Coincidence Measurements of Quasielastic Pion Scattering by ^{27}Al and ^{208}Pb

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A coincidence measurement of the quasifree scattering of 255-MeV pions by ^{27}Al and ^{208}Pb targets has been made. The measured results for the ratio of π^+ to π^- cross sections of 7.0 ± 0.7 for ^{27}Al and 4.5 ± 0.5 for ^{208}Pb are substantially below the classical impulse-approximation value of 9, showing the influence of charge exchange by the outgoing nucleons. The observed A dependence of this cross-section ratio is in agreement with the predictions of a simplified calculation based on the semiclassical charge-exchange theory for the knockout process.

In the last few years considerable progress has been made towards understanding the reaction process whereby a nucleon is emitted when a nucleus is struck by a fast pion. Early activation measurements[1] for pion-induced reactions on light nuclei show that a significant fraction of the reaction cross section consists of simply knocking out a nucleon (plus charge exchange). This quasifree scattering process is characterized by the scattering of an incident pion by a single bound nucleon, with the other nucleons in the nucleus remaining as spectators. However, the activation measurements give a value of roughly 1 for the ratio of π^- to π^+ total neutron-knockout cross sections rather than the value of 3 expected from simple impulse-approximation and isospin-coupling considerations at the peak of the (3, 3) resonance. A more recent activation experiment[2] at the Clinton P. Anderson Meson Physics Facility (LAMPF) involving the reaction ^{12}C($\pi^\pm$, $\pi^\pm n$)^{11}C gave a peak ratio of about 1.8. Similar results were obtained from neutron-knockout cross-section measurements on ^{14}N, ^{16}O, and ^{19}F targets.[3] Sternheim, Silbar, and collaborators have had considerable success in explaining the experimental results using a semiclassical reaction model which included as a key feature the effect of final-state charge-exchange interactions of the outgoing nucleons.[4] Since charge exchange affects both (π^+, $\pi^+ n$) and (π^-, $\pi^- n$) cross sections, it is easily seen that this effect can have a striking influence upon the cross-section ratio. Deviations from this simple picture, such as for the neutron-removal ratio for ^{64}Zn and for the ^{11}B(π^+, $\pi^0 n$)^{10}C cross section, appear to be resolved,[5] at least qualitatively by taking the detailed nuclear structure into account.

The activation experiments noted above involved the observation of β or γ radiation of the residual nucleus. Because neither of the reaction products of the knockout process (the scattered pion or the recoil proton) is observed in activation measurements, one is concerned that these measurements may include contributions from processes other than quasielastic knockout. Thus activation measurements are probably not the best way to test the charge-exchange ideas. Observation of the recoil proton in quasielastic pion scattering presents reaction theories with a more stringent test since the cross sections can be measured as a function of energy and angle of the observed particle. An estimate of the expected cross section for the case when the recoil proton is observed has been given recently using the semiclassical model approach,[6] along with a detailed discussion of the advantages of this method; however, in this work the effect of nucleon charge exchange was not explicitly taken into account. This was then remedied by a calculation[7] in which both the charge exchange in the primary pion-nucleon collision, $\pi^+n \to \pi^0 p$, and the quasifree π^+n collision followed by a forward (n,p) charge exchange were taken into account. The ratio R of cross sections then becomes [near the (3, 3) resonance]

$$R = \frac{\sigma^+}{\sigma^-} = \frac{(9Z+2N)Q+NP}{ZQ+(9N+2Z)P}, \qquad (1)$$

where P and Q are the probabilities that the recoil nucleon emerges from the nucleus with and without charge exchange, respectively. Results for P and Q in a semiclassical calculation are given in Ref. 7. For an $N=Z$ nucleus, R takes on the classical impulse-approximation value of 11 when no charge exchange is present. Inclusion of charge exchange gives rise to a dramatic reduction from this value, particularly at low proton energies.

While observation of the recoil-proton spectra is preferred to observation of β and γ radiation from the residual nucleus, this method still suffers from the flaw that the singles rate in the proton counter will also include events in which the pion was absorbed. The present study was motivated by the desire to remove this difficulty by measuring both the scattered pion and the recoil proton in coincidence, thereby providing a very clean measurement of the quasielastic ratio R. In this case, since the pion charge-exchange terms ($\pi^- p \to \pi^0 n$, $\pi^+ n \to \pi^0 p$) do not appear, Eq. (1) is slightly modified,

$$R = (9ZQ+NP)/(ZQ+9NP), \qquad (2)$$

and has the non-charge-exchange limit of 9. Also, the P's and Q's should be modified to include the attenuation factor for the outgoing pion flux and the quasielastic NN scattering.[7] In confronting the experimental data with the predictions of Eq. (2) we will ignore these latter corrections for the present.

The incident pion beam was obtained in the EPICS channel[8] of LAMPF. A crossed-field separator removed most of the protons from the π^+ beam, leaving only a 1–2% proton contamination. Two ion chambers with a 2.54-cm-thick aluminum absorber between them (to stop any residual protons) were placed at zero degrees to monitor the beam current. The front ion chamber gave information about all particles in the beam (π, μ, e, p) whereas the back chamber monitored only the (π, μ, e) component; roughly 70% of the latter was due to pions.

The arrangement of the proton and pion detectors is shown in Fig. 1. The knockout protons were detected in a counter telescope consisting of two multiwire proportional counters $HC1$ and $HC2$, two thin ΔE counters (0.16-cm-thick Pilot-B scintillator), a 12.7-cm-thick E scintillation counter, and a 0.64-cm-thick scintillator used as a veto counter. The delay-line readout wire chambers provided the position information needed to localize the point of origin of the detected protons. The E counter was thick enough to stop 140-MeV protons; those having an energy in excess of 140 MeV as well as all pions were eliminated as real events by the veto counter. The pion-detector telescope consisted of a thin 0.16-cm ΔE scintillator, a 15.2-cm-thick $E1$ scintillator, and a 1-in.-thick $E2$ scintillator, which was used either in a three-fold coincidence mode to detect pions or in a veto mode to reject events from a (π, $2p$) reaction. E-ΔE information was used for particle identification in each arm.

The experiment was run at $T_\pi = 255$ MeV using ^{27}Al and ^{208}Pb targets of 100, 250, and 350 mg/cm^2. Data were taken at four angular settings, $\theta_p - \theta_\pi = 45° - 67.5°$, $55° - 50°$, $64° - 37°$, and $90° - 50°$, which were enough to scan most of the region of interest and to show that no striking changes with angle were present. Combining the wire-chamber information to localize the event on the target with background π^+ and π^- runs us-

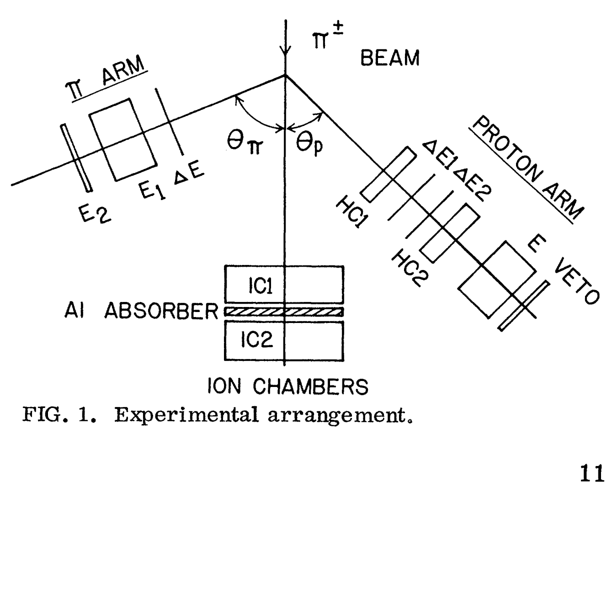

FIG. 1. Experimental arrangement.

ing a blank target enabled us to correct adequately for background contributions. Typical proton event rates for the π^+ beam incident on the ^{27}Al and ^{208}Pb targets (250 mg/cm^2) for $\theta_p = 55°$ were 48.5 and 16.0 events/sec for proton singles data and 0.28 and 0.07 events/sec for the coincidence data, respectively. Corresponding rates for the π^- beam were 3.5 and 1.92 events/sec for the singles data and 3.4×10^{-3} and 1.4×10^{-3} events/sec for the coincidence measurements. These rates were obtained with incident beam intensities of $(15.3\pm2.2)\times10^7$ sec^{-1} for π^+ and $(2.3 \pm 0.2)\times10^7$ sec^{-1} for π^-.

The triple-differential cross section $d^3\sigma/d^2\Omega dE$ is shown in Fig. 2 as a function of the knockout-proton kinetic energy in the laboratory for ^{27}Al at two angular settings. The error bars shown reflect primarily statistical uncertainties.

The present experiment provides the first worthwhile coincidence data for the quasielastic scattering of fast pions by nuclei. The important information gleaned from the coincidence experiment is summarized in Table I. The ratios shown in the third column were obtained by summing the data shown in Fig. 2 over all recoil-proton energies. Three important points are demonstrated as a result of the data from the present experiment. First, as seen from Table I, no useful conclusions can be drawn from the singles data without extensive further analysis of the background contributions. Next we note that the cross-section ratio $R=\sigma^+/\sigma^-$ is less than the impulse approximation, isospin coupling, and non-charge-exchange limit of 9. At $T_\pi = 255$ MeV the incident pions are slightly above the peak of the (3, 3) resonance. However, the ratio of the basic πN cross sections at this energy has only fallen to about 8, so that this should not appreciably affect the observed ratios. Finally, a strong A dependence of the cross-section ratio is observed, with R decreasing for increasing A.

A simplified calculation of R for various A in the spirit of the semiclassical model with charge exchange[7] is in substantial agreement with the observed results. It must be emphasized, however, that the P's and Q's used in Eq. (1) were calculated for a singles experiment and will undoubtedly be modified in the appropriate coincidence calculation. This latter calculation is considerably more complicated and will be reported later. The results of the present coincidence experiment can best be interpreted as supporting the view that charge exchange plays an important role in the quasielastic knockout process. Additional studies, such as those planned by the authors using the EPICS spectrometer at LAMPF, will be needed to confirm the correctness of this point of view.[9] It should also be pointed out that part of the A dependence of R may be due to nuclear-structure effects in ^{208}Pb.

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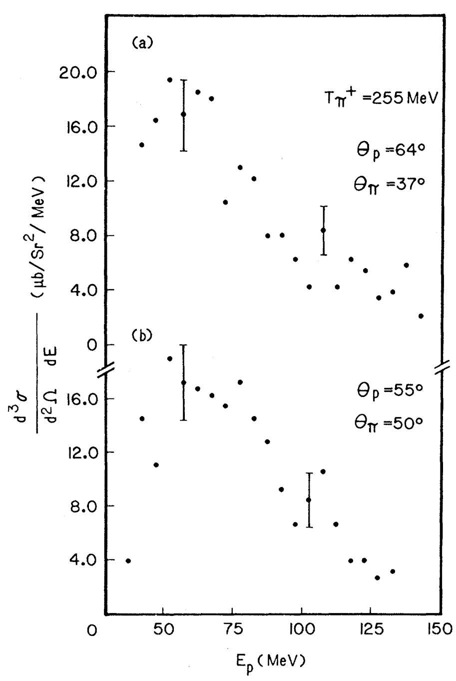

FIG. 2. Proton spectra in coincidence with pions from the reaction ^{27}Al(π^+, π^+p) at two angular settings.

TABLE I. Cross-section ratios for ^{27}Al and ^{208}Pb for two angular settings.

Target	$\theta_p - \theta_\pi$ (deg)	$R=\sigma(\pi^+,\pi^+p)/(\sigma(\pi^-,\pi^-p)$ Coincidence data	Singles data
^{27}Al	55 – 50	6.9 ± 0.7	2.4 ± 0.3
	64 – 37	7.2 ± 0.7	2.5 ± 0.3
^{208}Pb	55 – 50	4.6 ± 0.5	1.7 ± 0.2
	64 – 37	4.5 ± 0.5	1.9 ± 0.2
^{12}C	55 – 50	7.9 ± 1.0 [a]	

[a]Preliminary value obtained in a separate experiment No. 93 at LAMPF by a collaboration including participants from Oregon State University, University of Oregon, Virginia Polytechnical Institute, Florida State, Florida A & M University, and Los Alamos Scientific Laboratory (private communication).

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Evidence of a Direct Process in the (^{4}He,^{8}He) Reaction

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The transfer mechanism for the exotic (^{4}He,^{8}He) reaction has been investigated by measuring the angular distribution for the reaction ^{64}Ni(^{4}He,^{8}He)^{60}Ni. The structure in the angular distribution is reproduced by a direct four-neutron–cluster transfer. In addition, the relative (^{4}He,^{8}He) cross sections from ^{64}Ni and ^{58}Ni are predicted correctly if collective effects are included in the spectroscopic factors.

In the past few years there has been considerable interest in multinucleon-cluster transfer reactions. A number of four-nucleon (two-neutron, two-proton) pickup and stripping reactions have been characterized as α-particle–cluster transfers.[1] Also three-nucleon–cluster transfer models successfully account for transitions such as (^{10}B,^{7}Be) and (^{10}B,^{7}Li).[2] In addition, Delic and Kurath[3] have described the three-neutron transfer ^{13}C(^{3}He,^{6}He)^{10}C by a cluster model. In this Letter we present the first evidence on the (^{4}He,^{8}He) four-neutron–transfer mechanism and demonstrate that the transition can be characterized as a direct, one-step, four-neutron–cluster transfer. We further show that the reaction cross section is sensitive to collective effects in the nuclear wave functions.

We have measured the differential cross section for the reaction ^{64}Ni(^{4}He,^{8}He)^{60}Ni ($E_x = 0.0$) for c.m. angles between 4 and 60 deg using an 80-MeV α beam from the Texas A & M University 88-in. cyclotron. Data were obtained using an Engle split-pole magnetic spectrograph with a focal-plane detector which consisted of a 10-cm single-wire gas proportional counter backed by a 5 cm $\times$1 cm$\times$600 μm Si solid-state detector. This detection system has previously demonstrated particle discrimination to levels less than 100 pb/sr$\cdot$MeV for targets with $A \sim 60$, when the ^{8}He's are stopped by the Si detector.[4] The experimental setup was optimized for extremely low cross sections by operating with 2–3-μA beam currents, a 2.9-mg/cm^2 ^{64}Ni foil (98% ^{64}Ni), and a 2.1-msr solid angle corresponding to a 3° integration in θ. Absolute cross sections have been determined to an accuracy of 20% due to uncertainties in charge integration, target thickness, and vertical efficiency in the focal-plane detector. In addition to the ^{8}He angular distribution, data were obtained simultaneously for the reactions ^{64}Ni(^{4}He,^{6}He)^{62}Ni [ground state (0^+) and 1.17 MeV (2^+)].

The ^{64}Ni to ^{60}Ni[ground state (g.s.)] transition is particularly simple for theoretical analysis. The spins and parities of the projectile, target, reaction product, and final state are all 0^+. Thus in a cluster model, the most likely four-neutron cluster would be a relative ($s=0$, $l=0$, $T=2$) configuration and the transfer would proceed by the L value $L=0$. This cluster corresponds to an L-S–coupling [22] spatial symmetry and thus, because of the Pauli principle for the $4n$ system, requires one node in the relative ^{4}He$+(4n)$ wave function. The two-neutron transfer in (^{4}He,^{6}He) is considered to be identical to that of the (p,t) reaction. Thus the two neutrons are assumed to be transferred in an ($s=0$, $l=0$, $T=1$) cluster with a spatial symmetry [2]. This symmetry is equivalent to a 0s two-neutron cluster and hence a node in the relative ^{4}He$+(2n)$ wave function.