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Interaction of Fast Negative Pions with ^{60}Ni†

H. E. Jackson, L. Meyer-Schützmeister, and T. P. Wangler
Argonne National Laboratory, Argonne, Illinois 60439

and

R. P. Redwine, R. E. Segel, and J. Tonn
*Argonne National Laboratory, Argonne, Illinois 60439, and Northwestern University, Evanston, Illinois 60201**

and

J. P. Schiffer
Argonne National Laboratory, Argonne, Illinois 60439, and University of Chicago, Chicago, Illinois 60637
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The γ-ray spectra resulting from the bombardment of ^{60}Ni and ^{28}Si with 500-MeV/c negative pions were measured. For ^{60}Ni, lines were present from the decay of first excited states of ^{56}Fe (^{60}Ni-1α), ^{52}Cr (^{60}Ni-2α), and ^{48}Ti (^{60}Ni-3α). Single neutron removal was not observed. Similar results were obtained for ^{28}Si. A comparison is made with results obtained with stopped K^- and proton beams.

In an experiment[1] studying the interaction of stopped kaons with natural Cu and Ni targets, it was found that the resulting γ-ray spectrum implied that the removal of one or more α particles is a prominent decay mode for the system. Since with these natural targets two isotopes dominate, γ-ray lines from two strings of isotopes were seen. Because of the size of the samples needed, separated isotopes were not used in the stopped kaon experiment. It did not appear that the major features of the spectra could be due to a statistical evaporation mechanism. Other evidence, scattered and fragmentary,[2-4] has indicated that when s-d shell nuclei are bombarded with negative pions or protons of energy $\gtrsim 100$ MeV, single and multiple α knockout is a favored channel. It is difficult to explain these results within the context of present-day nuclear theory, and thus we are led to the notion that we are seeing evidence of some new aspects of nuclear structure. In order to follow this trail further, an experiment has been performed to investigate the interaction of fast pions with ^{60}Ni. This particular target material was chosen as it is in this mass region that the kaon results were most provocative.

Fast pions were produced by the 12-GeV beam in the Argonne National Laboratory zero-gradient synchrotron (ZGS) striking a Cu target, and the 500-MeV/c negative pion beam was focused onto a 10-g/cm^2 ^{60}Ni target (enrichment 99.8%) viewed by a 30-cm^3 Ge(Li) detector. A gas Cherenkov counter was used in anticoincidence to eliminate electrons which were approximately 2.5 times as numerous as the pions. Production studies at the ZGS have shown that heavier negative particles are a negligible contamination in a π^- beam.[5] Pulses from the Ge(Li) in coincidence with two plastic scintillators placed just in front of the target were processed and recorded by a 4096-channel analyzer. An anticoincidence counter was placed in front of the Ge(Li) detector in order to eliminate events where charged particles

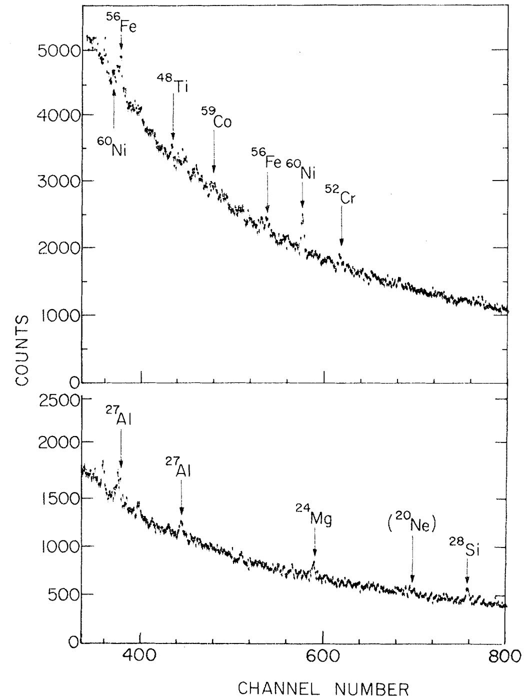

FIG. 1. Spectra obtained when (a) ^{60}Ni and (b) ^{28}Si were bombarded with a 500-MeV/c π^- beam. The total pion charge during the ^{60}Ni run was 1.6 times that of the ^{28}Si run.

entered the Ge(Li). The pulses from the Ge(Li) first passed through an amplifier with short time constants and then through a gated integrator. Thus, it was possible to tolerate high singles rates without introducing a major deterioration in resolution in the coincident spectrum.

Figure 1 shows the spectrum recorded for a total of 5×10^9 pions incident on the target. Next to annihilation radiation the most prominent line is, as expected, the 1.33-MeV line from the first excited state in ^{60}Ni, produced with a cross section of ~14 mb. Next most prominent are the 0.85-MeV line from ^{56}Fe and the 1.43-MeV line from ^{52}Cr, both produced with a cross section of ~7 mb. A weak line at 0.98 MeV, the energy of the first excited state in ^{48}Ti, is also present. Background lines from Pb and Ge were also seen. The spectrum appears to contain a number of other weak lines though many of these are of dubious statistical significance. A singles spectrum taken with the beam detuned showed no prominent lines at the energies where prompt lines from the pion reaction were assigned. Thus, none of these lines are attributable to accidental coincidences with residual activity. The plastic scintillators in the beam were so thin that the efficiency of the system for detecting a γ-ray cascade was negligibly small.

At these bombarding energies one would expect direct reactions to dominate. Inelastic scattering might be expected to be strongest with single-nucleon removal competitive. Weak γ rays corresponding to single-proton removal are observed. Because the largest spectroscopic factor for picking up a proton leads to the ground state of ^{59}Co in low-energy reactions,[6] the observation of lines corresponding to excited states suggests that single-proton removal may be of comparable strength to α removal. However, in picking up a neutron[7] the $\frac{7}{2}^-$ state at 2.63 MeV in ^{59}Ni has the largest spectroscopic factor. The primary decay of this state is a 2.29-MeV line, and such a line is not observed in our spectrum with an upper limit of 2 mb. The data are quite similar to those of Si where proton and α removal, but not neutron removal, were observed. The results obtained here are similar to those of Ref. 1 with stopped kaons on natural Ni, namely the γ rays corresponding to 1α and 2α removal are strong—the γ ray from 3α removal present but weaker (Table I). As expected, the lines from the string of isotopes originating with ^{60}Ni are seen, but not those originating with ^{58}Ni. It is not likely that the prominent lines emanate from states that are strongly fed as the end product of a statistical evaporation since such a process should not only lead to nuclei removed from the target by an integral number of α particles. In an evaporation process neutron emission would compete favorably with charged-particle emission, thus leading to an enhanced production of neutron-poor isotopes. However, γ rays from ^{54}Fe, ^{50}Cr, or ^{46}Ti were not observed outside the uncertainty in the measurement.

In the present work ^{28}Si (natural Si, which is 92.2% ^{28}Si) was also examined and a prominent line was seen corresponding to the first excited state of ^{24}Mg, but there are also lines of comparable intensity from ^{27}Al, which is formed by knocking a proton out of ^{28}Si. The ^{27}Al lines cannot be primarily due to background since the 1.014-MeV line is prominent in the Si spectrum but at most a weak line in the Ni spectrum. However, the corresponding lines from ^{27}Si, which would be formed by removing a neutron from ^{28}Si, were not observed. This is contrary to both the low-energy charged-particle data[8,9] and the 150-MeV proton-scattering data in which single-proton and neutron removal occur with comparable

TABLE I. Production of various γ rays when ^{60}Ni and ^{28}Si interact with fast pions, fast protons, and stopped kaons. For the fast particles, production cross sections are given in millibarns, while for the stopped kaons, rates are relative to the strongest x ray from the K^- atom, which is given an intensity of 100. The Ni data from stopped kaons are for a natural target. For pure ^{60}Ni, the intensity per x ray would presumably be 3.8 times this strong. Only the lines corresponding to ^{60}Ni are listed. Parentheses indicate intensities which are uncertain because of the possible presence of unresolved background lines.

	Line		Bombarding particle		
Target	Nucleus	Energy (MeV)	380 MeV π^- (mb)	Stopped K^- [a] (per 100 x rays)	140 MeV p [b] (mb)
^{60}Ni	^{60}Ni	0.826	3.5		
	^{56}Fe	0.847	6.8	60	
	^{48}Ti	0.983	3.3	20	
	^{59}Co	1.098	(3.0)	40	
	^{59}Co	1.190	(2.0)	20	
	^{56}Fe	1.236	4.9	40	
	^{60}Ni	1.333	14.7	40	
	^{52}Cr	1.434	7.0	40	
	^{59}Ni	2.29	<2.0		
^{28}Si	^{27}Si	0.780	≤ 0.4		7
	^{27}Al	0.843	4.3	30	9
	^{27}Si	0.957	≤ 0.4	20	6
	^{27}Al	1.014	4.2	20	12
	^{24}Mg	1.369	3.9	30	29
	^{20}Ne	1.634	(2)	30	19
	^{28}Si	1.779	6.5	30	25

[a]Ref. 1. [b]Ref. 4.

strengths. The 1.63-MeV line for ^{20}Ne was weak but probably present. Again similar results were seen in the kaon work.[1] Lind *et al.*[2] have looked at the γ spectra from the pion bombardment of nuclei with $A \lesssim 40$ and found the spectra to be dominated by lines corresponding to single and multiple α removal when an even-even nucleus was the target. For an odd-Z nucleus, ^{3}H removal appears to precede α removal.

Foley, Clegg, and Salmon,[4] working with 140-MeV protons and a NaI detector, observed the γ-ray spectrum for targets with $A \approx 25$. They identified lines corresponding to one and two α-particle removal and single-nucleon removal. Their results for ^{28}Si are included in Table I. Because of the resolution of the NaI detector, the assignments of the γ rays to particular nuclear transitions are less definitive than for spectra obtained with Ge(Li) detectors.

In the s-d shell nuclei it is perhaps no great surprise that α-particle removal is an important channel in the interaction with energetic particles. It is much less clear how such a mechanism can come about in the region of Ni, where multiple α-particle removal is comparable with nucleon removal. We do not even know at this time whether for pions the mechanism involves annihilation or inelastic scattering.

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