Directional Correlation of Gamma Rays Following the Decay of Eu^{152}†

R. W. LIDE* AND M. L. WIEDENBECK
Department of Physics, University of Michigan, Ann Arbor, Michigan
(Received October 2, 1958)

Directional correlation measurements have been made on the 245 kev–122 kev, 969 kev–122 kev, 1118 kev–122 kev, 1416 kev–122 kev, 872 kev–245 kev, and 1170 kev–245 kev cascades in Sm^{152}, and on the 782 kev–345 kev cascade in Gd^{152}. The spins of Sm^{152} are found to be 0, 2, 4, 2, 3, 3, for the ground, 122-kev, 367-kev, 1092-kev, 1240-kev, and 1538-kev levels. The 245-kev gamma ray is found to be pure quadrupole; the 872-kev gamma ray is 98% quadrupole, 2% dipole; the 969-kev gamma ray is 98% quadrupole, 2% dipole; the 1118-kev gamma ray is 99.8% quadrupole, 0.2% dipole; the 1170-kev gamma ray is 98% quadrupole, 2% dipole; the 1416-kev gamma ray is 15% quadrupole, 85% dipole. In Gd^{152} the spin of the 1127-kev level is found to be 3 and the 782-kev gamma ray is found to be pure dipole. A spin assignment of 1, 2, or 3 for the 757-kev level would not be inconsistent with the data. For any of these cases the 412-kev gamma ray must be mostly dipole; the quadrupole content must be less than 15%.

I. INTRODUCTION

THE decay of 13-year Eu^{152} has been studied by many authors.[1–5] The pertinent parts of the decay scheme proposed by Cork *et al.*[4] are shown in Figs. 1 and 2. The spin of the ground state of Eu^{152} has been measured to be 3.[6,7] Hartmann and Wiedling[8] have studied the angular correlation of the 1416 kev–122 kev cascade proposing a spin sequence of 0, 2, 6 for the ground state, 122-kev, and 1538-kev levels, respectively. Since the present investigation was completed, Ofer[9] has reported on the angular correlation of the 122 kev–245 kev, 122 kev–969 kev, 122 kev–1118 kev, and 122 kev–1415 kev cascades in Sm^{152}, and the 345 kev–782 kev cascade in Gd^{152}. He assigns a spin sequence of 0, 2, 4, 2, 3, 2, to the ground state, 122, 367, 1092, 1240, and 1538 kev levels in Sm^{152}, and a spin sequence of 0, 2, 3, to the ground state, 345-, and 1127-kev levels in Gd^{152}. In addition to those cascades investigated by Ofer, the angular correlation of the 245 kev–872 kev and 245 kev–1170 kev cascades in Sm^{152} have been investigated and are reported here.

II. EXPERIMENTAL PROCEDURE

A fast-slow coincidence circuit having a resolving time of 3×10^{-8} second was used for the measurement. This instrument has been described in a previous paper.[10] The scintillation detectors consisted of NaI(Tl) crystals, $1\frac{1}{2}$-in. diameter by 1-in. height, mounted on DuMont type 6292 photomultipliers. To reduce the counter-to-counter scattering, each crystal was shielded laterally by 12 mm of lead and frontally by $\frac{1}{2}$ in. of aluminum in addition to the 32 mils of aluminum and $\frac{3}{32}$ in. of packed magnesium oxide of the commercial crystal mounting.

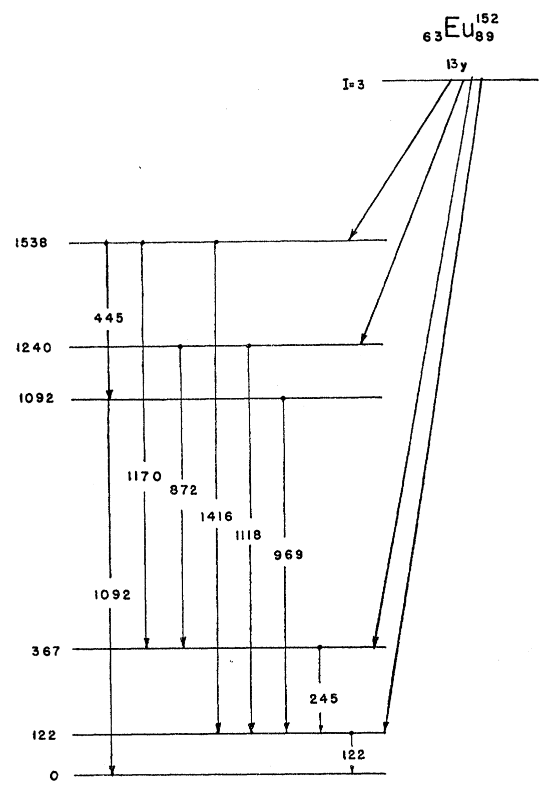

FIG. 1. Level scheme for the Sm^{152} nucleus according to Cork *et al.*[4] Only those gamma rays and energy levels are shown which are pertinent to the present investigation.

† Supported in part by the Office of Naval Research.
* Present address: University of Tennessee, Knoxville, Tennessee.
[1] Slattery, Lu, and Wiedenbeck, Phys. Rev. **96**, 465 (1954).
[2] L. Grodzins and H. Kendall, Bull. Am. Phys. Soc. Ser II, **1**, 164 (1956).
[3] O. Nathan and M. A. Waggoner, Nuclear Phys. **2**, 548 (1956/57).
[4] Cork, Brice, Helmer, and Sarason, Phys. Rev. **107**, 1621 (1957).
[5] Bhattacherjee, Nainan, Raman, and Sahai, Nuovo cimento **7**, 501 (1958).
[6] Abraham, Kedzie, and Jeffries, Phys. Rev. **108**, 58 (1957).
[7] Manenkov, Prokhorov, Trukhliaev, and Iakovlev, Doklady Akad. Nauk S.S.S.R. **112**, 623 (1957) [translation: Soviet Phys. Doklady **2**, 64 (1957)].
[8] B. Hartmann and T. Wiedling, Arkiv Fysik **10**, 355 (1954).
[9] S. Ofer, Nuclear Phys. **4**, 477 (1957).
[10] W. H. Kelly and M. L. Wiedenbeck, Phys. Rev. **102**, 1130 (1956).

TABLE I. Summary of results of several correlations.

Cascade	A_2	A_4	Spin sequence	Character of gamma rays
245 kev–122 kev	0.089 ± 0.013	0.010 ± 0.017	4-2-0	245-kev $E2$; 122-kev $E2$
969 kev–122 kev	0.023 ± 0.035	0.375 ± 0.050	2-2-0	969-kev, $Q=0.983\pm0.011$ ($\delta=+7.68$)
1118 kev–122 kev	-0.169 ± 0.024	-0.064 ± 0.022	3-2-0	1118-kev, $Q=0.9980_{-0.0037}^{+0.0081}$ ($\delta=-22.2$)

The source material for the present investigation was made available to us by J. M. Cork. It was in the form of Eu_2O_3 dissolved in dilute hydrochloric acid. The isotope Eu^{151} had been enriched to 92% before irradiation in the Argonne reactor.

III. METHOD OF ANALYSIS

To correct for source alignment and instrument drift, the real coincidence rate was divided by the energy-discriminated single rates and the mean value of these figures for each angle determined. A least-squares fit of these values was made to a finite series of even-order Legendre polynomials. The coefficients of these polynominals were corrected for the finite angular resolution of the detectors by the method of Rose[11] to yield a corrected function of the form $W(\theta)=1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)$, where P_k is the Legendre polynomial of order k.

For those cases in which there appeared to be a mixture of dipole and quadrupole radiation the results were further analyzed by a method due to Arns and Wiedenbeck.[12] It has been shown[13] that $A_2=A_2^{(1)}A_2^{(2)}$ and $A_4=A_4^{(1)}A_4^{(2)}$, where $A_2^{(1)}$ and $A_4^{(1)}$ depend only on the first transition, and $A_2^{(2)}$ and $A_4^{(2)}$ depend only on the second transition. If the first gamma ray is mixed dipole-quadrupole and the second pure quadrupole, these coefficients are given by the relations:

$$A_2^{(1)}=F_2(11j_1j)(1-Q)+2F_2(12j_1j)\times[Q(1-Q)]^{\frac{1}{2}}+F_2(22j_1j)Q,$$

$$A_4^{(1)}=F_4(22j_1j)Q,$$

$$A_2^{(2)}=F_2(22j_2j),$$

$$A_4^{(2)}=F_4(22j_2j).$$

The $F_k(LL'j'j)$ are the F coefficients defined and tabulated by Ferentz and Rosenzweig,[14] and j_1, j, j_2 are the angular momenta of the initial, intermediate, and final states, respectively. Q is the quadrupole content of the first radiation and is equal to $\delta^2/(1+\delta^2)$, where δ is defined as the ratio of the reduced matrix elements β and α for quadrupole and dipole radiation, respectively.[15] Arns and Wiedenbeck[12] have plotted $A_2^{(\nu)}$ and $A_4^{(\nu)}$ for many cases. The pertinent curves have been taken from this source and the experimental results superimposed to obtain the values of Q consistent with experiment.

IV. RESULTS

Ofer has previously reported the results of the angular correlation of the 245 kev–122 kev, 969 kev–122 kev, and 1118 kev–122 kev correlations in Sm^{152}. These correlations have also been carried out in the present work and are summarized in Table I for completeness. The errors which are quoted include the uncertainties arising from the correction of any interfering cascades.

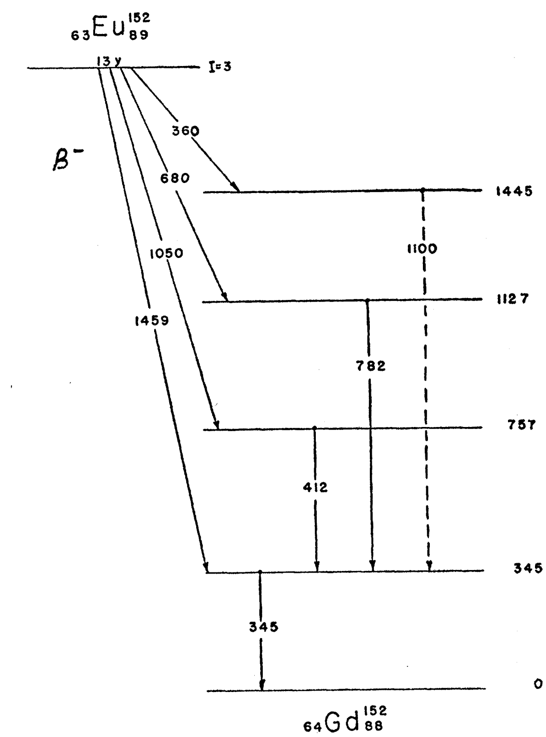

FIG. 2. Level scheme for the Gd^{152} nucleus according to Cork *et al.*[4]

[11] M. E. Rose, Phys. Rev. **91**, 610 (1953).
[12] R. G. Arns and M. L. Wiedenbeck, University of Michigan Engineering Research Institute, Technical Report 2375-3-T, January, 1958 (unpublished).
[13] See for instance H. Frauenfelder, in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 549.
[14] M. Ferentz and N. Rosenzweig, Argonne National Laboratory Report ANL-5324, 1955 (unpublished).
[15] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

872 kev–245 kev Correlation in Sm^{152}

The 872-kev gamma ray does not appear distinctly in the gamma-ray spectrum of Eu^{152}. However, it appears quite strongly in that part of the spectrum in coincidence with the 245-kev gamma ray as shown in Fig. 3. With one discriminator window set on the 245-kev photopeak, the other discriminator window was set to straddle the position of the 872-kev photopeak.

After all background correlations had been subtracted, the correlation function was found to be

$$W(\theta)=1+(0.141\pm0.034)P_2(\cos\theta)-(0.235\pm0.046)P_4(\cos\theta).$$

Assuming that the 122-kev and 367-kev levels in Sm^{152} have spins of 2 and 4, respectively, one obtains $A_2^{(1)}=-0.315\pm0.076$ and $A_4^{(1)}=+0.772\pm0.152$. This large positive value for $A_4^{(1)}$ can only be explained by assigning a spin of 3 to the 1240-kev level of Sm^{152}. The best value of Q is 0.979 ± 0.013 corresponding to $\delta=+6.90$.

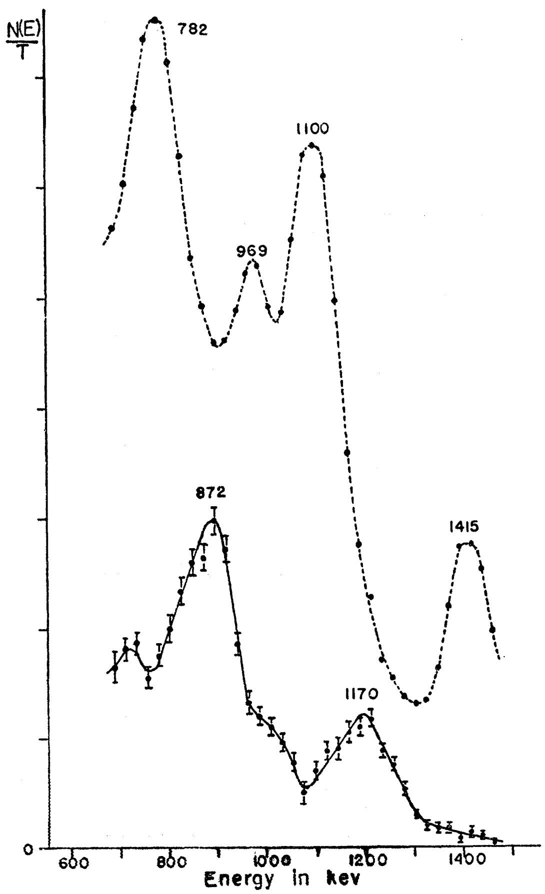

FIG. 3. Part of gamma-ray spectrum of Eu^{152}. The broken curve is the singles distribution. The solid curve is that part which is in coincidence with the 245-kev gamma ray. (Data taken by R. G. Helmer.)

If one assumes positive parity for the 1240-kev, 367-kev, and 122-kev level in Sm^{152}, the experimental value of Q means that the 872-kev transition is mostly $E2$. Nathan and Waggoner's[3] K-conversion coefficient is closer to the theoretical one for an $M1$ transition. However, their value is not inconsistent with $E2$ radiation when one considers that conversion coefficients are only accurate to $\pm40\%$.

1170 kev–245 kev Correlation in Sm^{152}

The 1170-kev gamma ray reported by Cork *et al.*[4] is apparently the same as the 1210-kev gamma ray reported by Grodzins and Kendall,[2] and the 1200-kev gamma ray reported by Nathan and Waggoner.[3] It has been observed only by gamma-ray coincidence methods; its conversion electrons have not been observed. Evidence for its existence is shown in Fig. 3.

The 1170 kev–245 kev cascade is relatively free of background coincidences because only the 1416-kev gamma ray, which is not in coincidence with the 245-kev transition, has an energy greater than 1170 kev. The weighted mean of two sets of data gives

$$W(\theta)=1+(0.140\pm0.039)P_2(\cos\theta)-(0.217\pm0.060)P_4(\cos\theta).$$

The errors quoted above are the standard deviations calculated by the method given by Rose.[11] The experimental results are shown in Fig. 4.

Because of the large negative balue of A_4, the only possible interpretation of this correlation is $3(D,Q)4(Q)2$. Dividing by the appropriate F functions of the second transition gives $A_2^{(1)}=-0.313\pm0.087$ and $A_4^{(1)}=+0.71\pm0.20$. Figure 5 shows that to fit both $A_2^{(1)}$ and $A_4^{(1)}$, Q must be 0.979 ± 0.015 corresponding to $\delta=+6.81$. The conclusion is that the 1170-kev gamma ray must come from a level whose spin is 3 and must be 98% quadrupole and 2% dipole.

1416 kev–122 kev Correlation in Sm^{152}

The angular correlation function for this cascade was found to be

$$W(\theta)=1+(0.191\pm0.011)P_2(\cos\theta)+(0.003\pm0.015)P_4(\cos\theta).$$

These results are the same within experimental error as those obtained by Ofer.[9] The A_2 term is slightly smaller than that obtained by Hartmann and Wiedling[8] while the A_4 term is within experimental error of their value.

This correlation function can be explained theoretically as due to a 6-2-0 spin sequence (the interpretation given by Hartmann and Wiedling[8]), a 5-2-0 spin sequence, a $3(D,Q)2(Q)0$ spin sequence, or a $2(D,Q)2(Q)0$ spin sequence (the interpretation given by Ofer[9]).

The interpretation depends on whether one adopts the decay scheme of Cork *et al.*,[4] or the decay scheme of

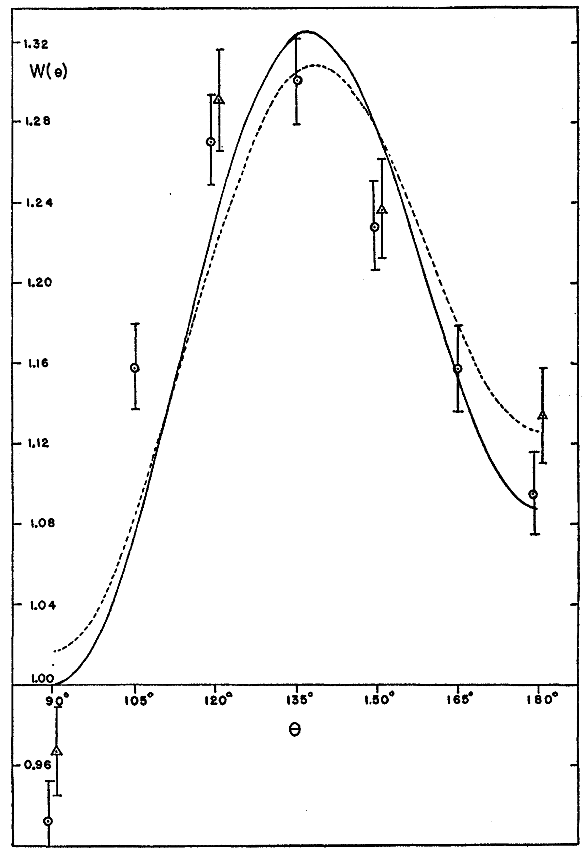

FIG. 4. Directional correlation of the 1170 kev–245 kev cascade in Sm^{152}. The triangles represent the first and the circles the second set of data corrected for finite geometry. The solid curve is the least-squares fit to both sets of data. The broken curve is the theoretical correlation function for a $3(D,Q)4(Q)2$ sequence with a 97.9% quadrupole, 2.1% dipole mixture in the first transition.

Nathan and Waggoner.[3] Since the 1170-kev gamma ray has not been observed by electron conversion, its energy is uncertain to about ±30 kev. In the decay of 9-hr Eu^{152m}, Grodzins and Kendall[2] have observed a gamma ray of 1380 kev in coincidence with the 122-kev gamma ray. Nathan and Waggoner[3] have measured the energy of this gamma ray to be 1416 kev and concluded that it was the same Sm^{152} transition as the 1416-kev transition following the decay of 13-yr Eu^{152}. It is unlikely that this gamma ray, the 1416-kev gamma ray from 13-yr Eu^{152}, and the 1170-kev gamma ray all result from the de-excitation of the same Sm^{152} level. This is because the spin of 9-hr Eu^{152m} is most probably 0,[16,17] and the present investigation shows that the 1170-kev gamma ray comes from a spin 3 level of Sm^{152}. A 0–3 spin change should give a high log*ft* value so that one would not expect to observe the decay of Eu^{152m} to a spin-3 level of Sm^{152}.

If one follows Nathan and Waggoner[3] and assumes that the 1415-kev and 1170-kev gamma rays come from different levels in Sm^{152}, then the present investigation leaves the spin of the 1537-kev level in their level scheme for Sm^{152} undetermined, but other considerations would favor a spin of 2 in agreement with Ofer.[9]

If, however, one follows Cork *et al.*[4] (as is done here) and assumes that the 1416-kev and 1170-kev gamma rays following the decay of 13-yr Eu^{152} come from the same energy level (this would seem to require the assumption that the 1380-kev gamma ray following the decay of 9-hr Eu^{152m} comes from a different level), then one is led to the conclusion that the 1416 kev–122-kev cascade must be $3(D,Q)2(Q)0$ with $Q=0.153 \pm 0.018$ corresponding to $\delta=-0.425$.‡

A third possibility is that the 1416-kev gamma ray following the decay of 13-yr Eu^{152} is in reality two gamma rays of nearly the same energy and comparable intensity. If this is so, then there is insufficient information to interpret the present data on the 1416 kev–122 kev correlation.

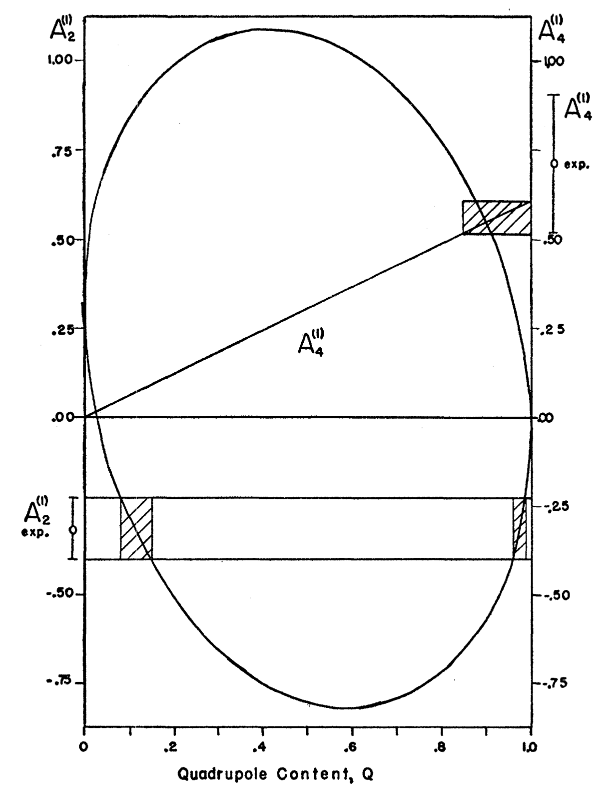

FIG. 5. Partial Legendre coefficients $A_2^{(1)}$ and $A_4^{(1)}$ *versus* Q, the quadrupole content, for a $4(D,Q)3$ transition, where the spin of the intermediate state is 4 and that of the initial state is 3. The shaded regions show the values of Q consistent with the experimental values of $A_2^{(1)}$ and $A^{(1)}$ obtained for the 1170 kev–245 kev cascade in Sm^{152}.

[16] L. Grodzins, Phys. Rev. **109**, 1014 (1958).
[17] Goldhaber, Grodzins, and Sunyar, Phys. Rev. **109**, 1015 (1958).

‡ *Note added in proof.*—Recent measurements by I. Marklund [Nuclear Phys. **9**, 83 (1958)] have shown that Eu^{152} and Eu^{152m} decay to different levels at 1530 kev and 1511 kev, respectively.

782 kev–345 kev Correlation in Gd^{152}

With one discriminator window set on the 782-kev photopeak and the other discriminator window set on the 345-kev photopeak, the correlation function obtained after correction for finite geometry was

$$W(\theta)=1-(0.081\pm0.013)P_2(\cos\theta)+(0.014\pm0.019)P_4(\cos\theta).$$

The uncertainty of the A_4 term is larger than the term itself. If one assumes that $A_4=0$, the correlation function becomes

$$W(\theta)=1-(0.076\pm0.011)P_2(\cos\theta).$$

This is in agreement with the theoretical correlation function for a $3(D)2(Q)0$ cascade, namely $W(\theta)=1-0.0714P_2(\cos\theta)$. Hence, a spin of 3 may be assigned to the 1127-kev level in Gd^{152}. This result is in agreement with Ofer.[9] Grodzins and Kendall,[2] Nathan and Waggoner,[3] and Bhattacherjee *et al.*[5] obtain K-conversion coefficients for the 782-kev gamma ray that are consistent with $E1$ radiation. Hence the 1127-kev level in Gd^{152} is probably a $3-$ state.

PHYSICAL REVIEW VOLUME 113, NUMBER 3 FEBRUARY 1, 1959

Neutron-Capture Gamma Rays in Cl^{36}†

R. E. SEGEL*
Aeronautical Research Laboratory, Wright-Patterson Air Force Base, Dayton, Ohio
(Received October 13, 1958)

γ-γ coincidences on the gamma rays following thermal neutron capture in Cl^{35} have been measured. Combining these results with the energy levels in Cl^{36} known from the $Cl^{35}(d,p)Cl^{36}$ reaction and the $Cl^{35}(n,\gamma)Cl^{36}$ gamma-ray spectrum measured by other workers, a decay scheme is constructed which unambiguously places most of the known gamma rays in Cl^{36}. An examination is made of the reduced widths of gamma rays emanating from the capturing state, and it is shown that the reduced widths for gamma rays of the same multipolarity can fluctuate widely, and that these fluctuations do not appear to be correlated with the final-state shell model configuration. It is also shown that the reduced widths for $E1$ and $M1$ transitions emanating from the capturing state are significantly smaller than those calculated from the single-particle estimate, and that $E1$ transitions are more intense than $M1$ transitions by about a factor of four. Evidence is presented for there being collective motion present in some of the higher excited states in Cl^{36}.

THE experiment reported herein represents a continuation of the program of investigations of gamma-ray cascades following thermal neutron capture undertaken by the Aeronautical Research Laboratory group at Brookhaven National Laboratory. The experimental technique and philosophy are virtually identical to that employed in the previously reported[1] measurements of gamma-ray cascades in Hg^{200}. Briefly summarized, this technique consists of placing a target in a thermal neutron beam, and measuring coincidences between two gamma-ray detectors placed close to the target. One detector is a 3-in.×3-in. NaI(Tl) crystal, while the other is a three-crystal pair spectrometer, also composed of NaI(Tl) crystals.

The gamma-ray spectrum resulting from thermal neutron capture in Cl^{35} has been measured by Groshev, Adyasevich, and Demidov.[2] Their results are shown in Table I. The energy levels in Cl^{36} have been investigated by Paris, Buechner, and Endt,[3] who magnetically analyzed the protons produced by the $Cl^{35}(d,p)Cl^{36}$ reaction. These results are shown in Table II. From the Paris *et al.* measurement of the Q value of the ground-state group, the neutron binding energy can be deduced to be 8.58 Mev, in agreement with the value of 8.57 Mev derived from the mass measurements.[4] Comparing Table I with Table II, one can see that all of the higher energy gamma rays measured by Groshev *et al.*[2] correspond to transitions from the capturing state to states found in the $Cl^{35}(d,p)Cl^{36}$ reaction, with the highest energy gamma ray corresponding to the ground-state transition. However, at excitation energies in Cl^{36} greater than ~2.5 Mev, the level spacing is comparable to the resolution under which the gamma-ray measurements were made.

The angular distributions of several of the proton groups from the $Cl^{35}(d,p)Cl^{36}$ reaction have been studied by Teplov.[5] The angular distributions could be analyzed in terms of a stripping mechanism, and the

† Work performed under the auspices of the U. S. Atomic Energy Commission.
* Guest scientist at Brookhaven National Laboratory, Upton, New York.
[1] R. E. Segel, Phys. Rev. **111**, 1620 (1958).
[2] Groshev, Adyasevich, and Demidov, *Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, 1955* (United Nations, New York, 1956).
[3] Paris, Buechner, and Endt, Phys. Rev. **100**, 1317 (1955).
[4] C. F. Biese and J. L. Benson, Phys. Rev. **110**, 712 (1958).
[5] I. B. Teplov, J. Exptl. Theoret. Phys. U.S.S.R. **31**, 25 (1956) [Translation: Soviet Phys. JETP **4**, 31 (1957)].