Energy and Mass Dependence of Low-Energy Pion Single Charge Exchange to the Isobaric Analog State

F. Irom, M. J. Leitch,[a] H. W. Baer, J. D. Bowman, M. D. Cooper, and B. J. Dropesky[a]
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

E. Piasetzky
Los Alamos National Laboratory, Los Alamos, New Mexico 87545, and Physics Department, Tel Aviv University, Tel Aviv, Israel

and

J. N. Knudson
Arizona State University, Tempe, Arizona 85287
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Forward-angle differential cross sections at low energies (≤ 80 MeV) are reported for pion single charge exchange to the isobaric analog state for nuclei from ^{7}Li to ^{120}Sn. A minimum in the 0° excitation function near 50 MeV persists for all of the measured nuclei and reflects the analogous minimum in the $\pi^- p \to \pi^0 n$ cross section that is caused by a nearly perfect cancellation of the *s*- and *p*-wave π-nucleon amplitudes. The persistence of this feature in these nuclei indicates a strong suppression of the net effect of the medium and constrains the interplay of the medium effects.

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At energies well below the (3,3) resonance the forward-angle π-nucleon charge exchange is characterized by an interference phenomenon with a sharp energy dependence. This is caused by a nearly complete cancellation between the repulsive *s*-wave and attractive *p*-wave isovector interactions and results in a very deep and sharp minimum in the forward-angle π-nucleon charge-exchange cross section near 45 MeV.[1] The appearance of this cancellation could be substantially modified in nuclei because of medium effects. Its manifestation and existence in nuclei will depend on the relative contribution of the *s*- and *p*-wave parts of the amplitude. Because these contributions can be altered by effects such as nucleon correlations, Pauli blocking, and true absorption, the investigation of forward-angle pion single charge exchange (SCX) to the isobaric analog state (IAS) in this energy regime can be a sensitive method for the study of nuclear-medium effects.

Pion single charge exchange to the IAS at low energies is also a cornerstone for the construction of a more complete picture of low-energy π-nucleus interactions, along with elastic scattering and double charge exchange (DCX). The latter involves two nucleons, and it will be necessary to understand the sequential-SCX contribution to DCX before conclusions about other effects, such as correlations, can be reached.[2]

In this Letter we present foward-angle measurements of π^+ SCX-IAS transitions on ^{7}Li, ^{14}C, ^{15}N, ^{39}K, and ^{120}Sn at several energies between 30 and 80 MeV and compare them to measurements of the $\pi^- p \to \pi^0 n$ reaction. The new data extend the few previous measurements[3–6] to heavy nuclei and give the energy dependence for several of the lighter nuclei. These data will also be presented in more detail, along with theoretical comparisons and analyses, in a later paper.[7]

The data were obtained with the LAMPF π^0 spectrometer at the low-energy pion channel of the Clinton P. Anderson Meson Physics Facility (LAMPF). The π^0 spectrometer (described in detail by Baer *et al.*[8]) was set up in its one-post configuration. For obtaining most of the data, the distance to the first converter was 55 cm, and the angle between the spectrometer arms was 92.42°. This configuration optimized the acceptance of the spectrometer for 52-MeV π^0's. For obtaining the 80-MeV data, the distance to the first converter was 73 cm and the opening angle between the two photon detectors was 75.70°. The π^0 energy resolution (FWHM) was 4–6 MeV, depending on target thickness, spectrometer angle, and the momentum spread.

Cross-section normalization was obtained with use of the techniques described in Refs. 1 and 3–7. The pion flux of 5×10^6 to 3×10^7 π/s was determined relative to the known activation cross sections for the reaction ^{12}C($\pi^\pm$, πn)^{11}C.[9] The targets used in these measurements were (1) a ^{7}Li target, enriched to 99% with a thickness of 0.801 g/cm^2; (2) a cryogenic ^{15}N target, which was a supercooled liquid with thickness 0.867 g/cm^2; (3) a ^{39}K target, consisting of natural potassium (93.3% ^{39}K) of thickness 0.541 mg/cm^2, enclosed in a stainless-steel frame with 0.033-mm Havar windows; (4) a ^{120}Sn target ($\sim 98.6\%$ ^{120}Sn) with a thickness of 1.46 g/cm^2; and (5) a ^{14}C target

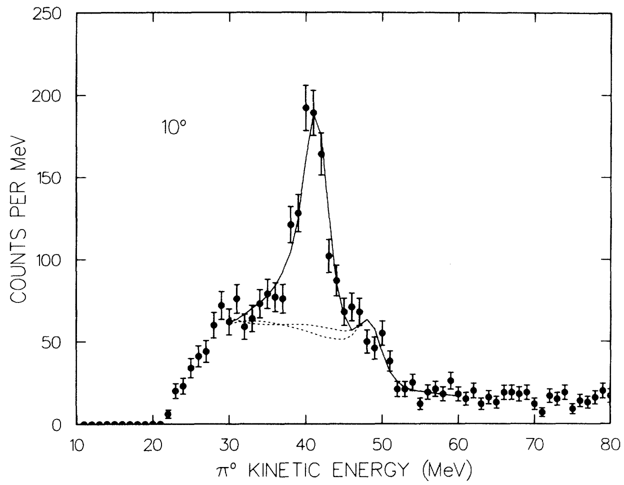

FIG. 1. Measured π^0 spectrum for the reaction $^{120}Sn(\pi^+,\pi^0)^{120}Sb(IAS)$ at 48.4-MeV incident energy. The solid line represents a fit to the data including the IAS peak and a nonanalog state. The dashed lines correspond to two of several backgrounds considered.

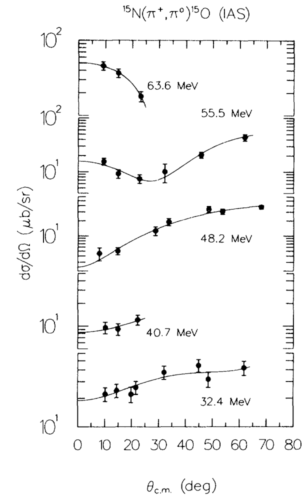

FIG. 2. Angular distribution for the IAS at 32.4-, 40.7-, 48.2-, 55.5-, and 63.6-MeV incident energies. The curves are the result of a Legendre polynomial fit to the data and are used to extrapolate to the cross section at 0°.

(described in detail in Ref. 6). Empty-target runs were taken to determine the background resulting from charge-exchange reactions in the air near and downstream of the targets and in the target containers.

A typical π^0 spectrum for the reaction $^{120}Sn(\pi^+,\pi^0)^{120}Sb(IAS)$ at an incident-pion energy of 48.4 MeV is shown in Fig. 1. The spectra consist of four components: an isobaric-analog transition peak, contributions from nonanalog states, continuum charge exchange, and a smooth background. The empty-target runs, along with the random counts obtained by making an out-of-coincidence cut on the γ-γ time difference, established the smooth background. A Monte Carlo simulation of the spectrometer, beam, and target[8] gave the angle-dependent line shapes that were used to fit the data, and described it well. The prominent IAS peak in a ^{120}Sn spectrum is shown in Fig. 1, along with a fit to this peak and two of several possible background shapes; other fitting examples can be found in the above references. The fitting uncertainty was adjusted to account for the possibility of including or not including excited states in the fit and for various possible background shapes.

For each spectrometer setting, the data were divided into three scattering-angle bins. In Fig. 2, we present the measured cross sections for $^{15}N(\pi^+,\pi^0)^{15}O(IAS)$ at the mean acceptance angle for each bin (the data at 48.2 MeV are from Ref. 3). The quoted uncertainties are the full errors and include contributions from uncertainties in the fitting, in the instrumental efficiency, and in the pion-flux normalization. The shape of the angular distribution is very energy dependent, reflecting the analogous behavior of the free-nucleon SCX cross section. It has a fairly flat shape at 32.4 MeV and a deep minimum at 0° for 48.2 MeV. The minimum moves to near 25° for 55.5 MeV, with the angular distribution finally becoming strongly forward peaked at 63.6 MeV. This energy dependence is caused by a change in the relative strength of the *s*- and *p*-wave amplitude contributions to the interference. Extrapolated 0° IAS cross sections were obtained by fitting of the forward-angle distributions with a Legendre polynomial series in scattering angle. The uncertainty in the extrapolation was derived from the goodness of the fits and, where possible, by consideration of the variations when higher-order polynomials were used.

The 0° cross sections are presented in Table I. The quoted errors are the full uncertainties and include the normalization uncertainties. The energies correspond to the kinetic energy of the incident charged pions at the center of the target. The 0° cross sections are presented in Fig. 3 as a function of the incident $\pi^\pm$ energy. As can be seen, all of the 0° excitation functions have an almost universal shape, with a minimum between 40 and 60 MeV. The minimum is less pronounced in ^{120}Sn, but persists as a feature even in this heavy nucleus.

To characterize the relative trends of the A dependence, we fitted the 0° cross sections with a quadratic function in pion kinetic energy (T): $d\sigma_{IAS}(0°)/d\Omega = \sigma_m[1+(T-T_m)^2/W^2]$, where T_m is the kinetic energy at the minimum and σ_m is the cross section at this energy. The width of the function is characterized by W. The fitted curves, shown in Fig. 3, represent the data well. The resulting parameters are presented in Fig. 4. The minimum location is plotted versus the

TABLE I. The 0° IAS cross sections, $d\sigma_{IAS}(0°)/d\Omega$ (c.m. system).

Nucleus	Pion kinetic energy (MeV)	$d\sigma_{IAS}(0°)/d\Omega$ (μb/sr)
^{7}Li	33.5[a]	16.6 ±7.5
	41.1[a]	8.0 ±2.9
	48.7[a]	16.7 ±4.3
	58.8[a]	58.7 ±10.6
^{14}C	34.2[b]	62 ±12
	41.8[b]	18 ±6
	49.3[b]	6.0 ±3.0
	64.4[b]	160 ±30.0
	79.5[b]	640 ±130.0
^{15}N	32.4	21.0 ±2.0
	40.7	8.3 ±1.9
	48.2[c]	2.7 ±1.0
	55.5	18.0 ±4.0
	63.6	50.6 ±5.4
^{39}K	41.4	37 ±6
	48.0[d]	12 ±5
	56.6	9.1 ±3.6
	64.1	49.1 ±6.7
	79.2	193 ±24
^{120}Sn	40.7	372 ±38
	48.4	320 ±33
	56.0	119.2 ±10.5
	63.6	103.6 ±9.4
	78.7	453 ±38

[a]Reference 4.
[b]Reference 6.
[c]Reference 3.
[d]Reference 5.

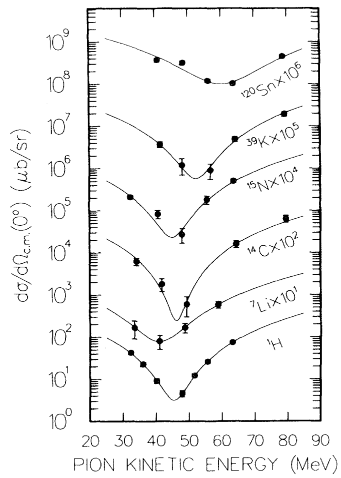

FIG. 3. The measured 0° excitation function for the free πN process and the IAS transition on ^{7}Li, ^{14}C, ^{15}N, ^{39}K, and ^{120}Sn. The curves represent the fit to the data discussed in the text.

outgoing π^0 energy, $T_m^{\pi^0} = T_m + Q(\text{IAS})$. The use of the π^0 energy has been suggested as an approximate way to correct for Coulomb effects.[10] This simple quadratic form is used here only for a systematic comparison over a broad range in nuclear mass. As has been seen in other studies, the uncertainties in the minimum cross section may be larger if other functional forms are also considered.[11] Except for ^{7}Li, which seems to violate the general systematics, a general picture emerges: (1) The location of the minimum, $T_m^{\pi^0}$, is constant within the uncertainties; (2) the width does not increase substantially except for the heaviest nucleus, ^{120}Sn; and (3) the cross sections per excess neutron at the minimum, $\sigma_m/(N-Z)$, are all statistically consistent with that of the free-nucleon charge exchange, although the errors are large.

These features make the forward-angle charge-exchange IAS transition in nuclei appear very similar to that of the free-nucleon charge exchange. This is surprising because nuclear-medium effects might be expected to diffuse this phenomenon. They are known to be important in this energy region, as is indicated by the large cross sections for pion true absorption[12] and optical-model fits to elastic scattering.[13] Also, the relatively high penetration of pions at these low energies causes the interaction to sample a large

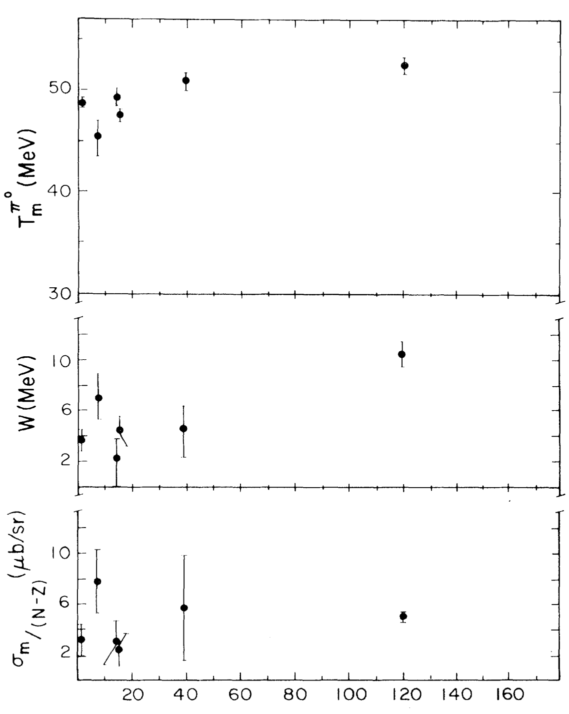

FIG. 4. The mass dependence of the fitted parameters describing the excitation function of the 0° IAS transitions (see text for details).

range of nuclear densities, thereby making the reaction sensitive to density-dependent effects. However, it appears that the interplay between the different nuclear-medium effects produces a small net effect on the forward-angle IAS cross sections. Several theoretical models that involve such interplay have been advanced in the literature; these include effects of Lorentz-Lorenz correlations[14] and Pauli blocking.[15]

In a distorted-wave Born-approximation description, the IAS scattering amplitude is expressed as a transition between incoming and outgoing distorted waves. Since the distortions arise primarily from the isoscalar part of the optical potential,[13] which is not strongly energy dependent at low pion energies, the measured 0° cross sections should reflect the energy dependence of the medium-modified charge-exchange transition operator. Thus the observed similarity between the free-charge-exchange and the nuclear-IAS-transition cross sections indicates that the energy dependence of the isovector pion-nucleon interaction is not strongly modified by the nuclear medium.

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[a]Isotope and Nuclear Chemistry Division.

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