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Systematics of Pion and Proton Interactions with Ni Nuclides*

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γ-ray spectra have been observed following the interaction of 220-MeV π^+ and π^- and 200-MeV protons with ^{58}Ni and ^{60}Ni and 100-MeV π^+ with ^{58}Ni. Product nuclides have been identified from characteristic γ-ray lines corresponding to total cross sections of ~ 500 mb. The systematic trends with projectile and energy are explored; rather substantial differences are found between pions and protons.

Our knowledge of the interaction of pions with complex nuclei is rather limited. A number of experiments carried out with stopped negative pions, primarily on light targets, have provided some information on the pion-absorption process; in addition we have some knowledge of elastic scattering and total cross sections at higher energies.[1] For nuclei heavier than ^{12}C almost nothing is known of how much of the total cross section corresponds to the pion suffering an inelastic collision and maintaining its identity, and how much to the pion disappearing altogether. Nor is there much information on whether pion absorption occurs mainly on pairs of nucleons or whether larger clusters play a role. We have investigated the distribution of residual nuclides produced by the bombardment of ^{58,60}Ni with $\pi^\pm$ and also with protons; such results can provide substantial constraints on the gross features of possible models of the pion-nucleus interaction.

The residual nuclides were identified by measuring prompt γ-ray spectra. In contrast to activation measurements, this technique is sensitive to stable residual nuclei, where most of the total cross section is concentrated. γ rays are seen when a given residual nuclide is left with insufficient excitation energy for particle emission; this technique cannot distinguish whether this nuclide was reached by a direct primary process or whether it is the end of a chain of successive evaporations. The present measurements are similar to ones performed in the past few years[2-5] but with greater emphasis on accurate absolute cross sections and on studying the systematic dependence of the interaction on projectile type, charge, and energy and the neutron excess of the target.

The pion measurements were carried out on the Clinton P. Anderson Meson Physics Facility (LAMPF) low-energy-pion channel. Pion beams of $\sim 10^6$/sec were focused on to isotopically enriched (> 99.8%) targets, ~ 8 g/cm^2 in thickness. The γ rays were detected at 90° by a shielded 50-cm^3 Ge(Li) detector. Contaminants in the pion beam were small and the room background was low, making it possible to take singles γ-ray spectra gated only on macroscopic beam pulses. The incident flux was measured by integrating the current in a phototube which viewed a plastic scintillator through which the beam passed.[6] Dead-time and pileup losses in the Ge(Li) circuitry were measured by feeding a pulser, triggered by the scattered beam, into the preamplifier and comparing the number of triggers with the pulser peak in the spectrum. γ-ray energy resolution was about 3 keV and spectra were obtained in 3–6 h. The quality of these was better than that published in Ref. 3 but not as good as the proton-induced spectrum of Ref. 5. Spectra were collected for 220-MeV π^+ and π^- on both targets and 100-MeV π^+ on ^{58}Ni only. In addition, 200-MeV proton measurements on both targets were carried out with the same apparatus using a high-energy (P^3) channel at LAMPF.

γ-ray lines were identified and assigned to particular final nuclides on the basis of their energies. Production cross sections for the various residual nuclides were computed assuming isotropic angular distributions and are listed in Table I. All the even nuclides along the line of β stability were seen and some of the odd and odd-odd nuclides; many of the latter may well have been missed because of the lack of easily identifiable γ lines.

The gross pattern of cross sections does, as expected, roughly follow the line of β stability. Several averages over the data have been computed and are listed in Table II. Here we note that (1) the mean number of nucleons removed is constant for ^{58}Ni and ^{60}Ni and independent of the pion charge and energy. The value is substantially larger than that for protons. The fact that even 100-MeV pions remove as many nucleons as 200-MeV pions suggests that the pion rest mass is absorbed in the process. Similar data to ours, but with 100-MeV protons on ^{58}Ni,[5] yield $\langle A\rangle \approx 3.2$ which implies a drastic energy dependence for protons not seen with pions. (2) The average neutron excess of residual nuclides $\langle N-Z\rangle$ shows little dependence on pion charge or energy, but there is a substantial dependence on target nucleus. For both targets the

TABLE I. Cross sections from Ni isotopes[a] (in millibarns).

Target A	58	58	58	60	60	58	60
E_0 (MeV)	220 π^+	220 π^-	100 π^+	220 π^+ [c]	220 π^- [e]	200 P	200 P
Residual Nuclide							
^{60}Ni[b]				(85)[b]	(99)[b]		(58)[b]
^{59}Ni				51±15	55±15		50
^{58}Ni[b]	(64)[b]	(94)[b]	(57)[b]	8±3	17	(46)[b]	19
^{57}Ni[d]	7	11	9			13	
^{59}Co				49±20	29±15		11±7
^{57}Co	61	59	36	55	50	38	38
^{56}Co	30	70	31±9	~8	~4	34	~10
^{56}Fe	26±8	29±11	26±8	48	85	22±5	35
^{55}Fe[b]	87±25	91	90	79±25	76±25	71	48
^{54}Fe	47	43	34	18	14±6	44	18±5
^{55}Mn[d]	9±4	20	14±5	12±4	8±3	10	9
^{52}Cr	20	37	20	37	45	17	15
^{50}Cr	40	46	45	28	18±6	26	11
^{49}V[d]	28	22	20	24	23±6	9	6
^{48}Ti	12±4	28	7	14	22±6	5±2	4±2
^{47}Ti[d]	21	32	17	13±5	5	10	2±1
^{46}Ti	34	33	23	22	17	9	≤1
^{45}Ti[d]	7±3	14±6	4±2				
^{42}Ca[d]	10	13±4	6			<2	
Total[f]	439	548	382	466	468	310	277

[a]All cross sections are believed to be accurate to ±20% unless otherwise noted.

[b]The secondary γ rays produced by neutrons may be considerable for (n,n') and (n,α) reactions. A rough estimate indicates that 50–100% of the inelastic γ rays and 10–20 mb of the ^{55}Fe yield could be of secondary origin.

[c]A γ-ray line was identified, in this measurement only, which could be assigned to ^{57}Fe with 17 mb. The cautions of footnotes b and d apply.

[d]These assignments are based on the observation of a single γ-ray line and should be regarded with more caution than the others.

[e]The π^- data on ^{60}Ni are of somewhat lower quality than the rest. The possible errors in assignments are somewhat greater, the errors in cross sections are comparable.

[f]Not including inelastic cross sections.

TABLE II. Some averages computed for pions or protons incident on isotopic Ni targets.

Target A	58	58	58	60	60	58	60
E_0 (MeV)	200 π^+	220 π^-	100 π^+	220 π^+	220 π^-	200 P	200 P
$\langle A \rangle$[a]	5.4	5.4	5.2	5.4	5.3	4.1	4.2
$\langle N-Z \rangle$[b]	2.7	2.7	2.7	3.3	3.3	2.7	3.1
$\Sigma\sigma_{(N-Z)=2}$[c]	<u>131</u>	<u>135</u>	<u>108</u>	67	49	<u>81</u>	30
$\Sigma\sigma_{(N-Z)=4}$[c]	58	94	53	<u>99</u>	<u>152</u>	44	<u>54</u>
R[d]	0.44	0.70	0.49	1.48	3.10	0.54	1.80

[a]The target atomic weight minus the cross-section—weighted average atomic weight of residual nuclides, not counting inelastic scattering.

[b]The cross-section—weighted average neutron excess of residual nuclides.

[c]Summed cross sections (in millibarns) for even nuclides only, not including Ni. The numbers corresponding to the α removal chains are underlined.

[d]Ratio of the summed cross sections in the previous two lines: $\Sigma\sigma_{(N-Z)=4}/\Sigma\sigma_{(N-Z)=2}$.

proton bombardment yields essentially the same value of $\langle N-Z\rangle$ as do the pions, despite removing fewer nucleons; this suggests a more rapid convergence towards the line of β stability than for pions. In the ratio R, defined as the summed cross section for $N-Z=4$ even-Z nuclides, divided by that for $N-Z=2$, we see clear evidence of pion charge dependence as well as target dependence.

Table II shows clearly that even nuclei with the same neutron excess as the target (in other words nuclei which differ from the target by integral numbers of α particles) appear with significantly larger cross sections than the other even nuclides. It is not clear whether this feature reflects a special mechanism, in which the interaction preferentially selects α-particle clusters. Similar effects had been reported with stopped kaons on Ni and Cu[2] and 370-MeV π^- on ^{60}Ni.[3]

Earlier data on π^+/π^- comparisons have been reported for 65-MeV pions on Cu.[7] Strong variations in yields of specific radionuclides were seen, generally far from the line of β stability. Cascade calculations using a Monte Carlo technique and including absorption via the (3, 3) resonance have fit these earlier data reasonably well.[8] Some results from such calculations[9] have been compared to the present data. While they reproduce the gross independence of pion charge, they tend to overestimate the yield for nearby nuclides, and underestimate that for more distant ones, giving $\langle \Delta A\rangle \approx 3.9$ to compare with 5.4 in Table II. The "α-removal" chain is favored in the calculations for ^{58}Ni, but not for ^{60}Ni.

Clearly our data reflect both the precompound (or direct) stage of the pion-nucleus interaction, whether it be scattering or absorption, and any subsequent evaporation of nucleons and/or α particles. If we assume that the evaporation process is reasonably well understood and we impose charge-symmetry constraints on the π^+-versus-π^- precompound yields, then it may be possible to work backwards from the present data, in conjunction with the charged-particle spectra now becoming available,[10] to determine the distribution of nuclides and excitation energy remaining after the precompound processes. This would be an important step in advancing our understanding of the pion interaction with complex nuclei.

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Collisional Angular Momentum Mixing in Rydberg States of Sodium*

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Collisions with rare-gas atoms are observed to produce a lengthening of the lifetime of the highly excited ($n = 5-10$) d states of Na. The effect is interpreted as collisional angular momentum mixing of the d state with $l > 2$ states; thus the average lifetime of all states for which $l \geq 2$ is observed. The cross section for the process appears to increase as the geometrical cross section of the excited atom.

In a program to investigate the properties of highly excited or Rydberg atoms we first measured the radiative lifetimes of the Na s and d states for $n = 5-13$.[1] We have recently studied the effects of collisions of rare-gas atoms with sodium atoms in these high-lying s and d states. We chose to use the rare gases as collision partners to begin with since they are chemically inert, cannot absorb energy internally from the sodium atoms, and might be a good buffer gas for future experiments. In the experiments described here, when a rare gas was added to the sodium cell, we observed a lengthening of the fluorescent decay times of the nd levels of sodium. This effect is interpreted as a collisional mixing of the initially excited nd level with the higher angular momentum substates of the same n.

The experiment was done by a laser-fluorescence technique using the apparatus described in Ref. 1. The only change is the addition of a Baratron pressure gauge to measure the rare-gas pressure. An N_2 laser pumps two dye lasers which are tuned to the $3s \to 3p$ and $3p \to ns, nd$ transitions of sodium. The two laser beams are merged in a Pyrex cell containing Na vapor and the rare gas. We observe the time-resolved fluorescence, usually back to the $3p$ state, emitted as the population in the ns or nd state decays.

The behavior of the $8d$ state typifies the qualitative features of our observations with the excited Na d states. At argon pressures up to 1 mTorr, the $8d$ fluorescent decay time was not observed to be faster than the measured radiative or "vacuum" value, 502 nsec. In the 1–10-mTorr range, two easily distinguishable components were observed in the decay. The fast component was faster than the radiative decay rate, and the slow component was considerably slower than the radiative decay rate. As an example, the pressure dependence of the fast decay rate of the $10d$ state is shown in Fig. 1. At argon pressures from 10 mTorr to 1 Torr, the fast decay was too fast for us to observe; we only observed a single exponential with a pressure-independent decay time τ_{eff} considerably longer than the radiative decay time. Neon and helium showed similar behavior. The s states showed no rare-gas-pressure effects except for $n = 10$ which showed the onset of a longer decay at 1 Torr of argon.

These observations suggest that collisions with the rare-gas atoms transfer the sodium atoms in the excited d states into all the higher angular momentum states of the same n. Thus, the fast decay reflects the d-state population decaying at a rate equal to the sum of the collisional and radiative rates. The initial d-state population is then distributed over all the angular momentum states for which $l \geq 2$. Similarly, subsequent col-