($\pi^{\pm}$,p) reactions at low excitation energy

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Results of the first experimental search for the excitation of discrete final states following exclusive (π^-,p) reactions are reported. The measurements include differential cross section at $\theta_{\rm lab}=25°$ for ($\pi^{\pm}$,p) reactions on ^{24}Mg, ^{27}Al, ^{40}Ca, and ^{58}Ni at $T_\pi=120$ MeV and (π^-,p) on ^{12}C at $T_\pi=145$ MeV. The (π^-,p) reactions yield peaks with $d\sigma/d\Omega\leq 1$ μb/sr compared to 7–22 μb/sr for peaks from (π^+,p) reactions. The shape of the continuum in an excitation energy range of 10–40 MeV was found to be independent of pion charge and target. The ratios of (π^+,p)/(π^-,p) averaged over excitation energy and the ratios of the same reaction on different nuclei are presented. The magnitude of the proton yield in the low excitation continuum is more than 20 times larger for π^+ than for π^-, which supports a two-nucleon absorption model including pion charge exchange.

Pion production and absorption have been studied intensely throughout the last decade. Recent reviews on the (p,π) and (π,p) channels summarize the extensive literature on this subject.[1–4] Results from the Indiana University Cyclotron Facility (IUCF) have demonstrated that the (p,π^-) reaction is selective in the population of discrete excited states in the residual nucleus.[5,6] This reaction is characterized by a high-momentum transfer ($q=2.0$–3.5 fm^{-1}) to the nucleus and the necessity for at least a two-nucleon mechanism (e.g., pn$\rightarrow$ppπ^-). With a range of targets from ^{14}C to ^{90}Zr, Vigdor *et al.*[5] found that the (p,π^-) reaction excited only one or a few low-lying states. The angular distributions for these states were strongly forward peaked with magnitudes at forward angles comparable to those of the (p,π^+) reaction. The interpretation of those data is that the excited states observed with the largest cross sections are stretched or nearly stretched 2p-1h states, i.e., states with maximum angular momentum coupling. Shell model calculations are able to predict spectra with the correct relative strengths when compared with data on a series of isotopes near ^{48}Ca.[7]

The motivation for the measurements presented here is to determine the selectivity of the (π^-,p) reaction compared to that of the (p,π^-) reaction. Before this experiment there were no data for the (π^-,p) reaction to bound final states. There have been only a few reported (π^-,p) experiments involving pionic atoms, activation techniques, or measurements of the continuum at high excitation energies.[8–10]

The present ($\pi^{\pm}$,p) measurements[11] cover excitation energies from 0 up to about 40 MeV. The EPICS facility[12] at LAMPF was used to measure both the (π^-,p) and the (π^+,p) reactions at $T_\pi=120$ MeV and a laboratory angle of 25° on ^{24}Mg, ^{27}Al, ^{40}Ca, and ^{58}Ni; ^{12}C(π^-,p) was measured at $T_\pi=145$ MeV. Elastic scattering of 120 MeV π^- on these nuclei and CD$_2$ (π^+,p) at 220 MeV serve as normalized.[13] An average current of 0.9 mA of 800 MeV protons, plus a redesign of the front slits in the pion channel yielded beams of more than 10^7 π^-/s and 2×10^8 π^+/s. The densities of the targets were 194 (CD$_2$), 196 (^{24}Mg), 408 (^{27}Al), 500 (^{40}Ca), and 292 (^{58}Ni) in mg/cm^2.

Spectra for (π^-,p) and (π^+,p) are shown in Figs. 1 and 2. The spectrometer acceptance has been unfolded from the spectra using the correction for the lower magnetic field setting required for elastic scattering measured in a previous experiment.[11] Due to low statistics the spectra

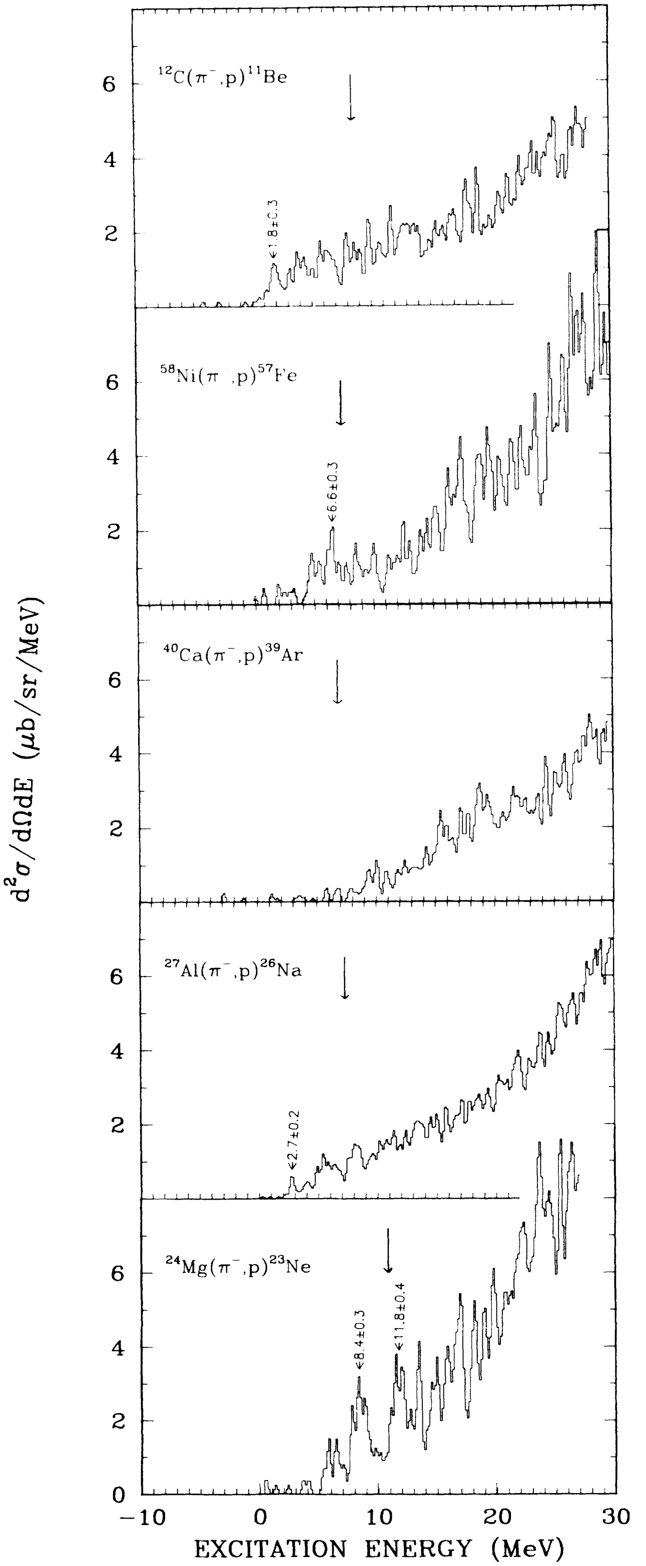

FIG. 1. The excitation energy of the residual nucleus following the (π^-,p) reaction. $\theta_p=25°$ and $T_\pi=145$ MeV for ^{12}C and $T_\pi=120$ MeV for other nuclei. Excitation energies for the peaks of interest are given in the figure. The energy at which alpha breakup begins is denoted by an arrow in each spectrum.

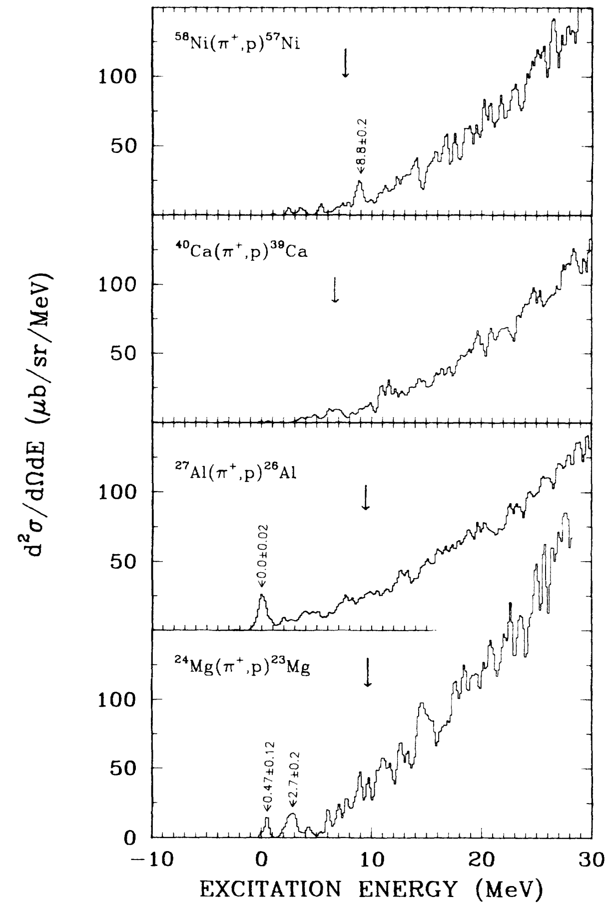

FIG. 2. Same as Fig. 1 but for the (π^+,p) reaction.

have been smoothed for plotting purposes using a prescription that takes nearest channels into account and preserves the total area. The width of most of the observed peaks indicates the excitation of at least a few nearby states, since the width is larger than the resolution of 350 keV measured for ^{27}Al(π^+,p)^{26}Al ground state transition. Differential cross sections for selected peaks indicated in the figures are given in Table I. The (π^-,p) reactions yield peaks with cross sections $\lesssim 1$ μb/sr compared with 7–22 μb/sr for peaks from (π^+,p) reactions.

The shape of the proton spectra above an excitation energy of 10 MeV is approximately independent of the target mass and of the incident pion charge. Ratios of cross sections for (π^+,p)/(π^-,p) and ratios of the same reaction on different nuclei are flat over the range of excitation energies observed here. The ratios averaged over excitation energies from 10 to 40 MeV are presented in Table II. ^{40}Ca has arbitrarily been chosen as the standard for nuclide ratios. As seen in the table, the magnitude of proton yield from all targets is more than 20 times larger for π^+ than for π^-. Both (π^+,p) and (π^-,p) continuum cross sections are found to have little mass dependence, with the cross sections for both reactions on ^{24}Mg slightly enhanced compared to the other nuclei. The ratios of

TABLE I. Differential cross sections for $(\pi^{\pm},p)$ at 120 MeV and $\theta_{lab}=25°$.

Reaction	Excitation[a] energy (MeV)	No. of events	$\left[\frac{d\sigma}{d\Omega}\right]_{c.m.}$ (μb/sr)
$^{24}Mg(\pi^-,p)$	8.4 ±0.3	36±10	2.4 ±0.6
	11.8 ±0.4	20±9	1.3 ±0.6
$^{24}Mg(\pi^+,p)$	0.47±0.1	28±6	8.1 ±1.7
	2.71±0.2	61±9	17.6 ±2.6
$^{27}Al(\pi^-,p)$	2.7 ±0.2	13±5	0.22±0.08
$^{27}Al(\pi^+,p)$	0.0 ±0.02	288±21	22 ±2
$^{58}Ni(\pi^-,p)$	6.6 ±0.3	14±5	0.9 ±0.3
$^{58}Ni(\pi^+,p)$	8.8 ±0.2	49±10	17.5 ±3
$^{12}C(\pi^-,p)$[a]	1.8 ±0.3	14±6	0.5 ±0.2

[a]This reaction was measured at 145 MeV.

$(\pi^+,p)/(\pi^-,p)$ are higher than most previously published values,[8–10] which averaged over a larger range of proton energy. Those ratios thus included protons from secondary processes. The present high ratio is consistent with absorption on two nucleons if the possibility of charge exchange of the π^- during the transport process before absorption is considered.[14] It would be interesting to see if similar calculations to those which explain the shape of the continuum for (p,π^-) reactions[15] also account for the present data.

TABLE II. Ratios of (π,p) cross sections averaged over an excitation energy interval from 10 to 40 MeV. Statistical errors are given in parentheses.

	π^+/π^-	π^+/π^+ ^{40}Ca	π^-/π^- ^{40}Ca
^{24}Mg	26.7 (2.4)[a]	2.45 (0.20)[a]	2.43 (0.22)
^{27}Al	22.1 (1.6)	1.25 (0.09)	1.41 (0.10)
^{40}Ca	25.8 (1.9)		
^{58}Ni	20.4 (1.6)	1.18 (0.09)	1.55 (0.12)
^{12}C			1.35 (0.11)

[a]These ratios have been averaged over a range from 10 to 33 MeV.

In summary, the $^{24}Mg(\pi^-,p)$ reaction study revealed peaks in the low excitation energy region with cross sections comparable in strength to those seen in $^{24}Mg(\pi^+,p)$. A similar shape for both (π^+,p) and (π^-,p) was found for the continuum between excitation energies of 10 and 40 MeV independent of target mass. The observed factor of 20 for the ratio of π^+ to π^- continuum cross sections is consistent with a two-nucleon absorption mechanism. Other measurements, including angular distributions, are planned.

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