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Energy Dependence of the Small-Angle Differential Cross Sections to Isobaric Analog States in $^{7}\mathrm{Li}(\pi^{+},\pi^{0})^{7}\mathrm{Be}$ and $^{13}\mathrm{C}(\pi^{+},\pi^{0})^{13}\mathrm{N}$

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(Received 16 September 1981)

The forward-angle differential cross sections of pion single charge exchange on ^{7}Li and ^{13}C were measured at 70, 100, 150, 165, and 180 MeV. The cross sections rise steeply up to 150 MeV and remain almost constant between 150 and 180 MeV. Comparisons with theoretical calculations and with the free charge-exchange cross sections are presented. There is poor agreement with the data. Only phenomenological calculations can fit the resonance region. The isobaric analog excitation functions rise more steeply than the continuum single-charge-exchange cross sections.

PACS numbers: 25.80.+f, 24.30.Eb, 27.20.+n

In the last few years much attention has been given to pion single-charge-exchange (SCE) reactions.[1] The measurements of the reactions to the isobaric analog states (IAS), $^{7}\mathrm{Li}(\pi^{+},\pi^{0})^{7}\mathrm{Be(IAS)}$[2,3] and $^{13}\mathrm{C}(\pi^{+},\pi^{0})^{13}\mathrm{N(IAS)}$,[3] provided the first excitation functions of angle-integrated cross sections for SCE to a single state. Much theoretical effort has been devoted to understanding these results.[1] Distorted-wave impulse-approximation (DWIA) calculations, using first-order optical potentials,[1] produced a dip in the excitation functions at the (3, 3) resonance, with cross sections too low by as much as a factor of 5. Higher-order calculations reduced the discrepancies to a factor of 1.5 and produced flatter excitation functions.[1] Recently, there have been calculations[4-7] for $^{13}C(\pi^+,\pi^0)^{13}N$(IAS) based on differences between amplitudes in the different isospin channels.

To date, calculations have usually been compared with angle-integrated cross sections as differential cross sections to single states have not been formally published. Different angular distributions, when integrated, may predict the same total cross section. Thus, even before complete angular-distribution data become available, the excitation function at a fixed forward angle provides a new constraint on the calculations.

In this Letter we present the excitation functions of the 7-deg differential cross sections for the SCE reactions $^{13}C(\pi^+,\pi^0)^{13}N$(IAS) and $^7Li(\pi^+,\pi^0)^7Be$(IAS). The present data agree with preliminary observations,[8] within their error range, but are the result of a more complete and refined analysis. The A dependence of the forward-angle SCE reaction at 100 MeV has already been published.[9]

We used the π^0 spectrometer built at the Clinton P. Anderson Meson Physics Facility (LAMPF), mounted in the low-energy-pion (LEP) channel. A detailed description of the apparatus is given elsewhere.[10] The best π^0 energy resolution achieved, by applying severe cuts to the data, was 2.5 MeV full width at half maximum (FWHM). In the present analysis we included more events resulting in a typical resolution of 3.5 MeV. The ^{7}Li (99%) target was 0.5 g/cm^2 thick, and the ^{13}C (87%) target was 1.8 g/cm^2 thick. The pion flux (approximately 10^6/sec) was normalized by monitoring the primary proton beam flux, and by measuring the ^{11}C (β) activity[11] produced in thin scintillator disks. The effective solid-angle normalizations at each energy were determined by bombarding thick CH$_2$ targets, and using the phase shifts of Rowe, Salomon, and Landau[12] to calculate the $p(\pi^-,\pi^0)n$ cross sections. The instrumental overall normalization uncertainty varied from 35% at 70 MeV to 10% at 150–180 MeV.

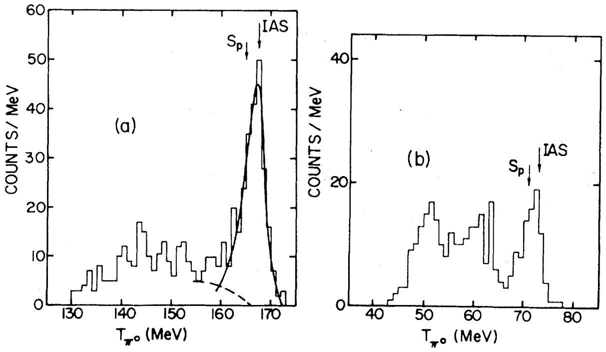

FIG. 1. Spectra of the π^0 from $^{13}C(\pi^+,\pi^0)$ at (a) 165 MeV; (b) 70 MeV. The solid line in (a) is the line shape obtained from $p(\pi^-,\pi^0)n$ and used for unfolding. Note the different contributions of low-energy π^0. The dashed line in (a) represents their contribution to the IAS peak area. S_p is proton separation energy.

Spectra of π^0 from ^{7}Li and ^{13}C are shown in Fig. 1 representing an angular range of 0 to 15 deg. In Fig. 1(a) we present a spectrum obtained at 165 MeV. The solid line indicates the line shape obtained for CH$_2$ which was used to determine the peak area. The continuum part of the spectrum was accounted for as shown by a dashed line. The spectrum shown in Fig. 1(b) was obtained at 70 MeV. We note that the contribution of the continuum relative to the IAS peak is more pronounced at 70 MeV than at 165 MeV. This effect is even stronger than indicated in the spectrum because of the lower spectrometer acceptance for lower π^0 energies.[10] The statistical errors in the peak areas varied from 6% to 11%, while the estimated systematic errors due to background subtraction varied from 6% to 15%.

The first excited state of ^{7}Be ($\frac{1}{2}^-$ at 0.43 MeV) is the spin-flip state of the IAS. The spin-flip contribution to the amplitude is proportional to $\sin(\theta)$ and is therefore negligible at the small angles where this measurement was done. Thus,

TABLE I. Small-angle differential cross sections from pion SCE to IAS. All cross sections are in mb/sr.

T_π MeV	$d\sigma/d\Omega$ [a] (average) (lab)	θ_{eff} [b]	$d\sigma/d\Omega\,(7°)$ [c] (model dependent) (c.m.)	$d\sigma/d\Omega\,(0°)$ [d] (model dependent) (c.m.)
		$^7Li(\pi^+,\pi^0)\,^7Be$(IAS)		
70	0.16 ± 0.05	8.2	0.15	0.16
98	0.89 ± 0.11	6.6	0.82	0.88
149	3.60 ± 0.60	6.9	3.30	3.57
164.8	4.12 ± 0.62	6.2	3.70	4.03
180.4	3.60 ± 0.65	7.5	3.33	3.69
		$^{13}C(\pi^+,\pi^0)\,^{13}N$(IAS)		
70	0.10 ± 0.04	8.2	0.10	0.11
97.5	0.43 ± 0.06	6.6	0.40	0.44
148.3	1.65 ± 0.32	6.9	1.57	1.77
164.8	1.70 ± 0.34	6.2	1.57	1.80
179.7	1.58 ± 0.32	7.4	1.53	1.78

[a] Average cross section in the laboratory.

[b] Effective angle of measurement; see text.

[c] The percentage errors are the same as in column 2.

[d] The percentage errors are somewhat larger than in column 2; see text.

to a good approximation, the peak in our spectrum represents the IAS transition only.

The first excited state in ^{13}N ($\frac{1}{2}^+$, at 2.37 MeV) is very weakly excited in π inelastic scattering[13] and in (p,n) reactions.[14] Transitions to this state must have $\Delta L = 1$ and consequently the contribution of transitions to this state is considered negligible at very forward angles.

In Table I we present our measured cross sections for ^{7}Li and ^{13}C. These are average cross sections in the range of the angular acceptance of the π^0 spectrometer. With an experimentally determined form of the spectrometer acceptance and reasonable angular distribution shapes we deduced an effective angle of measurement which is almost model independent. This angle was very close to 7 deg for all measurements. The spectrometer acceptance was determined from CH_2 bombardments, using calculated $p(\pi^-,\pi^0)n$ differential cross sections.[12] For the angular distribution we assumed the shape calculated by Hirata.[15] Since the extrapolation to 7 deg is very small, these results can be assumed to be practically model independent. Then, using this same angular distribution, one can extrapolate the cross sections from the effective angle to any other angle. Various reasonable angular distribution shapes were used to estimate the extrapolation error, which turned out to be smaller than the experimental errors of column 2. Thus, in Table I we present the cross sections at 7 deg and those extrapolated to 0 deg as well.

In Fig. 2 we show the 7-deg excitation functions of the SCE on ^{7}Li and ^{13}C. The cross sections for both nuclei increase from 70 to 150 MeV, but do not rise thereafter. The results of several calculations are plotted as well. The DWIA calculations of Warszawski, Gal, and Eisenberg[16] are shown by dotted lines. They do not reproduce the shape of the excitation functions nor their magnitude in the resonance region. The dash-dotted lines are the excitation functions of the $p(\pi^-,\pi^0)n$ forward-angle cross section, normalized to our experimental points at 100 MeV. It is worth noting that the increase in cross sections from 70 to 100 MeV is very similar to the increase in the free cross sections, whereas above 100 MeV the data are lower, expressing the enhanced effect of absorption in the resonance region. On the other hand, the DWIA calculations[16] probably overemphasize the absorption in this region. The solid line in Fig. 2(a) is due to Saharia and Woloshyn.[7] This is the result of a phenomenological isobar-doorway model calculation fitted to the angle-integrated cross sections. It agrees well in the resonance region but fails at lower energies. The solid line in Fig. 2(b) is the result of the calculation of Landau and Thomas.[6] In their calculation they have introduced a phenomenological energy shift between the energies at which the isospin amplitudes are calculated. The calculation is very similar to the earlier one by Saharia and Woloshyn[5] but uses a smaller and constant energy shift due to an improved optical potential. As was the case for ^{7}Li, there is reasonable agreement in the resonance region but not at lower energies. The dashed line in Fig. 2(b) is due to a calculation of Hirata[15] in the isobar-doorway model. He has included high-order effects in a nonstatic treatment of the model. The 0-deg calculations of Eisenberg[17] and of Johnson[4] do not agree with the data in shape nor in magnitude.

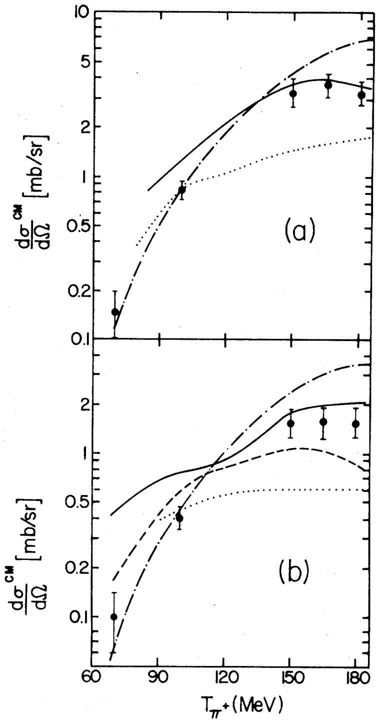

FIG. 2. Excitation functions of $(d\sigma/d\Omega)_{c.m.}$ at 7 deg from (a) ^{7}Li; (b) ^{13}C. The error bars represent the absolute uncertainty. The solid line in (a) is from Saharia and Woloshyn (Ref. 7) at 2 deg. The solid line in (b) is from Landau and Thomas (Ref. 6) at 6 deg. The dashed line is from Hirata (Ref. 15) at 0 deg. The dotted lines are from Warszawski, Gal, and Eisenberg (Ref. 16) at 0 deg. The dash-dotted lines are the $p(\pi^-,\pi^0)n$ cross section at 6 deg.

It is of interest to compare our results with the older integrated cross sections[3] as a function of energy. It requires the assumption of a specific shape for the angular distributions at the various energies. A recently measured[18] angular distribution for ^{13}C at 164 MeV yields a cross section, integrated to 60 deg, of 0.72 ± 0.18 mb, and some contribution to the integral from larger angles has yet to be added. Thus the result at 164 MeV is consistent with the older measurement of 0.92 ± 0.14 mb.

We draw the following conclusions: (1) The forward-angle differential cross sections rise as a function of energy. At low energies, up to 100 MeV, the excitation functions follow the shape of free charge exchange whereas in the resonance region they vary less rapidly. DWIA calculations fall below the data in the resonance region. These results are consistent with those obtained from angle-integrated cross sections.[3] (2) At forward angles the IAS cross sections rise faster with bombarding energy than the cross sections to the continuum. (3) Phenomenological adjustments to the energies at which the isospin amplitudes are evaluated[6,7] give good fits to the present data and to the integrated cross sections as well. However, this does not guarantee that they also agree at larger angles.[18]

We wish to thank the technical staff at LAMPF for their efforts before and during the experiments. John Sandoval was particularly effective in the preparation and maintenance of the instrument. The users groups are especially thankful for the warm hospitality encountered at LAMPF. We thank Dr. M. Hirata, Dr. M. Johnson, Dr. R. Landau, Dr. Y. Saharia, Dr. E. Siciliano, Dr. A. Thomas, and Dr. R. Woloshyn for providing us with their results prior to publication. We also acknowledge useful discussions with Dr. J. Eisenberg, Dr. A. Gal, and Dr. W. Gibbs.

This work was supported in part by the U. S. Department of Energy and by the U. S.-Israel Binational Science Foundation, Jerusalem, Israel.

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