Neutron Capture γ-Rays from Titanium, Chromium, Iron, Nickel, and Zinc

B. B. KINSEY AND G. A. BARTHOLOMEW
Physics Division, Atomic Energy of Canada, Limited, Chalk River, Ontario, Canada
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The neutron capture γ-rays emitted by the even-charge elements, from titanium to zinc, have been investigated with the aid of a pair spectrometer.

Titanium emits a very simple spectrum. Two strong γ-rays, 6.756 ± 0.006 and 6.412 ± 0.006 Mev, are produced by capture in Ti^{48}. Neither the direct transition to the ground state of Ti^{49}, nor the transitions to the ground states of Ti^{48} and Ti^{50} were detected. From chromium the γ-rays corresponding to transitions to the ground state (9.716 ± 0.007 Mev) and to the first excited state (8.881 ± 0.007 Mev) of Cr^{54} are prominent and have intensities of 13 and 35 photons per 100 captures in Cr^{53}. The direct transition to the ground state of Cr^{51} was not detected. The iron spectrum is dominated by a strong γ-ray with the energy 7.639 ± 0.004 Mev resulting from neutron capture in Fe^{56}. This γ-ray is produced in the transition in Fe^{57} either to the ground state or to the excited state at 14 kev. Two weaker γ-rays with nearly equal energies close to 6 Mev are also produced in this isotope. The ground state γ-ray and the γ-rays leading to the first two excited states of Fe^{55} have been identified. Of these, the ground-state γ-ray (9.298 ± 0.007 Mev) is strong, about 50 photons per 100 captures in Fe^{54}. A part of the counting rate ascribed to this γ-ray, however, may be due to the γ-ray producing the first excited state of Fe^{58} in a direct transition. The ground state γ-ray in Fe^{58} (10.16 ± 0.04 Mev) accounts for about 5 percent of all captures by Fe^{57}. The nickel spectrum contains an intense γ-ray with an energy of 8.997 ± 0.005 Mev, which is produced in 50 percent of the captures in Ni^{58}. Another prominent γ-ray at 8.532 ± 0.008 Mev may represent the transition to the ground state in Ni^{61}; if so, it accounts for some 80 percent of captures in Ni^{60}. From considerations of intensity, five of the remaining nickel γ-rays can be ascribed to transitions to excited states in Ni^{59}. In the spectrum of zinc, few discrete γ-rays can be discerned above a background of unresolved radiations. Of these, a very strong γ-ray, with an energy to 7.876 ± 0.007 Mev, probably producing directly the ground state of Zn^{65}, is emitted in 40 percent of neutron captures by Zn^{64}.

INTRODUCTION

In earlier communications,[1] we have reported investigations of the neutron capture γ-rays produced by various elements between beryllium and calcium. These measurements were made with the aid of a pair spectrometer. In this paper we describe the results obtained for the even-charge elements: titanium, chromium, iron, nickel, and zinc. The preliminary survey of the γ-ray spectra from these elements was made in 1949, and a few of these results have already been published.[2] Since that time the apparatus has been modified, and the spectra have been carefully remeasured. The coincidence counting rates have been increased, and this improvement has been used to obtain better resolution. The stability and control of the magnetic field has also been improved, and it has been possible to count coincidences automatically at a series of predetermined values of the magnetic field. The strength of the field, averaged over the orbits of the electron pairs, is known absolutely to 0.05 percent, while relative values are known to 0.002 percent.

Absolute measurements of the intensities of capture radiations were made by comparison with the 9.0-Mev capture γ-ray produced by nickel. In this method, as previously described,[1] use was made of a calculated curve for the variation of the peak coincidence counting efficiency with the energy. Previously published intensity measurements, however, were certainly too high in the 5-Mev region. In the present paper, the intensity measurements were made on the basis of a semi-empirical counting efficiency curve and are undoubtedly much more reliable. Full details of the derivation of this curve and of the method of energy measurement are given elsewhere.[3] Ignoring errors introduced by uncertainties in the values of the thermal neutron absorption cross sections, the intensity measurements from 3 to 5 Mev should not now be in error by more than 15 percent, and from 6 to 8 Mev, by not more than 10 percent. From 8 to 11 Mev, the counting efficiency is much more difficult to estimate, and at the latter energy, the error may be 30 percent.

In the present experimental arrangement, the sample to be studied is enclosed in an aluminum container fitted with Bakelite ends, and is located, as before, in a hole in the concrete radiation shield of the Chalk River pile. A bismuth block, about six inches in length, is placed between the sample and the reactor and prevents unwanted γ-radiation from entering the spectrometer. The center of the pair spectrometer is about fifteen feet from the sample, and two collimators ensure that any point on the radiator of the spectrometer is exposed only to radiations from the central part of the sample. Unwanted radiations produced by the aluminum container, or by the walls of the hole in the pile shield, are thereby eliminated. Those parts of the collimating system which are, of necessity, located in a strong neutron flux are made of bismuth which emits little capture radiation of its own; the remainder is made of lead.

In the absence of a sample, a low background of unresolved radiations is obtained on which is superposed a coincidence peak near 4 Mev, due to bismuth, and two low peaks at 7.3 and at 7.6 Mev, produced, respectively, by the capture radiations of lead and aluminum. Except in the case of materials of excep-

[1] Kinsey, Bartholomew, and Walker, Phys. Rev. **83**, 519 (1951); **85**, 1012 (1952); Can. J. Phys. **29**, 1 (1951).
[2] Kinsey, Bartholomew, and Walker, Phys. Rev. **78**, 481 (1950).
[3] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. (to be published).

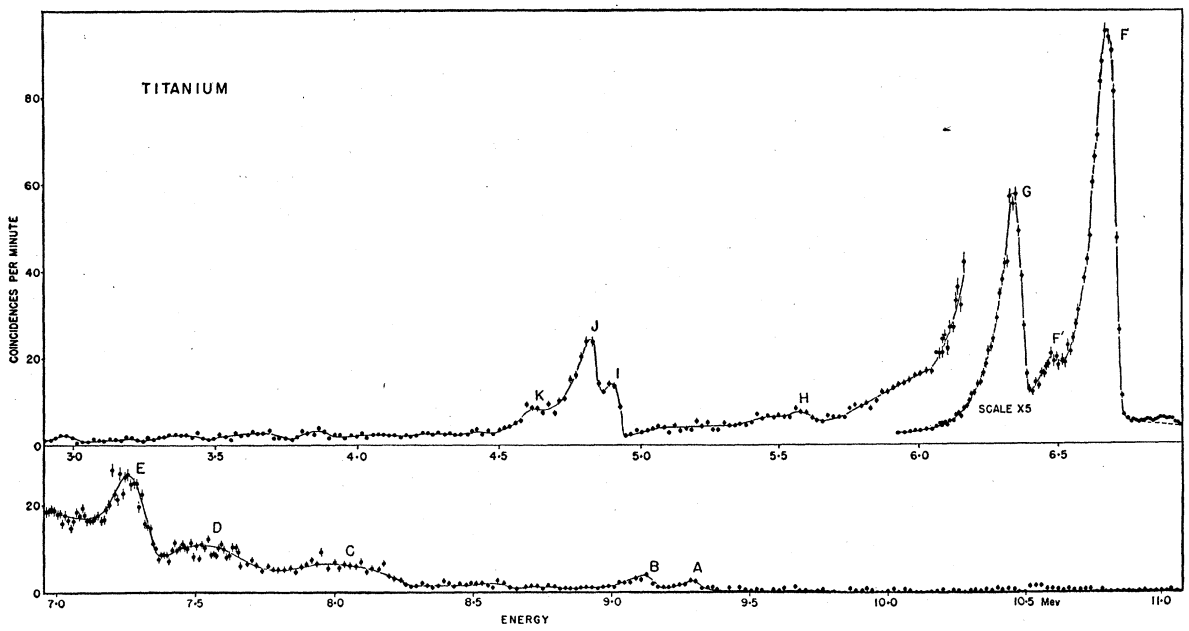

FIG. 1. Coincidence spectrum produced by titanium.

tionally low cross section, these background radiations are of little practical importance; after taking into account the absorption in the sample and in the materials between it and the spectrometer, suitable corrections can be applied to the coincidence spectrum.

The intensity of the fast neutrons in the γ-ray beam from the sample is reduced with a plate of polythene $\frac{3}{4}$ inch in thickness, and the slow neutrons are filtered out by a disk of similar size containing boron carbide. The absorption of the γ-rays, by these filters and the air, is about 10 percent at 4 Mev.

The present measurements were made with gold slits in front of the stilbene crystals used as detectors. The slits were 1 mm wide and 1.5 mm thick and about 23 cm apart. In these circumstances, for a homogeneous γ-ray, the width of a coincidence peak at half-maximum, hereafter called the line width, is about 100 kev at all energies. This slit width represents a satisfactory compromise between the higher counting rates with less resolution obtained with a wider slit, and the much lower counting rate with only slightly improved peak width obtained when the slits are made much narrower.

A tail, produced by the scattering of the pair components within the vacuum chamber, is observed beyond the upper end of each intense coincidence peak. At the point where the tail joins the upper edge of the peak, it is about 5 percent of the peak height; beyond that point, it rises to a maximum of about 6.5 percent and then falls slowly producing a spurious peak. This ghost peak is the result of scattering of the pair components from an aluminum frame in which the slits are recessed. It did not appear in the measurements made with the previous apparatus in which the slits were differently mounted. In the figures illustrating this paper, the spurious peaks are distinguished from the genuine peaks by a broken line, drawn beneath the experimental points (for example, see Fig. 9 near 9.2 Mev).

The method of correcting the coincidence pair spectrum to find the γ-ray spectrum has been described in other communications.[1,3] In Figs. 2, 5, 7, 10, and 12, the ordinates $\nu(E)$ of the corrected γ-ray spectra are given in absolute units, i.e., the number of photons emitted per unit energy range per capture. The height of a coincidence peak of unit intensity, i.e., one photon per capture, is equal to 6.7 Mev^{-1}.

TABLE I. Energies and intensities of titanium γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures in natural Ti	Probable origin
A	9.39 ±0.03	0.1	Ti^{48} ?
B	9.19 0.03	0.2	
C	8.27 0.02	0.4	
D	7.80 0.04	0.8	
E	7.38 0.01	1.5	Ti^{49}
F	6.756 0.006	53	Ti^{49}
F'	6.53 0.02	4	Ti^{49}
G	6.412 0.006	32	Ti^{49}
H	5.65 0.03	0.4	
I	4.96 0.01	3.5	Ti^{49}
J	4.88 0.01	5.0	Ti^{49}
K	4.67 0.03	1.4	

TITANIUM

The coincidence pair spectrum from a sample of about 500 g of titanium dioxide is shown in Fig. 1. Except for the two very strong γ-rays *F* and *G*, few other γ-rays appear in the spectrum and the background of unresolved radiation at the lower energies is

low. The energies and intensities of the more intense resolved radiations are listed in Table I. The absolute intensities were determined by comparing the coincidence counting rate of the peak F with that of the 9.00-Mev nickel γ-ray, both γ-rays being emitted from an intimate mixture of titanium and nickel oxides in the ratio of roughly 5:1 by weight. The capture cross section of titanium for thermal neutrons was assumed to be 5.8 barns. The corrected γ-ray spectrum is shown in Fig. 2. This was obtained from the coincidence spectrum by correcting for γ-ray absorption in the titanium sample and in the neutron filters, and by correcting for the counting efficiency of the spectrometer as a function of the energy.

The abundances and the contributions to the total capture cross section of the separate titanium isotopes and the neutron binding energies of the product nuclei are listed in Table II. The neutron binding energies were calculated from recent mass values obtained by Collins, Nier, and Johnson,[4] and from measurements on the (d,p) reaction by Harvey[5] and by Pieper.[6] Of the five stable isotopes of titanium, it will be seen that only the first four, Ti^{46}, Ti^{47}, Ti^{48}, and Ti^{49}, contribute appreciably to the thermal neutron capture cross section of natural titanium. Of these isotopes, by far the greater part[7] of the capture cross section is due the more abundant isotope Ti^{48}.

An inspection of Table I and Fig. 1 will show that there is no distinct γ-ray corresponding to any of the neutron binding energies listed in Table II. We estimate that the direct transitions to the ground states of Ti^{48} and Ti^{50} produce γ-rays for which the intensities are less than 0.02 photon per 100 captures in natural titanium. Since Ti^{47} and Ti^{49} each contribute roughly 2 percent of the capture cross section of natural titanium, these ground state γ-rays are weaker than 1 photon per 100 captures in the separate isotopes.

TABLE II. Abundances, neutron capture cross sections, and neutron binding energies of titanium isotopes.

Isotope	Abundance percent	Contribution to cross section in percent	Neutron binding energy of product nucleus in Mev: From Harvey[c]	From Collins, Nier, and Johnson[d]	From Pieper[e]
Ti^{46}	8.0	0.8[a]	8.74±0.1	8.64±0.11	
Ti^{47}	7.8	2.1[a]	11.05±0.4	11.63±0.11	
Ti^{48}	73.4	95 [a]	8.15±0.05	7.99±0.08	8.04±0.05
Ti^{49}	5.5	1.6[a]		10.99±0.06	
Ti^{50}	5.3	0.2[b]			

[a] See reference 7.
[b] See reference 25.
[c] See reference 5.
[d] See reference 4.
[e] See reference 6.

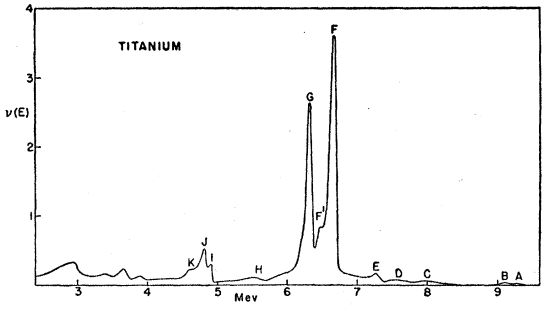

FIG. 2. Corrected γ-ray spectrum of titanium.

From Table II, it is clear that the neutron binding energy of Ti^{49} is close to 8.05 Mev. This energy lies near the middle of the broad peak C in Fig. 1, which clearly represents the contribution of several unresolved γ-rays. If the ground-state γ-ray in Ti^{49} is present, and there is no clear evidence in Fig. 1 for its existence, it must contribute a peak coincidence counting rate of less than 2 counts per minute, which corresponds to an intensity of less than 0.2 photons per 100 captures in Ti^{48}.

The main feature of the titanium spectrum is the presence of the two very strong γ-rays F and G, both of which must originate in Ti^{49}. Between them lies a small peak F', which, on account of its intensity, must also come from Ti^{49}. The γ-rays I and J, and probably also E and K, are produced by this isotope.

From a study of the (d,p) reaction, Pieper[6] has shown that excited states exist in Ti^{49} at 1.40, 1.74, 2.45, and 3.14 Mev. If the energies of the γ-rays F and G are added to the energies of the first two of these excited states, we obtain 8.16 and 8.15 Mev, respectively, in fair agreement with the neutron binding energies listed in Table II. It seems probable, therefore, that the γ-rays F and G derive from transitions to the first and second excited states of Ti^{49} found by Pieper (see Fig. 3). Transitions to the third excited state are not found. The group of γ-rays I, J, and K may originate in transitions to a group of levels near the fourth excited state at 3.14 Mev. The γ-rays E and F' have not been identified though their high intensities suggest that they are emitted by Ti^{49}. It is possible that they represent transitions to low-lying levels not detected in Pieper's experiments.

Two excited states in Ti^{48}, at 0.98 and at 2.31 Mev, are known from the decay[8] of Sc^{48} and V^{48}; these states have also been produced[9] in the reaction $Sc^{45}(\alpha,p)Ti^{48}$. Assuming that the neutron binding energy of Ti^{48} is 11.63±0.11 Mev (from Table II), γ-rays producing these states directly will have the energies 10.65±0.11 and 9.32±0.11 Mev. There is an indication in Fig. 1 of a γ-ray at an energy of about 10.6 Mev, although the statistics are not good enough to establish its existence

[4] Collins, Nier, and Johnson, Phys. Rev. **86**, 408 (1952).
[5] J. A. Harvey, Phys. Rev. **81**, 353 (1951).
[6] G. F. Pieper, Phys. Rev. **87**, 215 (1952).
[7] H. Pomerance, Phys. Rev. **88**, 412 (1952). We are indebted to Dr. Pomerance for the privilege of seeing his results before publication.
[8] W. C. Peacock and M. Deutsch, Phys. Rev. **69**, 306 (1946); also C. T. Hibdon and M. L. Pool, Phys. Rev. **67**, 313 (1945); C. E. Mandeville, Phys. Rev. **64**, 147 (1943).
[9] E. Pollard, Phys. Rev. **54**, 411 (1938).

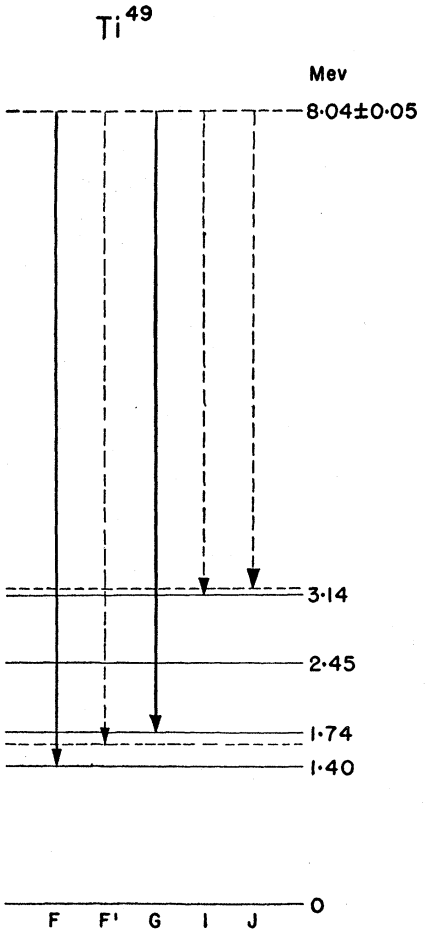

FIG. 3. Decay scheme for the capture γ-rays from Ti^{49}. The level energies are those obtained by Pieper.[6] Other possible levels, inferred from the capture γ-ray spectrum, are indicated by broken horizontal lines.

with certainty. Probably one of the γ-rays A or B, represents a transition to the second of these two states. There is little doubt that these weak γ-rays are produced by titanium, for a spectrographic analysis of the sample material revealed no impurities in sufficient concentration to account for the weak radiations with energies about 7.5 Mev.

The γ-rays which contribute to the broad peak at C have not been identified. Some of the γ-rays in Fig. 1 must be produced by capture in Ti^{49}, but no details of the positions of the excited states in Ti^{50} have been published, and such radiations therefore cannot be distinguished.

CHROMIUM

The sample consisted of about a kilogram of chemically pure chromic oxide. The coincidence spectrum of the neutron capture γ-rays is shown in Fig. 4, and the energies and intensities are listed in Table III. In previous measurements, no chromium γ-rays were detected between the energy of peak A and 12.4 Mev. Since the peak B in the chromium spectrum overlaps that produced by the 9.00-Mev nickel γ-ray, the absolute intensities of the chromium γ-rays were measured by comparing the peak coincidence counting rate of the γ-ray B with that of the 9.30-Mev γ-ray B of the iron spectrum, using an equal mixture of Cr_2O_3 and Fe_2O_3. The chromium capture cross section was assumed to be 2.90 barns. The corrected chromium spectrum is shown in Fig. 5.

Natural chromium possesses four stable isotopes, Cr^{50}, Cr^{52}, Cr^{53}, and Cr^{54}, of which only the first three contribute appreciably to the thermal neutron capture cross section in the natural element. The abundances and the contributions of the various isotopes to the cross section,[10] together with the neutron binding energies of the product nuclei are given in Table IV.

The neutron binding energy of Cr^{51}, obtained from the Q of the reaction[11] $V^{51}(p,n)Cr^{51}$, is 9.07±0.09 Mev. This value can be checked by subtracting the neutron binding energy of Cr^{52} from the sum of the binding energies (21.4 Mev) of two neutrons in Cr^{52} obtained from the mass measurements.[4] For the former, Sher, Halpern, and Mann,[12] find 11.80±0.25 Mev. A more accurate value can be deduced from the Q of the reaction, $V^{51}(p,n)Cr^{51}$; the neutron binding energy[5] of V^{52}, 7.3 Mev; and the energy[13] of the decay of V^{52}, 4.2 Mev. The value obtained is 12.2±0.1 Mev. When this is subtracted from the binding energy of two neutrons in Cr^{52}, the neutron binding energy of Cr^{51} is found to be 9.2±0.2 Mev.

The neutron binding energies of Cr^{53} and Cr^{54}, given in Table IV, were calculated from the mass measurements. Since the activity of Cr^{55} has not been identified with certainty, its binding energy cannot be calculated;

TABLE III. Energies and intensities of chromium γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures in natural Cr	Probable origin
A	9.716±0.007	7	Cr^{54}
B	8.881 0.007	19	Cr^{54}
C	8.499 0.007	7	
D	7.929 0.008	8	
D'	7.67 0.02	0.2	
E	7.54 0.02	0.2	
F	7.364 0.007	3	
F'	7.21 0.02	0.2	
G	7.097 0.006	2.6	
H	6.872 0.008	0.6	
I	6.644 0.006	3.0	
J	6.358 0.007	0.3	
K	6.26 0.02	0.9	
L	6.12 0.01	0.7	
M	6.00 0.01	1	
N	5.61 0.01	2	
O	5.26 0.02	1	
P	4.83 0.01	0.6	
Q	3.72 0.02	0.5	

[10] H. Pomerance, Phys. Rev. **76**, 195 (1949).
[11] R. V. Smith and H. T. Richards, Phys. Rev. **74**, 1257 (1948).
[12] Sher, Halpern, and Mann, Phys. Rev. **84**, 387 (1951).
[13] R. Bouchez and G. A. Renard, J. phys. et radium **8**, 289 (1947).

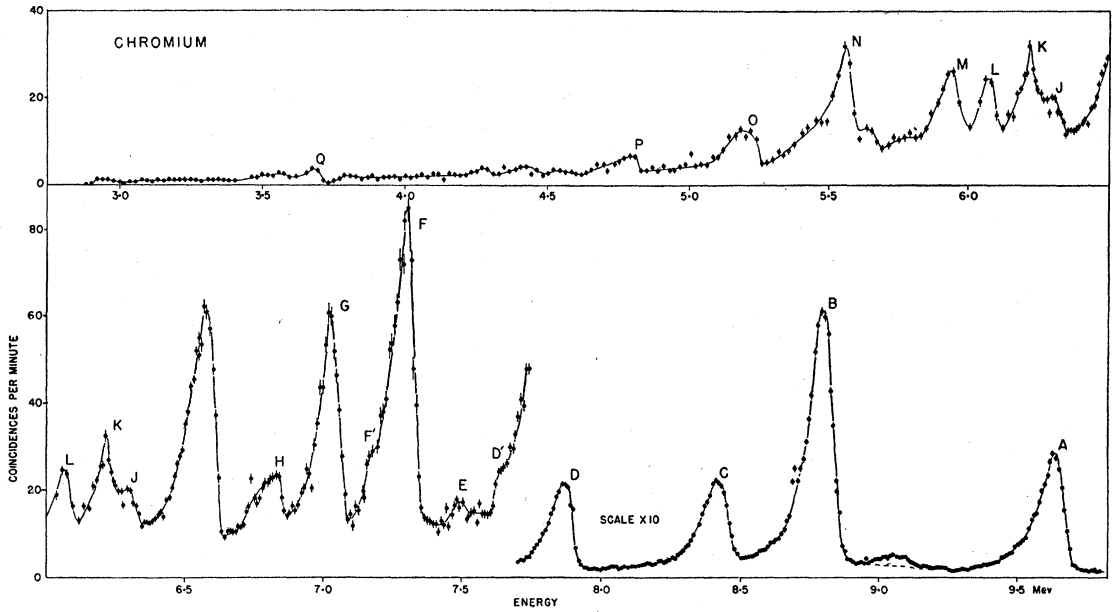

FIG. 4. Coincidence spectrum produced by chromium.

however, this binding energy is not relevant to the present work, for the contribution of that isotope to the cross section of natural chromium is negligible.

The energy of the γ-ray *A* is very close to that of the neutron binding energy of Cr^{54}. The difference between the energies of the γ-rays *A* and *B* is 0.835±0.005 Mev. The error in this difference is smaller than the error in either γ-ray measurement, because it depends only on the statistical errors, the systematic errors in the measurement of the magnetic field disappearing in the difference. This difference is in excellent agreement with the energy of the γ-ray produced in the decay of Mn^{54}, which is 0.835±0.015 Mev, according to Deutsch and Elliott.[14] We conclude that the γ-ray *A* is emitted in the direct transition to the ground state of Cr^{54} and that the γ-ray *B* is emitted in the transition to the first excited state. Both *A* and *B* are very strong γ-rays, and together account for half of the captures in Cr^{53}. No other excited states of Cr^{54} are known, and it is not possible, therefore, to identify any other γ-rays in Fig. 4 with capture in Cr^{53}.

It can be seen from Fig. 4 that a 9.1-Mev γ-ray, corresponding to the ground-state transition in Cr^{51}, would be superposed on the spurious peak caused by the γ-ray *B*. There is no evidence for such a γ-ray at this energy, and if it exists, its intensity is less than one photon per 100 captures in Cr^{50}. The positions of four excited states in Cr^{51} have been determined by Stelson, Preston, and Goodman[15] in their study of the neutron energies of the reaction $V^{51}(p,n)Cr^{51}$. If the neutron binding energy of Cr^{51} is assumed to be 9.07±0.09 Mev, it follows that the γ-rays producing these states in direct transitions should have energies of 8.29±0.11, 7.90±0.11, 7.65±0.13, and 7.54±0.13 Mev. From Table III it will be seen that these energies are in rather good agreement with the energies of the γ-rays *C*, *D*, *D'*, and *E*. If this identification is correct, then the intensities of the γ-rays *C* and *D* are both about 30 photons per 100 captures in Cr^{50}. Now the neutron binding energy of Cr^{53} is 7.76±0.11 Mev; with an equal validity, therefore, it is possible to identify one or the other of the γ-rays *D* or *D'* with the ground-state transition in that isotope. It is clear that much more accurate measurements on the neutron binding energies and on the level energies of the chromium isotopes are

TABLE IV. Abundances, neutron capture cross sections, and neutron binding energies of the chromium isotopes.

Isotope	Abundance percent	Contribution to cross section in percent[a]	Neutron binding energy of product nucleus in Mev
Cr^{50}	4.4	24.5	9.07±0.09
Cr^{52}	83.7	20.5	7.76±0.11[b]
Cr^{53}	9.5	55	9.70±0.20[b]
Cr^{54}	2.4		

[a] See reference 10.
[b] See reference 4.

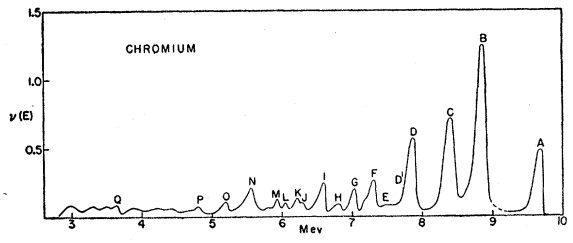

FIG. 5. Corrected γ-ray spectrum of chromium.

[14] M. Deutsch and L. G. Elliott, Phys. Rev. **65**, 211 (1944).

[15] Stelson, Preston, and Goodman, Phys. Rev. **80**, 287 (1950).

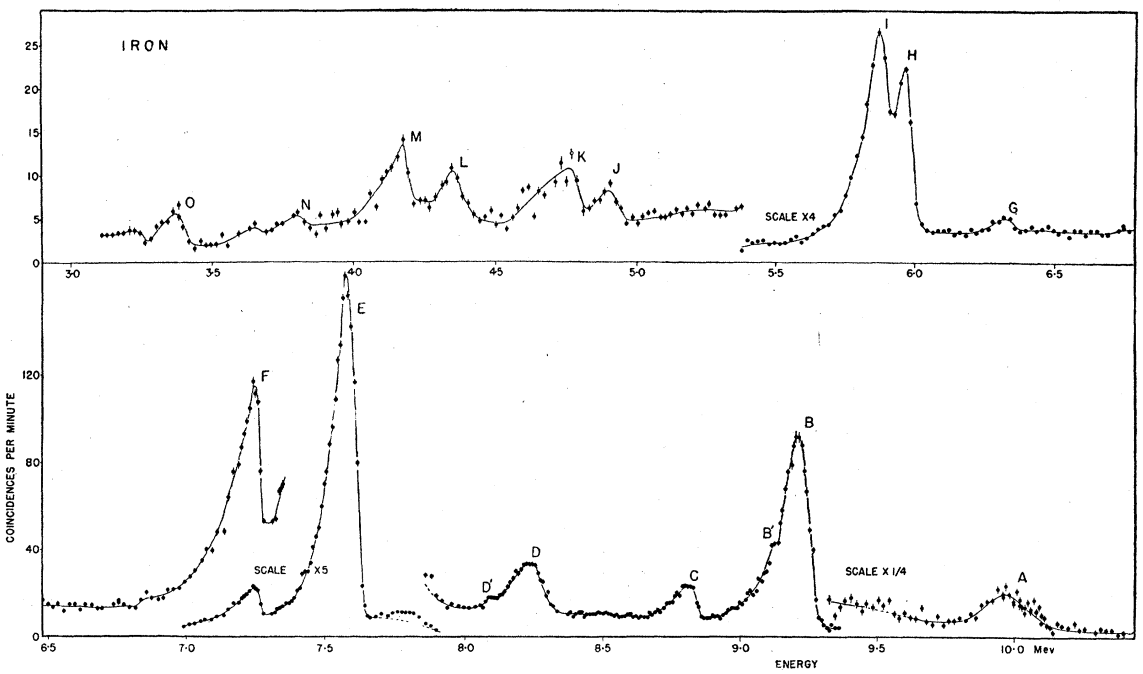

FIG. 6. Coincidence spectrum produced by iron.

required before these radiations can be identified with certainty.*

IRON

The coincidence spectrum of the neutron capture γ-rays from a very pure sample of metallic iron[16] are shown in Fig. 6, and the energies and intensities of individual γ-rays are listed in Table V. The absolute intensities were measured by a comparison of the counting rates of the 7.64-Mev γ-ray (peak *E*) and the 8.53-Mev γ-ray of nickel in a mixture of iron and nickel oxides. This procedure was chosen because the 9.00-Mev nickel γ-ray which is usually used for comparison has an energy too close to that of the 9.30-Mev iron γ-ray (peak *B*). The 8.53-Mev nickel γ-ray, however, lies between two peaks in the iron spectrum, and only small corrections need to be applied to allow for the contribution of the spectrum of the one element to the counting rate produced by the other. The capture cross section of iron was assumed to be 2.43 barns. The corrected γ-ray spectrum is shown in Fig. 7.

TABLE V. Energies and intensities of iron γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures in natural iron	Probable origin
A	10.16 ±0.04	0.1	Fe^{58}
B	9.298 0.007	2.7	Fe^{55}, Fe^{58}
C	8.872 0.010	0.5	Fe^{55}
D	8.345 0.011	0.8	Fe^{55}
E	7.639 0.004	36	Fe^{57}
F	7.285 0.009	3.5	Fe^{57}
G	6.369 0.009	0.4	
H	6.015 0.007	5.6	Fe^{57}
I	5.914 0.010	5.2	Fe^{57}
J	4.968 0.011	0.5	
K	4.81 0.02	1	
L	4.44 0.03	1	
M	4.21 0.03	2	
N	3.86 0.05	0.5	
O	3.43 0.03	2.0	

Iron has four stable isotopes, Fe^{54}, Fe^{56}, Fe^{57}, and Fe^{58}. The abundances, the contributions[7] to the total thermal neutron capture cross section, and the neutron binding energies are listed in Table VI. The greater part of the neutron capture cross section of natural iron is due to Fe^{56}, and therefore the stronger γ-rays in the iron spectrum can be ascribed to capture by that isotope.

The dominant features of the coincidence spectrum are the very strong peak *E*, and the weaker, but higher energy, peak *B*. The energy of the γ-ray *E* (7.639±0.004 Mev) is in very good agreement with the neutron binding energy deduced from the *Q* value of the stronger of the two high energy groups of protons found by Harvey[5] in the (d,p) reaction. The *Q* values of these two groups are 5.42 and 7.11 Mev. The intensity of the stronger shows that it is derived from Fe^{56}, and therefore the neutron binding energy of Fe^{57} is 7.65±0.10 Mev, in agreement with the energy of the γ-ray *E*.

* *Note added in proof:* McFarland, Bretscher, and Shull [Bull. Am. Phys. Soc., **27** (No. 5) 7 (1952)] have reported measurements on the $Cr^{52}(d,p)Cr^{53}$ reaction, from which it follows that the energies of the γ-rays leading to the ground state and to the first excited state of Cr^{53} are 7.93 and 7.39 Mev, respectively, in good agreement with the energies of the γ-rays *D* and *F*.

[16] We are indebted to the Division of Physical Metallurgy, Department of Mines and Technical Surveys, Ottawa, for the provision of this sample.

Harvey has shown that the weaker group of protons corresponds to the production of Fe^{55} in its ground state and that the neutron binding energy obtained (9.34 $\pm$0.05 Mev) is consistent with the neutron binding energy of that nucleus deduced from disintegration data. It is also consistent with the value 9.24$\pm$0.10 Mev deduced from mass measurements[4] and the Q of the $Mn^{55}(p,n)Fe^{55}$ reaction.[17] These results are in good agreement with the energy of the γ-ray B, which, we conclude, represents the direct transition to the ground state of Fe^{55}.

The γ-rays with energies above that of E must be due to capture in Fe^{54} or Fe^{57}, because the highest energy produced by capture in Fe^{56} is that of the γ-ray E, and the energy produced by capture in the heavier even isotope Fe^{58} must be lower. The weak γ-rays, C and D, correspond to transitions to the first and second excited states of Fe^{55} (see Fig. 8). This can be seen from Table VII. The first column contains the positions of the excited states of Fe^{55} found by Stelson and Preston[17] from a measurement of the energies of the neutrons

TABLE VI. Abundances, neutron capture cross sections, and neutron binding energies of the iron isotopes.

Isotope	Abundance percent	Contribution to cross section in percent	Neutron binding energy of product nucleus in Mev	
Fe^{54}	5.9	5.1[a]	9.34$\pm$0.05[b]	9.24$\pm$0.10[c,d]
Fe^{56}	91.6	92 [a]	7.65 0.10[b]	7.62 0.13[e]
Fe^{57}	2.2	2.0[a]		9.8 0.4[e]
Fe^{58}	0.3	0.5[e]		

[a] See reference 7.
[b] See reference 5.
[c] See reference 4.
[d] See reference 17.
[e] See reference 25.

in the $Mn^{55}(p,n)Fe^{55}$ reaction; the second column contains the position of the excited states found by Deutsch and Hedgran[18] from the study of the decay of Co^{55}; and the third column, the differences in the energies of neutron capture γ-rays. The errors in these energy differences are the root mean square values of the sums of the statistical errors of measurement; as in the case of the two most energetic chromium γ-rays, the systematic errors are approximately the same for each γ-ray and disappear in their differences. For the first two excited states, there is quite close agreement between the energies obtained by the different measurements. The third excited state of Fe^{55} near 1.4 Mev, which, according to the neutron measurements, may consist of two or more closely spaced levels, could be excited directly by a γ-ray with an energy of about 7.94 Mev. This energy lies near the upper end of the scattering tail of the peak E, and consequently, the detection of a weak γ-ray in this position is difficult. If this γ-ray is present, the counting rate produced by it must be less than 5 counts per minute, which at this

[17] P. H. Stelson and W. M. Preston, Phys. Rev. **82**, 655 (1951).
[18] M. Deutsch and A. Hedgran, Phys. Rev. **75**, 1443 (1949).

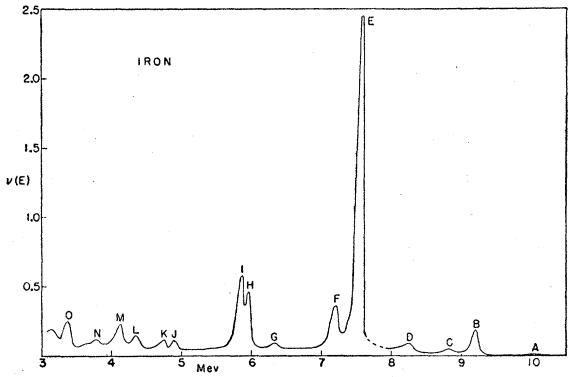

FIG. 7. Corrected γ-ray spectrum of iron.

energy, is equivalent to an intensity of less than 4 photons per 100 captures in Fe^{54}. The energy of the γ-ray F is equal to that expected from a transition to the fourth excited state of Fe^{55} at 2.08 Mev. The intensity of this γ-ray, however, would seem to be rather high; a more probable alternative explanation of F is given below.

We return to a consideration of peak B. The sum of the intensities of B, C, and D together corresponds to about 80 percent of the neutron capture rate in Fe^{54}. If the peak B is produced only by the direct transition to the ground state in Fe^{55}, it occurs very frequently, *viz.*, in about 50 percent of all captures in Fe^{54}. This intensity, however, is an upper limit, for it will be shown below that the peak B may contain a contribution from Fe^{58}.

The γ-ray responsible for the bump B' has an energy about 100 kev less than that of B and cannot be interpreted as the transition to the ground state in Fe^{55} in view of the good agreement in the energy differences obtained with the γ-ray B in Table VII. It will also be shown below that B' cannot be produced in Fe^{58}. We conclude that B' indicates the presence of a low-lying excited state in Fe^{55}, possibly connected with the emission of the 95-kev radiation observed by Deutsch and Hedgran[18] in the decay of Co^{55}.

Excited states are known[18,19] to exist in Fe^{57} at 0.014 Mev and at 0.131 Mev. Although the energy of the γ-ray E is in agreement with that deduced from the strong proton group found by Harvey in the (d,p) reaction, it is not clear from the present measurements

TABLE VII. Excited states of Fe^{55}.

From Stelson and Preston[a] in Mev	From Deutsch and Hedgran[b] in Mev	γ-ray differences in Mev
0.42		B–C 0.425$\pm$0.009
0.94	0.935	B–D 0.953 0.011
1.36	1.41	γ-ray not detected
2.08		B–F 2.013$\pm$0.010

[a] See reference 17.
[b] See reference 18.

[19] L. G. Elliott and M. Deutsch, Phys. Rev. **64**, 321 (1943).

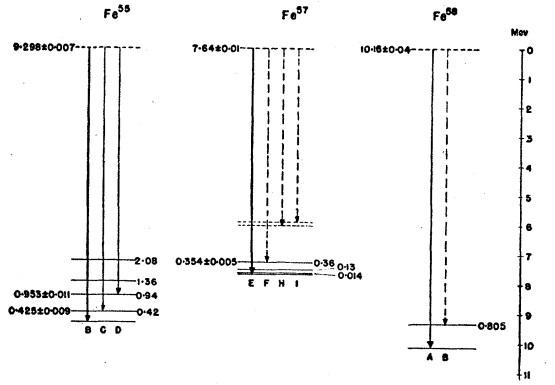

FIG. 8. Decay scheme for the capture γ-rays from Fe^{55}, Fe^{57}, and Fe^{58}. The level energies on the left are obtained from the γ-ray measurements, those on the right from the results of other authors (see text). Two levels, whose presence is inferred from the γ-ray spectrum, are shown in the level scheme of Fe^{57}.

whether E represents the direct transition to the ground state or the transition to the first excited state of Fe^{57}, for the line width used in the present measurements does not allow of the resolution of two γ-rays separated by only 14 kev. The proton group found by Harvey, however, is of exceptional width, and he has interpreted his results as showing the presence of an excited state at 0.36 Mev. This energy is equal to the difference between the energies of the γ-rays E and F, 0.354 ± 0.005 Mev, and the latter γ-ray, therefore, is very probably the direct transition to that excited state. A direct transition to the excited state at 0.131 Mev must be very infrequent by comparison with the intensity of the γ-ray E, for the width of peak E is normal and there is no evidence for the presence of any γ-ray between E and F.

The γ-rays producing the peaks at H and I in Fig. 6 are of such a strength that it is clear that they must both arise from the capture of neutrons in Fe^{56}. The transitions represented by these γ-rays and those of lower energy cannot be identified with certainty for no details of the positions of the higher excited states of Fe^{57} have yet been published. However, it is very probable that these γ-rays produce directly excited states at 1.73 and 1.62 Mev, respectively. Between the peaks H and F there is a continuous background part of which may be due to γ-rays emitted by highly excited states.

From the mass measurements, the neutron binding energy of Fe^{58} is found to be 9.8 ± 0.4 Mev. The energy of the γ-ray A, 10.16 ± 0.04 Mev, is in agreement with this value, and we identify this γ-ray, therefore, with the direct transition to the ground state in that nucleus. Its intensity, 0.10 photon per 100 captures, is equivalent to 5 photons per 100 captures in Fe^{57}.

An excited state is known[14] to exist in Fe^{58} at 0.805 ±0.012 Mev; we should expect, therefore, to find a γ-ray corresponding to the direct transition to this state with an energy of 9.35 ± 0.04 Mev. From natural iron, such a γ-ray would be hard to distinguish from the γ-ray B, the ground state transition in Fe^{55}. The γ-ray B' cannot be confused with this transition for its energy is certainly too low.

Neutron capture in Fe^{58} accounts for only 0.5 percent of the total absorption cross section. The neutron binding energy of Fe^{59} may be calculated from the neutron binding energy[12] of Co^{59} and the decay energies[14] of Co^{58} and of[20] Fe^{59}. Assuming that the latter quantities are 2.30 and 1.56 Mev, respectively, the neutron binding energy of Fe^{59} is found to be 6.4 ± 0.2 Mev. Another value for the same quantity can be found from the masses of Fe^{58} and Ni^{58}, the neutron binding energy of Ni^{59} and the decay energy[21] of Ni^{59} and of Fe^{59}: it is 7.2 ± 0.4 Mev. These values are too inaccurate to permit the identification of any of the iron γ-rays with the ground state transition in Fe^{59}.

NICKEL

In the previous investigation of nickel, no γ-rays were detected between 9.0 and 14.0 Mev. Consequently, when studying the nickel spectrum again with the improved apparatus, we have only examined the spectrum from 3 to 9 Mev. The coincidence spectrum obtained from a kilogram of chemically pure Ni_2O_3 is shown in Fig. 9, the corrected spectrum in Fig. 10. Table VIII contains the energies and intensities of the γ-rays observed. The absolute intensities were obtained by comparison of the relative intensities with that of the 9.00-Mev γ-ray, for which the absolute intensity had been previously determined[3] by direct comparison with the 2.75-Mev γ-ray of Na^{24}. The intensities are based on capture cross sections of 0.54 and 4.80 barns for sodium and nickel, respectively. Below 5 Mev no distinct peaks can be detected on the continuous unresolved background. As in the iron spectrum, this background is low, the γ-rays in Table VIII accounting for some 75 percent of the total energy emitted.

TABLE VIII. Energies and intensities of nickel γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures in natural nickel	Probable origin
A	8.997 ± 0.005	35	Ni^{59}
B	8.532 0.008	14	Ni^{61}
C	8.119 0.010	2.8	
D	7.817 0.008	6.5	Ni^{59}
E	7.528 0.011	4	Ni^{59}
F	7.22 0.02	0.5	
G	7.05 0.02	0.5	
H	6.839 0.010	9	Ni^{59}
I	6.58 0.02	2.0	
J	6.34 0.02	0.6	
K	6.10 0.02	1.0	
L	5.99 0.02	0.3	
M	5.82 0.02	3	Ni^{59} ?
N	5.70 0.02	0.4	
O	5.31 0.02	1	

[20] Deutsch, Downing, Elliott, Irvine, and Roberts, Phys. Rev. **62**, 3 (1942).
[21] J. J. G. McCue and W. M. Preston, Phys. Rev. **84**, 384 (1951).

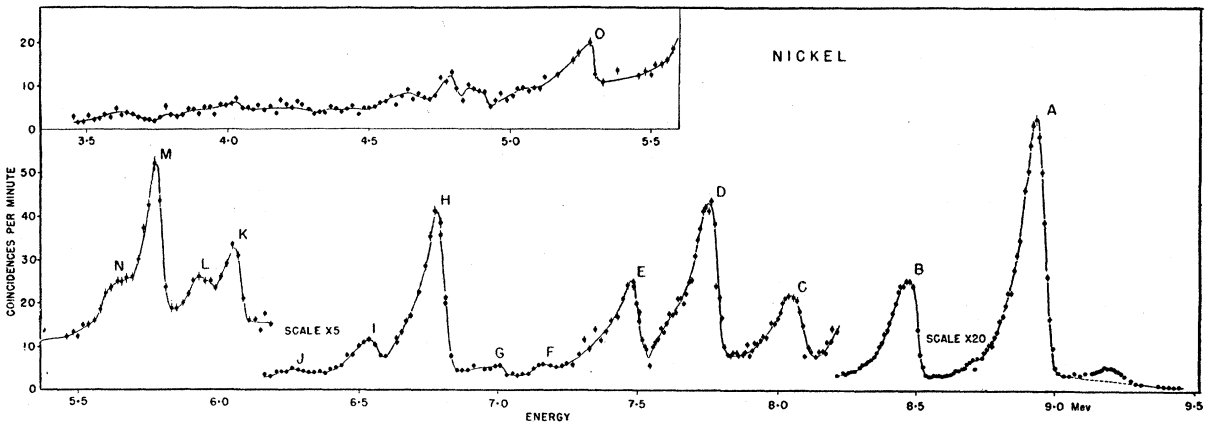

FIG. 9. Coincidence spectrum produced by nickel.

Nickel contains five isotopes of which only Ni^{58}, Ni^{60}, and Ni^{62} contribute appreciably to the cross section of the natural element. The abundances, the contributions to the thermal neutron capture cross section, and neutron binding energies are given in Table IX. The contributions to the cross section were calculated from the results obtained by Pomerance.[10]

The neutron binding energy of Ni^{59} may be deduced from Harvey's measurements[5] of the energy balance in the (d,p) reaction. The result obtained, 9.01 ± 0.10 Mev, is in good agreement with the energy of the γ-ray A. In the absence of any evidence of γ-radiation with energies above that of A, we conclude that this γ-ray represents the direct transition to the ground state in Ni^{59}. It is emitted in 50 percent of all captures in Ni^{58}. There is no evidence for a γ-ray leading to the first excited state[22] of Ni^{59} at 0.33 ± 0.05 Mev; if it is present, its intensity must be less than 0.5 photons per 100 captures in Ni^{59}.

The energy of the γ-ray B (8.532 ± 0.008 Mev) is close to the neutron binding energy of Ni^{61} deduced from the masses of Ni^{60} and Ni^{61} (see Table IX). This value, however, disagrees with the tentative binding energy (7.5 Mev) of Ni^{61} found by Sherd, Halpern, and Stephens.[12] In a previous communication, we have identified the γ-ray B with the ground-state transition in Ni^{61}. This identification would appear to be correct, for the energy of the γ-ray B is in agreement with the neutron binding energy of Ni^{61} deduced from the Q of the reaction $Ni^{60}(d,p)Ni^{61}$ recently measured by Hoesterey.[23] The γ-ray B, therefore, like A, is exceptionally strong, and is produced in about 80 percent of all neutron captures by Ni^{60}.

The γ-rays D, E, H, and I cannot be emitted by Ni^{62} or Ni^{65} since their intensities separately exceed the contributions of either Ni^{61} or Ni^{64} to the cross section of the natural element; they cannot be emitted by Ni^{63} since their energies exceed the neutron binding energy of that nucleus. Moreover, if the γ-ray B is indeed emitted by Ni^{61}, the combined intensity of the remaining Ni^{61} γ-rays is only about 2 photons per 100 captures. This difference, which may be in error by a factor of two, is equal to the intensity of the γ-ray I, but is less than that of D, E, or H. We conclude, therefore, that the γ-rays D, E, and H, and perhaps also the γ-ray I, are all emitted by Ni^{59}.† Together with the

TABLE IX. Abundances, neutron capture cross sections, and binding energies of nickel isotopes.

Isotope	Abundance percent	Contribution to cross section, in percent	Neutron binding energy of product nucleus in Mev
Ni^{58}	67.9	69 [a]	9.01 ± 0.10 [c]
Ni^{60}	26.2	16 [a]	$8.31\ 0.34$ [d]
Ni^{61}	1.2	0.5 [a]	$10.46\ 0.23$ [d]
Ni^{62}	3.7	13 [a]	$6.0\ 0.1$ [e]
Ni^{64}	1.0	0.4 [b]	$5.5\ 0.1$ [f]

[a] See reference 10.
[b] See reference 25.
[c] See reference 5.
[d] Deduced from the results of Collins, Nier, and Johnson, see reference 4.
[e] Deduced from mass measurements and the decay of Ni^{63} (0.05 Mev).
[f] Deduced from the mass measurements and the decay of Ni^{65} (2.1 Mev).

[22] P. H. Stelson and W. M. Preston, Phys. Rev. **86**, 807 (1952).

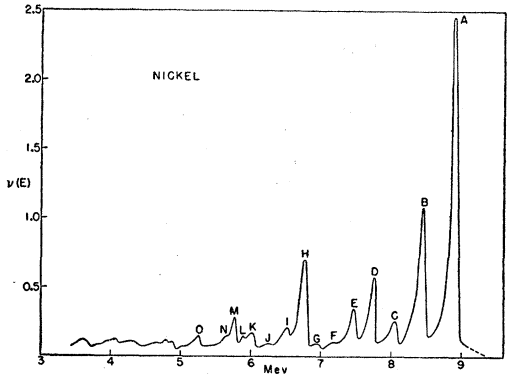

FIG. 10. Corrected γ-ray spectrum of nickel.

[23] D. C. Hoesterey, private communication.

† *Note added in proof.*—All of these assignments may be incorrect, for, according to McFarland, Bretscher, and Shull (see note added in proof, page 380), the first excited state of Ni^{59} is 0.42 Mev and the second at 3.08 Mev. These results suggest that

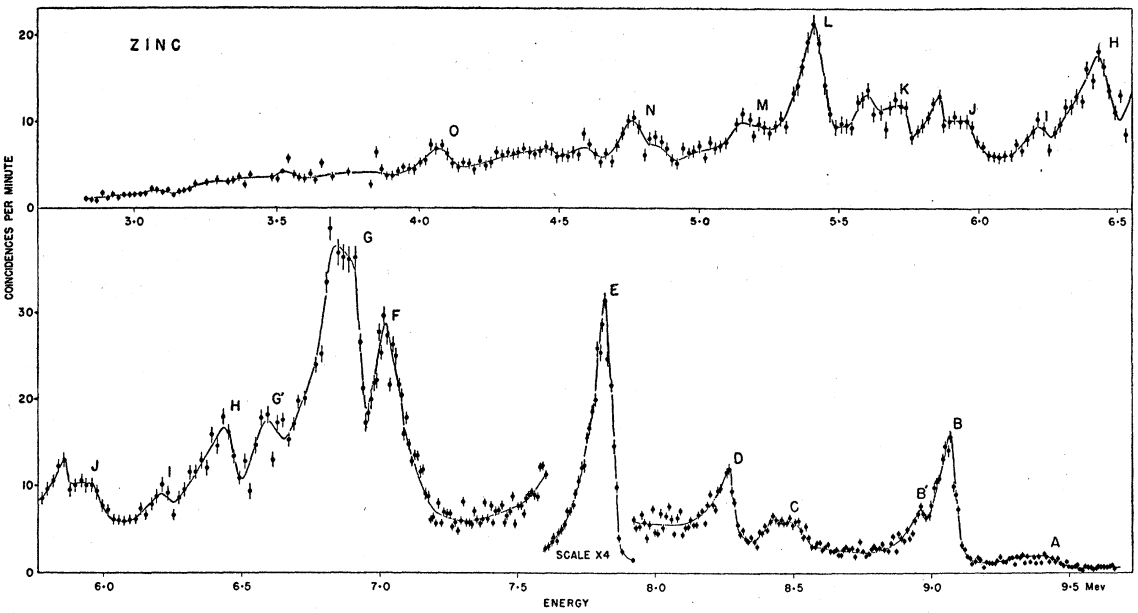

FIG. 11. Coincidence spectrum produced by zinc.

γ-ray A, these radiations then account for about 80 percent of the captures in Ni^{58}.

Three excited states are believed to exist[24] in Ni^{61} at the energies 0.655 ± 0.003, 0.939 ± 0.004, and 1.015 ± 0.004 Mev. Direct transitions to these states would produce γ-rays with the energies 7.877 ± 0.008, 7.593 ± 0.009, and 7.517 ± 0.009 Mev. Since the combined intensities of these γ-rays must be, at most, about two photons per 100 captures, they cannot be detected with certainty in the presence of the stronger radiations D and E.†

Because of the small contributions of both Ni^{61} and Ni^{64} to the thermal cross section, no radiations produced by capture in these isotopes can be identified.

ZINC

The γ-rays emitted from a sample of about 2 kg of very pure zinc metal[16] are shown in Fig. 11 and are listed in Table X. In the preliminary investigation, the γ-ray spectrum was explored to a maximum energy of 10 Mev, and, therefore, in the recent and more detailed investigation no attempt was made to search above the energy of the γ-ray A. Table X contains only the more prominent of the numerous γ-rays which make up the zinc spectrum. Of those coincidence peaks which cannot be resolved by the present instrument, e.g., C, F, G, etc., the energies listed in Table X are those of the components of highest energy. The absolute intensities were measured by comparing the counting rate of the peak E with the counting rates of the two nickel peaks A and B. A composite source was used, consisting of three similar zinc plates, about $\frac{1}{2}$ inch in thickness, each sandwiched between two sheets of nickel of 0.1 g per cm^2. The capture cross section of zinc was assumed to be 1.06 barns. The corrected γ-ray spectrum is shown in Fig. 12.

Zinc possesses five stable isotopes, of which only four contribute to the total thermal neutron cross section, that due to Zn^{70} being negligible. The abundances, the contributions to the thermal neutron capture cross section, and the neutron binding energies are listed in Table XI. The contributions to the cross section of Zn^{64} and Zn^{68} are known from activation experiments.[25] The separate contributions of Zn^{66} and Zn^{67} have not been measured. The neutron binding energy of Zn^{65} was calculated from the masses of Zn^{64}

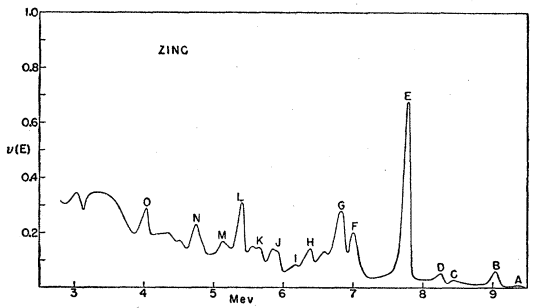

FIG. 12. Corrected γ-ray spectrum of zinc.

part, at least, of peak B (which, however, is of normal width) is caused by Ni^{59}. If this is the correct interpretation of B, it does not follow that the γ-rays D, E, H, and I, are produced by Ni^{59}. The peaks D and E could be produced by Ni^{61}, for it will be noted that the difference between the energies of these γ-rays is very close to the difference between the energies of the first and second excited states of Ni^{61} quoted above.

[24] Owen, Cook, and Owen, Phys. Rev. **78**, 686 (1950); Boehm, Blaser, Marmier, and Preiswerk, Phys. Rev. **77**, 295 (1950).

[25] Seren, Friedlander, and Turkel, Phys. Rev. **72**, 888 (1947).

and Cu^{65}, and the energy of the decay[26] of Zn^{65} (1.34 Mev). The result obtained (8.14±0.06 Mev) is in fair agreement with the value obtained by Harvey from the (d,p) reaction (7.92±0.05 Mev). The neutron binding energies of Zn^{67} and Zn^{68}, listed in Table X, were obtained from mass measurements. The neutron binding energy of Zn^{69} was obtained from the masses[4] of Zn^{68} and Zn^{70} and the (γ,n) threshold[27] of Zn^{70}, 9.20±0.20 Mev.

TABLE X. Energies and intensities of zinc γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures in natural Zn	Probable origin
A	9.51 ±0.03	0.07	Zn^{68}
B	9.12 0.01	1	Zn^{68}
B'	8.98 0.01	0.2	Zn^{68}
C	8.58 0.03	0.2	Zn^{68}
D	8.31 0.02	0.6	Zn^{68}
E	7.876 0.007	10	Zn^{65}
F	7.19 0.03	2.0	
G	6.94 0.02	2.7	
G'	6.65 0.03	0.5	
H	6.49 0.02	1	
I	6.26 0.03	0.3	
J	6.03 0.02	0.8	
K	5.77 0.02	1	
L	5.48 0.02	2.5	
M	5.23 0.03	0.7	
N	4.84 0.04	1.6	
O	4.14 0.03	1.2	

The agreement between the energy of the γ-ray *E* and the neutron binding energy of Zn^{65} obtained by Harvey, suggests that this γ-ray is the product of the transition either to the ground state or to some low-lying state in that nucleus. If this identification is correct, the γ-ray is of exceptional strength, for it must be produced in 40 percent of all neutron captures in Zn^{64}. However, the possibility that this γ-ray is caused by capture by Zn^{67} is not excluded; capture by this isotope must be frequent, for the product nucleus Zn^{68} is certainly responsible for the emission of the γ-rays *A*, *B*, *B'*, *C*, and *D*.

[26] Mann, Rankin, and Daykin, Phys. Rev. **76**, 1719 (1949).
[27] Hanson, Duffield, Knight, Diven, and Palevsky, Phys. Rev. **76**, 578 (1949).

TABLE XI. Abundances, neutron capture cross sections, and neutron binding energies of zinc isotopes.

Isotope	Abundance percent	Contribution to cross section in percent	Neutron binding energy of product nucleus in Mev	
Zn^{64}	49	25[a]	7.92±0.05[b]	8.14±0.06[c]
Zn^{66}	27.8	52		7.49 0.08[c]
Zn^{67}	4.1			9.57 0.08[c]
Zn^{68}	18.6	23[a]		6.6 0.2[c,d]
Zn^{70}	0.6	0.05[e]		

[a] See reference 25.
[b] See reference 5.
[c] See reference 4.
[d] See reference 27.
[e] National Bureau of Standards Circular No. 499 (1950).

The existence of the γ-ray *A* with 9.51±0.03 Mev is indicated but not well established in Fig. 11. Its energy is equal to the calculated neutron binding energy of Zn^{68} and, therefore, may be produced in the transition to the ground state in that nucleus. The γ-rays *B*, *B'*, *C*, and *D* probably represent transitions to low-lying excited states in Zn^{68}.

Although the positions of some of the excited states of Zn^{67} are known from the decay of Ga^{67}, it is not possible to identify any of the γ-rays of Table X with transitions in this nucleus for most of the capture γ-rays are only partially resolved and their energies cannot be measured with sufficient precision. Similarly, none of the γ-rays in Zn^{69} due to capture by Zn^{68} can be identified.