Using the appropriately chosen curves, $\mathcal{A}_2^{(1)}$ can now be deduced from the experimentally determined directional correlation coefficients, A_2 and A_4 (see Sec. III of reference 5). This is illustrated in Fig. 2. The value of $J(\pi/2)$ to be expected in a polarization-directional correlation experiment then follows at once from Eq. (15). The term $(-1)^{\sigma(L_1)}$ is equal to $+1$ if the dipole is electric, or to -1 if the dipole is magnetic.

III. DOUBLY-MIXED CASCADES

If both steps of the cascade are a mixture of dipole and quadrupole radiation, the result of the polarization-directional correlation experiment is again given by Eq. (15). However, the partial coefficients $A_2^{(2)}$ and $\mathcal{A}_2^{(1)}$ must now be determined from a double-mixture analysis of the γ-γ directional correlation data. This method is treated in detail in Sec. IV of reference 5 and will not be repeated here.

IV. PURE RADIATIONS OR SINGLE-MIXED CASCADES WITH POLARIZATION OF THE PURE RADIATION OBSERVED

If both steps of the cascade are pure radiation or if the polarization of the pure radiation (in a singly-mixed cascade) is observed, the result of the polarization-directional correlation is given as follows:

(a) If one or both gamma rays is a pure dipole,

$$J(\pi/2)=(-1)^{\sigma(L)}\frac{-3A_2}{2-A_2}. \tag{16}$$

(b) If both gamma rays are pure quadrupole, or if the mixed gamma ray has an appreciable quadrupole content,

$$J(\pi/2)=(-1)^{\sigma(L)}\frac{-3A_2-(5/4)A_4}{2-A_2+(3/4)A_4}. \tag{17}$$

Here again $(-1)^{\sigma(L)}$ is equal to $+1$ if the radiation (the polarization of which is observed) is of type $E1$ or $M2$ and to -1 if it is of type $M1$ or $E2$.

PHYSICAL REVIEW VOLUME 121, NUMBER 6 MARCH 15, 1961

Neutron Capture Gamma-Ray Spectra of the Nickel Isotopes*

P. A. Treado† and P. R. Chagnon
Physics Department, The University of Michigan, Ann Arbor, Michigan

(Received September 14, 1960)

The spectra of gamma radiation following pile-neutron capture in separated isotopes of nickel have been measured with a three-crystal scintillation pair spectrometer as well as with a single-crystal scintillation counter. Energies and intensities of the gamma rays from each isotope are reported. Each of the lines observed with natural nickel has been assigned to $Ni^{58}(n,\gamma)Ni^{59}$, $Ni^{60}(n,\gamma)Ni^{61}$, or $Ni^{62}(n,\gamma)Ni^{63}$. In some cases, gamma rays of nearly identical energies are found in two, or in all three, isotopes. Additional gamma rays not resolved in the natural nickel spectrum appear in $Ni^{58}(n,\gamma)Ni^{59}$ at 7.65 Mev, and in $Ni^{60}(n,\gamma)Ni^{61}$ at 7.65 Mev, and in $Ni^{60}(n,\gamma)Ni^{61}$ at 4.70 and 5.55 Mev. The spectrum of $Ni^{62}(n,\gamma)Ni^{63}$ is dominated by a strong line at 6.80 Mev, presumably the ground-state transition.

INTRODUCTION

THE gamma-ray spectrum following thermal-neutron capture in natural nickel has been investigated by Ad'yasevich *et al.*[1] and Kinsey and Bartholomew[2] using external conversion spectrometers, and by Braid[3] using a Compton scintillation spectrometer. In the present work, natural nickel in the form of nickel oxide powder and Ni^{58}, Ni^{60}, and Ni^{62} in the form of isotopically enriched metallic bars and lumps were irradiated in a neutron beam at the Ford Nuclear Reactor at the University of Michigan, and the gamma-ray spectra were detected by means of a single scintillation crystal and a three-crystal scintillation spectrometer.[4] The single crystal was used in the 0–2.0 Mev energy range and the three-crystal spectrometer in the 1.5–10.0 Mev range.

EXPERIMENTAL CONSIDERATIONS

Geometry

The nickel samples, whose masses and isotopic constitutions are indicated in Table I, were placed in a beam of 2×10^6 neutrons/sec approximately 1 cm^2 in area. The Ni^{60} sample was not large enough to intercept the entire beam, requiring a correction in the intensity measurements. Each sample was thick enough to capture or scatter nearly all of the neutrons impinging upon it.

* Work supported by a contract with the U. S. Atomic Energy Commission.

† National Science Foundation Predoctoral Fellow.

[1] V. P. Ad'yasevich, L. V. Groshev, A. M. Demidov, and B. N. Lutsenko, Atomnaya Energ. **1**, 28 (1956); J. Nuclear Energy **3**, 325 (1956) [translation: Soviet J. Atomic Energy **1**, 171 (1956)].

[2] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **89**, 375 (1953).

[3] T. H. Braid, Phys. Rev. **102**, 1109 (1956).

[4] R. Hofstadter and J. A. McIntyre, Phys. Rev. **79**, 389 (1950); S. A. E. Johansson, Phil. Mag. **43**, 249 (1952).

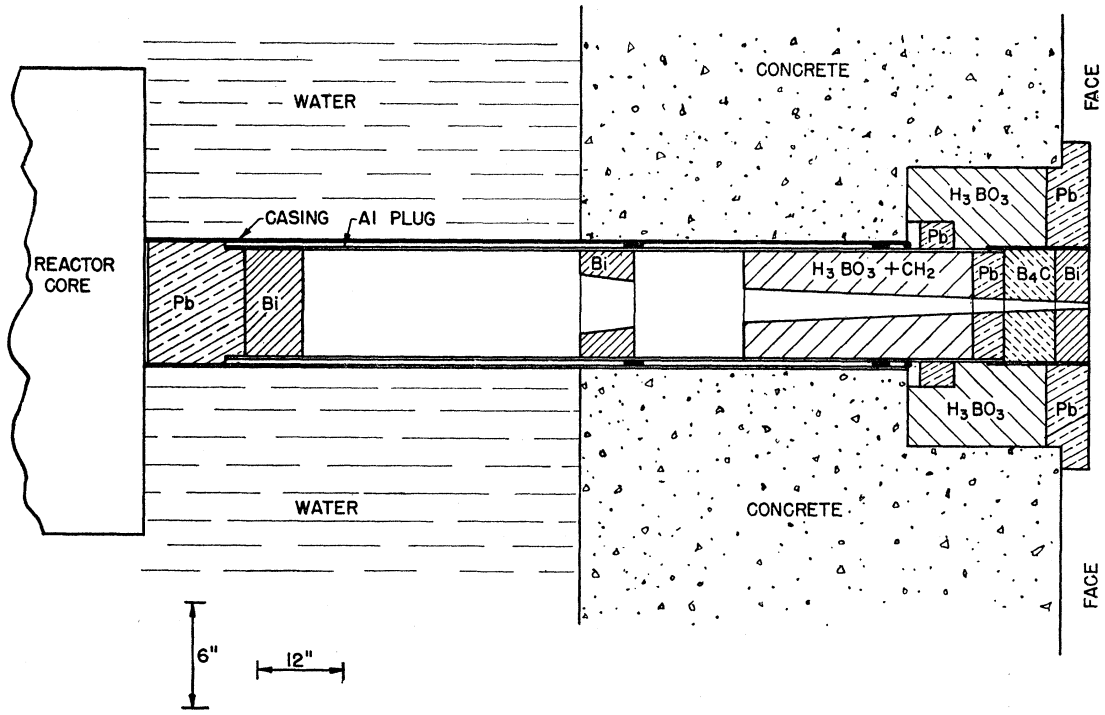

FIG. 1. Beam shielding and collimation arrangement in a beam port of the swimming-pool reactor.

The collimation and shielding of the neutron beam internal to the reactor are illustrated in Fig. 1 while the external shielding and counter placement are shown in Fig. 2. The center crystal of the three-crystal spectrometer is 1.25 in. in diameter and 1.5 in. long, approximately 4 in. from the sample.

Resolution and Efficiency

The energy resolution of the single crystal was measured to be 10.1% at 0.662 Mev. The three-crystal spectrometer resolution has been measured to be 2.9% at 6.8 Mev and 5.5% at 2.75 Mev by using gamma rays

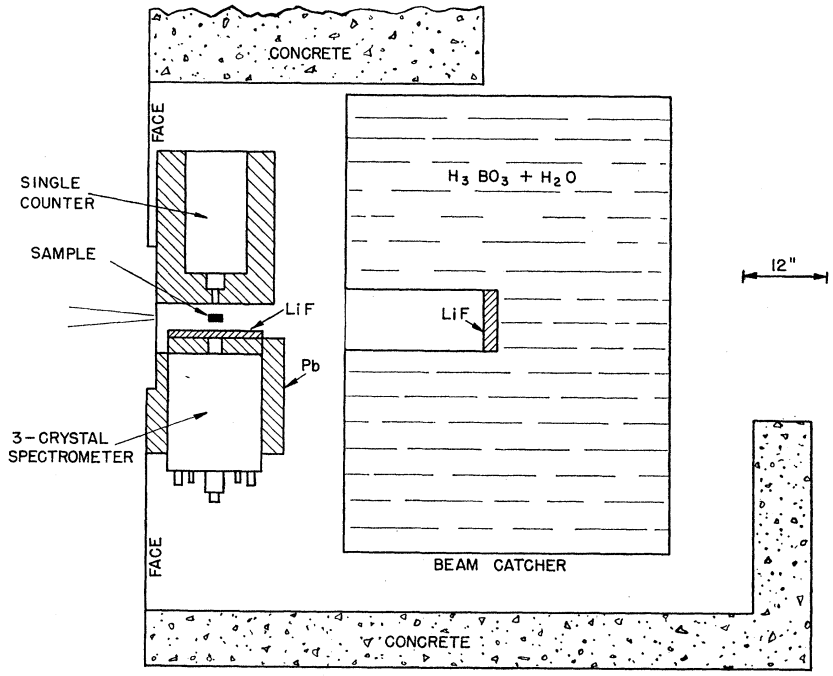

FIG. 2. Geometry of the sample, counters, and shielding external to the reactor.

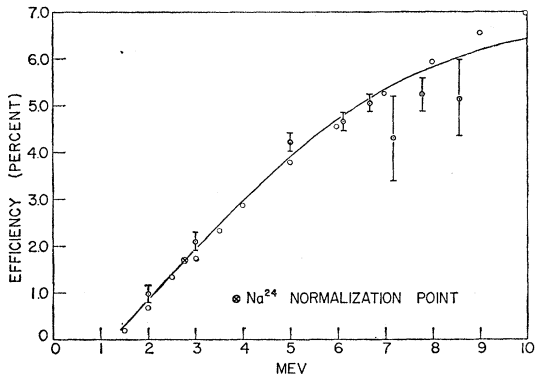

FIG. 3. Efficiency curve of the 3-crystal spectrometer. The open points are calculated, relative values; the solid points are experimental relative values; the curve represents a compromise between these and is normalized to a direct measurement at 2.75 Mev. (See text.)

from $Ni^{62}(n,\gamma)Ni^{63}$ and the radioactive decay of Na^{24}, respectively.

The relative efficiency of the spectrometer was estimated in two ways: (a) by calculation of the relative intensity of the pair production process in the primary crystal, from known cross sections of NaI, assuming that the fraction of two-escape processes is independent of incident photon energy—this calculation is represented by the open points in Fig. 3; (b) by measuring the relative intensities of the chlorine (n,γ) spectrum, and comparing with the results of Groshev *et al.*[5]—these are the solid points in Fig. 3. The two efficiency curves were then fitted to each other, and the average curve shown in Fig. 3 was normalized to a direct measurement of the spectrometer efficiency made at 2.75 Mev using a Na^{24} source. The accuracy attrib-

TABLE I. Isotopic constitution of the nickel samples. The chemical impurities in each sample were less than 0.05%.

Sample (nominal)	Mass (grams)	Constitution (%) Ni^{58}	Ni^{60}	Ni^{61}	Ni^{62}	Ni^{64}
Natural	7.8	67.8	26.2	1.2	3.7	1.2
Ni^{58}	21.2	99.9	0.06	...	...	...
Ni^{60}	5.4	1.45	98.5	0.02	0.01	...
Ni^{62}	3.0	0.42	0.47	2.8	96.2	0.04

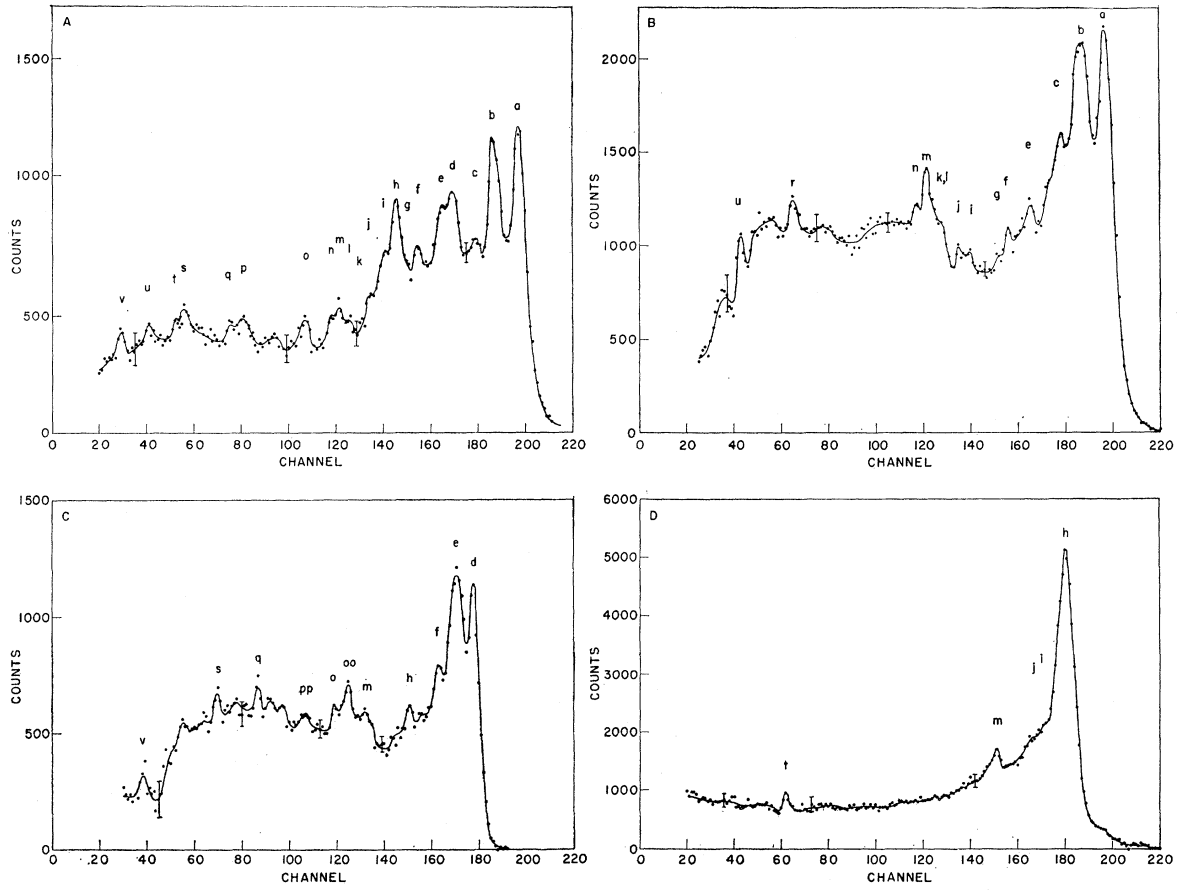

FIG. 4. Nickel capture gamma-ray spectra taken with the 3-crystal spectrometer: (a) natural nickel, (b) Ni^{58} sample, (c) Ni^{60} sample, (d) Ni^{62} sample. Identification letters correspond to those in Tables II and III.

[5] L. V. Groshev, B. N. Lutsenko, A. M. Demidov, and V. I. Pelekov, *Atlas of Gamma-Ray Spectra from Radiative Capture of Thermal Neutrons* (Pergamon Press, New York, 1958).

uted to the final efficiency curve varies from $\pm 10\%$ near the normalization point to $\pm 25\%$ at the high energies.

Procedure

Various nickel spectra were measured over a total of 150 hours of reactor operation. Each three-crystal spectrum was accumulated for two hours, and each single-crystal one for approximately five minutes. The 150 hours of reactor operating time was broken into several eight- and sixteen-hour periods. Because of the length of the experiment and because photomultipliers drift for varying lengths of time when initially placed in a high neutron or gamma-ray flux, the energy scale of each three-crystal spectrum was adjusted according to a calibration curve obtained from a chlorine spectrum taken immediately following every two nickel spectra. The magnitude of the adjustments was of the order of 2%. Each final spectrum in Fig. 4 represents the sum of ten to twenty two-hour runs. Each single-crystal spectrum in Fig. 5 is similarly composed of several runs made on different days. Background has been subtracted in the spectra of Figs. 4 and 5.

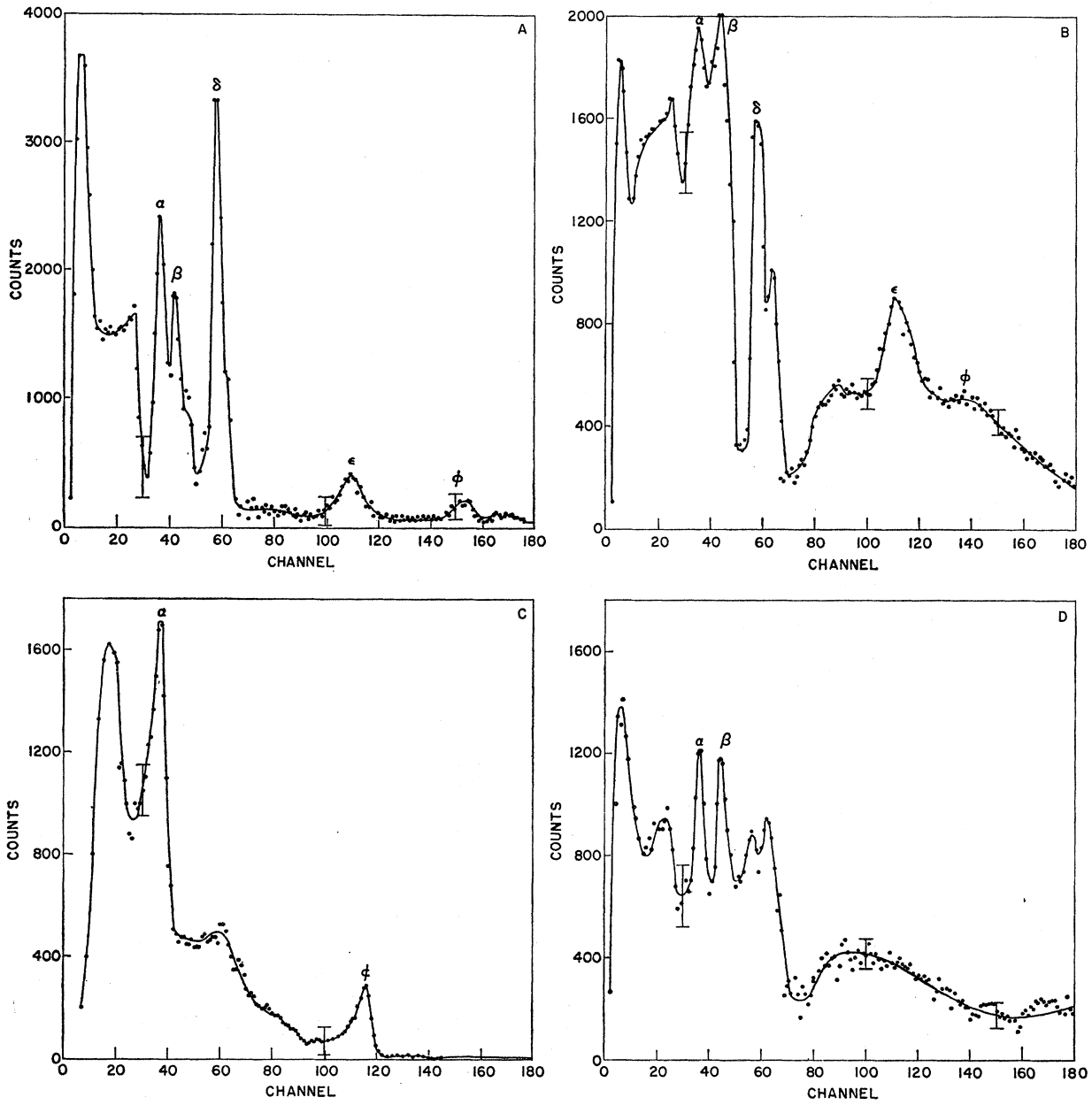

FIG. 5. Low-energy capture gamma-ray spectra measured with a single-crystal scintillation counter: (a) natural nickel, (b) Ni^{58} sample, (c) Ni^{60} sample, (d) Ni^{62} sample.

Background

Contributions to the background come principally from three causes, all comparable in magnitude: (1) reactor gamma rays and neutron-capture gamma rays in the shielding, as observed without a sample in place; (2) additional reactor gamma rays scattered into the counters by the sample; and (3) additional capture gamma rays produced in the shielding by neutrons scattered by the sample. In order to evaluate (2) and (3), spectra were taken with samples of water, aluminum, and lead. The Compton-scattering and neutron-scattering cross sections of these materials are sufficiently different to allow background components (2) and (3) to be isolated. Of course, the known gamma-ray lines from these scattering samples were subtracted out in preparing background curves. It is then possible to construct a background curve for each nickel sample using the proper amounts of components (1), (2), and (3).

Neutron activation of the counters and shielding was found not to make any significant contribution to the background of the three-crystal spectra. The background spectrum constructed for the Ni^{62} sample is shown in Fig. 6; the others are similar.

The background used for the single-counter spectra is simply that obtained with no sample in place. Consequently no intensity values are quoted for the low-energy lines.

TABLE II. Energies of neutron-capture gamma rays in natural nickel. The energies are in Mev; uncertainty in the last given digit is indicated in parenthesis. The identification letters correspond to those in Figs. 4 and 5.

Key	Present results	Kinsey and Bartholomew[a]	Ad'yasevich *et al.*[b]	Braid[c]
a	8.99(1)	8.997(5)	8.996(10)	
b	8.53(4)	8.532(8)	8.51(3)	
c	8.14(4)	8.119(10)	8.10(3)	
d	7.82(4)	7.817(8)	7.82(2)	
e	7.54(4)	7.528(11)	7.57(3)	
f	7.23(5)	7.22(2)	7.19(5)	
g	7.03(7) (?)	7.05(2)	7.02(5)?	
h	6.80(6)	6.839(10)	6.84(2)	
i	6.60(6)	6.58(2)	6.64(3)	
j	6.35(7)	6.34(2)	6.32(3)	
k	6.13(8) (?)	6.10(2)	6.13(3)	
l	6.03(7)	5.99(2)	6.03(3)	
m	5.83(7)	5.82(2)	5.84(3)	
n	5.71(7)	5.70(2)	5.72(3)	
o	5.30(10)	5.31(2)	5.31(3)	
p	4.20(10)		4.20(4)?	
q	3.95(7)		4.05(4)?	
r			3.67(3)?	
s	3.19(5)		3.17(6)?	
t	3.01(6)		3.03(4)?	
u	2.58(7)			2.68(3)
v	2.11(6)		2.15(3)?	2.06(3)
x			1.74(3)?	
			1.53(3)?	
	1.16(10)		1.10(3)?	1.24(3)
	0.86(8)			0.86(3)
	0.47(6)		0.467(8)	0.45(3)
			0.436(15)	
	0.35(4)		0.330(15)	
	0.29(3)		0.280(15)	

[a] See reference 2.
[b] See reference 1.
[c] See reference 3.

RESULTS

Table II gives the energies of the gamma-ray lines observed with the natural nickel sample, in comparison with other recent work. The energy scale is based on the energies of the chlorine capture gamma rays given by Groshev *et al.*[5] Intensities were not measured in this case, but there is good qualitative agreement with the other published spectra.

In interpreting the separated isotope spectra, a gamma ray was assigned to a particular isotope and listed in Table III if: (a) it had an energy corresponding to a natural nickel gamma-ray energy, and (b) the counting rate in the peak exceeded that in the corresponding valley by at least 3 times the standard deviation. In cases where two isotopes seemed to have the same energy gamma ray, data from $Ni^{58}(d,p)Ni^{59}$ and $Ni^{60}(d,p)Ni^{61}$ were consulted. If a level existed there which was compatible with the energy of the gamma ray, the assignment was made in agreement with the (d,p) data. Many of the gamma rays observed correspond to transitions observed in (d,p) experiments. The gamma rays and corresponding (d,p) proton groups are listed in Table IV.

Intensities, also given in Table III, were determined by sketching the known line shape of the spectrometer under each peak and measuring the area of the line with a planimeter. The uncertainties quoted include three components: an uncertainty of 10 to 30% in determining the area under each peak, 10 to 25% in the spectrometer efficiency, and 10% in beam intensity, geometry, and published cross sections.

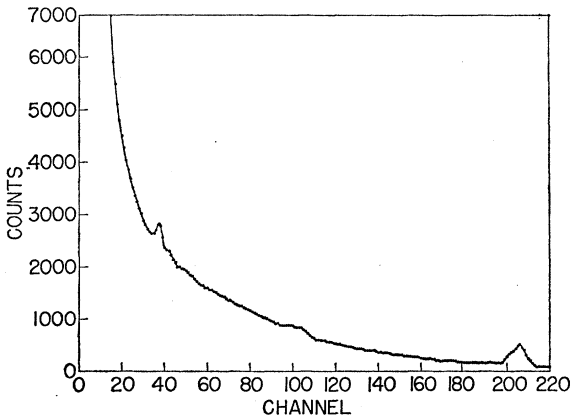

FIG. 6. A background spectrum constructed as described in the text. This one is for the Ni^{62} sample and corresponds to Fig. 4(d).

TABLE III. Energies (E_γ) in Mev and intensities (I_γ), in photons per 100 captures in the individual isotope, of the neutron-capture gamma rays from separated nickel isotopes. Uncertainty in the last given digit is indicated in parentheses.

Key	Natural nickel E_γ	$Ni^{58}(n,\gamma)Ni^{59}$ E_γ	I_γ	$Ni^{60}(n,\gamma)Ni^{61}$ E_γ	I_γ	$Ni^{62}(n,\gamma)Ni^{63}$ E_γ	I_γ
a	8.99(1)	8.99(1)	26(9)				
b	8.53(4)	8.54(4)	19(7)				
c	8.14(4)	8.15(4)	11(6)				
d	7.82(4)			7.81(2)	12(4)		
e	7.54(4)	7.65(6)	9(4)	7.52(3)	13(4)		
f	7.23(5)	7.24(6)	8(4)	7.18(5)	7(3)		
g	7.03(7)?	7.00(7)?					
h	6.80(6)			6.72(10)	7(3)	6.80(2)	62(14)
i	6.60(6)	6.57(8)	7(4)			6.50(12)[a]	
j	6.35(7)	6.30(8)	6(3)			6.35(12)[a]	
k	6.13(8)?	6.08(10)[a]	5(3)				
l	6.03(7)	5.97(10)[a]	5(3)				
m	5.83(7)	5.81(6)	15(7)	5.79(10)	3(2)	5.88(5)	8(4)
n	5.71(7)	5.65(9)	6(3)				
oo[b]				5.55(5)	9(4)		
o	5.30(10)			5.28(8)	8(4)		
pp[b]				4.70(10)	7(4)		
p[c]	4.20(7)						
q	3.95(7)			3.94(10)?			
r[b]		3.70(10)?					
s	3.19(5)			3.20(5)?			
t	3.01(6)					3.01(7)?	
u	2.58(7)	2.65(18)?					
v	2.11(6)			2.25(10)?			
φ	1.16(10)	1.17(10)		1.11(8)			
ϵ	0.86(8)	0.86(3)					
δ	0.47(6)	0.46(3)					
β	0.35(4)	0.35(4)				0.37(3)	
α	0.29(3)	0.30(4)		0.27(3)		0.31(3)	

[a] Unresolved doublet.
[b] Not observed in natural nickel.
[c] Not observed in Ni^{58}, Ni^{60}, or Ni^{62}.

DISCUSSION

The level schemes of the nickel isotopes have been studied by (d,p) reactions,[6–10] and radioactive decay of neighboring nuclei.[11] According to these data, the ground-state gamma-ray energies should be 8.99 Mev for Ni^{59} and 7.80 Mev for Ni^{61}. Mass-spectroscopic measurements by Quisenberry *et al.*[12] show that the binding energies should be 8.99 Mev, 7.77 Mev, and 6.82 Mev for Ni^{59}, Ni^{61}, and Ni^{63}, respectively. In the present work, the highest-energy gamma ray found in each isotope should be the ground-state gamma ray. These gamma rays should be quite intense, because the capture state in all three isotopes has $J=\frac{1}{2}$, as the target nuclei are all even-even, and the ground-state spins[5,6] of Ni^{59} and Ni^{61} are $J=\frac{3}{2}$ and that of Ni^{63} is $J=\frac{5}{2}$. From this experiment then, the neutron binding energy for Ni^{59} is 8.99 Mev, for Ni^{61} is 7.81 Mev, and for Ni^{63} is 6.80 Mev.

TABLE IV. Comparison of capture gamma-ray energies (E_γ) with excitation energies (E_x) from (d,p) reactions in Ni^{58} and Ni^{60}. Assignments are in terms of the product nucleus. Energies are in Mev.

Present results E_γ	Assignment	(d,p) results E_x	Assignment	Reference
		9.01	Ni^{59}	c, d
8.99	Ni^{59}	8.99	Ni^{59}	b
		8.92	Ni^{59}	a
		8.67	Ni^{59}	d
		8.58	Ni^{59}	b
8.52	Ni^{59}	8.54	Ni^{59}	d
		8.53	Ni^{61}	e
		8.50	Ni^{59}	a
		8.19	Ni^{59}	a
8.14	Ni^{59}	8.13	Ni^{59}	d
7.81	Ni^{61}	7.82	Ni^{61}	d, e
		7.82	Ni^{59}	d
		7.78	Ni^{59}, Ni^{61}	a
		7.75	Ni^{61}	d
7.52	Ni^{61}	7.54	Ni^{61}	d
7.24	Ni^{59}	7.23	Ni^{59}	d
7.18	Ni^{61}	7.16	Ni^{61}	d
7.00	Ni^{59}	7.06	Ni^{59}	d
6.72	Ni^{61}	6.72	Ni^{61}	d
6.57	Ni^{59}	6.59	Ni^{59}	d
6.30	Ni^{59}	6.38	Ni^{59}	d
5.97	Ni^{59}	5.97	Ni^{59}	d
5.81	Ni^{59}	5.80	Ni^{59}	d
5.79	Ni^{61}	5.69	Ni^{61}	d
5.28	Ni^{61}	5.21	Ni^{61}	d

[a] See reference 6.
[b] See reference 7.
[c] See reference 8.
[d] See reference 9.
[e] See reference 10.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the continued assistance and cooperation of the staff of the Ford Nuclear Reactor. Thanks are also due to Dr. M. L. Wiedenbeck for many valuable suggestions.

[6] W. W. Pratt, Phys. Rev. **94**, 1086 (1954); **95**, 1517 (1954).
[7] C. E. McFarland, M. M. Bretscher, and F. B. Shull, Phys. Rev. **89**, 892 (1953).
[8] J. A. Harvey, Phys. Rev. **81**, 353 (1951).
[9] C. H. Paris and W. W. Buechner, Bull. Am. Phys. Soc. **3**, 38 (1958).
[10] H. N. Hoesterey, Phys. Rev. **87**, 216 (1952).
[11] G. E. Owen, C. S. Cook, and P. H. Owen, Phys. Rev. **78**, 686 (1950).
[12] K. S. Quisenberry, T. T. Scolman, and A. O. Nier, Phys. Rev. **104**, 461 (1957).