PHYSICAL REVIEW C VOLUME 37, NUMBER 2 FEBRUARY 1988

Low-energy pion double charge exchange on Ca isotopes

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(Received 29 June 1987)

Differential cross sections for the double-isobaric-analog-state transition in the $^{42,44}Ca(\pi^+, \pi^-)$ reactions were measured at an incident energy of 35 MeV and 40°. The ^{42}Ca cross section (2.0 ± 0.5 μb/sr) is nearly as large as those of the lighter $T=1$ nuclei and only slightly smaller than that previously measured for ^{48}Ca (2.4 ± 0.7 μb/sr). The cross section for ^{44}Ca (1.1 ± 0.3 μb/sr) is half of this amount. These results are surprising when compared with simple expectations and point to the importance of the nonanalog route contribution at low energies.

Pion double-charge-exchange (DCX) transitions to double-isobaric-analog states (DIAS) are of fundamental interest since the process must involve at least two nucleons in order to conserve charge. These reactions are therefore directly sensitive to the magnitude and nature of two-nucleon correlations in nuclei. Earlier theoretical work[1-3] has pointed to the particular sensitivity of low-energy DCX reactions to the short-range properties of these correlations.

Previous measurements[4] of DIAS transitions at 50 MeV on the $T=1$ nuclei ^{14}C, ^{18}O, and ^{26}Mg showed that the angular distributions and the 0° cross sections are nearly nucleus independent. It was therefore expected that the ^{42}Ca DIAS cross section would be the same as for the other $T=1$ nuclei, while that for ^{48}Ca would be substantially larger due to its greater number of uncorrelated neutron pairs. In contrast, a recent measurement of the ^{48}Ca DIAS cross section at 35 MeV showed it to be about equal to that of the $T=1$ nuclei.[5]

In view of this unexpected result, we have measured the DIAS cross sections for ^{42}Ca and ^{44}Ca. The data point to a large role of nonanalog intermediate states and are consistent with recent theoretical treatments of DCX reactions in which shell-model correlations are explicitly included.[6]

The measurements were made at an incident beam energy of 35 MeV and a scattering angle of 40° using the Clamshell spectrometer on the low-energy pion channel at the Clinton P. Anderson Meson Physics Facility (LAMPF).[5] The Clamshell spectrometer is a single-dipole magnetic spectrometer with nonparallel pole faces, a flight path of about 2 m, and a solid angle of ~40 msr. After passing through a 1.6-mm scintillator, the outgoing pions were momentum analyzed in the magnetic field and were detected in an array of three scintillators of thicknesses 6.4 mm, 6.4 mm, and 10.2 cm, and two preceding *X-Y* drift chambers in the focal plane. The drift chambers were used to determine the trajectory, and hence the momentum, of each particle. Since the pions stopped in the scintillators, their total stopping energies were also determined from the measured pulse heights. The event trigger was provided by a coincidence between the scintillator at the entrance of the spectrometer and the first scintillator in the focal plane.

The DCX capability of the Clamshell rests upon the rejection of background events with low pulse heights in the first two scintillators (primarily electrons) and the selection of proper time of flight between these scintillators. Further reduction of background was accomplished using a comparison between the determinations of the pion energy from the trajectory in the magnetic field and the total stopping energy. The software cuts on time-of-flight and stopping energy were determined from π^- elastic scattering on ^{12}C with the same outgoing energy as the DIAS transitions. Since the π^- from DCX will star upon stopping the cut was opened from that for π^+ at large stopping energy.

The acceptance of the spectrometer across the focal plane was determined by measuring the yields of π^+ elastic scattering from ^{12}C as a function of magnetic field strength. Relative pion fluxes were measured by means of a toroidal current monitor through which the primary proton beam was passed. The absolute cross sections were determined with respect to π^+ elastic scattering from ^{12}C.[7]

The ^{42}Ca target consisted of two 5.15×5.15 cm plates of $CaCO_3$ with polystyrene binder. The total areal density of the two plates was approximately 0.805 g/cm^2, of which 0.286 g/cm^2 was ^{42}Ca (93.65% enrichment). The ^{44}Ca target was a single 5.0×10.0 cm plate of $CaCO_3$ with polystyrene binder. The total areal density of this target was approximately 1.564 g/cm^2 of which 0.422 g/cm^2 was ^{44}Ca (98.44% enrichment). The energy at the center of the targets was 33.6 MeV for ^{42}Ca and 32.0 MeV for ^{44}Ca.

The Q values for the DIAS transitions on the calcium isotopes are essentially equal. The DIAS transition on ^{42}Ca proceeds to the ground state of ^{42}Ti, with a Q value of -12.40 MeV. In the case of ^{44}Ca, the ground-state Q value is -2.90 MeV while that for the DIAS is -12.33 MeV. Thus, the DIAS appears at an excitation energy of 9.44 MeV in ^{44}Ti. For ^{48}Ca, the ground-state Q value is 5.29 MeV and the DIAS Q value is -11.84 MeV and the peak appears at an excitation energy of 17.13 MeV. The measured spectra for the three calcium isotopes [$A=42$, 44, and 48 (Ref. 5)] are shown in Fig. 1. The observed structures appear at the expected position in the spectra and are consistent with the shape of a single peak. The widths of the peaks are the result of the energy resolution and are dominated by energy-loss straggling in the targets. It is clear that for ^{44}Ca the overall energy resolution is not enough to distinguish the DIAS from the nearby nonanalog transitions. Nevertheless, within the errors discussed later, there are several reasons that justify assigning the full strength of the observed peak to the DIAS transition. First, the energy resolution and shape of the peak are consistent with what is expected from a single peak located at the expected DIAS excitation energy. Second, as can be deduced from the other two spectra as well as from measurements with better energy resolution on ^{14}C,[8] the nonanalog final state strength at this energy is small.

The measured differential cross sections are given in Table I. The cross sections were calculated by integrating the area of the observed peak after the background was subtracted. The background was assumed to contribute one count per channel. The statistical uncertainties are 13% for ^{42}Ca and 11% for ^{44}Ca. The systematic uncertainty of 16% is dominated by errors from normalization to the elastic scattering (11%), background subtraction (4%), acceptance correction (5%), and the software cuts (10%). The total uncertainties are about 25% for ^{42}Ca and 20% for ^{44}Ca. The relative uncertainties appropriate for comparing the different isotopes are smaller and are given in the table.

The ^{42}Ca cross section is nearly as large as those of the light $T=1$ nuclei.[4] Although much of the data for the lighter nuclei is about 50 MeV it has been seen that the cross sections for ^{14}C and ^{18}O are fairly constant in the 30 to 50 MeV energy range,[8] so a comparison of this 35 MeV data with the 50 MeV data on lighter nuclei is not unreasonable. This result establishes that the A dependence of low-energy DIAS cross sections for $T=1$ nuclei from ^{14}C up to ^{42}Ca is very weak. The differential cross section for ^{48}Ca is only slightly larger than that for ^{42}Ca and that for ^{44}Ca is only about half of this amount. These results are surprising when compared to the simple expectation

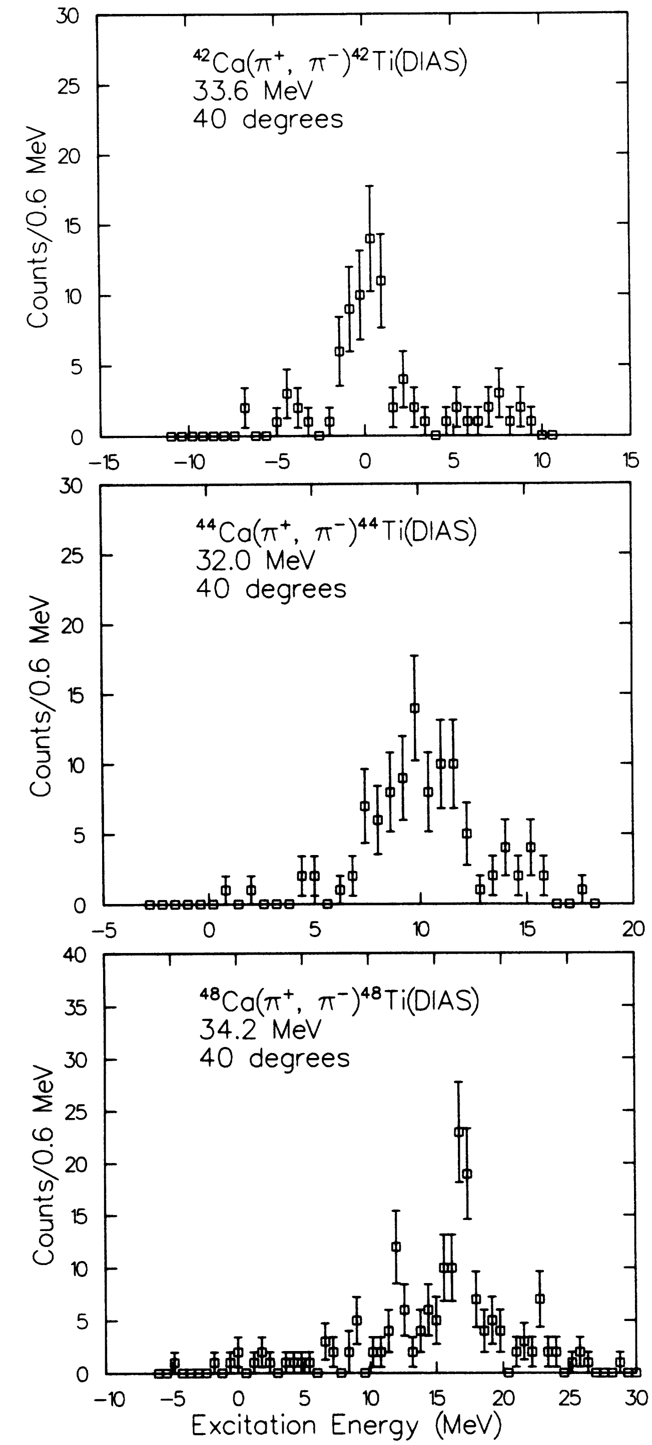

FIG. 1. Missing mass spectra for DCX reactions on ^{42,44,48}Ca at 35 MeV and 40°. The ^{48}Ca data are from Ref. 5.

that the DIAS cross section will increase as the total number of excess neutron pairs is increased.

One may compare our results with those from the (p,t) reaction within a model in which a $J=0$ neutron pair is converted to a proton pair. The DCX cross sections would then be proportional to the square of the ground-state (p,t) cross sections for the same target. Since the latter

TABLE I. The measured laboratory cross sections for the calcium isotopes at a laboratory scattering angle of 40°.

Isotope	T_π[a] (MeV)	$d\sigma/d\Omega$ (μb/sr)	Relative uncertainties[b] (μb/sr)
^{42}Ca	33.6	2.0 ± 0.5	(± 0.3)
^{44}Ca	32.0	1.1 ± 0.3	(± 0.15)
^{48}Ca	34.2	2.4 ± 0.7[c]	(± 0.6)

[a]Kinetic energy at the center of the target.
[b]Relative uncertainties appropriate for the isotopic comparison.
[c]Reference 4.

are known[9] to be approximately in the $(f_{7/2})^n$ shell-model ratio of 1:1.5:1 for the three calcium isotopes, the corresponding (π^+,π^-) cross sections would then be, within this simple model, in the ratio 1:2.25:1. Although the near equality of the ^{42}Ca and ^{48}Ca cross sections is correct, the ratio for ^{44}Ca is inverted from the data.

The forward-angle DIAS excitation functions for ^{42,44,48}Ca are displayed in Fig. 2. Contrary to the data at low energies, at high energies the ^{48}Ca cross section is much larger than for ^{42}Ca and that for ^{44}Ca is between the ^{42}Ca and ^{48}Ca values. At these high energies the DIAS transition is thought[12] to proceed predominantly by sequential scattering through the intermediate isobaric-analog state (IAS). At energies near 50 MeV a nearly complete cancellation between $\pi-N$ s and p waves produces a deep minimum in the forward-angle SCX cross sections to the IAS on nuclei.[13] This leads to a suppression of the analog route for the DIAS transition and a corresponding increase in the importance of transitions through nonanalog intermediate states.

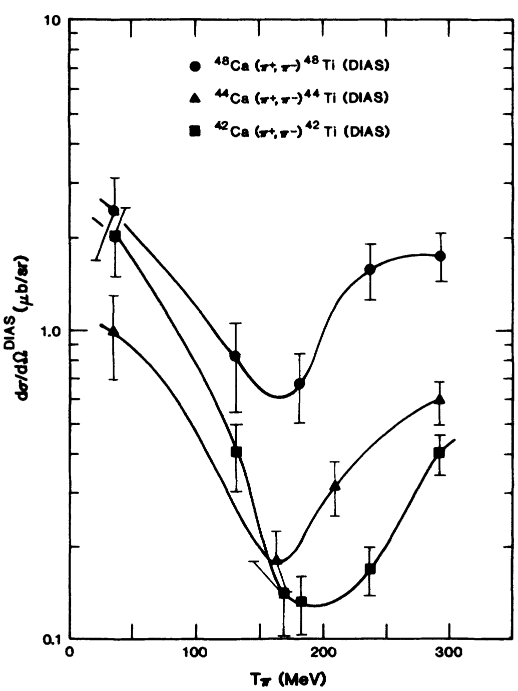

FIG. 2. ^{42}Ca, ^{44}Ca, and ^{48}Ca cross sections at forward angle vs incident pion energy from 35 to 290 MeV. The lines are to guide the eye. The 35 MeV data is at 40°. The ^{42}Ca data above 35 MeV are from Ref. 10 and the ^{44}Ca data from Ref. 11 (for a laboratory scattering angle of 5°).

Our results can be understood in terms of the shell-model description of DIAS transitions given recently by Auerbach, Gibbs, and Piasetzky.[6] The model is restricted to seniority-zero initial and final states within a single j shell. The DIAS cross sections can be represented in terms of two amplitudes A and B by the expression

$$\frac{d\sigma}{d\Omega}=\frac{n(n-1)}{2}\left[A+\frac{(2j+3-2n)}{(n-1)(2j-1)}B\right]^2 .$$

The A term represents the $L=0$ multipolarity of the two-body transition operator, while the B term represents sums over all $L\neq 0$ even multipoles. The B term vanishes in the absence of two-nucleon correlations and, in that case, the A term largely corresponds to sequential single-charge-exchange transitions through the IAS.[6] The factor in front of the B term is $+1$ for ^{42}Ca, $+\frac{1}{9}$ for ^{44}Ca, and $-\frac{1}{7}$ for ^{48}Ca.

The amplitudes A and B are complex. Therefore, three data points are required to empirically determine their values to within an overall phase. We have extracted values from the present 35-MeV data and these are given in Table II. These phenomenological A and B values are not physically unreasonable as confirmed by the preliminary results of plane-wave impulse calculations by Kaufmann and Gibbs.[14] The magnitude of B is nearly four times that of A. However, the weighting factor for the B term greatly suppresses its influence on the ^{44}Ca and ^{48}Ca transitions, whereas for ^{42}Ca the B term dominates the cross section. Thus, this model offers a natural explanation for the seemingly anomalous cross-section ratios across the Ca isotopes and supports the explanation that the relatively large ^{42}Ca cross section is due to a much larger role of short-range nucleon-nucleon correlations for this nucleus.

In summary, the cross sections for pion DCX reactions on the calcium isotopes at 35 MeV are not monotonically increasing functions of the total number of excess neutron pairs. Instead, the data require a treatment of shell-model correlations. A seniority-zero model of j^n configurations can produce agreement with the present data. The data we have presented point to the energy region, near 35 MeV, where nonanalog intermediate state contributions are especially important, and where further studies, both theoretical and experimental, should be performed. Such studies will improve our understanding of the reaction

TABLE II. Empirical magnitudes of the A and B amplitudes, and the relative phase angle ϕ between them.

$\lvert A\rvert$ [(μb/sr)$^{1/2}$]	$\lvert B\rvert$ [(μb/sr)$^{1/2}$]	ϕ (deg)	$\lvert B\rvert/\lvert A\rvert$
$0.34^{+0.03}_{-0.03}$	$1.20^{+0.13}_{-0.14}$	59^{+10}_{-13}	3.5 ± 0.5

mechanism and the correlations between the neutrons that undergo the transition.

We would like to thank the LAMPF staff for their assistance and support. We especially acknowledge the help of R. L. Boudrie. Illuminating discussions with N. Auerbach, M. Bleszynski, A. Gal, W. R. Gibbs, W. B. Kaufmann, and R. J. Glauber are gratefully acknowledged. This work was supported in part by the U.S.-Israel Binational Science Foundation, the Department of Energy, and the National Science Foundation.

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