(π⁺,p) reactions at low excitation energy

Department of Physics, University of South Carolina, Columbia, South Carolina 29208

J. -P. Egger
Institue de Physique, Universite de Neuchatel, CH-2000 Neuchatel, Switzerland

C. L. Morris
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

H. Breuer, N. S. Chant, and B. G. Ritchie
Department of Physics, University of Maryland, College Park, Maryland 20742

B. H. Wildenthal
Department of Physics and Atmospheric Science, Drexel University, Philadelphia, Pennsylvania 19104

B. Höstad
Gustaf Werner Institute, University of Uppsala, S-75121 Uppsala, Sweden

B. A. Brown
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824

(Received 16 June 1986; revised manuscript received 22 December 1986)

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 θlab=25° for (π⁻,p) reactions on 24Mg, 27Al, 40Ca, and 58Ni at T=120 MeV and (π⁺,p) on 12C at T=145 MeV. The (π⁺,p) reactions yield peaks with dσ/dΩ<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→ppπ⁻). With a range of targets from 14C to 90Zr, 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 40Ca.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 (π±,p) measurements11 cover excitation energies from 0 up to about 40 MeV. The EPICS facility at LAMPF was used to measure both the (π⁻,p) and the (π⁺,p) reactions at T=120 MeV and a laboratory angle of 25° on 24Mg, 27Al, 40Ca, and 58Ni; 12C(π⁻,p) was measured at T=145 MeV. Elastic scattering of 120 MeV π⁻ on these nuclei and CD2(π⁺,p) at 220 MeV serve as normalization.11 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 10⁷ π⁻/s and 2×10⁶ π⁺/s. The densities of the targets were 194 (CD2), 196 (24Mg), 408 (27Al), 500 (40Ca), and 292 (58Ni) in mg/cm².

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

1567 ©1987 The American Physical Society
The excitation energy of the residual nucleus following the \((\pi^- p)\) reaction. \(\theta_p = 25^\circ\) and \(T_p = 145\) MeV for \(^{12}\text{C}\) and \(T_p = 120\) 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.

In the \((\pi^+ p)\) reaction, peak cross sections are given in Table I. 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 \((\pi^+ p)/(\pi^- p)\) 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. \(^{40}\text{Ca}\) 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 \(\pi^+\) than for \(\pi^-\). Both \((\pi^+ p)\) and \((\pi^- p)\) continuum cross sections are found to have little mass dependence, with the cross sections for both reactions on \(^{24}\text{Mg}\) slightly enhanced compared to the other nuclei. The ratios of

\[
\frac{d^2\sigma}{d\Omega dE} \quad \text{(ab/sr/MeV)}
\]

\[
\begin{align*}
^{12}\text{C}(\pi^- p)^{11}\text{Be} \\
^{56}\text{Ni}(\pi^- p)^{57}\text{Fe} \\
^{40}\text{Ca}(\pi^- p)^{39}\text{Ar} \\
^{27}\text{Al}(\pi^- p)^{26}\text{Na} \\
^{24}\text{Mg}(\pi^- p)^{23}\text{Na}
\end{align*}
\]

\[
\begin{align*}
^{56}\text{Ni}(\pi^+ p)^{57}\text{Ni} \\
^{40}\text{Ca}(\pi^+ p)^{39}\text{Ca} \\
^{27}\text{Al}(\pi^+ p)^{28}\text{Al} \\
^{24}\text{Mg}(\pi^+ p)^{23}\text{Mg}
\end{align*}
\]
TABLE I. Differential cross sections for $(\pi^\pm, p)$ at 120 MeV and $\theta_{\text{lab}}=25^\circ$. 

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Excitation$^a$</th>
<th>No. of events</th>
<th>$\frac{d\sigma}{d\Omega}$ $^{c.m.}$ ($\mu$b/str)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{24}\text{Mg}(\pi^-p)$</td>
<td>$8.4 \pm 0.3$</td>
<td>$36 \pm 10$</td>
<td>$2.4 \pm 0.6$</td>
</tr>
<tr>
<td>$26\text{Mg}(\pi^+p)$</td>
<td>$0.47 \pm 0.1$</td>
<td>$28 \pm 6$</td>
<td>$1.7 \pm 1.7$</td>
</tr>
<tr>
<td>$37\text{Al}(\pi^-p)$</td>
<td>$2.7 \pm 0.2$</td>
<td>$13 \pm 5$</td>
<td>$0.22 \pm 0.08$</td>
</tr>
<tr>
<td>$37\text{Al}(\pi^+p)$</td>
<td>$0.0 \pm 0.02$</td>
<td>$288 \pm 21$</td>
<td>$22 \pm 2$</td>
</tr>
<tr>
<td>$58\text{Ni}(\pi^-p)$</td>
<td>$6.6 \pm 0.3$</td>
<td>$14 \pm 5$</td>
<td>$0.9 \pm 0.3$</td>
</tr>
<tr>
<td>$58\text{Ni}(\pi^+p)$</td>
<td>$8.8 \pm 0.2$</td>
<td>$49 \pm 10$</td>
<td>$17.5 \pm 3$</td>
</tr>
<tr>
<td>$^{12}\text{C}(\pi^-p)$</td>
<td>$1.8 \pm 0.3$</td>
<td>$14 \pm 6$</td>
<td>$0.5 \pm 0.2$</td>
</tr>
</tbody>
</table>

$^a$This reaction was measured at 145 MeV.

$(\pi^+, p)/(\pi^-, p)$ are higher than most previously published values, 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 $\pi^-$ during the transport process before absorption is considered. It would be interesting to see if similar calculations to those which explain the shape of the continuum for $\pi^-p$ reactions also account for the present data.

In summary, the $^{24}\text{Mg}(\pi^-p)$ reaction study revealed peaks in the low excitation energy region with cross sections comparable in strength to those seen in $^{24}\text{Mg}(\pi^+p)$. A similar shape for both $(\pi^+, p)$ and $(\pi^-, p)$ 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 $\pi^+$ to $\pi^-$ continuum cross sections is consistent with a two-nucleon absorption mechanism. Other measurements, including angular distributions, are planned.

The authors would like to thank Don F. Geesaman and the Argonne National Laboratory for the $^{58}\text{Ni}$ target used in this experiment. This research was supported in part by the U.S. National Science Foundation, the Department of Energy, and the Swiss National Science Foundation.

---

11For more details see C. S. Mishra, Ph.D. dissertation, University of South Carolina, 1987.