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Observation of the Pion Double-Charge-Exchange Reaction $^{18}O(\pi^+, \pi^-)^{18}Ne$†

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The pion double-charge-exchange reaction $^{18}O(\pi^+, \pi^-)^{18}Ne$ has been observed. A value of $(d\sigma/d\Omega)(0°) = 1.78 \pm 0.30$ μb/sr was obtained at a pion energy of 139 MeV for the $\Delta T_z = 2$ isobaric analog transition from the ground state of oxygen-18 to the ground state of neon-18.

It has long been recognized that the pion double-charge-exchange (DCE) reaction could be a very useful tool in nuclear structure research.[1] In the simplest description, the $(\pi^{\pm}, \pi^{\mp})$ reaction is assumed to proceed through a two-step process whereby two neutrons (protons) in the nucleus are changed to two protons (neutrons). Thus, with this reaction one might expect to identify $\Delta T_z = 2$ isobaric analog states and nuclei off the line of stability (particularly proton-rich nuclei). Although numerous experiments[2] have been performed over the past twelve years in an attempt to detect nuclear transitions to specific final states, none has yet convincingly demonstrated such a transition. In this Letter, we report an unambiguous measurement of the pion DCE reaction $^{18}O(\pi^+, \pi^-)^{18}Ne$. The transition involved is the $\Delta T_z = 2$ isobaric analog transition from the ground state of oxygen-18 to the ground state of neon-18.

The differential cross-section $(d\sigma/d\Omega)(0°)$, at a mean pion energy of 139 MeV, was measured by utilizing the low-energy pion channel (LEP) of the Los Alamos Meson Physics Facility as both a pion channel and a spectrometer. The LEP channel is a four-bend vertical magnetic channel[3] in which the dispersed beam is momentum analyzed by a collimator at the channel midpoint between the second and third bending magnets. In this experiment, the pion DCE targets were placed at the channel midpoint immediately following the momentum collimator. As indicated schematically in Fig. 1, the first half of the channel was tuned for a π^+ beam, with a point focus

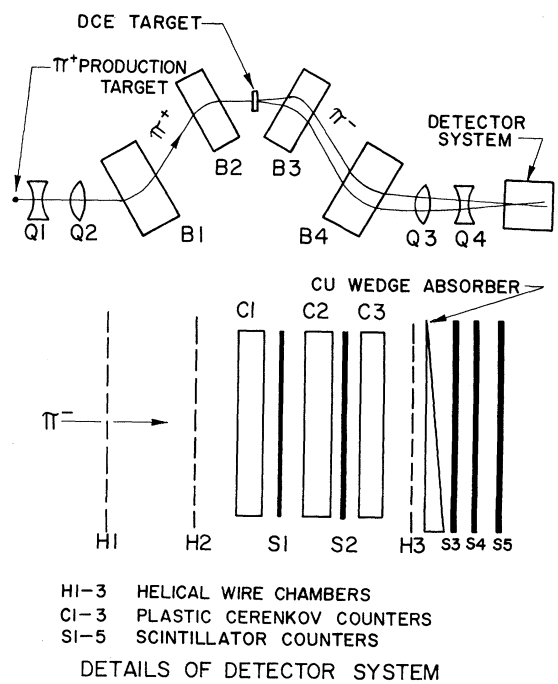

FIG. 1. Schematic layout of the LAMPF low-energy pion channel and DCE spectrometer.

at the channel center, while the second half of the channel was tuned with opposite polarity as a π^- spectrometer at a fixed zero-degree scattering angle. During the experiment, the incident pion flux was about 4×10^7 π^+/sec and was monitored by recording the integrated current of the primary proton beam used to produce the pion beam. The calibration of the pion-proton ratio was obtained from activation of a carbon sample and used the measured $^{12}C(\pi^+,\pi^+n)^{11}C$ cross section.[4] With the DCE target mounted at the channel midpoint, the second half of the channel approximately functions as an energy-loss spectrometer with a momentum acceptance $\Delta p/p = \pm 5\%$ and a solid angle $\Delta\Omega = 6.7$ msr.

The detection apparatus located at the end of the spectrometer, shown in detail at the bottom of Fig. 1, served to identify outgoing particles and to define their position on the spectrometer focal plane. An array of plastic Čerenkov and scintillation counters was used to discriminate between electrons and pions. Pion candidates were identified by the logic trigger requirement $S_1 \cdot S_2 \cdot S_3 \cdot$ anti(C_1 or C_2 or C_3). Electron-pion discrimination was achieved by the threefold Čerenkov-counter veto, pulse-height selection in scintillators S_3, S_4, and S_5, and time of flight between counter S_1 and the accelerator 201-MHz phase signal. Particle trajectories were measured with helical wire proportional chambers and were used to project the pion events onto the spectrometer focal plane. The spectrometer dispersion, approximately (2.4 cm)($p/100\Delta p$), yielded an intrinsic resolution of about 500 keV, although the observed resolution for this experiment was determined by target thickness.

Data from a run where the spectrometer was set for a central π^- energy of 130 MeV while the incident pion beam had a mean energy of 139 MeV are shown in Fig. 2(a). The DCE target was water, enriched to 91% ^{18}O, in the form of a 3.44-g/cm^2-thick gelatin disk. Events shown are those that passed the Čerenkov veto and scintillator pulse-height criteria. Particle time of flight (TOF) relative to the 201-MHz accelerator rf is plotted on the ordinate while the particle energy corresponding to position on the focal plane is plotted along the abscissa. Two bands are apparent in the TOF spectrum; as projected in Fig. 2(b), the upper band corresponds to the correct TOF for pions and the lower to the TOF for electrons. The two-dimensional spectrum allows observation of asynchronous background particles, and the region between the pion and electron bands is free, to 5%, from such contaminants. A dense clustering of events in the upper band appears at a pion energy of about 130 MeV. After eliminating the electrons by making the cut on TOF indicated in Fig. 2(b), we obtain the projection on the energy axis shown in Fig. 2(c). The peak in the energy spectrum at 130.7 MeV occurs at the expected location for the ^{18}Ne ground state. The width of 4 MeV is due mostly to multiple scattering and energy straggling in the thick $H_2{}^{18}O$ target. Since there is no evidence for appreciable excitation of the first ^{18}Ne excited state ($J^P = 2^+$, 1.89 MeV), we attribute the entire peak at 130.7 MeV to the transition to the ^{18}Ne ground state.

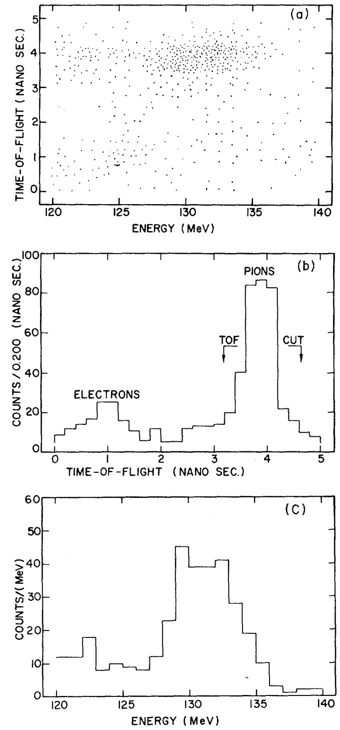

FIG. 2. Data at an incident mean pion energy of 139 MeV and a spectrometer setting of 130 MeV for events surviving the Čerenkov and scintillator electron rejection: (a) scatter plot of energy vs TOF; (b) projection on the TOF coordinate, showing a small residual electron band and very little (less than 5%) asynchronous background; (c) projection [after making TOF cut shown in (b)] on the energy coordinate, showing a peak at 130.7 MeV at the expected location of the ^{18}Ne ground state.

Measurements of the π^- spectra were taken for three different spectrometer energy regions. The combined results with central spectrometer settings of 130, 124, and 112 MeV, all for a 139-MeV π^+ beam on the DCE target, are shown in

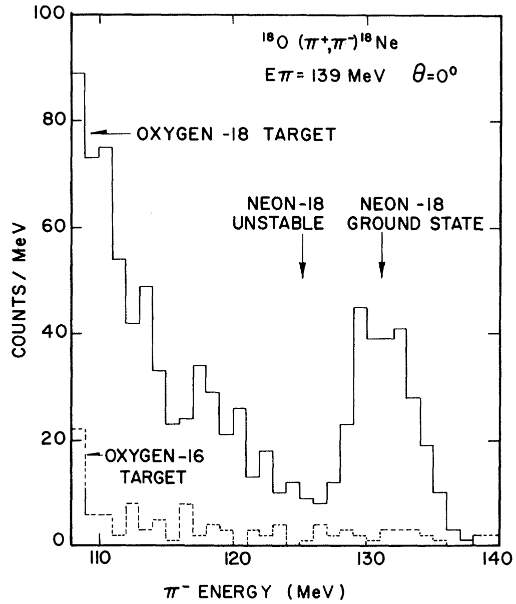

FIG. 3. Combined π^- spectra for three spectrometer settings. The DCE isobaric analog transition to the neon-18 ground state is clearly separated from the continuum. The dashed line shows a small background, as measured with an oxygen-16 target.

Fig. 3. Spectrometer acceptance and relative detector efficiency at the different settings have been unfolded from the spectrum shown. The peak from the DCE isobaric analog transition $^{18}O(\pi^+,\pi^-)^{18}Ne$ is clearly separated from the DCE continuum, which begins at about 4.5-MeV excitation in neon-18 and corresponds to a pion energy of 126 MeV. Data were also taken for an oxygen-16 target and are displayed in Fig. 3. Since the Q value for DCE on ^{16}O is 25.2 MeV, this target provides a realistic background measurement for the reaction $^{18}O(\pi^+,\pi^-)^{18}Ne$: All of the *non*pion DCE sources of background are present for pion energies around 130 MeV, while pions from DCE are present only for energies less than 110 MeV. It is evident from Fig. 3 that the background in the region of the DCE peak is quite small and flat. After subtracting this small background, we obtain a net number of 242 ± 17 events under the peak at 130-MeV π^- energy. Folding in a pion detection efficiency of 36%, obtained by sending a 130-MeV π^- beam through the spectrometer, we get a zero-degree differential cross section for the DCE reaction $^{18}O(\pi^+,\pi^-)^{18}Ne$ of

$$(d\sigma/d\Omega)(0°) = 1.78 \pm 0.30\ \mu\text{b/sr}.$$

The quoted error is dominated by systematic uncertainties in knowledge of the pion flux and detector efficiency.

Early calculations[5,6] of pion DCE on oxygen-18 gave cross sections considerably higher than the upper limits seen in experiments on other nuclei.[2] In anticipation of this experiment, there have been several recent predictions[7-9] which have attempted to improve upon the earlier work. These calculations are based upon some form of multiple-scattering theory and each has had reasonable success when applied to pion-carbon elastic scattering above 100 MeV; consequently, it is interesting to compare them to the results of this experiment. Table I lists the available results for $T_\pi = 139$ MeV. All calculations used the free-pion–nucleon scattering amplitudes as input and assumed transitions between pure $1d_{5/2}$ states. It is apparent from Table I that there is qualitative agreement between theory and experiment—in particular, that our results are bracketed by the several theories.

More detailed discussion of the present results, as well as additional data, will be presented in future publications. It is already clear, however, that the measured magnitude of the cross section, besides providing constraints on the theoretical analyses, also is large enough to allow pion double charge exchange to be used as a spectroscopic tool for the investigation of nuclear structure.

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TABLE I. Comparison of our experimental result with recent calculations based upon some form of multiple-scattering theory.

Theory and experiment	σ_T(DCE) (μb)	$(d\sigma/d\Omega)(0°)$ (μb/sr)	Ref.
Glauber approximation	0.9	2.2	7
Fixed scatter approximation	4.1	5.7	8
Optical (Laplacian)	0.7	0.6	9
(Laplacian with correlations)	46.0	38.0	
This experiment		1.78 ± 0.30	

opment of this experiment. We also thank the staff of the Clinton P. Anderson Meson Physics Facility (LAMPF) for their cooperation.

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High-Momentum-Transfer Electron Scattering from ^{208}Pb

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^{208}Pb elastic electron scattering data have been extended to large momentum transfer ($q = 3.7$ fm^{-1}). The present data combined with previous electromagnetic data allow a precise determination of the charge density. It shows a small central depression and density fluctuations much less pronounced than theoretically predicted.

Recent electron-scattering experiments have determined the density fluctuations of nuclear charge densities $\rho(r)$. Such measurements are one of the most stringent tests of theoretical microscopic wave functions. Furthermore, they are very sensitive to the details of the N-N force. For the only two well-investigated cases,[1-3] ^{48}Ca and ^{58}Ni, the experimental densities show much less structure than the best available theories. The most ideal nucleus for a quantitative comparison with theory is ^{208}Pb; its density is hardly influenced by long-range correlations,[4] and Hartree-Fock (HF) theory is most directly applicable to this heavy, doubly magic nucleus. The very large number of theoretical calculations available for ^{208}Pb offers an optimal opportunity to test present theories. Furthermore, as discussed by Friar and Negele,[5] the amount of structure predicted by different calculations varies strongly with the relative phase of the oscillations of neutron and proton densities. In Ca and Ni, these oscillations are in phase, while they are completely out of phase for ^{208}Pb. A measurement for Pb then would provide a valuable complementary information on the lack of structure previously observed.

Because of the maximum momentum transfer $q_{max} = 2.7$ fm^{-1} previously reached,[6] the fluctuations of $\rho(r)$ have not been determined to the precision necessary [$\delta\rho(0) = \pm 7\%$, as discussed below]. Moreover, previous analyses[6-8] provide conflicting values for $r < 4$ fm; this concerns in particular the possible existence of the much-disputed central depression.[6-9] The high-q experiment presented in this Letter was carried out in order to yield a precise determination of $\rho(r)$ at small radii.

The experiment was performed at the Saclay linear accelerator using the HE 1 end station.[10] The electron energy of 502 MeV was determined