Isobaric Analog States in Pion Single-Charge-Exchange Reactions on and above the (3,3) Resonance Energy

U. Sennhauser, E. Piasetzky, H. W. Baer, J. D. Bowman, M. D. Cooper, H. S. Matis, and H. J. Ziock
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

and

J. Alster, A. Erell, and M. A. Moinester
Tel Aviv University, Ramat Aviv, 69978 Tel Aviv, Israel

and

F. Irom
Arizona State University, Tempe, Arizona 85281

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The 0° differential cross sections of (π^+, π^0) reactions on a series of nuclei to isobaric analog states were determined at 165, 230, and 295 MeV. For each energy, the A dependence is well described by a power law of the form $\sigma = g(E)(N-Z)A^{-\alpha(E)}$, where $\alpha(E)$ is a decreasing function of energy. The 0° excitation functions peak around the (3,3) resonance energy for all nuclei except ^{90}Zr. A possible explanation in terms of neutron and proton densities is discussed.

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Pion-nucleus single charge exchange (SCE) to isobaric analog states (IAS) is, in principle, a simple process because of the similarity of the initial and final nuclear states. Although in the last few years much theoretical and experimental work has been done to study this reaction, discrepancies remain between theories and experimental data. Until now systematic measurements of these reactions were restricted to pion kinetic energies below the (3, 3) resonance energy. At energies above the (3, 3) resonance, better agreement between experiments and calculations is expected as a result of the greater reliability of the theory, resulting from the expected lesser role of nucleon correlation terms (ρ^2) and the decreased distortion in the pion waves.

IAS cross sections at forward angles are reported for (π^+, π^0) transitions on ^{7}Li, ^{90}Zr, ^{120}Sn, and ^{208}Pb at pion kinetic energies of 230 and 295 MeV and on ^{60}Ni, ^{90}Zr, ^{140}Ce, and ^{208}Pb at 165 MeV. These are the first direct measurements of differential cross sections on nuclei throughout the periodic table at energies above the (3, 3) resonance. The results of this work will be compared with previous pion SCE measurements of 0° IAS cross sections at a lower energy[1] and on light nuclei.[1-4]

The experiment was performed with the π^0 spectrometer mounted in the low-energy pion (LEP) channel at the Clinton P. Anderson Meson Physics Facility (LAMPF). The π^0 spectrometer, described in detail elsewhere,[5] was used to measure energy and direction of the outgoing π^0. It was set in its one-post configuration with its center line at an angle of 5°. The distances to the first converter were 113, 123, and 132 cm for the 165-, 230-, and 295-MeV measurements, respectively. These setups gave an angular coverage of the π^0 scattering angle from 0° to ~15°. In the analysis the data were sorted into four angular bins.

The variation of the spectrometer acceptance with π^0 energy and the mean acceptance angle for each θ bin were calculated by Monte Carlo simulations for each spectrometer configuration. The effective solid-angle normalization at each energy was determined by using CH_2 targets and the known $\pi^- p \to \pi^0 n$ cross sections.[6] The pion flux ($\sim 2\times 10^7$ s^{-1}) was determined by the scintillator activation technique.[7] The thicknesses of the targets were 0.5 g/cm^2 for Li and 1.5 to 3 g/cm^2 for the heavy nuclei. The data presented here have a cut on the energy-balance parameter $X=(E_1 - E_2)/(E_1+E_2) \leq 0.15$ which gives a π^0 energy resolution of 4 to 5 MeV. E_1 and E_2 are the energies of the two decay γ rays. The π^0 energy spectra from the heavier nuclei (^{90}Zr, ^{120}Sn, and ^{208}Pb) at 230 MeV are shown in Fig. 1 for the four angular bins.

The extraction of the IAS peak areas is subject to the uncertainty of background shape. To extract the peak area the fitting program LOAF[8] was

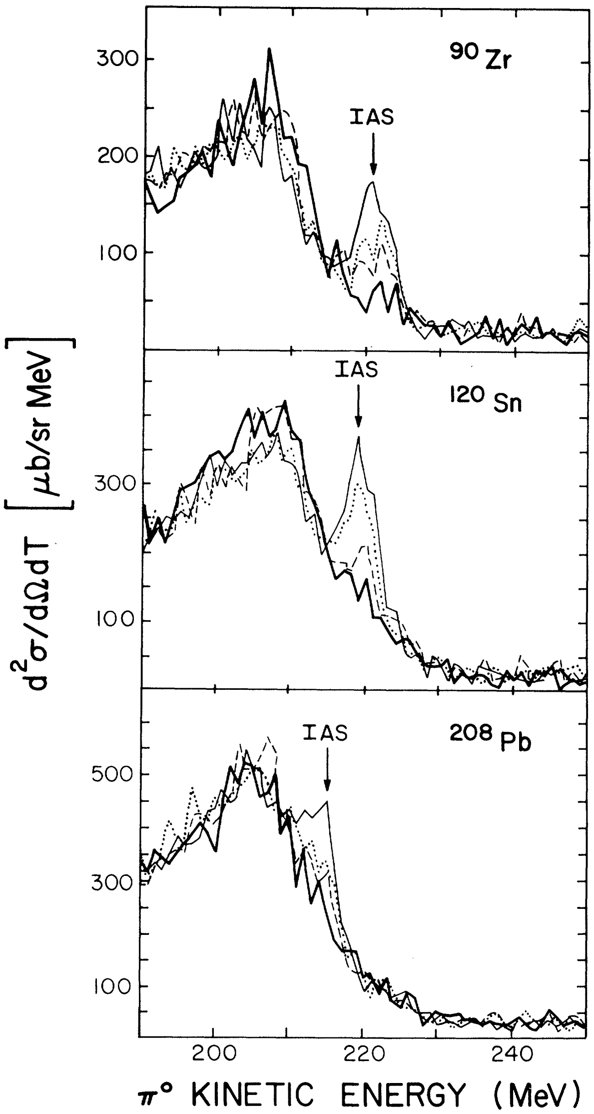

FIG. 1. π^0 spectra measured for SCE reactions at $T_{\pi^+} = 230$ MeV on targets of ^{90}Zr, ^{120}Sn, and ^{208}Pb. The thin solid lines show the spectra of the first angular bin (~ 0–4.5°); the dotted line, the second bin (~ 4.5–7°); the dashed line, the third bin (~7–10°), and the thick solid line, the fourth bin (~ 10–15°).

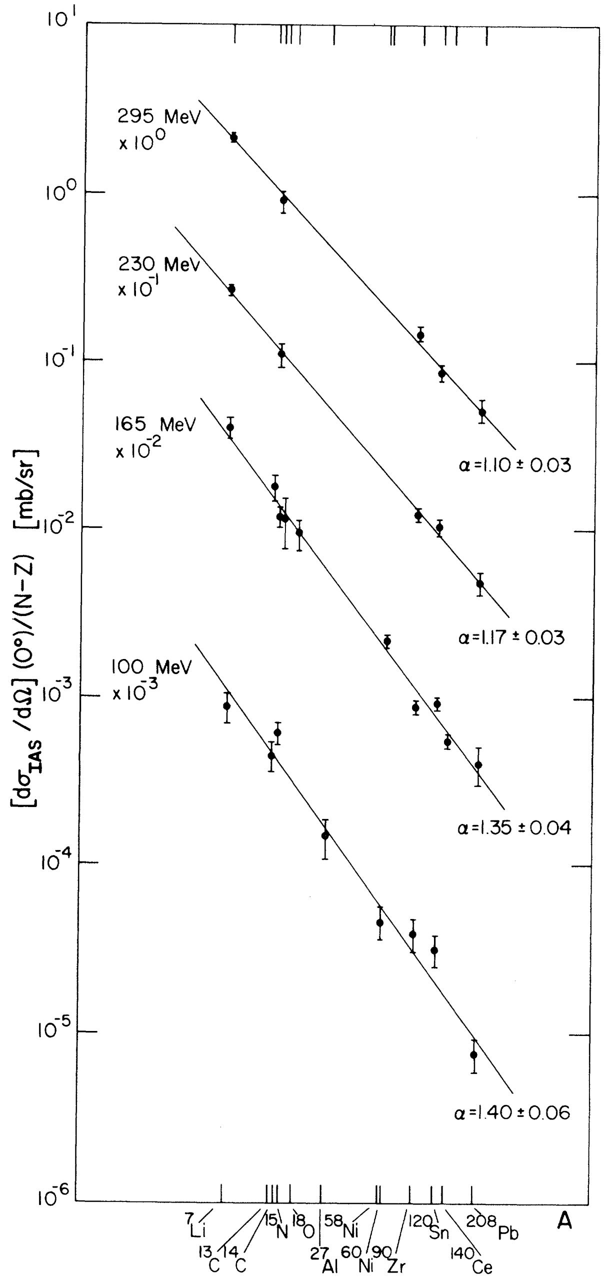

FIG. 2. A dependence of the 0° IAS cross sections (c.m. system) normalized with the neutron excess ($N - Z$) for $T_{\pi^+} = 100$, 165, 230, and 295 MeV. The lines show fits with a power law $\sigma \sim A^{-\alpha(E)}$. All published cross sections from previous work are included.

used with a line shape taken from the Monte Carlo simulation[5] and a polynomial background. The 0° IAS cross sections were extrapolated from the measured cross sections $\Delta\sigma/\Delta\Omega$ of the first angular bin with use of the form

$$d\sigma(0°)/d\Omega = (\Delta\sigma/\Delta\Omega)\int A(\nu)d\nu / \int J_0^2(\nu)A(\nu)d\nu.$$

$A(\nu)$ is the spectrometer acceptance of the first angular bin calculated by the Monte Carlo simulation. This assumes that the angular distribution of the IAS cross section follows a Bessel-function shape $J_0^2(qR)$. This form for the angular distribution is obtained from the diffraction picture of the scattering process.[9] R is taken from elastic data[10] for 165 and 295 MeV and scaled with the total cross section to 230 MeV and q is the transverse momentum transfer. This function was

TABLE I. The o° IAS cross sections $d\sigma_{IAS}(0°)/d\Omega$ [mb/sr] (c.m. system) at 165, 230, and 295 MeV.

Nucleus \ Pion kinetic energy (MeV)	165	230	295
^{7}Li	4.03 ± 0.60 [a]	2.64 ± 0.16	2.15 ± 0.11
^{14}C	2.37 ± 0.36 [b]	2.19 ± 0.36 [b]	1.84 ± 0.30 [b]
^{18}O	1.90 ± 0.40 [c]		
^{60}Ni	0.87 ± 0.09		
^{90}Zr	0.89 ± 0.09	1.23 ± 0.12	1.48 ± 0.16
^{120}Sn	1.87 ± 0.14 [d]	2.10 ± 0.25	1.74 ± 0.21
^{140}Ce	1.33 ± 0.15		
^{208}Pb	1.80 ± 0.48	2.17 ± 0.36	2.28 ± 0.33

[a]Ref. 2.
[b]Ref. 4.
[c]Ref. 11.
[d]Ref. 12.

found to be a reasonably good description of the data at angles smaller than 7°. The extrapolation factors are between 3% (Li at 165 MeV) and 50% (Pb at 295 MeV). Distorted-wave impulse-approximation calculations of these extrapolation factors are in good agreement with the $J_0^2(qR)$ prescription. The error in this model-dependent extrapolation procedure was taken to be 20% of these factors. The statistical errors in the peak areas are 3% to 7%. The estimated systematic errors due to background subtraction vary from 5% for the light nuclei to 15% for Pb.

Table I presents the 0° IAS cross sections compared with previous experiments. The errors given in the table are the combined statistical, fitting, and extrapolation errors discussed above. An overall normalization uncertainty of ~10% due to flux measurement, target thickness, γ attenuation in the target, and knowledge of the πN cross sections used for the normalization is not included in the table. The A dependence of the 0° differential cross sections to IAS found in this work, supplemented with previous data points from Refs. 1–4, 11, and 12 is presented in Fig. 2. The shapes are well represented by a form $\sigma(0°) = g(E)(N-Z)A^{-\alpha(E)}$. The fitted parameters $[g(E), \alpha(E)]$ are [17 ± 4 mb/sr, 1.40 ± 0.06], [49 ± 9 mb/sr, 1.35 ± 0.04], [26 ± 3 mb/sr, 1.17 ± 0.03], and [18 ± 2 mb/sr, 1.10 ± 0.03] for 100, 165, 230, and 295 MeV, respectively. A significant decrease in the power of A with increasing energy is observed. Furthermore the data at 230 and 295 MeV are better represented by the power law ($\chi^2 \simeq 1$) than at 100 and 165 MeV ($\chi^2 \simeq 2$).

Figure 3 presents $\sigma_{IAS}(0°)$ as a function of incoming pion kinetic energy. For comparison we show in Fig. 3 the energy dependence of the free cross section $\sigma_{\pi^- p \to \pi^0 n}(0°)$. In general the maximum of the 0° IAS cross section is observed on the (3, 3) resonance energy. It drops quickly below and slowly above the resonance. These trends follow the shape of the free cross section but are less pronounced. An anomalous behavior is ob-

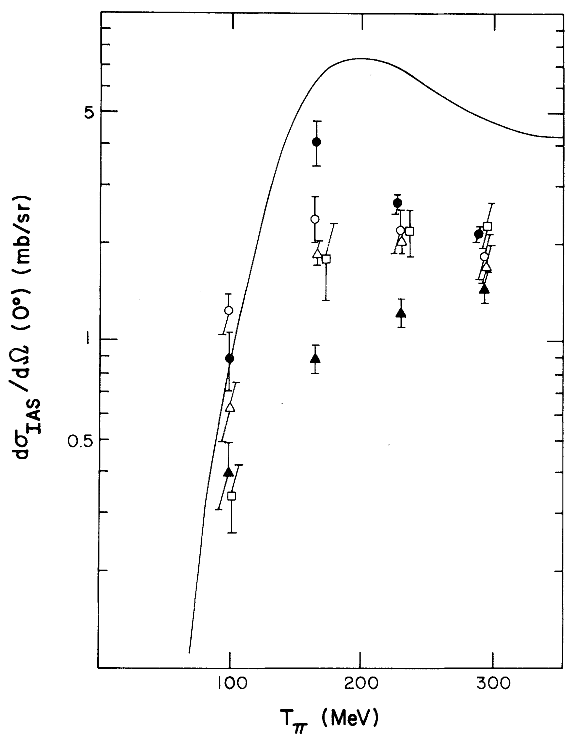

FIG. 3. Excitation function of the 0° IAS cross sections (c.m. system) for ^{7}Li (full circles), ^{14}C (open circles), and ^{90}Zr (full triangles), ^{120}Sn (open triangles), and ^{208}Pb (open squares). The line represents the c.m. cross section of the free charge-exchange reaction $\pi^+ + n \to \pi^0 + p$.

served for the ^{90}Zr nucleus where the cross section is monotonically increasing with the energy and does not reflect the (3, 3) resonance as do the other nuclei. This effect might be related to the neutron-proton density difference at the surface. In general, the ratio of the number of neutrons to protons evaluated as $\int_R^\infty \rho_n \, d\tau / \int_R^\infty \rho_p \, d\tau$ with use of density-matrix expansion or Hartree-Fock Skyrme III force densities[13,14] exceeds the N/Z ratio in the surface region probed by the strongly absorbed pions. ^{90}Zr is an exception, and the calculated ratio is very close to N/Z. This means that for ^{90}Zr the SCE cross section around the (3, 3) resonance is relatively suppressed because the interaction occurs near the surface, which has a comparatively low neutron density. At higher energies with a larger penetration depth the behavior is closer to an average nucleus. This interpretation is in agreement with the observation that the reduced cross section (Fig. 2) of ^{90}Zr at 165 MeV is lower than the fitted line whereas that of ^{120}Sn (a nearby nucleus with large "neutron halo") is higher.

It is interesting to observed that the 0° cross sections (Fig. 3) differ by as much as a factor of 5 over the periodic table at the two lower energies whereas the difference is only a factor of 2 at the two higher energies. This phenomenon, as well as the fact that there are more deviations from the power law at 100 and 165 MeV (see Fig. 2), might be due to larger sensitivity to details of the nuclear structure at the lower energies.

In conclusion, we determined the first 0° differential IAS cross sections in pion SCE reactions on nuclei throughout the periodic table at energies above the (3, 3) resonance. The data show that 0° IAS cross sections follow a regular pattern when plotted against $g(E)(N-Z)A^{-\alpha(E)}$. The trend established by the data showing that α decreases from 1.35 at the resonance energy to 1.10 at 295 MeV appears to reflect the changing nature of pion SCE scattering, going from approximately black-disk scattering at 165 MeV to increased volume scattering at higher energies. The function $g(E)$ has a maximum at 165 MeV, reflecting the role of the (3, 3) resonance. An anomalously low cross section is observed for ^{90}Zr at 165 MeV, which may have its explanation in terms of the unusually small neutron halo predicted by realistic density calculations. We qualitatively interpret the 0° IAS excitation functions in terms of the elementary reaction cross sections, the neutron and proton densities at the nuclear surface, and the diffraction and attenuation of the pion wave functions. It is hoped that detailed calculations will be performed and will shed more light on the discussed phenomena.

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