from the entrance aperture. In Ref. 1, for intensity reasons, the spectrometer was mounted at 45° to the main beam and the center crystal was placed flush with the entrance aperture of the annulus. The arrangement in the present experiment gives a much cleaner spectrum.

In each experiment, we had eight runs to measure the differences. In Ref. 1 the amplitude of each peak was about 80 counts. In the present experiment the amplitude of each peak was about 200 counts.

As noted in Table II, we find the energy of the $2p \rightarrow 1s$ transition in muonic Ca^{40} is 0.9 ± 0.3 keV more energetic than that in muonic Ca^{44}.

If the radius of the charge distribution was the same for the Ca^{40} and Ca^{44} nuclei, the $2p \rightarrow 1s$ transition in Ca^{44} would be 0.2 keV more energetic than that in Ca^{40} because of the reduced mass effect.

Unfortunately, the result of this experiment is not in agreement with the earlier result of Ref. 1. We believe that the present experiment is superior in that we achieved a much more stable detecting system, that the quality of the spectra is superior, that possible sources of systematic error have been eliminated, and that greater statistical accuracy has been attained.[12]

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[12] We have been informed by Dr. C. Missim-Sabat that the group at Columbia University has made a similar measurement and has obtained 0.65 ± 0.27 keV for the difference between the $2p \rightarrow 1s$ transitions in muonic Ca^{40} and Ca^{44}. We appreciate Dr. Missim-Sabat's communicating his result to us prior to publication.

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Angular Correlation Measurements in the Decay of Cd^{115m}

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Levels in In^{115} at 650, 930, 1125, 1285, 1420, and 1540 keV are populated in the decay of Cd^{115m} (43 days). The experimentally determined coefficients of the gamma-gamma angular correlation function for the cascades 485–930 and 160–1125 keV are $A_2 = -0.023 \pm 0.005$, $A_4 = 0.013 \pm 0.012$; $A_2 = -0.107 \pm 0.011$, $A_4 = 0.021 \pm 0.017$, respectively. The coefficient of the $\beta-\gamma$ directional correlation function between the unique first forbidden beta transition and the following 930-keV gamma ray is found as $A_2 = 0.0088 \pm 0.0076$. Spin assignemnts for the excited states in In^{115}, which are consistent with the experimental results, are 7/2 (930 keV), 11/2 (1125 keV), 9/2 (1280 keV) and 9/2 (1420 keV). The quadrupole-dipole mixing has been determined for the cascading gamma rays. From delayed-coincidence measurements, the half-lives of 930- and 1420-keV levels were found to be shorter than 3×10^{-10} sec and 1.1×10^{-9} sec, respectively.

I. INTRODUCTION

The decay of Cd^{115m} with a half-life of 43 days to In^{115} has been studied previously[1–3] by using scintillation coincidence techniques and magnetic beta-ray spectrometer. The decay scheme is well established and is shown in Fig. 1. Spin and parity assignments to levels of In^{115} have been made on the basis of calculated $\log ft$ values for the beta transitions which are classified as first forbidden types. The measured spin and parity of Cd^{115m} is $11/2-$,[4] which correspond to an $h_{11/2}$ single-particle state for the odd neutron and those of In^{115} is $9/2+$,[5] indicating a $g_{9/2}$ state for the proton hole. The beta transition feeding the 930-keV level has been shown[2,3] to be of unique first forbidden type. Nothing definite is known about the multipolarities of the gamma transitions as no internal conversion coefficients have been measured due to the intense beta transition to the ground state. The angular correlation between the 480- and 930-keV gamma rays has been measured by Varma and Mandeville[1] and by Van Der Kooi *et al.*,[6] but their results are not in good agreement with each other as is evident from Table I. The latter group concludes that the quadrupole ad-

Table I. Angular correlation coefficients for the 480–930-keV cascade.

Authors	A_2	A_4
Varma[a]	0.017	0.016
Van Der Kooi[b]	-0.022 ± 0.006	0.029 ± 0.011
Present work	-0.023 ± 0.005	0.013 ± 0.012

[a] Reference 1.
[b] Reference 6.

[1] J. Varma and C. E. Mandeville, Phys. Rev. **97**, 977 (1955).
[2] O. E. Johnson and W. G. Smith, Phys. Rev. **116**, 992 (1959).
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mixture for one gamma transition is >65% and that for the other transition >92%.

The levels at 930, 1125, and 1285 keV have been observed in Coulomb excitation[7,8] by ions of nitrogen. Silverberg[9] has recently calculated the energy levels of In^{115} assuming the coupling of the proton hole to the quadrupole vibrations of the even-even Sn^{116} core. Such a coupling gives rise to five levels with spins 5/2, 7/2, 9/2, 11/2, and 13/2. The electromagnetic transitions from such a multiplet to the ground state have been discussed by de-Shalit.[10] The study of such collective excitations in odd-A spherical nuclei is of great importance.

In the present work we report the results of beta-gamma and gamma-gamma angular correlations performed using scintillation coincidence spectrometer. Directional correlations between the unique first forbidden beta transition and 930-keV gamma ray and between the gamma rays of two cascades, 480–930 and 160–1125 keV, were measured. The quadrupole admixtures for each of these gamma transitions have been obtained by comparing the theoretical coefficients with our experimental results. Spin assignments for the excited states in In^{115} are made on the basis of this comparison. The life-times of the 930- and 1420-keV levels have also been measured by delayed coincidence technique.

II. EXPERIMENTAL PROCEDURE

A. Source Preparation

The Cd^{115m} source was obtained by irradiating an enriched sample of Cd^{114} (98%) in the DIDO Reactor at Harwell for $3\frac{1}{2}$ weeks at a flux of 10^{14} neutrons/cm^2/sec. The measurements were started after about 40 days when the 53-h Cd^{115} activity had practically died out. Chemical purification of the source was carried out to remove the possible contamination from Zn, Ag, and Mn, etc.

B. Apparatus

A conventional slow-fast coincidence scintillation spectrometer using 2-in.-diam×2-in.-thick NaI(Tl) crystals for detection of gamma rays was employed for angular correlation measurements. The source in liquid form was contained in a thin Perspex tube and kept at a distance of 5.5 cm from the detectors. A coincidence resolving time of $2\tau=35$ nsec was used. The true to chance coincidence rate was larger than 20 in all measurements. The stability of the electronic units as determined from the variations in the singles counting rate within a day's observation was better than 1%. The two detectors were aligned so that their axes of symmetry were in the same horizontal plane and passed through the center of the source. The accuracy in centering of the source was better than 0.5%. Suitable Perspex discs were used on both sides for absorbing beta rays.

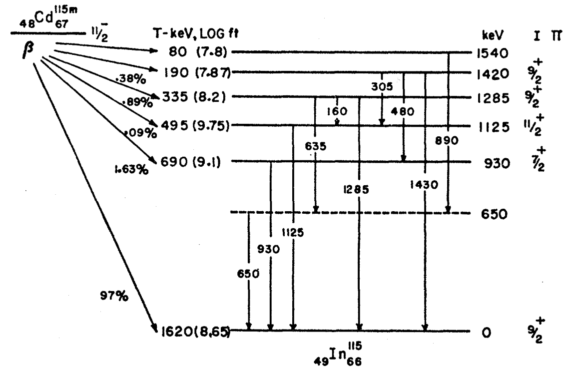

FIG. 1. Decay scheme of Cd^{115m}. The spin and parity assignment to the 930-, 1125-, 1285-, and 1420-keV levels are made from the present work.

Earlier a check of the complete system was carried out by measuring the gamma-gamma angular correlation with Co^{60} source. The experimental correlation coefficients agreed very well after making geometrical corrections, with the theoretical coefficients for the 1170–1330-keV cascade.

For measuring beta-gamma angular correlation one of the NaI(Tl) detectors was replaced by 1-in.-diam ×0.25-in.-thick anthracene crystal with the source mounted at a distance of 3.5 cm. The source was deposited on a Mylar film. The source and the anthracene detector were enclosed in 4-in.-diam thin aluminum dome evacuated to about 5×10^{-3} mm Hg. The contribution of the beta rays scattered from the surroundings was determined by using a shadow shield to stop the direct beam. This was found to be less than 1%.

III. RESULTS AND ANALYSIS

A. Angular Correlations

The directional correlation between the unique first forbidden beta transition and the following 930-keV gamma ray was measured at two angles, 90 and 180°. The experimental coefficient A_2 was calculated by expressing the correlation function in the form

$$w(\theta)=1+A_2P_2(\cos\theta). \quad (1)$$

The energy of beta rays selected was between 375 and 475 keV. The contributions from other beta groups and the Compton background of the 485-keV gamma rays, which are in coincidence with 930-keV gamma rays, are thus avoided. The observed correlation function was corrected for solid-angle attenuation as given

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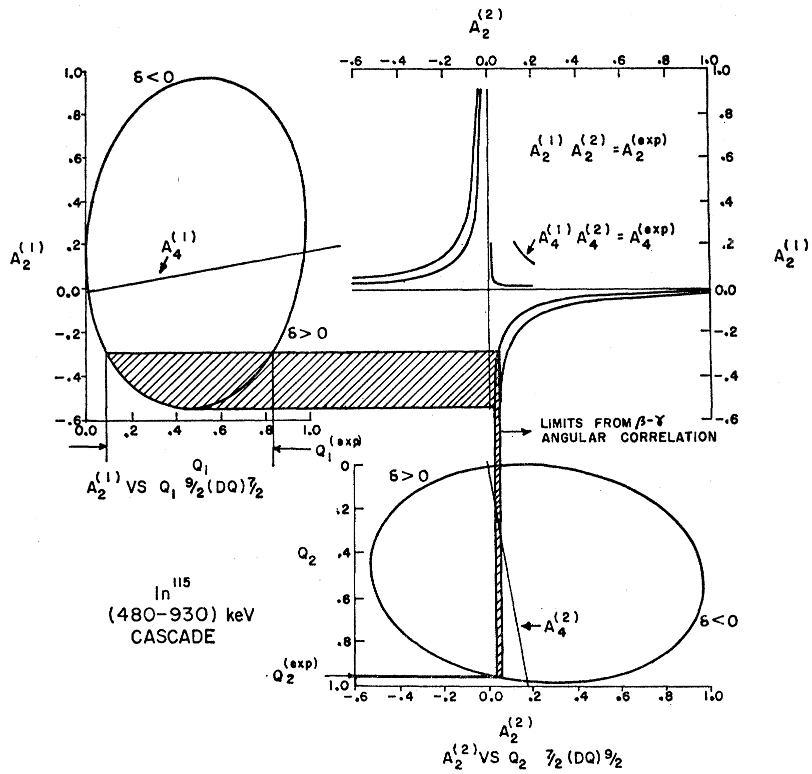

FIG. 2. The gamma-gamma angular correlation analysis of the 480–930-keV cascade.

by Breitenberger[11] and Rivers and Stanford.[12] For the correlation coefficient we obtain

$$A_2 = 0.0088 \pm 0.0076. \quad (2)$$

The gamma-gamma angular correlations for two cascades 480–930 and 160–1125 keV were measured at three angles 90, 135, and 180°. The correlation coefficients were obtained by expressing correlation function in the form

$$w(\theta) = 1 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta). \quad (3)$$

The solid-angle attenuation corrections were made according to Rivers and Stanford.[12] The coefficients are obtained as follows.

485–930-keV cascade:

$$A_2 = -0.023 \pm 0.005, \quad A_4 = 0.013 \pm 0.012; \quad (4)$$

160–1125-keV cascade:

$$A_2 = -0.107 \pm 0.011, \quad A_4 = 0.021 \pm 0.017. \quad (5)$$

The gamma-gamma angular correlation for the 480–930-keV cascade has been measured earlier by Varma and Mandeville[1] and Van Der Kooi *et al.*[6] Their results are summarized in Table I along with ours for comparison. Our results are in good agreement with those of Van Der Kooi *et al.*[6]

The positive sign of the A_4 term in the correlation function for 485–930-keV cascade uniquely assigns a spin $9/2^+$ to the 1420-keV level. The other two possibilities $7/2^+$ and $11/2^+$ yield negative A_4 term and thus are ruled out.

The quadrupole admixture in these gamma transitions has been estimated by the method of Arns and Wiedenbeck.[13] The coefficients A_2 and A_4 in the angular correlation function for the cascade $j_1(DQ)j_0(DQ)j_2$ can be written as $A_2 = A_2^{(1)} A_2^{(2)}$ and $A_4 = A_4^{(1)} A_4^{(2)}$. The $A_k^{(\nu)}$'s are given by

$$A_2^{(\nu)} = F_2(11j_\nu j_0)(1-Q_\nu) + 2F_2(12j_\nu j_0)[Q_\nu(1-Q_\nu)]^{1/2} + F_2(22j_\nu j_0)Q_\nu,$$

$$A_4^{(\nu)} = F_4(22j_\nu j_0)Q_\nu.$$

The Q_ν is the quadrupole fraction in the νth transition and bears the following relation with δ_ν:

$$Q_\nu = \delta_\nu^2/(1+\delta_\nu^2),$$

δ_ν^2 being the ratio of the intensity of the quadrupole to the dipole radiation in the νth transition. The F coefficients are tabulated by Ferentz and Rosenzweig.[14]

The analysis consists in graphically comparing the products $A_2^{(1)} A_2^{(2)}$ and $A_4^{(1)} A_4^{(2)}$ with the experimental

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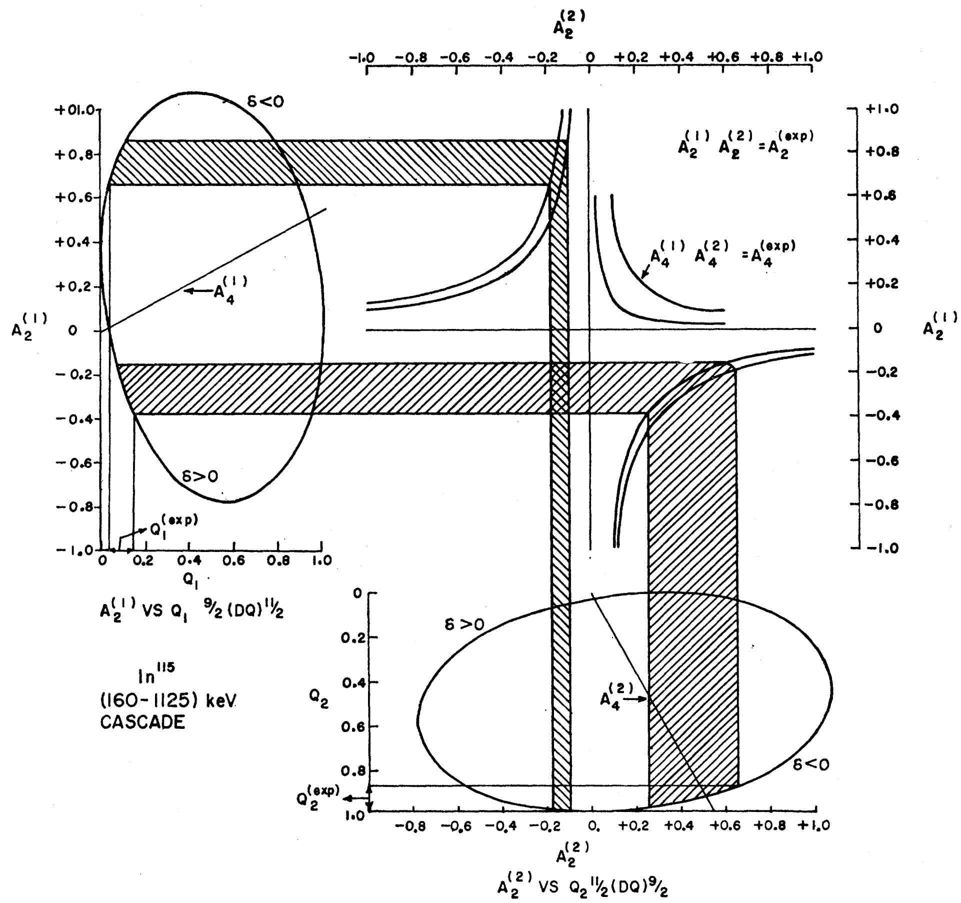

FIG. 3. The gamma-gamma angular correlation analysis of the 160–1125-keV cascade.

values and locating the values of Q_1 and Q_2 consistent with the data.

The analysis of 485–930-keV cascade is shown in Fig. 2. For the 930-keV transition the coefficient $A_2^{(2)}$ was obtained from the beta-gamma directional correlation measurement described above. The general expression for the beta-gamma directional correlation, involving a first forbidden unique type of beta transition, has been given by Kotani and Ross.[15] The correlation function for spin sequence $J_0(\beta)J_1(\gamma)J_2$ can be written as $w(\theta)=1+A_2P_2(\cos\theta)$, where

$$A_2=(-7/2)^{1/2}G_{22}^{(2)}[p^2\lambda_1/(q^2+p^2\lambda_1)],$$
$$G_{22}^{(2)}=(-1)^{J_1-J_0}w(J_1J_122;2J_0)(2J_1+1)^{1/2}A_2^{(2)}.$$

λ_1 are the functions representing the effect of the Coulomb field of the nucleus and are tabulated by Kotani and Ross[15] and w is the Racah coefficient. For the spin sequence $11/2^-(\beta)7/2^+(\gamma)9/2^+$ the correlation coefficient $A_2=-0.2778A_2^{(2)}$. Using the experimental value for the coefficient A_2 we get the limits for $A_2^{(2)}$ as $0.004\leqslant A_2^{(2)}\leqslant 0.06$ for the 930-keV gamma transition. The intersect at $Q_2=0.01$ (Fig. 2) being inconsistent with A_4 measurement the only Q_2 value possible for 930-keV transition is $Q_2=0.96\pm0.01$.

[15] T. Kotani and M. Ross, Phys. Rev. **113**, 622 (1959).

The gamma-gamma angular correlation function for the 160–1125-keV cascade can be made to fit any of the following three spin sequences: $9/2(\gamma)7/2(\gamma)9/2$; $9/2(\gamma)9/2(\gamma)9/2$; $9/2(\gamma)11/2(\gamma)9/2$. This assigns a spin $9/2^+$ to the 1285-keV level. The spin of the 1125-keV level is chosen as $11/2^+$ for reasons explained in the last section. The analysis of this cascade is shown in Fig. 3. Since no other data are available it is not possible to make unambiguous assignment of multipolarity for the gamma rays involved. One of these transitions is predominantly $M1$ and the other is predominantly $E2$. The shaded areas are those intersections which are consistent with both A_2 and A_4 values. Table II gives the quadrupole admixtures and

TABLE II. Proposed quadrupole admixtures for gamma-ray transitions.

Gamma-ray energy (keV)	Magnitude of quadrupole mixture Q	Sign of δ	Multipolarity
160	0.09 ± 0.05	+ or −	$M1+(E2)$
480	0.47 ± 0.37	+	$M1+E2$
930	0.96 ± 0.01	+	$E2+(M1)$
1125	0.94 ± 0.06	+ or −	$E2+(M1)$

multipolarity assignments for all the four-gamma transitions.

B. Lifetime Measurements

The lifetimes of the states 930 and 1420 keV were measured by delayed coincidence technique using a bridge type time-to-amplitude converter.[16] For the 930-keV level this was studied with the 485–930-keV gamma cascade using 2-in.×2-in.-diam NaI(Tl) crystals. The time spectrum thus obtained was found to be identical with the prompt one which was taken with Co^{60} under identical conditions. For studying the lifetime of the 1420-keV level the 485-keV gamma ray was taken in coincidence with beta rays in the region of 80 keV. In this case one of the NaI crystals was replaced by Anthracene detector to detect beta particles. The prompt curve was obtained by studying Na^{22} source under identical conditions. The two curves thus obtained agreed well within statistics. Thus the slopes of the prompt curves are used to give the upper limits of the half-lives. These are 3×10^{-10} sec and 1.1×10^{-9} sec, respectively, for the 930- and 1420-keV levels.

IV. DISCUSSION

The coupling of the 2^+ phonon to the 9/2 proton hole in In^{115} gives rise to a multiplet with spins and parities $5/2^+$, $7/2^+$, $9/2^+$, $11/2^+$ and $13/2^+$. The levels of this multiplet are expected to decay to the ground state by an $E2$ transition. The reduced $E2$ matrix elements $T_{i\to f}/E^5$ for these transitions[10] should be of the same order as that for $2^+\to0^+$ transition in Sn^{116}. In the case of In^{115} the levels at 930-, 1125-, and 1285-keV decay by the emission of strong ground-state transitions. As described above the transition from 930-keV level has actually been found to be $E2$ in character by angular correlation measurements. Also all the three levels are observed in Coulomb excitation. Table III gives the reduced $E2$ matrix element $T_{i\to f}/E^5$ for the 930- and 1125-keV transitions as calculated from the data provided by Vasilev *et al.* The Table also includes the reduced $E2$ matrix element for the 1270-keV transition from the first 2^+ excited state of Sn^{116} for comparison. The data for Sn^{116} have been obtained from Nuclear Data Sheets.[17] It is evident from Table III that the reduced $E2$ matrix elements for the 930- and 1125-keV transitions in In^{115} appear to be of the same order as that of 1270-keV transition in Sn^{116}. It is thus indicated that the 930-, 1125-, and 1280-keV levels of In^{115} may belong to the above-mentioned multiplet.

TABLE III. Reduced $E2$ matrix elements for In^{115} and Sn^{116}.

Nucleus	$E2$ transition	$T_{i\to f}/E^5$ in $Sec^{-1}\ MeV^{-1}$
$_{49}In^{115}$	930 keV	$0.24\times10^{+12}$
$_{49}In^{115}$	1125 keV	$1.8\times10^{+12}$
$_{50}Sn^{116}$	1290 keV	$0.56\times10^{+12}$

The spin assignments for the 930- and 1280-keV levels are 7/2 and 9/2, respectively, while that for 1125-keV level can be 7/2, 9/2, and 11/2. But since the 7/2 and 9/2 members of the multiplet have already been identified, the probable spin of the 1125-keV level is 11/2. The ground-state transition from this level is then expected to be $E2$ and the 160-keV transition in between the members of the multiplet could be $M1$. The analysis of the angular correlation measurement for the 160–1125-keV cascade, as described above, has shown that one of the two transitions is $E2$, the other being mostly $M1$. Thus, the angular correlation measurement also justifies the assignment of 11/2 to the 1125-keV level.

ACKNOWLEDGMENTS

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