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Decay of Cd^{115m}

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The decay of Cd^{115m} has been investigated with scintillation and magnetic spectrometers along with the coincidence technique. Gamma rays of 485-, 930-, 1125-, 1285-, and 1430-keV energy have been observed and their intensities have been calculated from the analysis of the gamma spectrum. Weak-intensity gamma rays of energies 160, 310, 650, and 890 keV have been observed in the coincidence spectra. The shape of the beta transition to the ground state deviates from the statistical shape and the correction factor for this is calculated. The beta spectrum in coincidence with 930-keV gamma ray has been shown to have a unique first-forbidden shape. A decay scheme consistent with these results is presented.

I. INTRODUCTION

THE decay of Cd^{115m} with a half-life of 43 days has been investigated earlier by several workers and the generally accepted decay scheme has been established by Varma and Mandeville[1] using scintillation spectrometers and coincidence techniques. They have shown that the beta decay of Cd^{115m} populates levels at 935, 1300, and 1420 keV in In^{115}. These de-excite by the emission of 935- and 1300-keV gamma rays and a 485–935-keV cascade.

Johnson and Smith[2] have studied the beta spectrum using a 4π scintillation spectrometer. They observed a slight curvature near the high-energy end of the Fermi plot of the ground-state beta transition with the end-point energy 1630 keV. This deviation from linearity was attributed by them to the presence of inner beta groups and the summing of pulses due to these betas and the pulses due to the Compton electrons from the corresponding gamma rays in coincidence with these betas. They also studied the beta spectrum in coincidence with the 935-keV gamma ray and showed that the beta transition to the 935-keV state was of the first-forbidden unique type.

Apart from the study of the decay of Cd^{115m}, investigations of the inelastic scattering of neutrons, protons, and α particles by indium have also provided information about the excited states of In^{115}. Levels at 610 and 920 keV have been indicated by the studies of inelastic scattering of 2.5-MeV neutrons.[3] Sharp and Buechner[4] have used a 7.04-MeV proton beam and analyzed the inelastically scattered protons with a high-resolution magnetic spectrometer. They observe excited states at 1078, 1135, 1292, and 1982 keV in In^{115}. Cohen[5] has reported that levels at 630, 1140, and 1480 keV are excited in In^{115} by the inelastic scattering of protons.

It is known[6] that the direct-interaction inelastic scattering preferentially excites the collective levels in nuclei. Such collective excitations in odd A nuclei are of great interest from the point of view of theories of nuclear structure. It was, therefore, thought worthwhile to undertake a careful study of the decay of Cd^{115} in order to see whether such collective levels indicated by the inelastic scattering experiments are excited in this decay. Moreover, it was hoped that a determination of the relative transition probabilities of the gamma transitions between the various excited states would throw some light on the character of the excited states. The present work was started from this point of view and also in order to reinvestigate the shapes of the beta transitions to the ground and the 935-keV excited state.

II. EXPERIMENTAL PROCEDURE AND RESULTS

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^{65} and other impurities. The source was deposited on a thin perspex holder for the measurements of the gamma spectrum. The beta-ray spectrometer source was prepared by evaporating a drop of the active material on a Mylar film of 500 μg/cm^2 thickness. Uniform spreading of the source was achieved by using a drop of insulin and the source was estimated to be about 100 μg/cm^2 thick.

B. Gamma-Ray Spectrum

The gamma-ray spectrum was studied with a 3-in.-diam$\times$3-in.-thick NaI(Tl) crystal coupled to a DuMont 6363 photomultiplier. The resolution of this scintillation spectrometer was $\sim$8.5% for the 662-keV gamma ray of Cs^{137}. The source was kept at a distance of 10 cm from the crystal and the beta particles were absorbed with a $\frac{1}{2}$-in.-thick perspex absorber. The spectra were recorded on a Nuclear Data 512 channel analyzer. In order to be able to correct for the contribution of the bremsstrahlung produced by the intense beta transition

[1] Jagdish Varma and C. E. Mandeville, Phys. Rev. **97**, 977 (1955).
[2] O. E. Johnson and W. G. Smith, Phys. Rev. **116**, 992 (1959).
[3] E. A. Elliot, D. Hicks, L. E. Beghian, and H. Halban, Phys. Rev. **94**, 144 (1954).
[4] R. D. Sharp and W. W. Buechner, Phys. Rev. **112**, 897 (1958).
[5] B. L. Cohen and A. G. Rubin, Phys. Rev. **111**, 1568 (1958).
[6] B. L. Cohen, in *Proceedings of the Rutherford Jubilee International Conference, Manchester, 1961*, edited by J. B. Birks (Academic Press Inc., New York, 1961), p. 207.

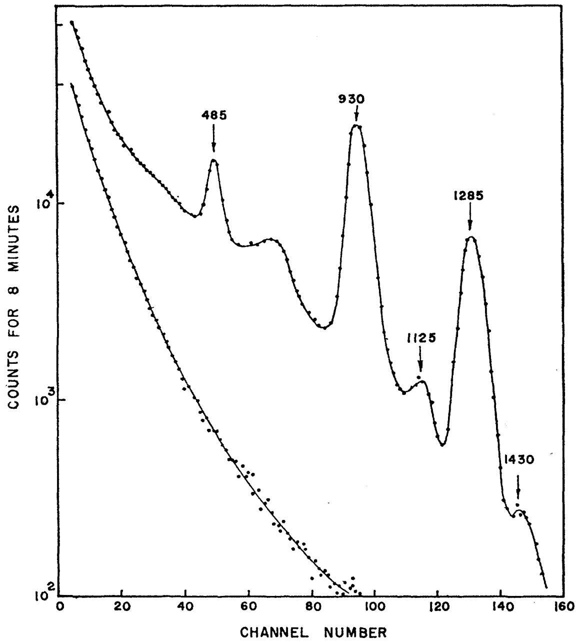

FIG. 1. Cd^{115m} gamma-ray spectrum. The lower line corresponds to the bremsstrahlung spectrum from P^{32}.

to the ground state, a source of P^{32} of almost the same strength was prepared with the help of a 4π proportional counter. The bremsstrahlung spectrum of this P^{32} source was taken under identical conditions of geometry. The two spectra are reproduced in Fig. 1. The gamma spectrum was studied over a period of two half-lives and it was confirmed that all the gamma rays were decaying with the same half-life. The contribution of the bremsstrahlung was subtracted and the gamma spectrum was analyzed as usual by subtracting out the contributions due to individual gamma rays starting from the high-energy end of the spectrum. The line shapes of the gamma rays from Na^{22}, Zn^{65}, and Mn^{54} were used as standards for this analysis. The intensities of the various gamma rays corrected for photopeak efficiency and normalized to a value of 100 for the intensity of the 930-keV gamma ray are given in Table I.

C. Gamma-Gamma Coincidences

The gamma-gamma coincidences were carried out with two scintillation spectrometers consisting of $1\frac{3}{4}$-in.-diam×2-in.-thick NaI(Tl) crystals coupled to RCA 6810A photomultipliers. A standard fast-slow coincidence circuit with a resolving time $2\tau = 0.07$ μsec was used. The detectors were kept at right angles and a 1-in.-thick lead absorber covered with cadmium and copper was placed in between to prevent spurious coincidences due to Compton scattering. The coincidence spectra were recorded on the 512 channel analyzer. The coincidence efficiency was checked to be 100% from 60 to 1280 keV, using the annihilation radiation from a

TABLE I. Relative gamma-ray intensities in the Cd^{115m} decay.

E (keV)	Relative intensity Singles spectrum	Coincidence spectra
160±15		0.93±0.14
310±15		0.16±0.03
485±5	18.4 ±2	
650±15		1.3 ±0.3
890±15		0.54±0.11
930±5	100	
1125±10	4.7 ±0.5	
1285±5	44.9 ±3	
1430±10	0.83±0.12	

Na^{22} source. It was often necessary to record the coincidences for a period of 800 min because most of the gamma rays are rather weak in intensity. The stability of the system was found to be satisfactory and the shifts in photopeak positions were less than 1% over a 24-h period.

The gamma spectrum in coincidence with the 1125-keV photopeak in gate is shown in Fig. 2(a) where photopeaks of 160- and 310-keV gamma rays can clearly be seen. Figure 2(b) shows the gamma spectrum in coincidence with the 160-keV region in gate. Here the photopeak of the 1130-keV gamma ray can be seen along with the photopeaks of 930- and 485-keV

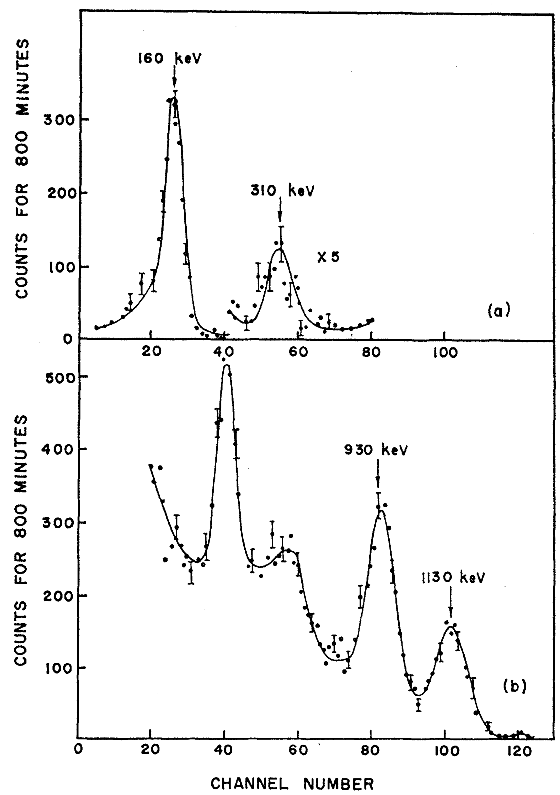

FIG. 2. Coincidence gamma-ray spectrum with (a) 1125-keV region (1050 → 1180 keV) and (b) 160-keV region (145 → 175 keV) in the gate.

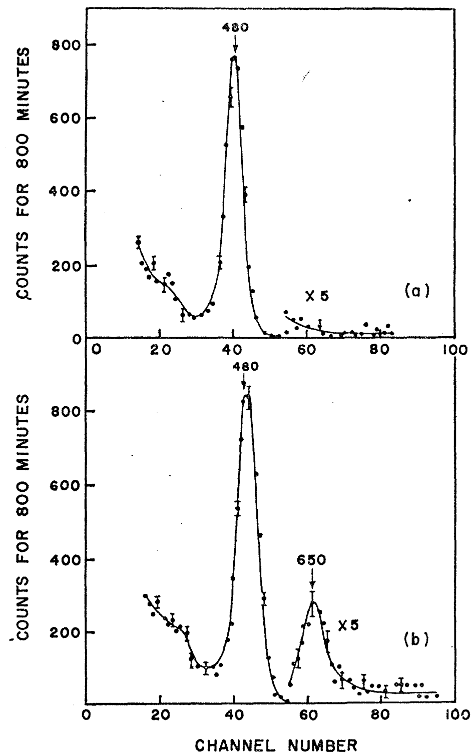

FIG. 3. Coincidence gamma-ray spectrum with (a) higher part of 930-keV photopeak (970 → 1040 keV) and (b) lower part (830 → 900 keV) in the gate.

gamma rays which are due to the inclusion in the gate of a part of Compton distributions of these gamma rays which are in coincidence with each other. These coincidences indicate a level at 1125 keV which is fed from the levels at 1285 and 1420 keV established in the earlier work.[1]

The coincidence spectrum with 930-keV gamma ray in gate showed the photopeak of a 650-keV gamma ray along with the previously known 485-keV gamma ray. The photopeak of this 650-keV gamma ray vanishes almost completely when the gate is fixed on the higher side of the photopeak of the 930-keV gamma ray [Fig. 3(a)]. If, however, the gate is fixed on the lower side of the 930-keV photopeak, the photopeak of the 650-keV gamma ray is quite prominent in the coincidence spectrum [Fig. 3(b)]. This was interpreted as indicating that the 650-keV gamma ray is not in coincidence with the 930-keV gamma ray but with a weak gamma ray of energy about 890 keV. This was confirmed by taking the 650-keV region in gate. The coincidence spectrum is reproduced in Fig. 4 and clearly shows a peak at 890 keV, and also at about 650 keV. These coincidences indicate a level at about 650 keV and also another at 1540 keV which decays to the former with the emission of an 890-keV gamma ray. The occurrence of the 1540-keV level was also confirmed by studying the sum spectrum taken with the source inside the well of a 3-in.×3-in.-well-type NaI(Tl) crystal. The sum peak corresponding to the 1540-keV level could be clearly seen in the sum spectrum. The 650-keV gamma observed in coincidence with 650 keV itself shows that there is a transition from the 1285-keV level to the 650-keV level.

The gamma rays of energies 160, 310, 650, and 890 keV are too weak to be observed in the analysis of the gamma spectrum. Their intensities were calculated from the coincidence measurements and are included in Table I. Possible angular correlation effects were neglected in these calculations.

D. Ground-State Beta Transition

The beta spectrum of Cd^{115m} was studied with a Siegbahn–Slätis-type magnetic spectrometer. The spectrometer has been modified for beta-gamma coincidence measurements and uses a 3-mm-thick anthracene crystal for the detection of the focused electrons. The performance of the instrument has been described earlier.[7] The beta spectrum of Cd^{115m} was recorded collecting more than 10 000 counts at each point except near the end. The Fermi plot of this beta spectrum in the energy region 700 to 1620 keV is shown in Fig. 5. It is clear that the Fermi plot shows a deviation from linearity. This deviation cannot be due to the presence of any other beta group with a lower end-point energy because there is no other known beta group in the decay of Cd^{115m} with an end-point energy greater than 680 keV.

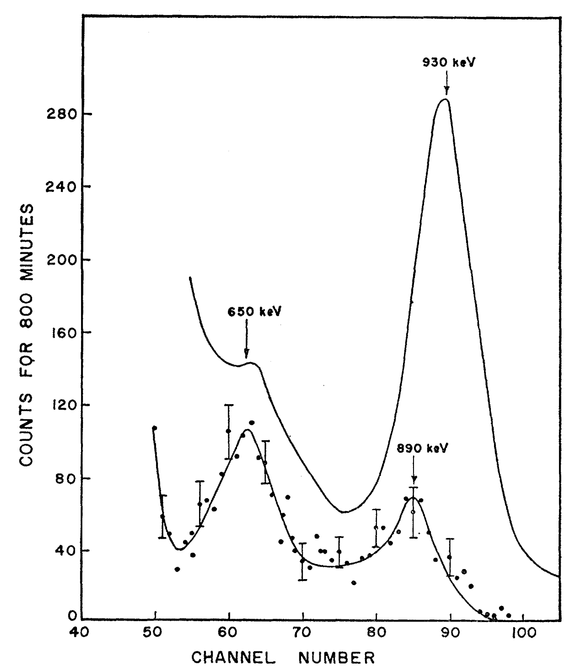

FIG. 4. Coincidence gamma-ray spectrum with 650-keV region (610 keV → 690 keV) in the gate. Singles gamma-ray spectrum is shown above the coincidence spectrum.

[7] R. P. Sharma, S. H. Devare, and Babulal Saraf, Phys. Rev. **125**, 2071 (1962).

The beta feeding of the 650-keV level, if present, must be very weak in intensity, as can be seen from the intensity of the 650-keV gamma ray and therefore, will not be able to affect the Fermi plot of the ground-state transition. The possibility of any interference due to the ground-state beta transition from Cd^{115} with an end-point energy 1150 keV is ruled out because there is no evidence for any $E5$ isomeric transition from Cd^{115m} and as such there cannot be any Cd^{115} in equilibrium with Cd^{115m}. Therefore, the deviation from linearity of the Fermi plot has to be regarded as due to a deviation of the beta spectrum from the statistical shape. The correction factor $C(W)=n/P^2F(W_0-W)^2$ plotted as a function of the energy is shown in Fig. 5(a). Here the end-point energy W_0 was taken to be 1618 keV so that the points near the end-point energy do not show a sudden large upward trend. A quadratic least square fit of this curve for the correction factor to the expression $C(W)=k(1+aW+b/W)$ shows that the correction factor can be expressed as

$$C(W)=k(1-0.78W-17.2/W).$$

To make sure that the observed deviation from linearity of the Fermi plot was not of instrumental origin, the performance of the beta-ray spectrometer was checked with a P^{32} source. The P^{32} decays with a single beta group which can serve as a suitable standard because, firstly, it has an end-point energy of 1710 keV which is not very much different from that of the Cd^{115m} beta spectrum and, secondly, the shape of this beta spectrum has been studied very carefully.[8] The P^{32} source was prepared in the same way as Cd^{115m} and was made almost similar in size and thickness. The beta spectrum was recorded immediately after taking the Cd^{115m} observations, with a statistical accuracy better than 1% for all points except at the end. The Fermi plot and the plot of the correction factor as a function of energy are shown in Fig. 6. The correction factor shows a variation of about 6% over a range of 400 to 1600 keV which is in fair agreement with previous measurements.[8] This shows that the observed deviation from statistical shape of the Cd^{115m} beta spectrum is not due to any spurious effect.

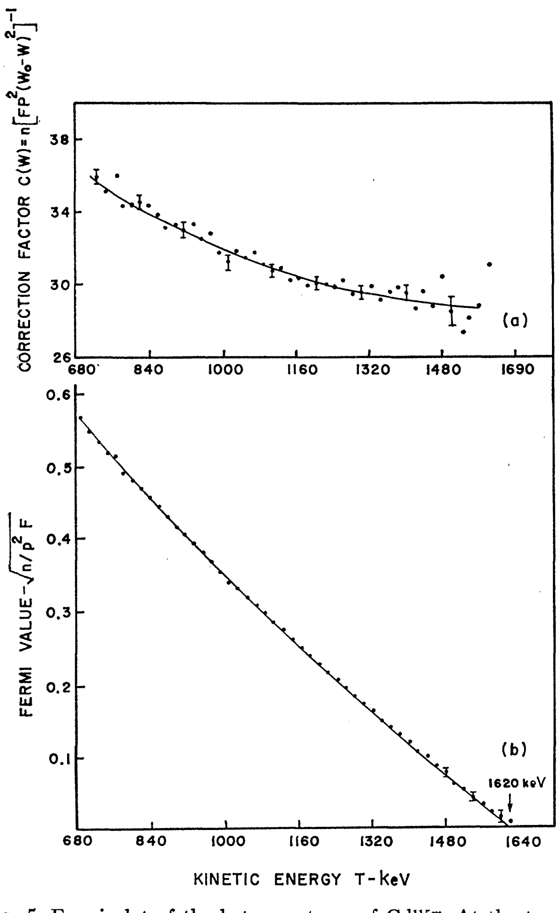

FIG. 5. Fermi plot of the beta spectrum of Cd^{115m}. At the top is plotted the shape correction factor $C(W)$ for this spectrum.

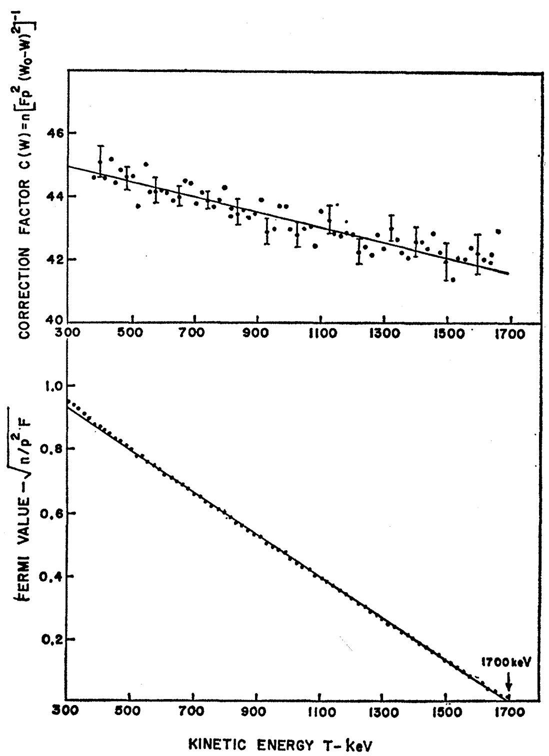

FIG. 6. Fermi plot of the beta spectrum of P^{32}. At the top is shown the shape correction factor $C(W)$ for this spectrum.

E. Beta Transition to the 930-keV Level

The beta feeding to the 930-keV level of In^{115} has been studied by observing the beta spectrum in coincidence with the 930-keV gamma ray. The pole piece on the source side of the Siegbahn–Slätis spectrometer

[8] R. T. Nichols, R. E. McAdams, and E. N. Jensen, Phys. Rev. **122**, 172 (1961).

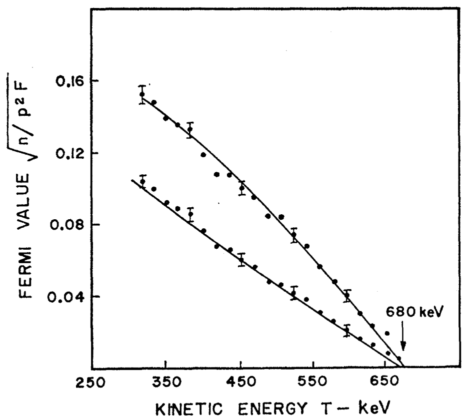

FIG. 7. Fermi plot of the beta spectrum in coincidence with 930-keV gamma ray. The spectrum corrected for the first-forbidden unique shape is plotted below.

has been suitably modified to enable placing of a 3-in.-diam×3-in.-thick NaI(Tl) crystal at a distance of 2 in. from the source. This crystal is directly coupled to a DuMont 6363 photomultiplier and the effect of the stray magnetic field on the photomultiplier has been neutralized by compensating coils. The pulses due to the beta particles focused on the anthracene crystal placed on the detector side were put in coincidence with the pulses due to the gamma rays detected by the NaI(Tl) crystal. A fast-slow coincidence circuit of the usual type using three wide band amplifiers in cascade on each side and having a resolving time $2\tau=0.05$ μsec was used. The photopeak of the 930-keV gamma ray was taken in gate and the beta spectrum in coincidence was recorded. The number of counts for each momentum setting was integrated over ten runs taken under identical conditions. The Fermi curve of the coincidence spectrum is shown in Fig. 7. It shows a deviation from a straight line corresponding to the well-known first-forbidden unique shape. The figure also shows the straight-line Fermi plot obtained after applying the usual first-forbidden unique shape correction factor, viz., $\alpha_1=p^2+q^2$. This confirms the earlier finding[2] that the transition to the 930-keV level is of the first-forbidden unique type corresponding to a spin change of 2 and a change of parity.

F. Beta Branching to the Various Levels

The relative intensities of the beta transitions to the various levels were estimated from the intensities of the gamma rays. These along with the logft values are given in Table II. The end-point energies of the ground-state beta transition and the transition to the 930-keV state have been determined from the beta-ray spectrometer measurements as described above and for the remaining transitions, they have been calculated from the energies of the levels which they feed as determined from the measurements of the gamma spectra. No estimate could be made for any beta transition to the

TABLE II. Beta transition data for Cd^{115m}.

End-point energy of different beta groups (keV)	Intensity	log ft
1620±10	97%	8.65
680±10	1.63	9.1
495	0.072	9.9
335	0.91	8.4
190	0.39	7.9
80	≲0.02	7.8

650-keV level as the intensity of the 650-keV gamma ray is obtained only from gamma-gamma coincidence measurements and is not the absolute intensity.

III. DECAY SCHEME AND DISCUSSION

A decay scheme based on the results of the present observations is shown in Fig. 8. Here, apart from the previously established levels at 930, 1280, and 1430 keV, new levels are suggested at 650, 1125, and 1540 keV on the basis of gamma-gamma coincidence measurements. The level at 1125 keV is also supported by the presence of the photopeak of the 1125-keV gamma ray in the gamma spectrum and the level at 1540 keV by the occurrence of the sum peak at that energy in the total absorption gamma-ray spectrum taken with the source inside the well of a NaI(Tl) crystal. The 650-keV level has justification only from the gamma-gamma coincidence measurements and is shown dotted, as there is no other supporting evidence. The relative intensities and the logft values for the beta transitions to the various levels have been calculated from the gamma-ray intensities. The logft values for the beta transitions to the 1285-, 1420-, and 1540-keV levels are all around 8 and all these beta transitions may be classified as first-forbidden types. The possible spin and parity assignments to these three levels on the basis of logft considerations would, therefore, be 9/2+, 11/2+, or 13/2+. The logft values for the transitions to the 1125- and 930-keV states are larger, being 9.9 and 9.1, respectively. These values would be consistent with an assignment of first-forbidden unique character to these

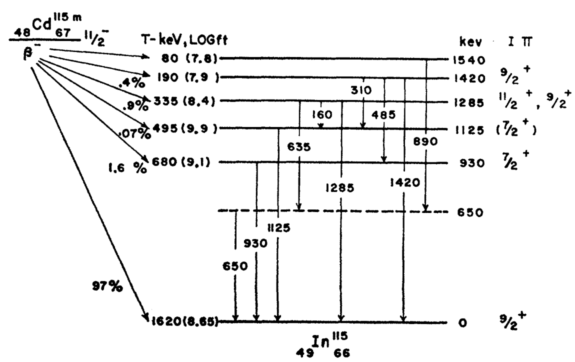

FIG. 8. Decay scheme of Cd^{115m} ($\tau_{1/2}=43$ days).

transitions. This is confirmed in the case of the transition to the 930-keV level by the shape of the beta spectrum in coincidence with the 930-keV gamma ray. Spin and parity assignment of 7/2+ has, therefore, been made to the 930-keV level and also to the 1125-keV level. Varma and Mandeville[1] have observed that the gamma-gamma angular correlation of the 480–930-keV cascade is isotropic and that this is consistent with the assignment of spin 9/2 to the 1420-keV level and 7/2 to the 930-keV level, the ground state being 9/2+ from shell-model considerations. The spin and parity of the 1420-keV level is, therefore, most probably 9/2+ and of the 1285-keV level, 9/2+ or 11/2+, the 13/2+ possibility being ruled out because of the observed 160-keV transition between this level and the 1125-keV 7/2+ level. No information about the spin and parity of the 650-keV level can be obtained from our measurements.

The gamma transitions from the 1420-, 1285-, and 1125-keV levels show certain interesting peculiarities. The 1420-keV level de-excites almost entirely through the 485–930-keV cascade and instead of the expected strong $M1+E2$ crossover transition, only a very weak 1430-keV transition is observed. The 1285- and 1125-keV levels, on the other hand, decay almost entirely by direct transitions to the ground state and the branching to intermediate levels is very much smaller than what would normally be expected. This suggests that these three levels may perhaps be of collective origin. The fact that these levels are also excited in the direct-interaction inelastic-scattering processes, while the 930-keV level is not excited, points to the same possibility. Silverberg[9] has recently calculated the energy levels of In^{115} taking into account the coupling of the proton hole to the quadrupole vibrations of the even-even Sn^{116} core. According to this calculation, out of the five levels which can arise due to the coupling of the proton hole in ground state to the 2+ one-phonon vibrational state, three levels have energies 1130, 1280, and 1430 keV, respectively. The 1125-, 1285-, and 1420-keV levels can perhaps be identified with these as the energies seem to agree well. Nothing definite, however, can be said about this as the spin assignment of the predicted as also the observed levels is not very definite.

The measured spin and parity of Cd^{115m} is $11/2^-$,[10] which correspond to a $h_{11/2}$ single particle state for the odd neutron. The ground state of In^{115} has a measured spin and parity value of[11] $9/2^+$ indicating a $g_{9/2}$ state for the proton hole. The beta transition to the ground state is thus $\Delta j=1$, yes type. The $\log ft$ value 8.6 for this first-forbidden transition is rather high. The shape of the beta spectrum also deviates from the statistical type. Both these effects may be due to an accidental cancellation of matrix elements for this transition. A quadratic least-squares fit for the correction factor gives $C(W)=k(1-0.78W-17.2/W)$. The large value of the $1/W$ term which affects the shape of the beta spectrum should also influence the longitudinal polarization of the beta particles, and such a measurement may be helpful in clarifying the nature of this beta transition.

ACKNOWLEDGMENTS

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[9] Lars Silverberg, Arkiv Fysik **20**, 341 (1961).

[10] B. Perry, M. N. McDermott, and R. Novick, Bull. Am. Phys. Soc. **7**, 533 (1962).

[11] J. E. Mack, Rev. Mod. Phys. **22**, 64 (1950).