Multiple-Scattering Approach to Pion Double Charge Exchange at 50 MeV

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The observed differential cross section for the process $^{14}C(\pi^+,\pi^-)^{14}O$ at 50 MeV is successfully reproduced in the framework of multiple-scattering theory, with medium effects on π and Δ propagation fitted to elastic π-^{12}C scattering.

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The double-charge-exchange (DCX) reaction $^{14}C(\pi^+,\pi^-)^{14}O$(g.s.) has recently attracted experimental and theoretical interest, as a substantial forward differential cross section was measured at 50 MeV,[1,2] despite the almost perfect cancellation of the *S*-wave and forward P_{33} amplitudes ($-0.312-0.013i$ and $0.302+0.031i$ fm, respectively) for the elementary π-*N* single-charge-exchange (SX) process at the same energy. We report here the results of a calculation of the differential cross section for this process at an incident energy of 50 MeV.

Our approach is essentially identical to our recent Δ-hole treatment of the DCX on ^{18}O, in the energy region of the Δ resonance.[3] We build the DCX amplitude out of a sequential and a Δ-*N* interaction part. The sequential process consists of two consecutive single charge exchanges, proceeding via the resonant P_{33} and the *S*-wave π-*N* interaction (the background *P*-wave interaction accounts for $\sim 6\%$ of the total *P*-wave π-*N* charge-exchange amplitude and can be safely disregarded for our purposes). In connection with the present calculation the following points also need to be mentioned specifically.

(i) All pion waves are distorted by the Δ-hole optical potential, calculated for a closed ^{12}C core. The phenomenological spreading potential, which appears as a Δ self-energy in the resonant part of the optical potential and represents multihole medium effects, was fitted to π^+-^{12}C elastic scattering at 50 MeV.[4] In the optical potential, the strength of a repulsive, isoscalar *S*-wave term, proportional to the square of the nuclear density, was also allowed to vary. It has been noticed in previous analyses of π elastic scattering below 100 MeV and pionic-atom data[5] that a substantial *S*-wave repulsive interaction is needed in order to reproduce the measured cross sections, energy shifts, and widths. The origin of this repulsion, which cannot be accounted for by lowest-order optical theory, is unclear. For a spreading potential with central and spin-orbit components of strength $30-23i$ and $-6-3i$ MeV, respectively, and an *S*-wave repulsive potential of central strength 20 MeV, the cross section shown in Fig. 1 was calculated. The Δ propagators in the DCX amplitude are dressed by the same spreading potential.

(ii) The ground states of ^{14}C and ^{14}O are described as two-hole states, with the (8-16)POT parametrization of Cohen and Kurath.[6]

The result of our calculation is displayed in Fig. 2. The effect of the Δ-*N* interaction is shown for three values of the complex strength parameter, differing widely in magnitude and phase. Obviously, the Δ-*N* interaction does not alter the order of magnitude of the cross section and will not be considered in what follows. It suffices only to mention that, at the low pion energy considered here, one expects the long-range sequential process to dominate over the short-range Δ-*N* process. We observe that the absolute size of the calculated cross section is consistent with experiment.

In view of the much lower forward cross section predicted by other calculations (see, for example, the calculations of Siciliano quoted in Refs. 1 and 2), we have looked into the sources of the discrepancy. We indicate in Fig. 3 the cross sections obtained, when we repeated our calculation under one or more simplifying assumptions. When the pions are described in plane-wave approximation, the forward cross section is reduced by a factor of 2.4 (solid curve). The size of the effect is hardly surprising, in view of the fact that pion

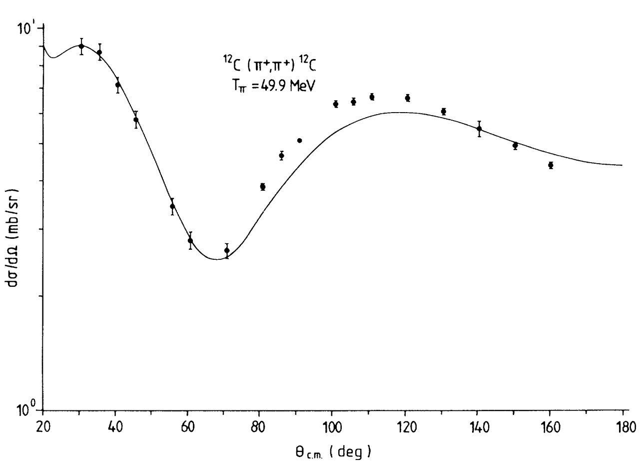

FIG. 1. Elastic differential cross section calculated with the parameters quoted in the text. The experimental points are from Ref. 4.

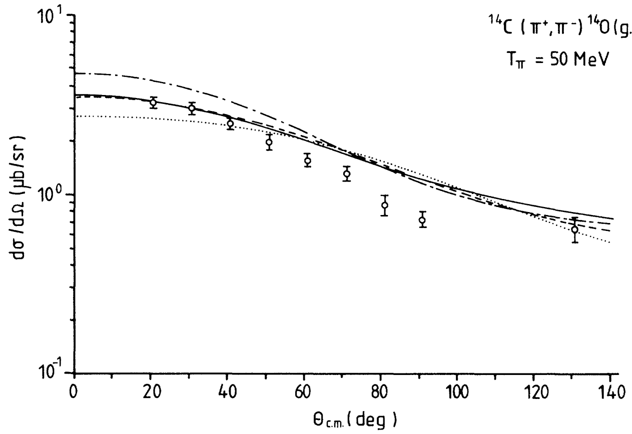

FIG. 2. DCX differential cross section: sequential process only (solid curve); including Δ-N interaction of strength $\delta v = 0.5 - 1.0i$, $0.2 - 2.8i$, and $1.0 + 0.4i$ fm^2 (dashed, dotted, and dot-dashed curve, respectively; for the definition of δv, see Ref. 3). The experimental points are from Ref. 2.

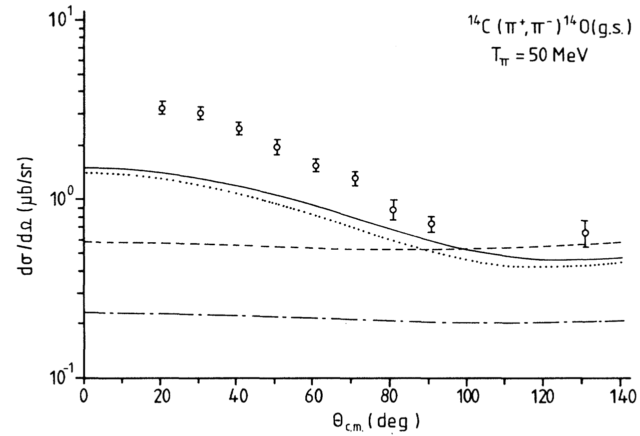

FIG. 3. DCX differential cross section calculated in various approximations specified in the text.

distortions enter at three stages of the sequential DCX process. It is interesting, however, that distortions act so as to increase the cross section. In all remaining curves pion distortion is neglected. Assuming closure on the Δ states (i.e., keeping only a constant kinetic-energy term in the Δ self-energy) results in the dotted curve. The shape of the cross section, as well as its size at forward angles, is substantially modified when the ^{14}C and ^{14}O ground states and the intermediate ^{14}N states are assumed to have a $(p_{1/2})^2$ structure, with a closed $(0s_{1/2})^4(0p_{3/2})^8$ core (dashed curve). Simple observation of the partial amplitudes shows that the difference is due to the 2^+ intermediate state, which is of course absent in the $(p_{1/2})^2$ model. With the π-n charge-exchange cross section and the cross section for excitation of the 4.44-MeV 2^+ state[7] in ^{12}C known to peak for backward angles at 50 MeV, it is natural to speculate that the dominant nonanalog contribution is associated with two backward scatterings of the pion. Finally, neglect of nucleon recoil in the $\pi N\Delta$ vertex (in addition to all previous approximations) leads to the dot-dashed curve of Fig. 3. It is interesting to note that incorrect treatment of nucleon recoil can by itself lead to an underestimation of the DCX cross section by a factor of 2.5, as can be seen by comparison of the last two curves.

It is already clear from the preceding discussion that there need be no simple connection between the forward DCX and SCX cross sections to the respective analog states. We have also calculated the ^{14}C(π^+,π^0)^{14}N(IAS) cross section at $T = 50$ MeV. The SCX cross section was obtained from the single-scattering amplitude, with the spreading potential parameters fitted to elastic scattering at 50 MeV —higher-order graphs are estimated to contribute no more than 20–30 μb/sr at all angles and would certainly not alter qualitatively our conclusions. In Fig. 4 we display the calculated SCX cross section, together with the "cross section" obtained for resonant-only (dashed curve) or S-wave-only (dotted curve) π-N charge exchange. At forward angles a cancellation by a factor of ~ 20 takes place. The cancellation is so delicate that one need only vary the P-wave transition operator by an amount corresponding to a 3% change in the P-wave cross section (strong transition operators are certainly not known to a better than 10% accuracy), in order to reduce the full forward SCX cross section by a factor of ~ 4.5 (dot-dashed curve). This is to be contrasted to the DCX amplitude, where there are no signs of a similar cancellation. Indeed, the forward DCX cross section changes only by 3% when the above modifield P-wave transition operator is used.

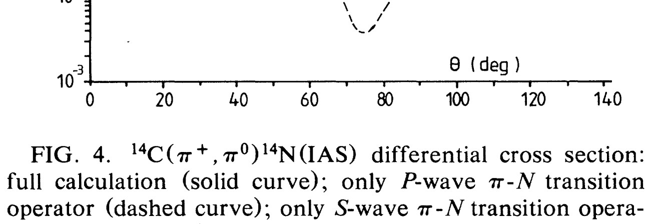

FIG. 4. ^{14}C(π^+,π^0)^{14}N(IAS) differential cross section: full calculation (solid curve); only P-wave π-N transition operator (dashed curve); only S-wave π-N transition operator (dotted curve); full calculation with modified P-wave transition operator (dot-dashed curve).

The most interesting implication of our calculation is that one can understand pion DCX on ^{14}C at low energies as a sequential process, in the framework of multiple-scattering theory. Although the observed cross section is well reproduced, the precise quantitative agreement should not be overemphasized in view of the known sensitivity of the DCX cross section to nuclear structure and the uncertainties resulting from the Δ-N interaction. On a qualitative level, the strong coupling to the intermediate 2^+ state shows that long-range correlations play an important role. It is natural that pions with a wavelength of ~ 10 fm should be more sensitive to such mechanisms than to the short-range ones speculated in connection with the DCX reaction at low energies.[8]

Interestingly enough, DCX may provide some information about the S-wave repulsion, which appears to be required by low-energy elastic and atomic data. In our calculation, the S-wave repulsion was included in the optical potential responsible for the pion distortions, but no such interaction was required in the DCX transition operator itself, which acts on nucleon pairs of isospin $T=1$. This suggests the absence of any substantial interaction of this kind between the pion and $T=1$ nucleon pairs. A possible source of the repulsive interaction observed in elastic scattering and pionic atoms is pion absorption. If absorption on $T=1$ nucleon pairs contributed substantially, simple isospin arguments would imply an equally large effect on the DCX transition operator. It appears, therefore, that, if the additional repulsion is a dispersive effect of S-wave pion absorption, the latter has to involve predominantly proton-neutron pairs.

In conclusion, pion DCX at low energies can be adequately described by multiple-scattering theory and can, by its selectivity, contribute to our microscopic understanding of the low-energy π-nucleus interaction.

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