# Neutron-Capture $\gamma$ Rays from Various Elements

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(Received January 26, 1956)

Neutron-capture $\gamma$-ray spectra have been measured in the energy range 0.3 to 3 Mev by means of a two-crystal Compton scintillation spectrometer. The efficiency of the instrument as a function of energy was determined experimentally. The uniqueness of the 2.23-Mev $\gamma$ ray following capture of a neutron by hydrogen has been confirmed, and this $\gamma$ ray was used as a standard to establish the absolute intensity of $\gamma$ rays from other elements.

Most of the $\gamma$ rays observed can be understood in terms of known levels, and many appear to be emitted in transitions from such levels to the ground state. In many cases, the information obtained complements high-energy data in establishing preferred modes of decay of the product nucleus.

In sodium a very strong $\gamma$ ray is emitted from the first excited state of $Na^{24}$ at 0.47 Mev, and another ground-state $\gamma$ ray appears to be emitted from the level at 1.34 Mev. The strongest $\gamma$ ray in the magnesium spectrum is an $E1$ transition between the levels at 3.41 and 0.58 Mev in $Mg^{25}$. The aluminum spectrum is very complex, and only a few peaks have been resolved. A ground-state transition is seen from the level at 2.27 Mev in $Al^{28}$.

In silicon two $E1$ transitions are observed from the capturing level to the levels at 4.93 and 6.38 Mev, and a ground-state transition is seen from the first excited state at 1.28 Mev. Ground-state transitions are observed from the levels at 0.52, 1.15, and 2.18 Mev in $P^{32}$. In sulfur, there is a strong ground-state $\gamma$ ray from the first excited state at 0.84 Mev, and a strong $E1$ transition to this level from that at 2.34 Mev.

In chlorine almost all of the observed $\gamma$ rays can be understood as ground-state transitions from known levels in $Cl^{36}$ at 0.79, 1.16, 1.95, 2.47, and 2.87 Mev. In $K^{40}$ the decay scheme involves several level to level transitions. $\gamma$ rays to the ground state are observed from the levels at 2.05 and 3.40 Mev in $K^{40}$, and possibly from the 1.18-Mev level in $K^{42}$.

The spectra from calcium and titanium are very simple. A strong $\gamma$ ray occurs almost once per capture in $Ca^{40}$ from the 1.95-Mev first excited state of $Ca^{41}$, and a strong $\gamma$ ray from the 1.39-Mev first excited state of $Ti^{49}$ occurs almost once per capture in $Ti^{48}$.

In $V^{52}$ most of the observed $\gamma$ rays are emitted by levels below 1 Mev. Ground-state transitions occur from the levels at 0.42 and 0.83 Mev. In $Cr^{54}$ a very strong $\gamma$ ray to the ground state is emitted by the level at 0.84 Mev, and a weak transition may be from the 0.54-Mev level in $Cr^{53}$ to the ground state.

$\gamma$ rays to the ground state are observed from levels at 0.42 and 0.88 Mev in $Ni^{59}$. No definite identification can be made of the four $\gamma$ rays observed from zinc. The $Cd^{114}$ spectrum contains many unresolved radiations; by far the most intense is the 0.56-Mev $\gamma$ ray which is emitted from the first excited state.

## I. INTRODUCTION

EXTENSIVE measurements of the spectra of $\gamma$ radiation following the capture of slow neutrons by nuclei have been made by Kinsey, Bartholomew, and Walker by means of a magnetic pair spectrometer.[1] The information obtained, however, is limited to the energy range above 3 Mev, and measurements at lower energies are necessary to confirm decay schemes.

Measurements at lower energies have been made with single-crystal scintillation spectrometers[2–4] where it is difficult to see any but the most prominent peaks. In a few cases Motz[5] and Groshev *et al.*[6] have employed special magnetic spectrometers.

A preliminary report[7,8] has been made of $\gamma$-ray energies observed in the range 0.3 to 3 Mev by means of a two-crystal Compton scintillation spectrometer[9] and in the present paper a complete account is given of the measured energies and intensities of the $\gamma$ rays from fifteen elements.

Two-crystal spectrometers have also been employed for this purpose by Reardon, Krone, and Stump[10] and by Reier and Shamos.[11]

The $\gamma$ rays were produced in samples placed in the neutron flux of the Chalk River reactor. The variation with energy of the efficiency of the spectrometer was determined by an empirical method and the absolute intensities of the $\gamma$ rays in the spectra were obtained by comparison with the $\gamma$ ray following neutron capture in hydrogen, which occurs once per capture. The energy resolution was not high, and for this reason not all of the $\gamma$ rays appear to have been observed, but in many cases it has been possible to complement the pair spectrometer data and establish the preferred modes of decay of the excited nuclei.

No radiations were observed above background from carbon and nitrogen, the capture cross sections being very small. The spectra from manganese, iron, cobalt, copper, and arsenic were examined, but it was found that too many $\gamma$ rays were present to be resolved by the spectrometer.

## II. APPARATUS

The general experimental arrangement is shown in Fig. 1, together with a block diagram of the electronic circuits. A sample of the element under investigation was placed near the reacting vessel of the Chalk River

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[1] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. **31**, 537 (1953).
[2] B. Hamermesh and V. Hummel, Phys. Rev. **88**, 916 (1952).
[3] Thornton, der Mateosian, Motz, and Goldhaber, Phys. Rev. **86**, 604 (1952).
[4] Pringle, Taylor, and Roulston, Phys. Rev. **87**, 1016 (1952).
[5] H. T. Motz, Phys. Rev. **90**, 355 (1953), and **93**, 925 (1954).
[6] Groshev, Demidov, and Adyasevich, Geneva Conference, 1955 (to be published).
[7] T. H. Braid, Phys. Rev. **90**, 355 (1953).
[8] T. H. Braid, Phys. Rev. **91**, 442 (1953).
[9] R. Hofstadter and J. A. McIntyre, Phys. Rev. **78**, 619 (1950).
[10] Reardon, Krone, and Stump, Phys. Rev. **91**, 334 (1953).
[11] M. Reier and M. H. Shamos, Phys. Rev. **95**, 636 (1954), and **100**, 1302 (1955).

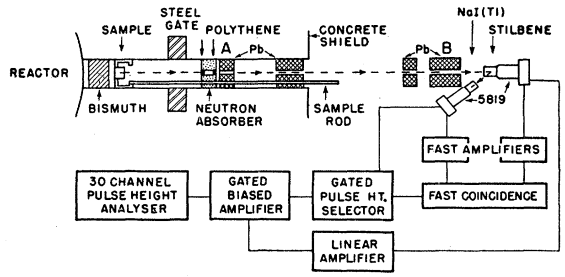


FIG. 1. Physical arrangement of spectrometer and block diagram of the electronics. The lead blocks at $A$ and $B$ collimate the beam through $\frac{1}{4}$ inch apertures. The sample and the spectrometer are 18 feet apart. Additional shielding surrounding the spectrometer is not shown.

pile and a finely collimated beam of $\gamma$ rays, emitted after capture of slow neutrons, was brought out through the shielding to the two-crystal spectrometer.

Since the energy range of interest extended well below the threshold for pair production, the Compton effect was used in the spectrometer and every effort was made to suppress any contribution from the pair effect. A coincidence between the two crystals indicated a $\gamma$ quantum which had undergone in the center crystal a Compton scattering between 130 and 160 degrees. In this case the pulse-height distribution from the center crystal shows a single peak for each energy present in the incident $\gamma$-ray spectrum.[9] The center crystal was a *trans*-stilbene cylinder, 2 cm high and 2 cm in diameter. This was chosen in preference to NaI(Tl) despite its poorer energy resolution because the absence of a pair peak made interpretation of spectra simple. The off-center crystal was NaI(Tl), 2 inches in diameter and 1 inch high. RCA 5819 photomultipliers were used. For a count to be registered, a coincidence was required and also the pulse from the off-center crystal was required by a single-channel pulse-height analyzer to lie in the energy range 120–250 kev. This latter requirement reduced background considerably. The amplified pulses from the center crystal were fed through a gate and a biased amplifier to a thirty-channel pulse-height analyzer. By varying the amplifier bias, spectra could be displayed over a range of seventy channels.

The elements investigated were contained in cylindrical aluminum sample cans, 3 inches by 2 inches diameter, with ends of 0.005-inch aluminum foil. The cans were mounted, in a cradle, centrally in the 4-inch diameter hole through the pile shielding. The collimation was arranged so that only the central portion (about 1 inch diameter) of the sample was visible to the spectrometer. A 9-inch thick bismuth block heavily attenuated direct radiation from the pile. Shielding and collimating lead blocks were placed in the pile hole outside the region of slow-neutron flux and at the spectrometer itself. A boron-paraffin neutron shield was also used but a hole along the axis was left for the passage of $\gamma$ rays. Here only 2 cm of polythene were placed to scatter some neutrons from the beam. A thin sheet of cadmium removed thermal neutrons. The sample could be moved very quickly in or out of the neutron flux by means of a long rod. This meant that $\gamma$ rays whose origin was not the $(n,\gamma)$ process, but radioactive decay of a product nucleus, could quickly be studied behind the steel gate with the same collimation and solid angle as when the sample was in the flux.

Figure 2 shows some typical line shapes. The long flat tail extending down to low energies in the $Na^{24}$ spectrum was due mainly to end effect in the crystal and in part to radiation penetrating the lead collimator and scattering. No contribution from the pair effect was visible above statistical uncertainties on this tail. The peak from the 280-kev $\gamma$ ray of $Hg^{203}$ was symmetrical and had the expected width but that from the 238-kev $\gamma$ ray of ThB was distorted as pulses from the low-energy side became too small to operate the coincidence circuit reliably. The lower useful limit of the spectrometer was therefore taken to be 300 kev.

The energy calibration was made with thirteen known $\gamma$ rays in the range 238 kev to 2.76 Mev.

Intensities were measured by taking the area under the peak and neglecting the flat tail. The efficiency of the instrument as a function of energy was found empirically and is shown in Fig. 3. The points shown were found in a variety of ways. Six were obtained from substances in which the decay scheme is clearly established, $Hg^{203}$, $Au^{198}$, $Cs^{137}$, $Co^{60}$, and $Na^{24}$. The sources were normalized to the same disintegration rate by means of an ionization chamber.[12]

To the curve given by these points three sets of relative points were fitted. One set was from $Na^{22}$, and another from ThB and ThC″ in equilibrium. In the latter case the $L$ and $M$ $\gamma$ rays were not resolved, and the $(L+M)/X$ intensity ratio was taken to be 1.2.[13] The third set was obtained by exposing hydrogen, boron, and aluminum to the slow-neutron flux in the arrangement of Fig. 1, and comparing the counting rates for the $H(n,\gamma)D$, $B^{10}(n,\alpha\gamma)Li^7$, and $Al^{28}$ $\gamma$ radiations. Of these, the first and third occur once per capture

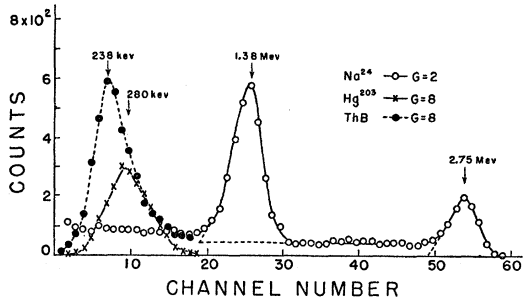


FIG. 2. Typical line shapes. The amplifier gain for $Hg^{203}$ and ThB was four times that for $Na^{24}$. The dotted lines on the $Na^{24}$ peaks show the area taken for intensity measurements.

[12] G. C. Laurence, Can. J. Research **A15**, 67 (1937).
[13] L. G. Elliot (private communication).

and the second 0.93 times per capture.[14] The $Al^{28}$ radiation was counted as the activity decayed behind the steel gate after the sample had been withdrawn from the flux. Thus there was no background from the aluminum $(n,\gamma)$ process.

The accuracy of the efficiency calibration was ten percent or better in the range 280 kev to 2.76 Mev. A standardized $Co^{60}$ source was used to establish the absolute efficiency at 1.25 Mev, (the mean energy of the $Co^{60}$ $\gamma$ rays) as $5\times10^{-4}$/quantum/cm$^2$. Only the relative efficiency for different energies was required in the $(n,\gamma)$ measurements, however.

A daily check of the efficiency was made by counting the $(L+M)$ peak from a thorium source and the 280-kev peak from $Hg^{203}$. The stability at 0.54 Mev was as good as the statistical uncertainty of 3% in the determination over a period of several months, and the variation at 280 kev was not more than 5%.

## III. PROCEDURE

### Background

The background spectrum which was obtained with an empty sample can in position is shown in Fig. 4(a). The peak at 0.51 Mev was attributed to pair production in the bismuth block by $\gamma$ rays from neutron capture in the surrounding material. There was a distribution at lower energy with a broad maximum near 250 kev, presumably due to backward Compton scattering of such $\gamma$ rays. The weak continuous spectrum above 0.51 Mev, extending to the highest energy measured, showed no maxima at all, and no radiations could be assigned to captures in bismuth. The $\gamma$ rays arising from captures in the thin aluminum foil over the ends of the can were not observed above this background.

It was found that the height of the 0.51-Mev peak was independent of the presence of the sample can. A large quantity of cadmium foil was wrapped around a can so that it was not directly visible to the spectrometer and the height of the peak increased by a factor of four. Since the total capture area of the cadmium was enormously greater than that of any of the samples which were used in the measurements, it was clear that the presence of the sample material did not affect the height of the annihilation peak except for the calculable attenuation of the beam passing through to the spectrometer. A simple subtraction could thus be made where necessary.

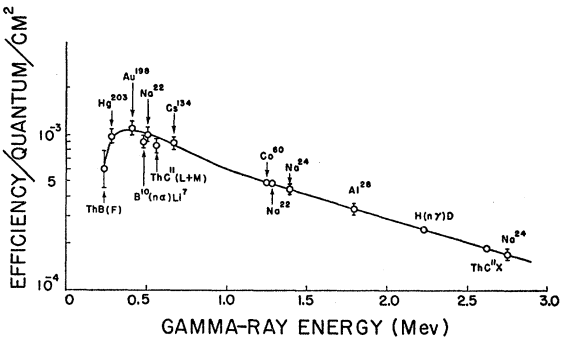


FIG. 3. Spectrometer efficiency as a function of energy. The $Co^{60}$ point is the mean energy of the two $\gamma$ rays. Where no error is shown the point has been fitted to the curve.

[14] G. C. Hanna, Phys. Rev. **80**, 530 (1950).

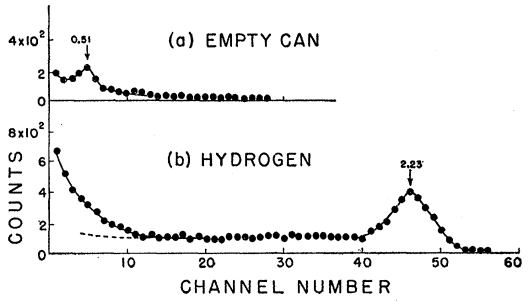


FIG. 4. (a) Background from empty sample can. (b) Capture spectrum from hydrogen. The dotted line shows subtraction of the annihilation background. The pile-up of pulses in the lowest channels is due to the imperfection of the gate.

### Hydrogen Spectrum

Figure 4(b) shows the capture $\gamma$-ray spectrum from hydrogen, contained in a polythene sample. Carbon has a low capture cross section, and contributed nothing to the spectrum. Nakagawa[15,16] has reported radiations at 0.8 and 1.4 Mev of equal intensity to the well-known 2.23-Mev $\gamma$ ray, but these have not been observed by Bracci, Faccini, and Malvicini[17] or Hamermesh and Culp[18] who used single-crystal scintillation spectrometers.

It is clear from Fig. 4(b) that when allowance is made for the energy variation of the efficiency, the cascade suggested by Nakagawa cannot be present in greater intensity than 3% of the direct transition. This is in agreement with theory, which does not allow a lower lying level.

### Intensity Comparison

The hydrogen capture $\gamma$ ray was used as a standard with which other spectra were compared to obtain the fraction of times per neutron capture that a particular radiation was emitted.

Neutron captures in the outer layers of the sample reduced the flux in the interior so that the $\gamma$-ray intensity seen by the spectrometer was not directly proportional to the total capture area. This had to be allowed for in making the comparison with hydrogen.

One method of making the comparison was simply to mix hydrogen with the element in the same sample.

[15] Nakagawa, Sumoto, and Andarai, Proc. Imp. Acad. (Tokyo) **19**, 373 (1947).

[16] S. Nakagawa, J. Sci. Research Inst. Tokyo **43**, No. 1196 (1949).

[17] Bracci, Faccini, and Malvicini, Phys. Rev. **90**, 162 (1953).

[18] B. Hamermesh and R. J. Culp, Phys. Rev. **92**, 211 (1953).

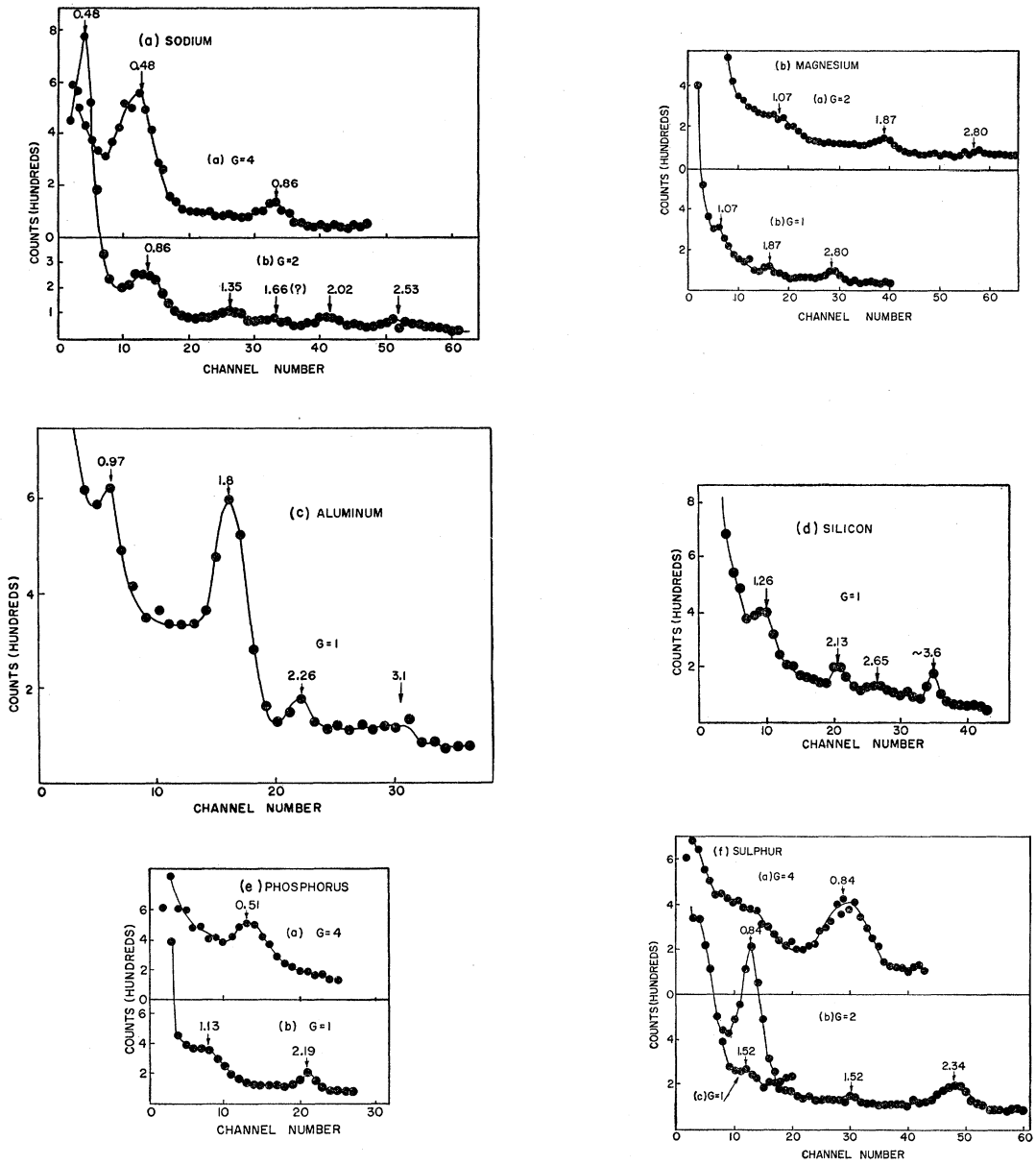


FIG. 5. Neutron-capture $\gamma$-ray spectra from sodium, magnesium, aluminum, silicon, phosphorus, and sulfur. Pulse-height distributions are in general shown for several values of the amplifier gain ($G$).

This was not always convenient, however, and an empirical correction to the counting rate from a pure sample of the element was determined as a function of the total capture area. This corrected value was than compared with a similarly corrected counting rate from a sample containing only hydrogen. The correction was established from a series of measurements made with mixed samples of boron and polystyrene powder. The boron content was varied to give different capture areas. Since hydrogen has a high ratio of scattering to capture cross section, the correction to be applied to the hydrogen standard was found in a separate series of measurements with samples containing different amounts of hydrogen as a chemical constituent.

Comparisons between the two methods of obtaining absolute intensities in several cases gave good agreement, and the second method was usually used. The magnitude of the correction was less than 20% for all the elements studied.

The spectrum obtained from any element was corrected to a standard neutron flux in terms of the pile power level and certain other operating conditions. Other corrections which had to be made were for absorption of the $\gamma$ rays in the sample itself, and in the

polythene neutron scatterers and the air between the sample and the spectrometer, which was 18 feet distant.

The uncertainty in the quoted $\gamma$-ray intensities is about 20%, except in the case of weak $\gamma$ rays.

## IV. SODIUM

The sodium capture spectrum shown in Fig. 5(a) was obtained from a sample of pure sodium fluoride. Since the $Na^{24}$ $\beta$ activity slowly built up while the sample was in the neutron flux, the area of the peak at 1.34 Mev had to be corrected for the contribution from the 1.39-Mev $\gamma$ ray of $Na^{24}$ and a similar correction was applied to the high-energy side of the 2.53-Mev peak for the $Na^{24}$ 2.75-Mev $\gamma$ ray. These corrections have not been made to the spectra shown in Fig. 5(a), but to the intensities which are listed in Table I. A correction was also made to the 0.48-Mev peak for annihilation background as discussed in the previous section.

In calculating the intensities, the capture cross section of sodium was taken to be 0.50 b.[19]

The capture $\gamma$ rays above 3 Mev have been measured by Kinsey, Bartholomew, and Walker[20] with the magnetic pair spectrometer. Included in Table I are the measurements of Motz[5] and Groshev *et al.*[6] in the low-energy region. There is general agreement with the present results, though additional $\gamma$ rays have been observed due to the higher resolution of the magnetic spectrometers. Groshev's measurements extend over the complete energy range, and they have found a number of $\gamma$ rays between 2.5 Mev and 3.56 Mev (the lowest energy reported by Kinsey) and also several additional $\gamma$ rays at higher energies.

The energy levels of $Na^{24}$ have been measured by Sperduto and Buechner[21] by the $(d,p)$ reaction. The observed $\gamma$ rays have been fitted to these levels in Fig. 6, together with some of the higher energy $\gamma$ rays.

The three lowest energy $\gamma$ rays fit naturally as transitions involving the first and third excited levels. The position of the 1.66-Mev $\gamma$ ray is uncertain. For the 2.02- and 2.53-Mev $\gamma$ rays there are several possibilities. The best assignment appears to be that shown, in which the 2.02-Mev $\gamma$ ray is emitted in a transition between the levels at 2.56 and 0.56 Mev. The 2.56-Mev level does not seem to be strongly excited by a high-energy transition so it is necessary to assume that it is excited by a transition from the strongly excited state at 3.41 Mev from which there is no direct transition to the ground state. Thus a fraction of the 0.86-Mev peak must be due to this transition; the intensity is in agreement with this. The 2.53-Mev $\gamma$ ray could be a ground-state transition from the 2.56-Mev level, but it is in better agreement with the intensity balance at the lower levels to assign it between the levels at 3.85 and 1.34 Mev. The strong excitation of the upper level must take place through one of the medium-energy $\gamma$ rays.[6] The 0.79-Mev $\gamma$ ray[6] (intensity 0.04 quanta per capture) presumably goes between the 1.34- and 0.56-Mev levels.

Since no 0.56-Mev $\gamma$ ray has been observed, the 0.56-Mev level must be de-excited by a very low energy $\gamma$ ray to the first excited state. This must then be excited at least 0.57 times per capture, in good agreement with the intensity of the 0.48-Mev $\gamma$ ray. The decay scheme shown is of course incomplete, as only the lower levels have been considered. The number of quanta per capture reaching the ground state is in good agreement with the correct value (which should of course be unity).

Angular distributions of the protons from the $(d,p)$ reaction on $Na^{23}$ have been measured by Shapiro[22] and

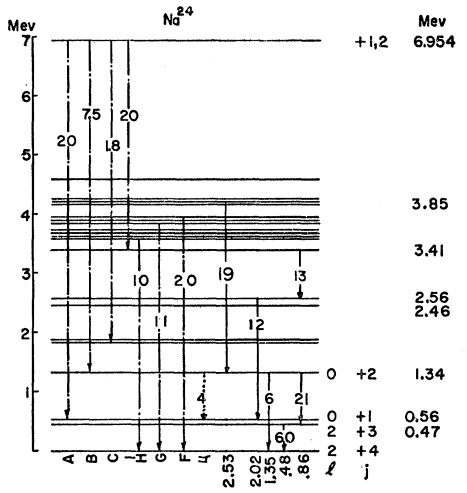


FIG. 6. Decay scheme for neutron-capture $\gamma$ rays of $Na^{24}$. The energy levels are drawn to scale. $\gamma$-ray transitions found in the present work are drawn in full lines. The energies are printed underneath and the intensities are printed in the middle of the lines. High-energy $\gamma$ rays from reference 20 are drawn dashed and dotted, and are identified underneath by the letter given in reference 20. The transition shown dotted is from reference 6.

TABLE I. Capture $\gamma$ rays from sodium and magnesium.

| Element | Energy (Mev) | Intensity in photons per 100 captures | Ref. 5 Energy (Mev) | Ref. 6 Energy (Mev) |
|---|---|---|---|---|
| Sodium | 0.48±0.02 | 60 | 0.475 | 0.47 |
| | 0.86±0.02 | 34 | 0.877 | 0.79<br>0.86 |
| | 1.35±0.03 | 6 | | 1.35 |
| | 1.66±0.05 | 5 | 1.75 | 1.66 |
| | 2.02±0.03 | 12 | 2.07 | 2.02<br>2.21<br>2.41 |
| | 2.53±0.03 | 19 | 2.52 | 2.52 |
| Magnesium | 1.07±0.05 | 13 | | |
| | 1.87±0.03 | 22 | | |
| | 2.80±0.03 | 49 | | |

[19] F. C. W. Colmer and D. J. Littler, Proc. Phys. Soc. (London) **A63**, 1175 (1950).
[20] Kinsey, Bartholomew, and Walker, Phys. Rev. **83**, 519 (1951).
[21] A. Sperduto and W. W. Buechner, Phys. Rev. **88**, 574 (1952).
[22] P. Shapiro, Phys. Rev. **93**, 290 (1954).

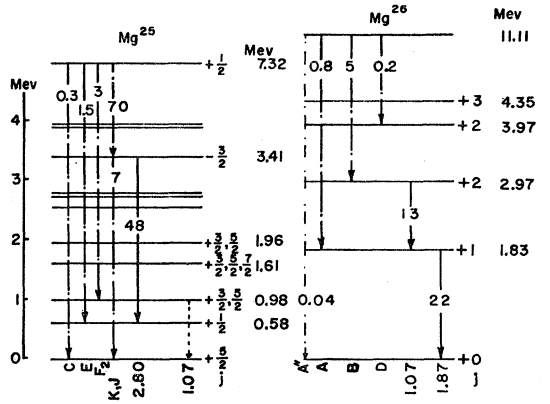


FIG. 7. Decay schemes for neutron-capture $\gamma$ rays in $Mg^{25}$ and $Mg^{26}$. For explanation see Fig. 6. High-energy $\gamma$ rays are from references 20, 33. The dotted transition is doubtful (see text).

Bretscher *et al.*[23] for the low-lying levels. The values of orbital angular momentum and parity found by them are shown on Fig. 6. The spin of the ground state has been measured to be $j=4$.[24] Since the spin of $Na^{23}$ is $j=\frac{3}{2}^+$, capture of an $s$ neutron forms $Na^{24}$ at the capturing excitation with $j=1$ or $2(+)$ in an unknown ratio.

Of the wide variety of spins allowed for the first three excited levels by the coupling of the odd neutron with a $d_{\frac{5}{2}}$ proton the values $j=3$, 1, and 2, with even parity seem in best agreement with the data. A spin $j=3^+$ for the 0.47-Mev level would account for the absence of a direct transition from the capturing state if the latter is mainly $j=1^+$, but would allow the de-excitation of the 0.56-Mev level by cascade through it rather than by a direct ground state $\gamma$ ray. The 1.34- and 0.86-Mev $\gamma$ rays would then be $E2$ and $M1$ transitions in competition.

## V. MAGNESIUM

The magnesium capture spectrum is shown in Fig. 5(b). Because of the low capture cross section of magnesium a special large sample was used. This was a block of pure magnesium metal 6 inches long and 4 inches in diameter. The sharp rise in the counting rate at low energies is presumably due to scattering into the beam of $\gamma$ rays produced in the outer regions of this block. The intensity correction curve did not apply to this sample, so another run was made with magnesium oxide powder in a standard-size can to determine the intensity of the strongest $\gamma$ ray. The other intensities were then obtained relative to this from the spectrum shown.

In calculating the intensities, the cross section of natural magnesium was taken to be 57 mb.[19]

The energies and intensities of the observed $\gamma$ rays are listed in Table I. In the magnetic pair spectrometer measurements Kinsey *et al.*[20] have observed a 2.83-Mev $\gamma$ ray whose intensity (0.39 quanta per capture) is in reasonable agreement with the value reported here.

In Fig. 7 these $\gamma$ rays are fitted to the known levels of $Mg^{25}$ and $Mg^{26}$. The positions of the levels have been measured by Endt *et al.*[25,26] by the $(d,p)$ reaction. Holt and Marsham[27] have obtained values of the orbital angular momentum and parity for many of the levels in $Mg^{25}$ from $(d,p)$ angular distributions. The spins shown for the 1.61-Mev level are those consistent with the $\beta$ decay of $Na^{25}$.[28] For $Mg^{26}$ the spins shown are those suggested by May and Foster[29] as being consistent with the $\gamma$ decay following the $Na^{23}(\alpha,p)Mg^{25}$ reaction.

The main features of the $(n,\gamma)$ decay scheme of $Mg^{25}$ have been established by Kinsey and Bartholomew.[30] In this scheme the 2.80-Mev $\gamma$ ray occurs as an $E1$ transition between levels at 3.41 and 0.58 Mev. This, together with a strong ground-state transition accounts for most of the de-excitation of the 3.41-Mev level. However, other transitions might be expected to the other even-parity levels at 0.98, 1.61, and 1.96 Mev. The energies of the other $\gamma$ rays observed in the present experiment are in rough agreement with a cascade from the 3.41-Mev level to the 0.58-Mev level through the 1.61-Mev level. But this identification may be ruled out on the basis of evidence from the $(p,\gamma)$ reaction in $Mg^{24}$ and inelastic proton scattering from $Mg^{25}$.

It has been found[31] in the de-excitation of $Al^{25}$, the mirror nucleus of $Mg^{25}$, that the $j=\frac{3}{2}^-$ analog of the 3.41-Mev level does not decay through the analog of the 1.61-Mev level, but only to the ground state and to the first and second excited states. Also, following inelastic proton scattering in $Mg^{25}$, the 1.61-Mev level

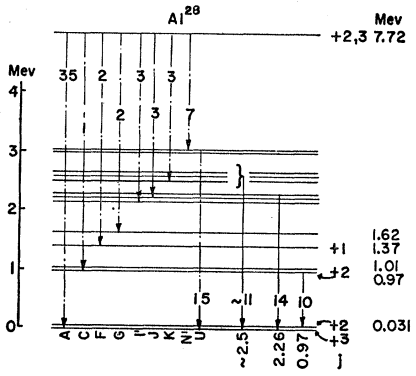


FIG. 8. Decay scheme for neutron-capture $\gamma$ rays in $Al^{28}$. For explanation see Fig. 6.

[23] Bretscher, Alderman, Elwyn, and Shull, Phys. Rev. **96**, 103 (1954).
[24] E. H. Bellamy and K. F. Smith, Phil. Mag. **44**, 33 (1953).
[25] Endt, Haffner, and Van Patter, Phys. Rev. **86**, 518 (1952).
[26] Endt, Enge, Haffner, and Buechner, Phys. Rev. **87**, 27 (1952).
[27] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 258 (1953).
[28] E. Bleuler and W. Zunti, Helv. Phys. Acta **20**, 195 (1947).
[29] J. E. May and B. P. Foster, Phys. Rev. **90**, 243 (1953).
[30] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **93**, 1260 (1954).
[31] Litherland, Paul, Bartholomew, and Gove (to be published).

TABLE II. Capture $\gamma$ rays from aluminum and silicon.

| Element | Energy (Mev) | Intensity in photons per 100 captures (a) in natural element | (b) in $Si^{28}$ | Ref. 20 Energy (Mev) | Ref. 20 Intensity (a) natural element | Ref. 20 (b) $Si^{28}$ |
|---|---|---|---|---|---|---|
| Aluminum | 0.97±0.03 | 10 | | | | |
| | 2.26±0.03 | 14 | | | | |
| | approx. 2.5 | 11 | | | | |
| | approx. 2.8 | 14 unresolved | | 2.84 | 13 | |
| | approx. 3.1 | 17 | | 3.01 | 15 | |
| Silicon | 1.26±0.03 | 14 | 17 | | | |
| | 2.13±0.03 | 19 | 24 | | | |
| | 2.65±0.03 | 11 | (14) | 2.69 | 65. | |
| | 3.6 ±0.06 | 49 | 61 | 3.57 | | 60 |

is de-excited almost entirely by a direct transition to the ground state.[32]

The 1.07- and 1.87-Mev $\gamma$ rays then cannot be assigned to transitions between known levels of $Mg^{25}$. There must evidently be a strong 0.58-Mev $\gamma$ ray from the first excited state, but it has not been observed because of the large continuous background in this region.

In the decay of $Mg^{26}$ the 1.07- and 1.87-Mev $\gamma$ rays would appear to occur as transitions between levels at 2.97 and 1.83 Mev, and from the 1.83-Mev level to the ground state. The energy agreement is not good, and it may be that the 1.07-Mev peak is composite, containing, possibly, contributions from $\gamma$ rays from the levels at 0.98 Mev in $Mg^{25}$ and 0.99 Mev in $Mg^{27}$. Kinsey *et al.*[21] and Campion and Bartholomew[33] have found several high-energy $\gamma$ rays which could definitely be assigned in $Mg^{26}$. The transitions to the lower excited states are shown in Fig. 7. The strongest of these goes to the second excited state and is weaker than the two $\gamma$ rays reported here. There must therefore be unobserved transitions to the first excited level, and possibly to the second. May and Foster[29] found by coincidence measurements on the $\gamma$ rays following $Na^{23}(\alpha,p)Mg^{26}$ that the de-excitation of the levels up to 4.35 Mev proceeds predominantly through the 1.83-Mev level. It is not surprising, therefore, that the 1.87-Mev $\gamma$ ray should be the most intense of the observed $\gamma$ rays in $Mg^{26}$.

## VI. ALUMINUM

The aluminum capture spectrum was obtained from a block of pure aluminum. It is shown in Fig. 5(c). It is obvious that there is a considerable background of unresolved radiations, showing that the spectrum is complex. This is to be expected since Kinsey *et al.*[20] have found 29 $\gamma$ rays above 2.84 Mev and from the $(d,p)$ reaction one hundred levels have been found in $Al^{28}$.[34] The most intense $\gamma$ ray in the spectrum is the 1.8-Mev $\gamma$ ray following the 2.3-minute $\beta$ decay of $Al^{28}$. It occurs once per capture. The energies and intensities of the other $\gamma$ rays are listed in Table II. The unresolved part of the spectrum from about 2.5 to 3.1 Mev appears to contain the radiations at 3.02- and 2.84-Mev energy found in the pair spectrometer measurements, and a component of roughly 2.5 Mev.

In calculating the intensities in Table II, a value of 0.21 b was taken for the aluminum capture cross section.[19]

The first thirteen levels of $Al^{28}$ as found from the $(d,p)$ reaction[35] are shown in Fig. 8. Many of these are excited in transitions from the capturing level, but only very weakly.

The 3.02- and 2.84-Mev $\gamma$ rays are readily accounted for as transitions from the level at 3.01 Mev and to the level at 4.9 Mev.[20,35] Then the unresolved 2.5-Mev component may be assigned to a transition to the ground state from one or more levels of the triplet of this approximate energy. The 2.26-Mev $\gamma$ ray agrees well with a transition to the ground state from the level at 2.27 Mev.

The 0.97-Mev $\gamma$ ray corresponds to the energy of the second excited level but the accuracy of the energy measurement is not sufficient to decide between which of the levels of the ground state and 1-Mev doublets the transition actually occurs.

A $\gamma$ ray of this energy (0.95±0.02 Mev) occurs following the decay of $Mg^{28}$. Sheline *et al.*[36] have established that the transition is from the 0.97-Mev level to the 0.031-Mev level. On the basis of their measurements and the values of orbital angular momentum and parity found by Holt and Marsham,[37] they have assigned as most probable the spins shown in Fig. 8. The transition is shown as being between the 0.97- and 0.031-Mev levels but it is quite probable that a transition from the 1.01-Mev level is also contained in the peak.

The intensity of these transitions to the ground state

[32] Gove, Litherland, Paul, and Bartholomew, Phys. Rev. **99**, 1649 (1955), and Bull. Am. Phys. Soc. Ser. II, 1, 29 (1956).
[33] P. J. Campion and G. A. Bartholomew, Bull. Am. Phys. Soc. Ser. II, 1, 28 (1956).
[34] Buechner, Sperduto, and Mazari, Phys. Rev. **99**, 644(A) (1955).
[35] Enge, Buechner, and Sperduto, Phys. Rev. **88**, 963 (1952).
[36] Sheline, Johnson, Bell, Davis, and McGowan, Phys. Rev. **94**, 1642 (1954).
[37] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 249 (1953).

TABLE III. Capture $\gamma$ rays from phosphorus and sulfur.

| Element | Energy (Mev) | Intensity in photons per 100 captures |
|---|---|---|
| Phosphorus | 0.51±0.02 | 28 |
| | 1.13±0.03 | 14 |
| | 2.19±0.03 | 41 |
| Sulfur | 0.84±0.02 | 56 |
| | 1.52±0.05 | 1 |
| | 2.34±0.03 | 37 |

is in each case much greater than the intensity of the direct transition to the parent level, showing that there must be a considerable number of transitions between levels. The total number of quanta shown reaching the ground state in Fig. 8 is 0.85 per capture.

## VII. SILICON

The silicon capture spectrum, shown in Fig. 5(d), was obtained from a sample of pure silicon carbide. The energies and intensities of the $\gamma$ rays are listed in Table II. The capture cross section used to calculate the number of quanta per capture in the natural element was 160 mb.[19,38] Pomerance[39] has found that roughly 80% of the cross section is due to $Si^{28}$ and this figure has been used to calculate the intensities in the third column.

The 2.65- and 3.6-Mev $\gamma$ rays were also measured at these energies by Kinsey *et al.*[20,30] The 3.6-Mev $\gamma$ ray is outside the calibration range of the crystal spectrometer and the values shown for the energy and intensity were obtained by extrapolation. They agree well with the pair spectrometer values. In the case of the 2.65-Mev $\gamma$ ray, however, there is a very considerable disagreement in the value of the intensity.

Figure 9 shows the decay scheme in $Si^{29}$ proposed by Kinsey and Bartholomew[30] into which the 2.13- and 3.6-Mev $\gamma$ rays fit naturally as electric dipole transitions. The 1.26-Mev transition to the ground state agrees well in intensity with the intensity of the $\gamma$ rays feeding the first excited level. Since there are presumably competing transitions from the 6.38-Mev level to the lower even-parity states the intensity of the 2.13-Mev $\gamma$ ray agrees quite well. The 2.65-Mev $\gamma$ ray cannot be fitted into the known levels of $Si^{29}$. Its intensity is sufficiently low that it might be due to capture in $Si^{29}$. It might therefore occur in the decay of $Si^{30}$ between levels at 10.04 and 7.35 Mev.[40] This would require a $\gamma$ ray to the upper level, from the capturing state, of only 0.56-Mev energy. No such $\gamma$ ray was observed in the capture spectrum.

## VIII. PHOSPHORUS

The phosphorus sample was pure red phosphorus. The spectrum is shown in Fig. 5(e). Only three $\gamma$ rays were clearly resolved. In calculating the intensities shown in Table III, a capture cross section of 190 mb was used.[19]

The levels[41] of $P^{32}$ and most of the high-energy transitions found by Kinsey *et al.*[42] are shown in Fig. 10. The three $\gamma$ rays measured are obviously transitions to the ground state from levels at 0.52 and 1.15 Mev and from one or both of the doublet levels at 2.2 Mev.

Since the energies of the $\gamma$ rays $Q$ and $N$[42] add up to the neutron binding energy in $P^{32}$ it is possible that they involve a level at 4.38 Mev.[42] Another possibility for the $\gamma$ ray $Q$ is shown on Fig. 14, where $Q$ is drawn as a transition between the levels at 4.03 and 0.52 Mev. This transition would account very well for the intensity of the 0.51-Mev $\gamma$ ray.

The intensities of the other $\gamma$ rays do not agree well with the number of direct excitations of the levels concerned and there must be many level-to-level transitions.

## IX. SULFUR

Pure sulfur was melted into a standard sample can to obtain the spectrum shown in Fig. 5(f). Two strong $\gamma$ rays are resolved, and one very weak one. These are listed in Table III. The intensity calculation was made with a cross section for natural sulfur of 490 mb.[19]

The positions of the energy levels in $S^{33}$ up to 6.30 Mev have been measured by Davison[43] from the $(d,p)$ reaction, and those up to 4.75 Mev have been measured

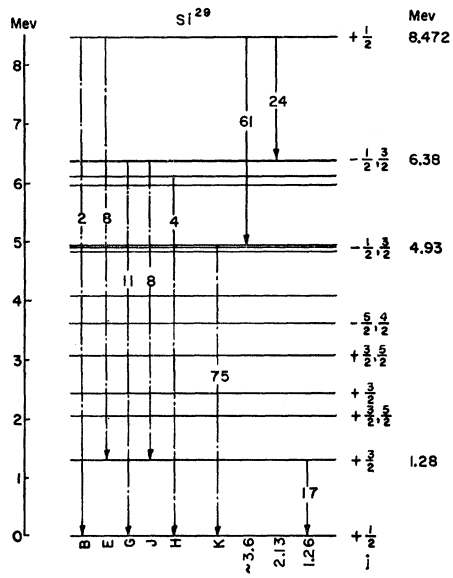


FIG. 9. Decay scheme for neutron-capture $\gamma$ rays in $Si^{29}$ (reference 30). For explanation see Fig. 6.

[38] Harris, Muehlhause, Rasmussen, Schroeder, and Thomas, Phys. Rev. **80**, 342 (1950).
[39] H. Pomerance, Phys. Rev. **88**, 412 (1952).
[40] Brolley, Sampson, and Mitchell, Phys. Rev. **76**, 624 (1949).
[41] Van Patter, Endt, Sperduto, and Buechner, Phys. Rev. **86**, 502 (1952).
[42] Kinsey, Bartholomew, and Walker, Phys. Rev. **85**, 1012 (1952).
[43] P. W. Davison, Phys. Rev. **75**, 757 (1949).

with high precision by Paris *et al.*[44] by the $Cl^{35}(d,\alpha)S^{33}$ reaction. Values of the orbital angular momentum and parity for some of the levels have been measured from $(d,p)$ angular distributions by Holt and Marsham.[45]

Kinsey *et al.*[42] have measured the high-energy $\gamma$ rays and have proposed a scheme for the predominant mode of de-excitation of $S^{33}$. The $j=(\frac{1}{2},\frac{3}{2})^-$ level at 3.227 Mev is excited 0.6 times per capture by a direct $E1$ transition from the capturing level. It is de-excited by two $E1$ transitions, one of 0.2 quanta per capture to the ground state ($j=\frac{3}{2}^+$) and the 2.34-Mev $\gamma$ ray here reported, which goes to the $j=\frac{1}{2}^+$ first excited state at 0.844 Mev. This state is then de-excited by the $\gamma$ ray of that energy. The intensity balance at the 3.227-Mev level is good. Several other transitions must occur to the first excited state. According to Paris *et al.*[44] such transitions are those of energy 7.78, 3.36, and 2.94 Mev, which have a total intensity of 0.28 quanta per capture.[42]

Groshev *et al.*[6] have also measured the capture $\gamma$-ray spectrum over the whole range and have proposed a decay scheme based on the level measurements of Davison.[43] At high energies their results are in agreement with those of Kinsey *et al.*[42] At lower energies they find $\gamma$ rays of energy 0.84 and 2.415 Mev whose intensities agree roughly with those of the two strong $\gamma$ rays reported here. In addition, they find weak radiations at 2.00, 2.29, 2.55, 2.70, and 2.82 Mev. Of these, two may correspond to transitions to the 0.844-Mev level. The 2.00-Mev $\gamma$ ray may be a transition from the 2.869-Mev level and the 2.55-Mev $\gamma$ ray may be a transition from the 3.365-Mev level. If these assignments are correct, the first excited state is excited approximately 0.70 times per capture. This is higher than the measured intensity of the 0.84-Mev $\gamma$ ray but is within the errors of measurement.

The 1.52-Mev $\gamma$ ray might be due to a transition between levels at 2.31 and 0.84 Mev or between levels

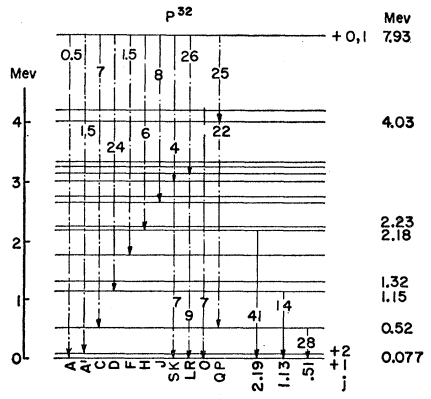


FIG. 10. Decay scheme for neutron-capture $\gamma$ rays in $P^{32}$. For explanation see Fig. 6.

[44] Paris, Buechner, and Endt, Phys. Rev. **100**, 1317 (1955).
[45] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 467 (1953).

TABLE IV. Capture $\gamma$ rays from chlorine.

| Energy (Mev) | Intensity in photons per 100 captures | Groshev (Ref. 6) Energy (Mev) | Intensity |
|---|---|---|---|
| 0.48±0.03 | 10 | 0.485 | 26 |
| 0.75±0.03 | 10 | 0.77 | 23 |
| 1.14±0.03 | 8 | 1.165 | 36 |
| | | 1.60 | 2 |
| | | 1.67 | 1 |
| | | 1.72 | 1 |
| 1.96±0.03 | 34 | 1.97 | 29 |
| 2.42±0.05 | 1 | 2.51 | 1 |
| | | 2.68 | 2 |
| 2.84±0.03 | 6 | 2.87 | 9 |

at 3.84 and 2.31 Mev. The 2.29, 2.70, and 2.82 Mev $\gamma$ rays may be fitted to the known levels as, respectively, transitions from the 2.312-Mev level to the ground state, between levels at 7.44 Mev[45] and 4.749 Mev, and between levels at 5.63 Mev and 2.869 Mev.[6]

## X. CHLORINE

The chlorine capture $\gamma$ rays were studied with a sample of pure hexachlorobenzene ($C_6Cl_6$). The spectrum is shown in Fig. 11(a). Since the carbon cross section is very small and that of $Cl^{37}$ is also small,[46] all the $\gamma$ rays observed are due to the decay of $Cl^{36}$. The energies and intensities of the $\gamma$ rays are collected in Table IV.

A precise comparison of the chlorine $\gamma$-ray intensities with the hydrogen capture $\gamma$ ray (to establish the absolute intensites) was not made since the sample was contained in a nonstandard sample can for which the correction to be applied for the flux distortion by captures in the outer layers of the sample had not been measured. However, an approximate calculation for this correction was made. This gave the intensities shown. These absolute intensities may be seriously in error, but the relative values are known much more accurately since they depend only on the spectrometer efficiency and calculable $\gamma$-ray absorption effects. The intensity of the 0.75-Mev $\gamma$ ray agrees with the number of direct high-energy transitions observed to the 0.79-Mev level of $Cl^{36}$ in the high-energy spectra observed by Kinsey *et al.*[42] and Groshev *et al.*[6] with magnetic spectrometers. Table IV shows the results obtained by the latter authors below 3 Mev. Many of these $\gamma$ rays have been previously observed by scintillation spectrometers.[2,10]

The agreement in respect of the measured energies is good, but the weak $\gamma$ rays have not been observed in the present experiment. An exception to this is the 2.42-Mev $\gamma$ ray which is seen as a very weak peak on curve (c) only. There is considerable disagreement in the intensities, even when only relative values are considered. Groshev[6] finds the three lowest-energy $\gamma$ rays to be roughly as strong as the 1.96-Mev $\gamma$ ray,

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

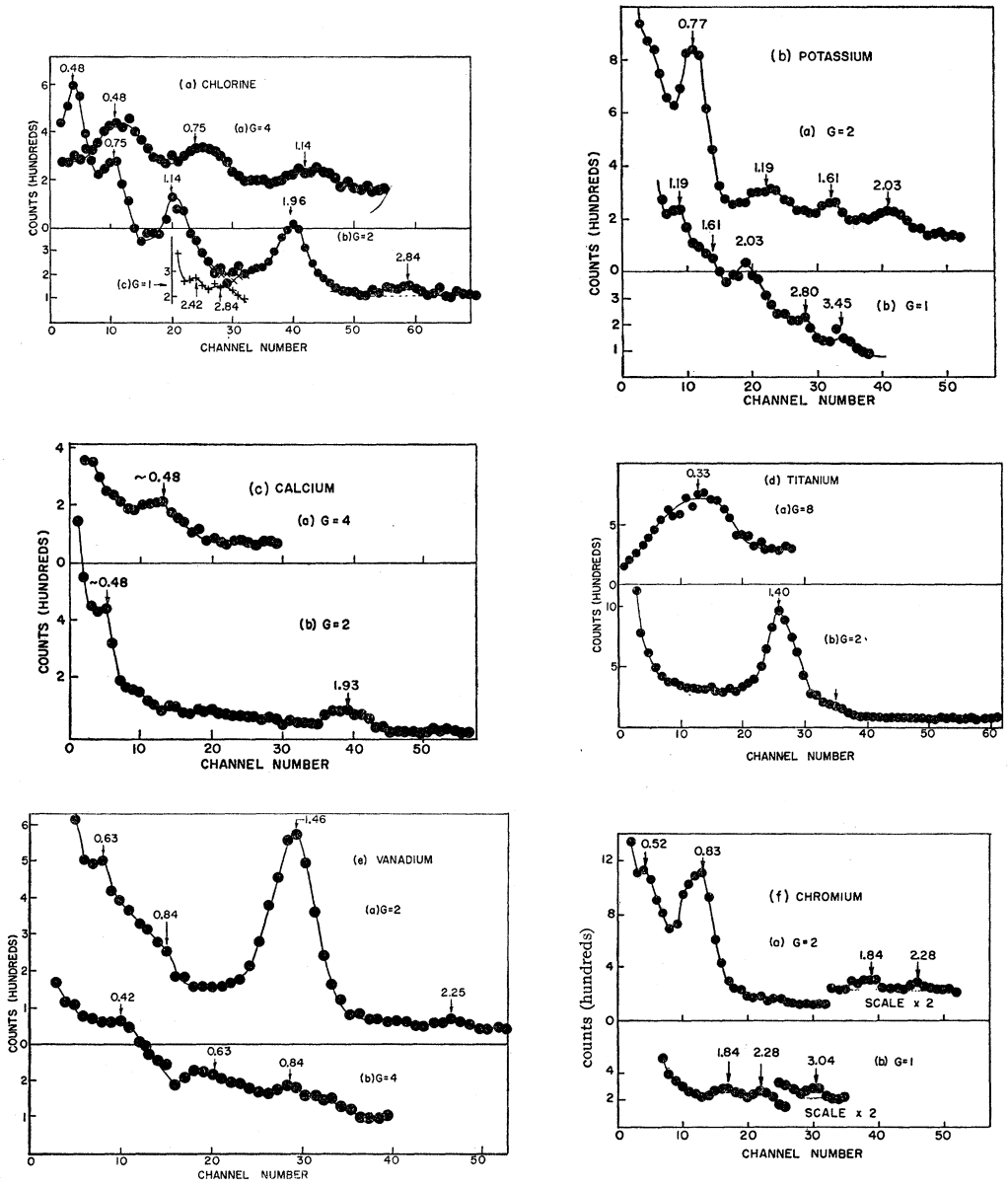


FIG. 11. Neutron capture $\gamma$-ray spectra from chlorine, potassium, calcium, titanium, vanadium, and chromium. Pulse-height distributions are shown for several values of the amplifier gain ($G$). In the case of chlorine, the crosses shown in curve (b) were obtained in a different run.

whereas the present intensities are only about one third as great. The disagreement is much greater than the experimental errors.

In Fig. 12 these $\gamma$ rays and some of the high-energy $\gamma$ rays are shown on the energy level diagram of $Cl^{36}$. The levels have been observed in the $(d,p)$ reaction.[47] All but the 0.48-Mev $\gamma$ ray are readily understood as direct transitions to the ground state from levels which are excited by direct transitions from the capturing level.[6,42] Evidence for such two-step cascades has been found by coincidence measurements.[48] The 0.48-Mev $\gamma$ ray may occur between two levels at higher excitation,[47] but it is in better agreement with the intensity balance at the 2.47- and 1.95-Mev levels to suppose that it is emitted in a transition between them. The energy agreement is not good, however.

## XI. POTASSIUM

The potassium capture spectrum, shown in Fig. 11(b), was measured with a sample of pure potassium

[47] Paris, Buechner, and Endt, Phys. Rev. **100**, 1317 (1955).

[48] A. L. Reckseidler and B. Hamermesh, Phys. Rev. **96**, 109 (1954).

carbonate. The energies and intensities of the observed $\gamma$ rays are shown in Table V. The intensities were calculated with a capture cross section of 1.89 b.[19] The contribution of $K^{40}$ to the cross section is 10 mb and that of $K^{41}$ is 80±6 mb.[39]

The high-energy capture $\gamma$ rays have been measured by Kinsey *et al.*[42,49] They found a complex and only partly resolved spectrum. The proposed decay scheme for $K^{40}$ is shown in Fig. 13. The positions of the levels have been measured in the $(d,p)$ reaction[50,51] but the accuracy is not high in the case of the levels above 2 Mev and so the quoted values are those obtained from the energetic capture $\gamma$ rays. The spins shown for the lower excited levels are those considered[52] most probable on the basis of the shell model and intensities in the $(d,p)$ reaction.

The 0.77-Mev $\gamma$ ray is readily accounted for as a transition between the second and first excited states. That the 0.80-Mev level should be de-excited in this fashion is in agreement with the suggested spins for these levels.[52] The 2.03-Mev $\gamma$ ray may be a ground state transition from the level near 2 Mev, or it may be due to a transition to the first excited state. The energy determination is not sufficiently accurate to distinguish between these two possibilities. Since the spin of $K^{39}$ is $j=\frac{3}{2}^+$, capture of an $s$ neutron forms $K^{40}$ at the capturing level with $j=1$ or $2^+$. Since the $\gamma$ rays to the first, second, and fourth excited states are of comparable intensity, they must all be of the $E1$ type. The spin of the 2.05-Mev level must than be $j=1$, 2, or $3^-$. This level would then not decay to the 0.89-Mev level if its spin is indeed $j=5^-$, but it is not possible to rule out transitions to the ground state or either of the first two excited states. The 1.19-Mev $\gamma$ ray may be emitted in a transition between the 2.05- and 0.80-Mev levels, though the energy agreement is at the limit of the errors. Alternatively, it may occur in the de-excitation

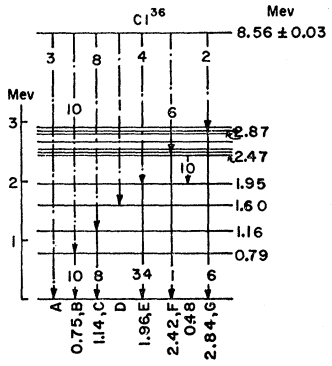


FIG. 12. Decay scheme for neutron-capture $\gamma$ rays in $Cl^{36}$. For explanation see Fig. 6.

TABLE V. Capture $\gamma$ rays from potassium and calcium.

| Element | Energy (Mev) | Intensity in photons per 100 captures (a) in natural element | (b) in $Ca^{40}$ |
|---|---|---|---|
| Potassium | 0.77±0.03 | 24 | |
| | 1.19±0.03 | 8 | |
| | 1.61±0.03 | 5 | |
| | 2.03±0.03 | 13 | |
| | 2.80±0.03 | 6 | |
| | 3.45±0.05 | 8 | |
| Calcium | 0.48±0.05 | 15 | 32 |
| | 1.93±0.03 | 45 | 98 |

of $K^{42}$ as a ground state transition from the second excited state at 1.18±0.07 Mev.[50] However, the intensity, 0.08 quanta per capture, is twice the total contribution of $K^{41}$ to the capture cross section, so at least half of the 1.19-Mev peak must be due to the transition in $K^{40}$. The position of the 1.61-Mev $\gamma$ ray is uncertain. It could be emitted between levels at 4.2 and 2.61 Mev, but it is better, because of the measured intensities, to assign it between the 3.67- and 2.05-Mev levels. A strong $\gamma$ ray of energy 5.38 Mev[42] has been observed. It is in excellent agreement with the neutron binding energy to suppose that this $\gamma$ ray and the 1.61-Mev $\gamma$ ray occur in a cascade to the 0.80-Mev level, (and the two $\gamma$ rays are of equal intensity). However, this would require a level at 2.41 Mev which has not been observed in the $(d,p)$ reaction. The 2.80-Mev $\gamma$ ray may be emitted in a transition between the 4.8- and 2.05-Mev levels, and the 3.45-Mev $\gamma$ ray may be a ground state transition from the level at 3.40 Mev (this $\gamma$ ray is outside the calibrated range of the spectrometer and so the uncertainty in the energy measurement is greater than for the other $\gamma$ rays).

The decay scheme is obviously incomplete. The strength of the 0.77-Mev $\gamma$ ray is not accounted for by the transitions shown reaching the second excited

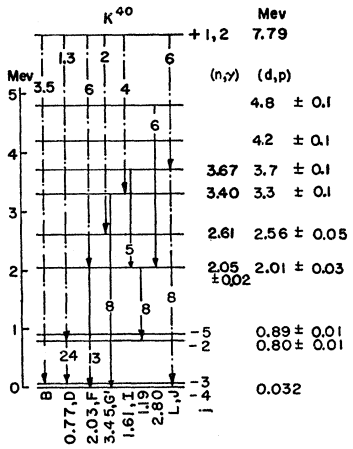


FIG. 13. Decay scheme for neutron-capture $\gamma$ rays in $K^{40}$. For explanation see Fig. 6.

[49] G. A. Bartholomew and B. B. Kinsey, Can. J. Phys. **31**, 927 (1953).
[50] V. L. Sailor, Phys. Rev. **77**, 794 (1950).
[51] Buechner, Sperduto, Browne, and Bockelman, Phys. Rev. **91**, 1502 (1953).
[52] P. M. Endt and J. C. Kluyver, Revs. Modern Phys. **26**, 95 (1954).

level. Also, as in chlorine, the total intensity reaching the ground state is only about 0.5 quanta per capture. There must be many unresolved radiations.

## XII. CALCIUM

The capture spectrum of calcium [Fig. 11(c)] was obtained from a sample of pure calcium fluoride. Fluorine contributes a negligible amount to the capture rate. Pomerance[39] has found that $Ca^{40}$ and $Ca^{42}$ are each responsible for roughly half the capture cross section of the natural element (0.21 and 0.25 b, respectively). The only two $\gamma$ rays clearly resolved may be attributed to capture in $Ca^{40}$, and their intensities are shown in Table V. No $\gamma$ rays are observed above background between 1.93 and 3 Mev. The energy and intensity of the 0.48-Mev $\gamma$ ray were obtained after subtraction of the underlying background from annihilation radiation. The errors are for this reason rather large.

Kinsey *et al.*[42] have measured the high-energy $\gamma$ rays and find, amongst others, two strong radiations to the first and third excited states of $Ca^{41}$ at 1.95 and 2.47 Mev[53] of intensity 0.80 and 0.12 photons per capture[30] in $Ca^{40}$. They have explained the principal features of the $Ca^{41}$ decay scheme in terms of two $E1$ transitions to these two states which are then de-excited by a 0.5-Mev transition between the levels and a 1.95-Mev transition to the ground state.[30] The energies and intensities agree excellently with this scheme. The spins of the two levels in question are $j=(\frac{1}{2},\frac{3}{2})^-$ [54] and that of the ground state is $j=7/2^-$.

The intensities of the two $\gamma$ rays are rather greater than those of the direct transitions to the two levels, and indeed the transition from the first excited state seems to occur essentially once per capture, suggesting that the other radiations emitted by the capturing state cascade predominantly through the 2.47- and 1.95-Mev levels.

## XIII. TITANIUM

The titanium sample was pure titanium oxide. The spectrum is shown in Fig. 11(d). Only two $\gamma$ rays were resolved, though there is a definite suggestion of unresolved radiations on the high-energy side of the 1.4-Mev peak. The energies and intensities of the $\gamma$ rays are given in Table VI, along with energies which have been measured below 3 Mev by Motz[55] and Reier and Shamos[11] with magnetic and scintillation spectrometers respectively. The high-energy $\gamma$ rays have been measured by Kinsey and Bartholomew.[56] The agreement with the other low-energy measurements is very good in the case of the strong $\gamma$ rays but weaker radiations have been missed. The unresolved region at about channel 35 on Fig. 11(d) appears to contain the 150-, 1.51-, 1.59-, 1.78-, and 1.79-Mev $\gamma$ rays. It is possible to make an estimate of the total intensity of these. The figure obtained is not more than 0.1 photon per capture.

The capture cross section of natural titanium is about 6 b, of which 95% is due to $Ti^{48}$.[39] Thus there is no doubt that the $\gamma$ rays occur in the decay of $Ti^{49}$.

The high-energy spectrum shows two strong $\gamma$ rays which have been interpreted[30] as $E1$ transitions from the capturing state to levels at 1.39 and 1.73 Mev. The 0.33- and 1.40-Mev $\gamma$ rays then de-excite these levels, the upper to the lower and the lower to the ground state, just as in $Ca^{41}$. The measured values of the intensities agree well with the intensities of the high-energy transitions, which are 0.53 photon per capture to the 1.39-Mev level and 0.35 photon per capture to the 1.73-Mev level.

According to the shell model the ground state of $Ti^{49}$ has a spin $j=7/2^-$. Bretscher *et al.*[23] have found that in the $(d,p)$ reaction the captured neutron is accepted with $l=1$ to the 1.39- and 1.73-Mev levels. This gives spins $j=(\frac{1}{2},\frac{3}{2})^-$ in confirmation of the decay scheme. (The capturing level has $j=\frac{1}{2}^+$, since for $Ti^{48}$ $j=0^+$ and it is an $s$ neutron which is captured.)

## XIV. VANADIUM

The vanadium sample was vanadium pentoxide. The spectrum is shown in Fig. 11(e), and the energies and intensities of the $\gamma$ rays are shown in Table VI. The intensities were calculated with a value for the vanadium capture cross section of 4.7 b[57] which appears to be almost wholly due to the abundant isotope, $V^{51}$.

The strongest peak in the spectrum is due to the $\gamma$ ray which follows the $\beta$ decay of $V^{52}$. The energy is measured to be 1.46±0.03 Mev, in agreement with other values of 1.44±0.02[58] and 1.40±0.06.[59] Since the

TABLE VI. Capture $\gamma$ rays from titanium, vanadium, and chromium.

| Element | Energy (Mev) | Intensity in photons per 100 captures | Motz (Ref. 55) Energy (Mev) | Reier (Ref. 11) Energy (Mev) |
|---|---|---|---|---|
| Titanium | 0.33±0.02 | 29 | 0.34 | 0.334 |
| | | | | 1.06 to 1.10 |
| | 1.40±0.03 | 90 | 1.385 | 1.39 |
| | | | 1.51 | |
| | | | 1.59 | 1.53 to 1.58 |
| | | | 1.78 | |
| Vanadium | 0.42±0.03 | 5 | | 0.43 |
| | 0.63±0.03 | 6 | | 0.64 |
| | 0.84±0.03 | 8 | | 0.82 (2 unresolved) |
| | 2.25±0.03 | 5 | | |
| Chromium | 0.52±0.03 | 2 | | 0.740 |
| | 0.83±0.03 | 40 | | 0.815 |
| | 1.84±0.03 | 6 | | 1.07 |
| | 2.28±0.03 | 10 | | |
| | 3.04±0.03 | 4 | | |

[53] C. M. Braams, Phys. Rev. **95**, 650 (1954).
[54] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 565 (1953).
[55] H. T. Motz, Phys. Rev. **93**, 925 (1954).
[56] B. B. Kinsey and G. A. Bartholomew, Phys. Rev. **89**, 375 (1953).
[57] H. Pomerance, Phys. Rev. **83**, 641 (1951).
[58] LeBlanc, Cork, Burson, and Jordan, Phys. Rev. **93**, 1124 (1954).
[59] T. Wielding, Phys. Rev. **91**, 767 (1953).

half-life is 3.75 min,[58] the activity quickly built up to equilibrium with the neutron flux. The $\beta$ spectrum is believed to be simple[58,60] and therefore the equilibrium intensity of the $\gamma$ ray should be one quantum per capture. The measured value is 0.87 quanta per capture, in reasonable agreement.

The energies measured by Reier and Shamos[11] are also shown in Table VI. The high-energy $\gamma$ rays have been measured by Bartholomew and Kinsey.[61] The positions of the levels of $V^{52}$ have been measured by the $(d,p)$ reaction by Abramov[62] and by Schwager and Cox.[63] The latter authors find more than twenty levels below 3.31 Mev. The energies of the first five of these are 0.13, 0.42, 0.78, 0.83, and 1.40 Mev, and in addition a weak capture $\gamma$ ray of energy $6.62\pm0.02$ Mev might possibly correspond to a level at 0.69 Mev[61] though this is not otherwise confirmed.

The 0.42- and 0.84-Mev $\gamma$ rays are presumably emitted in transitions to the ground state from the levels of these energies. It is possible that the 0.84-Mev peak contains the ground state transition from the 0.78-Mev level also, but the measured energy is rather high. It seems more probable that it is the 0.63-Mev $\gamma$ ray which occurs in a transition from the 0.78-Mev level to the level at 0.13 Mev. The 2.25-Mev $\gamma$ ray does not correspond to the energy of any known level, and must be emitted in a level to level transition.

According to Bartholomew and Kinsey,[61] the 0.42, 0.78, and 0.83 Mev states are each excited about 0.12 times per capture. This figure is in only moderate agreement with the intensities shown in Table VI. The agreement is least good for the 0.42-Mev $\gamma$ ray, but if part of the de-excitation of this level proceeds by a cascade through the 0.13-Mev first excited state the $\gamma$ rays would have too low an energy to be seen by the spectrometer.

All of these levels and the ground state are excited a comparable number of times by direct transitions from the capturing level,[61] so that they must all have the same parity and spins which are not far different. In these circumstances level to level transitions may well compete with direct transitions to the ground state.

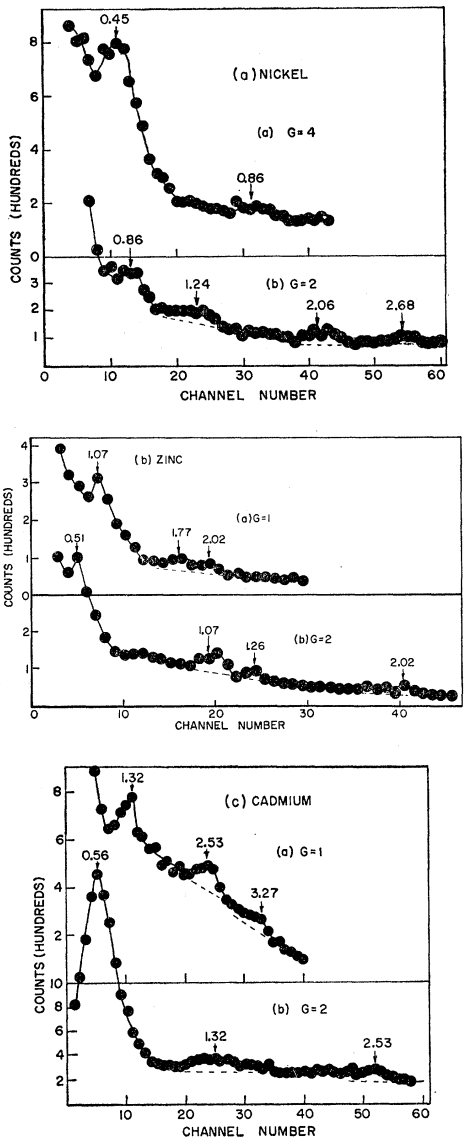


FIG. 14. Neutron-capture $\gamma$-ray spectra from nickel, zinc, and cadmium. Pulse-height distributions are shown for several values of the amplifier gain ($G$).

## XV. CHROMIUM

The chromium capture spectrum [Fig. 11(f)] was obtained from a sample of pure chromic oxide. According to Pomerance[39] the capture cross section is 2.99 b and the contributions to this figure of $Cr^{50}$, $Cr^{52}$, and $Cr^{53}$ are 0.73 b, 0.61 b, and 1.65 b.

The energies and intensities of the observed capture $\gamma$ rays are listed in Table VI. Also listed are the energies measured by Reier and Shamos.[11] There is agreement only in the case of the strong 0.83-Mev $\gamma$ ray.

This strong radiation can only be due to capture in $Cr^{53}$ because of its intensity. It agrees well with the 0.835-Mev $\gamma$ ray which is observed in the $\beta$ decay of $Mn^{54}$,[64] and corresponds to a level of that energy in $Cr^{54}$. The intensity is 0.73 quanta per capture in $Cr^{53}$; this is roughly twice the number of direct transitions to this level,[56] so that it must be involved in other cascades.

The peak at 0.52 Mev is only in part due to the background of annihilation radiation. When this is subtracted the $\gamma$ ray appears to have an intensity of

[60] R. Bouchez and G. A. Renard, J. phys. radium **8**, 289 (1947).
[61] G. A. Bartholomew and B. B. Kinsey, Phys. Rev. **89**, 386 (1953).
[62] A. Y. Abramov, Doklady Akad. Nauk U.S.S.R. **73**, No. 5, 92 (1950).
[63] J. E. Schwager and L. A. Cox, Phys. Rev. **89**, 386 (1953).
[64] M. Deutsch and L. G. Elliott, Phys. Rev. **65**, 211 (1944).

TABLE VII. Capture $\gamma$ rays from nickel, zinc, and cadmium.

| Element | Energy (Mev) | Intensity in photons per 100 captures | Relative intensity |
|---|---|---|---|
| Nickel | 0.45±0.03 | 8 | |
| | 0.86±0.03 | 3 | |
| | 1.24±0.03 | 2 | |
| | 2.06±0.03 | 3 | |
| | 2.68±0.03 | 2 | |
| Zinc | 1.07±0.03 | 11 | |
| | 1.26±0.03 | 7 | |
| | 1.77±0.03 | 12 | |
| | 2.02±0.03 | 10 | |
| Cadmium | 0.56±0.02 | ··· | 100 |
| | 1.32 (broad, several unresolved) | ··· | 13 |
| | 2.53±0.03 | ··· | 15 |
| | 3.27±0.03 | ··· | 9 |

0.02 quanta per capture. It may possibly be identified with a level found in $Cr^{53}$ at 0.54 Mev by the $(d,p)$ reaction.[65] It is excited 0.03 times per capture by a direct transition from the capturing state.[56]

It is not possible to make any assignments for the remaining $\gamma$ rays.

## XVI. NICKEL

The nickel capture spectrum was measured from a sample of pure nickelic oxide, and is illustrated in Fig. 14(a). The energies and intensities of the observed $\gamma$ rays are listed in Table VII. For the calculation of the intensities the capture cross section of nickel was taken to be 4.5 b,[57] to which $Ni^{58}$, $Ni^{60}$, and $Ni^{62}$ contribute 2.87 b, 0.67 b, and 0.54 b, respectively.[39]

The high-energy capture radiation from nickel has been examined by Kinsey and Bartholomew.[56] McFarland, Bretscher, and Shull[65] have measured the positions of energy levels in $Ni^{59}$ by the $(d,p)$ reaction. They find the first excited state to be at 0.42 Mev and the second at 3.08 Mev. However, Pratt[66] has found, also from the $(d,p)$ reaction, additional levels at 0.74±0.2, 1.15±0.2 Mev, and 1.62±0.2 Mev. These may be associated with high-energy capture $\gamma$ rays which may be supposed to make direct transitions to these states from the capturing level in $Ni^{59}$.[56,66] The energies are then fixed more accurately (since the binding energy of a neutron in $Ni^{59}$ is known to ±5 kev[56]) as 0.878±0.015 Mev, 1.180±0.013 Mev, and 1.777 ±0.025 Mev.

The levels are shown in Fig. 15. Also shown are spin values assigned by Pratt[66] on the basis of $(d,p)$ angular distributions. There is some doubt, however, about the spin of the 1.18-Mev level, since this proton group was not resolved from one due to $Ni^{61}$. The value given, $j=7/2^-$, is clearly inconsistent with a strong $\gamma$-ray transition from the capturing state to that level. The spin of the ground state is $j=\frac{3}{2}^-$, and the spin of the capturing state is $j=\frac{1}{2}^+$, since the target nucleus, $Ni^{58}$, is even-even. The direct transition to the ground state is therefore of the $E1$ type. The 7.528-Mev $\gamma$ ray to the 1.18-Mev level is about one-fifth as intense[56] as the ground-state $\gamma$ ray. Therefore, it could hardly be $E3$ as required by the spins assigned by Pratt.

It is possible that this particular $\gamma$ ray is not connected with this level. Then the energy would not be accurately fixed. In this case the 1.24-Mev $\gamma$ ray could be assigned as a ground-state transition, since it agrees with the approximate energy found in the $(d,p)$ reaction.

An 8.532-Mev $\gamma$ ray in the high-energy spectrum could correspond to a direct transition to the 0.42-Mev first excited state of $Ni^{59}$. However, it is more probably emitted to the ground state of $Ni^{61}$, for the energy agreement is better. The arguments used above also concern the spin of the 0.42-Mev level, and they make the latter alternative the more probable.

The 0.45- and 0.86-Mev $\gamma$ rays agree well with the energies of the first and second excited states of $Ni^{59}$, and the 2.68-Mev $\gamma$ ray may be emitted in a transition between the 3.08- and 0.42-Mev levels.

It has not been possible to assign the other $\gamma$ rays.

## XVII. ZINC

The zinc sample was pure zinc oxide powder. The spectrum is shown in Fig. 14(b). The energies and intensities of the resolved $\gamma$ rays are listed in Table VII. To calculate the intensities the capture cross section for the natural element was taken to be 1.09 b.[19] $Zn^{64}$ and $Zn^{68}$ contribute about 25% each to this figure[46] and the remainder comes from $Zn^{66}$ and $Zn^{67}$.

The high-energy capture $\gamma$ rays have been measured by Kinsey and Bartholomew.[56] They found the spectrum to be very complex, containing many unresolved $\gamma$ rays.

From their measurements they give the neutron binding energy of $Zn^{68}$ as 9.51±0.03 Mev, and that of $Zn^{65}$ as 7.876±0.007 Mev.

By subtraction from these numbers it is found that the 1.26-Mev $\gamma$ ray could correspond to the de-excitation of a possible level in $Zn^{68}$ to which a direct transition is made from the capturing level by a $\gamma$ ray of

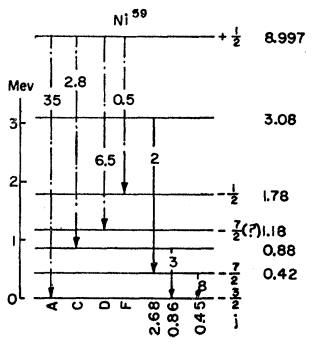


FIG. 15. Decay scheme for neutron-capture $\gamma$ rays in $Ni^{59}$. For explanation see Fig. 6. The spins shown for the levels are those suggested by Pratt (reference 66).

[65] McFarland, Bretscher, and Shull, Phys. Rev. **89**, 892 (1953).
[66] W. W. Pratt, Phys. Rev. **95**, 1517 (1954).

energy 8.58±0.02 Mev. This $\gamma$ ray is known[56] to occur in the decay of $Zn^{68}$ since its energy exceeds the binding energy in the other isotopes. Alternatively it might correspond to a level in $Zn^{65}$ since the energy difference agrees with a $\gamma$ ray of energy 6.65±0.03 Mev.[56] It is not known, however, by which of the isotopes this latter $\gamma$ ray is emitted.

None of the other $\gamma$ rays can be assigned in this way. The intensities of the low-energy $\gamma$ rays are higher by a factor five to ten than the intensities of almost all the high-energy $\gamma$ rays, showing that they take part in a large number of cascades.

### XVIII. CADMIUM

The cadmium capture spectrum, shown in Fig. 14(c), was obtained from a very thin sheet of cadmium metal. The energies and intensities (which in this case are relative intensities only) are given in Table VII. The $\gamma$ rays are emitted by $Cd^{114}$ since $Cd^{113}$ is responsible for the large capture cross section of cadmium.

The high-energy capture $\gamma$ rays from cadmium have been measured by Kinsey and Bartholomew[67] and Adyasevich *et al.*[68] have made measurements over the whole energy range with a magnetic spectrometer. Motz[69] has made measurements up to 1.7 Mev with a magnetic spectrometer. Many other measurements have been made at low energies by scintillation spectrometers.[2–4,10] The magnetic spectrometer measurements show that the spectrum is extremely complex, and, indeed, individual lines have not been resolved between 3 and 5 Mev.

The spectrum measured here agrees with the gross features of these other measurements. The strongest observed $\gamma$ ray is that at 0.56 Mev. It is already well established and is emitted in the de-excitation of the first excited state of $Cd^{114}$.[70] The tail of this peak extends up to about 0.8 Mev and must contain the $\gamma$ rays of energies 0.65, 0.73, and 0.80 Mev which have been reported. Similarly, the 1.32-Mev peak is very broad, and appears to contain seven $\gamma$ rays between 1.2 and 1.8 Mev.[68,69] The 2.53-Mev peak agrees with a group of four fairly strong $\gamma$ rays between 2.45 and 2.78 Mev.[68] The 3.27-Mev peak corresponds to a region in which the magnetic spectrometers no longer resolve the spectrum, and it is therefore apparent that this peak too must be composite. The relative intensities shown in Table VII do not agree well with those of Motz[69] and Adyasevich *et al.*[68]

### ACKNOWLEDGMENTS

The assistance of Miss Anne Rutledge in recording some of the data is gratefully acknowledged. It is a pleasure to thank Dr. B. B. Kinsey and Dr. G. A. Bartholomew for valuable discussions.

[67] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. **31**, 1051 (1953).

[68] Adyasevich, Groshev, and Demidov, Academy of Science U.S.S.R. Atomic Energy Conference Report, 1955 (Academy of Science, Moscow, 1955).

[69] H. T. Motz, Phys. Rev. **99**, 656 (1955).

[70] Johns, Cox, Donelly, and McMullen, Phys. Rev. **87**, 1134 (1952).