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Prompt gamma rays from nuclear reactions induced by 380-MeV π^-†

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Using a Ge(Li) detector, γ-ray spectra coincident with incident 380-MeV π^- have been measured for targets of S, Ar, Ca, V, ^{60}Ni, and As. The production cross sections for identified γ rays vary from about 200 to about 500 mb, depending on the target, although there is considerable uncertainty in the absolute cross sections. Comparison with data taken at lower energies leads to the conclusion that the spectra do not significantly change with pion energy over the range 100 MeV $\leq T_\pi \leq 400$ MeV. Formation of nuclei which can be made by removing an integral number of α particles, or, in the case of odd targets, a triton plus an integral number of α particles, appears to be usually favored but it is not certain that it is necessary to invoke special clustering effects in order to explain the presently available data. Some clues as to the reaction mechanism can be found in the data.

[NUCLEAR REACTIONS 380-MeV π^- on S, Ar, Ca, V, ^{60}Ni, As. Measured γ-ray spectra, cross sections.]

I. INTRODUCTION

High-resolution γ-ray spectroscopy has been shown to be an effective method for studying the interaction of mesons with complex nuclei.[1-4] In particular, measurements of the prompt γ rays accompanying the interaction of stopped kaons,[1] 25–100-MeV pions,[3] 220-MeV pions,[4] and 380-MeV pions[2] have indicated that single- and multiple-α removal is in the exit channel a significant fraction of the time. The data, however, have been too fragmentary to permit any unique interpretation of these results. In the present work six nuclei, ranging in mass from $A = 32$ to $A = 75$, were studied. Thus, the work is concentrated in the region where the strongest α removal has been reported. Some evaporation calculations have been performed and are compared with the experimental data.

II. EXPERIMENTAL PROCEDURE

Utilizing the low-momentum-enriched beam facility of the Argonne ZGS, negative pions produced by proton bombardment of a copper target were focussed onto a $\approx$10-g/cm^2 target. For all of the work the momentum spread in the beam of incident pions was about ±4% of the 500-MeV/c (T_π = 380 MeV) selected value. Pulses from a Ge(Li) detector were analyzed if they were in coincidence with two plastic scintillators which defined the incident beam. In anticoincidence were a Čerenkov counter in the beam to veto electrons, which constituted about two-thirds of the beam, and a plastic scintillator whose function was to veto charged particles entering the Ge(Li) detector. A schematic of the experimental arrangements is shown in Fig. 1.

Standard fast electronics was used with the plastic scintillators and the Čerenkov counter. A crossover pickoff was used to define the time signal from the Ge(Li), and with this system a width of about 8 nsec was observed on the spectrum from the time-to-pulse-height converter. Dead times were minimized by passing the pulses from the Ge(Li) through a short-time-constant amplifier followed by an integrator gated by the fast logic. In particular, there was a considerable rate of very large pulses, whose height corresponded to ionization losses $\approx$100 MeV, which, if ungated electronics with the usual approximately

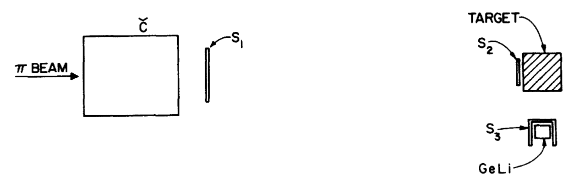

FIG. 1. Schematic of the experimental geometry. S_1, S_2, and S_3 refer to plastic scintillation detectors, while $\hat{C}$ symbolizes a gas-filled Čerenkov detector. Pulses from the Ge(Li) that fulfilled the condition $\bar{C}S_1S_2\bar{S}_3$ Ge(Li) were analyzed.

2-μs integrating time had been used, would have resulted in a significant amount of dead time and spectral distortion. When only the coincident pulses were integrated, these undesirable effects were minimized.

Linewidths were typically about 5 keV and overall spectral quality was significantly better than that obtained previously.[2] Pion fluxes were about 10^5 per pulse and satisfactory spectra were obtained in from about 6 to 12 hours.

III. EXPERIMENTAL RESULTS

Spectra were taken with targets of S, Ar, Ca, V, ^{60}Ni, and As. Except for the case of ^{60}Ni, all of the targets contained the natural mixture of isotopes but in each case one isotope is dominant. Table I lists the properties of the various targets. The observed spectra are shown in Figs. 2–7, while Table II lists the various lines that were observed.

Energy and efficiency calibrations were obtained with the aid of radioactive sources. Self-absorption in the target was corrected for and this correction was usually no more than about 30%. Energies are usually believed to be accurate to ±3 keV although in some cases, such as at ~1.5 MeV with a V target, systematic deviations of as much as 5 keV appear. Assignments rendered dubious by the discrepancy between the measured and expected energies are given in parentheses. For any one target relative cross sections are believed accurate to ±20% for lines that stand clearly out of the continuum. Because of the large electron contamination in the incident beam, absolute cross sections could not be accurately determined and for most of the targets the error could be as great as ±50%. However, we do note that a careful absolute cross-section measurement[5] for 380-MeV π^+ on ^{60}Ni found values within about 15% of those quoted here. The vanadium data were taken with the most intense beam and, consequently, the determination of the pion flux could have been very inaccurate. Therefore, it is felt that the vanadium cross sections could be low by as much as about a factor of 2 and, indeed, the values for vanadium do appear to be somewhat out of line with the others. Furthermore, the vanadium cross sections found here are only about 40% of those reported at 220 MeV, while for ^{60}Ni the values reported here are comparable to those at 220 MeV.[6]

Since rather thick targets were used, some of the observed γ rays could have been produced by secondaries. Neutrons, being uncharged, are likely to be the most troublesome and the observed spectra indicate that ~2–3 neutrons are produced per π^--nucleus interaction. Most of the secondary neutrons can probably be represented by an evaporation spectrum which should be similar to the spectrum of neutrons that accompanies fission. Fission neutrons have an average energy of about 2 MeV, and at these energies inelastic-neutron-scattering cross sections are large. It is estimated that these secondary neutrons may be responsible for a significant fraction of the inelastic scattering observed in the present work. We therefore attach little significance to any inelastic scattering cross sections quoted here. Down substantially in cross section, but possibly still significant, are (n, α) reactions which would appear as ^{3}He removal in the present work. All over low-energy neutron-induced reactions are expected to be weaker and, since the observed ^{3}He removal was always small, it can be concluded that only the γ rays from inelastic scattering were significantly enhanced by secondary reactions.

As the atomic number of the target increases the spectra tend to get increasingly difficult to analyze, primarily because (1) more lines are present and (2) γ rays have lower energies and tend to get closer together. These trends are apparent in the spectra of Figs. 2–7. A special problem is present in the Ca data as here several of the important lines are strongly Doppler-broadened. While, in analyzing the calcium spectrum, we have attempted to account properly for the Doppler broadening it should be noted that there is an extra uncertainty in the intensity of the 1.970-MeV ^{36}Ar, 2.230-MeV ^{32}S, and 1.779-MeV ^{28}Si lines.

TABLE I. Targets and fluxes for the various spectra.

Target	Dominant isotope A	(%)	Thickness to beam (g/cm^2)	Incident pions ($\times 10^9$)
S	32	95.0	11.2	1.5
Ar	40	99.6	7.1	1.7
Ca	40	96.9	10.4	2.0
V	51	99.7	14.9	0.63
Ni	60	>99	6.6	1.2
As	75	100	5.6	1.3

IV. ANALYSIS OF RESULTS

From Table II a lower limit for producing each nuclear species can be determined. In even-even nuclei, where most cascades come down through the first excited states, the total cross section for producing that nucleus is likely to be little more than the lower limit. More lines are apt to be missed in odd nuclei, although such nuclei below $A = 60$ often have simple enough low-lying spectra so that most of the production will lead to

TABLE II. γ rays observed in coincidence with 500-MeV/c negative pions bombarding various targets. Lines attributed to ^{27}Al may be partially due to background.

Target	E_γ (keV)	Identification	σ (mb)
S	417	^{26}Al 418	4
	439	^{23}Na 439, ^{24}Al 439	8
	679	^{30}P 678	4
	709	^{30}P 709	7
	844	^{27}Al 844	6
	1015	^{27}Al 1013	7
	1216	?	8
	1251	^{31}S 1249	7
	1268	^{31}P 1266	26
	1368	^{24}Mg 1369	35
	1779	^{28}Si 1778	30
	2032	(^{29}Si 2028)	18
	2237	^{32}S 2237, ^{31}P 2234, ^{30}Si 2236	56
Ar	396	^{39}Cl 396	5
	429 438	?	12
	718	?	7
	790	^{36}Cl 790	13
	841	^{33}S 840, ^{27}Al 843	12
	906	(^{36}S 902)	9
	1013	^{27}Al 1013	17
	1064	^{40}Ar 1063	6
	1267	^{39}Ar 1267	29
	1301	^{39}Cl 1301	5
	1431	^{40}Ar 1431	15
	1459	^{40}Ar 1460	69
	1516	^{39}Ar 1517	15
	1998	?	7
	2128	^{34}S 2127	6
	2167	^{38}Ar 2168	15
	2221	^{40}Ar 2220	21
	2237	(^{32}S 2230)	8
	3295	^{36}S 3291	17
Ca	1272	^{39}Ar 1267 ^{31}P 1267	29
	1368	^{24}Mg 1369	11
	1611 [a]	^{37}Ar 1611	16
	1638	^{20}Ne 1634 + ^{38}Ar 1643	5
	1779	^{28}Si 1779	29
	1970 [a]	^{36}Ar 1970	47
	2134	(^{34}S 2127)	23
	2170	^{38}Ar 2168	22
	2209	^{36}Ar 2208	10
	2228	^{32}S 2230	56
	2817	^{39}K 2814	6
	3734 [a]	^{40}Ca 3734	16
V	320	^{51}V 320	36
	812	^{47}Sc 808	14
	834	^{50}V 838	11
	890	^{46}Ti 889	24
	931	^{51}V 929	23
	985	^{48}Ti 983	36
	1092	^{47}Ti 1090	15
	1122	^{46}Ti 1120 ^{44}Ca 1125	33
	1158	^{44}Ca 1156	17
V	1234	?	18
	1286	^{47}Ti 1283	20
	1310	^{48}Ti 1311	22
	1343	^{46}Ca 1347	10
	1376	^{49}Ti 1382	10
	1516	(^{42}Ca 1524)	12
	1548	^{50}Ti 1554	18
	1603	^{51}V 1609	35
	1810	^{51}V 1813	21
	2172	^{38}Ar 2168	12
^{60}Ni	342	^{59}Ni 340	19
	380	^{53}Mn 378	15
	439	(^{58}Co 433)	15
	461	^{59}Ni 466	20
	473	^{55}Fe 475	11
	743	(^{51}Cr 749)	15
	785	^{50}Cr 783	28
	832	^{54}Cr 835	32
	848	^{56}Fe 847	70
	893	^{46}Ti 889	15
	932	^{55}Fe 931 (^{52}Cr 936)	17
	983	^{48}Ti 983	24
	1100	^{59}Co 1098	37
	1128	(^{54}Fe 1131)	37
	1192	^{59}Co 1190	7
	1227	^{57}Co 1224	29
	1242	^{56}Fe 1238	44
	1292	^{59}Co 1292	27
	1316	^{55}Fe 1316	14
	1332	^{60}Ni 1332	84
	1408	^{54}Fe 1408	25
		^{55}Fe 1408	4
	1432	^{52}Cr 1434	34
	1452	^{58}Ni 1454	19
	1525	^{42}Ca 1524	12
	1806	^{56}Fe 1811	24
	2164	^{55}Co 2168	15
As	390	^{71}Ge 391 ^{71}Ga 390	7
	419	^{75}As 419	9
	469	^{75}As 469	12
	562	?	
	572	^{75}As 572	7
		^{69}Ga 574	24
	594	^{74}Ge 596	25
	607	^{74}Ge 609	23
	718	?	11
	820	^{75}As 822	7
	835	^{72}Ge 835	33
	867	^{74}Ge 869	10
	911	^{71}Ga 911	8
	991	^{64}Zn 992	16
	1039	^{70}Ge 1040 ^{66}Zn 1039	29
	1112	^{70}Ge 1113	13

[a] These lines were used for energy calibration.

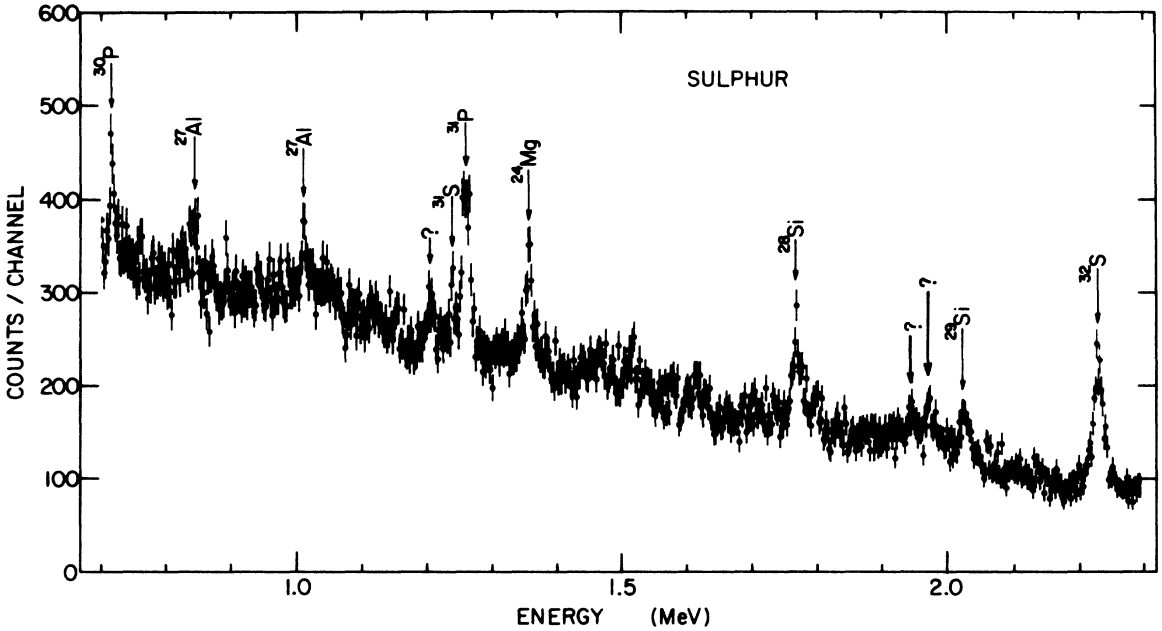

FIG. 2. Spectrum obtained with natural sulfur target.

identifiable lines. Indeed, the total identified production cross section for odd nuclei is sometimes rather large; an example is the 35 mb found for γ rays in ^{55}Fe when ^{60}Ni was the target. In contrast, the level spectra of most odd-odd nuclei are so complex that much of their production may have been missed. Thus, the fact that no odd-odd nucleus was strongly observed may merely be a consequence of this experimental technique. Table III lists various quantities extracted from the observed production cross sections.

While there do not appear to have been total reaction cross sections reported in this energy region, an extrapolation from lower-energy data[7] indicated that about 25–40% of the total reaction cross section is accounted for in these measure-

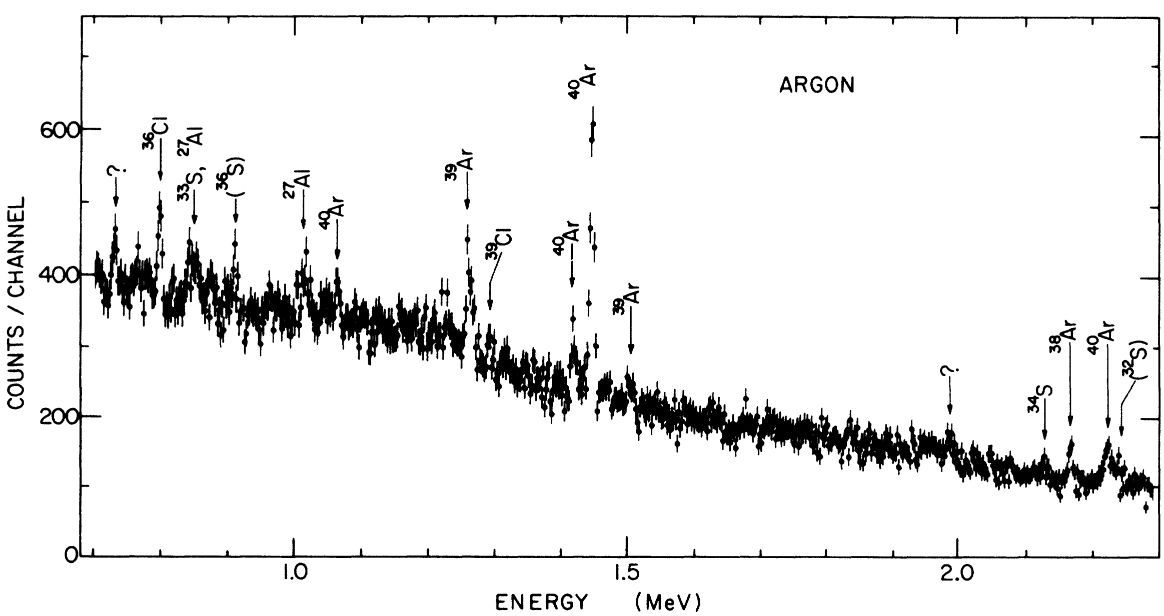

FIG. 3. Spectrum obtained with liquid natural argon target.

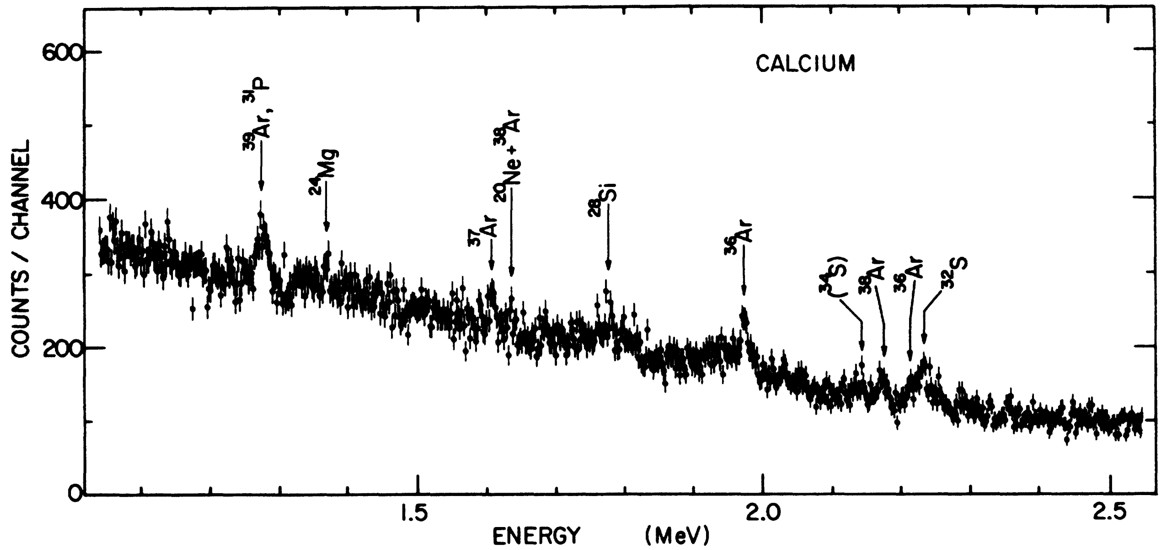

FIG. 4. Spectrum obtained with natural calcium target.

ments when ^{60}Ni or a lighter nucleus was the target. Similar results have been obtained at 220 MeV.[5,6] The smaller summed cross section in the As data can be attributed to the greater complexity and lower average energy of its spectrum.

It can be seen from Table III that α removal is certainly a favored exit channel, particularly for those nuclei which can be broken up into an integral number of α particles. However, even for a ^{40}Ca target the present results indicate that it is unlikely that more than about 20% of the total reaction cross section (estimated, as noted above, from lower-energy reaction cross-section data) goes into producing nuclei which correspond to the target minus an integral number of α particles.

Were quasifree elastic scattering the mechanism

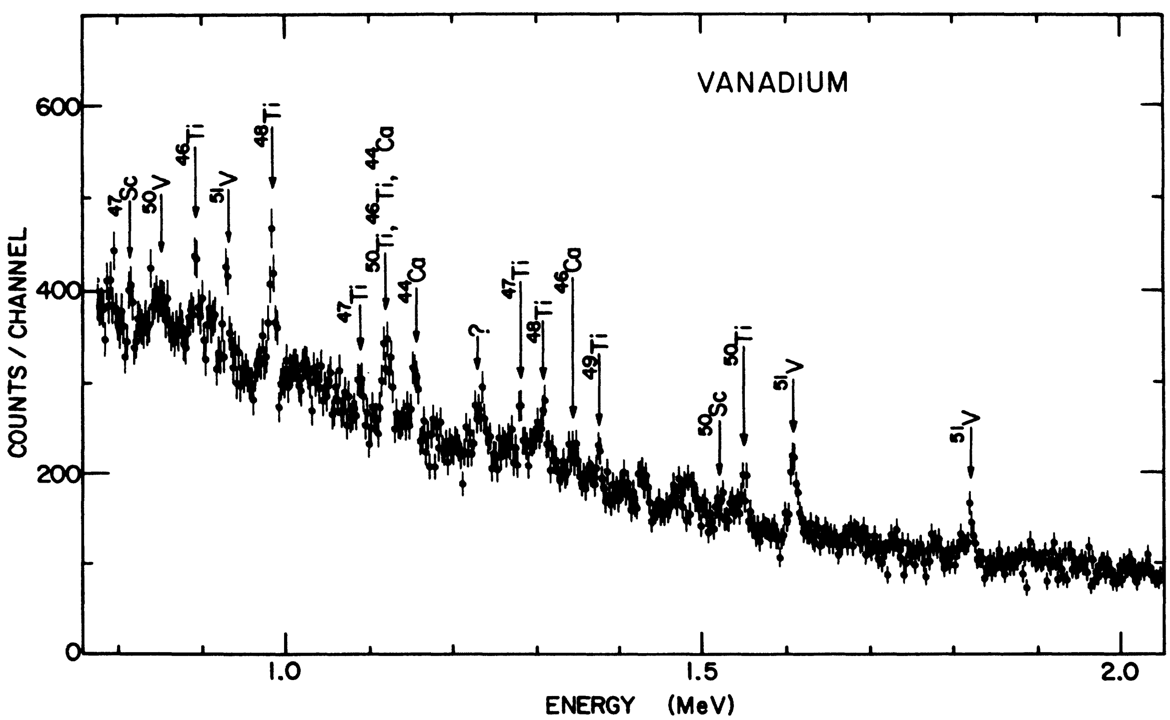

FIG. 5. Spectrum obtained with natural vanadium target.

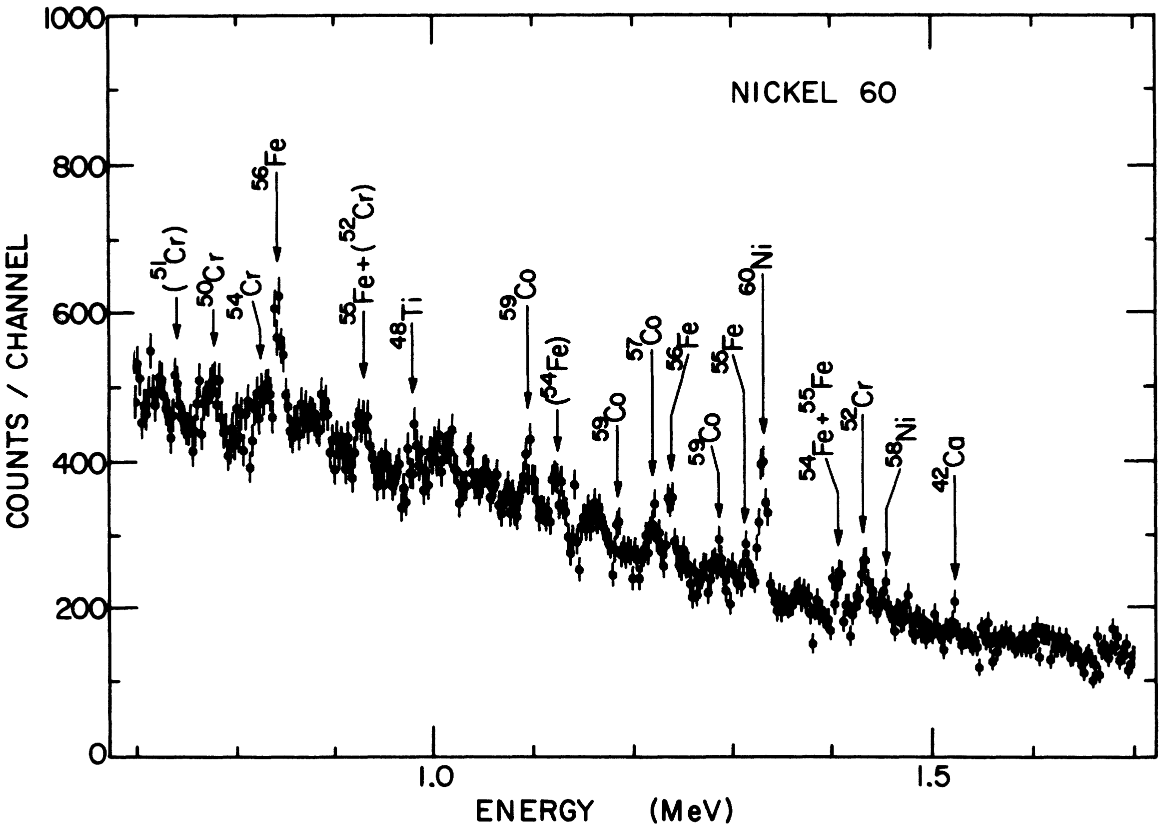

FIG. 6. Spectrum obtained with ^{60}Ni target. The ^{60}Ni enrichment was over 99%.

for single nucleon removal, the ratio of single neutron to single proton removal for incident 380-MeV π^- would be about 1.5 : 1 when the target nuclei have the same number of neutrons and protons. Experimentally, however, we find that both for ^{32}S and ^{40}Ca single proton removal is favored. In fact, the only case where single neutron removal is favored is that of ^{40}Ar which is also the only case where the neutron binding energy is less than the proton binding energy. It therefore appears that a primary mechanism for single nucleon removal involves an energy sharing among the nucleons. Whether this is the result of the pion interacting with the nucleus as a whole, followed by evaporation, or of quasifree elastic scattering modified by final-state charge exchange, remains to be determined. Further evidence against quasifree scattering playing a major role in single nucleon removal is present in data taken near the (3, 3) resonance[6] where for ^{58}Ni the ratio of single proton to single neutron removal was found to be virtually the same for incident π^+ as for π^-. It should be noted that it is not likely that pion absorption plays a major role in single nucleon removal, since one-nucleon emission after the nucleus ^{Z}A absorbs a $\pi^+(\pi^-)$ cannot form the nucleus $^{Z-1}(A-1)[^{Z}(A-1)]$. In fact, if a π^+ is absorbed, in order to form a nucleus with atomic number $Z' = Z - m$ it is necessary that $A' \leq A - m - 1$, while if a π^- is absorbed then it is necessary that $Z' \leq Z - 1$. Thus, the presence in the present work of strong lines from lighter isotopes of the target nucleus is evidence that the incident pion survives a significant proportion of the primary reactions. The same argument also indicates that charge exchange (π^-, π^0) contributes negligibly to the yield of nuclides near the target.

A comparison of the average number of neutrons removed with the average number of nucleons removed (Table III) indicates that for the self-conjugate nuclei protons are somewhat more likely to come off, probably because of their lesser binding energy. On the average, more neutrons than protons seem to be removed from targets which have a neutron excess, with there being a rough correspondence between the favoring of neutron removal and the neutron excess in the target nucleus. The larger number of nucleons removed from Ca is a reflection of the rather strong multi-α particle removal apparently observed with this nucleus, i.e., the ^{32}S, ^{28}Si, and ^{24}Mg lines listed in Table II. However, as noted above the Doppler

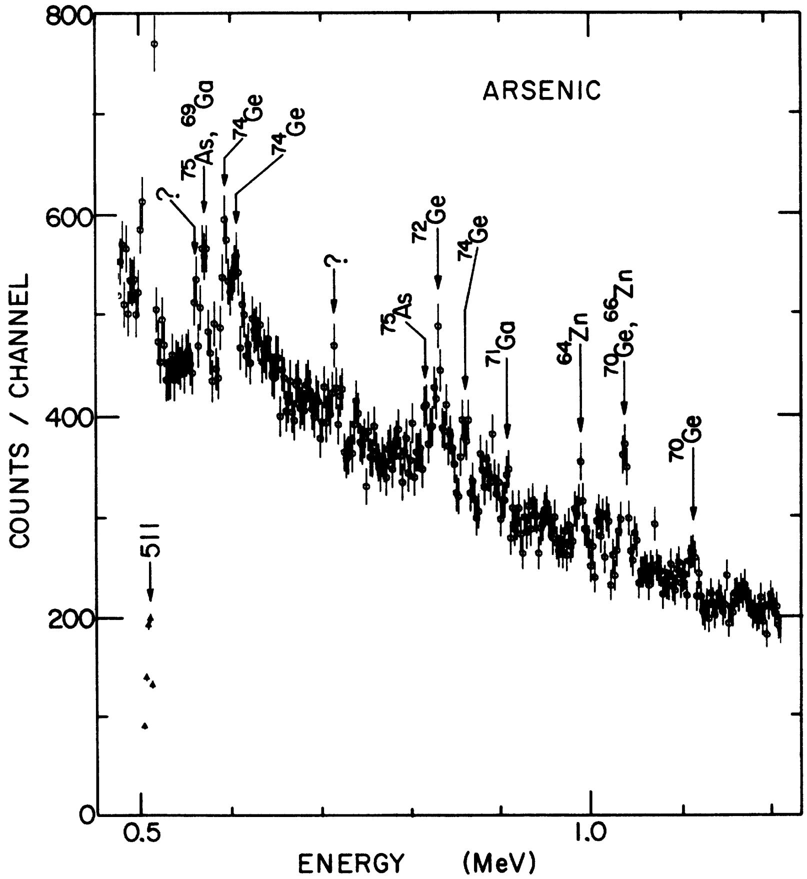

FIG. 7. Spectrum obtained with arsenic target.

broadening of the main lines in ^{28}Si and ^{32}S is considerable, leading to a markedly greater than usual uncertainty in the quoted intensity of these lines. It is therefore not certain how much greater the nucleon removal is in calcium although the 220-MeV data[4-6] does also indicate some peaking at ^{40}Ca in the average number of nucleons removed.

By comparing the present results with those obtained at lower energies, some aspects of the energy dependence of pion-induced reactions can be determined which, in turn, give important clues as to possible reaction mechanisms. The most extensive data at lower energies were taken on the nickel isotopes.[6] Qualitatively, the present data look similar to those taken with 220-MeV π^- on ^{60}Ni

TABLE III. Various quantities extracted from the γ-ray spectra.

Quantity \ Target	S	Ar	Ca	V	^{60}Ni	As
$\sum$ observed[a] (mb)	144	125	239	199	512	111
$\frac{\sum \alpha(+t) \text{ removal}}{\sum \text{observed}^{a}}$	0.44	0.14	0.60	0.34	0.25	0.44
$\frac{1n \text{ removal}}{1p \text{ removal}}$	0.27	4.40	<0.5	0.61	0.55	
$\langle n \rangle$ removed	1.9	2.2	3.2	2.9	2.8	2.7
$\langle$nucleons$\rangle$ removed	4.2	3.1	6.9	4.6	5.2	4.2

[a] Excluding inelastic scattering.

where the 847-keV ^{56}Fe γ ray was the strongest line (except, possibly, for inelastic scattering), and γ rays from other nuclei in the α-removal chain were also prominent. In fact, the α-removal nuclei were somewhat more prominent at 220 MeV. Most important, the average number of nucleons removed was 5.3 which is indistinguishable from the 5.2 found at 380 MeV in the present work. It has also been previously reported[6] that for π^+ on ^{58}Ni the average number of nucleons removed at 220 MeV was not significantly different from the average of 5.2 nucleons removed at 100 MeV. Noting that at 220 MeV for both ^{58}Ni and ^{60}Ni little difference was found between the spectra induced by π^+ and by π^-, it then follows that in the nickel region, at least, the number of nucleons removed is virtually independent of pion energy between 100 and 400 MeV. This result suggests that in those interactions that result in a substantial number of nucleons being removed the pion is usually absorbed. It has been noted above that the cross sections for the removal of a small number of nucleons require that for these reactions the pion must often survive.

For vanadium, too, the present spectra at 380 MeV are similar to those obtained at 220 MeV (Ref. 8) with the ^{48}Ti 983-keV line being most prominent if, again, inelastic scattering is excluded. Smaller absolute cross sections were found in the present work but, as has been noted previously, this difference may well be due to experimental error. An average of 4.8 nucleons were found to be removed at the 220-MeV bombarding energy which, in view of the experimental errors, is probably not significantly different from the 4.3 nucleons removed found here at 380 MeV. At any rate, it is clear that the number of nucleons removed does not increase with increasing bombarding energy, in agreement with the results obtained with ^{60}Ni. In both the present work and the LAMPF[5,6,8] 220-MeV data about $\frac{1}{3}$ of the identified spectrum, excluding inelastic scattering, is attributed to triton, or triton + α, removal. In the 220-MeV data taken at Space Radiation Effects Laboratory (SREL)[4] large cross sections were reported for making the third and fourth excited states of ^{47}Sc, which is the nucleus formed by removing an α particle from ^{51}V. While the standard compilation[9] lists the energies of the ^{47}Sc levels as being very poorly known, level energies with errors of less than 0.5 keV have been published.[10] Using these rather precise values, only one line in the present work can be attributed to ^{47}Sc. In particular, neither the 1.12- nor the 1.16-MeV γ rays fit transitions in ^{47}Sc, and we therefore cannot accept the large cross sections for producing ^{47}Sc reported in Ref. 4.

As noted above, the Doppler broadening of the first excited state to ground transitions in ^{36}Ar, ^{32}S, and ^{28}Si renders the Ca data particularly prone to error. In the LAMPF 220-MeV π^--on-Ca data the α-removal lines appear to be somewhat less prominent than in the present work.[5] On the other hand, the 220-MeV SREL data[4] do report very prominent lines from the chain of nuclei formed by removing from one to five α particles from ^{40}Ca. However, in interpreting the SREL results it must be remembered that (1) a normalization error which reduces all their calcium cross sections by a factor of 2.4 has been discovered[11] and (2) a complete analysis of the data has not been published. Reflecting the lower cross sections quoted for α removal, the LAMPF data yield an average of only 5.1 nucleons removed as against the 6.9 found here. However, the difficulties in analyzing the Ca data are sufficiently great so that this difference may merely represent differences in the data analysis.

In an effort to ascertain to what degree the data can be explained without specifically introducing extra clustering, evaporation calculations have been performed. Let $O^{\pm}(F)$ denote the cross section for the production of a final nucleus F by $\pi^{\pm}$ interacting with some target nucleus. It is assumed that the nucleus F has excitation energy less than the particle-emission threshold E_F. Let $\sigma^{\pm}(C,E)$ denote the cross section—per unit excitation energy—for the primary event yielding nucleus C at excitation energy E. The observed cross sections $O^{\pm}(F)$ can then be expressed in terms of the primary cross sections $\sigma^{\pm}(C,E)$ as

$$O^{\pm}(F)=\int_0^{E_F} dE\sigma^{\pm}(F,E)+\sum_C \int dE\sigma^{\pm}(C,E)\Gamma(C,F,E)\,, \tag{1}$$

where $\Gamma(C,F,E)$ is the branching ratio for the evaporation of nucleus C (with excitation energy E) to the final nucleus F. For given C and E, Γ is normalized so that $\sum_C \Gamma(C,F,E)=1$. The quantities $\Gamma(C,F,E)$ were calculated using the evaporation code of Blann and Plasil.[12]

TABLE IV. Primary reactions considered as the pre-equilibrium processes on a target nucleus ^AZ in the nuclear evaporation calculations. The resultant nucleus is designated C in Eq. (1).

Resultant nucleus	Possible reactions
^ZA	(π,π')
$^Z(A-1)$	$(\pi,\pi'n)$
$^{Z-1}(A-1)$	$(\pi,\pi'p)$, (π^-,n), (π^-,π^0n)
$^Z(A-2)$	$(\pi,\pi'2n)$
$^{Z-1}(A-2)$	$(\pi^-,2n)$, $(\pi,\pi'np)$, (π^-,π^02n)
$^{Z-2}(A-2)$	(π^-,np), $(\pi,\pi'2p)$, (π^-,π^0np)

It has previously been reported[6] that Monte Carlo calculations of the primary processes, the $\sigma^{\pm}(C,E)$ in Eq. (1), do not lead to agreement with the observed production cross sections. A set of primary cross sections, satisfying known invariance requirements, was therefore sought which, utilizing Eq. (1) and calculated[12] values of Γ, would reproduce the observed spectra of final nuclei. Since, as noted above, it appears that nuclei far removed from the target result from an interaction in which the pion is absorbed, the simplest possible primary reaction is pion absorption on a pair of nucleons as conservation of energy and momentum makes absorption on a single nucleon very improbable. Within this restriction, it was found that only very simple assumptions about primary processes were necessary in order to satisfactorily predict, except, possibly, for the case of the calcium target, the spectra of final nuclei removed from the target by four or more nucleons. For example, the spectrum observed from the ^{60}Ni target is reasonably well produced if it is assumed that the only primary process is

$$\pi^- + {}^{60}\text{Ni} \to {}^{58}\text{Fe}^* + p + n \tag{2}$$

with the associated cross section $\sigma^-({}^{58}\text{Fe}, E)$ constant if $0 \leq E \leq 150$ MeV and zero if $E > 150$ MeV. Choosing the constant so as to best fit the data, Table V compares calculated production cross sections (column $-pp$) to those observed. Also shown in Table V (column $-np$) are the results of a similar calculation, where it is assumed that the only significant primary process is

$$\pi^- + {}^{60}\text{Ni} \to {}^{58}\text{Co} + n + n\,. \tag{3}$$

The calculations fail to predict the rather significant amount of ^{54}Cr that is observed, although it should be noted that the ^{54}Cr line does not stand out clearly (Fig. 6). Furthermore, ^{54}Cr was not found when ^{60}Ni was bombarded with 220-MeV pions[6] although in this case the ^{54}Cr line could have been obscured by background. The calculated ^{42}Ca production could be raised by rounding off the initial energy distribution $\sigma^-({}^{58}\text{Fe}, E)$ which would, in fact, be a more plausible assumption. Because, as discussed above, the experiment is likely to miss much of the cross section to odd and odd-odd nuclei, there is little point in comparing observations of these nuclei with any calculations. However, it is worth noting that using the normalization of Table V, the calculated cross sections for producing all nuclei by evaporation from ^{58}Fe uniformly excited to 150 MeV will total about 760 mb, which is quite a reasonable number. It is perhaps surprising that a primary process in which a π^- is absorbed by two protons gives the better fit to the data, since both the quasideuteron and isobar models[13] of π^- absorption predict that the absorption is more likely to take place on an np pair. However, final-state nucleon charge exchange could explain this apparent discrepancy.[14]

TABLE V. Comparison of experimental results with production rates calculated under the assumption that the primary reaction removes either two protons or a neutron and a proton leaving ^{58}Fe or ^{58}Co nuclei with a rectangular energy distribution which cuts off at 150 MeV. Only even-even nuclei are considered and the calculated results are normalized by requiring the sum of calculated cross sections for the nuclei listed below, excepting ^{54}Cr, to equal the corresponding sum of measured cross sections.

Final nucleus	Production cross section Calculated $-pp$	$-np$	Measured
^{56}Fe	63	23	70
^{54}Fe	26	42	25
^{54}Cr	0	0	32
^{52}Cr	46	50	34
^{50}Cr	18	34	28
^{48}Ti	34	28	24
^{46}Ti	19	24	15
^{42}Ca	3	5	12

Insight into the above model can be gained by considering the production of individual nuclei and in Fig. 8 the calculated production of ^{56}Fe and ^{48}Ti from a ^{60}Ni target is shown. It can be seen that, as expected, a nucleus near to the target nucleus in atomic number is likely to result when the primary reaction leaves the secondary nucleus with relatively little excitation energy. Conversely, when a lot of energy is left, the evaporation is likely to

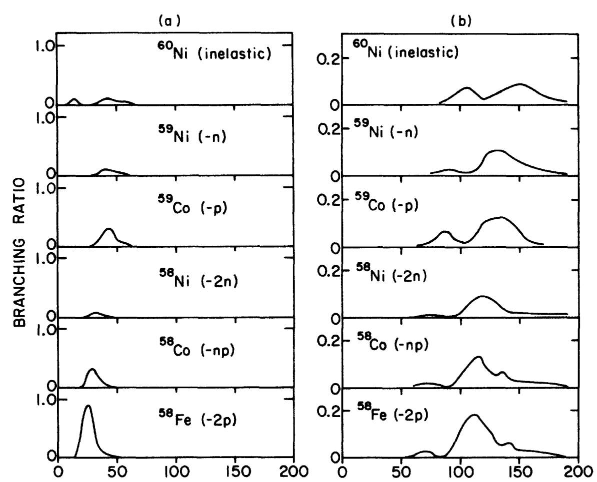

FIG. 8. The branching ratios $\Gamma(C,F,E)$ for the evaporation of nucleus C to the final nucleus F as functions of the excitation energy E of C. In (a) F equals ^{56}Fe and C is the nucleus indicated for each curve. In (b) F equals ^{48}Ti and C is again indicated for each curve.

end in a nucleus far from the target. Since ^{48}Ti is produced in significant quantities from ^{60}Ni, the curves of Fig. 8 show that if the present results are to be explained on the basis of this model the distribution of excitation energy following the initial interaction must extend beyond 100 MeV.

While the calculations described above are, with the possible exception of the data taken with a calcium target, reasonably successful in reproducing the spectra of final nuclei far removed from the target, it must be remembered that the results are not unique in that other combinations of primary processes followed by evaporation are likely to reproduce the data equally well. Furthermore, although it is plausible that pion absorption is a major primary process there are not likely to be many events in which only two nucleons are removed and the residual nucleus is left with 100–150-MeV excitation energy. Removing even the two most tightly bound nucleons from a nickel nucleus will result in only about 80 MeV in excitation energy, and it is difficult to see how another 70 MeV could be deposited without more fast nucleons escaping. Such secondary, pre-equilibrium, events are allowed for in the intranuclear cascade calculations, and yet such a calculation[15] did not give good agreement with the data taken on nickel at 220 MeV.[6] Specifically, the calculation predicted too many nuclei near to the target and too few far away. This disagreement can be interpreted as indicating that the calculated pre-equilibrium phase does not leave the secondary nuclei with enough excitation energy and/or does not remove enough nucleons. A confirmation of this discrepancy is seen in the energy distribution of charged particles resulting from the interaction of 235-MeV π^+ with nickel nuclei[16] where the observed number of higher-energy protons is far fewer than what is predicted. It is interesting to note that pion absorption on clusters of more than two nucleons would tend to reconcile the disagreement between the calculations and the experimental results.

V. CONCLUSIONS

The present experiment has examined the prompt γ-ray spectra accompanying the bombardment of a range of light-medium nuclei with 380-MeV negative pions. A preference for residual nuclei which can be formed by removing one or more α particles from the target nucleus or, in the case of an odd target, a triton plus α particles, does appear to exist but, except when calcium is the target, the results are consistent with being the end product of an evaporation process initiated either by the absorption of a pion on a pair of protons or by an np pair followed by nucleon charge exchange. However, in order to explain the rather large cross sections for producing nuclei far removed from the target, it is necessary to assume that the escaping nucleons leave the residual nucleus with an unreasonably large amount of excitation energy. Thus, a better knowledge of the initial pion-nucleus interaction is required if the results of these and other similar studies are to be understood. While it does appear that some form of clustering is needed to explain the calcium data, the relevant lines are strongly Doppler-broadened and therefore the determination of their intensity is subject to considerable experimental error.

Where the same nuclei have been studied at lower energies the present results are quite similar, particularly as to the average number of nucleons removed. It is thus likely that the pion is absorbed in those interactions in which a large amount of energy is transferred to the nucleus. In contrast, the observation of nuclei which can be made by removing one or two protons from the target requires that the pion in its original charge state sometimes survives. Measurements of particle spectra as well as coincidence measurements between the various radiations (pions, nucleons, and γ rays) are probably required before the initial step in the pion-nucleus reaction can be detailed.

The data obtained in the study of the interaction of fast pions with nuclei are clearly qualitatively different from those obtained in the more conventional experiments performed at lower-energy accelerators. Only now are the systematics for these reactions starting to emerge and then only for lighter nuclei. Nevertheless, sufficient data have been reported to indicate that the field is a fruitful one, which is likely to lead to new insights into nuclear structure.

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