Evidence for the peripheral quasifree nature of single-nucleon removal from ^{27}Al by 190-MeV $\pi^{\pm}$

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A comparison of nucleon-removal differential scattering cross sections at 35° for 190-MeV $\pi^{\pm}$ on ^{27}Al shows $p2n$ removal and single-nucleon removal as the most dominant. Single-nucleon removal is consistent and in good agreement with the one-step-quasifree πN scattering model, but only if the pion interacts principally with a $p2n$ system. The outgoing nucleon charge exchange probability is measured to be $\sim 1/3$ for ~ 16-MeV nucleons. The πN angular distribution and the proton energy spectrum at 35° also support the one-step-quasifree scattering with the outermost nucleons model.

[NUCLEAR REACTIONS ^{27}Al($\pi^{\pm}$,$\pi^{\pm}$)^{27}Al*, ^{27}Al($\pi^{\pm}$,$\pi^{\pm}p$)^{27}Mg, ^{27}Al($\pi^{\pm}$,$\pi^{\pm}n$)^{26}Al, ^{27}Al($\pi^{\pm}$,$\pi^{\pm}pn$)^{25}Mg, ^{27}Al($\pi^{\pm}$,$\pi^{\pm}p2n$)^{24}Mg, ^{27}Al($\pi^{\pm}$,$\pi^{\pm}2p2n$)^{23}Na, ^{27}Al($\pi^{\pm}$,$\pi^{\pm}3p3n$)^{21}Ne. Measured σ(35°) using scattered $\pi^{\pm}$ in coincidence with γ rays. Compare single-nucleon removal with quasifree scattering.]

In pion-induced single nucleon removal, the measured ratios of the cross sections for incident π^+ and π^- do not agree with the values obtained on free nucleons. The discrepancy raises the question as to what degree the interaction may be considered quasifree. With the inclusion of nucleon charge exchange[1,2] and nuclear structure effects[3,4] the ratios for ^{12}C (Ref. 5) and some other targets[2,6-8] are explained, but there are exceptions.[9,10] In further support of the one-step-quasifree (OSQF) picture are the following: (1) the results of singles-γ-ray experiments[11] which give nuclear spectroscopic factors in agreement with other OSQF processes induced by other projectiles; (2) the character of pion energy spectra in (π, π') single arm scattering experiments[12]; and (3) a recent (π, $\pi'p$) coincidence experiment.[13]

This paper presents data from a particle-γ-ray coincidence experiment which show consistency for OSQF scattering among seven separate cross-section measurements of the five reactions ^{27}Al ($\pi^{\pm}$, $\pi^{\pm}p$) ^{26}Mg, ^{27}Al(π^+, π^0p) ^{26}Al, and ^{27}Al($\pi^{\pm}$, $\pi^{\pm}n$) ^{26}Al. Ratios of cross sections are found to be in agreement with theory. In addition, ratios of spectroscopic factors agree with those determined from other nuclear probes. This agreement yields a unique measured value for the nucleon charge exchange probability and implies an unexpected configuration for the pion-interacting nucleons in ^{27}Al. The proton energy spectra fits the OSQF model and provides further evidence that the reaction is peripheral.

A chemically pure 2 g/cm^2 target of ^{27}Al was bombarded with 190-MeV $\pi^{\pm}$ from the LAMPF P^3 channel. Coincidences were recorded between γ rays, detected with a Ge(Li) detector at 90° to the beam, and the final-state charged particles (primarily protons of energy $\gtrsim 35$ MeV and pions of energy $\gtrsim 15$ MeV), detected with a ΔE-E particle telescope at 35° to the beam. Details have been

described earlier.[14] The number of incident pions for the π^+ experiment was 6.39×10^{10}; for the π^- experiment it was 8.6×10^{10}.

Figure 1(a) shows a portion of the off-time (accidental) γ-ray spectrum in coincidence with π^+ scattered at 35° and Fig. 1(b) shows the same portion of the true coincidence spectrum (on-time spectrum minus off-time spectrum). The 478-keV peak in Fig. 1(a) arises from the Ge(Li) shielding. The peak around 840 keV in Fig. 1(b) contains several unresolved γ rays and hence was not labeled. The true-to-accidental ratio was about 4:1. Table I presents the differential cross sections for the stronger lines from Fig. 1(b) as well as the differential cross sections for the π^--γ coincidence spectrum reported earlier.[14] The corrections applied to the π^+ cross sections were of the same type as those used for the π^- case.[14] The errors reported in Table I are statistical only. Systematic errors are estimated to be $\lesssim \pm 15\%$ for both the π^+ and π^- case and arise mostly from the absolute normalization. The γ-ray spectra

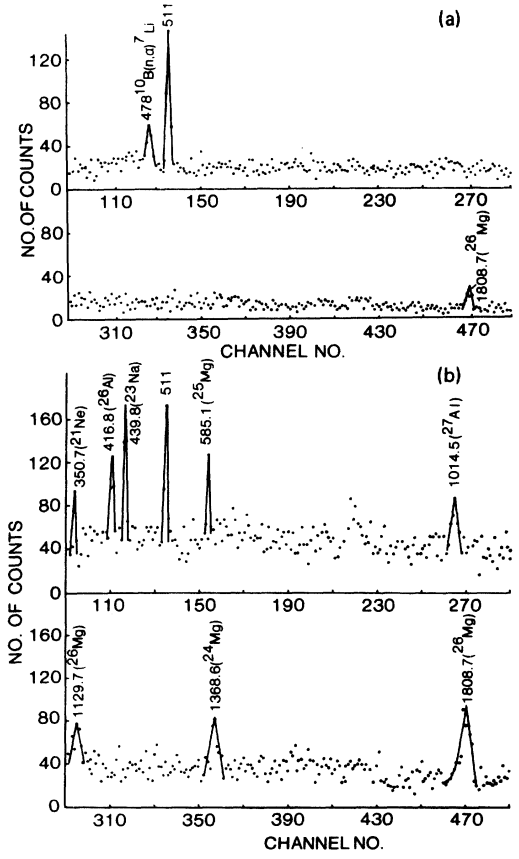

FIG. 1. Gamma-ray spectra in coincidence with scattered pions at 35° from 190-MeV π^+ on ^{27}Al. (a) The off-time (accidental) spectrum, with 194 nsec delay. (b) The true gamma-ray coincidence spectrum (on-time spectrum minus off-time spectrum).

TABLE I. Differential cross sections for γ-ray transitions observed in coincidence with scattered pions at 35° for 190-MeV π^+ and π^- on ^{27}Al.

γ line	E_γ (keV)	$\frac{d\sigma}{d\Omega}(\pi^+)$ (μb/sr)	$\frac{d\sigma}{d\Omega}(\pi^-)$ (μb/sr)
^{27}Al, II → 0	1014.5	480 ± 80	660 ± 110
^{26}Al, II → 0	416.8	130 ± 30	420 ± 45
^{26}Mg, I → 0	1808.7	2200 ± 200	2380 ± 270
^{26}Mg, II → I	1129.7	520 ± 100	680 ± 170
^{25}Mg, I → 0	585.1	190 ± 40	230 ± 52
^{24}Mg, I → 0	1368.6	790 ± 120	1230 ± 160
^{23}Na, I → 0	439.8	270 ± 30	350 ± 44
^{21}Ne, I → 0	350.7	131 ± 20[b]	170 ± 28[b]

[a] These values differ slightly from Ref. 14 due to refinements in the data analysis.

[b] These values may be low because the gamma-ray line is on the edge of the electronic discrimination cutoff.

taken in coincidence with emerging protons have been reported elsewhere.[15]

By forming the ratios of single-nucleon removal cross sections for π^- and π^+ under identical kinematical conditions and for the same nuclear level, nuclear effects such as spectroscopic factors cancel. The probability P that the struck nucleon will undergo charge exchange, however, does not cancel; it is included according to a generalized semiclassical equation of the type given by Silbar *et al.*[3]:

$$R_N = \frac{d\sigma_{\pi^- N}/d\Omega}{d\sigma_{\pi^+ N}/d\Omega} = \frac{f_N^-(\theta)B(1-P) + f_{N'}^-(\theta)B'P}{f_N^+(\theta)B(1-P) + f_{N'}^+(\theta)B'P}, \quad (1)$$

where N is the removed nucleon type (n or p), B and B' are the number of nucleons of type N and N' with which the pion interacts, respectively, and the $f(\theta)$'s are the free πN differential scattering amplitudes at this energy.

The correct values for B and B' are not known. However, since the interaction length of the pion is small ($\ll 1$ fm) it probably interacts mostly with the outer nucleons. If one chooses a noninteracting core such as ^{16}O or ^{20}Ne, $B \simeq B'$. (This is also true if the interaction is with all nucleons in ^{27}Al.) When $B \simeq B'$, unphysical and inconsistent values of P are obtained for our data which rules out no core, ^{16}O and ^{20}Ne. If one allows the $f(\theta)$'s to be different from the free values as a possible solution, one finds that the proton-removal data from Table I gives $P \simeq 0.5$, approximately independent of the $f(\theta)$'s. Using this value for the n-removal data gives a negative value for the ratio of the two $f(\theta)$'s and the results are again unphysical.

Motivated by the fact that the cross sections for $p2n$ removal (Table I) are much larger than

for other types of multinucleon removal the interacting nucleons were assumed to be only those outside ^{24}Mg, namely $p2n$, so that B and B' take on the values of 2 and 1, respectively (or vice versa). Under this assumption all the values of P obtained are reasonable and consistent. The values of P were calculated according to Eq. (1) using the cross sections from Table I, these values of B and B', and known values for $f(\theta)$,[16] 9:2:1. For n removal, $P = 0.29 \pm 0.08$. For p removal, differential cross sections for the production of the ^{26}Mg 1809-keV first excited state were corrected for feeding from the second excited state via the 1130-keV γ ray. The value of P obtained is $P = 0.34 \pm 0.06$.

A third value of P can be obtained from our p-γ data by sorting the data so as to give protons at 35° instead of pions in coincidence with the 1809-keV γ ray from ^{26}Mg. The cross sections so obtained are (5920 ± 33) and (1150 ± 240) μb/sr for incident π^+ and π^-, respectively.[15] This yields a value for $P = 0.041 \pm 0.02$. But this is for very different kinematical conditions. One can compare this value of P with the other two as follows: Protons detected at 35° from free π-N scattering have an energy of ~70 MeV, while the nucleon energy, when the π is detected at 35°, is ~16 MeV. Figure 2 shows the energy distribution of the protons detected at 35° arising from proton removal. The distribution has a full width at half maximum of about 50 MeV with the peak at ~75 MeV. For the sake of comparison of these two values of the charge exchange probability we assume we can use the free values. To compare the 70-MeV P with the P at 16 MeV, we follow the lead of Sternheim and Silbar[2] who have shown $\sigma_{ex} \sim T^{-1.9}$ and $P = \frac{1}{2}[1 - \exp(-\alpha\sigma_{ex})]$, where T is the nucleon kinetic energy, σ_{ex} is the charge exchange cross section, and α is a constant for a given target. This gives $P = 0.38 \pm 0.09$. This consistency suggests the correctness of our model and allows us to give a weighted average of the three values of $P = 0.33 \pm 0.04$.

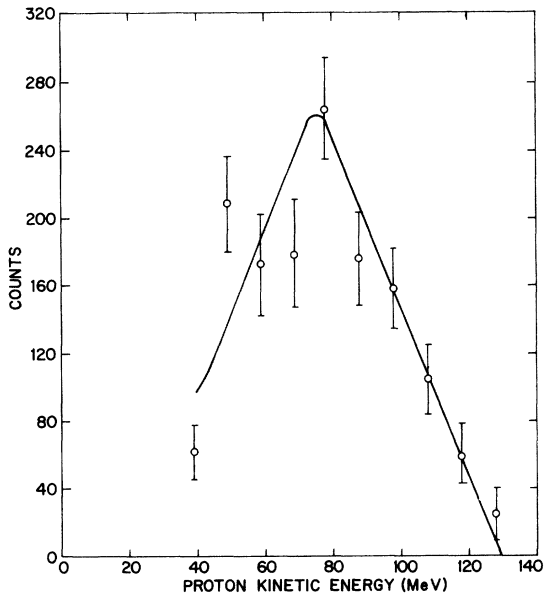

FIG. 2. The energy distribution for protons in coincidence with γ rays from all residual nuclei formed in single-nucleon removal due to 190-MeV $\pi^\pm$ on ^{27}Al. The solid line is an OSQF model calculation as explained in the text.

The two kinematically different conditions also give two points on an angular distribution and permit a comparison of the angular dependence with the $(1 + 3\cos^2\theta_{c.m.})$ of the free πN scattering, where c.m. is the center of momentum. In the case of p removal for the γ rays in coincidence with pions at 35°, $\theta_{c.m.} = 45°$ for the pions, while for the γ rays in coincidence with protons at 35°, $\theta_{c.m.}$ for the pions is 108°. The four differential cross sections give only two experimental values for $d\sigma/d\Omega$ because two were used to evaluate P. One must correct for the nuclear charge exchange factors, for the Jacobian from the lab to the center of momentum frame, and normalize in order to compare with the expected free values for $\theta_{c.m.} =$ 45° and 108°, which are 2.50 and 1.29. The normalized experimental values of $d\sigma/d\Omega$ are 2.69 ± 0.19 and 1.23 ± 0.07, respectively.

One can also get two relative values for $d\sigma/d\Omega$ from n removal by using the differential cross sections for $^{27}\mathrm{Al}(\pi^+, \pi^0 p)^{26}\mathrm{Al}$ and $^{27}\mathrm{Al}(\pi^+, \pi^+ n)^{26}\mathrm{Al}$. The differential cross sections for the $(\pi^+, \pi^0 p)$ reaction is (370 ± 60) μb/sr.[15] The normalized experimental values obtained for $d\sigma/d\Omega$ in this case are 2.25 ± 0.29 and 1.54 ± 0.25, respectively, again good agreement.

The nature of the OSQF process is further tested by comparing the differential cross-section ratio, after removing the effect of nucleon charge exchange, for the reactions $(\pi^+, \pi^+ p)$ and $(\pi^-, \pi^- n)$ with the ratio for $(\pi^-, \pi^- p)$ and $(\pi^+, \pi^+ n)$. The ratios are 7.4 ± 1.3 and 8.5 ± 2.6, respectively. These two values are, within errors, in agreement with each other and also with the ratio of the average spectroscopic factors[17] for the two levels, which is ~6.5. (The 1809-keV $d\sigma/d\Omega$ from Table I was corrected for feeding by 1130-keV γ rays in the calculations of these spectroscopic factor ratios.) The cross-section ratio of the 1809-keV line to the 1130-keV line is 3.0 ± 0.6 compared to a spectroscopic ratio[17] of ~3.6.

It has been suggested that for forward-scattered pions the struck low-energy nucleon may undergo multiple-step processes which would swamp

quasielastic scattering.[18] This effect, if present, would be the same for π^+ as π^- and for protons as neutrons; it should cancel and not affect the ratios, hence the values of P or the spectroscopic factor ratios. However, it may affect the comparison of the experimental $d\sigma/d\Omega$ with $(1+3\cos^2\theta_{\text{c.m.}})$. The agreement we have obtained is taken as an indication that the effect is not large in our experiment.

Additional evidence for the OSQF nature, which is independent from any of our above assumptions, is obtained from the energy of the emerging particles. The energy distributions of ejected protons in coincidence with the 1809- and 1129.7-keV lines for the $(\pi^-, \pi^- p)$ and $(\pi^+, \pi^+ p)$ reactions and with the 417-keV line for the $(\pi^+, \pi^0 p)$ reaction have been summed into one energy distribution (Fig. 2). A background distribution, obtained by setting a window on the γ ray distribution next to the γ ray in coincidence with the proton from the reactions given above, has been subtracted. The broad peak in the resultant data clearly coincides in position and shape with the peak expected for OSQF πN scattering shown as a solid curve in Fig. 2. That curve was generated by a Monte Carlo phase-space code PHASE.[19] Weighting factors included are (1) a Fermi distribution of the form $p^2 \exp(-p^2/b^2)$, where p is the lab momentum of the recoiling nucleus and b is the peak; and (2) the characteristic Breit-Wigner resonance shape and angular distribution of the $\Delta(1232)$. Threshold effects, namely proton energy losses in the target and scintillators, were also simulated in the calculation. The slope of the high-energy portion of the curve is sensitive to the choice for b. Several values of b were tried and the best fit came from $b = 150$ MeV/c. When $b = 268$ MeV/c (the average nucleon Fermi momentum), the slope is much less than that given by the data. A lower value of b supports the supposition that the interaction is peripheral in nature. Because of this we added a $\sin^2\phi$ weighting term, where ϕ is the nuclear recoil angle, to further simulate the peripheral nature. The fit improved slightly.

In summary, the consistency of data, as interpreted, indicates that in 190-MeV π^+ induced single-nucleon removal from ^{27}Al: (1) the interaction is predominantly OSQF scattering followed by charge exchange of the emerging nucleon with a probability of $\sim\frac{1}{3}$ for ~16 MeV protons; (2) the interaction takes place mostly on the outer $p2n$ nucleons of ^{27}Al; and (3) these outer nucleons have a Fermi momentum of ~150 MeV/c.

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