SYSTEMATICS IN THE INTERACTION OF INTERMEDIATE ENERGY PROTONS WITH MEDIUM MASS NUCLEI

M. Sadler, J. Jastrzebski*, A. Nadasen and P.P. Singh
L.L. Rutledge**, Jr., T. Chen** and R.E. Segel**

Studies of gamma-ray spectra accompanying the interaction of medium energy pions[1-3], protons[3-6] and complex projectiles[7] with nuclei have demonstrated the potential effectiveness of this method in studying such reactions. Experiments were therefore undertaken in which gamma ray spectra were measured at a number of incident proton energies between 80 and 164 MeV with a range of medium mass targets.

The gamma rays following the proton bombardment of 1-5 mg per cm^2 thick isotopically-enriched targets of ^{58}Ni, ^{60}Ni, ^{62}Ni, ^{64}Ni, ^{54}Fe, ^{56}Fe, ^{59}Co and ^{48}Ti were detected with an overall resolution of 3 keV. Data were taken on and between beam bursts using a 10% Ge(Li) detector placed at 90° to the incident beam direction. Dead-time was monitored by recording pulses from a pulser, triggered by the current integrator, in the

Table 1. Cross sections for producing final nuclei following bombardment of various isotopic nickel targets with protons in 80-164 MeV range.

PRODUCT NUCLEUS	E_p = 136 MeV[a]				E_p - MeV 80	100	164
	^{58}Ni	^{60}Ni	^{62}Ni(d)	^{64}Ni	^{58}Ni	^{58}Ni	^{58}Ni
^{64}Ni				13			
63				50			
62			30	103			
61			39	94			
60		26	64	40			
59		83	38	25			
58	16	34	19	17	31	29	11
57	15	8	0(2)		20	22	9
^{61}Co			6(23)	18			
60			13(31)	14			
59		16	21	15			
58		33	31(59)	21			
57	18	44	22(46)	12	29	24	16
56	63	33	15[c](11)		83	90	51
55	b	1	(1)		b	b	b
54	3				8	7	3
^{59}Fe			0(3)				
58		2[c]	8[c]	10[c]			
57		12	17	28			
56	22	67	40	39	18	16	15
55	52	58	28	10	71	69	49
54	45	27	9	2	49	60	38
53	5	2	(1)		5	5	3
52			(.1)				
^{56}Mn			0(3)				
55	3	11	11	11	2	1	1
54	14	29	19(22)	10	19	16	9
53	37	21	11	10	25	41	29
52	14	16	5(5)		10	8	10
51	11	4	2		11	10	8
50	2				2	1	1
^{54}Cr		11	10	10			
53		11[c]	7[c]	2[c]			
52	18	21	12	6	8	15	26
51	16	12	16(10)		18	16	10
50	23	11	(.4)		7	20	17
49	3				2		5
^{51}V			4				2
50	5	5	2		1	5	6
49	6	4	2		2	4	12
48	7	5	2(1)		3	4	9
47	3[c]						6
^{48}Ti	6		4		2	3	11
47						2	
46	5					2	9
Total	444	607	541	563	468	515	432

Footnotes to Table 1.

[a] Cross sections for each case are in mb.

[b] Gamma rays of ^{55}Co were outside the dynamic range of detection.

[c] These cross sections are relatively more uncertain.

[d] The cross sections given in parenthesis are those determined by the radioactivity method. These measurements also revealed the production of Copper isotopes (62-60) with a cross section of 14, 7 and 2 mb and of ^{48}Sc, ^{47}Sc, ^{46}Sc with a cross section of 0.1, 0.2 and 1.0 mb, respectively.

γ-spectrum. Count rate effects were investigated by altering the beam intensity and the detector location. Effects of timing gates were determined by comparing the measurements with and without the coincidence requirements. These and other checks indicated that systematic errors in absolute cross sections for individual gamma lines were less than 10%. Some measurements were also made at 125°; no significant angular effects were found. For most targets measurements were made at 100 and 136 MeV, but for ^{58}Ni and ^{62}Ni measurements were also made at 80 and 164 MeV. For ^{62}Ni targets off-beam γ-ray measurements were performed to determine the total production cross section of nuclei with lifetimes larger than about an hour. Typically, in-beam γ-spectra with adequate statistics were obtained in about an hour using 1/2 na of beam on target. Production cross sections based upon strong ($\sigma \geq$ 30 mb) γ-lines are accurate to about ± 15%, with this uncertainty rising to $\sim$50% for those based upon the weakest ($\sigma \simeq$ 2 mb) lines. The production cross sections were determined by identifying the observed γ-rays with the known gamma transitions among the low lying states. At least two transitions, within 1 keV in energy to the known transition energies and including one to the ground state, were required for positive identification of any nucleus. In some cases as many as 6-8 transitions were observed.

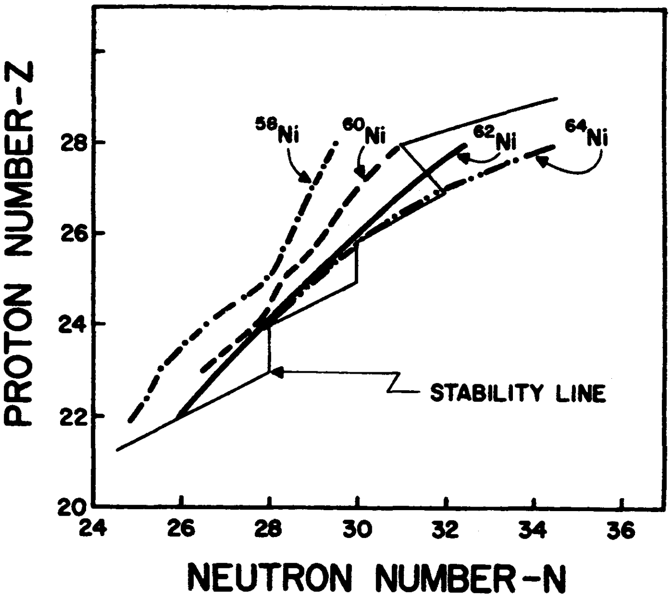

Figure 1. The position of the cross section weighted centroids of the nuclei produced of a given Z plotted as a function of the neutron number N for the four Ni targets. The zigzag line represents the abundance weighted stability line based upon naturally occurring isotopes of various nuclear species.

Production cross sections for final nuclei for ^{58}Ni, ^{60}Ni, ^{62}Ni and ^{64}Ni at 136 MeV and for the ^{58}Ni target at 80, 100 and 164 MeV are given in Table 1. The cross sections for ^{58}Ni (and ^{56}Fe) at 100 MeV are about a factor of three larger than those reported by Chang *et al.*,[4] although relative cross sections are in good agreement. Considering the precautions taken in the present work to determine absolute cross sections, the fact that a large fraction of the total reaction cross section is accounted for (see below), and the consistency of these data with those taken at 200 MeV, it is felt that the present cross sections are correct to the quoted accuracy.

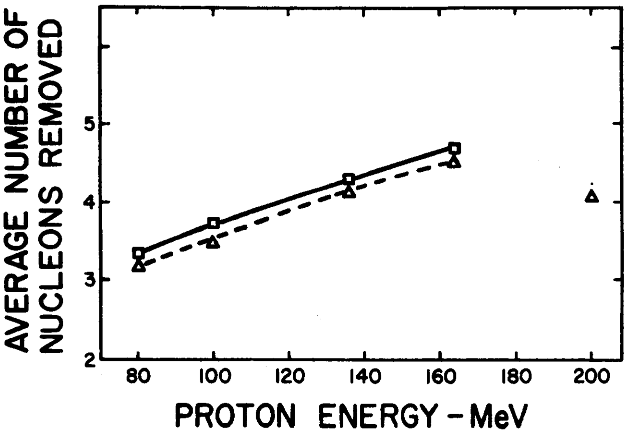

Figure 2. The average number of nucleons removed, <ΔA>, versus the proton energy for ^{58}Ni (▲) and ^{62}Ni targets (□). The magnitudes of <ΔA> at a given energy and trends with energy are similar for the other targets investigated. The 200 MeV points are from reference 3.

The main features of the cross sections are listed below. The data taken with all targets support these observations.

(a) With in-beam measurements 50-70% of the reaction cross section as estimated in terms of the optical model is observed. Radioactivity measurements, which include direct population of the ground states and direct feeding to it from higher lying states (missed in the in-beam measurements), account for an additional 15-20% of the reaction cross section. Since the radioactivity measurements were confined to two energies, only in-beam cross sections are used for the rest of the discussion.

(b) The pattern of nucleons removed is such as to populate residual nuclei near the line of stability. This effect is illustrated in Figure 1 where centroids of the distributions for each Z are plotted as a function of the neutron number N for the four Ni targets.

(c) The cross sections for nuclear species which are one or two protons removed from the compound system usually decrease with energy, while for those which are four or more protons removed the cross sections tend to increase with increasing energy.

(d) The average number of nucleons removed, <ΔA>, from the target increases with energy in this energy range (Figure 2) with an approximate slope of 0.015 nucleon per MeV. No significant dependence on target mass is observed for <ΔA>, which has the above energy dependence for all targets studied. The value of 4.2 reported for 200 MeV is below that obtained by extrapolating the above trend, but this discrepancy may be due to the 200 MeV work failing to detect nuclei formed by removing many nucleons from the target which are produced with relatively smaller cross sections.

(e) The difference in the average number of neutrons and protons removed, <ΔN>-<ΔZ>, is found to increase with the isospin of the target at about the rate of 0.63 per unit of target isospin. This behavior is nearly independent of the bombarding energy in the 80-200 MeV range.

The nucleon-nucleus interaction is envisaged as first proceeding through a pre-equilibrium phase in which the incident nucleon scatters off the target nucleons with the struck nucleon and the incident nucleon undergoing further scatterings or escaping from the nucleus. At the end of this phase the residual nucleus de-excites through the evaporation process. From the present data an estimate of the number of nucleons emitted in the pre-equilibrium phase can be made. The situation is most transparent in the case of ^{64}Ni as here a large fraction of the observed cross section, 70% at 100 MeV and 60% at 136 MeV, goes into producing lighter nickel isotopes (Table 1). Therefore, about half of the time only one proton is able to escape from the ^{64}Ni plus incident proton system. Noting that neutrons and protons should behave similarly in the pre-equilibrium phase, emission of one fast neutron is also quite likely. Thus, for ^{64}Ni in 60-70% of the cases only one or two fast nucleons appear to be emitted, leaving the residual nuclei of ^{64}Cu, ^{64}Ni, and ^{63}Ni in a broad range of excitation from which the evaporation subsequently drives the production towards the lighter nickel isotopes lying near the line of stability. The rapid convergence towards the line of stability observed for all cases (Figure 1) indicates that for all targets investigated here the number of pre-equilibrium nucleons emitted is small. Relatively slow increase of $<\Delta A>$ with energy, 0.016 nucleons per MeV in contrast to 0.1 nucleons per MeV expected for the evaporation phase$^{8)}$ alone, implies that over the energy range studied most of the incident energy is taken away by the fast nucleons. The decrease with energy of cross section observed for nuclei one or two protons removed from the compound system implies that the average number of fast (pre-equilibrium) nucleons emitted increase somewhat with increasing bombarding energy.

Relatively large cross sections with which '1α' (2n2p) removed nuclei are produced with ^{58}Ni and ^{62}Ni targets (12% and 11% of the total observed cross section, respectively) are believed to be a consequence of the fact that for these targets the '1α' nuclei lie close to the line of stability. In contrast, for ^{62}Ni and ^{64}Ni the '1α' removed nuclei lie relatively far from the line of stability and therefore the production cross section for these nuclei is small. The variations in the production cross section of two or more α-removed nuclei with the target can similarly be understood.

The data reported on here considerably exceeds the sum of all previous measurements of this kind. It is gratifying that from this body of data a number of details of the reaction mechanism have become apparent.

* IUCF Visiting scientist; permanent address: INR, Swierk, Poland

** Northwestern University, Evanston, Illinois 60204

1) V.G. Lind *et al.*, Phys. Rev. Lett. **31**, 1353 (1973).

2) D. Ashery *et al.*, Phys. Rev. Lett. **32**, 943 (1974).

3) H.E. Jackson *et al.*, Phys. Rev. Lett. **35**, 641 (1975).

4) C.L. Chang, N.S. Wall and Z Fraenkel, Phys. Rev. Lett. **33**, 1493 (1974).

5) V. Artun *et al.*, Phys. Rev. Lett. **35**, 773 (1975).

6) R.E. Segel *et al.*, Phys. Rev. **C13**, 1566 (1976).

7) P.P. Singh *et al.*, Phys. Rev. **C14**, 1655 (1976).

8) Code ALICE, M. Blann, University of Rochester report no. COO-3494-9.