DIRECTIONAL CORRELATION OF GAMMA RAYS IN THE DECAY OF $2 \cdot 3$ d ^{115}Cd

By M. M. Bajaj,* S. L. Gupta,* and N. K. Saha*

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Summary

The gamma–gamma directional correlation of the 35–493 keV cascade in the decay of $2 \cdot 3$ d ^{115}Cd has been studied by the coincidence method. The results seem to favour the spin and parity assignments $^1/_2{}^+$, $^3/_2{}^+$, and $^1/_2{}^-$ for the levels at 864, 829, and 336 keV respectively, and indicate that the 35 keV transition is $(96 \cdot 5 \pm 0 \cdot 5)\%$ M1 and $(3 \cdot 5 \pm 0 \cdot 5)\%$ E2, with a mixing parameter $\delta = -0 \cdot 191 \pm 0 \cdot 014$. These results agree with the recent I.C.C. measurements of Bäcklin, Fogelberg, and Malmskog but differ from those of earlier work. Computation of the partial lifetimes of the 35 keV radiation on this basis indicates that the M1 transition is retarded by a factor of $\simeq 23$ and the E2 transition is enhanced by a factor of $\simeq 958$. The E1 component of 493 keV radiation is estimated to be hindered by a factor of $\simeq 4 \times 10^{-7}$, while the M2 component is retarded by a factor of $\simeq 3$. The possible collective nature of the 829 keV level is discussed.

I. Introduction

The low lying excited states of the odd-mass isotopes of indium have been of considerable interest in recent years. Of particular interest are the energy levels of ^{115}In at 336, 597, 829, 864, and 934 keV above the ground state. Beta transitions of the $2 \cdot 3$ d ground state and the 43 d isomeric state of ^{115}Cd populating the ^{115}In levels and the resulting de-excitation γ-rays have been studied by a number of authors (Cork *et al.* 1950; Hayward 1952; Langer, Moffat, and Graves 1952; Wahl and Bonner 1952; Estulin and Moiseeva 1955; Varma and Mandeville 1955; Gorodetzky *et al.* 1960; Gorodetzky, Manquenonille, and Knipper 1961; Hans and Rao 1963; Bornemeier *et al.* 1964; Tandon and Devare 1964; Graeffe and Tang 1966; Graeffe *et al.* 1966; Pandharipande *et al.* 1966; Bäcklin, Fogelberg, and Malmskog 1967; McDonald, Porter, and Stewart 1967; Ranakumar and Lakshminarayana 1967). The spins and parities of these levels, assigned from the above studies, are shown in Figure 1; uncertain values are given in parentheses.

The ground state of ^{115}In has the well-established spin and parity of $\frac{9}{2}+$ and the isomeric state at 336 keV is $\frac{1}{2}-$. From the shell model, they are expected to be single-proton hole states $g_{9/2}$ and $p_{1/2}$ respectively. The spin and parity of the 597 keV level are also more or less well established as $\frac{3}{2}-$, and those of the 934 keV level as $\frac{7}{2}+$. However, considerable uncertainty seems to exist for the spin and parity of the two excited levels at 829 and 864 keV. The 864 keV level de-excites

* Department of Physics and Astrophysics, University of Delhi, Delhi–7, India.

to the 336 keV level via the 35–493 keV gamma–gamma cascade. Directional correlation measurements on this cascade seem to have been performed only by Hans and Rao (1963), who also determined the K-conversion coefficient α_K for the 35 keV radiation. On the basis of these data, they assigned spins and parities $\frac{3}{2}^-$ or $\frac{1}{2}^-$ to the 864 keV level, $\frac{3}{2}^-$ to the 829 keV level, and an M1 multipolarity for the 35 keV transition. Bornemeier *et al.* (1964) remeasured the K-shell conversion coefficient of the 35 keV γ-ray and assigned E1 multipolarity to it. Consequently, the 864 keV level would have positive parity (assuming negative parity for the 829 keV level) and this contradicts the earlier conclusions. Recently Graeffe *et al.* (1966) have performed accurate α_K measurements for the 35 keV γ-ray using a Ge(Li)

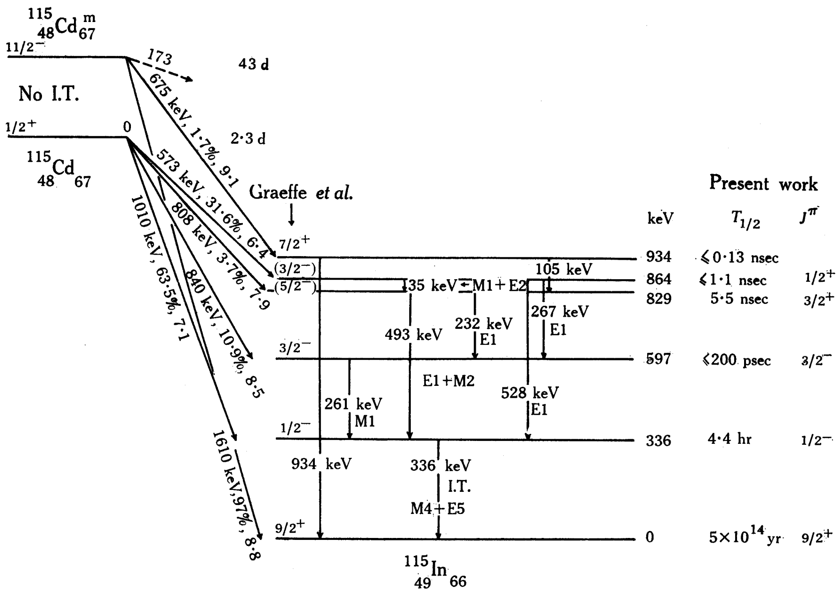

Fig. 1.—Decay scheme of 2·3 d ^{115}Cd (and part of 43 d ^{115}Cd^m) based on some of the earlier results and on results obtained in the present work.

detector and a NaI(Tl) scintillation counter. They have obtained the spin and parity $\frac{3}{2}^-$ for the 864 keV level and find a predominantly M1 multipolarity for the 35 keV transition (with some mixing of E2). Further, the possible spins and parities of the 829 keV level according to these authors are either $\frac{3}{2}^+$ or $\frac{5}{2}^-$. One way of deciding between the two alternatives would be to ascertain the multipolarity of the observed 105 keV γ-transition (between the 934 and 829 keV excited states), which has not been previously attempted. Quite recently Bäcklin, Fogelberg, and Malmskog (1967) measured the conversion coefficients of the various transitions in ^{115}In. They favour $\frac{3}{2}^+$ for the 829 keV level, $\frac{1}{2}^+$ (or $\frac{3}{2}^+$) for the 864 keV level, and predominantly E1 multipolarity for the 493 keV radiation. The overall data for these two levels are therefore fairly conflicting.

The importance of the low lying levels of ^{115}In stems from the fact that, while the ground state and the first isomeric state at 336 keV are considered to be the two single-proton hole states, the higher excited states might arise from a coupling of the 2^+ vibrational phonon of the doubly even core to the lowest two levels. This picture would be consistent with the observed behaviour (McGowan and Stelson 1958) of the 45- and 47-proton nuclides in their collective core excitations and their possible couplings with single quasi-particles to produce the low lying excited states. In view of the observed half-life of 5·5 nsec for the 829 keV level in ^{115}In, the study of multipolarities of the 35 and 493 keV γ-transitions would be of great importance. This is the more so because Graeffe *et al.* (1966) have concluded from their recent work that the collective effect of the 49-proton nucleus ^{115}In is rather weak, and this nucleus may stand out from the general pattern of behaviour of the neighbouring odd-proton nuclei.

In view of the position stated above, we considered it necessary to remeasure the directional correlation of the 35–493 keV gamma–gamma cascade and to examine the spin values of the excited levels involved as well as the multipole character of the γ-transitions.

II. Coincidence Measurements

The source used in the present work was in the form of cadmium nitrate dissolved in nitric acid solution. It was produced by irradiating spectrographically standardized pure cadmium metal with neutrons in the Apsara Reactor, Trombay.

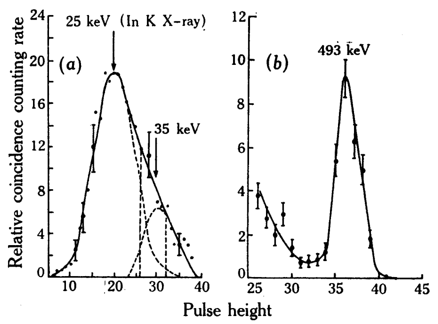

Fig. 2.—Gamma spectrum in coincidence with:
(*a*) 493 keV γ-ray
(*b*) 35 keV γ-ray

All the coincidence and directional correlation measurements were carried out with a fast–slow scintillation coincidence spectrometer with an effective resolving time of $\simeq$ 30 nsec. The counting time for directional correlation measurements was over 30 hr at each angular position.

Figures 2(*a*) and 2(*b*) show the γ-spectra recorded in coincidence with the 493 and 35 keV γ-rays respectively. These spectra clearly establish the coincidence relationship between the 493 and the 35 keV γ-rays.

III. Results

(*a*) *Directional Correlation of 35–493 keV Cascade*

Evaluation of the experimental data yielded the solid-angle corrected directional correlation function

$$W(\theta) = 1+(0\cdot0695\pm0\cdot0175)P_2(\cos\theta) -(0\cdot0036\pm0\cdot0431)P_4(\cos\theta). \qquad (1)$$

The only contribution in this cascade comes from the interference produced by the coincidence of the 493 keV γ-ray with the 25 keV K-conversion quanta of the 35 keV γ-ray. A careful analysis of the coincidence spectrum (Fig. 2(*a*)) shows that this interference is $(37\cdot6\pm5\cdot0)\%$ of the observed number of total coincidences. Since this interference is isotropic in nature, the directional correlation function after correction is

$$W(\theta) = 1+(0\cdot111\pm0\cdot029)\mathrm{P}_2(\cos\theta) -(0\cdot006\pm0\cdot069)\mathrm{P}_4(\cos\theta). \qquad (2)$$

As the half-life of the 829 keV intermediate state is $5\cdot5\pm0\cdot2$ nsec (Tandon and Devare 1964), an attenuation of the expansion coefficients may possibly occur. By using solid and liquid sources, however, we observed that there is no appreciable change in the anisotropy within the statistical error. We, therefore, conclude that the measured directional correlation is unperturbed, and equation (2) does not require further correction. A discussion of the directional correlation data in terms of equation (2) is set out below.

(*b*) *Spin and Parity of 829 and 864 keV Levels*

This cascade involves the excited states at 336, 829, and 864 keV (Fig. 1). For the 336 keV isomeric state, the $\frac{1}{2}^-$ spin and parity assignment has been made on the basis of the log *ft* value of the beta group feeding this level and the I.C.C.* measurement of the 336 keV ground state transition in ^{115}In (Estulin and Moiseeva 1955; Hans and Rao 1963). The results of beta spectra and some theoretical considerations (Walters, Bemis, and Gordon 1965) allow a wide range of spin and parity values for the 829 keV level, namely, $\frac{1}{2}^+$, $\frac{1}{2}^-$, $\frac{3}{2}^+$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$. Nevertheless, the situation has been carefully analysed by Graeffe *et al.* (1966). The 934 keV level has been shown to have a spin and parity value of $\frac{7}{2}^+$ as a result of the beta transition feeding it from ^{115}Cd$^{\mathrm{m}}$ and its formation by the Coulomb excitation of the $\frac{9}{2}^+$ ground state of ^{115}In. Further, because of the observed 105 keV transition from this level to the 829 keV level, we can limit the assignments to $\frac{3}{2}^+$, $\frac{3}{2}^-$, or $\frac{5}{2}^-$ for the latter. Recent I.C.C. measurements carried out with Ge(Li) detectors and a double-focusing beta spectrometer by Bäcklin, Fogelberg, and Malmskog (1967) show that the 493 keV transition from the 829 to the 336 keV level ($\frac{1}{2}^-$) is predominantly E1 with an M2 content of 4%. The spin values $\frac{3}{2}^-$ and $\frac{5}{2}^-$ are then not compatible with the E1 multipolarity of the 493 keV transition. Therefore, the only possible assignment for this state is $\frac{3}{2}^+$. In conclusion, we may say that the experimental result of Bäcklin, Fogelberg, and Malmskog has been a decisive factor in uniquely determining the spin and parity of the 829 keV level.

For the 864 keV level, the probable spin values are $\frac{1}{2}^+$, $\frac{3}{2}^+$, or $\frac{5}{2}^+$ because the 35 keV transition between the 864 and 829 keV levels has been shown to be predominantly M1 on the basis of I.C.C. measurements (Hans and Rao 1963; Graeffe *et al.* 1966; Bäcklin, Fogelberg, and Malmskog 1967). Of these, $\frac{5}{2}^+$ is unlikely because of the E1 character of the 528 keV transition between the 864 and 336 keV levels found on the basis of conversion coefficient measurements (Bäcklin, Fogelberg, and Malmskog 1967). The probable values are thus limited to $\frac{1}{2}^+$ and $\frac{3}{2}^+$.

* I.C.C. = internal conversion coefficient.

As a result of the above discussion, two alternative spin sequences, namely (i) $\frac{1}{2}$(D, Q) $\frac{3}{2}$(D, Q) $\frac{1}{2}$ and (ii) $\frac{3}{2}$(D, Q) $\frac{3}{2}$(D, Q) $\frac{1}{2}$, follow for the 35–493 keV cascade. Taking approximately 4% M2 admixture (Bäcklin, Fogelberg, and Malmskog 1967) in γ_{493}, the mixing ratio analysis of equation (2) carried out in terms of the spin sequence (i) (Fig. 3) shows that the 35 keV transition is predominantly M1 with an E2 content of $(3\cdot5\pm0\cdot5)$%. This is in close agreement with Bäcklin, Fogelberg,

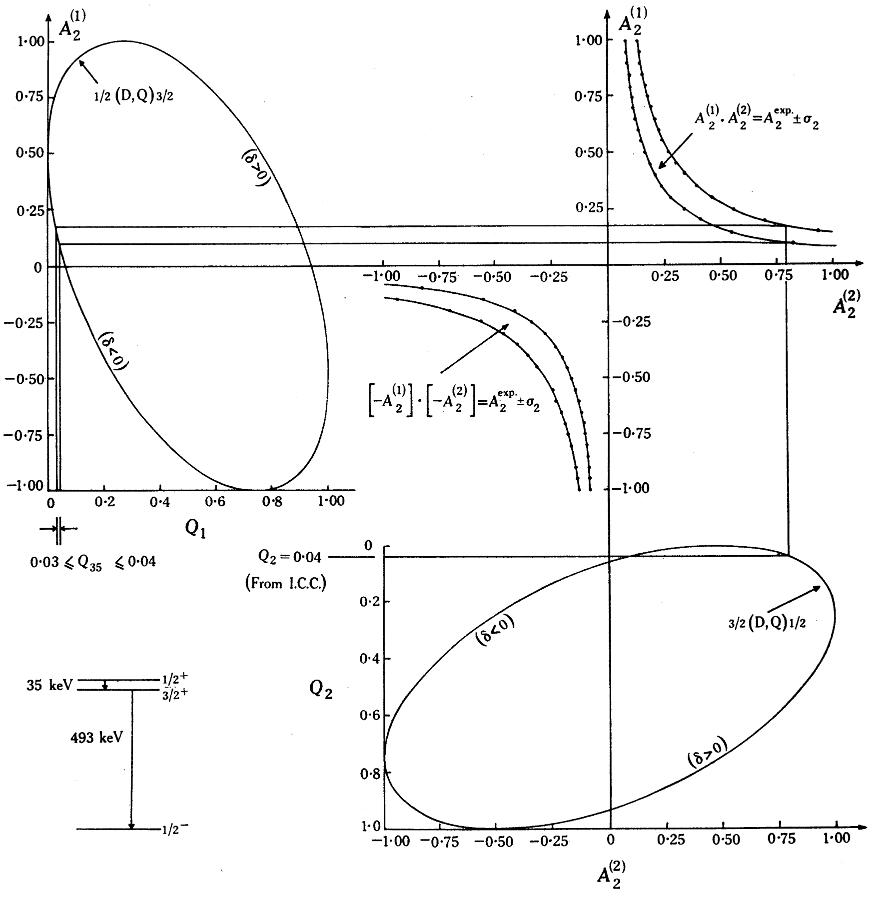

Fig. 3.—Mixing ratio analysis of the 35–493 keV cascade in terms of a $^1/_2$(D, Q)$^3/_2$(D, Q)$^1/_2$ spin sequence.

and Malmskog's recent result of $\simeq$ 97% M1 and $\simeq$ 3% E2 admixture for this transition. The analysis also gives the mixing parameter δ $(= \{I(\mathrm{E2})/I(\mathrm{M1})\}^{\frac{1}{2}})$ of the 35 keV transition as $-0\cdot191\pm0\cdot014$. The spin sequence (ii), on the other hand, leads to an E2 admixture of $(11\cdot15\pm1\cdot85)$% $(\delta_{35} < 0)$ for the same transition and is therefore not acceptable. As a result of the present directional correlation measurements and the other known data, the spin and parity of the 864 keV level are assigned as $\frac{1}{2}^+$ and those of the 829 keV level as $\frac{3}{2}^+$.

IV. Discussion

It will be noticed that the expansion coefficients obtained here differ markedly from those reported by Hans and Rao (1963), namely, $A_2 = -0\cdot10\pm0\cdot03$, $A_4 = +0\cdot03\pm0\cdot03$. These authors assigned spin and parity values of $\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{1}{2}^-$ to the levels at 864, 829, and 336 keV respectively. As the multipolarity of γ_{493} was not known earlier, their conclusions could not be unambiguous. From the present directional correlation data and other recent results, we arrive at definite assignments of $\frac{1}{2}^+$ and $\frac{3}{2}^+$ to the levels at 864 and 829 keV.

Graeffe *et al.* (1966) favoured a $\frac{5}{2}^-$ spin value for the 829 keV level, because they found an E1 multipolarity for the 105 keV transition. The assignment $\frac{5}{2}^-$, however, would be difficult to reconcile with the E1 multipolarity of the 493 keV transition (Bäcklin, Fogelberg, and Malmskog 1967).

Using the half-life (1·1 nsec) of the 864 keV level, the conversion coefficient $\alpha_K = 9\cdot6\pm1\cdot2$, and the measured value $(-0\cdot191\pm0\cdot014)$ of the mixing parameter from the present work for the 35 keV γ-ray, we find that the experimental lifetimes for the M1 and E2 components of the 35 keV transition are 17·4 and 479·7 nsec respectively. Comparing these partial lifetimes with the corresponding Weisskopf estimates, the M1 component is found to be retarded by a factor of $\simeq 23$ while the E2 component is enhanced by a factor of $\simeq 958$. This fast rate of the E2 transition is consistent with Sorensen's (1964) superconductivity model for the 28–50 proton-shell region, as here the Fermi energy λ falls above the single-proton levels.

Using the half-life (5·5 nsec) of the 829 keV level, the quadrupole admixture ($\simeq 4\%$) in the 493 keV E1 transition (Bäcklin, Fogelberg, and Malmskog 1967), and the theoretical α_K (E1+M2) value (0·002373) extrapolated from the tables of Sliv and Band (1957, 1958), we have computed the transition probabilities for the E1 and M2 components of the 493 keV transition. The result shows that the E1 part of this radiation is hindered by a factor of $\simeq 4\cdot14\times10^{-7}$ while the M2 component is retarded by a factor of $\simeq 3$ compared with the corresponding Weisskopf estimates. A comparison with the available systematics (Perdrisat 1966) of E1 transition probabilities shows that this E1 hindrance factor is in line with the general trend observed in this region.

Assignment of $\frac{5}{2}^-$ to the 829 keV state led Graeffe *et al.* (1966) to the conclusion that the 493 keV γ-transition was too slow for a phonon-mixed E2 transition. The dominant collective effects generally observed in the nuclei having $Z = 45$ or 47 were therefore supposed to have markedly changed in ^{115}In. This difficulty clearly vanishes when we assign $\frac{3}{2}^+$ to the 829 keV level, the resulting predominantly E1 493 keV γ-transition having the right order of the hindrance factor consistent with nuclear systematics.

Attempts have been made to construct theoretically (Vogt 1963) the levels of ^{115}In by a first-order perturbation treatment of the interaction of the 2^+ vibrational phonon of the core to the lowest two single-proton hole levels (Kisslinger and Sorensen 1960). The collective levels have been extrapolated further by Silverberg (1961). However, these theoretical treatments appear to be far from satisfactory in describing the experimentally observed levels of ^{115}In. The present spin and parity assignments to the observed levels do not bring us any nearer to agreement, but a qualitative picture of the collective nature of the levels seems to be generally supported.

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VI. References

Bäcklin, A., Fogelberg, B., and Malmskog, S. G. (1967).—*Nucl. Phys.* A **96**, 539.

Bornemeier, D. D., Ellsworth, L. D., Mandeville, C. E., and Potnis, V. R. (1964).—*Phys. Rev.* **134**, B740.

Cork, J. M., Rutledge, W. C., Stoddard, A. E., Branyan, C. E., and LeBlanc, J. M. (1950).—*Phys. Rev.* **79**, 938.

Estulin, I. V., and Moiseeva, E. M. (1955).—*Soviet Phys. JETP* **1**, 463.

Gorodetzky, S., Manquenonille, R. R., and Knipper, A. (1961).—Electromagnetic lifetimes and properties of nuclear states. p. 79. Nat. Acad. Sci. Publ. No. 974.

Gorodetzky, S., Manquenonille, R., Richert, R., and Knipper, A. (1960).—*J. Phys. Radium, Paris* **21**, 439.

Graeffe, G., and Tang, C. W. (1966).—*Bull. Am. phys. Soc.* **11**, 394.

Graeffe, G., Tang, C. W., Coryell, C. D., and Gordon, G. E. (1966).—*Phys. Rev.* **149**, 884.

Hans, H. S., and Rao, G. N. (1963).—*Nucl. Phys.* **44**, 320.

Hayward, R. W. (1952).—*Phys. Rev.* **87**, 202A.

Kisslinger, L. S., and Sorensen, R. A. (1960).—*Math.-fys. Meddr* **32**(9), 1.

Langer, L. M., Moffat, R. D., and Graves, G. A. (1952).—*Phys. Rev.* **86**, 632A.

McDonald, J., Porter, D., and Stewart, D. T. (1967).—*Nucl. Phys.* A **104**, 177.

McGowan, F. K., and Stelson, P. H. (1958).—*Phys. Rev.* **109**, 901.

Pandharipande, V. R., Prasad, K. G., Singru, R. M., and Sharma, R. P. (1966).—*Phys. Rev.* **143**, 740.

Perdrisat, C. F. (1966).—*Rev. mod. Phys.* **38**, 41.

Ranakumar, N., and Lakshminarayana, V. (1967).—Proc. Low Energy Nucl. Phys. Symp., Kanpur, Dep. Atomic Energy, Government of India.

Silverberg, L. (1961).—*Ark. Fys.* **20**, 341.

Sliv, L. A., and Band, I. M. (1957).—Rep. No. 57 ICC K1 Phys. Dept, Univ. Illinois, Urbana, Illinois.

Sliv, L. A., and Band, I. M. (1958).—Rep. No. 58 ICC L1, Phys. Dept, Univ. Illinois, Urbana, Illinois.

Sorensen, R. A. (1964).—*Phys. Rev.* **133**, B281.

Tandon, P. N., and Devare, H. G. (1964).—*Phys. Lett.* **10**, 113.

Varma, J., and Mandeville, C. E. (1955).—*Phys. Rev.* **97**, 977.

Vogt, E. W. (1963).—*Phys. Lett.* **7**, 61.

Wahl, A. C., and Bonner, N. A. (1952).—*Phys. Rev.* **85**, 570.

Walters, W. B., Bemis, C. E., Jr, and Gordon, G. E. (1965).—*Phys. Rev.* **140**, B268.