

Neutron Capture γ -Rays from Fluorine, Sodium, Magnesium, Aluminum, and Silicon

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The energies and the absolute intensities of the γ -rays produced by neutron capture in fluorine, sodium, magnesium, aluminum, and silicon have been measured with the aid of a pair spectrometer. Direct transitions to the ground states of the product nuclei are predominant in the γ -ray spectra of fluorine and aluminum. The neutron binding energy in F^{20} is 6.63 ± 0.03 Mev and in Al^{28} , 7.724 ± 0.010 Mev. The γ -ray representing the direct transition to the ground state of Na^{24} was not detected. The interpretation of the magnesium spectrum presents some difficulties. A weak γ -ray with the binding energy of a neutron in Mg^{26} was detected, but none could be found to correspond to the direct transition to the ground state in Mg^{26} . In silicon, most captures are due to Si^{28} which produces Si^{29} by the emission of two γ -rays in cascade. Very weak γ -rays representing direct transitions to the ground states in Si^{29} and Si^{30} were detected. Their energies are 8.51 ± 0.04 (Si^{29}) and 10.55 ± 0.05 Mev (Si^{30}).

I. EXPERIMENTAL ARRANGEMENT

THE spectra of γ -rays of neutron capture are being explored with a pair spectrometer. A diagram of the experimental arrangement is shown in Fig. 1. The neutron-capturing sample under investigation is placed in a high neutron flux near the reacting core of the Chalk River pile. A block of bismuth, 5 inches thick, is located in the experimental hole between the sample and the reactor to reduce the γ -radiation from the latter to negligible proportions. Two cylindrical lead collimators in the hole limit the field of view of the spectrometer so that only the central portion of the neutron-capturing sample is visible. In this way the γ -radiations from the aluminum lining in the hole are eliminated. A cylinder, containing a mixture of boric acid and paraffin, and a sheet of cadmium prevent the escape of neutrons from the hole.

II. ENERGY AND RELATIVE INTENSITY MEASUREMENTS

The γ -ray spectrum is obtained by plotting the coincidence counting rate of the pair spectrometer against the strength of the magnetic field, a homogeneous γ -ray being revealed by a peak of characteristic shape. The energy of a γ -ray is determined from the distance between the inner edges of the slits which define the aperture of the counters, the value of the magnetic field obtained by the linear extrapolation of the high energy edge of the coincidence peak, and a small additive correction.¹

The line width of the spectrometer, defined as the width of a coincidence peak at half maximum, is determined by the ratio of the widths of the slits to the distance separating them. The line width, in energy units, is nearly independent of the γ -ray energy, and for most of the present work it was 130 kev. The γ -ray spectrum of aluminum, however, was studied with a line-width of 65 kev.

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¹ The method of energy measurement and the calculation of the efficiency of this instrument will be fully described elsewhere.

The relative intensities of the γ -rays producing the coincidence spectrum are determined from the peak coincidence counting rates and from calculated values of the efficiency of the spectrometer as a function of the γ -ray energy. The results are then corrected for the absorption of the γ -ray in the boron-paraffin cylinder and for self-absorption in the sample. The relative intensities given by this method have been verified by a direct determination with an ionization chamber of the intensities of the 2.75-Mev γ -ray produced by the decay of Na^{24} and of the 7.4-Mev neutron capture radiation from lead. The counting efficiency rises very rapidly with energy, at 3 Mev nearly as the fifth power. At 3 Mev the efficiency is very low, and for this reason it is difficult to detect and measure γ -rays with a lower energy unless they are exceptionally intense. At higher energies the instrument is much more efficient, and it is easy to measure very weak radiations.

In Figs. 2, 3, 4, 5, 6, 7, 9, 12 and 15, the ordinates of the γ -ray spectra are the coincidence counting rates observed, uncorrected for absorption or for the variation of the efficiency of the spectrometer. The errors given in the curves represent the statistical errors of counting. When the counting rates were very low, it was necessary to average the counting rates obtained for several adjacent values of the magnetic field, and these averages are indicated in the spectra by horizontal lines drawn through representative points. The abscissas are adjusted so that the extrapolated limits of the high energy edges of the coincidence peaks are equal to the energies of the γ -rays which have been calculated from the magnetic field corresponding to these limits and include the additive correction mentioned above.

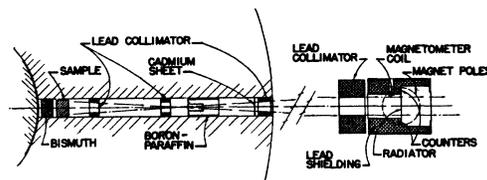


FIG. 1. General arrangement of apparatus.

III. ABSOLUTE INTENSITY MEASUREMENTS

The absolute intensities of the capture γ -rays of sodium, i.e., the number of photons produced per neutron captured, have been determined from the intensities measured relative to that of the 2.75-Mev γ -ray of Na^{24} . Since one photon of 2.75 Mev is produced per capture when radioactive equilibrium is established between Na^{24} and the neutrons producing it, the ratio of the intensities of the capture radiations to that of the 2.75-Mev γ -ray is equal to the number of photons produced per capture.

In principle, the absolute intensities of the capture radiations produced by any other material can be determined by mixing a weighed amount of it with a weighed amount of a sodium compound, provided that the capture cross sections of both are known. Let N be the number of atoms of this material in the container, σ its capture cross section, N_0 and σ_0 the similar quantities for sodium, and let the intensity in photons per second be I_r ; then

$$I_r/I_0 = N\sigma P_r T_r / N_0\sigma_0 T_0, \quad (1)$$

P_r being the number of photons of the γ -ray, r , emitted per capture, and T_r the fraction which escape from the sample in the direction of the spectrometer. The transmission coefficients T are easily calculated, and P_r may be determined therefore from the intensity ratio and from known or measurable quantities.

In practice, such comparisons are difficult because the coincidence counting rate produced by the Na^{24} γ -ray is very low even if kilogram amounts of sodium compounds are used. We have used, therefore, the 9.0-Mev capture γ -ray of nickel as a substandard. Nickel is more suitable than other materials as a substandard for intensity comparisons, because the coincidence spectrum consists mainly of a 9.0-Mev peak which is exceptionally strong and can be easily measured when nickel is used in very small quantities. The absolute intensity of this γ -ray was determined in a separate experiment in which a small weighed amount of nickel sesquioxide was mixed uniformly with a weighed amount of sodium fluoride. The result obtained was 0.43 photon per capture, assuming that the capture cross sections of sodium and nickel are respectively 0.47² and 4.8 barns.³

Provided the cross sections of sodium and of the sample element are known with sufficient precision, the reliability of the nickel method depends on the calculated efficiency of the spectrometer and on the statistical accuracy of measurement of the coincidence peaks. There is reason to believe, however, that this method gives intensities which are too high for γ -rays near 5 Mev. As will be shown below, the intensities obtained for the strongest silicon γ -rays are certainly too high by 30 percent. Too high an intensity might correspond

to too high a value for the absorption cross section of sodium or too low a value for silicon. Neither of these quantities is likely to be in serious error, for the absorption and the activation⁴ cross sections of sodium agree within the limits of experimental error (20 percent), and the cross section of silicon, determined from the reactivity of a pile, owing to the possible presence of impurities, is generally more likely to be too high than too low. We conclude that the calculated efficiency of the spectrometer, which seems to give the correct ratio of efficiency at 7.38 and 2.75 Mev, gives too low results between these values. Unfortunately, we have so far found no way of checking the efficiency at energies other than these.

Another method for making the nickel comparison may be applied to samples with low capture cross sections. The neutron flux in a reactor decreases in a radial direction outwards from the center. The change in the flux over the length of a sample is small, and, in the case of weakly absorbing materials, there is no variation of the flux on a plane through the sample and perpendicular to the axis of the hole. Consequently, if, instead of mixing nickel oxide with the sample, two nickel sheets are fixed to the front and back faces of the container, the nickel capture radiation produced is proportional to the average value of the neutron flux in the weakly absorbing sample, and the intensity ratio obtained should be equal to that found when an equivalent amount of the oxide is mixed with the material. For magnesium, aluminum, and silicon it has been more convenient to make the intensity comparison in this way, and for the latter element an identical result was obtained with that found using the nickel mixture.

In using the sheet method we assume that the absorption of neutrons in the material is so low that the distribution of the neutron flux is not disturbed by the presence of the sample. This assumption seems to be justified for samples containing a few hundred grams of the absorbing element for which the cross section is small compared with one barn. Using a lead sample, for which the cross section is about 200 mb, we have found by a direct measurement with manganese foils within the material that the neutron flux is uniform to 5 percent. In this experiment, the lead sample was of similar size to those used in the pile and was exposed to a uniform neutron flux in a paraffin-lined enclosure.

For samples containing about the same number of atoms with cross sections in excess of one barn, the flux at the center of the sample is considerably less than that at the ends and the nickel sheet method will indicate intensities which are too low. In this case, the mixture method is essential; the result is then given by Eq. (1) and depends to a small extent only (in fact, to the second order of small quantities) on the axial variation of the flux and the self-absorption of the capture radiation.

² This cross section is a mean value of that of Colmer and Littler and the values quoted in Circular No. 499 of the U. S. National Bureau of Standards, September, 1950.

³ F. C. W. Colmer and D. J. Littler, Proc. Phys. Soc. (London) **A63**, 1175 (1950).

⁴ Seren, Friedlander, and Turkel, Phys. Rev. **72**, 888 (1947).

IV. FRACTION OF γ -RAYS OBSERVED

A check on the intensity measurements may be obtained from a consideration of the total energy detected in the form of capture radiation.

The fraction of the total binding energy which is not promptly emitted in the form of capture γ -radiation is negligible, for that which may be delayed by the production of an isomeric state is usually small compared with the neutron binding energy and the amount of internal conversion is of the order of 0.1 percent. Consequently, the sum of the products of the γ -ray energies with their intensities, in photons per capture, should be very nearly equal to the binding energy. Any difference observed represents the energy emitted as γ -rays with energies below the limit of detection by the pair spectrometer. If E_m is the lower limit of detection, and if B is the neutron binding energy, the sum of the intensity-weighted energies is

$$S = \sum_{E_m}^B P(E)E \lesssim B. \quad (2)$$

For the elements which are the subject of the present paper, the quantities S/B are usually near unity.

If the spectrum contains unresolved components, the contribution to the total energy radiated must be calculated on the assumption of a continuous spectrum. Let $q(E)$ be the counting rate at energy E , C a quantity proportional to the number of captures in the sample, and $\epsilon(E)$ the relative efficiency of the spectrometer at energy E . Then the counting rate is given by

$$q(E) = kCT(E)\epsilon(E)\nu(E)A,$$

where k is a constant, $\nu(E)$ is the number of photons emitted per capture per unit energy range at E , and A is the area under the coincidence peak of a homogeneous γ -ray with unit peak height at energy E . The counting rate of the 9-Mev nickel γ -ray is given by:

$$q_1 = 0.43C_1T_1\epsilon_1k.$$

The absolute intensity of the continuous spectrum emitted by the sample may then be calculated by combining these equations. Hence:

$$\nu(E) = \frac{q(E) C_1}{q_1 C} \frac{T_1 \epsilon_1}{C T(E) \epsilon(E)} \frac{0.43}{A}. \quad (3)$$

The coincidence spectrum obtained with a homogeneous γ -ray contains a tail extending to low energies, which for various reasons it has not been possible to study in detail below an energy less than that of the extrapolated limit by four or five times the width of the peak. To this extent, the area under a coincidence peak is roughly independent of the energy of the γ -ray; the average value of A for a line-width of 130 kev was found to be 135 kev. Using Eq. (3), the sum of the intensity-weighted energies for an unresolved spectrum

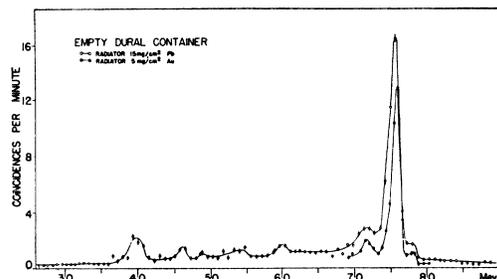


FIG. 2. Coincidence spectrum produced by an empty Dural container. A part of the peak near 4 Mev is due to bismuth capture radiations.

is

$$S' = \int_{E_m}^B \nu(E)E dE \lesssim B. \quad (4)$$

Equation (3) is derived on the assumption that the resolution of the instrument is such that $\nu(E)$ does not vary much over a range of energy equal to the width of the peak of a homogeneous γ -ray. For most of the light elements this assumption is certainly untrue. Further, no account is taken in Eq. (3) of the long tail at the lower energy side of a coincidence peak. The tails of the higher energy peaks will contribute appreciably—and by an unknown amount—to the background counting rate at lower energies and the contribution to the γ -ray spectrum and to (4) will be greatly exaggerated by the rapidly decreasing sensitivity of the instrument at low energies. Consequently, the value of the integral S' will generally be too high.

V. SAMPLE CONTAINER

Compounds of fluorine and sodium were irradiated in Dural containers, four inches in diameter and six inches long. The container itself produces a γ -ray spectrum, in which the radiations of aluminum are prominent. This spectrum must be subtracted from that obtained when the container is full of the material to be studied. From each ordinate of the combined spectrum is subtracted the contribution of the empty container scaled so that the peaks due to the 7.72-Mev aluminum γ -ray coincide. The container spectrum, Fig. 2, was obtained with a somewhat thicker radiator (15 mg/cm² of lead) than that normally used (5 mg/cm² of gold). Apart from the higher counting rate, the difference in the shape of coincidence spectra obtained with these two radiator thicknesses is negligible for the purposes of making this subtraction. The strong peak at 7.72 Mev and the weaker peaks at 4.7 and at 6.1 Mev are due to aluminum. Two small peaks appear on the tails of the peak at 7.72 Mev. The γ -ray at 7.9 Mev is due to the copper, and that at 7.2 Mev to the manganese component in the Dural.

Magnesium and aluminum were available in the form

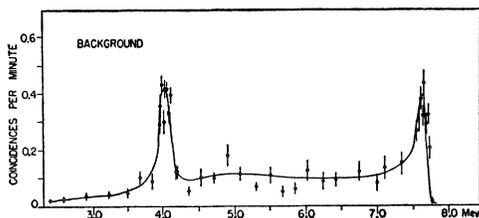


FIG. 3. Background spectrum due to hole containing only the bismuth block and the lead collimators. The 4.17-Mev γ -ray is due to bismuth; the 7.7-Mev γ -ray to aluminum.

of metallic cylinders,⁵ and for this reason it was not necessary to place them in containers. The γ -rays of these elements are superposed on radiation produced by the reactor filtered through the bismuth block (Fig. 1), and the radiation emitted by the block itself. This background spectrum, shown in Fig. 3, was obtained from measurements made without a sample. To within 10 percent the ordinates of Fig. 3 correspond to the same pile power as that used in the study of magnesium, aluminum, and silicon. The peak at 4.17 Mev in Fig. 3

TABLE I. Energies and intensities of sodium capture γ -rays.

γ -ray	Energy in Mev	Intensity in photons per 100 captures
A	6.41 ± 0.03	20
B	5.61 ± 0.03	7.5
C	5.13 ± 0.03	1.8
F	3.96 ± 0.03	20
G	3.85 ± 0.05	11
H	3.60 ± 0.03	10
I	3.56 ± 0.05	20

is due to the γ -ray of bismuth⁶ and that at 7.7 Mev to aluminum.

Silicon has been studied in a container of a new design consisting of an aluminum tube with end walls of Bakelite. Since the field of view of the spectrometer covers the central parts of the sample only, aluminum γ -rays do not then contribute appreciably to the spectrum. The capture γ -rays produced by the Bakelite ends are extremely weak and cannot be detected under these conditions.

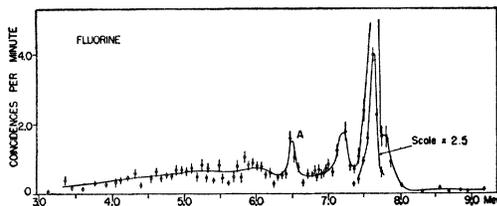


FIG. 4. Coincidence spectrum produced by fluorine (as Teflon) in a Dural container.

⁵ For the provision of magnesium and aluminum metal of exceptional purity we are indebted to the Division of Physical Metallurgy, Department of Mines and Technical Surveys, Ottawa.

⁶ Kinsey, Bartholomew, and Walker, Phys. Rev. **82**, 380 (1951).

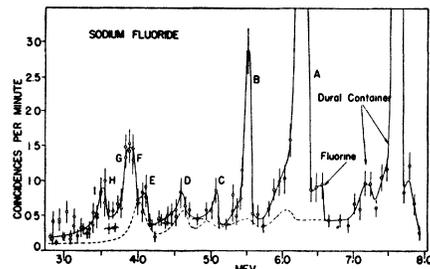


FIG. 5. Coincidence spectrum produced by sodium fluoride in a Dural container. Line-width: 130 kev. The contribution to this spectrum below 7 Mev produced by the container and the bismuth block is shown by the dotted line.

VI. FLUORINE

Fluorine capture radiation was investigated from 2.5 Mev to 10.4 Mev using a sample of about 1700 grams

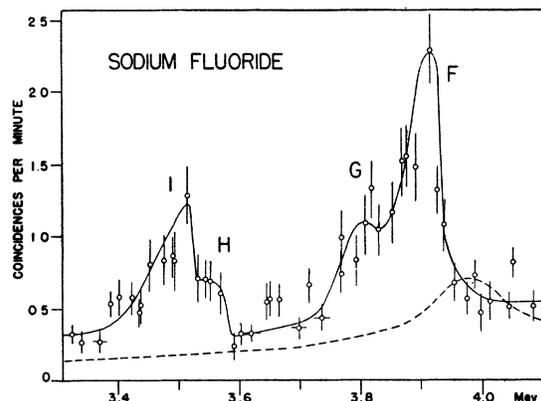


FIG. 6. Coincidence spectrum produced by sodium fluoride showing details between 3.4 and 4.0 Mev. Line-width: 130 kev. The contribution of the Dural container and the bismuth radiation is shown by the dotted line.

of Teflon (C_2F_4) in a Dural container. The results are shown in Fig. 4. Only one γ -ray, A, was resolved above the background due to the container. This γ -ray has an

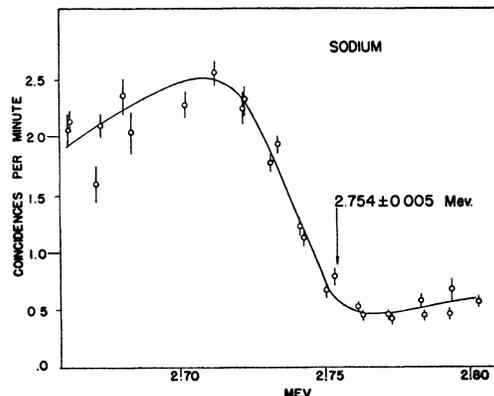


FIG. 7. Coincidence spectrum produced by sodium fluoride between 2.65 and 2.80 Mev. The peak represents the 2.75-Mev γ -ray emitted by Na^{24} in radioactive equilibrium.

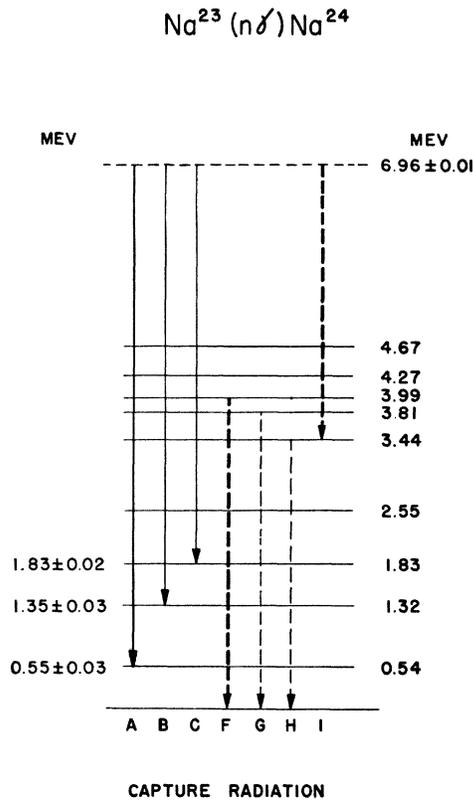


FIG. 8. Decay scheme for the capture γ -rays of sodium. The energy levels are drawn to scale according to the results of Whitehead and Heydenburg (reference 13) (right hand figures). The energies of the first three excited states of Na^{24} , obtained by subtracting the γ -ray energies from 6.96 Mev, are shown on the left.

energy of 6.63 ± 0.03 Mev, which agrees with the binding energy of 6.5 Mev, obtained from the results of Bower and Burcham,⁷ and with 6.52 ± 0.08 Mev, obtained from those of Allen and Rall⁸ from studies of the energy balance in the (d,p) reaction. The background due to the container was too high to permit a search for γ -rays of lower energy.

The absolute intensity of the 6.63-Mev γ -ray, in

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

γ -ray	Energy in Mev	Intensity in photons per 100 captures
A	9.26 ± 0.04	1
B	8.16 0.03	9
C	7.37 0.08	0.5
D	7.15 0.04	1
E	6.75 0.04	2.5
F	6.39 0.05	5
G	5.73 0.04	1
H	5.50 0.04	7
I	5.05 0.07	9
J	3.92 0.03	94
K	3.45 0.07	16
L	2.83 0.05	39

⁷ J. C. Bower and W. E. Burcham, Proc. Roy. Soc. (London) **A173**, 379 (1939).

⁸ R. C. Allen and W. Rall, Phys. Rev. **78**, 337A (1950).

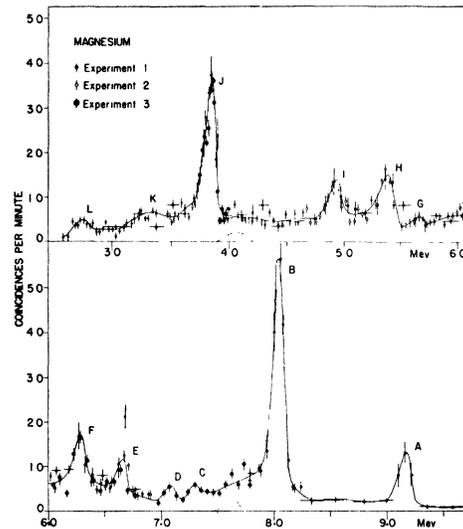


FIG. 9. Coincidence spectrum produced by magnesium compiled from a combination of results. Line-width: 130 kev. The contribution due to bismuth is shown by the dotted line near 4.1 Mev, and that due to a small amount of aluminum, near 7.7 Mev. No coincidence peaks were discovered between that of the γ -ray A and 12.5 Mev.

photons per capture in fluorine, has been estimated in two ways. In the first method, the peak coincidence counting rate was compared with that of the 6.797-Mev γ -ray⁹ of beryllium. Assuming that the capture cross sections of fluorine and beryllium are the same (9 millibarns) and taking into account the number of fluorine and beryllium atoms in the two samples, the absorption of the γ -rays in the samples and in the boron-paraffin plug used to remove the neutrons from the beam, and the energy dependence of the counting efficiency in the spectrometer, we find that the intensity of the fluorine γ -ray is 0.27 ± 0.10 of that of the beryllium γ -ray. Only one γ -ray has been detected in the beryllium capture spectrum and, assuming that that γ -ray is emitted at the rate of one photon per capture, the intensity of the fluorine γ -ray is 0.27 ± 0.10 photon per capture.

In the second method, the intensity of the fluorine γ -ray emitted by sodium fluoride was compared with the intensity of the 2.75-Mev γ -ray emitted by Na^{24} in radioactive equilibrium with the neutrons producing it (see Fig. 5). The fluorine γ -ray is partially obscured by the strong sodium γ -ray at 6.41 Mev, and only a rough estimate of its intensity is possible. The result is 0.42 ± 0.10 photon per capture.

The results of the two methods are in rough agreement; taking a mean value, we conclude that the 6.63-Mev fluorine γ -ray is emitted in 0.35 ± 0.10 photon per capture. The neutron captures which do not result in the emission of this γ -ray must produce others which, on account of their low intensity or lower energy, are not detected.

⁹ Kinsey, Bartholomew, and Walker, Can. J. Phys. **29**, 1 (1951).

VII. SODIUM

The sodium sample consisted of 900 grams of chemically pure sodium fluoride enclosed in a Dural container. The energy range from 2.8 to 8.0 Mev was examined in a survey experiment, the results of which are illustrated in Fig. 5. The broad peaks between 3.3 and 4.2 Mev were studied in more detail and are shown in Fig. 6. In both Figs. 5 and 6 the resolution is 130 kev. The dotted curves indicate the background due to the container.

In Fig. 5 the counting rate between 7 and 8 Mev is due entirely to the container. The peak due to the fluorine γ -ray lies just above the strong sodium peak at *A*. The peak counting rates at *D* and *E* can be accounted for by the spectrum of the container. Below 3.3 Mev (Fig. 5) there is some evidence for the existence of other radiations which have not been resolved.

The 2.75-Mev γ -ray of Na^{24} , which does not appear in Fig. 5, is shown in equilibrium intensity in detail in Fig. 7. Its energy was found to be 2.754 ± 0.005 Mev, in agreement with recent measurements. Wolfson¹⁰ has obtained the value 2.755 ± 0.005 Mev by comparison with the 1.33-Mev γ -ray of Co^{60} . Bishop and co-workers¹¹ found 2.757 ± 0.004 Mev by comparison with the ThC'' γ -ray which was assumed to be 2.618 ± 0.004 Mev.

The binding energy of the neutron in the Na^{24} nucleus may be derived from the *Q* value of the (*d*,*p*) reaction by adding the binding energy of the deuteron obtained by Bell and Elliott.¹² The *Q* value obtained by Whitehead and Heydenburg¹³ was 4.76 Mev in agreement with earlier results obtained by Murrell and Smith.¹⁴ Recently, the M.I.T. group have obtained a value of 4.731 ± 0.009 Mev for the same quantity.¹⁵ From this we deduce that the neutron binding energy in Na^{24} is 6.961 ± 0.012 Mev. No γ -ray with this energy has been found; however, the coincidence peak due to a weak γ -ray at this energy might be hidden beneath the tail of the aluminum γ -ray in the spectrum of the container.

TABLE III. Abundances, cross sections, and binding energies of magnesium isotopes.

Target nucleus	Abundance percent	Contribution to capture cross section in millibarns	Binding energy or product nucleus in Mev
Mg^{24}	78.6	52 ± 6 ^a	7.334 ± 0.012
Mg^{25}	10.1		10.93 ± 0.10
Mg^{26}	11.3		6.44 ± 0.10

^a See reference 3.

^b See reference 4.

¹⁰ J. L. Wolfson, Phys. Rev. **78**, 176 (1950).

¹¹ Bishop, Collie, Halban, Hedgran, Siegbahn, DuToit, and Wilson, Phys. Rev. **80**, 211 (1950).

¹² R. E. Bell and L. G. Elliott, Phys. Rev. **79**, 282 (1950).

¹³ W. D. Whitehead and N. P. Heydenburg, Phys. Rev. **79**, 99 (1950).

¹⁴ E. B. Murrell and C. L. Smith, Proc. Roy. Soc. (London) **A173**, 410 (1939).

¹⁵ Strait, Van Patter, Buechner, and Sperduto, Phys. Rev. **81**, 747 (1951).

The energies and the absolute intensities of the capture γ -rays are listed in Table I.

The most complete data for the positions of the energy levels of Na^{24} are those given by Whitehead and Heydenburg.¹³ The neutron capture radiations are fitted to these levels in the scheme shown in Fig. 8, in which the positions of the levels determined by these authors are shown on the right, and the positions found by subtracting the γ -ray measurements from 6.96 Mev are shown on the left. It seems quite clear that the proper interpretation of the γ -rays *A* and *B* are transitions from the capturing state to the first and second excited states, respectively. The γ -ray *C* is very weak but seems to correspond to a transition to the third excited state. The assignment of the other γ -rays is less obvious and possible locations for them are shown by the broken lines in Fig. 8. Alternative schemes are possible. However, all these γ -rays can be understood in terms of transitions between the states found by Whitehead and Heydenburg without introducing new levels at higher excitation energies. No radiative transition to the level at 2.55 Mev has been detected.

VIII. MAGNESIUM

The magnesium sample used in the present experiment was a cylinder of pure metal, six inches long and four inches in diameter. Impurities were present in a concentration of less than 0.02 percent. The elements which produce exceptionally strong homogeneous γ -rays, *viz.*, Mn, Fe, Ni, and Cu, were present to the extent of only a few parts per million and measurements of the intensities of the γ -rays from these elements show that the impurities of these elements in the magnesium sample could not contribute appreciably to the spectrum observed.

Three sets of measurements were made to obtain the capture γ -ray spectrum shown in Fig. 9. Coincidence peaks were looked for up to 12.5 Mev but none were found above the energy of peak *A*. In experiments Nos. 1 and 2 the bismuth block placed between the sample and the reactor was contained in a Dural cylinder with a Dural end wall facing the sample. Radiations produced by neutron capture in the Dural were transmitted through the sample with sufficient intensity to obscure the magnesium spectrum in the region from 6.8 to 7.8 Mev and the results in this energy range have been omitted in Fig. 9. The Dural contribution to the coincidence spectrum below 7 Mev is negligible. In experiment No. 3, the bismuth block was replaced by another which was so constructed that no Dural was exposed to the field of view of the spectrometer. The spectrum, in this case, is nearly free from unwanted radiations. In plotting Fig. 9 the three sets of data were normalized to the same pile power. Except for a few isolated points the results coincide within the statistical error.

The energies and intensities of the resolved magnesium radiations are listed in Table II. These γ -rays

TABLE IV. Energies of the excited states of Mg^{25} and Mg^{26} in Mev.

Mg^{25}				
Schelberg ^a $Al^{27}(d,\alpha)Mg^{25}$	French and Treacy ^b $Al^{27}(d,\alpha)Mg^{25}$	Pollard ^c <i>et al.</i> $Al^{27}(d,\alpha)Mg^{25}$	Allan ^d <i>et al.</i> $Mg^{24}(d,p)Mg^{25}$	Bleuler and Zünti ^e $Na^{25}(\beta^-)Mg^{25}$
0.57±0.05	0.58		0.58	
0.96 0.05	0.94	0.81	0.98	1.0
1.63 0.04	1.54	1.58		
1.97 0.05	1.87			
2.74 0.04		2.54		
3.36 0.04				
4.01 0.05				
4.81 0.05				
5.48 0.05				
5.95 0.05				

Mg^{26}			
Motz ^f $Na^{23}(\alpha,p)Mg^{26}$	Humphreys and Pollard ^g $Na^{23}(\alpha,p)Mg^{26}$	Livingston and Bethe ^h $Na^{23}(\alpha,p)Mg^{26}$	Alburger, ⁱ γ -rays following $Na^{23}(\alpha,p)Mg^{26}$
	0.23		
0.44	0.60		
	1.18		
1.91	1.92		1.85
		2.2	
2.85	2.75		2.80
		4.0	
		5.0	

^a Schelberg, Sampson, and Cochran, Phys. Rev. **80**, 574 (1950).
^b See reference 18.
^c Pollard, Sailor, and Wyly, Phys. Rev. **75**, 725 (1949).
^d See reference 17.
^e E. Bleuler and W. Zünti, Helv. Phys. Acta **20**, 195 (1947).
^f See reference 22.
^g R. F. Humphreys and E. Pollard, Phys. Rev. **59**, 924 (A) (1941).
^h See reference 24.
ⁱ D. E. Alburger, Phys. Rev. **73**, 1014 (1948).

are superposed on a relatively high background. The contribution to the spectrum due to the background of bismuth and pile radiation (Fig. 3) is very small and for the same pile power the two prominent peaks are shown by the dotted lines in Fig. 9. After subtracting this contribution and using Eq. (3) the γ -ray spectrum of Fig. 10 was obtained.

The contribution of the γ -rays of Table II to the energy radiated per capture [Eq. (2)] is $S=7.5$ Mev. If, as seems likely, the calculated efficiency curve of the spectrometer gives too high intensities near 5 Mev, this is a low result and may indicate that a portion, at least, of the background is due to unresolved radiations. The integral [Eq. (4)] of Fig. 10 is $S'=17$ Mev. This very high result must be due to the effect of the tails of the peaks due to homogeneous γ -rays, as pointed out in an earlier paragraph.

The neutron binding energies of the magnesium isotopes can be computed from the energy release in a number of nuclear reactions. Only the neutron binding energies of Mg^{25} , Mg^{26} , and Mg^{27} are relevant to the present work.

The neutron binding energy of Mg^{25} can be obtained from the energy balance of the $Mg^{24}(d,p)Mg^{25}$ reaction. For this quantity Allan and Wilkinson¹⁶ have found

¹⁶ H. R. Allan and C. A. Wilkinson, Proc. Roy. Soc. (London) **A194**, 131 (1948).

5.03 ± 0.05 Mev and Allan, Wilkinson, Burcham, and Curling¹⁷ have confirmed this value using a target of separated Mg^{24} . More recently, the M.I.T. group¹⁵ have obtained 5.094 ± 0.010 Mev for the same quantity. Another value consistent with this result can be obtained by subtracting the Q 's of the $Al^{27}(d,\alpha)Mg^{25}$ and $Al^{27}(p,\alpha)Mg^{24}$ reactions. For the former quantity, French and Treacy¹⁸ obtained 6.62 ± 0.05 Mev and for the latter, they have quoted an unpublished value of Freeman of 1.58 ± 0.01 Mev. The difference, 5.04 ± 0.05 Mev, agrees with the results of Allan and Wilkinson and of the M.I.T. work quoted above. A more accurate value for the Q of the $Al^{27}(d,\alpha)Mg^{25}$ reaction has been obtained recently by the M.I.T. group;¹⁵ it is 6.694 ± 0.010 Mev. The difference between the Q 's of the two reactions then becomes 5.114 ± 0.014 Mev, which is in close agreement with the value 5.094 ± 0.010 Mev. When the binding energy of the deuteron¹² is added to the average of these two quantities, the neutron binding energy of Mg^{25} is found to be 7.334 ± 0.012 Mev.

The neutron binding energy of Mg^{26} cannot be obtained from the energy balance of the (d,p) reaction with Mg^{25} for the group of protons which should

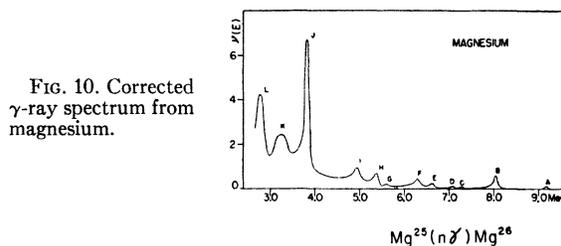


FIG. 10. Corrected γ -ray spectrum from magnesium.

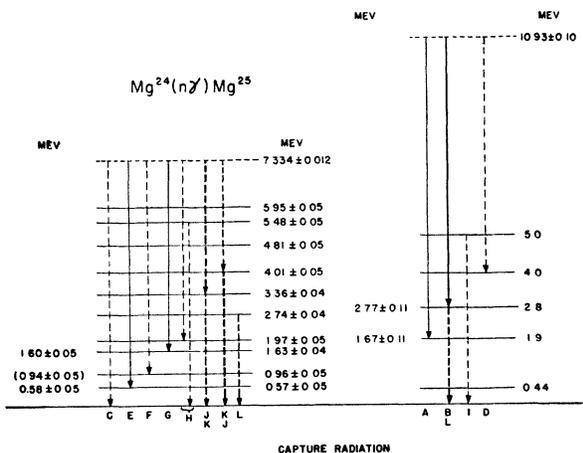


FIG. 11. Decay scheme for the capture γ -rays of magnesium. The level system of Mg^{26} (right-hand figures) is that obtained by Schelberg, Sampson, and Cochran (reference a, Table IV); that of Mg^{25} was obtained from various sources. The positions of the energy levels determined from γ -ray measurements are given on the left.

¹⁷ Allan, Wilkinson, Burcham, and Curling, Nature **163**, 210 (1949).

¹⁸ A. P. French and P. B. Treacy, Proc. Phys. Soc. (London) **A63**, 665 (1950).

produce the ground state of Mg^{26} has never been detected. The neutron binding energy, however, can be computed by the addition of the following equations, using the masses of the light nuclei given by Tollestrup, Fowler, and Lauritsen:¹⁹

$$Mg^{26} + d = Mg^{27} + p + 4.21 \pm 0.1 \text{ Mev},^{17}$$

$$Mg^{27} = Al^{27} + 2.64 \pm 0.05 \text{ Mev},^{20}$$

$$Al^{27} + d = Mg^{25} + \alpha + 6.694 \pm 0.010 \text{ Mev}.^{15}$$

The result is $11.01 \pm 0.12 \text{ Mev}$.

An independent estimate may be made from the following equations:

$$Mg^{24} + d = Mg^{25} + p + 5.104 \pm 0.010 \text{ Mev},$$

$$Na^{23} + d = Na^{24} + p + 4.731 \pm 0.009 \text{ Mev},^{15}$$

$$Na^{24} = Mg^{24} + 5.53 \pm 0.01 \text{ Mev},^{21}$$

$$Na^{23} + \alpha = Mg^{26} + p + 1.66 \pm 0.09 \text{ Mev}.$$

The Q value of the last equation, $1.66 \pm 0.09 \text{ Mev}$, is a weighted average of the results of Motz,²² Merhaut,²³ and the value quoted by Livingston and Bethe.²⁴ For the neutron binding energy of Mg^{26} , we obtain the result: $10.85 \pm 0.10 \text{ Mev}$. The mean value for the two calculations of the neutron binding energy is $10.93 \pm 0.10 \text{ Mev}$.

The neutron binding energy of Mg^{27} may be obtained from the Q of the $Mg^{26}(d,p)Mg^{27}$ reaction. According to

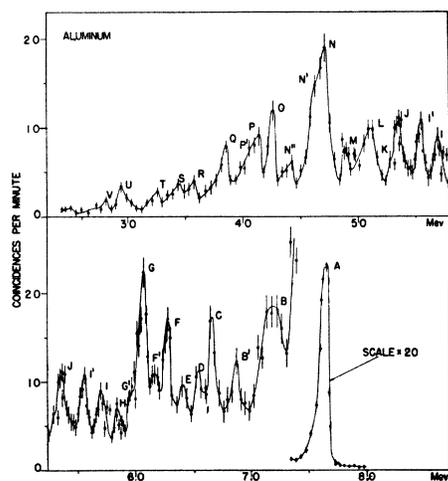


Fig. 12. Coincidence spectrum produced by pure aluminum with a line width of 65 keV.

¹⁹ Tollestrup, Fowler, and Lauritsen, *Phys. Rev.* **78**, 372 (1950).

²⁰ Benes, Hedgran, and Hole, *Arkiv. Mat. Astron. Fysik* **35**, No. 12 (1949). The errors in the decay energies of Mg^{27} and Al^{28} are not given in the text of that paper and those quoted above are our estimates. Motz and Humphreys (see reference 30), quoting these results, give much larger errors.

²¹ K. Siegbahn, *Phys. Rev.* **70**, 127 (1946).

²² H. T. Motz, private communication.

²³ O. Merhaut, *Physik. Z.* **41**, 528 (1940).

²⁴ M. S. Livingston and H. A. Bethe, *Revs. Modern Phys.* **9**, 245 (1937).

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

γ -ray	Energy (Mev)	Difference energy (Mev)	Possible difference γ -ray	Intensity in photons per 100 captures
A	7.724±0.010	0.00		35
B	7.34 0.04	0.38±0.04		0.7
B'	6.98 0.04	0.74 0.04		0.7
C	6.77 0.02	0.95 0.02		1.4
D	6.61 0.03	1.11 0.03		0.4
E	6.50 0.03	1.22 0.03		0.4
F	6.33 0.02	1.39 0.02		2
F'	6.22 0.03	1.50 0.03		0.7
G	6.13 0.02	1.59 0.02		2
G'	6.01 0.05	1.71 0.05		0.7
H	5.89 0.04	1.83 0.04		1.0
I	5.78 0.03	1.94 0.03		1.4
I'	5.60 0.02	2.12 0.02		3
J	5.41 0.03	2.31 0.03		3
K	5.32 0.03	2.40 0.03		1.0
L	5.21 0.02	2.51 0.02		3
M	4.94 0.05	2.78 0.05	V	1.4
N	4.79 0.02	2.93 0.02		9
N'	4.66 0.05	3.06 0.05	U	7
N''	4.45 0.02	3.27 0.02	T	3
O	4.29 0.02	3.43 0.02	S	8
P	4.16 0.02	3.56 0.02	R	6
P'	4.06 0.04	3.66 0.04		3
Q	3.88 0.02	3.84 0.02	Q	8
R	3.62 0.02	4.10 0.02		6
S	3.46 0.02	4.26 0.02		4
T	3.29 0.02	4.43 0.02		5
U	3.02 0.05	4.70 0.05		15
V	2.84 0.03	4.88 0.03		13

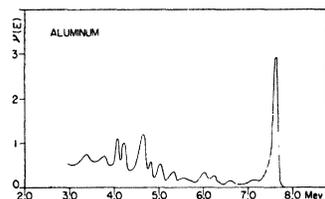
Allan *et al.*,¹⁷ this quantity is $4.21 \pm 0.1 \text{ Mev}$, whence the neutron binding energy of Mg^{27} is $6.44 \pm 0.1 \text{ Mev}$.

The results of the binding energy calculations, the abundances of the magnesium isotopes and their contributions to the total neutron absorption cross section, are summarized in Table III.

Only two of the magnesium capture γ -rays have energies which might be identified with the neutron binding energies. A weak γ -ray is indicated at C in Fig. 9, for which the energy is $7.37 \pm 0.08 \text{ Mev}$ in agreement with the binding energy of the neutron in Mg^{25} . The statistics, however, are not good enough to establish its presence with certainty. No γ -ray near 11 Mev has been found to correspond with the neutron binding energy in Mg^{26} (10.93 Mev). A γ -ray with an energy of 11 Mev would have been detected if its intensity were 0.2 quantum per 100 captures or greater. The γ -ray F, which has an energy of $6.39 \pm 0.05 \text{ Mev}$, may represent the transition to the ground state in Mg^{27} . The intensity of this γ -ray is of the order of 0.05 photon per capture. Now the total absorption cross section of magnesium³ is $58 \pm 6 \text{ mb}$, and the contribution to this cross section due to the capture of neutrons in Mg^{26} is⁴ $5.4 \pm 1.0 \text{ mb}$, i.e., about 10 percent of the total. If, then, the γ -ray F is due to capture in Mg^{26} , it must account for about one-half of the cross section due to that isotope. As will be shown below, an alternative explanation for F is possible.

The energies of the excited states of Mg^{25} and Mg^{26} have been measured in a number of ways and by different authors; the results are summarized in Table IV.

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



The positions of the excited states of Mg^{25} appear to be well defined by the measurements listed in Table IV. Our present knowledge of Mg^{26} is less satisfactory; in that isotope only two levels, near 1.9 and 2.8 Mev, have been detected and measured by more than one experimenter. These levels were also reported by Pollard and Humphreys²⁵ in an investigation of the $Mg^{25}(d,p)Mg^{26}$ reaction, but it is doubtful if their results really refer to Mg^{26} for Allan and co-workers,¹⁷ using a target of separated Mg^{25} , failed to detect any proton groups which could not be ascribed to the $Mg^{24}(d,p)Mg^{25}$ reaction. The level energies in the third column are the results of König²⁶ and of May and Vaidyanathan,²⁷ corrected by Livingston and Bethe.²⁴ The existence of the two levels at 4 and at 5 Mev has not been confirmed.

No excited states are known in Mg^{27} . Allan and co-workers¹⁷ have studied the $Mg^{26}(d,p)Mg^{27}$ reaction using magnesium enriched in Mg^{26} , but did not report groups with energy less than that of the ground-state group for which the Q is 4.21 Mev.

In Fig. 11 an attempt has been made to fit the capture γ -rays into a level scheme based on the excitation energies listed in Table IV. In those cases where there seems to be little doubt of the γ -ray assignment the

TABLE VI. Energies of the excited states of Al^{28} in Mev.

Whitehead and Heydenburg ^a	Pollard, Sailor, and Wylie ^b	Allan and Wilkinson ^c	Allan and Clavier ^d	Present work
1.01	1.03	1.00	1.00	0.95 ± 0.02
1.37				1.39 0.02
1.65	1.57	1.48		1.59 0.02
2.23	2.16	2.15	2.15	2.12 0.02
2.67	2.61			2.51 0.02
3.03	2.97			
3.33	3.41			
3.64				
4.03	3.90			
	4.47			
4.78	4.72			
	4.88			
5.02	5.16			
5.26				
	5.44			
5.68	5.76			
				6.98 0.04
				7.34 0.04

^a See reference 13.

^b See reference c, Table IV.

^c See reference 16.

^d See reference 28.

²⁵ E. C. Pollard and R. F. Humphreys, Phys. Rev. **59**, 466 (A) (1941).

²⁶ A. König, Z. Physik **90**, 197 (1934).

²⁷ A. N. May and R. Vaidyanathan, Proc. Roy. Soc. (London) **A155**, 519 (1936).

transition is represented by a full line and the level energy obtained from the γ -ray energies and the value of the binding energy in Table III is given on the left of the diagram. The level energies shown on the right are those reported by Schelberg, Sampson, and Cochran for Mg^{25} , and by Motz, and Livingston and Bethe for Mg^{26} .

Only the γ -rays A and B can be fitted with certainty into this scheme. They have energies greater than the binding energies of Mg^{25} and Mg^{27} and they must be due, therefore, to Mg^{26} . Assuming that the neutron binding energy of Mg^{26} is 10.93 ± 0.10 Mev, these γ -rays can be accounted for in terms of transitions to excited states at 1.67 ± 0.11 and 2.77 ± 0.11 Mev, values which are in agreement with those given in Table IV. The strong γ -ray L appears to be the product of the transition from the latter state to the ground state. One other possible location for L is shown in the Mg^{25} scheme and yet others are possible which involve transitions between intermediate excited states.

There is little doubt concerning the assignment of the γ -rays E and G . Assuming that the neutron binding energy is that given in Table III and subtracting from this quantity the energies of these γ -rays, we obtain excited states in Mg^{25} at 0.58 ± 0.05 and 1.60 ± 0.05 Mev in good agreement with the level energies reported by Schelberg *et al.* In a similar manner, the γ -ray F , which, as pointed out above, can represent the ground-state transition in Mg^{27} , can also be accounted for by a transition in Mg^{25} leading to an excited state at 0.94 ± 0.05 Mev. It is possible that contributions to the coincidence peak at F are made by both these transitions; this point, however, can only be settled after more accurate measurements have been made of the energy of the γ -ray F and the binding energies of Mg^{25} and Mg^{27} .

The γ -ray H can be fitted into the decay scheme for

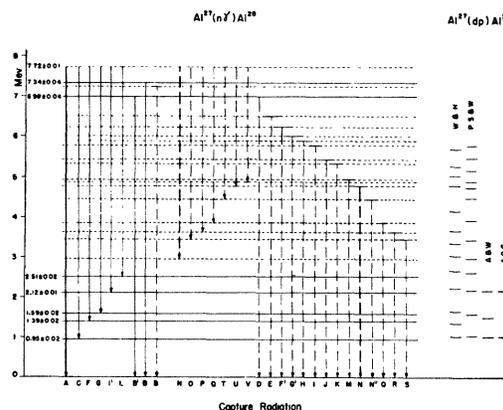


FIG. 14. Decay scheme for the capture γ -rays of aluminum. The positions of the energy levels of Al^{28} obtained from (d,p) reactions is given on the right; W and H : Whitehead and Heydenburg (reference 13); P , S and W : Pollard, Sailor, and Wylie; A and W : Allan and Wilkinson (reference 16); A and C : Allan and Clavier (reference 28). The positions of the energy levels obtained from the γ -ray measurements are shown on the left.

Mg^{25} in two ways. The γ -ray I is less easy to fit into a scheme for Mg^{25} and probably represents the de-excitation of the 5-Mev level in Mg^{26} .

The γ -ray J is remarkable in that its intensity, with the exception of that of L , is five times as great as that of any other radiation in the spectrum. The measured intensity of J is nearly one quantum per capture unless two γ -rays of equal energy contribute to the coincidence peak observed. This intensity is clearly much too high. While it is possible for J to originate in a cascaded pair of γ -rays in Mg^{26} , both components must possess the same energy for the profile of the coincidence peak has the width characteristic of a monochromatic γ -ray.

The sum of the energies of γ -rays J and K is 7.37 ± 0.09 Mev in agreement with the energy of γ -ray C . This suggests that J is produced by capture of neutrons in Mg^{24} . The level energies given by Schelberg *et al.* provide two possible routes for such a cascade process and these are shown in Fig. 11. However, while a considerable γ -ray intensity is associated with the peak at K , the energy is not well defined and it is not possible to choose between these alternatives.

IX. ALUMINUM

The sample was a cylinder of the pure metal, six inches long and four inches in diameter. Impurities were believed to be present in a total concentration of less than 0.01 percent by weight. The coincidence spectrum obtained with a line-width of 65 kev is shown in Fig. 12. There is only one stable isotope in aluminum, Al^{27} ; hence the entire spectrum is due to the de-excitation of Al^{28} . The most significant feature of the spectrum is the predominance of the γ -ray A which corresponds to a

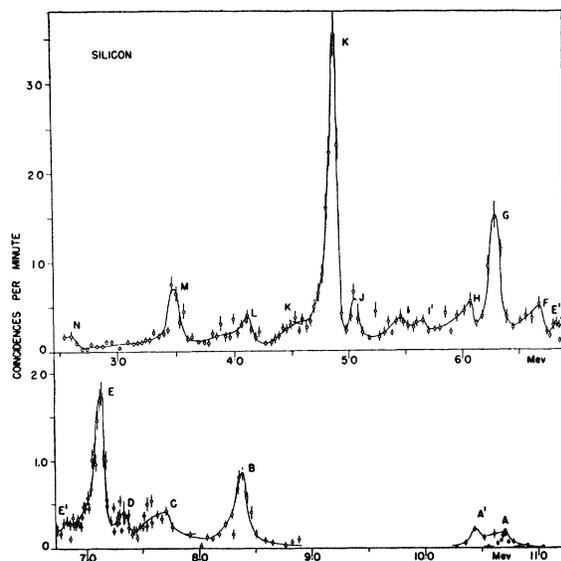


FIG. 15. Coincidence spectrum of silicon. The coincidence peak with an end point near 10.8 Mev is due to nitrogen; the measurements represented by the full circles were made under similar conditions with the silica sample withdrawn.

direct transition from the capturing state to the ground state in Al^{28} .

A detailed study of this γ -ray shows that it has an energy of 7.724 ± 0.010 Mev. There can be little doubt that it represents the direct transition to the ground state for its energy is in good agreement with the neutron binding energy in Al^{28} deduced from the energy balance in the (d,p) reaction. From the Q value obtained by Allan and Clavier,²⁸ the neutron binding energy found by the addition of the binding energy of the deuteron, is 7.73 Mev; from Allan and Wilkinson,¹⁶ 7.69 Mev; from Pollard, Sailor, and Wyly, 7.68 Mev; and from Whitehead and Heydenburg,¹³ 7.95 Mev. Recently, accurate measurements have been made by Enge, Van Patter, Buechner, and Sperduto,²⁹ using a magnetic method of analysis; they find a Q value of 5.494 ± 0.010 Mev, which is equivalent to a neutron binding energy of 7.724 ± 0.012 Mev, in very good agreement with our measurements. These authors have

TABLE VII. Energies and intensities of silicon capture γ -rays.

γ -ray	Energy in Mev	Intensity in photons per 100 captures
A'	10.55 ± 0.05	0.4
B	8.51 0.04	4
C	7.79 0.05	1
D	7.36 0.08	2
E	7.18 0.03	9
E'	6.88 0.03	0.7
F	6.76 0.04	4
G	6.40 0.03	19
H	6.11 0.05	4
I'	5.70 0.04	2
I	5.52 0.05	2
J	5.11 0.04	9
K	4.95 0.03	112
K'	4.60 0.08	4
L	4.20 0.03	19
M	3.57 0.06	94
N	2.69 0.05	65

found an excited state in Al^{28} only 31 kev above the ground state. The γ -ray A may well consist of two components which differ in energy by this amount, but the resolution of Fig. 12 is not sufficient to reveal them.

The absolute intensity of the γ -ray A was measured by the nickel method. Assuming that the cross section of aluminum is 212 mb we find that the intensity of this γ -ray is 0.35 photon per capture. The predominance of this γ -ray in the aluminum spectrum is well shown in Fig. 13, which is the corrected γ -ray spectrum obtained from Eq. (3), for a line width of 130 kev.

The energies and the intensities of the aluminum γ -rays are listed in Table V. The first column contains the designation of the γ -ray according to Fig. 12, the second, its energy, and the third the difference between its energy and that of the γ -ray A (the binding energy). In some cases, these differences represent the energies

²⁸ H. R. Allan and C. A. Clavier, *Nature* **158**, 832 (1946).

²⁹ Enge, Van Patter, Buechner, and Sperduto, *Phys. Rev.* **81**, 317 (1951).

of known excited states. The fourth column contains the designation of the γ -rays which have an energy nearly equal to the difference in the third column. The energies of a pair of γ -rays, such as V and M , or U and N' , add to give the energy of A , and these γ -rays, therefore, may be in cascade. The fifth column contains the intensity of the γ -rays in photons per capture, obtained by a comparison of the intensity relative to that of the γ -ray A .

The positions of the energy levels of Al^{28} at the present time are known only from the results of investigations of the (d,p) reaction. The results of four investigators are listed in Table VI. There is general agreement on the positions of the excited states up to 3 Mev, but above this energy agreement is less satisfactory. The experiments of Whitehead and Heydenburg seem to have been performed with a greater resolution than that of Pollard, Sailor, and Wyly; and above 3 Mev, for this reason, their results are to be preferred although their Q value for the ground-state transition in the (d,p) reaction differs widely from the rest.

With the aid of these results, and with that of similar data kindly furnished by Dr. D. M. Van Patter, the capture γ -rays have been fitted into the decay scheme shown in Fig. 14. This can be done with some assurance for the higher energy γ -rays since they probably represent transitions from the capturing state to levels up to 3 Mev. Of these, the γ -rays, C , F , G , I' , and L represent transitions to the first five excited states given by Whitehead and Heydenburg. The remaining γ -rays in this energy range, from B at 7.34 to K at 5.32 Mev, cannot be emitted by the capturing state. The broad coincidence peak B , which must represent more than one γ -ray, is of interest, for it is unlikely that it represents transitions from the capturing level to a group near 0.4 Mev, no level at this energy having been detected in the (d,p) process. The γ -rays B must, therefore, be direct transitions from levels with high excitation to the ground state. These levels must be excited by transitions of only 0.4 Mev from the capturing state.

The strong γ -ray N has an energy of 4.79 ± 0.02 Mev. It could be ascribed to a transition between the 7.72-Mev level and a state known to exist near 3.0 Mev, or it could represent the transition between a level at 4.78 Mev to the ground state. The latter level was found by Whitehead and Heydenburg and is produced by a strong group of protons from the (d,p) reaction.

The relatively strong γ -rays, O , P , and Q can be accounted for in terms of transitions to levels rather less well established between 3.4 and 3.9 Mev. The remaining γ -rays are harder to interpret in a reliable way. The lower energy γ -rays are poorly resolved, and while some of them can be accounted for as transitions to the ground state from known excited states, in many cases there are other alternatives. A distinction between these alternatives cannot be made on the basis of the present data

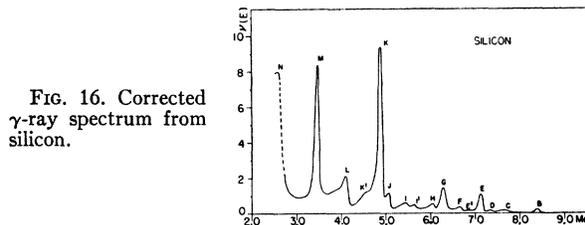


FIG. 16. Corrected γ -ray spectrum from silicon.

The positions of the energy levels deduced from the differences between the γ -ray energies and the binding energy has been included in the fifth column of Table VI where the identification is clear.

The contribution of the aluminum γ -rays to the total energy radiated is 6.7 Mev per capture. This low result, like that obtained with magnesium, suggests that many γ -rays are emitted with escape detection. The integrated energy [Eq. (4)] is 10.2 Mev.

X. SILICON

The silicon source consisted of chemically pure silicic acid. The amount of silicon in the material used was estimated by driving off the water in chemical combination at 1000°C and assuming that the remainder was pure silica, SiO_2 . Impurities were present in too low a concentration to affect the gamma-ray spectrum. Two separate surveys of the spectrum were made with the two types of sample container described above. The Dural spectrum seriously interfered with that of the silicon, and the results of the first experiment (with Dural end walls in the container) could only be used to confirm the energy measurements of the stronger γ -rays obtained from the second.

The silicon spectrum is shown in Fig. 15, which contains the results of the second experiment only. The region from 8.8 to 10 Mev is not covered, since the first experiment revealed the presence of no radiations above background in this region. One interesting feature of this spectrum is that radiation A appears to be double. The low energy component is a genuine silicon γ -ray, for its energy is in agreement with the neutron binding energy of Si^{30} .

The more energetic component, at 10.8 Mev, has the binding energy of a neutron in N^{15} . That nitrogen in the air in the experimental hole (see Fig. 1) is indeed the origin of the γ -ray A , is shown in Fig. 15 by the full circles which are the results of measurements made with the same pile power with the silicon sample withdrawn

TABLE VIII. Abundances, cross sections, and binding energies of silicon isotopes.

Target	Abundance percent	Contribution to cross section in millibarns	Binding energy product nucleus of in Mev
Si^{28}	92.2	156 ^a	8.476 ± 0.013
Si^{29}	4.7		10.53 ± 0.10
Si^{30}	3.1		6.597 ± 0.014

^a Reference 3.

^b Reference 4.

TABLE IX. Energies of the excited states of Si²⁹, Si³⁰, and Si³¹ in Mev.

Si ²⁹							
Endt <i>et al.</i> ^a Si ²⁸ (<i>d, p</i>)Si ²⁹	Endt <i>et al.</i> ^a P ³¹ (<i>d, α</i>)Si ²⁹	Motz, Humphreys ^b Si ²⁸ (<i>d, p</i>)Si ²⁹	Allan, Wilkinson ^c Si ²⁸ (<i>d, p</i>)Si ²⁹	Seidlitz <i>et al.</i> ^d Al ²⁹ (<i>β</i>)Si ²⁹			
1.273±0.010	1.286±0.020	1.29±0.04	1.29	1.25±0.20			
2.022±0.010	2.044±0.020	2.06±0.04	2.00				
2.426±0.010	2.443±0.020	2.43±0.04	2.41	2.35±0.20			
3.066±0.010	3.084±0.020	3.08±0.05					
3.620±0.010	3.631±0.020	3.60±0.05					
	4.090±0.020	4.09±0.06					
4.934±0.010	4.959±0.020	4.87±0.10					
Si ³⁰							
Pollard, Humphreys ^e Si ²⁹ (<i>d, p</i>)Si ³⁰	Motz, Humphreys ^b Si ²⁹ (<i>d, p</i>)Si ³⁰	Landon ^f Si ²⁹ (<i>d, p</i>)Si ³⁰	Livingston, Bethes ^g Al ²⁷ (<i>α, p</i>)Si ³⁰	Benson ^h Al ²⁷ (<i>α, p</i>)Si ³⁰	Brolley <i>et al.</i> ⁱ Al ²⁷ (<i>α, p</i>)Si ³⁰	Merhaut ^j Al ²⁷ (<i>α, p</i>)Si ³⁰	Alburger ^k γ-rays Al ²⁷ (<i>α, p</i>)Si ³⁰
0.9							
1.0							
2.8	2.4 ±0.2	2.4	2.28	2.28		2.24	
3.6	3.91±0.15	3.7	3.58	3.66	3.49	3.40	3.5±0.3
	5.00±0.15	5.0	4.75	4.6			
	5.7 ±0.2						
					5.44		
					7.18		
					8.20		
					9.26		
					9.87		
					10.86		
Si ³¹							
Motz, Humphreys ^b Si ³⁰ (<i>d, p</i>)Si ³¹			Metzger <i>et al.</i> ^l P ³¹ (<i>n, p</i>)Si ³¹	Van Patter <i>et al.</i> ^m Si ³⁰ (<i>d, p</i>)Si ³¹			
0.73±0.15			0.7±0.2	0.763±0.011			
1.23±0.15				1.701±0.10			
1.73±0.15							
2.33±0.15							

^a See reference 31.

^b See reference 30.

^c See reference 16; the 4.16-Mev *Q*-value obtained by these authors is assumed to correspond to the excited state at 2.00 Mev in Si²⁹, following Motz and Humphreys.

^d Seidlitz, Bleuler, and Tendam, Phys. Rev. **76**, 861 (1949).

^e See reference 25.

^f H. H. Landon, Phys. Rev. **78**, 338 (A) (1950).

^g See reference 24.

^h See reference 36.

ⁱ See reference 35.

^j O. Merhaut, Z. Physik **115**, 77 (1940).

^k See reference i, Table IV.

^l Metzger, Alder, and Huber, Helv. Phys. Acta **21**, 278 (1948).

^m See reference 34.

from the hole. Both the peak coincidence counting rate of *A* and its energy have the values to be expected of the ground-state γ-ray produced by capture in nitrogen.

The energies and intensities of the silicon radiations are given in Table VII. The intensities were determined by the nickel calibration method. The corrected γ-ray spectrum of silicon is shown in Fig. 16.

The stable silicon isotopes are Si²⁸, Si²⁹, and Si³⁰. The binding energy of Si²⁹ may be obtained from the *Q*-value of the (*d, p*) reaction after addition of the binding energy of the deuteron. For the former, Allan and Wilkinson¹⁶ obtained 6.16±0.06 Mev and Motz and Humphreys³⁰ have obtained 6.18±0.09 Mev. Recently, the M.I.T. group³¹ have found the more accurate value 6.246±0.010 Mev, from which it may be deduced that the binding energy of Si²⁹ is 8.476±0.013 Mev.

The group of protons producing the ground state of Si³⁰ in the reaction Si²⁹(*d, p*)Si³⁰ has recently been measured by Motz and Humphreys,³⁰ who find a *Q* value of 8.36±0.10 Mev, which is equivalent to a binding

energy in Si³⁰ of 10.59±0.10 Mev. The same quantity may be estimated from the *Q*'s of other reactions in two ways with an accuracy better than that obtained from the (*d, p*) measurements. By adding the equations:

$$P^{31} + d = Si^{29} + \alpha + 8.170 \pm 0.020 \text{ Mev},^{31}$$

$$Si^{30} + d = Si^{31} + p + 4.364 \pm 0.010 \text{ Mev},^{15}$$

$$Si^{31} = P^{31} + 1.50 \pm 0.02 \text{ Mev},^{32}$$

the neutron binding energy of Si³⁰ is found to be 10.60 ± 0.06 Mev. Again, the addition of the following equations:

$$Si^{30} + d = Al^{28} + \alpha + 3.120 \pm 0.010 \text{ Mev},^{15}$$

$$Si^{28} + d = Si^{29} + p + 6.246 \pm 0.010 \text{ Mev},^{31}$$

$$Al^{28} = Si^{28} + 4.81 \pm 0.05 \text{ Mev},^{20}$$

leads to a neutron binding energy of 10.37±0.06 Mev. This result is appreciably less than the previous one and the discrepancy may arise from an overestimate of the decay energy of Al²⁸. For this quantity, the result used above, *viz.*, that obtained by Benes *et al.*,²⁰ is much

³⁰ H. T. Motz and R. F. Humphreys, Phys. Rev. **80**, 595 (1950).

³¹ Endt, Van Patter, and Buechner, Phys. Rev. **81**, 317 (1951).

³² H. W. Newson, Phys. Rev. **51**, 624 (1937).

higher than that obtained by Bleuler and Zünti, but it should be much more accurate.

The neutron binding energies of Si^{29} and Si^{30} may also be calculated from the masses obtained by Duckworth and his associates³³ and from the mass of the neutron given by Tollestrup, Fowler, and Lauritsen. For the binding energy of Si^{29} we obtain 8.46 ± 0.15 Mev, and for that of Si^{30} , 10.95 ± 0.19 Mev. The first of these values is in good agreement with that obtained from the (d,p) reaction, but the second is much higher.

The Q values obtained for the $\text{Si}^{30}(d,p)\text{Si}^{31}$ reaction are in good agreement. Motz and Humphreys³⁰ obtained 4.33 ± 0.15 Mev, and more recently the M.I.T. group³⁴ have found 4.364 ± 0.010 Mev. The latter figure leads to 6.597 ± 0.012 Mev for the neutron binding energy in Si^{31} . Allan and Wilkinson¹⁶ obtained 4.16 ± 0.06 Mev, a value which, as pointed out by Motz and Humphreys,³⁰ is probably due to $\text{Si}^{28}(d,p)\text{Si}^{29}$.

The binding energies of the silicon isotopes relevant to the present discussion are collected in Table VIII. For the binding energies of Si^{29} and Si^{31} we have chosen the M.I.T. values as probably the most accurate; for that of Si^{30} , we have taken a weighted mean of all the results calculated above.

The most energetic silicon γ -ray, A' in Table VII, has an energy of 10.55 ± 0.05 Mev and clearly corresponds to the ground-state transition in Si^{30} . The γ -ray B , with an energy of 8.51 ± 0.05 Mev, is probably the ground-state transition in Si^{29} for its energy is in agreement with the neutron binding energy of that isotope. However, this identification cannot be regarded as established, for there is good evidence for the existence of an excited state in Si^{30} near 2.3 Mev (Table IX), and it is not impossible that B may be associated with a transition to this level following capture in Si^{29} . The only γ -ray near 6.6 Mev which would correspond to a transition to the ground state in Si^{31} , is the γ -ray F (6.76 ± 0.04 Mev). This would seem to have too high an energy. The intensity of F is only 4 photons per 100 captures, which is what is to be expected if all the energy produced by capture in Si^{30} were concentrated in one γ -ray. Thus, unless a large proportion of the captures in Si^{30} produced the 6.6-Mev γ -ray, the capture radiation of that isotope would probably not be detected by the present apparatus. No γ -rays leading to the excited states of Si^{31} (see Table IX) can be identified in Fig. 15.

The energies of the excited states of the silicon isotopes are listed in Table IX, and in Fig. 17 an attempt has been made to fit the capture γ -rays to the known levels of Si^{29} and Si^{30} . The positions of the excited states of Si^{29} have been obtained by Endt *et al.*,³¹ in two different reactions and the results are consistent within themselves and with those of other experimenters. In Si^{30} , there is general agreement about the existence of levels

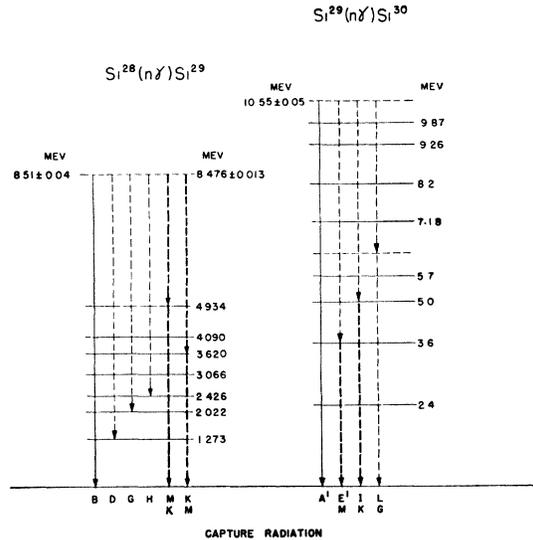


FIG. 17. Decay scheme for the capture γ -rays of silicon. The positions of the energy levels of Si^{29} are those obtained by Endt and co-workers (reference 31), from a study of the (d,p) reaction. The energies of the levels of Si^{30} from 7.18 Mev upwards, are those given by Brolley, Sampson, and Mitchell (reference 35), and below that energy, a mean value of the results of various experimenters.

near 2.3 and 3.6 Mev, and some evidence for another near 4.6 Mev. There is a well-established level near 5.0 Mev and another, according to Motz and Humphreys, at 5.7 Mev. From 5.4 Mev upwards a series of levels have been reported by Brolley, Sampson, and Mitchell³⁵ of which the energies are based on results obtained by Benson.³⁶

The outstanding feature of Figs. 15 and 16 is the strength of the two γ -rays K and M , which have a comparable intensity and are much stronger than any others in the spectrum. The sum of the energies of these two γ -rays is 8.52 ± 0.07 Mev, which is in very good agreement with that of the γ -ray B and with the neutron binding energy in Si^{29} . It follows that the greater part of the silicon capture cross section is due to Si^{28} and leads to the emission of these two γ -rays. They can be fitted into the scheme of Fig. 17 in two ways. (1) The γ -ray K , 4.95 ± 0.03 Mev, can represent a transition to the ground state from the level with the energy of 4.934 ± 0.010 Mev (see Table IX). The γ -ray M , 3.57 ± 0.06 Mev, could therefore, represent a transition from the capturing state to this level; subtracting the energy of that level from the binding energy (Table VIII) we obtain 3.542 ± 0.015 Mev, which differs from that of M by only 28 kev. (2) M may also be identified with a transition to the ground state from the level at 3.620 ± 0.010 Mev. K could then be due to the transition from the capturing state to this level; the energy difference in this case is 4.856 ± 0.015 Mev. This quantity is less than the energy of K by nearly 100 kev or three

³³ Duckworth, Preston, and Woodcock, Phys. Rev. **79**, 188 (1950). H. E. Duckworth and R. S. Preston, Phys. Rev. **79**, 402 (1950).

³⁴ Van Patter, Enge, and Buechner, Phys. Rev. **82**, 304 (1951).

³⁵ Brolley, Sampson, and Mitchell, Phys. Rev. **76**, 624 (1949).

³⁶ B. B. Benson, Phys. Rev. **73**, 7 (1948).

times the probable error of the latter. Although the second scheme cannot be ruled out, the first is clearly to be preferred. A clear distinction between the two alternatives will require more accurate measurement and is much to be desired, for it is remarkable that the excitation of the 4.93-Mev level is the one most frequently occurring in the (d,p) process.³⁰

As shown in Fig. 17 both K and M can be made to combine with the energy levels of Si^{30} , for the sum of the energies of K and I , and of E' and M are 10.47 ± 0.06 and 10.45 ± 0.07 Mev, respectively. Possibly a small fraction of the peak counting rates of K and M are due to transitions of this kind. If K and M were entirely due to Si^{30} , their high intensities would be difficult to explain. For this reason, it is better to assume that they are the result of a simple cascade process in Si^{29} .

Few of the other γ -rays can be identified with any certainty. The γ -rays C and D are not well defined in Fig. 15. D may correspond to the production of the first excited state in Si^{29} ; if this is true, the energy of this excited state is 1.12 ± 0.09 Mev which is not in good agreement with the value found by Endt *et al.*, *viz.*, 1.273 ± 0.010 Mev. The γ -rays G and H correspond to transitions leading to excited states at 2.08 ± 0.05 and 2.36 ± 0.06 Mev, respectively, in only fair agreement with the positions of the energy levels given in Table IX. A part of G may also be associated with L , for the sum of L and G is 10.60 ± 0.05 Mev, in agreement with the neutron binding energy of Si^{30} . This assignment would introduce a level at 6.4 Mev which is not substantiated by any other evidence.

It is clear from a consideration of Table VII and Fig. 17 that the sum of the intensities of the γ -rays emitted by silicon exceeds the rate of neutron capture. The sum of the energies of the γ -rays of Table VII is $S = 15.5$ Mev, which greatly exceeds the highest binding energy in the Si isotopes. The computation of S ignores the unresolved background; when this is taken into account, the integrated energy is $S' = 23$ Mev.

XI. DISCUSSION

The large number of γ -rays observed from aluminum seems remarkable at first sight. However, the resolution used in this case (65 kev) was twice that employed with the other elements. The relative simplicity of the spectra obtained from magnesium and silicon may be due to the lower neutron capture rate used with these elements (18 percent of the aluminum capture rate for magnesium and 7 percent for silicon). If it had been possible to increase the amount of sample material to give a capture rate similar to that of aluminum, it is possible that the low intensity backgrounds of Figs. 9 and 15 could have been examined with 65-kev resolution and many more γ -rays would have been detected. However, this is not true of sodium, where the neutron capture rate was about 50 percent of that of the aluminum sample.

The sharp contrast between the strong transitions

to the ground states in fluorine and aluminum and the weak transitions in sodium, magnesium, and silicon calls for some comment.

The relatively high absolute intensity of the fluorine γ -ray and the existence⁸ of numerous excited states in F^{20} between the ground state and the neutron binding energy, suggest, by analogy with the aluminum spectrum, that the 6.63-Mev γ -ray is predominant in the spectrum of fluorine. This would place fluorine among the few nuclei which produce, in the product nuclei, strong transitions leading directly to the ground states.³⁷ The capturing state of F^{20} which is responsible for the emission of the γ -ray must have a spin of 0 or 1 and even parity, for it seems to be established from a consideration of the spin (1/2) and magnetic moment of F^{19} and of the angular correlation of the γ -rays and α -particles in the $\text{F}^{19}(p,\alpha)\text{O}^{16}$ reaction,³⁸ that the parity of F^{19} is even. Recently, a weak β -transition has been observed³⁹ between the ground states of F^{20} and Ne^{20} and if this transition is second forbidden, as its intensity would indicate, the parity of the ground state of F^{20} is even and the spin is 2 or 3. It follows that the 6.63-Mev γ -ray produces no change in parity and therefore is of the magnetic dipole or electric quadrupole type. This capture γ -ray is one of the very few for which it is possible, at the present time, to determine the order of multipolarity on the basis of experimental rather than theoretical evidence.

The strong transition to the ground state of Al^{28} seems to be of the same multipole order as that of the γ -ray from F^{20} , for recently, Butler,⁴⁰ from a consideration of the angular distribution of the protons, has shown that the production of Al^{28} in its ground state from the (d,p) reaction occurs with the transfer of a neutron with zero orbital angular momentum. The spin of Al^{27} being 5/2, it follows that the spin of Al^{28} is 2 or 3, and its parity is the same as that of Al^{27} . These results are consistent with the β -disintegration of Al^{28} for the β -rays which pass to the ground state of Si^{28} have not been detected and must be at least first forbidden.

It seems possible to account for the absence, or weakness, of the ground-state transition which follows the capture of neutrons in sodium in terms of the high angular momentum which would be radiated in that γ -ray. The spin of the level responsible for the first neutron resonance in sodium at 3 kev is 2 units⁴¹ and it is probable that this state is the one most frequently excited by neutrons at thermal energies. Now the half-life and β -decay energy of Na^{24} correspond to a first-forbidden transition which is followed by the successive emission of two γ -rays from excited states in Mg^{24} . The spin of the uppermost state excited in this sequence is probably 4 and that of the lower state, probably 2 units.

³⁷ Kinsey, Bartholomew, and Walker, *Phys. Rev.* **78**, 481 (1950).

³⁸ Barnes, French, and Devons, *Nature* **166**, 145 (1950).

³⁹ R. M. Littauer, *Phil. Mag.* **41**, 1214 (1950).

⁴⁰ S. T. Butler, *Phys. Rev.* **80**, 1095 (1950).

⁴¹ Hibdon, Muehlhause, Selove, and Woolf, *Phys. Rev.* **77**, 730 (1950).

Recently, Grant⁴² has attempted to detect the β -transition to the lower level of Mg^{24} and has shown that it must be at least three degrees more forbidden than that to the higher level. He has concluded that the decay of Na^{24} is consistent, on the current theories of β -disintegration, only with the observed β -decay being of the allowed-unfavored type, the spin of Na^{24} in its ground state being 5 units. If this is true, it follows that the capture γ -ray producing Na^{24} in its ground state must radiate 3 units of angular momentum. This should be sufficient to forbid its emission to a high degree. The parity change, however, associated with this radiation cannot be directly determined.

The weakness of the magnesium and silicon ground-state γ -rays are difficult to explain in terms of changes in parity or spin. The spin of the even isotopes of magnesium being zero, and that⁴³ of Mg^{25} being 5/2, a minimum of two units of angular momentum must be radiated in the direct transition to the ground state. That required for the ground-state transition in Mg^{26} is two or three depending on the orientation of the spin of Mg^{25} at the resonance responsible for the thermal neutron capture. The spin changes involved in the silicon γ -rays are not known, for the spin of Si^{29} is not established with certainty. If the spin⁴⁴ of Si^{29} is 1/2, spin changes alone will not account for the weakness of the ground-state transition in Si^{29} due to the capture of neutrons in Si^{28} . The same is true in Si^{30} , for the intensity of the ground-state γ -ray (A') is weak compared with that of the other γ -rays ascribed to this isotope. Probably for both magnesium and silicon, the origin of the weakness of the ground state γ -rays is to be found in specific properties of the ground states other than those concerned with spin and parity.

The recent measurements on the angular distribution of the (d,p) reaction in aluminum would seem, at first sight, to provide a clue to the solution of this problem. As pointed out above, Butler⁴⁰ has shown that Al^{28} is formed in its ground state by addition to Al^{27} of a neutron without orbital angular momentum. Now if we consider an extreme independent particle model of the nucleus, in which the motions of the nucleons are still independent at excitation energies in the neighborhood of the neutron binding energy, and if, in addition, we assume that the spin of the ground state of an odd nucleus is determined by the total angular momentum of the odd nucleon, it follows that the resonance responsible for the capture of a thermal neutron must correspond to a configuration in which the neutron enters an s -orbit, for the neutron can contribute no orbital angular momentum. Both the capturing state and the ground state in Al^{28} contain s -orbits for the unpaired neutron and from experiment we know that the transition between them is a probable one. This unusual com-

bination of circumstances suggests that the condition for the emission of a strong ground-state γ -ray is that the ground-state configuration should contain an s -neutron orbit. Such an hypothesis clearly cannot apply to those heavier nuclei which produce strong ground-state γ -rays and to which, according to the current theories of shell structure, the addition of a neutron produces a change of parity. It also does not account for the intensities of the ground-state γ -rays of fluorine and of the silicon isotopes. However, it does seem to explain the weakness of the magnesium ground-state γ -rays and those of other elements for which the shell structure theories indicate that there is no difference in parity between adjacent isotopes.

The spin of Mg^{25} is 5/2 and, from the shell scheme of Mayer,⁴⁵ is presumably due to the 13th neutron being in a $d_{5/2}$ -orbit, the subshell being completed in Mg^{26} . This is consistent with the assumption that the 13th proton in the aluminum isotopes is in a $d_{5/2}$ -orbit for the positron decay of Al^{25} and Al^{26} , which are both super-allowed, occur without the emission of γ -radiation, showing that the wave function of the odd neutron and proton are very similar. Thus the weakness of the ground-state γ -ray in Mg^{25} and the failure to detect the corresponding γ -ray in Mg^{26} may be explained on the hypothesis discussed above as being due to a transition between an s - and a d -neutron orbit.

The capture of neutrons by Mg^{26} might be expected to follow a course similar to that of Al^{27} , for the latter differs from the former only by the presence of a proton. We have already discussed the possibility that the γ -ray produced by the direct transition to the ground state in Mg^{27} may be a strong one, and we have pointed out that further measurements are required to settle this point. If the 15th neutron in Mg^{27} is in an s -orbit, the forbidden nature of the β -decay of that nucleus to the ground state of Al^{27} is easily understood, and this mode of disintegration, like the similar one in Al^{28} , is at least first and probably second forbidden.

If the spin of Si^{29} is 1/2 and the 15th and 16th neutrons in Si^{29} and Si^{30} are in s -orbits, strong ground-state γ -rays might be expected from these nuclei contrary to the results of experiment. The value 1/2 for the spin of Si^{29} is consistent with the assumption that the proton in the phosphorus isotopes is in a similar orbit, for the spin of P^{31} (which has an even number of neutrons) is 1/2 and the super-allowed positron disintegration of P^{29} shows that the orbit of the 15th proton in that nucleus is identical with that of the 15th neutron in Si^{29} . If, on the contrary, we assume that the neutron in Si^{29} is in a $d_{3/2}$ -orbit, it follows that the odd proton in the phosphorus isotopes must change from a $d_{3/2}$ to an $s_{1/2}$ -level at P^{31} . The possibility of such re-arrangements has been discussed by Nordheim.⁴⁶

While there is, as yet, no confirmation of this re-ar-

⁴² P. J. Grant, Proc. Phys. Soc. (London) **63**, 1298 (1950).

⁴³ Crawford, Kelly, Schawlow, and Gray, Phys. Rev. **76**, 1527 (1949).

⁴⁴ Townes, Mays, and Dailey, Phys. Rev. **76**, 700 (1949).

⁴⁵ M. G. Mayer, Phys. Rev. **78**, 16 (1950).

⁴⁶ L. W. Nordheim, Phys. Rev. **75**, 1894 (1949).

rangement in the phosphorus isotopes, there is evidence that the configuration of the odd proton changes in the fluorine isotopes with increasing neutron content. For the super-allowed positron disintegrations of F^{17} and F^{18} suggest that the unpaired protons in these nuclei are converted into neutrons in the same orbit in the corresponding oxygen isotopes. But the spin⁴⁰ of O^{17} is probably $3/2$ or $5/2$ showing that the unpaired proton in F^{17} is in a d -orbit. The spin of F^{19} , however, which has an even number of neutrons, is $1/2$ and its parity and magnetic moment clearly show that the unpaired proton in this isotope is in an s -orbit. The strength of the fluorine ground-state transition is difficult to explain on the basis of the hypothesis discussed above. If the forbidden nature of the β -decay between the ground

states of F^{20} and Ne^{20} means that the spin of the former nucleus is 2 or 3 units, one would expect that the odd neutron in F^{20} is in a $d_{5/2}$ -orbit and that the addition of a neutron to F^{19} should produce a weak ground-state γ -ray. Therefore, the criterion for a strong ground-state γ -ray suggested by aluminum, *viz.*, that in the ground state of the product nucleus, the last neutron should be an s -orbit, does not appear to be generally applicable. Information about the spin of the ground state of F^{20} , possibly obtained by the angular distribution of the protons from the (d,p) reaction, and a confirmation of the spin of Si^{29} would contribute to the solution of this problem.

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Secondary Emission of Electrons from Liquid Metal Surfaces

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The secondary emission ratio as a function of primary energy is determined for targets of bismuth, gallium, lead, and mercury for the metals in both the liquid and solid state. The secondary emission characteristics for liquid surfaces are shown to be very nearly like those for solid surfaces, and in general the shape of the secondary efficiency curves for these materials are similar to those for other pure metals. A comparison of the observed maximum secondary ratios with predicted values is made.

I. INTRODUCTION

THE secondary emission characteristics of many pure metals in the solid state have been well investigated by many workers. For these targets the secondary emission ratio as a function of primary energy shows a broad maximum of about two secondaries per primary for primary energies in the range of 300 to 500 electron volts. However, the characteristics for targets in the liquid state have not been examined. The purpose of this paper is to report the results of such an investigation on targets of bismuth, gallium, lead, and mercury.

Since a good vacuum must be maintained above the surface being examined, metals with appreciable vapor pressures near their melting points must be avoided. This requires that targets be selected that have their melting and boiling points separated by a large temperature difference. For practical reasons, metals with high melting points cannot be used, since it is desired to carry out the work in a Pyrex envelope. Finally, the alkali metals were abandoned because of their chemical activity. These considerations reduced the possible target materials to four: bismuth, gallium, lead, and mercury. These metals are easily melted, have very low vapor pressures in the liquid state, and are not extremely active chemically.

II. EXPERIMENTAL TECHNIQUE

The experimental tube designed to carry out this work is shown in Fig. 1. The electron gun system consists of a tungsten filament surrounded by a nickel anode cylinder covered at one end except for a three-millimeter aperture. The rear end of the cylinder is covered by a disk attached to the negative filament lead to prevent the escape of electrons in this direction. Two nickel disks with four-millimeter apertures are mounted coaxially with the cylinder. Electrons emitted by the filament escape through the first aperture and are focused on the target by electric fields set up by the disks. The potential of the middle electrode is negative with respect to the other disks. The use of this electron lens system produces a primary beam very homogeneous in energy because secondary electrons produced on the electrodes are prevented from becoming part of the beam. Secondaries produced at the first aperture are returned to the cylinder because of the negative potential gradient in the first space. Few secondaries are produced at the second aperture since the net energy of the primary electrons at this point is very low. Finally, because of the focusing action no primaries strike the last disk and no secondaries are produced here.

A nickel cylinder open at both ends is positioned