Double Analog Transition $^{14}C(\pi^+,\pi^-)^{14}O$ at 50 MeV

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(Received 10 September 1984)

Differential cross sections for the double-isobaric-analog-state transition in the reaction $^{14}C(\pi^+,\pi^-)^{14}O$ were measured over the angular range 20° to 130°. The cross section extrapolated to 0° is 3.9 ± 0.5 μb/sr and the angle-integrated cross section is 15.3 ± 1.6 μb. These values are much larger than expected from the trends of data at higher energies and may indicate the presence of new phenomena. The results are compared to recent six-quark bag-model calculations which predict such trends.

PACS numbers: 25.80.−e, 27.20.+n

The cross sections for pion double-charge-exchange (DCX) reactions are sensitive to correlations among nucleons in nuclei because the scattering amplitude must involve at least two nucleons or quarks in order to conserve charge. The DCX reaction best suited for quantitative study is that connecting the ground state of the target with the double-isobaric-analog state (DIAS). In this case the initial and final states are in the same isospin multiplet and have the same spatial and spin wave functions, thereby reducing the influence of uncertainties in the nuclear structure. There has been a recent prediction[1] of large cross sections at forward angles for the DIAS transition at 50 MeV on ^{14}C arising from the presence of six-quark clusters in nuclei. A previous measurement[2] of this transition was restricted to angles $\geq 50°$, with the 50° point having a 36% uncertainty. Therefore the forward-angle behavior of the cross sections was not determined. We have measured the differential cross sections for this transition between 20° and 130° and have deduced 0° and angle-integrated cross sections. Both quantities are found to be much larger than expected on the basis of existing single- and double-charge-exchange systematics.[3,4] These results suggest that new features may be present in low-energy DIAS transitions.

At pion energies near 50 MeV, the *s*- and *p*-wave terms in the scattering amplitude of the elementary reaction $\pi^- p \rightarrow \pi^0 n$ are of comparable magnitude and interfere destructively to cause the 0° differential cross section[3] to almost vanish (~ 5 μb/sr). This feature is preserved in single-charge-exchange (SCX) reactions[4] on the light nuclei ^{7}Li, ^{14}C, and ^{15}N. Thus it was expected[1] that the DIAS transition amplitude for sequential charge-exchange scatterings with the isobaric analog state (IAS) as the dominant intermediate state would be small. The suppression of this sequential DCX amplitude at 50 MeV could allow the observation of other mechanisms.

A possible new DCX mechanism was proposed by Miller,[1] who argues that six-quark cluster components of nuclear wave functions lead to relatively large, forward-peaked, DIAS cross sections near 50 MeV. For the DIAS transition in ^{14}C, he obtained a sizable forward DCX amplitude for turning two down quarks into up quarks within a six-quark cluster formed out of the short-range correlation of the two $p_{1/2}$-shell valence neutrons in the ^{14}C ground state. DIAS cross sections of 8–12 μb/sr at 0° were obtained with a bag radius r_0 of 0.95 fm. This radius corresponds to a 6% probability for a six-quark cluster within the valence wave function. This six-quark model was also used[5] to explain the EMC effect, the depression of the ^{3}He charge density, and the magnetic moments of the $A=3$ systems.

To test Miller's prediction, as well as to provide basic data for the evaluation of DCX mechanisms at low pion energies, we measured differential cross sections for the DIAS transition $^{14}C(\pi^+,\pi^-)^{14}O$ at 49.2-MeV average incident energy in 10° steps between 20° and 90° and at 130°. The experiment was performed at the low-energy pion channel of the Clinton P. Anderson Meson Physics Facility (LAMPF). The momentum spread of the beam was 3% (full width), and the flux was about 4×10^7 π^+/s. The scattered particles were detected with a 180° double-focusing magnetic spectrometer[6] having a solid angle of about 13 msr. The detector system consisted of a multiwire proportional chamber between the two dipole magnets of the spectrometer, a pair of multiwire proportional chambers immediately behind the focal plane, a 1.6-mm-thick plastic scintillation detector, and a fluorocarbon Cherenkov detector. A coincidence among signals from all three wire chambers and the scintillation detector defined the event trigger. The first wire chamber established that the detected particle passed through the spectrometer. Its presence in the trigger reduced the background in the DCX data to nearly zero. The last two wire chambers measured the trajectories of the particles at the focal plane. Signals from the Cherenkov detector were used to discriminate against electrons. The spectrometer and the trigger logic provided excellent identification of (π^+,π^-) events, with the number of on-line triggers being only twice the number of good events identified in the off-line analysis. Corrections for pions that decay in the relatively short 3.5-m flight path and for muons that were recorded as good events were estimated by Monte Carlo simulation.[6]

A powder sample[7] of ^{14}C consisting of 77% ^{14}C, 14% ^{12}C, and 9% impurities by weight, was encapsulated in two thin-walled copper cells ($5\times5\times0.6$ cm^3). The combined ^{14}C target thickness of the two cells was 0.29 ± 0.02 g/cm^2. Each of the four copper windows had a thickness of 0.045 g/cm^2. Background spectra were measured with two empty target cells and with a graphite (^{12}C) target. Relative incident pion fluxes were measured by a toroidal pickup loop about the primary proton beam, as well as by two scintillator telescopes placed upstream of the experimental target to observe muons from π decay. We normalized our data with respect to ^{12}C elastic-scattering cross sections[8] by measuring $\pi^+ + {}^{12}C$ elastic yields at six angles, fitting these with the known ^{12}C cross sections,[8] and determining an average angle-independent normalization factor.

Figure 1(a) shows the spectrometer's acceptance function, which was measured by sweeping of the $\pi^+ + p$ elastic peak across the focal plane. As displayed in Fig. 1(b), the DIAS peak occupies approximately one-half of the focal plane. The momentum width of the peak is dominated by the 3% momentum spread of the incident beam. Regions to the left and right of the peak, where the acceptance is still large, contain almost no events, demonstrating the absence of background and the isolation of the DIAS peak. The backgrounds from the target cells and the ^{12}C contamination in the target were measured independently

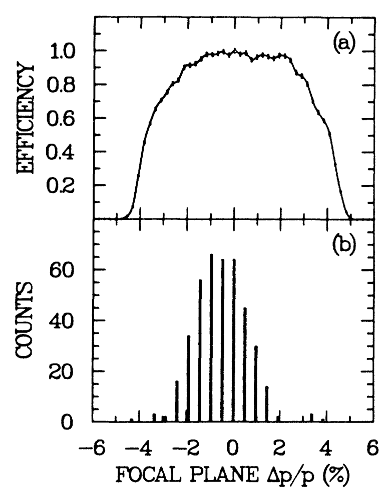

FIG. 1. (a) Spectrometer acceptance function measured with $\pi^+ + p$ elastic scattering. The elastic peak was stepped across the focal plane by variation of the spectrometer magnet current. (b) Measured π^- yield for the $^{14}C(\pi^+,\pi^-)^{14}O$(DIAS) reaction at 50 MeV and 20°. Note the small level of background counts for energies below and above the DIAS.

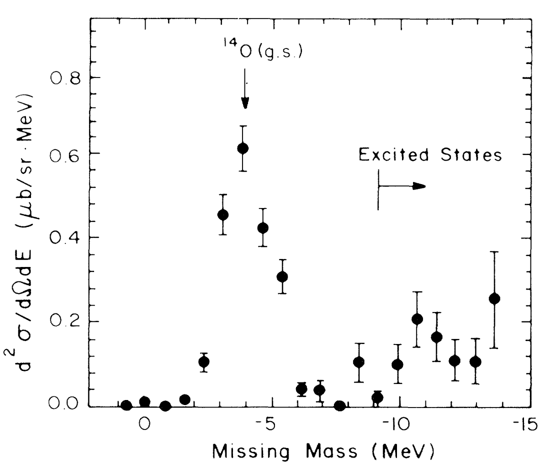

FIG. 2. Missing-mass spectrum measured for the $^{14}C(\pi^+,\pi^-)^{14}O$ reaction at 50 MeV and 60° scattering angle. The DIAS transition dominates the spectrum. Its expected position is shown by the arrow.

and found to be consistent with zero, as expected from the endothermic Q values for DCX on ^{12}C and for the DIAS transitions in copper. Figure 2 displays a more extensive (π^+,π^-) energy spectrum measured at 60° to show the relative strength of DIAS to non-DIAS transitions. These data were measured with three momentum settings of the spectrometer.

The measured DIAS cross sections as a function of scattering angle are presented in Table I and displayed in Fig. 3. The errors, which are dominated by counting statistics, represent all relative errors. The overall normalization uncertainty is estimated to be 10%, arising from a 7% uncertainty in the ^{14}C target thickness and a 7% uncertainty in the ^{12}C cross sections used for normalization. As is evident in Fig. 3, our results are in agreement with the measurements of Navon *et al.*,[2] over the angular range common to the two measurements. The new measurements are required to establish the forward-peaked nature of the angular distribution and provide a reliable basis for extrapolation to 0°.

The combined data of this work and Ref. 2 were found to be well represented by the convenient form $d\sigma/d\Omega_{\rm DIAS} = A\exp[\lambda(\cos\theta - 1)] + B$. The dashed curve in Fig. 3 is the result of a least-squares fit. It gives a 0° differential cross section $d\sigma/d\Omega_{\rm DIAS}(0°) = 3.9 \pm 0.5$ μb/sr and an integrated cross section $\sigma_{\rm DIAS} = 15.3 \pm 1.6$ μb. The error in the latter includes a 25% uncertainty assigned to the cross section obtained for the extrapolated region above 130°. The normalization uncertainty of 10% dominates the errors for $d\sigma/d\Omega_{\rm DIAS}(0°)$ and $\sigma_{\rm DIAS}$.

These cross sections are remarkable for their deviation from expectations based on previous data on IAS and DIAS transitions. The value of $d\sigma/d\Omega_{\rm DIAS}(0°)$ at 50 MeV is about 4 times larger than the values[2] measured for $d\sigma/d\Omega_{\rm DIAS}(5°)$ at energies 120 to 164 MeV that we have estimated from the available data.[3]

TABLE I. The measured differential cross sections for $^{14}C(\pi^+,\pi^-)^{14}O$ at 49.2 MeV (the laboratory pion energy at the center of the ^{14}C target.

$\theta_{\rm c.m.}$ (deg)	$(d\sigma/d\Omega)_{\rm c.m.}$[a] ($\mu$b/sr)
20.3	3.26 ±0.23
30.4	3.04 ±0.22
40.5	2.48 ±0.18
50.6	1.97 ±0.18
60.7	1.56 ±0.12
70.8	1.32 ±0.12
80.8	0.88 ±0.11
90.8	0.73 ±0.07
130.6	0.65 ±0.10

[a]The errors are relative; they do not include the 10% normalization error.

These large increases in $d\sigma/d\Omega_{\rm DIAS}(0°)$ and $\sigma_{\rm DIAS}$ at 50 MeV contrast sharply with the energy dependences of single-charge-exchange cross sections, both for the free nucleon and for ^{14}C. For the reaction $\pi^- p \to \pi^0 n$ the 0° cross section[4] decreases by a factor of nearly 3000 between 164 and 50 MeV and the integrated cross section decreases by a factor of about 10. For ^{14}C, the decrease in $d\sigma/d\Omega_{\rm IAS}(0°)$ over the same energy interval is more than a factor of 400.[4] This different behavior of the SCX and DCX cross sections is reflected in the ratio $[d\sigma/d\Omega_{\rm IAS}(0°)]/[d\sigma/d\Omega_{\rm DIAS}(0°)]$ which goes from a value 2.4×10^3 at 164 MeV to less than 1.5 at 50 MeV.

One might expect two large-angle SCX scatterings to produce a relatively large 0° DIAS cross section. However, if such sequential scatterings were the dominant contribution to $\sigma_{\rm DIAS}(0°)$, similar double-scattering diagrams, with one SCX scattering and one elastic scattering, would make even larger contributions to $\sigma_{\rm IAS}(0°)$.[1] Thus the smallness of the forward-angle IAS cross section (< 6 μb/sr) restricts the sequential scattering contributions for both IAS and DIAS transi-

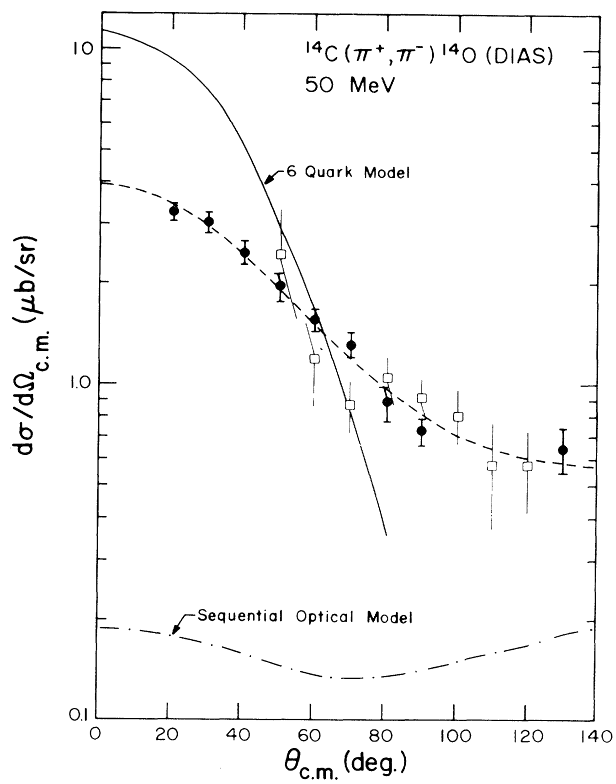

FIG. 3. Differential cross sections for the DIAS transition on ^{14}C: Solid data points are from the present experiment; open squares are from Ref. 2; the dashed line represents the function $A\exp[\lambda(\cos\theta - 1)] + B$ fitted to the data; the solid line shows the six-quark bag-model calculation of Ref. 1; the dot-dashed line is an optical-model calculation representing sequential SCX scatterings via the IAS.

tions. The expectation of small cross sections for such a process is confirmed by an optical-potential calculation representing sequential double-charge-exchange scattering through the IAS, as shown in Fig. 3. For this calculation,[9] optical-model parameters were used that give a good description of low-energy elastic scattering and of the measured[3] IAS angular distribution at 48 MeV on ^{15}N. Because the predicted sequential cross sections are considerably less than the measured values, we conclude that new mechanisms may play a large role.

One such mechanism is based on a six-quark cluster model as proposed by Miller.[1] In Fig. 3, we compare our measurements with the prediction of this model. The data are in qualitative agreement with the prediction of a forward-angle peak. A quantitative comparison shows that the measured angular distribution is not as sharply forward peaked as predicted and that the 0° cross section is overestimated by a factor of 3. The new data should provide impetus for further theoretical studies to determine whether mechanisms other than six-quark clusters can give the observed forward-angle cross section.

To summarize, we have measured the first nearly complete angular distribution for a DIAS transition. The deduced values of $d\sigma/d\Omega_{\mathrm{DIAS}}(0°)$ and σ_{DIAS} at 50 MeV are large compared to expectations based on extrapolations from higher-energy data. The angular distribution is forward peaked, in qualitative agreement with a prediction based on a six-quark bag model. Independent of this model, we conclude from the large size of the 50-MeV cross sections that new mechanisms may be required in future theoretical formulations of double-charge-exchange reactions at low pion energies.

We thank the LAMPF staff for the extraordinary assistance provided in mounting the experiment on very short notice. We thank E. R. Siciliano for permission to show his calculation in Fig. 3. This work was supported in part by the U.S. Department of Energy, the National Science Foundation, and the United States–Israel Binational Science Foundation.

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