi$ + SRC + $\rho$ + DINT + MEC	2.6	0.23	2
Expt	$3.5 \pm 0.8$	$0.55 \pm 0.3$	

<sup>a</sup>SEQ is the sequential process of Fig. 1a, without the  $\rho$  meson and without short-range correlations (SRC); DINT is the delta-nucleon interaction calculated as discussed in the text; and MEC are meson-exchange currents.

multiple quasi-elastic excitations (corresponding to the intermediate states having two nucleons and a meson in the continuum) and true absorption (intermediate states containing several nucleons and no meson). The Diagram in Fig. 1e is an example of an absorption-related process that does not involve the Delta(3-3).

Koltun and Singham<sup>47</sup> estimated the effect of the imaginary pieces of the absorption terms using data and unitary arguments. They concluded that true absorption can make a large contribution to DCX scattering, even though the absorption occurs on neutron pairs, a process that is normally expected to be small<sup>48</sup>.

Processes of the type shown in Fig. 1e were calculated and shown to make an important contribution to DCX at low energy<sup>49</sup>. A larger class of diagrams contributing to DCX has also been calculated and found to make large contributions to DCX at low-energy<sup>50</sup> by Oset, Khankhasayev, Nieves, Sarafian, and Vicente-Vacas<sup>51</sup>. These calculations have not substantiated the hopes of Koltun and Singham<sup>47</sup> that the absorption process would help to explain the location of the minimum in the DCX angular distribution of the DIAS transition at resonance.

**Exchange Currents:** The early calculations of exchange currents in DCX pertained to breakup of  $^4\text{He}$ . More recently, the interest has shifted to DCX to discrete states of the nuclei. Early calculations of DCX for the pole graph (Fig. 1f) by Oset et al.<sup>51</sup> at resonance energies and by Auerbach et al.<sup>20</sup> at low energy found very large results for exchange currents. Jiang and Koltun<sup>52</sup> criticized these works as not being consistent with the requirements of chiral symmetry, and they presented calculations of their own suggesting that the actual results should be rather small at medium energies. These results<sup>52</sup> are substantiated in more detailed calculations by Johnson et al.<sup>53</sup>, who also showed that for a light nucleus there may be some hope of seeing exchange currents. The fourth and fifth rows in Table 1 show the relative importance of the exchange currents to DCX. The effect is rather small on the scale of other effects shown there, consistent with the remarks made above.

Quarks: It has been hoped that the DCX reaction would reveal unique signatures of quark effects in nuclear physics. Early speculation<sup>54</sup> about a role for dibaryons was motivated by the large relative size of analog and nonanalog cross sections observed in the first high-energy DCX data. This, as well as other suggestions mentioned below, have all proved inconclusive.

Miller<sup>55</sup> proposed a somewhat different six-quark model to explain the large size of the 50 MeV DCX measurement on  $^{14}\text{C}$ <sup>32, 56</sup>. He found the predictions of his model comparable to the observed DCX cross section of  $5 \mu\text{b/sr}$ . The simultaneous observation of a small cross section for SCX to the isobaric analog state gave some additional support for this process. Later calculations at high energy lead to the prediction<sup>57</sup> of large, energy-dependent cross sections, which were not observed in the subsequent experiment<sup>58</sup>. Chiang and Zou<sup>59</sup> have also found similar effects as Miller. Uncertainty about the size of the six-quark structure is one source of uncertainty in the magnitude of six-quark effects in all calculations.

Quark models have also been applied in the resonance region<sup>60</sup>, motivated by the hybrid quark-hadron model<sup>61</sup>. These calculations were not able to explain the anomalies in the resonance-energy data, however.

Finally, we mention recent proposal of Bilger, Clement, and Schepkin<sup>62</sup>, who have proposed a particular dibaryon resonance, the  $d'$  of quantum numbers  $J^\pi = 0^-$ ,  $T = 0$ , to explain the universal energy dependence of the DCX cross section at low energy. This work will be reviewed by R. Bilger in the parallel session. In Fig. 4 one sees results from their paper showing the universal peaks in the DCX data, their calculations of the SEQ background, and the results of including the  $d'$ . The figure also illustrates the failure of previous theoretical calculations of the sequential process (dashed line) to explain the energy dependence of the low-energy data.

For the study of hadron dynamics in pion DCX, the most urgent theoretical problem is to realistically model the sequential background. Without a reliable evaluation of it, we will not be able to make further progress in sorting out the exotic physics that one has hoped to study in DCX. I have tried to argue that we have a few "filters" capable of eliminating it to some level of approximation, but it is now essential to do better. Fortunately, bringing SEQ under control is possible with a sufficiently dedicated experimental and theoretical program, as I will now describe.

To begin, I want to refer back to Figs. 1 and 2 where one sees that the SEQ process proceeds through two SCX scatterings through states of the intermediate nucleus. It is now feasible, with the new neutral meson spectrometer developed at Los Alamos, to actually measure the branches of the most important low-lying SCX routes to DCX. This type of measurement, along with elastic scattering, then provides a very stringent constraint on models of sequential scattering, making the calculation of SEQ quite reliable.

The second half of the problem is of course theoretical. Tools are being developed with which we can digest the elastic and SCX data and come up with the SEQ scattering amplitude. The prototypical theory is provided by the isospin invariant

model, which by using SCX data to the IAS was able to model the SSM essentially exactly. This led to the conclusion, essentially directly from the data, that the SSM fails and that there is a substantial isotensor background. Extending to a complete coupled-channel treatment along the lines discussed by Kagarlis<sup>38</sup>, will enable one to determine the extent to which the isotensor interaction is formed from SCX through the excited states of Fig. 2 and hadron dynamics of Fig. 1. One can make such a separation convincing only by doing a full coupled channel calculation and making full use of appropriate SCX data.

I have argued that DCX is likely to become a quantitative tool for testing models of hadron dynamics with the development of new theoretical methods and new sources of experimental data on single charge exchange with which to pin down the sequential contribution of DCX. The author would like to thank the local organizers, especially M. Khankhasayev, for their hospitality at the Conference.

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