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Pion single charge exchange on ^{7}Li at low energies

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Forward-angle differential cross sections for the isobaric-analog-state transition, $^7\mathrm{Li}(\pi^+,\pi^0)^7\mathrm{Be}$, were measured at 33.5, 41.1, 48.7, and 58.8 MeV. A minimum in the excitation function of ^{7}Li at 42.3 ± 1 MeV reflects the analogous minimum in the free πN cross section, which, according to current phase-shift analyses, is between 45 and 50 MeV. The data are compared with optical-model calculations.

At energies below 100 MeV, the interaction of pions with nuclei is fundamentally different from the interaction near (3,3) resonance energies. The pion-nucleus total cross section is much smaller and the nucleus appears relatively transparent in comparison to its strongly absorptive nature near the π-nucleon (3,3) resonance. The results of phenomenological optical-potential studies of low-energy pion-nucleus elastic scattering have revealed the need for higher order terms such as nucleon-nucleon correlations and true pion absorption.[1]

Near 50 MeV the free nucleon charge-exchange angular distribution is strongly backward-peaked with a deep forward minimum. Furthermore, phase-shift analyses predict that the 0° cross section has a minimum around 50 MeV. This minimum is a result of a near-perfect cancellation of the *s*- and *p*-wave π-nucleon amplitudes in the forward direction. Since the nucleus is relatively transparent at low energies, the nuclear single-charge-exchange (SCX) reaction to the isobaric-analog state (IAS) may show the same features. Of course, in nuclear matter these features will be modified by nuclear medium effects such as absorption and Pauli blocking. Recently the first such measurement, $^{15}\mathrm{N}(\pi^+,\pi^0)^{15}\mathrm{O}$, was made at 48 MeV and confirmed the backward peaking of the angular distribution.[2] Theoretical calculations with the optical-model code of Siciliano and Johnson[3] appear to require isovector nucleon-nucleon correlations in order to reproduce the backward peaking at low energies. In these calculations the correlations provide a decrease in the effective *p*-wave strength in the optical potential. In this paper we report the first measurement of the energy dependence of the 0° cross section for the $^7\mathrm{Li}(\pi^+,\pi^0)^7\mathrm{Be}$ (IAS) reaction in the range from 35 to 60 MeV. The data demonstrate the energy dependence of the *s*- and *p*-wave cancellation.

The experiment was performed at the low-energy pion channel of the Clinton P. Anderson Meson Physics Facility (LAMPF). Data were taken at pion energies of $T_{\pi^+}=33.5$, 41.1, 48.7, and 58.8 MeV. The π^0 spectrometer was set in its one-post configuration (horizontal scattering plane) at a 0° scattering angle.[4] The distance to the first converter was 54 cm and the angle between the spectrometer arms was 93.72°. This configuration optimized the acceptance of the spectrometer for 50-MeV π^0's and gave an angular coverage of the π^0 scattering angle from 0° to 25°.

The pion flux was 10^7 per second and was determined by the scintillator-activation technique,[5] which has an absolute accuracy of 5—12 % and a reproducibility of 2%. The 99%-enriched ^{7}Li target used in this experiment was 1.5 ± 0.03 cm thick. The determination of the absolute solid angle of the spectrometer involves knowledge of geometrical solid angle, the γ to charged-particle conversion probability of the converters, efficiencies of the detector elements, live time, and event-reconstruction efficiencies. The combined contribution of the geometrical solid angle and energy acceptance of the spectrometer was calculated with a Monte Carlo computer program simulating the data-taking conditions. The solid angle ranged from 5 to 8 msr. The γ-conversion probability was 0.39 ± 0.02. The reconstruction efficiency was 0.87 ± 0.03. Overall normalization of the cross section is accurate to 10—15 %. The same normalization procedure was applied to data for the $\pi^- p \rightarrow \pi^0 + n$ reaction at 130 MeV. The cross section determined agreed to within 10% with those given by phase-shift predictions.[6]

Typical π^0 spectra for the incident-pion beam energies of 33.5, 41.1, 48.7, and 58.8 MeV are shown in Fig. 1. The π^0 energy resolution (FWHM) in these measurements was 3—3.5 MeV. Angle-dependent line shapes, together with kinematic constraints on the energies of state in ^{7}Be and the three-body threshold, were used to separate the IAS peak from the continuum charge exchange and background. The line shapes were obtained by Monte Carlo simulation of the beam, target, and spectrometer conditions.[4] The Monte Carlo spectrum reproduces both the shape and the width of the real π^0 spectrum. The decomposition of the spectra into background and the IAS peak can be seen from the dashed lines in Fig. 1. The background to the IAS consisted of π^0's from the second excited state of ^{7}Be, the continuum from breakup channels, and charge exchange on the air. The second excited state is a $\frac{7}{2}^-$ state at 4.57 MeV and its cross section is expected to be small near 0°. The goodness-of-fit criteria favor its inclusion with an area small compared to the IAS area (see Fig. 1). The kinematic relations among the components of the spectra were maintained in the fitting. The data were fitted by the maximum likelihood described in Ref. 7. A contribution from the uncertainty in the background due to the second excited state is included in the error for the IAS peak. The statistical and instrumental error in the extraction of the IAS area is about 15%. The error due to the unfolding of the IAS peak was typically 50% of the statistical error.

In the ^{7}Li$(\pi^+,\pi^0)^7$Be (IAS) transition the initial and final states are $\frac{3}{2}^-$. The first excited state of ^{7}Be ($\frac{1}{2}^-$ at 0.43 MeV) is connected to the ground state of ^{7}Li by an $L=1$ spin-flip transition. At forward angles we expect this transition to be suppressed by both its $L=1$ character and the $\sin\theta$ dependence of the spin-flip amplitude. In the low-energy region, the cancellation in $L=0$ between s- and p-wave amplitudes makes the cross sections small. Therefore the contribution from an $L=2$ transition could be relatively important to the population of the IAS. In the plane-wave approximation the contribution from $L=2$ transition to the ground state is zero. However, in the presence of distortions one should expect contribution from $L=2$ transition to the cross sections. The non-spin-flip $L=2$ transitions initiated from the ground state of ^{7}Li are $\frac{3}{2}^- \rightarrow \frac{1}{2}^-$, $\frac{3}{2}^- \rightarrow \frac{3}{2}^-$, $\frac{3}{2}^- \rightarrow \frac{5}{2}^-$, and $\frac{3}{2}^- \rightarrow \frac{7}{2}^-$. In a strong-coupling model, the intrinsic state of all members of a rotational band is the same, and the transitions to the members of the band are related by Clebsch-Gordan coefficients.[8] The ratio of cross sections for populating the $\frac{3}{2}^-$ (0.0 MeV) and the $\frac{7}{2}^-$ (4.57 MeV) is 1:7. We estimate that the cross section of the $\frac{7}{2}^-$ state is less than one-third of the IAS cross section (see Fig. 1). Thus, we conclude that the $L=2$ contribution is less than that indicated by the error bars on the data. Although contributions from the spin-flip transition and quadrupole transition to the ground state should be negligible, we cannot absolutely rule out small contributions from them to the IAS peak.

In Fig. 2 and Table I we present the measured cross sections at the mean acceptance angle for each bin. The error bars include statistical fluctuations, instrumental error in the extraction of the IAS peak, and overall normalization uncertainty of the data. The shape of the angular distributions is energy dependent. The energy dependence is presumably because of the change in the relative size between the s- and p-wave scattering contributions to the interference. For comparison we show the ^{15}N$(\pi^+,\pi^0)^{15}$O (IAS) data of Cooper *et al.*[2] at $T_\pi = 48$ MeV. At forward angles there is a difference between the ^{7}Li data at $T_\pi = 48.7$ MeV and the ^{15}N data. The ^{7}Li data of the two largest angles were taken concurrently with the ^{15}N data. The difference between the forward-angle behavior in ^{7}Li

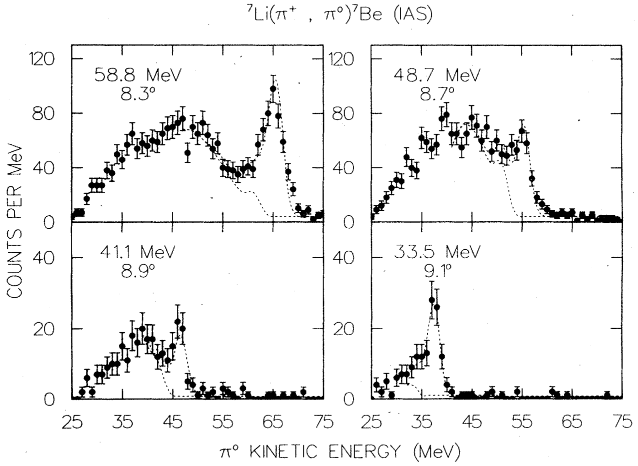

FIG. 1. Measured π^0 spectra for the ^{7}Li$(\pi^+,\pi^0)^7$Be (IAS) reaction at 33.5, 41.1, 48.7, and 58.8 MeV incident beam energy. The dashed curves show the fits to the IAS, and the second excited state.

TABLE I. The measured ^{7}Li$(\pi^+,\pi^0)^7$Be (IAS) cross sections.

T_π (MeV)	$\theta_{\text{c.m.}}$ (deg)	$d\sigma/d\Omega_{\text{c.m.}}$ (μb/sr)
33.5	0.0	16.6±7.5[a]
	9.3	22.0±3.6
	13.6	31.3±4.3
	21.0	31.0±5.1
41.1	0.0	8.0±2.9[a]
	9.2	11.1±1.4
	13.8	12.1±1.3
	20.6	14.8±1.9
48.7	0.0	16.7±4.3[a]
	8.9	16.6±2.4
	14.1	17.2±2.3
	21.1	16.4±2.6
58.8	0.0	58.7±10.6[a]
	8.5	55.4±6.3
	13.9	41.1±5.3
	21.6	40.9±6.3

[a] Measured 0° differential cross section, as discussed in the text.

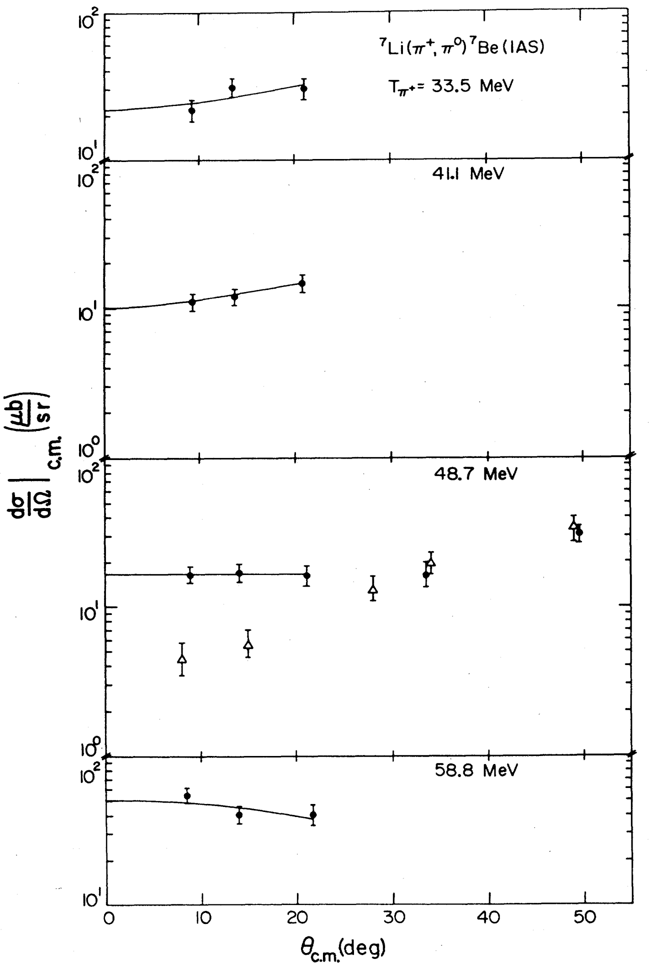

FIG. 2. Angular distribution for the IAS transition ^{7}Li(π^+,π^0)^{7}Be at $T_\pi=33.5$, 41.1, 48.8, and 58.8 MeV. The triangles represent ^{15}N(π^+,π^0)^{15}O data of Ref. 2 at $T_\pi=48$ MeV. The lines through the data points were used to extrapolate the cross section to 0°.

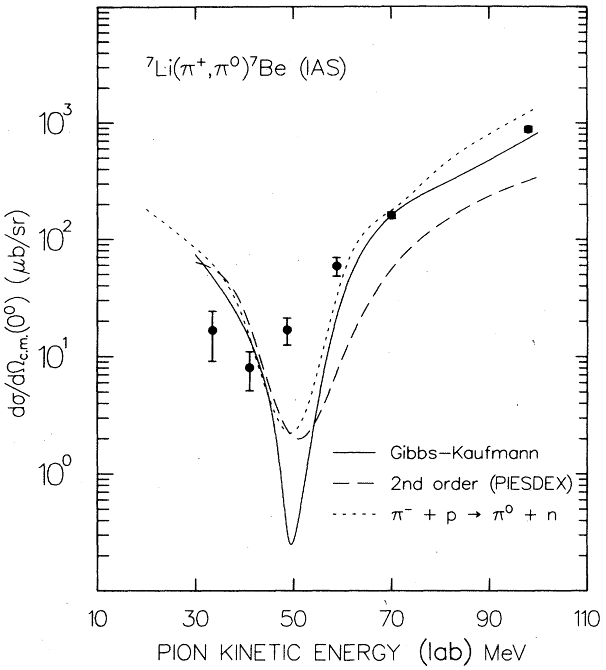

FIG. 3. Comparison of the measured 0° cross section with theoretical calculations. The dashed curve is the second-order optical-model calculations (Ref. 3). The dotted curve represents the free-πN cross sections (Ref. 6). The solid curve represents the Kaufmann-Gibbs calculations (Ref. 10).

and ^{15}N indicates that π-nucleus charge exchange at these low energies is sensitive to the effects of the nuclear medium. This may be interpreted as a shift in the relative strength of the *s*- and *p*-wave π-nucleon amplitudes, thus causing the delicate cancellation to be less complete for ^{7}Li than for ^{15}N. However, if there are contributions from $L=2$ transitions to the ground state or first excited state of ^{7}Be, the above discussion may be only a partial explanation.

The 0° cross sections were extrapolated by fitting the angular distributions with an $A+B\theta^2$ functional form. This is based on an expansion of angular distribution at small angles in terms of the Legendre polynomials. To keep the derivative of the angular distribution continuous at 0°, only even powers of angle were included in the expansion. Using the above functional form for extrapolation to 0° includes a possible contribution from the spin-flip state ($\sin^2\theta$ shape) and therefore the 0° extrapolated cross section should be free of any such spin-flip contribution. The measured 0° excitation function is shown in Fig. 3. The error bars are the combined error from the extrapolation to 0°, the uncertainty in the normalization, the statistical fluctuations, and error in the extraction of the peak area. The data points at 70 and 98 MeV were taken previously with the π^0 spectrometer.[9] There is a minimum in the 0° excitation function of ^{7}Li that reflects the analogous minimum in the excitation function of the free-nucleon charge exchange. To estimate the location of the minimum, we fitted the four data points with a parabolic function. The minimum of the parabola is at 42.3 ± 1 MeV.

In Fig. 3 we present the Kaufmann-Gibbs calculation[10] for ^{7}Li(π^+,π^0)^{7}Be (IAS) excitation function (solid line). This calculation was done in the distorted-wave-impulse approximation. The distorted waves are calculated with ^{16}O shell structure, but with a density scaled to the ^{7}Li nucleus. Also, effects of nucleon binding and Pauli blocking are explicitly considered in construction of the distorted waves. In this calculation the transition density is obtained from the product of wave functions that are solution in a Woods-Saxon well with proper binding energy. Charge-exchange amplitudes are obtained from the phase-shift analysis of Rowe *et al.*[6] (dotted curve in Fig. 3). The minimum in the free-πN excitation function is less shallow than the Kaufmann-Gibbs predictions for ^{7}Li.

The dashed curve in Fig. 3 represents the optical-model calculations that were done with the computer code PIESDEX developed by Siciliano and Johnson.[3] In this calculation the first-order terms in the optical potential are determined from the free-πN phase shifts.[6] A second-order term representing isovector nucleon-nucleon correlations is included in the optical potential. This second-order parameter was found to produce the deep minimum seen in the ^{15}N SCX cross section at 48 MeV.[2] The PIESDEX calculation shown in Fig. 3 was done with the Skyrme III model for the transition density; however, the 0° prediction is insensitive to the choice of the transition density.

There are discrepancies between different phase-shift predictions[6,11,12] for position and depth of the minimum in the elementary excitation function. These phase shifts predict this minimum to be between 45 and 50 MeV. Unfortunately, there are no published data at the present time to resolve these discrepancies. It is interesting to note that the location of the minimum in the ^{7}Li data obtained in this work is lower by 3 to 8 MeV compared to the π-nucleon minimum as predicted by various phase shifts. The Kaufman-Gibbs and PIESDEX calculations presented here both obtain the charge-exchange amplitudes from the phase-shift analysis of Ref. 6 (dotted curve in Fig. 3). The minimum in the ^{7}Li excitation function is lower by about 10 MeV than that predicted by PIESDEX and Kaufmann-Gibbs calculations. It is apparent that the failure of the both calculations in predicting the position and depth of the minimum is due partly to the phase-shift analysis used in the calculations. A PIESDEX calculation which obtains the nucleon charge-exchange amplitudes from the phase-shift analysis[6] evaluated at an incident energy 7 MeV higher than the actual energy can reproduce the location of the minimum. This also suggests that the phase-shift solution used in the calculation is likely to be incorrect. This problem will be resolved soon by new measurements of $\pi^- + p \to \pi^0 + n$ (Ref. 13). Hence, the discrepancy between calculation and data cannot be taken seriously at this time.

In summary, the measurements of the ^{7}Li(π^+,π^0)^{7}Be (IAS) transition at energies below 100 MeV have shown that the 0° excitation function has a minimum around 42 MeV. Optical-model calculations do not reproduce the position nor the depth of the minimum. No quantitative comparison of theory to experiment is possible until the $\pi^- + p \to \pi^0 + n$ cross sections at 0° are measured more precisely.

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