Neutron Capture γ-Rays from Phosphorus, Sulfur, Chlorine, Potassium, and Calcium

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The prominent capture γ-rays from phosphorus, sulfur, chlorine, potassium, and calcium have been studied with the aid of a pair spectrometer. The neutron binding energies obtained for P^{32}, S^{33}, Cl^{36}, and K^{40} are 7.94 ± 0.03, 8.64 ± 0.02, 8.56 ± 0.03, and 7.77 ± 0.03 Mev. Neutron capture in phosphorus produces a complicated spectrum in which the ground-state γ-ray is weak. Most of the captures in sulfur occur in S^{32} and produce S^{33} in a cascade process involving the fifth excited state near 3.2 Mev. The direct transition to the ground state in S^{33} is weak. In chlorine the ground state γ-ray and those produced by transitions from the capturing state to the first six excited states in Cl^{36} are of comparable intensity. In potassium there are relatively strong transitions to the ground state and to the second excited state of K^{40}. Some of the γ-rays produced by potassium can be identified with transitions in K^{42}, the excited state at 2.3 Mev being favored above all others. Three very weak γ-rays have been detected with energies above that to be expected from capture in K^{39} and K^{41}. These γ-rays do not appear to be due to impurities. It is possible that they arise from the capture of neutrons by K^{40} and, if this hypothesis is correct, that isotope must have a large capture cross section for thermal neutrons. In calcium the greater part of the γ-ray spectrum can be fitted into the energy level system of Ca^{41}. No γ-ray corresponding to the ground-state transition in Ca^{41} was detected.

I. INTRODUCTION

THE present paper contains the results of a study of the neutron capture γ-rays produced by a group of adjacent elements, *viz.*, phosphorus, sulfur, chlorine, potassium, and calcium. Because of the technical difficulties involved, no attempt has been made to study the neutron capture γ-rays produced by argon. A pair spectrometer has been used in these investigations; a description of the experimental arrangement is given in an earlier paper.[1] The relative intensities of the γ-rays from a particular sample were determined from the peak coincidence counting rates by using a calculated curve for the variation with energy of the counting efficiency of the spectrometer. For each spectrum the absolute intensity of one of the strong γ-rays was measured by comparing its peak coincidence counting rate with that of the 9.0-Mev γ-ray produced by neutron capture in nickel, using an intimate mixture of weighed amounts of the sample material and nickel sesquioxide. The absolute intensity of the nickel γ-ray in photons per capture was determined in a separate experiment. A more detailed description of the intensity measurements is given in the previous paper,[1] where the results indicate that the intensities of the γ-rays between 3 and 6 Mev are overestimated by this method. It seems probable that the theoretical counting efficiency may be incorrect in this energy range. A full description of the method of energy measurement will be published elsewhere.

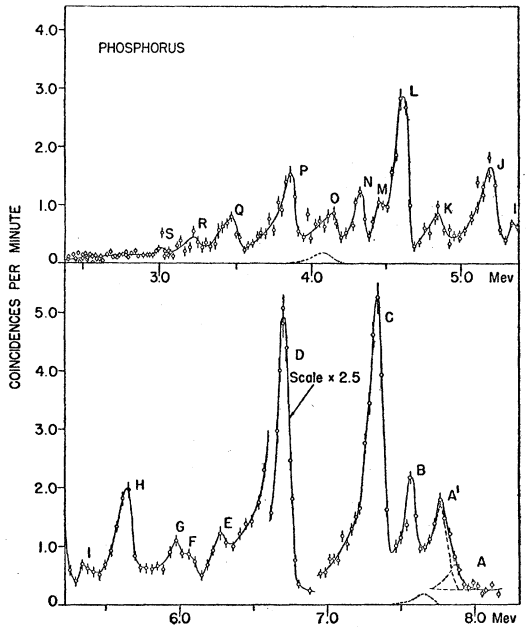

FIG. 1. Coincidence spectrum produced by phosphorus. Line width: 130 kev. The dotted lines represent the contribution to the spectrum from bismuth and aluminum radiations arising from the experimental arrangement.

II. PHOSPHORUS

The phosphorus source consisted of 940 grams of chemically pure red phosphorus enclosed in a container with Bakelite ends. The coincidence spectrum was studied from 2.5 to 10.0 Mev. The results up to 8.0 Mev are shown in Fig. 1. No coincidences were recorded above the background counting rate between 8.0 and 10.0 Mev. In this and the other coincidence spectra presented in this paper the abscissas of the curves are scaled so that the extrapolated end points of the peaks correspond to the energies of the γ-rays.

The end point of the peak of highest energy is at 7.94 ± 0.03 Mev. This γ-ray was not detected in a preliminary study[2] because the peak was masked by unwanted aluminum radiations. Its energy is in agreement with the binding energy of P^{32} calculated from the Q value of the $P^{31}(d,p)P^{32}$ reaction. The width of this peak and the slope of the high energy edge suggest that two γ-rays contribute to it. In an unresolved peak produced by two γ-rays of very nearly equal energies, the position of the end point of the higher

* Now at McMaster University, Hamilton, Ontario.
[1] Kinsey, Bartholomew, and Walker, Phys. Rev. 83, 519 (1951).
[2] Kinsey, Bartholomew, and Walker, Phys. Rev. 78, 481 (1950).

TABLE I. Energies and intensities of the phosphorus capture γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures
A	7.94±0.03	0.5
A'	7.85 0.05	1.5
B	7.62 0.03	2
C	7.42 0.03	7
D	6.76 0.03	24
E	6.33 0.03	0.7
F	6.14 0.03	1.5
G	6.02 0.04	1.5
H	5.71 0.03	6
I	5.41 0.03	2
J	5.27 0.03	8
K	4.92 0.03	4
L	4.68 0.03	26
M	4.49 0.03	4
N	4.38 0.03	11
O	4.20 0.03	7
P	3.92 0.03	25
Q	3.55 0.03	22
R	3.28 0.04	9
S	3.04 0.04	7

energy γ-ray will not be appreciably affected by the presence of the other γ-ray, and the separate contributions of the peaks to the observed coincidence spectrum can usually be estimated. The extrapolated end point of a homogeneous peak in this energy region falls approximately 80 kev above the energy corresponding to the maximum counting rate, and the peak width at half-maximum is approximately 130 kev. These values were used to determine the shape of peak A, and peak A' was obtained by subtraction. The background counting rate underlying the two peaks is derived mainly from the tails of the peaks B and C and is due to scattering of electrons by the walls of the spectrometer. It has a shape close to that shown by the almost horizontal broken line. The end point of peak A' falls at 7.85±0.05 Mev and, as shown below, corresponds to a transition from the capturing state to the first excited state of P^{32}. The energies and absolute intensities of the γ-rays are given in Table I. The absolute intensities were determined by the nickel method[1] by comparison of the intensity of the 9.0-Mev nickel γ-ray with that of the γ-ray D, assuming that the capture cross section of phosphorus for thermal neutrons is 193±7 mb;[3] the absolute intensities of the other γ-rays were determined relative to that of D. The corrected γ-ray spectrum is shown in Fig. 2. The ordinates $\nu(E)$, representing the number of photons produced per capture per unit energy range, were obtained by application of Eq. (3), reference 1.

The $P^{31}(d,p)P^{32}$ reaction was studied by Allen and Rall[4] who found the Q value of the most energetic proton group to be 5.52±0.10 Mev. With the deuteron binding energy of 2.226±0.003 Mev[5] it follows that the binding energy of P^{32} is 7.75±0.10 Mev. A more recent value for the energy balance has been obtained by Strait and his collaborators;[6] it is 5.704±0.008 Mev, whence the corresponding binding energy of P^{32} is 7.930±0.009 Mev. The energy of the γ-ray A is in excellent agreement with the latter value.

Some of the γ-rays have been fitted to the level scheme shown in Fig. 3. This is drawn to conform to the results of Van Patter and Endt[7] which are in good agreement with earlier measurements by Allen and Rall. In this diagram γ-rays for which the assignment seems certain have been drawn as full lines. Those for which the position in the scheme is uncertain or ambiguous are drawn in broken lines. Strong γ-rays are drawn in heavy lines. The level at 3.141 Mev is drawn as a dotted line because the existence of a level at this energy is indicated but not definitely established by the measurements on the (d,p) reaction. The level energies on the right are the results of Van Patter and Endt; those on the left are obtained by subtracting the γ-ray energies from Table I from the 7.930±0.009-Mev binding energy.

The identification of the γ-rays A and A' has already been discussed. The difference between the binding energy and the energy of the strong γ-ray D is 1.17 ±0.03 Mev in agreement with the energy of the third excited state found by Van Patter and Endt. The equally intense γ-ray L appears to lead to an excited state at 3.25±0.03 Mev and may be in cascade with the ill-defined γ-ray R, since the sum of their energies is 7.96±0.05 Mev. The intensity of R is only one-third of that of L; the excitation of the 3.25-Mev state, therefore, is more frequent than the emission of the γ-ray R, and consequently, softer radiation must also be emitted producing excited states at lower energies. The difference energy corresponding to the γ-ray P is 4.01±0.03 Mev which suggests that it corresponds to a transition to the fourteenth excited state. Among the weaker radiations the γ-ray C clearly corresponds to a

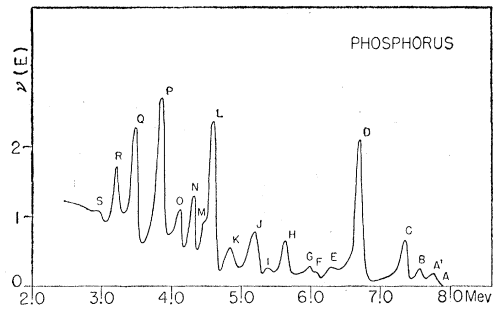

FIG. 2. Corrected γ-ray spectrum from phosphorus.

[3] F. C. W. Colmer and D. J. Littler, Proc. Phys. Soc. (London) **63**, 1175 (1950); H. Pomerance, Phys. Rev. **83**, 641 (1951), has obtained the value 0.15 barn (±10 percent). We choose the result with the lowest quoted error.

[4] R. C. Allen and W. Rall, Phys. Rev. **81**, 60 (1951).

[5] R. C. Mobley and R. A. Laubenstein, Phys. Rev. **80**, 309 (1950).

[6] Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951).

[7] We are indebted to Dr. D. M. Van Patter and Dr. P. Endt for the privilege of quoting these results before publication.

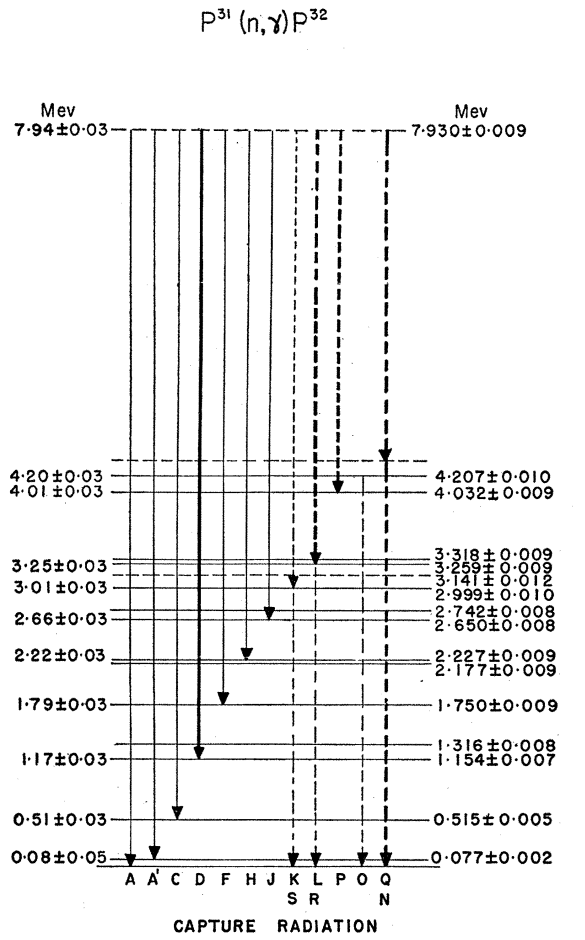

FIG. 3. Decay scheme for phosphorus. The energy levels are drawn to scale according to the results of Van Patter and Endt right-hand figures (see reference 7). The energies of these levels, obtained by subtracting the γ-ray energies from the neutron binding energy, are given on the left.

transition to the second excited state at 0.515 Mev and, the energy of H is equal to that of a transition to the 2.227-Mev level. The γ-ray J seems to correspond to a transition to the eighth excited state at 2.650 Mev. The

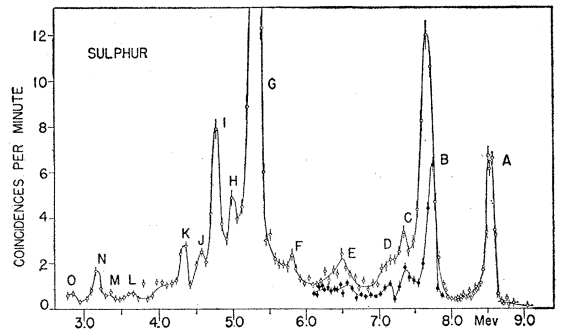

FIG. 4. Coincidence spectrum produced by sulfur. Line width: 130 kev. The results obtained using a container with Dural end walls are shown by open circles; those obtained in similar conditions with a container with Bakelite ends are shown by full circles.

difference between the binding energy and the energy of the γ-ray K is 3.01±0.03 Mev which is equal to the energy of the tenth excited state. The γ-ray S, the existence of which is not well established in the coincidence spectrum, may correspond to a transition from this state to the ground state in cascade with K. The difference energy for the γ-ray F is 1.79±0.03 Mev, and this suggests that F is emitted in a transition from the capturing state to the fifth excited state. The energy of the γ-ray O agrees with the energy of the fifteenth excited state. The strong γ-rays N and Q have a total energy of 7.93±0.04 Mev and may be in cascade. The weaker γ-rays B, E, G, I, and M cannot be identified with transitions from the capturing state to any of the known states of P^{32}. The γ-ray B may be due to a transition from a higher level to the ground state.

Both the γ-rays J and L in Fig. 3 correspond to transitions from the capturing state to the lowest

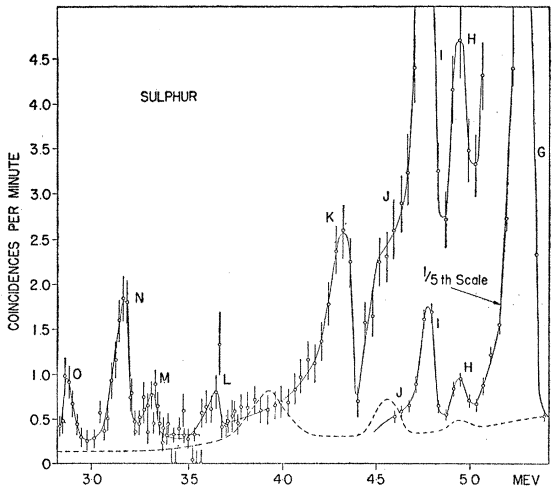

FIG. 5. Detail of coincidence spectrum from sulfur between 2.7 and 5.3 Mev. The contribution of the Dural container to this spectrum is shown by the dotted line.

member of a pair of levels. The doublet separation for the levels corresponding to J is 92 kev which is less than the resolution of the apparatus. The peak J in Fig. 1 is wider than that expected for a homogeneous γ-ray, and this fact suggests that a γ-ray corresponding to a transition to the higher level of the pair may be present. Referring now to the γ-ray L, it is not possible to determine whether a γ-ray is present which corresponds to a transition to the higher component of the doublet, *viz.*, the level at 3.318 Mev, for the separation of the level doublet is only about 60 kev. The peak H may also be complex since the 50-kev separation of the 2.227 and 2.177-Mev levels is small. There is no evidence for a transition to the level at 1.316 Mev though a weak γ-ray may be obscured by the tail of peak D.

If the numbers of photons per capture, which have been ascribed to γ-rays emitted by the capturing state,

are added together, it will be seen that the total exceeds unity by about 40 percent. If the product of the intensities and the energies of the γ-rays listed in Table I are added together, the result (8.2 Mev) is higher than the binding energy of P^{32}. A lower value is to be expected because low energy γ-rays are certainly radiated in the capture process and are not detected. An even higher value (11 Mev) is obtained by integrating the γ-ray spectrum of Fig. 2. Such discrepancies are probably caused by an overestimate of the intensities of γ-radiation between 3 and 6 Mev and have been discussed in a previous paper.[1]

III. SULFUR

The spectrum of sulfur was originally investigated using a sample consisting of 920 grams of chemically pure sulfur cast into a Dural container with Dural end walls. Under these conditions the spectrum was surveyed between 2.7 and 12.0 Mev. A portion of this spectrum is shown in Fig. 4 (open circles). No coincidence counting rate above that of the background was found above 9.0 Mev. In addition, the spectrum was examined in detail between 2.7 and 5.3 Mev (Fig. 5). In Fig. 4, the coincidence peak B includes a contribution from the 7.72-Mev γ-ray produced by the aluminum in the container. In order to obtain a more accurate measurement of the sulfur spectrum near 7 Mev, further measurements were made using a container with Bakelite ends and the results of these measurements are also plotted in Fig. 4 (full circles). The two curves in Fig. 4 have been adjusted using peak G, so that they represent the same neutron capturing rate for the two samples; the difference between them near 7 Mev, therefore, represents the contribution from the spectrum of the Dural container. The contribution of the container to the spectrum at lower energies, which is shown by the broken curve in Fig. 5, was determined in separate measurements with an empty container.[1]

TABLE II. Energies and intensities of sulfur capture γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures
A	8.64±0.02	3
B	7.78 0.03	4
C	7.42 0.03	0.7
D	7.19 0.03	0.5
E	6.64 0.03	0.7
F	5.97 0.06	1
G	5.43 0.02	84
H	5.03 0.06	5
I	4.84 0.06	20
J	4.60 0.06	5
K	4.38 0.03	13
L	3.69 0.05	5
M	3.36 0.05	7
N	3.21 0.03	30
O	2.94 0.05	19

The energies and intensities of the sulfur capture γ-rays are listed in Table II. The absolute intensity of the γ-ray G was determined by the nickel method, and the intensities of the remaining γ-rays were determined relative to that of G. The capture cross section of sulfur was assumed to be 0.49 barn.[3] The corrected γ-ray spectrum of sulfur is given in Fig. 6.

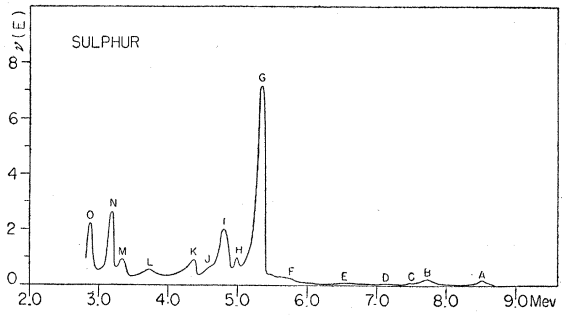

FIG. 6. Corrected γ-ray spectrum from sulfur.

The most energetic γ-ray A is produced in a direct transition to the ground state when a neutron is captured in S^{32}. The energy of this γ-ray, 8.64±0.02 Mev, is in agreement with the neutron binding energy of S^{33}, a quantity which may be deduced from the energy balance of the $S^{32}(d,p)S^{33}$ reaction. For the Q of this reaction Davison[8] obtained 6.48±0.11 Mev. More recently Strait and his collaborators[6] have obtained 6.422±0.011 Mev which corresponds to a neutron binding energy of 8.648±0.012 Mev in good agreement with the energy of the γ-ray A.

For the Q of the $S^{33}(d,p)S^{34}$ reaction Davison[8] found 8.67±0.25 Mev whence the binding energy of S^{34} is 10.90±0.25 Mev. The binding energy of the other isotopes of sulfur can be calculated from the mass values collected by Low and Townes.[9] These binding energies together with the abundances and contributions[10] to the total absorption cross section for the sulfur isotopes are summarized in Table III.

Neither the direct transition to the ground state in S^{34} nor the transition to the excited state at 0.82 Mev[8] was detected for, as already mentioned, no coincidence

TABLE III. Abundances, cross sections, and neutron binding energies of the sulfur isotopes.

Target nucleus	Abundance percent	Contribution to total cross section in barns	Reference	Binding energy of product nucleus in Mev	Reference
S^{32}	95.1	0.49	a	8.648±0.012	d
S^{33}	0.74			10.90 0.25	e
S^{34}	4.2	0.011	b	7.16 0.45	f
S^{36}	0.016	2×10^{-5}	c	5.78 0.60	f

[a] See reference 3.
[b] See reference 10.
[c] *Nuclear Data* (National Bureau of Standards Circular No. 499, Washington, D. C., 1950).
[d] See reference 6.
[e] See reference 8.
[f] See reference 9.

[8] P. W. Davison, Phys. Rev. **75**, 757 (1949).
[9] W. Low and C. H. Townes, Phys. Rev. **80**, 608 (1950).
[10] Seren, Friedlander, and Turkel, Phys. Rev. **72**, 888 (1947).

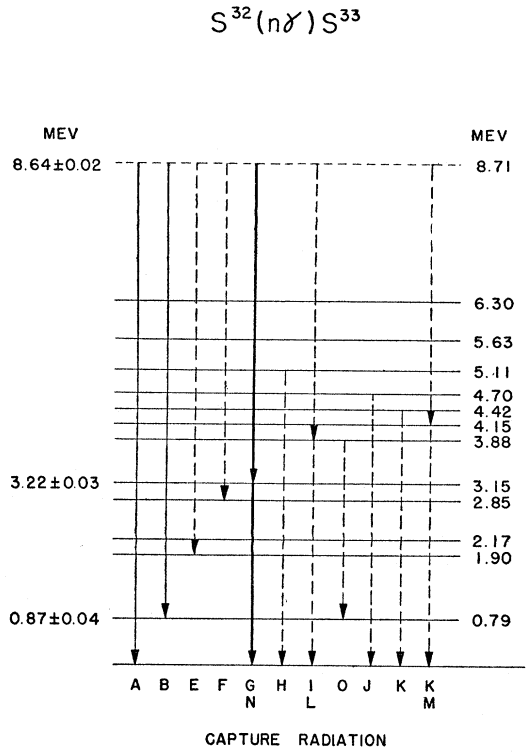

FIG. 7. Decay scheme for sulfur. The figures on the right are the positions of the energy levels determined by Davison (see reference 8); those on the left were obtained from the subtraction of the γ-ray energies from the neutron binding energy.

peaks were observed above 9 Mev. Alburger[11] has measured the γ-radiation emitted in the reaction $P^{31}(\alpha,p)S^{34}$ and found γ-rays with energies of 2.55 and 4.1 Mev. If these energies are those of two of the excited states in S^{34}, we might expect neutron capture γ-rays with energies of 8.3 and 6.8 Mev. No positive identification of such radiation can be made with any of the γ-rays of Table II.

The weak γ-rays C and D both have energies which fall within the probable error of the binding energy of S^{35} given in Table III and, therefore, either one may represent the ground state transition in that isotope. Until more accurate values of the γ-ray energies and of the binding energy of S^{35} are determined or until sulfur enriched in S^{34} is available, it will not be possible to determine if either of these γ-rays are produced by that isotope.

In view of the very small fraction of the total cross section contributed by S^{36} a 5.8-Mev ground-state γ-ray from S^{37} would not be detected in the presence of stronger γ-rays in its vicinity.

Some of the γ-rays listed in Table III can be explained in terms of capture by S^{32}, and an attempt has been made to fit most of them into a decay scheme in Fig. 7, which has been derived from the level energies obtained by Davison.[8] Those γ-rays whose positions in the scheme are subject to little doubt are indicated by full lines while those whose assignment is only tentative are shown by broken lines. The level energies found by Davison are given on the right of the decay scheme. The level energies on the left are obtained by subtracting γ-ray energies in Table II from the neutron binding energy in S^{33}, *viz.*, 8.648±0.012 Mev.

The two strongest γ-rays G and N appear to be in cascade, for their energies add up to 8.64±0.04 Mev in excellent agreement with the energy of the γ-ray A. In addition, their intensities, which are comparable, suggest that they are related in this manner. The energy of N is very close to that of the 3.15-Mev level in S^{33}, and it seems probable that N represents the transition between this state and the ground state. However, the γ-ray G is stronger than N, and this indicates that softer radiations also are emitted in transitions between the 3.15-Mev level and the levels lying between it and the ground state.

It is worth noting that the 3.15-Mev level, which is strongly excited in the neutron capture process, is also one of the levels most strongly excited in the (d,p) reaction. In a previous paper[1] we have noted that a similar phenomenon occurs in Si^{29}.

The assignment of the γ-ray B is clear for its energy corresponds to the formation of an excited state at 0.87±0.04 Mev, in fair agreement with Davison's first excited state at 0.79 Mev.

The remaining γ-rays are less certainly identified. Of the stronger γ-rays I, O, and L can be connected with the excited state near 3.88 Mev in the way shown in Fig. 7. Peak L is not well defined and may correspond to more than one γ-ray. The width of the peak at K is also large and several γ-rays may contribute

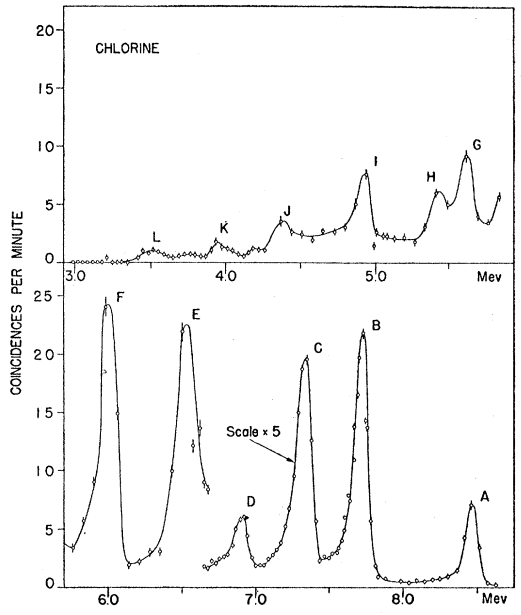

FIG. 8. Coincidence spectrum produced by chlorine. Line width: 130 kev.

[11] D. E. Alburger, Phys. Rev. **73**, 1014 (1948).

to it. A part of K could represent a transition to the level at 4.15 Mev or again another from the level at 4.42 Mev to the ground state.

Of the weaker γ-rays C and D, if they belong to S^{33}, must arise from hitherto unknown excited states at 7.42 and 7.19 Mev, respectively. Alternatively, they may arise from capture in S^{33}, for little is known about the excited states of S^{34}, or as we have already mentioned, one of them might represent the ground state transition in S^{35}. The γ-rays E and F apparently are complex, and as they are assigned in Fig. 7, their emission produces the excited states at 2.00 ± 0.04 and 2.68 ± 0.07 Mev, respectively, in rather poor agreement with Davison's values of 1.90 and 2.85 Mev. A very weak γ-ray corresponding to a transition to the level at 2.17 Mev may be present in the tail of the peak E. Peak J may be due entirely to radiation from the Dural container.

The total energy radiated from sulfur, according to the results of Table II, is 8.7 Mev which is equal to the binding energy of S^{33}. As in the case of phosphorus, a value lower than the binding energy is to be expected. The value obtained from the integral of the γ-ray spectrum (Fig. 6) is 13 Mev.

IV. CHLORINE

The chlorine sample consisted of 810 grams of chemically pure hexachlorobenzene (C_6Cl_6) enclosed in a Dural container with Dural ends. The neutron capture cross section of chlorine (32 barns) is much greater than that of carbon so that the carbon capture γ-rays do not appreciably affect the chlorine spectrum. The γ-rays caused by neutron capture in the Dural of the sample container are negligible for the same reason. Furthermore, since the contribution to the total cross section by Cl^{37} is only 0.14 barn,[10] the γ-ray spectrum observed is due largely to capture in the single isotope Cl^{35}. A sample consisting of a mixture of weighed amounts of hexachlorobenzene and nickel sesquioxide was used in an additional experiment to obtain the absolute intensities of the chlorine γ-rays.

The coincidence spectrum was measured from 2.5 to 9.5 Mev with a resolution of 130 kev. No γ-rays were detected below 3.3 Mev or above 8.6 Mev. The results

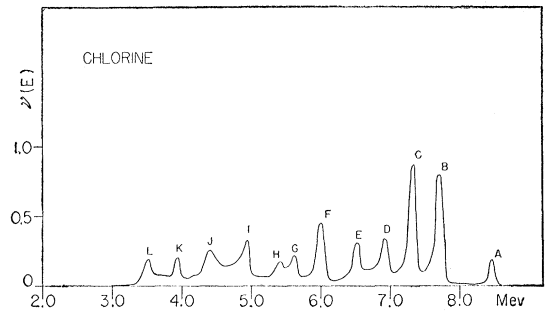

FIG. 9. Corrected γ-ray spectrum from chlorine.

TABLE IV. Energies and intensities of chlorine capture γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures
A	8.56 ± 0.03	3
B	7.77 0.03	10
C	7.42 0.03	8
D	6.98 0.03	1
E	6.62 0.06	4
F	6.12 0.03	6
G	5.72 0.03	2
H	5.51 0.03	1
I	5.01 0.03	4
J	4.46 0.04	2
K	4.06 0.04	3
L	3.62 0.05	2

obtained are shown in Fig. 8. The corrected γ-ray spectrum is given in Fig. 9.

The neutron binding energy of Cl^{36}, determined from the results of Shrader and Pollard[12] on the energy balance of the (d,p) reaction, is 8.54 Mev. This figure is in agreement with that derived from recent work by Ennis,[13] *viz.*, 8.49 Mev. Both are in agreement with the energy of the most energetic γ-ray at 8.56 ± 0.03 Mev (peak A), which can therefore be identified as the ground-state γ-ray in Cl^{36}.

Shrader and Pollard also report the presence of two levels at 0.96 and 4.81 Mev. The positions of other excited states in Cl^{36} have been observed by Ennis.[14] No other information concerning the excited states of Cl^{36} is available, and consequently, the positions of some of the capture γ-rays in the decay scheme cannot be determined with certainty. The energies of the γ-rays and their intensities determined by the nickel calibration method are given in Table IV. A tentative decay scheme for some of these radiations is given in Fig. 10. The level energies given on the left of the diagram are derived from the γ-ray measurements with the help of the results obtained by Ennis. The energies of the γ-rays B and C correspond to transitions from the capturing state to low-lying states at 0.79 and 1.14 Mev. These values bracket the 0.96-Mev energy level obtained by Shrader and Pollard. The γ-rays D, E, F, and G have energies which show that they correspond to transitions to the third, fourth, fifth, and sixth excited states found by Ennis, and H could be the γ-ray emitted by his tenth state. The total energy of γ-rays K and J is 8.52 ± 0.06 Mev; this quantity is close to the binding energy of Cl^{36} and suggests that these γ-rays may be in cascade. As indicated in Fig. 10, the order of their emission is unknown. The γ-ray I corresponds to a transition to an excited state at 3.55 Mev. The γ-rays I and L may be in cascade for the sum of their energies is 8.63 ± 0.06 Mev.

For the reaction $Cl^{37}(d,p)Cl^{38}$ Shrader and Pollard[12] found Q values of 4.02, 3.02, and 2.10 Mev. We might

[12] E. F. Shrader and E. Pollard, Phys. Rev. **59**, 277 (1941).
[13] W. W. Ennis, Phys. Rev. **82**, 304 (1951).
[14] We are indebted to Dr. W. W. Ennis for sending us these later results before publication.

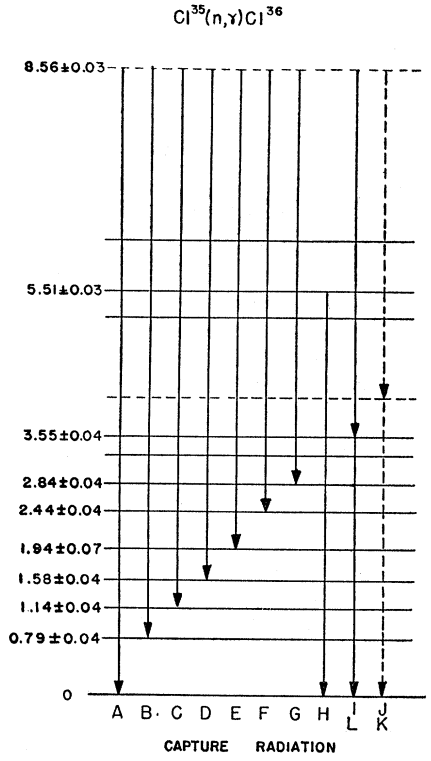

FIG. 10. Decay scheme for chlorine. The figures on the left are the positions of the energy levels of Cl^{36} obtained by subtracting the energies of the γ-rays from the neutron binding energy.

expect to observe, therefore, a ground-state γ-ray with an energy of 6.25 Mev and two others with energies of 5.25 and 4.33 Mev. The first has an energy close to that of the γ-ray F, but the intensity of that γ-ray is much greater than the neutron capture rate of Cl^{37}, and most of this peak therefore is a result of capture by Cl^{35}. Even if all the captures in Cl^{37} produced the ground-state γ-ray, its peak intensity[15] would be only some 3 percent of that of F. The other two γ-rays, if present, might be discernable in the spectrum between the peaks K and H if a much higher resolution were available.

The total energy radiated in the γ-rays listed in Table IV is only 3.0 Mev. This small amount, less than half of the binding energy, is surprising in view of the much larger values obtained for lighter elements. The integrated energy emitted is 5.8 Mev which again is much lower than the binding energy. As pointed out above, our estimates for these quantities are, for instrumental reasons, usually too high. Probably less energetic γ-rays are emitted in cascading processes which, on account of their low energy, escape detection. If this is the correct explanation, it is in accord with the measurements of Muehlhause[16] on the multiplicity of neutron capture γ-rays; for chlorine he obtains 3.1 γ-rays per capture, a rather high result for elements in this part of the periodic table. Numerous low energy γ-rays have been detected recently by Hamermesh and Hummel,[17] but their significance in relation to the decay scheme is not clear.

V. POTASSIUM

In the first survey experiments with potassium, the source consisted of one kilogram of the anhydrous carbonate enclosed in a Dural container. In more recent measurements a similar quantity of the carbonate was placed in a Dural container with Bakelite ends. The results of the latter measurements, obtained with a resolution of 170 kev, are shown in Figs. 11 and 12, and the energies and intensities of the γ-rays are listed in Table V. The absolute intensities were obtained by comparing the intensity of the 9.0-Mev nickel γ-ray with that of the γ-ray F, using a separate sample of potassium carbonate mixed with nickel sesquioxide. The corrected γ-ray spectrum is shown in Fig. 13.

Potassium possesses two stable isotopes K^{39} and K^{41} for which the abundances are 93.2 and 6.8 percent. According to Colmer and Littler[3] the total capture cross section is 1.89 ± 0.06 barns, and the contribution to this cross section caused by K^{41} is 67 mb.[10] The naturally occurring radioactive isotope K^{40} is present in ordinary potassium only to the extent of 0.01 percent, and its contribution to the cross section is unknown.

The positions of the excited states of the potassium isotopes K^{40} and K^{42} have been determined by Sailor[18] from a study of the (d,p) reaction using the separated isotopes K^{39} and K^{41} as targets. The Q value of the highest energy group of protons from the reaction $K^{39}(d,p)K^{40}$ was found to be 5.48 ± 0.08 Mev, whence, if this group produces the ground state, it follows that the binding energy of a neutron in K^{40} is 7.71 ± 0.08 Mev. The energy of the γ-ray B is 7.77 ± 0.03 Mev and is in good agreement with this value. It does not follow that this γ-ray should be identified with the direct transition to the ground state in K^{40} for γ-rays with a

TABLE V. Energies and intensities of potassium capture γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures
A''	9.28±0.05	0.2
A'	8.48 0.05	0.2
A	8.03 0.05	0.5
B	7.77 0.03	11
C	7.20 0.07	0.5
D	6.98 0.03	2
E	6.30 0.05	0.5
F	5.75 0.03	18
G	5.38 0.03	6
H	5.01 0.03	6
I	4.39 0.03	10
J	4.18 0.05	6
K	3.92 0.05	5
L	3.67 0.05	8

[15] In another communication, reference 2, we have incorrectly identified the γ-ray F with this ground state γ-ray.
[16] C. O. Muehlhause, Phys. Rev. **79**, 277 (1950).
[17] B. Hamermesh and V. Hummel, Phys. Rev. **83**, 663 (1951).
[18] V. L. Sailor, Phys. Rev. **77**, 794 (1950).

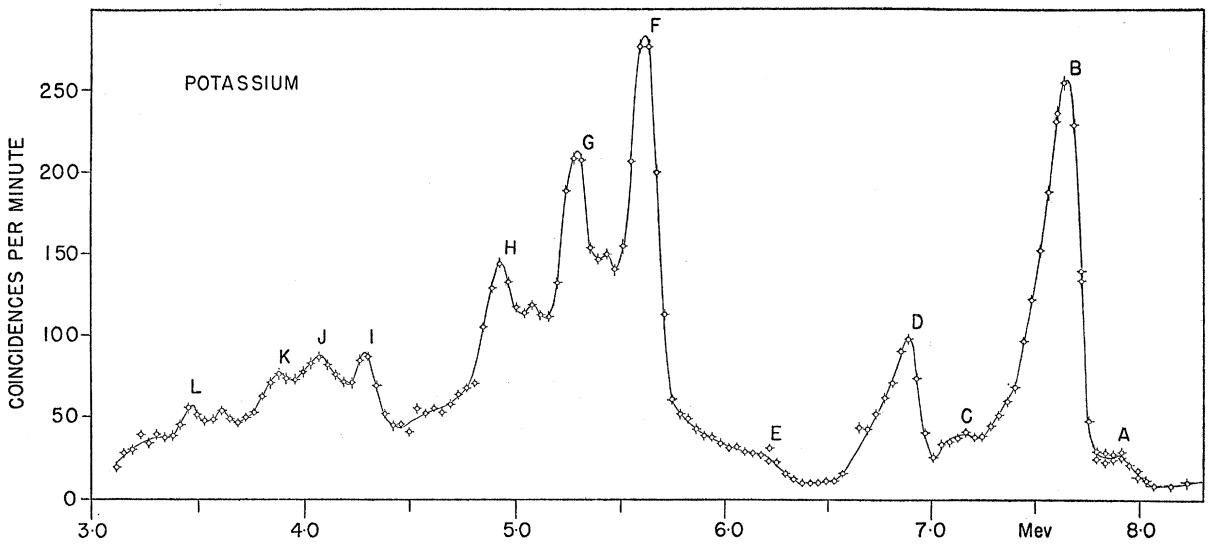

FIG. 11. Coincidence spectrum produced by potassium. Line width: 170 kev.

greater energy have been detected (Fig. 12). However, an independent check on the neutron binding energy of K^{40} in agreement with these values can be obtained from recent mass-spectrographic results and the energy of the β-decay of that isotope. From the results of Nier and Roberts,[19] we have 0.32 ± 0.08 mmu for the mass difference $Ca^{40}-A^{40}$. For the energy of the decay of K^{40} we take the mean value 1.35 ± 0.02 Mev,[20] which is equivalent to 1.45 ± 0.03 mmu for the mass difference $K^{40}-Ca^{40}$. Hence, the difference $K^{40}-A^{40}$ is 1.77 ± 0.09 mmu. The mass of A^{40} is 39.97524 ± 0.00003 amu.[21] Therefore the mass of K^{40} is 39.97701 ± 0.00010 amu. For K^{39} Collins, Nier, and Johnson[22] obtained a packing fraction of $-6.12\pm0.02\times10^{-4}$ which corresponds to a mass of 38.97613 ± 0.00008 amu. With the neutron mass of 1.008982 ± 0.000003 amu given by Li, Whaling, Fowler, and Lauritsen,[23] we calculate the neutron binding energy of K^{40} to be 8.10 ± 0.14 mmu or 7.54 ± 0.13 Mev. This result agrees with that obtained from the (d,p) reaction within the combined probable errors.

The highest Q value found by Sailor for the reaction $K^{41}(d,p)K^{42}$ is 5.12 ± 0.10 Mev, whence if we assume that the ground-state group was observed, it follows that the neutron binding energy of K^{42} is 7.35 ± 0.10 Mev. This result can also be checked by calculation from mass-spectrographic values. From the results of Collins *et al.*[22] the mass of K^{41} is 40.97499 ± 0.00008 amu, and the mass of Ca^{42} is 41.97228 ± 0.00008 amu. From the β-decay of K^{42} we have $K^{42}-Ca^{42}=3.83\pm0.20$ mmu.[24] Hence we calculate the mass of K^{42} to be 41.97611 ± 0.00022 amu and the neutron binding energy of K^{42} to be 7.86 ± 0.24 amu or 7.32 ± 0.22 Mev in good agreement with that derived from the results of Sailor. The energy of the partially resolved peak at C, Fig. 11, is 7.20 ± 0.07 Mev and may represent therefore the ground-state transition in K^{42}.

From the mass values aforementioned we can also calculate the neutron binding energy of K^{41}. It is 10.24 ± 0.13 Mev.

Figure 12 contains clear evidence for a γ-ray A at 8.03 ± 0.05 Mev and for two others: A' at 8.48 ± 0.05 Mev and A'' at 9.28 ± 0.05 Mev. The width of A' is excessive, and this γ-ray is certainly complex. All of these γ-rays have energies which exceed the neutron binding energies of K^{40} and K^{42} calculated above by a margin considerably greater than the combined probable errors, and none of them correspond to the γ-rays emitted by any of the forty-odd elements which we have studied and which could possibly be present as impurities. A spectroscopic analysis indicated that the sample material contained Ca, Cu, and Mg in concentrations of only one part per million and no other detectable impurities. It seems possible, therefore, that these γ-rays are caused by capture in K^{40}, for if the isotopic capture cross section of K^{40} for thermal neu-

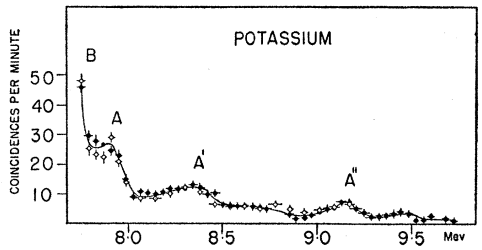

FIG. 12. Upper part of the coincidence spectrum of potassium. The full and open circles represent the results of two separate experiments.

[19] A. O. Nier and T. R. Roberts, Phys. Rev. **81**, 507 (1951).
[20] D. E. Alburger, Phys. Rev. **79**, 236 (1950); Bell, Weaver, and Cassidy, Phys. Rev. **77**, 399 (1950); L. Feldman and C. S. Wu, Phys. Rev. **81**, 298 (1950).
[21] A. O. Nier, Phys. Rev. **81**, 624 (1951).
[22] Collins, Nier, and Johnson, Phys. Rev. **83**, 228 (1951).
[23] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).
[24] K. Siegbahn, Arkiv Mat. Astron. Fysik **34B**, No. 4 (1947).

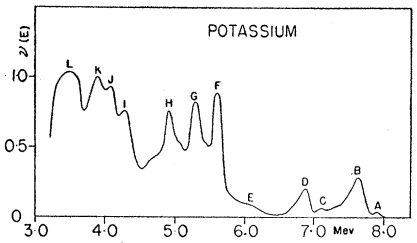

FIG. 13. Corrected γ-ray spectrum from potassium.

trons were 100 times greater than that of natural potassium, about one percent of the captures would be due to this isotope, and γ-rays with energies above 8.0 Mev and intensities above 10 percent per capture in K^{40} might be detected. Excited states of K^{41} are known at 1.34±0.15, 3.10, and 4.40 Mev.[25] If capture in K^{40} occurred to an appreciable extent, a γ-ray with an energy 1.34 Mev less than the binding energy, i.e., 8.9±0.2 Mev, might be observed. This energy is close to that of the γ-ray A''. However, such an assignment is not very convincing in view of the large probable errors associated with both the binding energy of K^{41} and the energy of the γ-ray A''. Although the coincidence spectrum has been explored up to 11 Mev, no evidence was found for the emission of a γ-ray near 10.3 Mev produced by the excitation of the ground state transition in K^{41}.

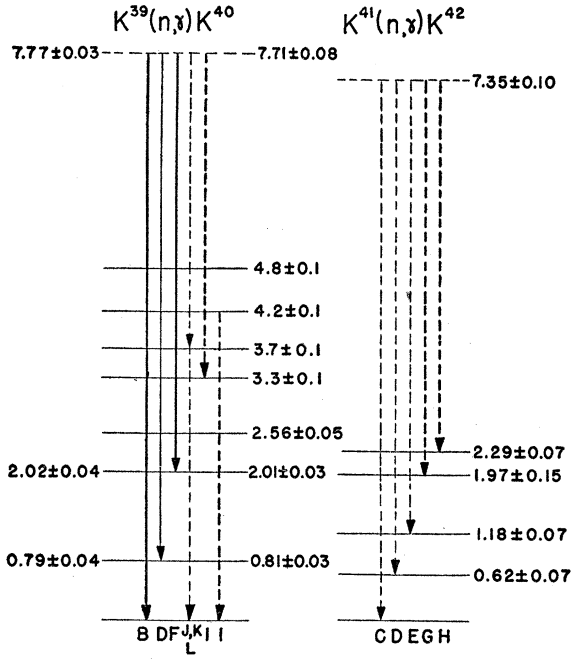

FIG. 14. Decay scheme for potassium. The figures on the right are the positions of the energy levels found by Sailor (see reference 18); those on the left were obtained by subtracting the γ-ray energy from the neutron binding energy.

[25] Bleuler, Boltmann, and Zünti, Helv. Phys. Acta **19**, 419 (1946); D. C. Worth, Phys. Rev. **78**, 378 (1950).

Most of the remaining γ-rays can be identified with transitions from the capturing state to energy levels found by Sailor. A tentative decay scheme is shown in Fig. 14, in which the positions of the energy levels found by Sailor are shown on the right and those calculated from the capture γ-rays, on the left. The γ-ray D, which is complex, corresponds to a transition to the first excited state of K^{40}, the strong γ-ray F to the second state. This state is again among those most strongly excited in the (d,p) reaction. The γ-ray I may represent a transition to the fourth excited state at 3.3 Mev although its energy is also in agreement with that of a transition from the 4.2-Mev state to the ground state. Either of the γ-rays J and K could correspond to the transition from the capturing state to the level at 3.7 Mev. As already mentioned, the

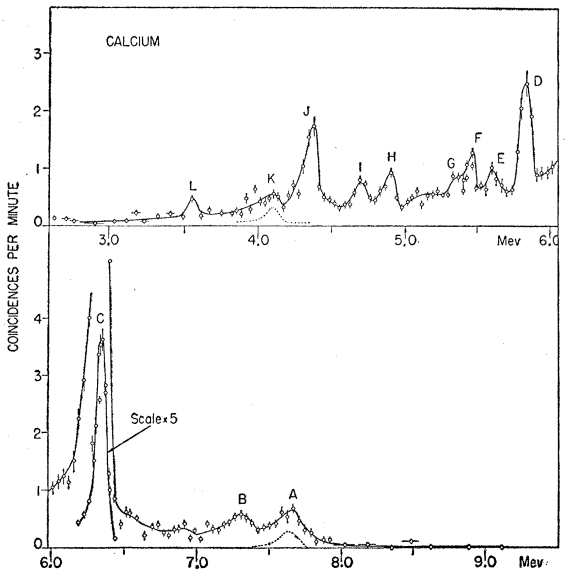

FIG. 15. Coincidence spectrum produced by calcium. Line width: 130 kev. The dotted lines represent the contributions caused by bismuth and aluminum radiations.

γ-ray C may be produced in the ground-state transition in K^{42}. The γ-ray E, 6.30±0.05 Mev, is in rough agreement with the energy difference 6.17±0.18 Mev between the capturing state and the second excited state in K^{42}. The γ-rays G and H are in good agreement with the transition energies from the capturing state to the third and fourth excited states of K^{42}. The γ-ray representing the transition to the first excited state of K^{42} is probably responsible for part, at least, of the excessive width of the peak D.

The γ-rays listed in Table V and shown in Fig. 14 only account for a fraction of the total captures in potassium. The sum of the intensities of the γ-rays which are probably radiated from the capturing state, i.e., all except I and L, amount to 60 percent of the rate of neutron capture and the total energy radiated per capture by the γ-rays of Table V is 3.8 Mev. These

low values merely indicate that the γ-rays, which appear resolved distinctly in Fig. 11, form only a part of the total radiation emitted, for when the unresolved radiations are taken into account by integration, the result is 10.1 Mev which is somewhat higher than the binding energy in K^{40}.

The γ-rays, which have been assumed to follow capture in K^{41}, account for about 13 percent of the total neutron capture rate. This fraction is three times greater than that to be expected from the ratio of the capture cross sections of the two isotopes. The discrepancy suggests that part of the poorly resolved peaks at *G* and *H*, which have been assigned to capture by K^{41}, must in fact be produced by capture in K^{39}.

VI. CALCIUM

The calcium capture γ-rays were obtained from a sample of pure calcium oxide contained in a Dural container with Bakelite ends. The spectrum was investigated up to 11 Mev with a resolution of 130 kev. No γ-ray was found with an energy greater than 7.83 Mev.

TABLE VI. Energies and intensities of calcium capture γ-rays.

γ-ray	Energy in Mev	Intensity in photons per 100 captures
A	7.83±0.05	1
B	7.43 0.05	1.4
C	6.42 0.03	83
D	5.89 0.03	11
E	5.66 0.06	3
F	5.49 0.05	4
H	4.95 0.03	8
I	4.76 0.03	6
J	4.45 0.05	30
L	3.62 0.05	16

The results are shown in the coincidence spectrum of Fig. 15, and the energies and intensities of the γ-rays are listed in Table VI. The corrected γ-ray spectrum is shown in Fig. 16. The absolute intensities of the γ-rays were determined by a comparison of the intensity of the strong γ-ray *C* with that of the 9.0-Mev nickel γ-ray, assuming that the capture cross section for thermal neutrons in calcium is 0.40 barn.[3]

The abundances and the thermal neutron capture cross sections of the calcium isotopes, so far as they are known, are listed in Table VII. The binding energy of Ca^{41} may be obtained from the *Q* value of the reaction $Ca^{40}(d,p)Ca^{41}$. For this quantity Sailor[26] obtained the value 6.17±0.05 Mev, whence the neutron binding energy is 8.40±0.05 Mev. This result is consistent with that which may be calculated from mass data and the *Q* of the reaction $K^{41}(p,n)Ca^{41}$. For the latter quantity Richards, Smith, and Browne[27] obtain −1.22 ±0.02 Mev from which we obtain $Ca^{41}-K^{41}=0.47$ ±0.02 mmu. With the mass of K^{41} referred to above, *viz.*, 40.97499±0.00008 amu, we obtain 40.97546

[26] V. L. Sailor, Phys. Rev. **75**, 1836 (1949).
[27] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).

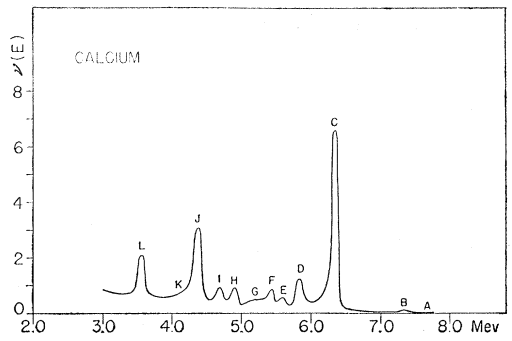

FIG. 16. Corrected γ-ray spectrum from calcium.

0.00008 amu for the mass of Ca^{41}. With the $Ca^{40}-A^{40}$ mass difference and the mass of A^{40} also quoted above, we obtain 39.97556±0.00009 amu for the mass of Ca^{40}. From these results it follows that the neutron binding energy of Ca^{41} is 8.45±0.10 Mev in agreement with the result obtained from the (d,p) reaction. The packing fractions given by Collins *et al.*[22] for Ca^{42}, Ca^{43}, and Ca^{44} may be used to calculate a neutron binding energy of 8.02±0.13 Mev for Ca^{43} and 11.50±0.13 Mev for Ca^{44}. There is insufficient information to enable one to determine the neutron binding energies of Ca^{45}, Ca^{47}, or Ca^{49} in the same way; these quantities may be estimated by means of the Bohr-Wheeler formula and are given in parentheses in Table VII. The γ-rays due to capture in Ca^{46} would be difficult to detect unless the capture cross section of that isotope were exceptionally large. The activity of the product nucleus Ca^{47} seems not to have been observed.

The excited states of Ca^{41} have been observed by Sailor[26] in a study of the $Ca^{40}(d,p)Ca^{41}$ reaction. The positions of these levels are shown on the right-hand side in Fig. 17. An excited state at about 0.4 Mev[28] has been observed in Ca^{43} from the β-decay of K^{43}. Another level near 1 Mev is excited in the decay of Sc^{43}, for a γ-ray with an energy at 1.0 Mev has been reported by Walke[29] and at 1.65 Mev by Hibdon, Pool, and Kurbatov.[30] From the decay of Sc^{44}, γ-rays of 0.52 and 1.25 Mev have been observed,[30] but the position of the excited states in Ca^{44} is not clear. No other data is

TABLE VII. Abundances, cross sections, and binding energies of the calcium isotopes.

Target nucleus	Abundance percent	Contribution to cross section in mb	Binding energy of product nucleus in Mev
Ca^{40}	96.9		8.40±0.05
Ca^{42}	0.64	386±30	8.02±0.13
Ca^{43}	0.14		11.50±0.13
Ca^{44}	2.1	13	(5.8)
Ca^{46}	0.0032	...	(4.6)
Ca^{48}	0.18	1	(3.7)

[28] Overstreet, Jacobson, and Stout, Phys. Rev. **75**, 231 (1949).
[29] H. Walke, Phys. Rev. **57**, 163 (1940).
[30] Hibdon, Pool, and Kurbatov, Phys. Rev. **67**, 289 (1945); A. Bruner and M. Langer, Phys. Rev. **79**, 236 (1950).

available on the energy levels of the calcium isotopes relevant to the present work.

An inspection of Table VI and Fig. 17 will show that the γ-rays A and B cannot be produced in transitions to any of the known low-lying levels of Ca^{41}. It is possible that A and B arise from transitions to the ground state from highly excited states in Ca^{41} lying near the capturing state, but it is more probable that they are produced in the decay of Ca^{43} and Ca^{44}. The energy of the γ-ray A agrees with the binding energy of Ca^{43} though the probable errors involved are too great for this identification to be made with certainty.

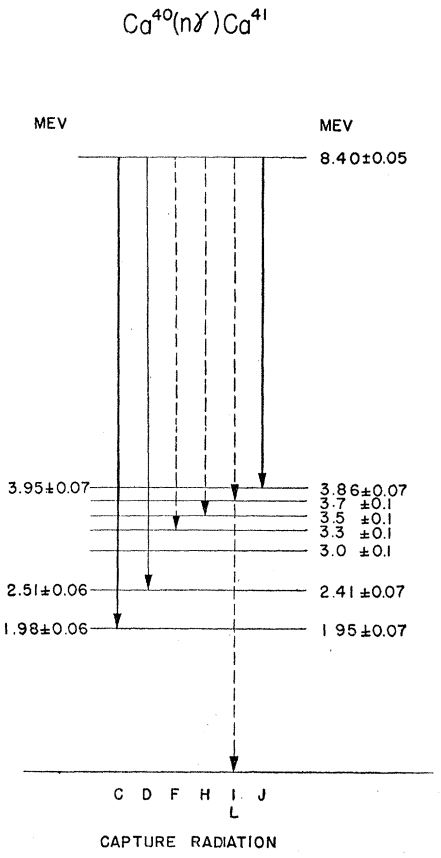

FIG. 17. Decay scheme for calcium. The figures on the right are the positions of the energy levels found by Sailor (see reference 26); those on the left were obtained by subtracting the γ-ray energies from the neutron binding energy.

However, as shown below, it is unlikely theoretically, that such a transition should be detected. A γ-ray corresponding to a transition from the capturing state to the 0.4-Mev level in Ca^{43} would have an energy of 7.6 Mev, and it is possible that γ-ray B is produced in this transition.

The origin of the remaining capture γ-rays cannot be determined with certainty because of the lack of information concerning the separate cross sections of Ca^{40}, Ca^{42}, and Ca^{43}. However, it will be shown below that the majority of these γ-rays can be fitted to the level scheme of Ca^{41}. Moreover, such an assignment for the strong γ-rays C and J seems very probable because of the high abundance of Ca^{40}. It will be noted that the γ-ray C could be fitted to the decay of Ca^{43}. For if the value of 1.65 Mev for the second excited state of this isotope is correct, the difference between this energy and the binding energy of Ca^{43} is 6.3 Mev in agreement with the energy of C. However, if the γ-ray C is produced by capture in Ca^{42}, that nucleus would require an isotopic capture cross section of at least 50 barns. While such a cross section is quite possible, it seems much more probable that C is a result of a transition in Ca^{41} between the capturing state and the first excited state at 1.95 Mev.

The γ-ray D very probably produces the second excited state at 2.41 Mev. The γ-rays F, H, and I probably represent transitions to the fourth, fifth, and sixth excited states. The strong γ-ray J corresponds to a transition to the seventh excited state. The existence of the γ-ray L in Fig. 15 is demonstrated by only one point; however, earlier measurements made with a Dural container indicate unmistakeably the presence of a γ-ray at this energy. L appears to be in cascade with I for the sum of the energies of L and I is 8.38 ± 0.07 Mev in agreement with the neutron binding energy of Ca^{41}. The peak K, however, is probably caused by the bismuth background.[1] Assuming then that C and J are due to Ca^{41}, that isotope is another example of the correspondence already noted between the frequency of excitation of nuclear states in the neutron capture and in the (d,p) process. In this instance, both the first and the seventh excited states are favored.

The γ-ray E and a background of unresolved radiation between H and F remain unaccounted for in the scheme of Fig. 17. The total energy represented by the radiations of Table VI amounts to 9.2 Mev. The integrated energy of the spectrum of Fig. 16 is much higher (15 Mev). These estimates, however, in view of the instrumental difficulties already discussed, are not unreasonable.

VII. DISCUSSION

According to the current shell structure theories, no parity change should be produced in a direct radiative transition to the ground state following the addition of any neutron between the ninth and the twentieth. No parity change is expected to be produced, therefore, in the ground-state transitions in P^{32}, S^{33}, or Cl^{36}. The spin of P^{32} has not been measured; it has been variously stated as 1 or 2. The ground-state transition in this nucleus therefore should be of the electric quadrupole or magnetic dipole type. In sulfur the state responsible for thermal neutron capture must have a spin of $\frac{1}{2}$, for the spin of S^{32} is zero. The spin of the product nucleus S^{33} is $\frac{3}{2}$, and the ground-state γ-ray in this case can radiate one or two units. The spin of Cl^{35} is $\frac{3}{2}$ and that of the radioactive nucleus Cl^{36} has been found to be 2 units. Although the capture of slow neutrons by

chlorine has been carefully investigated by Hibdon and Muehlhause,[31] the spin of the compound nucleus produced by thermal neutron capture, as a result of a resonance at negative energy, has not definitely been established. It follows that either one or two units of angular momentum must be radiated in this γ-ray. In all three nuclei the ground-state γ-rays are probably of the second order, and they are all relatively weak.

The addition of the odd neutron to the nuclei Cl^{37}, K^{39}, K^{41}, and Ca^{40} should produce a change in parity, for according to shell structure theories, this neutron will occupy an $f_{7/2}$ state. The β-decay of both Cl^{38} and K^{42} are of the first forbidden type and if, as would seem probable, the spins of these nuclei are both 2 units, the ground-state γ-rays are of the electric dipole type. Of these two γ-rays we have already noted that the one due to capture in Cl^{37} is obscured by the γ-ray F produced by capture in Cl^{35}. If the γ-ray C is indeed the ground-state γ-ray in K^{42}, its intensity is such that about one-sixth of the captures in K^{41} produce it.

The ground-state γ-ray in K^{40} is of unusual interest for the spin of K^{39} is $\frac{3}{2}$ and that of K^{40} in its ground state is 4 units. However, there is at present no slow neutron data nor fast neutron scattering data which can be used to determine the spin of the compound nucleus responsible for capture by K^{39}. If the odd neutron in K^{40} is in an $f_{7/2}$ state, the emission of the ground-state γ-ray is accompanied by a change in parity. This γ-ray will be of the electric octopole or magnetic quadrupole type according to whether the spin of the state responsible for capture is 1 or 2 units. If this γ-ray is identified with the γ-ray B in the potassium spectrum, it is surprising that its intensity is as great as it appears. In calcium the intensity of the ground-state γ-ray in Ca^{41} may be less than one photon per 500 captures, and the failure to detect it is to be expected. The spin of Ca^{41} has not been measured, but we should anticipate a spin of 7/2 from shell structure theory, and this value seems to be consistent with the very long life of this nucleus.[32] Since Ca^{40} has no spin, the ground-state γ-ray must be of the electric octopole type.

It would be interesting if the absolute, rather than the relative, rate of emission of these radiations were known. If the radiative width of the state responsible for capture is known, the partial widths for the various γ-rays emitted by this state can be obtained immediately by multiplying the total radiation width by the absolute intensities. For S^{33} a rough estimate of the total radiation width can be computed from neutron scattering data on the assumption that the observed thermal neutron capture cross section is caused entirely by the lowest S state which appears in the spectrum of the scattering cross section. Such a computation ignores the effect on the thermal neutron cross section states lying below the neutron binding energy, and the value obtained represents an upper limit for the width. For S^{33} the total width obtained in this way is about 20 volts, and the partial width of the ground-state transition is therefore about one volt. The fast neutron scattering data for the other elements considered in this paper are not sufficiently precise for the calculation of radiation widths.

The scattering and absorption of slow neutrons in chlorine[31] appears to be caused by a resonance at -75 ev with a radiation width of 0.3 volt. The low value of this resonance energy suggests that the level concerned is indeed the one responsible for the majority of the thermal neutron captures, and it follows that the radiation widths corresponding to the more energetic γ-rays in the chlorine spectrum have widths of the order of 10 millivolts. This result is very much less than that expected on the basis of current theoretical formulas[33] for magnetic dipole or electric quadrupole radiations.

[31] C. T. Hibdon and C. O. Muehlhause, Phys. Rev. **79**, 44 (1950).

[32] Brown, Hanna, and Yaffe, Phys. Rev. **84**, 1243 (1951).

[33] See the formulas quoted by M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).