Neutron Capture γ-Rays from Scandium, Vanadium, Manganese, Cobalt, and Copper

G. A. Bartholomew and B. B. Kinsey
Physics Division, Atomic Energy of Canada, Limited, Chalk River, Ontario, Canada
(Received September 10, 1952)

The neutron capture γ-ray spectrum from scandium consists of an exceptionally large number of γ-rays, and those of highest energy are only partially resolved when the line width in the coincidence spectrum is 130 kev. The γ-ray corresponding to the direct transition to the ground state in Sc^{46} (8.85±0.08 Mev), if correctly identified, has an intensity of 0.3 photon per 100 captures. Vanadium produces several strong γ-rays with intensities of about 10 photons per 100 captures. Of these, the γ-ray with the highest energy, 7.305±0.007 Mev, can be identified with the transition to the ground state of V^{52}. A group of partially resolved γ-rays with energies between 7.6 and 8.0 Mev are tentatively ascribed to capture in the rare isotope V^{50}. If this interpretation is correct, the isotopic capture cross section of V^{50} probably lies between 40 and 400 barns. The transition to the ground state in V^{51} was not detected. In manganese the transition to the ground state (7.261±0.006 Mev) is stronger than any other γ-ray in the spectrum (12 photons per 100 captures). With a line width of 100 kev it is only partially resolved from another strong γ-ray with an energy of 7.15±0.02 Mev. The remainder of the manganese spectrum is complex. From cobalt, about six γ-rays are produced each with intensities of the order of 5 photons per 100 captures. The γ-ray with the highest energy (7.486±0.006 Mev) may be identified with either the transition to the ground state or to the isomeric state at 59 kev. The copper spectrum is dominated by the strong γ-ray producing the ground state in Cu^{64}. Its energy is 7.914±0.006 Mev and its intensity is 24 photons per 100 captures in Cu^{63}. Another strong γ-ray at 7.634±0.006 Mev may be the transition to the ground state of Cu^{66}.

INTRODUCTION

PRELIMINARY pair spectrometer measurements of the neutron capture γ-rays produced by V, Mn, Co, and Cu were made in 1949, and some results have been published.[1] In the present paper we describe more detailed and more accurate measurements. The experimental conditions were similar to those for the measurement of the γ-ray spectra of the even-charge elements described in the preceding paper.[2] As before, we define the line width of the coincidence peak due to a homogeneous γ-ray as the width at half-maximum. The line width was 100 kev for all materials except scandium, for which it was 130 kev.

As in the preceding paper, the absolute intensities of the γ-rays (in photons per capture) were determined by the nickel comparison method. For this purpose we used thermal neutron capture cross sections and assumed that the effect caused by resonance capture was negligible. While this is certainly true for the even-charge elements, it may introduce an error in the case of manganese and cobalt, for it is well known that low-lying resonances can contribute to the activation cross sections of these elements.

To determine the resonance contribution to the capture γ-rays, we measured the intensity of the 7.261-Mev manganese γ-ray emitted by two equal (1 kg) samples of manganese dioxide, one of which was completely enclosed in a thick ($\frac{1}{16}$ in.) cadmium container. The contribution of cadmium radiation to the manganese peak was found from a measurement of the counting rate due to the 8.48-Mev cadmium γ-ray and the previously determined coincidence spectrum of that element. We found that the resonance capture effect was about one percent of that due to thermal

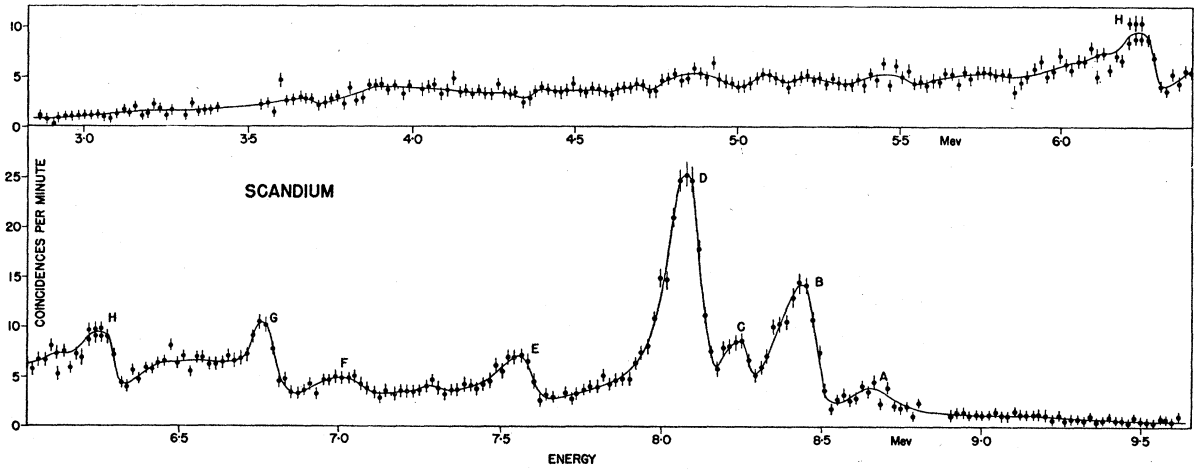

FIG. 1. Coincidence spectrum produced by scandium. Line width: 130 kev.

[1] Kinsey, Bartholomew, and Walker, Phys. Rev. 78, 481 (1950).
[2] B. B. Kinsey and G. A. Bartholomew, preceding paper [Phys. Rev. 88, 375 (1952)].

neutrons. Accordingly, we neglected this effect in the intensity measurements of both manganese and cobalt γ-rays.

SCANDIUM

Scandium has only the single stable isotope Sc^{45} and the capture γ-ray spectrum, therefore, is produced by Sc^{46}.

The scandium sample consisted of four grams of scandium oxide. Impurities capable of producing strong capture γ-rays, such as Al, Fe, and Mn, were present in quantities less than 0.02 percent by weight and hence could not contribute appreciably to the spectrum. Measurements were made from 2.9 Mev to 10 Mev. The results are shown in Fig. 1. There are no peaks in the coincidence spectrum below 6 Mev, and from 6 to 9 Mev a few peaks were observed, partially resolved or superposed on a continuous background.

The lack of structure shows that the level system of Sc^{46} must be exceptionally complicated. The absolute intensity of the γ-ray *D* was obtained by comparison[2] with that of the 9.00-Mev nickel γ-ray using a sample consisting of one gram of powdered Sc_2O_3 mixed with a plastic cement and sandwiched between two nickel sheets of the same area each of thickness of about 0.1 g per cm^2. The cross section of scandium was assumed to be 22 barns. This is the cross section for the production[3] of the 85-day activity of Sc^{46}, and also includes the cross section for the production of the 20-second isomeric state.[4] After correcting the coincidence spectrum (Fig. 1) for the sensitivity of the spectrometer and for the absorption of the radiations in the sample and in the neutron filters, the γ-ray spectrum shown in Fig. 2 was obtained. The ordinate scale in this figure represents the number of photons emitted per capture per unit energy range, and for the line width (130 kev) used in this experiment, a homogeneous γ-ray with an intensity of one photon per capture would produce a peak with a height of 5.6 Mev^{-1}. The energies and absolute intensities of the scandium γ-rays are given in Table I.

The complexity of the spectrum shown in Fig. 2 is remarkable in so light a nucleus. One might be tempted

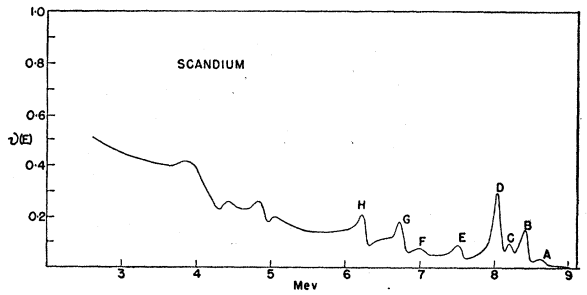

FIG. 2. Corrected γ-ray spectrum of scandium.

[3] Seren, Friedlander, and Turkel, Phys. Rev. **72**, 888 (1947).
[4] M. Goldhaber and C. O. Muehlhause, Phys. Rev. **74**, 1877 (1948).

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

γ-ray	Energy in Mev	Intensity in photons per 100 captures
A	8.85 ±0.08	0.3
B	8.539 0.010	2.5
C	8.31 0.02	1
D	8.175 0.011	5
E	7.65 0.03	1
F	7.15 0.04	0.7
G	6.84 0.02	2.5
H	6.35 0.01	2

to conclude that impurities of heavy elements not detected in the spectrographic analysis, have contributed to the results obtained. The only heavy elements which have sufficiently large cross sections to contribute are the rare earths, and of these,[5] gadolinium, which can be recognized by a prominent peak in the coincidence spectrum at 6.7 Mev, is the most important. A peak appears at *G* in Fig. 1, but if this were entirely due to gadolinium the coincidence spectrum at lower energies would be much more intense than that found, and therefore we estimate that gadolinium cannot contribute more than 10 percent to the neutron capture rate. Since that element will contribute the greater part of the neutron captures caused by any likely combination of rare earth impurities, we conclude that the complexity of the scandium spectrum is genuine.

None of the γ-rays listed in Table I can be identified with certainty. From the *Q* value (6.78 Mev) of the high energy proton group observed by Davidson in the $Sc^{45}(d,p)Sc^{46}$ reaction,[6] we find 9.0±0.1 Mev for the neutron binding energy of Sc^{46}. This result is in agreement with the value (8.90 Mev) calculated from the masses of Sc^{45} and Ti^{46} given by Collins, Nier, and Johnson[7,8] and the decay energy (2.37 Mev[9]) of Sc^{46}. Two excited states have been reported in Sc^{46}; one is an isomeric level at 0.17 Mev,[4] and the other, at 2.30 Mev, was found in a study of the $Sc^{45}(d,p)Sc^{46}$ reaction.[6] The energy of the γ-ray *A* in Table I is very close to the neutron binding energy of Sc^{46} and may represent the direct transition to the ground state. The difference between the energies of the γ-rays *A* and *B* (0.31±0.08 Mev) seems to be too great for the latter γ-ray to be identified with a transition to the isomeric state.

VANADIUM

Vanadium consists of two isotopes, V^{50} and V^{51}. The abundance of V^{50} is only 0.24 percent and its capture cross section is unknown.

The vanadium sample consisted of 300 grams of V_2O_5 powder enclosed in a Dural container with Bakelite ends. A sodium impurity was present in a concentration of 2 percent by weight, but it did not contribute a

[5] B. B. Kinsey and G. A. Bartholomew (to be published).
[6] W. L. Davidson, Phys. Rev. **56**, 1061 (1939).
[7] Collins, Nier, and Johnson, Phys. Rev. **83**, 228 (1951).
[8] Collins, Nier, and Johnson, Phys. Rev. **86**, 408 (1952).
[9] C. L. Peacock and R. G. Wilkinson, Phys. Rev. **74**, 297 (1948).

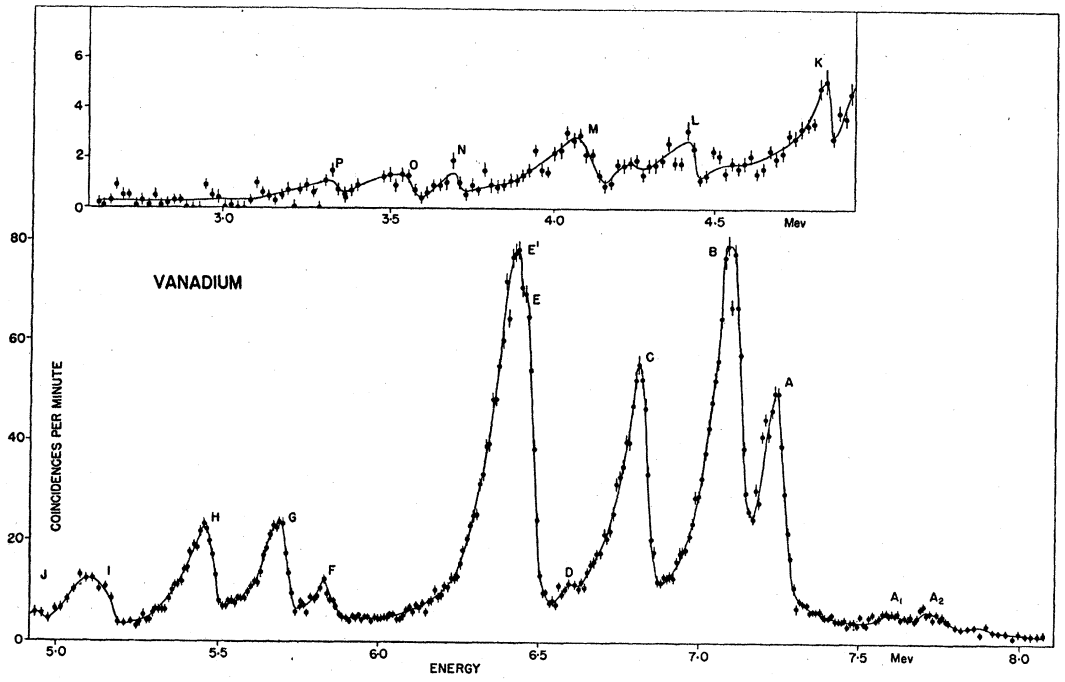

FIG. 3. Coincidence spectrum produced by vanadium. Line width: 100 kev.

detectable amount to the vanadium spectrum since its cross section is only one tenth of that of vanadium. Other impurities, such as Al, Si, Fe, and Pb, were each present in concentrations of about 0.02 percent, which are too low to produce capture radiation detectable in the presence of vanadium γ-rays.

The vanadium capture γ-rays were measured between 2.6 and 8.1 Mev. The coincidence spectrum is shown in Fig. 3. In earlier measurements, the spectrum was explored to an energy of 9.5 Mev with less resolution, and no γ-rays were found with energies above 7.3 Mev. Table II contains the energies and intensities of the vanadium capture γ-rays. The intensities were obtained by comparing the counting rates at the peak E' with that of the 9.00-Mev nickel γ-ray using a mixture of weighed amounts of Ni_2O_3 and V_2O_5, the cross section of vanadium being assumed to be 4.7 barns. The corrected γ-ray spectrum is shown in Fig. 4. In this figure, and in the corrected spectra for Mn, Co, and Cu, the peak height for a homogeneous γ-ray of unit intensity is 6.7 Mev^{-1}.

From the Q-value of the high energy proton group in the $V^{51}(d,p)V^{52}$ reaction, Harvey[10] obtained 7.25 $\pm$0.05 Mev for the neutron binding energy of V^{52}. This result is in agreement with the value (7.4$\pm$0.15 Mev) calculated from the masses of V^{51} and Cr^{52} given by Collins, Nier, and Johnson[8] and the decay energy (4.2$\pm$0.1 Mev[11]) of V^{52}. Both results are in agreement with the energy of the γ-ray A, 7.305$\pm$0.007 Mev, which we therefore identify with the direct transition to the ground state of V^{52}. Less satisfactory agreement is obtained if the work of Abramov[12] and of Davidson[6] is considered, both of whom used the (d,p) reaction. The former leads to a neutron binding energy of 7.66$\pm$0.15 Mev and the latter to a value of 10.0 Mev.

The energy levels of V^{52} were first investigated by Davidson,[6] who found levels at 2.47 and at 4.70 Mev. Because of the discrepancy between the Q values obtained by Davidson and by Harvey, the position of these energy levels is doubtful. A longer list of levels has been published by Abramov.[12] We have attempted

TABLE II. Energies and intensities of vanadium γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures
A	7.305$\pm$0.007	11
B	7.154 0.008	18.5
C	6.868 0.008	14
D	6.62 0.02	0.7
E	6.508 0.006	25
F	5.879 0.015	3
G	5.744 0.008	9
H	5.511 0.008	10
I	5.21 0.01	6
J	4.98 0.02	2
K	4.85 0.02	2
L	4.45 0.02	3
M	4.15 0.03	4
N	3.73 0.03	3
O	3.59 0.02	3
P	3.36 0.02	2

[10] J. A. Harvey, Phys. Rev. **81**, 353 (1951).
[11] R. Bouchez and G. A. Renard, J. phys. et radium **8**, 289 (1947).
[12] A. Y. Abramov, Doklady Akad. Nauk. U.S.S.R. **73** (No. 5), 92 (1950).

to fit the capture γ-rays into the tentative decay scheme shown in Fig. 5, the position of Abramov's levels being shown on the right. Our level scheme was constructed on the assumption that the γ-ray A is the ground-state γ-ray and that strong high energy γ-rays are always emitted by the capturing state and do not occur as the result of the de-excitation of other high energy states. This assumption is justified by the experimental fact that the most frequent transitions are those producing low-lying excited states; however, it is perhaps unsafe to apply this rule to establish excited states much above 2 Mev.

We assume, therefore, that the γ-rays B and C produce states at 0.15±0.01 and 0.44±0.01 Mev, respectively. No levels at these energies were found by Abramov [although this is possibly not surprising in view of the relatively low yields of the long range proton groups produced in the (d,p) reaction], nor is there a γ-ray leading to an isomeric state at 0.25 Mev reported by Renard.[13]

The partly resolved peak E, E' has a width of about 150 kev at half-maximum. When analyzed, this complex peak may be shown to consist of two peaks differing in energy by 50 kev, each with intensities of about 14 photons per 100 captures. As will be seen in Fig. 5, emission of these γ-rays is assumed to create a pair of levels near 0.8 Mev. A level near this position has been found by Abramov.

The identity of the remaining γ-rays is more obscure. The levels corresponding to the strong γ-rays G, H, I, and K do not agree well with those found by Abramov. Other possible energy levels, produced by weaker radiations, are indicated by horizontal broken lines in Fig. 5. The sum of the energies of the γ-rays N and O add up to 7.32±0.03 Mev, in good agreement with that of the γ-ray A. This agreement suggests that the γ-rays N and O are in cascade, and the two possible configurations are shown in Fig. 5.

Two peaks appear in Fig. 3 corresponding to γ-ray energies above that of the γ-ray A which we have identified with the neutron binding energy of V^{52}. Their positions on the energy scale are such that they cannot be identified as ghost peaks produced by the scattering

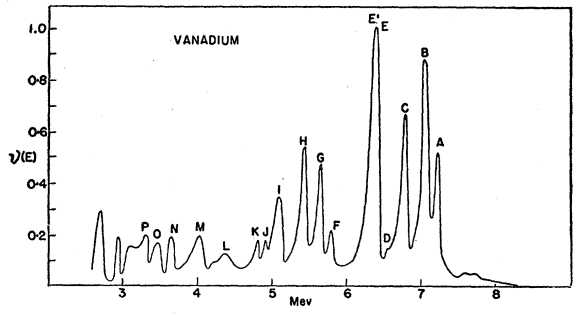

FIG. 4. Corrected γ-ray spectrum of vanadium.

[13] G. A. Renard, Ann. phys. 5, 385 (1950).

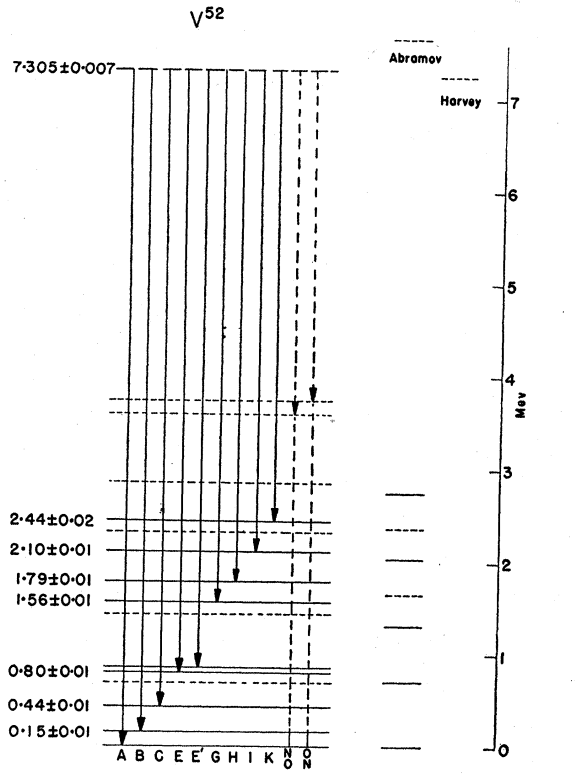

FIG. 5. Tentative decay scheme for the capture γ-rays from vanadium. The full horizontal lines represent levels whose existence is inferred from the strong γ-rays in the spectrum, the broken lines represent possible levels whose existence is suggested by weak γ-rays. The levels from the (d,p) reaction are shown on the right (see text).

effects which were described in the preceding paper. The peak counting rates are too great to be explained in terms of the background radiations of lead and of aluminum, which are known to be present and which produce coincidence peaks in a similar position. We therefore examined this region of the coincidence spectrum in greater detail, using a sample of vanadium oxide obtained from another source. A spectrographic analysis of the new sample material showed no trace of sodium, and only insignificant traces of other elements. In order to get more vanadium into the sample container, the oxide was melted and cast into disks of suitable size. With this sample measurements were made up to an energy of 11.2 Mev. The significant results obtained are shown in Fig. 6. The peaks A_1 and A_2 in Fig. 3, appear again in Fig. 6 in the same proportion to the peak A, which in this new sample has been increased by a factor of three. The proportional increase in the counting rate in A_1 and A_2 suggests that the γ-rays responsible for these peaks are due to vanadium. The expected ghost peaks produced by scattering from peaks A and B are now visible as a sudden change of slope on the upper edge of peak A. In addition, a peak A_3 appears on the high energy side of A_2. The energies and intensities of these γ-rays are listed in Table III.

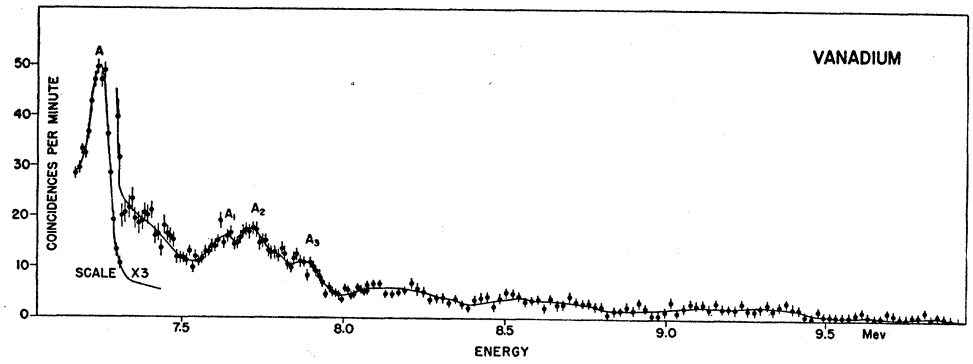

FIG. 6. Coincidence spectrum produced by higher energy vanadium γ-rays. Line width: 100 kev.

Beyond A_3, we find an undulating coincidence curve, with a few breaks in it, indicating the presence of γ-rays with energies extending to 9.5 Mev.

The most probable explanation of these γ-rays is that they are produced in V^{51}, following capture in the rare isotope V^{50}. If this is the correct explanation, the thermal neutron capture cross section of V^{50} must be very high. Since its abundance[14] is 0.24 percent, the capture cross section for the production of the γ-rays listed in Table III is at least 40 barns, and the total capture cross section is probably much higher. It is not likely to be higher than 400 barns because one would then expect to find a difference of more than 20 percent (which has not been detected) between the cross sections determined by activation and by pile oscillator methods.

Two determinations[15] of the (γ,n) threshold of V^{51} have been made giving neutron binding energies in V^{51} of 10.8±0.5 Mev and 11.15±0.2 Mev. From recent measurements of Johnson[16] the value 10.95±0.11 Mev is obtained. No evidence was found for a γ-ray of energy corresponding to the transition to the ground state of V^{51} nor to any excited states up to 1.5 Mev. The intensity of the ground-state γ-ray must be less than 0.06 photon per 100 captures in natural vanadium.

MANGANESE

Manganese has only one stable isotope, Mn^{55}. The neutron capture γ-rays are therefore produced in the product nucleus Mn^{56}.

TABLE III. Energies and intensities of γ-rays probably due to V^{51}.

γ-ray	Energy in Mev	Intensity in photons per 100 captures in natural vanadium
A_1	7.67±0.02	0.25
A_2	7.83 0.02	1.3
A_3	7.98 0.02	0.5

[14] D. C. Hess and M. G. Inghram, Phys. Rev. **76**, 1717 (1949); W. Leland, Phys. Rev. **76**, 1722 (1949).
[15] Sher, Halpern, and Stephens, Phys. Rev. **81**, 159 (1951); Sher, Halpern, and Mann, Phys. Rev. **84**, 387 (1951).
[16] W. H. Johnson, Phys. Rev. **87**, 166 (1952).

In the earlier measurements on the neutron capture γ-rays of manganese, a sample of metallic manganese was used and the spectrum was examined up to 9.1 Mev. No γ-rays were found above 7.25 Mev. In the more recent investigation, we examined the spectrum between 3.5 and 8.0 Mev emitted by a sample consisting of 1400 g of manganese dioxide. Spectrographic analysis showed that the amounts of other elements present were not sufficient to produce a detectable effect on the manganese spectrum. The coincidence spectrum is shown in Fig. 7.

The absolute intensities were determined from a comparison of the counting rate of the peak A with that of the 9.00 nickel γ-ray, using a sample containing a mixture of weighed amounts of manganese and nickel oxides. In this determination, the capture cross section of manganese was assumed to be 12.6 barns. The energies and intensities are listed in Table IV. The corrected γ-ray spectrum is shown in Fig. 8.

By other methods with less resolution, the manganese capture γ-rays have been studied by Pringle and Isford[17] and by Hamermesh.[18] The former authors report the presence of two prominent groups of radia-

TABLE IV. Energies and intensities of manganese γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures
A	7.261±0.006	12
B	7.15 0.02	4
C	7.048 0.008	6.5
D	6.779 0.008	2.5
E	6.43 0.01	0.5
F	6.11 0.01	1
G	5.91 0.02	0.5
H	5.77 0.01	1
I	5.63 0.02	0.3
J	5.528 0.010	4
K	5.21 0.01	3
L	5.04 0.02	6
M	4.81 0.01	2
N	4.72 0.02	2
O	4.55 0.01	2
P	4.24 0.01	2
P'	4.10 0.03	1
Q	3.82 0.02	1

[17] R. W. Pringle and G. Isford, Phys. Rev. **83**, 467 (1951).
[18] B. Hamermesh, Phys. Rev. **81**, 487 (1951).

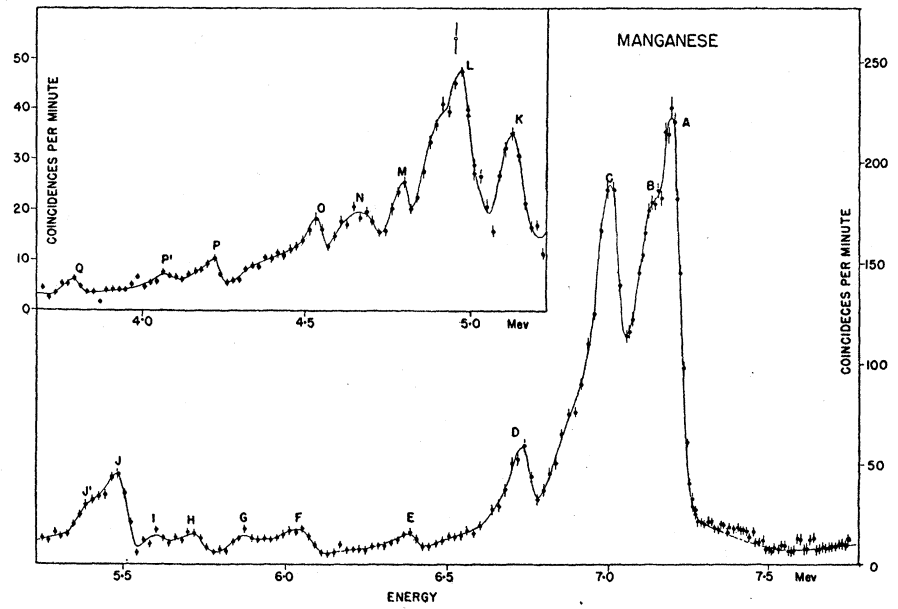

FIG. 7. Coincidence spectrum produced by manganese. Line width: 100 kev.

tions of comparable intensity, with energies of 5.32 ±0.05 and 7.16±0.05 Mev. Similar results were obtained by Hamermesh and Hummel.[19] These observations are in general agreement with the corrected spectrum of Fig. 8, which shows two groups of γ-rays near these energies.

The strong γ-ray *A* has an energy of 7.261±0.006 Mev. There would seem to be no doubt that this γ-ray represents the direct transition to the ground state in Mn^{56}, for its energy is in good agreement with the neutron binding energy determined from the highest *Q* value of the (*d*,*p*) reaction. A neutron binding energy of 6.99 Mev is obtained from the measurements of Martin,[20] 7.24 Mev from the more recent measurements of Whitehead and Heydenburg,[21] and 7.32±0.15 Mev from the measurements of Abramov.[12]

The energies of the known excited states in Mn^{56}, obtained from the $Mn^{55}(d,p)Mn^{56}$ reaction, are listed in Table V. With the aid of these results we have constructed the tentative decay scheme shown in Fig. 9, in which the levels from the (*d*,*p*) reaction are shown on the right and those inferred from the γ-ray measurements are shown on the left. The γ-rays *B*, *C*, and *D*, are not likely to be produced by transitions from highly excited states to the ground state, since it would be difficult to understand how the transitions producing these excited states could compete with the direct transition to the ground state. Accordingly, these γ-rays are assigned to transitions to three low-lying excited states hitherto undetected, at 0.11±0.02, 0.213±0.009, and at 0.482±0.009 Mev. The existence of the first of these, at least, is not inconsistent with the observations of Whitehead and Heydenburg, and of Martin, whose results showed an unusually broad proton group of highest energy.

The difference between the energies of the γ-rays *A* and *F* is 1.15±0.01 Mev, which corresponds to the energy of the lowest excited state observed by Martin and also that of Abramov. The strong γ-ray *J* is

TABLE V. Energy levels of Mn^{56} from the (*d*,*p*) reaction, in Mev.

Martin[a]	Whitehead and Heydenburg[b]	Abramov[c]
1.07	1.54	1.22?
1.77	1.88	1.77
...	2.16	2.07
2.48	...	2.45?
...	...	2.82
3.61	...	...
4.38	4.53	
	4.88	
	5.20	

[a] See reference 20.
[b] See reference 21.
[c] See reference 12.

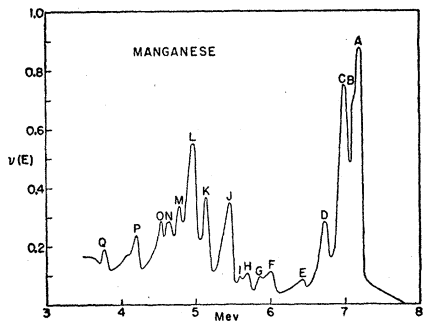

FIG. 8. Corrected γ-ray spectrum of manganese.

[19] B. Hamermesh and V. Hummel, Phys. Rev. **83**, 663 (1951).
[20] A. B. Martin, Phys. Rev. **72**, 378 (1947).
[21] W. D. Whitehead and N. P. Heydenburg, Phys. Rev. **79**, 99 (1950).

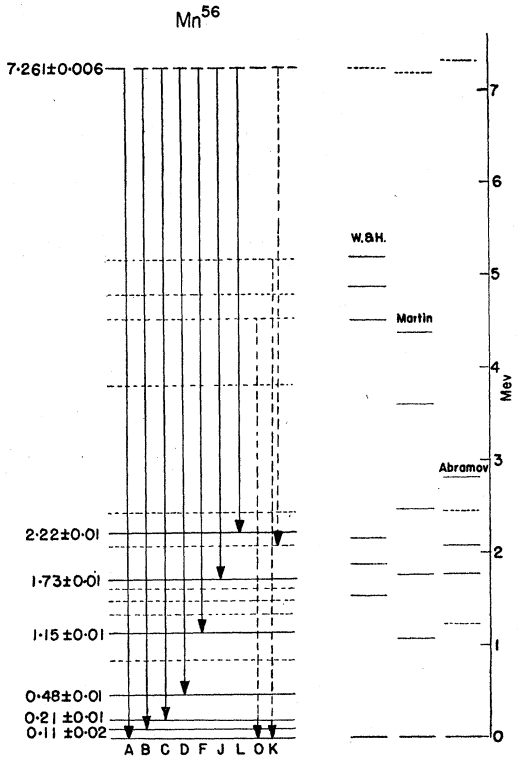

FIG. 9. Tentative decay scheme for the capture γ-rays from manganese. The full horizontal lines represent levels whose existence is inferred from the strong γ-rays in the spectrum, the broken lines represent possible levels whose existence is suggested by weak γ-rays. The levels from the (d,p) reaction are shown on the right (see text).

probably associated with a transition to a level at 1.73 ± 0.01 Mev, for proton groups corresponding to a level near this energy were obtained in all three (d,p) measurements. The γ-rays K and L are more difficult to assign. Two possible alternatives for K are shown in Fig. 9.

COBALT

Cobalt has one stable isotope, Co^{59}. All of the neutron capture γ-rays, therefore, must be ascribed to Co^{60}.

The cobalt sample consisted of 750 grams of very pure cobalt metal[22] mounted in a Dural cylinder with open ends. The spectrum was measured from 2.4 to 8.3 Mev, and the results are shown in Fig. 10. The absolute intensities of the cobalt γ-rays were determined from a comparison of the counting rate at the peak B with that of the 9.00-Mev nickel γ-ray, using a known mixture of nickel and cobalt oxides. The capture cross section of cobalt was assumed to be 34.8 barns. The energies and intensities of the cobalt γ-rays are listed in Table VI, and the corrected γ-ray spectrum is shown in Fig. 11.

The neutron binding energy of Co^{60} can be obtained from the Q value of the $Co^{59}(d,p)Co^{60}$ reaction. From the results of Bateson and Pollard[23] we find a neutron binding energy of 7.42 Mev, from those of Harvey,[10] 7.66 ± 0.2 Mev, and from those of Hoesterey,[24] 7.53 Mev. The binding energy can also be obtained from a consideration of the masses[8] of Ni^{58}, Ni^{60}, the energy[25] (2.81 Mev) of the decay of Co^{60}, the neutron binding

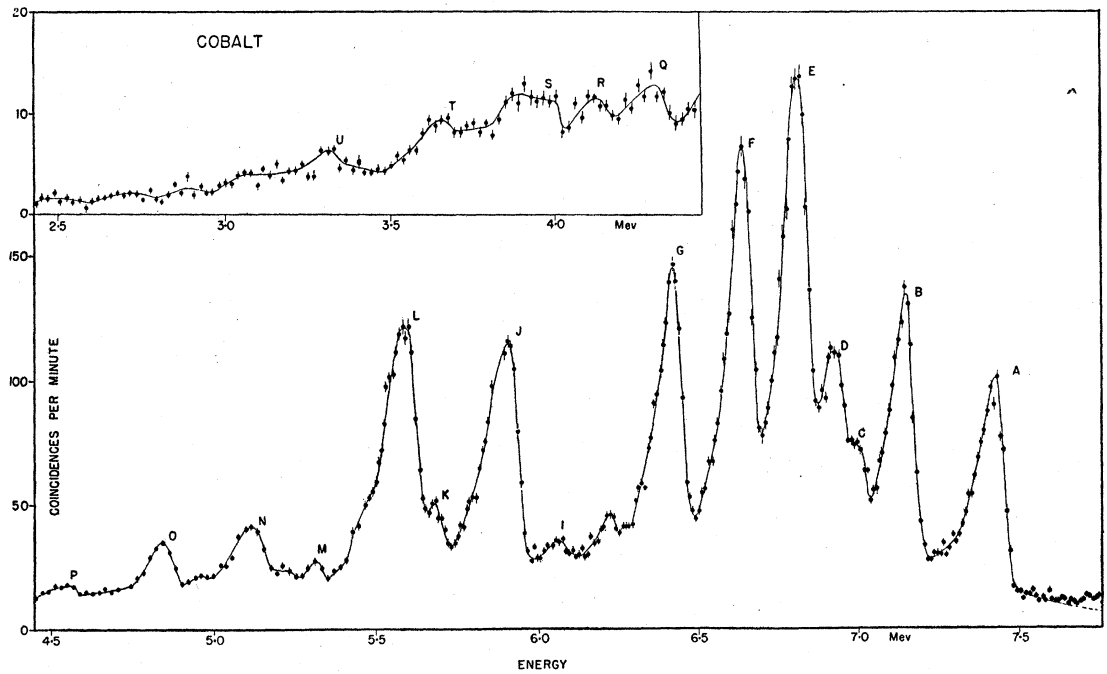

FIG. 10. Coincidence spectrum produced by cobalt. Line width: 100 kev.

[22] We are indebted to the Department of Mines and Technical Surveys, Ottawa, for the provision of this sample.
[23] W. D. Bateson and E. Pollard, Phys. Rev. **79**, 241 (1950).
[24] D. C. Hoesterey, Phys. Rev. **87**, 216 (1952).
[25] Deutsch, Elliott, and Roberts, Phys. Rev. **68**, 193 (1945); Lind, Brown, and DuMond, Phys. Rev. **76**, 591 (1949).

energy[2] of Ni^{59}, and the known mass difference[26] of Ni^{59} and Co^{59}. The result is 7.2±0.3 Mev, which is lower than, but not inconsistent with, the values obtained from the (d,p) reaction.

The energy of the γ-ray A (7.486±0.006 Mev) is close to the above values for the neutron binding energy of Co^{60}. However, the latter is not known with sufficient precision to identify this γ-ray with the direct transition to the ground state, since the energy of the first excited state, the well-known 58.9±0.5 kev[27] isomeric state of Co^{60}, is less than the error in the above values of the neutron binding energy. The γ-ray A must represent a transition either to the isomeric state or to the ground state, and the present measurements also are insufficient to distinguish between the two alternatives, for the width of the peak A in Fig. 10 is normal (100 kev) and there is no evidence for the presence of another γ-ray with an energy 60 kev above or below it. It follows that, if the γ-ray A represents the transition to the ground state, the γ-ray producing the isomeric state is weak, with an intensity less than one-tenth of that of A. On the other hand, if the γ-ray A represents a transition to the isomeric state, the ground-state transition must have an intensity less than 3 percent of A.

TABLE VI. Energies and intensities of cobalt γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures
A	7.486±0.006	3.0
B	7.201 0.006	4.0
C	7.041 0.010	1.3
D	6.974 0.010	2.5
E	6.867 0.006	7
F	6.690 0.006	6
G	6.474 0.006	5
H	6.250 0.009	0.7
I	6.110 0.015	0.5
J	5.966 0.006	5.6
K	5.726 0.010	1.7
L	5.646 0.006	6.3
M	5.351 0.010	0.7
N	5.179 0.010	2
O	4.903 0.008	2.5
P	4.59 0.02	0.6
Q	4.37 0.02	1
R	4.18 0.02	0.8
S	4.03 0.02	1
T	3.69 0.02	0.7
U	3.36 0.02	1

Six higher excited states in Co^{60} have been reported by Bateson and Pollard at 0.39, 0.81, 1.28, 1.73, 2.17, and 2.80 Mev. Hoesterey[24] reported a level at 0.44 Mev, which perhaps corresponds to the first excited state found by these authors. In Fig. 12 we have constructed a very tentative level diagram for Co^{60} on the assumption that the relatively strong γ-rays B, C, D, E, F, G, J, and L are all emitted in transitions from the capturing state to low-lying excited states, the γ-ray A being the transition to the ground state. All these γ-rays appear to be homogeneous except those producing the peaks J and L which are unusually broad. The positions of the excited states, obtained by subtracting the energies of the γ-rays from that of A are given on the left of Fig. 12, the results of the measurements of Bateson and Pollard on the right. It will be seen that there is agreement between the energies of these levels only for those produced by the γ-rays C, F, and L. If,

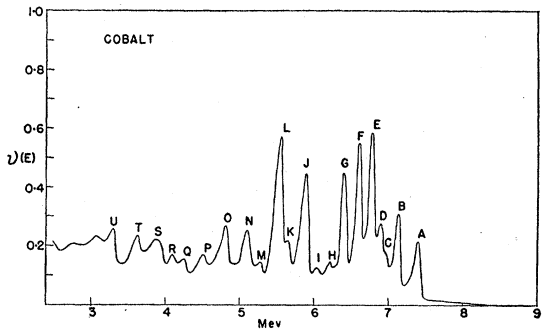

FIG. 11. Corrected γ-ray spectrum of cobalt.

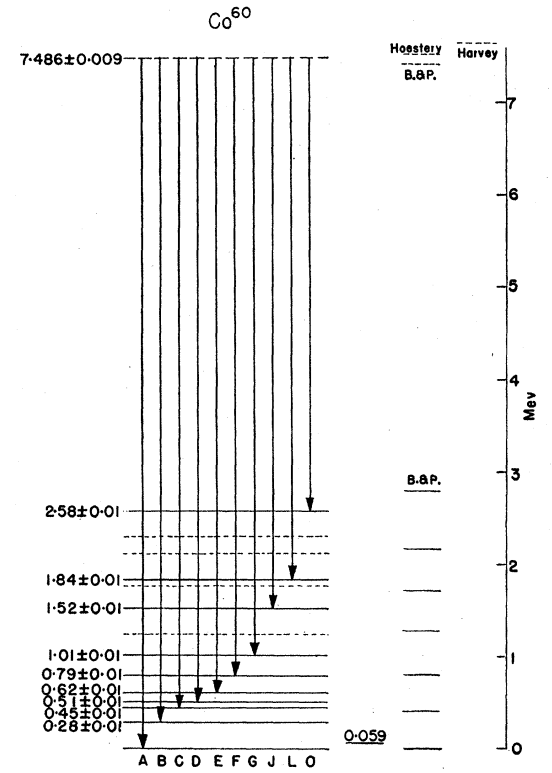

FIG. 12. Tentative decay scheme for the capture γ-rays from cobalt. It is assumed that γ-ray A is produced in the direct transition to the ground state and not to the isomeric state at 59 kev. The full horizontal lines represent levels whose existence is inferred from the strong γ-rays in the spectrum, the broken lines represent possible levels whose existence is suggested by weak γ-rays. The levels from the (d,p) reaction are shown on the right (see text).

[26] J. J. G. McCue and W. M. Preston, Phys. Rev. **84**, 384 (1951).
[27] R. L. Caldwell, Phys. Rev. **78**, 45 (1950).

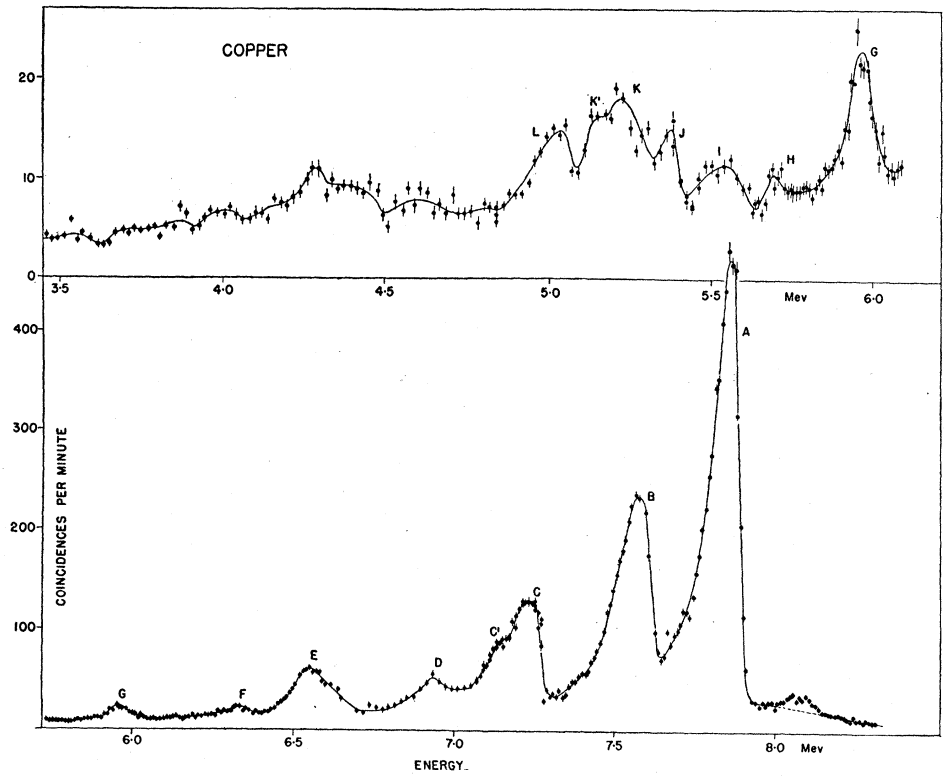

FIG. 13. Coincidence spectrum produced by copper. Line width: 100 kev.

on the other hand, the γ-ray A represents the transition to the isomeric state, the level system given on the left would be shifted upwards by only 59 kev, and the general agreement of the two level schemes would not be improved. It will be clear from this discussion that no progress can be expected in the identification of the capture γ-rays until much more accurate measurements on the (d,p) reaction are available.

COPPER

Copper consists of two isotopes, Cu^{63} and Cu^{65}. According to recent measurements by Pomerance,[28] about 82 percent of the thermal neutron capture cross section of the natural element is due to Cu^{63}.

TABLE VII. Energies and intensities of copper γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures
A	7.914±0.006	20
B	7.634 0.006	9
C	7.296 0.009	5.5
C'	7.16 0.02	1
D	7.01 0.02	2
E	6.69 0.03	3
F	6.41 0.02	1
G	6.05 0.02	1
H	5.75 0.03	0.2
I	5.64 0.03	0.5
J	5.43 0.02	1
K	5.31 0.03	1
K'	5.18 0.02	0.6
L	5.07 0.02	0.7

The copper sample consisted of a cylindrical bar of very pure copper, 2300 grams, mounted in a Dural cylinder with open ends. The coincidence spectrum, which was measured from 3.4 to 8.2 Mev, is shown in Fig. 13. The energies and intensities of the copper radiations are listed in Table VII. The intensities were determined by comparing the counting rate of the peak A of the copper spectrum with that of the 9.00-Mev nickel γ-ray, using a known mixture of nickel and copper oxides. The capture cross section of copper was assumed to be 3.59 barns. The corrected γ-ray spectrum is shown in Fig. 14.

The neutron binding energy of Cu^{64} has been determined by Harvey[10] from a study of the $Cu^{63}(d,p)Cu^{64}$ reaction. He found the value 7.78±0.2 Mev. Using copper enriched in Cu^{63}, Hoesterey[24] has determined the energy balance in the same reaction; his result corresponds to a neutron binding energy of 7.89 Mev, in good agreement with Harvey's result. Another value in agreement with these measurements can be obtained from a consideration of the reaction cycle involving the positron decay energy of Zn^{63} (2.36 Mev[29]), the β-decay energy of Cu^{64} (0.573 Mev[30]), and the photoneutron threshold of Zn^{64}. For the latter quantity,

[28] H. Pomerance, Phys. Rev. 88, 412 (1952). We are indebted to Dr. Pomerance for the privilege of seeing his results before publication.

[29] Huber, Medicus, Preiswerk, and Steffen, Helv. Phys. Acta 20, 495 (1947).

[30] C. S. Cook and L. M. Langer, Phys. Rev. 73, 601 (1948).

Hanson *et al.*,[31] obtained 11.80±0.2 Mev, and Sher and co-workers[15] obtained 11.65±0.2 Mev. Adopting the mean of the latter results, the neutron binding energy of Cu^{64} is found to be 7.8±0.2 Mev, in agreement with the measurements on the (d,p) reaction. If the masses of Cu^{63} and Zn^{64} obtained by Collins, Nier, and Johnson[8] are used instead, the lower value 7.52±0.06 Mev is obtained. The origin of this disagreement is not clear. However, the strong γ-ray *A* has an energy of 7.914±0.004 Mev in good agreement with the above estimates for the neutron binding energy of Cu^{64} with the exception of that obtained from the mass measurements. There seems to be little doubt, therefore, that the γ-ray *A* represents the direct transition to the ground state in Cu^{64}. According to Hoesterey,[24] excited states exist in Cu^{64} at 0.51 Mev and at 1.29 Mev. These energies agree with the difference between the energy of the γ-ray *A* and the energies of the γ-rays *C* and *E*, respectively, and we conclude that these γ-rays represent transitions to excited states at these positions.

In natural copper, Hoesterey[32] has found a high energy proton group which was absent in the protons emitted from a sample enriched in Cu^{63}. If the binding energy of the deuteron is added to the *Q* value of this group, the energy obtained is very close to the energy of the γ-ray *B* (7.634±0.006 Mev). This γ-ray, therefore, would appear to be the direct transition to the ground state in Cu^{66}. The energy, however, is inconsistent with the neutron binding energy of Cu^{66} deduced from the disintegration energies of Cu^{66} and Zn^{65} and the (γ,n) threshold of Zn^{66}. These quantities are respectively 2.63 Mev,[33] 1.34 Mev,[34] and 11.15±0.2 Mev[15]; and hence the neutron binding energy of Cu^{66} is 7.2±0.2 Mev. Another low value may be obtained from the masses[8] of Cu^{65} and Zn^{66} and the disintegration energy of Cu^{66}; this value is 6.8±0.1 Mev. Until these discrepancies are resolved, the γ-ray *B* cannot be identified with certainty.

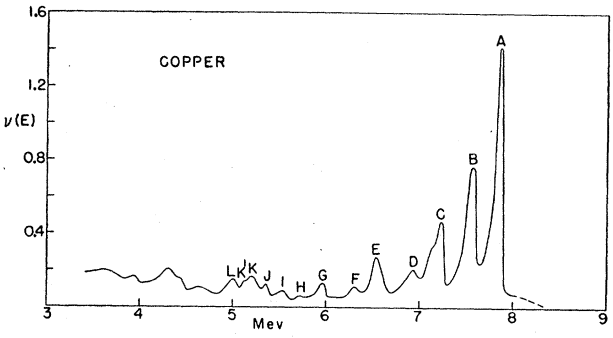

FIG. 14. Corrected γ-ray spectrum from copper.

An interesting feature of the γ-ray spectrum of copper is the great strength of the ground-state γ-ray *A*. It is produced in 24 percent of the captures by Cu^{63}. Also if the γ-ray *B* is caused by capture in Cu^{65}, its intensity is even greater, about 50 photons per 100 captures in that isotope.

[31] Hanson, Duffield, Knight, Diven, and Palevsky, Phys. Rev. **76**, 578 (1949).
[32] D. C. Hoesterey, private communication.
[33] G. Friedlander and D. E. Alburger, Phys. Rev. **84**, 231 (1951).
[34] W. M. Good and W. C. Peacock, Phys. Rev. **69**, 680 (1946).