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Meson exchange currents in pion double charge exchange

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We examine the influence of meson exchange currents (MEC) on pion double charge exchange (DCX) using the Weinberg Lagrangian. We calculate the corresponding amplitude for DCX and examine its interplay with more conventional mechanisms of DCX for ^{14}C at incident energies of 10 to 110 MeV and for the Ca isotopes at 35 MeV. The MEC effect includes the pion pole term and the contact term. In comparison to previous estimates, we find smaller but nevertheless non-negligible contributions of these effects to DCX. We stress the fact that the MEC contribution to DCX is strongly A dependent, with its effect in light nuclei comparatively larger than in heavy ones.

Pion double charge exchange (DCX) is an important reaction in nuclear physics because the pion must interact with at least two nucleons in order for the reaction to take place. This means that the sensitivity to two-body effects is relatively great, occurring in leading order for DCX. This stands in contrast to most reactions in nuclear physics, which are dominated by one-body processes. For this reason it is becoming of great interest to examine DCX data for evidence of two-body effects that are of significance in other areas of physics. Low-energy pion scattering (T_π about 50 MeV) has become the preferred energy for these studies because it is well separated from the resonance region where the strong delta excitation complicates the interpretation of the data.

In the last few years, much effort has been devoted to examination of DCX for signatures of various sources of two-body correlations. Well-established techniques of nuclear spectroscopy [1] suggested that one look at the DCX cross section for its dependence on the number of valence neutrons as a means to isolate two-body shell-model correlations [2]. Early numerical calculations in Ca isotopes (as well as ^{14}C) [3] gave supporting evidence that such correlations occur prominently in DCX. Sensitivity to dynamical short-range correlations, such as those arising from heavy meson exchange as expected from standard one-boson exchange models, were established in Ref. [4], where it is shown that these correlations can affect the DCX cross section at the level of about 50%.

Meson exchange currents (MEC's) occur, in principle, in DCX, and the first calculations of these were done in the resonance region [5], where MEC's were shown to be negligible. Results in the low-energy region were presented recently [6] for the Ca isotopes. The calculations in Ref. [6] showed that the MEC's were very sensitive to the pion-nucleon form factor and would give cross sections substantially larger than experiment for standard choices of this form factor. Unfortunately, these results are misleading because the cross sections of Ref. [6] were erroneously multiplied by a factor of 4 [7]; furthermore, both calculations [5,6] are based on the Veneziano-Lovelace model, and as such, they lose contact with chiral dynamics.

Here we study the effects of MEC's using the chiral Weinberg Lagrangian. Our MEC calculation includes the so-called pole and contact terms shown in Fig. 1. Details needed for the evaluation of the matrix elements of the chiral Lagrangian in Fig. 1 are found in Ref. [8]. Note that the kinematics of DCX requires evaluation of the interactions at off-shell values of the pion momenta, which is well defined since the calculation proceeds from a Lagrangian. The chiral Lagrangian is, however, not completely specified since the chiral symmetry-breaking parameter ξ is poorly known. We therefore show results with choices for ξ that we believe encompass its true value. Actual calculation of the DCX amplitude using the chiral Lagrangian employs the momentum-space techniques of Ref. [9].

The application of Ref. [9] requires the introduction of a pion-nucleon form factor. We take a monopole form with cutoff of 1.2 GeV/c, which is nearly the same as that of the Bonn potential [10]. There is also the possibility that the pion-pion amplitude could contribute its own form factor at the $\pi\pi$ scattering vertex. From one dynamical model of $\pi\pi$ dynamics [11], we have estimated [12] that the monopole cutoff at this vertex would exceed 2 GeV/c, and so at least in this model the additional cutoff can be safely ignored.

Our intention is to show the relative importance of the MEC and more conventional mechanisms in leading order where the theory can be formulated unambiguously. This means that we will present results calculated using plane waves for the initial, intermediate, and final pions. Distortions are thus omitted for all calculations presented below, except that they have been included approximately to indicate the trend of the energy dependence of the zero-degree ^{14}C cross section. Calculational details for the conventional sequential mechanism may be found in

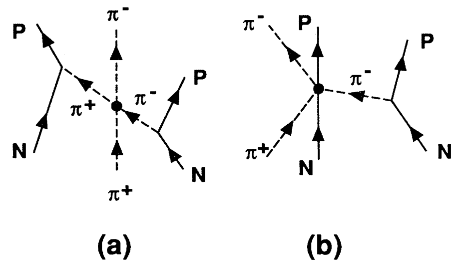

FIG. 1. Contributions to DCX arising from MEC (a) pole term and (b) contact term. The dots represent terms that originate in the Weinberg Lagrangian.

Ref. [4(a)]. Because the treatment of distortions is only approximate, we will not attempt to draw quantitative conclusions from a comparison of the magnitude of our cross sections and the experimental data.

Plane-wave results for the 50-MeV ^{14}C angular distribution are shown in Fig. 2. The dashed curve is the calculation for sequential scattering with the intermediate π meson (SEQ-π); the dot-dashed curve [SEQ-$(\pi+\rho)$] contains in addition an intermediate ρ coupled through the Δ_{33}, as in Ref. [4(a)]. These include a correlation function described by $\Gamma(r)$ [$\Gamma(r)=1$ in the absence of short-range repulsive correlations] and a specific off-shell pion-nucleon t matrix [4(a)]. The addition of the exchange currents with $\xi=0$ gives the solid curve. This value of ξ is preferred because it gives a better reproduction of the $\pi N \rightarrow \pi\pi N$ reaction near threshold [8,13]. The points labeled "1" and "-1" show the effect on the zero-degree cross section of changing ξ to 1 and -1, respectively. As we have not included distortions of the pion waves in the calculation of Fig. 2, the data [14] are shown only to set the scale. All cross sections in this figure as well as in Fig. 3 are evaluated with Cohen-Kurath wave functions.

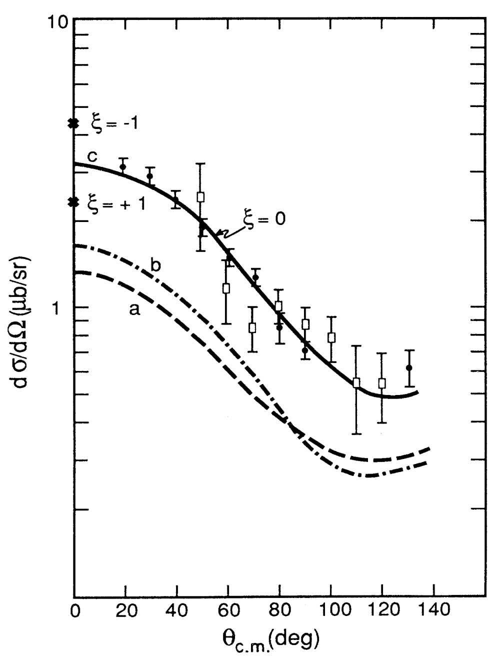

FIG. 2. Angular distribution for DCX to the double isobaric analog state from ^{14}C at 50 MeV in the plane-wave approximation with and without exchange currents: *a*, sequential π scattering including short-ranged correlations in $\Gamma(r)$; *b*, sequential π scattering *a* plus the ρ meson, including short-range correlations in $\Gamma(r)$; *c*, full sequential *b* plus MEC effects for $\xi=0$. The crosses show the effect on the zero-degree cross section of changing ξ as shown in the figure.

The zero-degree DCX excitation function is shown in Fig. 3. The data shown in the figure come from Ref. [15]. We see that MEC's are out of phase with SEQ-$(\pi+\rho)$ at 20 MeV and tend to lower the cross section there. Our results for SEQ-$(\pi+\rho)$ are increased by MEC's around 50 MeV by as much as 100%. It is instructive to examine the amplitudes in some detail. The purely real MEC amplitude is, at zero degrees, energy independent. At 50 MeV this amplitude (-0.0073 fm) interferes constructively with the real part of the SEQ-$(\pi+\rho)$ amplitude ($-0.0078+0.0103i$ fm), giving a moderately large increase in the cross section. Effects of MEC's are much less dramatic when added to the SEQ-π amplitude at 50 MeV ($-0.0011+0.0116i$ fm) because its real part is relatively small there. [See Table VIII of Ref. [4(a)] for a more detailed comparison of the amplitudes for correlated SEQ-π and SEQ-$(\pi+\rho)$; note that there is an overall sign difference in the phase convention for the scattering amplitudes used here and in Ref. [4(a)].] The larger real part of SEQ-$(\pi+\rho)$ results from an interplay between $\Gamma(r)$, the structure of the ρ meson propagator, and the form-factor cutoff at the ρNN vertex. This arises in a complicated way discussed in the literature; in particular, these considerations are essentially the same as those that apply to the calculation of the Landau-Migdal Fermi-liquid parameter g_0' [16–18]. Although the large

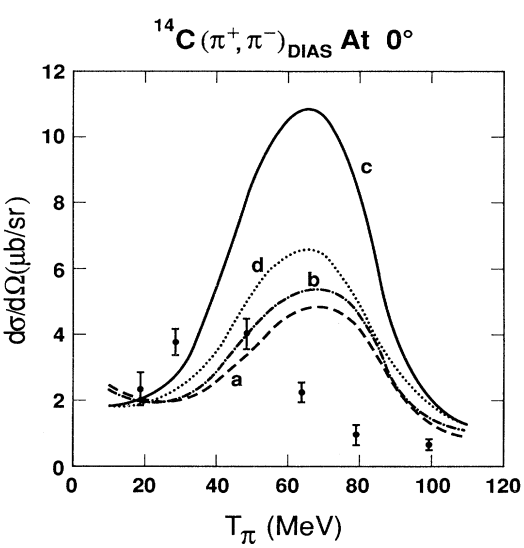

FIG. 3. Excitation function for DCX to the double isobaric analog state from ^{14}C including distortions as discussed in the text: *a*, sequential π scattering including short-ranged correlations in $\Gamma(r)$; *b*, sequential π scattering *a* plus the ρ meson, including short-ranged correlations in $\Gamma(r)$; *c*, full sequential *b* plus MEC effects for $\xi=0$; *d*, sequential π scattering *a* plus MEC effects for $\xi=0$.

enhancements seen in Figs. 2 and 3 depend on the details of this model, one should keep in mind that our values for the ρNN vertex and $\Gamma(r)$ are determined from the NN interaction [10] and nuclear-matter G-matrix results and that our model of these is confirmed independently in a comparison to the phenomenological value of $g_0'(\Delta\Delta)$ as explained in Ref. [4(a)].

Sequential calculations corresponding to curves a and b of Fig. 3 in the absence of distortions can be found in Fig. 10 of Ref. [4(a)]. The plane-wave excitation functions corresponding to all curves in Fig. 3 have a dip near 50 MeV. Distortions of the pion due to multiple scattering are included approximately in Fig. 3 by multiplying each plane-wave cross section by a common factor, which has been introduced [4(a)] as an approximate representation of their effects. As a result, the excitation functions in Fig. 3 have a peak that occurs slightly above this energy, similar to the data. The distortion factor thus changes rapidly with energy, but because all of the curves have been multiplied by a common factor, this treatment of distortions does not obscure the relative sizes of the DCX mechanisms underlying Fig. 3 (a,d) or the relative sizes of those in Fig. 3 (b,c). A comparison of the former set of curves thus reflects the energy dependence of the interference between SEQ-π and MEC's, and a comparison of the latter set of curves reflects the interference between SEQ-$(\pi+\rho)$ and MEC's, as discussed in the previous paragraph. A comparison of Figs 2 and 3 shows that our distortions enhance the forward cross section by about a factor of 2 around 50 MeV. Calculations by other groups [19] have also shown enhancements at this energy; however, the actual extent of the model dependence of the distortion effect remains an open question.

One index of the importance of the MEC, which may not be so strongly sensitive to distortions, is contained in the α and β parameters introduced in Ref. [2]. The DCX amplitude F in $^{40+n}$Ca is given in terms of α and β by $F=[n(n-1)/2]^{1/2}[\alpha+\beta/(n-1)]$. Data on the Ca isotopes have been analyzed in terms of A and B, which are related to α and β by $A=\alpha+\beta/4$, $B=3\beta/4$. The theoretical values of B/A and the corresponding experimental values [20] are given in Table I. The calculations shown here without MEC's can be found in Tables 1 and 2 of Ref. [4(b)], where they are discussed in detail. The theoretical values for the sequential amplitude with and without dynamical short-range correlations are taken from Ref. [4(b)]. Note that the MEC decreases β and increases the cross section at 35 MeV (the cross section can be obtained from α and β in Table I), at least for $\xi=0$ and -1. The MEC is still in of phase with sequential scattering, but to a lesser extent than in the case of ^{14}C at 50 MeV discussed earlier in some detail because of the strong energy dependence of the pion-nucleon charge exchange amplitude in this energy region (see Table VI of Ref. [4(a)]).

As the MEC effect is purely spin dependent at forward angles (because a pion of momentum $\mathbf{q}$ couples to nucleons as $\boldsymbol{\sigma}\cdot\mathbf{q}$), MEC's influence only β [21]. The MEC's therefore have the same effect on $[B/A]$ as the dynamical short-range correlations, because the correlation effect is also most pronounced in the real part of β. We see in Table I that correlations reduce the ratio $[B/A]$ and that including MEC's reduces it even further, undershooting the experimental value for our three choices of ξ. On the other hand, the value of the phase, $\cos\phi$, tends to improve. With MEC's the net effect is to bring B/A to within about two standard deviations of the experimental value for ξ greater than -1. The effect of MEC's on the overall size of the cross section in ^{42}Ca is much smaller (16% for $\xi=0$ [22]) than it is in ^{14}C, as seen in Figs. 2 and 3. It is also dramatically smaller [23] than the results of Ref. [6], expected in part because of the erroneous factor of 4 mentioned earlier.

The fact that MEC effects are larger in ^{14}C than in ^{42}Ca is a consequence of their short-range character. As discussed in Ref. [24], the relative effect of MEC's as compared to sequential scattering should decrease with increasing atomic mass. In the absence of distortions, the reasoning goes as follows: The average distance between the two valence nucleons involved in DCX is larger for larger nuclei. This suppresses MEC's which contribute only when the two nucleons are close to each other. However, sequential scattering between the same two nucleons is barely affected because of the importance of the exchange of an on-shell pion, which can travel freely over relatively large distances through the nucleus.

In conclusion, we find large effects of meson exchange currents in nuclei. Our results show, considering only the leading-order contributions to the cross section, that MEC's may be as large as 100% of the sequential process at 50 MeV in ^{14}C. However, our MEC results are a much smaller fraction of the sequential process in the Ca isotopes and, in particular, much smaller than results previously published for this nucleus in Ref. [6] by Auerbach

TABLE I. Values of A and B amplitudes for Ca isotopes at 35 MeV. δ includes corrections to the sequential process for the short-range repulsive correlation function, ρ meson, and delta-nucleon interaction.

Case	ξ	$10^3\alpha$ (fm)	$10^3\beta$ (fm)	$\lvert B/A\rvert$	$\cos\phi$	χ^2
SEQ-π $(\Gamma=1)$		$(-2.04,-1.25)$	$(5.51,8.01)$	7.2	0.23	23
SEQ-π $(\Gamma=1)+\delta$		$(-2.29,-1.26)$	$(3.35,7.76)$	3.96	0.03	3.2
SEQ-π $(\Gamma=1)+\delta$	-1	$(-2.29,-1.26)$	$(-2.48,7.76)$	2.04	0.51	3.4
+MEC	0	$(-2.29,-1.26)$	$(0.54,7.76)$	2.31	0.34	2.7
	$+1$	$(-2.29,-1.26)$	$(1.40,7.76)$	2.88	0.16	2.30
Experiment				3.5 ± 0.8	0.55 ± 0.3	

et al. It is difficult to say anything definitive about the need for MEC's by comparing the magnitude of our DCX cross-section results to experiment, because we have not included pion distorted waves realistically. However, we believe that B/A, as determined from DCX on the Ca isotopes, is less sensitive to the treatment of distortions. We find some modest improvement when the experiment is analyzed in terms of this observable. We are encouraged that DCX may provide a sensitive testing ground for meson dynamics in nuclei.

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