Angular Distribution for $^{15}N(\pi^+, \pi^0)^{15}O$(g.s.) at $T_\pi = 48$ MeV

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Pion single charge exchange to the isobaric analog state of ^{15}N was measured at $T_\pi = 48$ MeV over the angular range 0–150°. The angle-integrated cross section at 48 MeV is 0.43 ± 0.07 mb. The most prominent feature in the measured angular distribution is a deep minimum near 0°. The data are compared with optical-model calculations and the effects of various second-order terms in the potential are investigated.

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We report the first measurement of a complete angular distribution of pion-nucleus single charge exchange (SCE) for pion energies below 100 MeV. The data are complementary to both low-energy elastic scattering and resonance-energy charge-exchange measurements. The most important feature of the data is its deep minimum at zero degrees, which is fundamentally different from the strong forward-angle peaking at resonance energy. A unique feature of low-energy SCE is the almost perfect cancellation between the π-nucleon *s*- and *p*-wave amplitudes in the forward direction. This produces the deep forward minimum whose predicted character and even existence are extremely sensitive to various second-order effects which can be included in optical-model calculations. We have investigated the need for various second-order effects, within the framework of one optical-potential calculation, by comparison with our data. Without any isovector second-order terms the calculation gives a maximum at forward angles. Including isovector terms representing correlations or absorption in the calculation can produce the forward-angle minimum.

The choice of ^{15}N as a target is dictated primarily by the 5.2-MeV separation between the isobaric analog state (IAS) and the next excited state of ^{15}O. The separation is approximately twice the instrumental resolution. Secondly, the data can be compared to the measured resonance-energy angular distribution.[1] In addition, the ground states of ^{15}N and ^{15}O are nearly pure $p_{1/2}$ holes relative to ^{16}O, thereby reducing the nuclear-structure uncertainties in the theoretical cross sections.

The data were taken with the LAMPF π^0 spectrometer,[2] set in its one-post configuration, in the low-energy pion channel of the Los Alamos Meson Physics Facility (LAMPF). The technique used to measure the charge-exchange angular distribution is similar to that described by Cooper *et al.*[3] The horizontal scattering angle was varied in 20° steps. The targets used were 2.46 g/cm^2 of CH_2 and 0.87 g/cm^2 of ^{15}N.

The cryogenic ^{15}N target cell had dimensions 10 cm high by 15 cm wide by 1 cm thick. The evaporative refrigerant was ^{14}N held at a pressure of 120 mm by a vacuum pump, thereby keeping the ^{15}N supercooled. The windows were kept parallel by balancing the gas pressure of the ^{15}N and the hydrostatic level of ^{15}N liquid with He gas around the ^{15}N. The six vacuum and helium windows were Mylar and had a total thickness of 0.1 g/cm^2. The target thickness was obtained both from the measured depth and density and by the method of range differences[4]; the two results were the same to 2%.

The spectrum at 40° is shown in Fig. 1(a). The prominent peak just below 50 MeV is the IAS transition. It has a cross section of 26 μb/sr. As a result of the population of other excited states and continuum charge exchange, an unfolding technique was required to extract the area of the IAS peak. Angle-dependent spectrometer aberrations destroyed the good resolution at back angles [Fig. 1(b)] and made a reliable unfolding method essential.

The likelihood method described in Ref. 3, with a few modifications, was used in the unfolding. Instead of empirical line shapes, a Monte Carlo simulation of the acceptance of the spectrometer was used to obtain the angle-dependent line shapes. The resolution varied from 3.1 to 6.5 MeV for the angles 40 and 120°, respectively. All parameters of the simulation were experimentally determined. These parameters included the beam energy and phase space, the target characteristics, the wire-chamber and lead-glass resolutions, and the converter fiducial areas. Known kinematic energies of nuclear states and the threshold for three-body breakup were used in the fitting. Only the intensities of the peaks and the target-unrelated background were free parameters.

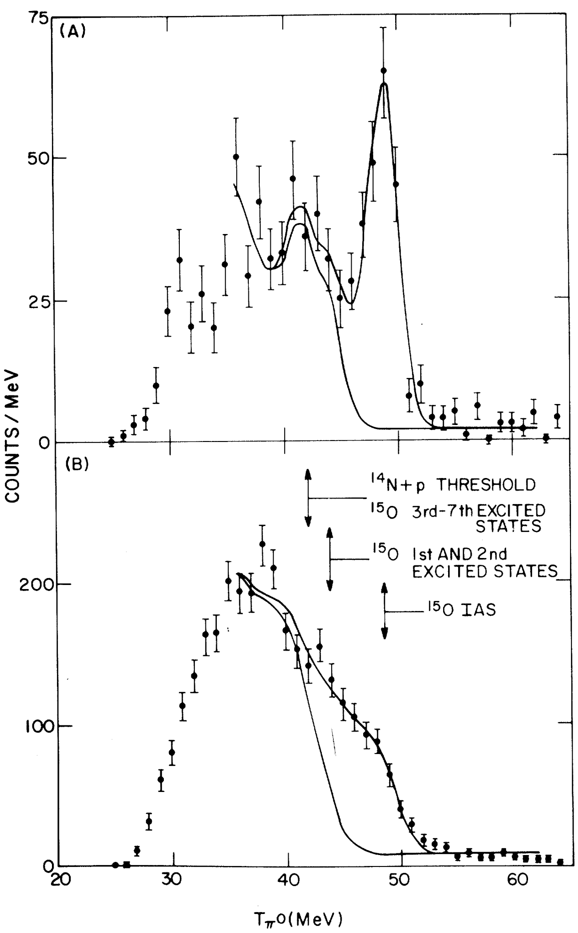

FIG. 1. Spectra for ^{15}N(π^+,π^0) at $T_{\pi^+}=48$ MeV for (a) $\theta=40°$ and (b) $\theta=120°$. The curves represent the fits to the spectra including the IAS, two groups of excited states, and the continuum. The background from all events excluding the IAS is shown also.

The extraction of the peak areas depends critically on the modeling of the line shapes. Figure 1(b) shows the fit to all events in the spectrum and the total background to the IAS. The procedure is convincing because of the high-quality fit to the 40° spectrum of Fig. 1(a). Contributions from two groups of states, each group treated as a single line, were required for a good fit at all angles. The first group was due to the first and second excited states of ^{15}O and the second group was due to the third through seventh excited states; the groups were also represented by the IAS line shape. Leaving out either group of states substantially degraded the value of the goodness-of-fit criterion. Additional support for this procedure is obtained from the excellent fit, even in the tails of the peak, to the π^0 spectrum from the reaction $\pi^-p\rightarrow\pi^0n$ on CH_2.

The normalization of the cross section required knowledge of the beam flux, the target thickness, and the geometric solid angle, efficiency, and energy acceptance of the π^0 spectrometer. The beam flux was monitored by a toroidal pickup loop about the primary proton beam. The monitor was calibrated to the pion flux by measuring ^{11}C activity from the reaction ^{12}C($\pi^\pm,\pi^\pm N$)^{11}C and comparing to the known[5] cross sections at 50 MeV of 10.3 ± 0.6 mb and 6.1 ± 0.5 mb for π^+ and π^-, respectively. The geometric solid angle and energy acceptance of the π^0 spectrometer were calculated in the Monte Carlo simulation.

The π^0 spectrometer efficiency was calculated from monitors of the multiwire chambers and live time, the photon absorption coefficients of materials between the target and detectors, and the photon conversion probability. Typical pion fluxes were 2×10^6 s^{-1}; the solid angle was about 3 msr in each angular bin; and the efficiency was about 20%. The dominant errors aside from counting statistics were from the flux normalization (6.2% in the activation cross sections) and the chamber efficiencies (5%). The normalization procedure was checked by comparing the cross section from the reaction $\pi^-p\rightarrow\pi^0n$ at 60° to phase-shift analyses. These analyses vary by 15%. The average value agreed to the 15% accuracy of the measurement.

The angular distribution at 48 MeV for $^{15}N(\pi^+, \pi^0)^{15}O$ is shown in Fig. 2(b). The error bars include both the angle-dependent and overall normalization errors. The 10% normalization error masks the angle dependence of the error from statistics (largest near 0°) and the error from unfolding the peaks (largest near 150°). The angular distributions of the excited-state groups are not shown because the groups are not isolated states and their errors are large. The angle-integrated cross section for the IAS is 0.43 ± 0.07 mb. This value is comparable to the 0.67 ± 0.07 mb measured radiochemically[6] for $^{13}C(\pi^+, \pi^0)^{13}N$.

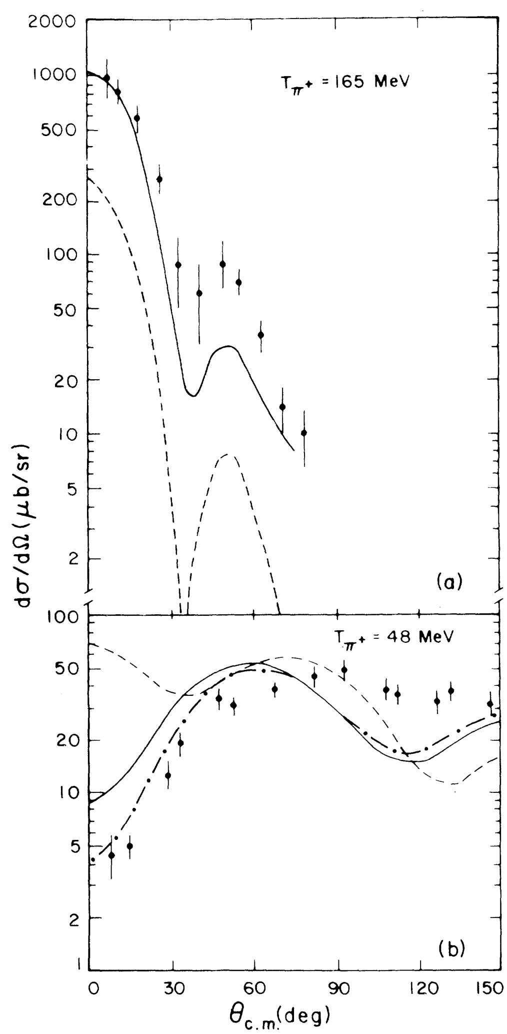

FIG. 2. Angular distribution for the IAS transition $^{15}N(\pi^+, \pi^0)^{15}O$ at $T_\pi = 165$ MeV and $T_\pi = 48$ MeV. The curves shown are optical-model calculations by E. R. Siciliano. The solid curve includes a correlation term. The dot-dashed curve has a correlation term and an absorption term. The dashed curve has neither.

The primary feature of the data is the deep minimum at forward angles. By contrast, the resonance-energy angular distribution is forward peaked and diffractive in character [Fig. 2(a)],[1] because of the localization of the scattering at the surface by the strong absorption. The low-energy charge exchange cannot be considered diffractive and the smoothness of the angular distribution is presumably related to the increased nuclear transparency for 50-MeV pions. The minimum occurs in an angular region where the corresponding elastic-scattering amplitudes are dominated by Coulomb scattering. Isovector contributions to the elastic scattering would be difficult to measure near 0°.

The deep forward-angle minimum in the ^{15}N SCE cross section at 48 MeV reflects the analogous minimum in the free-nucleon cross section, which is caused by a cancellation between the *s*- and *p*-wave π-nucleon amplitudes. This cancellation is nearly perfect and hence, in the nucleus, is extremely sensitive to medium effects which can cause changes in the relative strength of the *s* and *p* waves. Clearly this provides a valuable tool for studying medium effects such as correlations, Pauli blocking, and true pion absorption.

We have explored the need for so-called second-order effects within the framework of the theoretical model advanced by Siciliano and Johnson.[7] We realize that any specific conclusions we can draw are model dependent but we believe that the general conclusions drawn below are strong enough to survive within other future models. A future theoretical paper will present the details of this theoretical model and of the studies using it at low energies.

We used an optical potential which is analogous to that of Stricker, McManus, and Carr (MSU)[8] and which agrees well with elastic scattering at this energy. It contains second-order isoscalar terms which were found to be important for low-energy elastic scattering. This form of the potential cannot produce a forward-angle minimum for SCE at 50 MeV; in fact it produces a maximum at forward angles. We found that a second-order isovector term representing correlations, analogous to the isoscalar correlation term λC_0^2 of MSU, can produce the deep minimum and that a term representing absorption can also produce similar but less strong effects. This is illustrated in Fig. 2. Calculations by Landau and Thomas with Pauli blocking also produce similar qualitative agreement.[9]

Since the π-nucleon phase shifts are uncertain at this energy, and since at present only one active theoretical effort is studying this problem, it is difficult to make any conclusions other than the very general ones above. We anticipate that the measurements which will be made soon on ^{1}H and on other nuclei, along with a larger theoretical effort, will allow more specific conclusions to be drawn.

In summary, these data represent the first measurement of a complete angular distribution for pion charge exchange below the 3-3 resonance. The primary feature of the ^{15}N(π^+, π^0) data is the deep minimum near 0°. Optical-model calculations require inclusion of second-order isovector effects representing correlations, absorption, or Pauli blocking in order to reproduce this minimum. Future data which map out the systematics of this minimum with A and energy should prove a powerful tool in determining the nature and importance of these effects.

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