Gamma-Ray Spectrum in Coincidence with Scattered Pions from 190-MeV π^- Reactions on ^{27}Al

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In a pion–γ-ray coincidence spectrum from 190-MeV π^- reactions with ^{27}Al, prominent lines are observed corresponding to the equivalent removal of ^{6}Li, α, t, d, p, and n. When the data are normalized to n removal and compared to the inclusive singles γ-ray data, pion-scattering cross sections on the order of (50–100)% of the total for these reactions are implied.

Numerous studies of single-arm γ-ray experiments from pion-nuclear interactions have shown large cross sections for multinucleon removal and particularly those combinations corresponding to equivalent cluster or multicluster removal. Early interpretations suggested that these may result from pion scattering and hence the possibility of some clustering in the nucleus was implied.[1,2] From continued studies on a variety of targets and at various beam energies several experimenters have more recently concluded that pion absorption dominates the reactions and this is followed by cascading and evaporation of nucleons.[3-5] One group has concluded that "The same reaction mechanism (absorption) appears to explain pion-nucleus reactions over the energy range 0–400 MeV, contrary to the conclusions of earlier experiments."[4]

The inclusive nature of singles experiments precludes the possibility of directly verifying the absorption hypothesis, however. Detection of the pion in coincidence with the nuclear γ rays is needed to clearly identify the pion-scattering reactions. A coincidence experiment performed at Saclay at 70 MeV has recently reported multinucleon removal for γ rays in coincidence with emergent protons, but not with scattered pions.[6] They concluded that pion absorption accounted for (80–90)% of the pion-nuclear reaction cross section.

The short interaction length for the pion at resonance at about 180 MeV should imply less penetration, therefore more surface interactions and consequently more scattering at this energy. We report on results of a pion–γ-ray coincidence study at 190 MeV. The data were acquired on the

Clinton P. Anderson Meson Physics Facility (LAMPF) high-energy pion channel.

The beam was tuned to 300-MeV/c π^-. The target was 2-g/cm^2 chemically pure ^{27}Al. Emerging pions were detected with a scintillator telescope which also detected protons and deuterons from the reaction. The detector had a solid angle of 0.23 sr and was placed at 35° with respect to the beam so as to be out of the beam halo but still in a forward direction. The γ rays were detected with an 11%-efficient Ge(Li) detector placed at 90° with respect to the beam. The Ge(Li) detector was shadowed from the beam halo by lead and concrete.

A scintillator telescope of four scintillators was operated as a ΔE-E particle identifier. The first scintillator, S_1, measured ΔE, S_2 defined the solid angle, S_3 measured E, and S_4 determined whether or not the particle went all the way through the system. S_1, S_2, and S_4 were each 3.2 mm thick; S_3 was 15.2 cm thick, 15.9 cm wide, and 35.6 cm high. Only pions and protons with energies greater than ~73 and ~165 MeV, respectively, were able to enter S_4.

The data were recorded event by event on magnetic tape with eight parameters per event. A recorded event required a coincidence between S_1, S_2, S_3 and the Ge(Li) detector with a timing 2τ of 90 nsec. A delayed spectrum with the same 2τ and 194-nsec delay (well within the 500-msec beam pulse) between the particle and γ-ray arm was simultaneously recorded. When it is subtracted from the on-time spectrum, a real-coincidence spectrum results. The ratio of real to accidental events was 4.2:1.

The particle detector was particle and energy calibrated by placing it directly in the channel which contained π^+, p, and some deuterons of known momentum. Figure 1 shows a contour plot of the particles observed in the experiment. The loci compare well with those obtained during calibration. The inset shows a visual on-line display of ΔE versus E obtained for a sample of the data during the run. The pions, protons, and deuterons are seen to be cleanly separated one from another. The highest-energy protons (~300-MeV protons) begin to merge with the pion locus, but they are very few in number. High-energy protons which pass through S_4 originate from pion absorption. Thus no ^{26}Mg lines are expected to be present, and none are seen in the γ-ray spectrum in coincidence with these protons.[7] Pions, on the other hand, passing through S_4 are expected to show ^{26}Mg lines and strong lines are seen.[8]

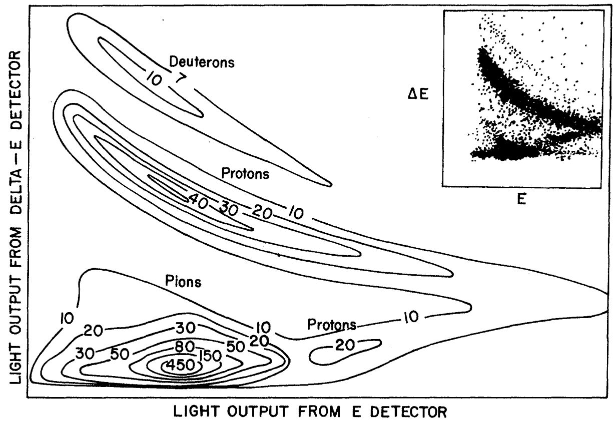

FIG. 1. A line drawing indicating the contours of the pion, proton, and deuteron loci obtained in the experiment. The highest-energy pions and protons observed are ~190 and ~300 MeV, respectively, whereas the lowest-energy pions and protons are ~15 and ~40 MeV, respectively. Inset: An actual on-line display of ΔE versus E light output from the particle telescope.

This further indicates that the pion locus is indeed dominantly due to pions and not to high-energy protons.

The Ge(Li) detector system was energy and efficiency calibrated using standard sources. Dead time of the Ge(Li) system was monitored with a scaled pulser signal triggered by random scattered particles and fed into the Ge(Li) system and rescaled. Dead time averaged 42% and was largely caused by saturating pulses in the detector. In a target-out run the count rate dropped from 2 events/sec to 0.1 event/sec, i.e. to about 5%, and the on-time to off-time ratio became unity. This assures us that our results are dominantly target related.

The average beam intensity was monitored with an ion chamber which was calibrated to the ^{11}C activity produced in a scintillator disk. It was ~2×10^6 π^-/sec. The total number of π^- for the run was 8.6×10^{10}.

A portion of the γ-ray spectrum in coincidence with the scattered pions (reals) is shown in Fig. 2. This includes both low- and high-energy pions. The accidental spectrum is shown in Fig. 3. (The proton–γ-ray coincidence spectra are similar, but individual lines differ in intensity.[7,8]) The prominent 478-keV peak in the accidental spectrum from ^{11}B(n, α)^{7}Li* due to the boron shielding is absent in the "real" spectrum, indicating that subtraction of off-time from on-time spectra is satisfactorily removing the background due to randoms. The remaining γ-ray lines are

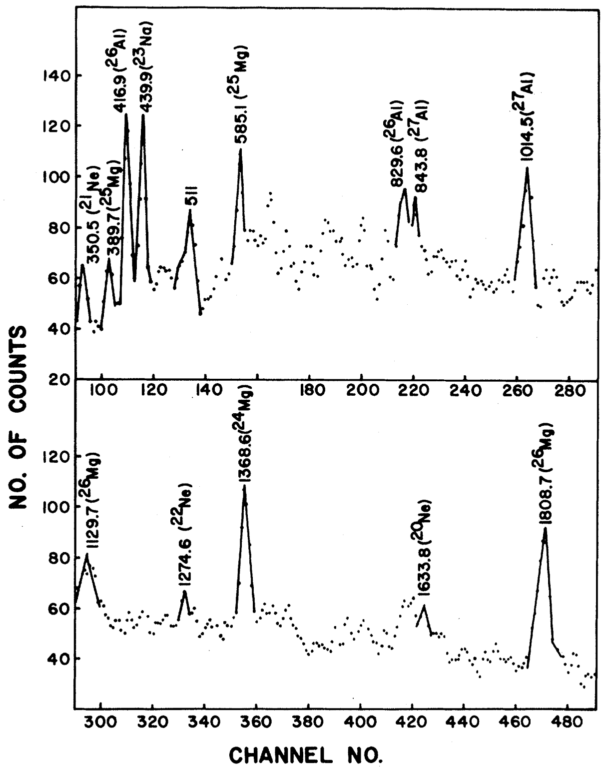

FIG. 2. A portion of the γ-ray spectrum in coincidence with scattered negative pions at 35° from 190-MeV π^- on ^{27}Al.

energy identified and assigned to transitions in residual nuclei. The data show prominent lines corresponding to de-excitations in ^{21}Ne, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{26}Mg, and ^{26}Al, i.e., to equivalent removal from ^{27}Al of ^{6}Li, α, t, d, p, and n, respectively. (Also target-excitation lines are observed.) Since these γ transitions are coincident with scattered pions, it is clear that the pions producing these reactions were not absorbed. (The implications for nuclear clustering from these data are considered elsewhere.)

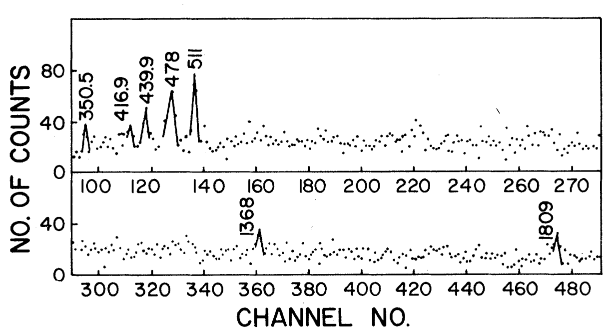

FIG. 3. An accidental-coincidence γ-ray spectrum accumulated simultaneously with the spectrum in Fig. 2.

TABLE I. Differential cross sections for γ-ray lines shown in Fig. 2 compared with singles experiments.

γ line	E_γ	$\frac{d\sigma(35°\ \pi^-)}{d\Omega}$ (μb/sr)	σ^a (singles) (mb)
^{27}Al (II→ 0)	1014.5	570 ± 95	29.9 ± 4.8
^{26}Al (II→ 0)	416.8	360 ± 40	10.1 ± 1.9
^{26}Mg (I→ 0)	1808.9	2070 ± 230	43.9 ± 7.9
(II→ 0)	1129.6	590 ± 150	11.5 ± 2.1
^{25}Mg (I→ 0)	585.1	200 ± 50	6.1 ± 1.1
^{24}Mg (I→ 0)	1368.6	1070 ± 140	33.5 ± 5.3
^{23}Na (I→ 0)	439.9	310 ± 40	20.7 ± 3.8
^{21}Ne (I→ 0)	350.5	150 ± 20^b	13.2 ± 2.5

^{a}Values taken from Lieb *et al.*, Ref. 10.
^{b}Probably low because of electronics discriminator cutoff.

Differential cross sections for the prominent transitions (Table I) were computed from the spectra and corrected for γ-detector dead time, narrow gates on the coincidence timing curve set to reduce accidentals, attenuation of the γ rays in the target, and losses of those pions from the pion locus which interacted with the thick scintillator. These losses in the scintillator were measured to be (20 ± 1)% of the total. Such events show up in the ΔE-E plot for low ΔE and large E but below the high-energy proton locus. Scintillator reactions leading only to neutrals have both a small ΔE and small E and are displaced to the left of the regular pion locus and constitute another (5 ± 2)%. A calculation using known cross sections[9] on ^{12}C gives 25% as an estimate for all such reactions, consistent with the observation. No corrections were made for losses due to pions whose energy was below detection threshold (less than 15 MeV) or due to particle-detector pileup or dead time, since their values are not known. Each of these effects tends to increase the reported cross sections, but they are unlikely to contribute more than 10% altogether. Protons with the same ΔE as low-energy pions may interact with the scintillator giving a low-E pulse and thus simulate a pion. Examination of the scintillator response due to monoenergetic protons obtained during detector calibration showed contamination by protons from this source that were within the pion gates to be very small (< 1% of the pions). Pions which undergo multiple scattering in the detector cause the pion locus to smear out towards low E. The pion gates were sufficiently broad so that they are included in the locus. The cumulative systematic errors from all causes may be ± 15%. These are in addition to the statistical errors (including background subtraction) stated in Table I.

From these scattering data one would like to deduce the total cross sections and make a comparison with the inclusive singles γ-ray data. It would then be possible to state the scattering-to-absorption ratio for each of the reactions. Unfortunately, the angular distribution of the various reactions has not been determined and so total cross sections cannot be given. At best, one can compare the relative strength of the multinucleon removal to a reaction such as $(\pi^-, \pi^{-\prime}n)$ since it must give the same cross section for both types of experiment. This gives some measure, therefore, of the importance of scattering for the other reactions. (Lines in ^{27}Al cannot be used for normalization since the inclusive data contain significant contributions from secondary neutrons. Contributions to single-nucleon removal due to secondaries can be considered insignificant by the complete absence of ^{26}Mg in the high-energy proton coincidence data,[7] which would also be produced by secondaries if they were important.)

Normalizing to the 417-keV line in ^{26}Al one obtains scattering cross sections which are near the singles values of Lieb *et al.*[10] except for the reactions leading to ^{23}Na and ^{21}Ne, which are about 50%. This implies that the fraction of the reaction due to scattering is large and approaches 100% for some of the reactions. One must be cautious, however, in reaching such conclusions since different reactions may have different angular distributions. In particular the $(\pi^-, \pi^{-\prime}p)$ reaction is somewhat overestimated by this normalization. Other reactions could be overestimated or underestimated. If one assumes that the distributions are isotropic, the scattering reaction drops to ~ (30–40)% but $(\pi^-, \pi^{-\prime}n)$ is now greatly underestimated.

In conclusion, the fraction of π^- surviving in multinucleon-removal reactions at 190-MeV beam energy appears to be significantly higher than the (10–20)% upper limit reported at 70 MeV.[6] This is in agreement with what one expects for pions interacting on the surface and disagrees with the earlier conclusion[4] that the same pion-nuclear mechanism explains all data from 0 to 400 MeV. The relatively weaker lines for ^{21}Ne and ^{23}Na indicate that absorption may be more important, however, as the number of removed nucleons increases.

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[1]H. E. Jackson *et al.*, Phys. Rev. Lett. 31, 1353 (1973).

[2]V. G. Lind *et al.*, Phys. Rev. Lett. 32, 479 (1974).

[3]R. E. Segel *et al.*, Phys. Rev. C 13, 1566 (1976).

[4]Y. Cassagnou *et al.*, Phys. Rev. C 16, 741 (1977).

[5]M. Zaider *et al.*, Phys. Rev. C 16, 2313 (1977).

[6]R. Legrain *et al.*, Phys. Lett. 74B, 207 (1978).

[7]O. H. Otteson *et al.*, in Contributed Papers, Third International Conference on Clustering Aspects of Nuclear Structure and Nuclear Reactions, Winnipeg, Manitoba, June 1978 (to be published), paper D13.

[8]R. E. McAdams *et al.*, Ref. 7, paper D11.

[9]F. Binon *et al.*, Nucl. Phys. B17, 168 (1979).

[10]B. J. Lieb *et al.*, Phys. Rev. C 14, 1515 (1976).