Angular Momenta and Parities of the Excited States of Cd^{114}†

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Angular correlation experiments have been performed on the 0.722-Mev—0.556-Mev gamma-gamma cascade of Cd^{114} in order to determine the angular momenta and the parities of the nuclear states involved. The directional correlation of the two gamma rays is indicative of a pure quadrupole—pure quadrupole cascade between states of angular momentum quantum number 4, 2 and 0. The polarization-directional correlation experiments show that all three states involved have the same parity, and furthermore, give strong support to the angular momentum assignment mentioned above. Hence, the K-capture decay in In^{114} which precedes this gamma-gamma cascade must originate in the 50-day isomeric state of In^{114} with $I=5$ and not in the 72-sec ground state with $I=1$. Observations of the gamma radiation directly following the 72-sec decay confirmed this result.

Directional correlation measurements on ten In^{114} sources of very different chemical and physical structure did not reveal any evidence of extranuclear perturbation effects on the Cd^{114} gamma-gamma correlation.

1. INTRODUCTION

THE nuclide In^{114} has a 50-day isomeric state 0.192 Mev above its 72-sec ground state. The latter decays by an allowed β^- transition (log $ft=4.5$) to the ground state of Sn^{114} ($I=0^+$). On this basis an angular momentum quantum number of $I=1$ and even parity has been assigned to the In^{114} ground state. The isomeric transition from the 50-day state to the 72-sec state is an $E4$ transition and therefore, an angular momentum of 5 (even parity) was suggested for the 50-day state.[1] Recently this angular momentum assignment has been confirmed by a direct measurement using the atomic beam magnetic resonance method.[2] The 72-sec ground state decays by β^+ emission and K-capture to the ground state of Cd^{114} and was also assumed to decay by K-capture to the second 1.28-Mev excited state of Cd^{114}.[3,4] Hence an angular momentum quantum number of 1 or 2 was indicated for this state. An angular momentum assignment of 0 was ruled out on the basis of the interpretation of a weak 1.28-Mev gamma ray as a direct transition from this state to the $I=0$ ground state of Cd^{114}. The ft value (log $ft=3.4$) of the K-capture transition from the 72-sec ground state to the second excited Cd^{114} level indicated a superallowed transition, which appeared to be very unlikely in this case. It was thus hypothesized[1] that this K-capture decay originates from the 50-day isomeric state of In^{114}, requiring an angular momentum quantum number of 4 or 5 for the second excited state of Cd^{114}.

A 0.722-Mev—0.556-Mev gamma-gamma cascade was known to proceed from this second excited state,[3–5] and the gamma-gamma directional correlation was measured in an attempt to find the angular momentum of the second excited state of Cd^{114}. With this information, the In^{114} state from which the K-capture decay originates could be determined.

The first directional correlation experiments[1] were consistent with an angular momentum assignment of 4, 2, 0 to the second excited, first excited, and ground states, respectively, and thus indicated that the K-capture decay indeed originated from the 50-day In^{114} state with $I=5$ rather than from the 72-sec ground state with $I=1$. The ft value of this K-capture decay was characteristic of a first-forbidden transition, and therefore an assignment of odd parity to the second excited state of Cd^{114} was made. These assignments, however, caused a serious discrepancy between the expected and the observed intensity of the 1.28-Mev gamma radiation, if the interpretation of this radiation as a cross-over transition was to be maintained.

In view of this difficulty several groups performed additional directional correlation experiments.[6–9] All of these measurements seemed to suggest an angular momentum assignment of 2-2-0 with the assumption of a mixed 96% dipole—4% quadrupole gamma transition from the second excited state. This assignment was consistent with the intensity of the crossover transition and strongly favored the conclusion that the electron capture takes place in the 72-sec ground state of In^{114}. Apparent discrepancies between the experimental and the theoretical 2-2-0 directional correlation function were attributed to the effects of competing cascades whose existence was reported by Johns *et al.*,[9,10] but which did not reappear in recent measurements performed in the same laboratory.[11]

Polarization—directional correlation measurements performed in this laboratory, however, furnished

† Supported in part by the U. S. Atomic Energy Commission.
[1] R. M. Steffen, Phys. Rev. **83**, 166 (1951).
[2] L. S. Goodman and S. Wexler, Phys. Rev. **100**, 1245 (1955).
[3] F. Boehm and P. Preiswerk, Helv. Phys. Acta **22**, 331 (1949).
[4] Mei, Mitchell, and Zaffarano, Phys. Rev. **76**, 1883 (1949).
[5] F. Maienschein and J. Lawrence Meem, Jr., Phys. Rev. **76**, 899 (1949).
[6] E. D. Klema and F. K. McGowan, Phys. Rev. **87**, 524 (1952).
[7] R. M. Steffen and W. Zobel, Phys. Rev. **88**, 170 (1952).
[8] Johns, Cox, and McMullen, Phys. Rev. **86**, 632, and Errata **86**, 581 (1952).
[9] Johns, Cox, Donnelly, and McMullen, Phys. Rev. **87**, 1134 (1952).
[10] Johns, McMullen, Donnelly, and Nablo, Can. J. Phys. **32**, 35 (1954).
[11] Johns, Williams, and Brodie, Can. J. Phys. **34**, 147 (1956).

decisive evidence for the $(4^+)-(2^+)-(0^+)$ assignment[12,13] (see Sec. 3). Hence, it was decided to remeasure the directional correlation of the 0.722-Mev—0.556-Mev cascade with the use of differential pulse-height selection in order to eliminate the effect of possible competing cascades. (See Sec. 2.) These data agreed very well with the 4-2-0 spin assignments, and moreover, did not support the findings of Daubin and Hamilton[14] that there existed a strong extranuclear influence on this gamma-gamma cascade.

Confirmation of these angular-momentum assignments was furnished by experiments on the 72-sec In^{114} ground state performed at Brookhaven[15,16] and Purdue[17] (see Sec. 4), which revealed that no excited state of Cd^{114} is involved in the 72-sec K-capture decay. The apparent discrepancy in the intensity of the cross-over transition was resolved by Grodzins and Motz[15,16] whose coincidence experiments indicated that the high-energy gamma transition, which was formerly interpreted as due to the crossover, is emitted by an excited state of Sn^{114} following a low-intensity β^- transition from the 72-sec In^{114}. These conclusions were also arrived at independently by Johns *et al.* in their recent experiments.[11]

2. DIRECTIONAL CORRELATION OF THE Cd^{114} GAMMA RAYS

2.1 Choice of Chemical and Physical State of the In^{114} Source

It is well known that directional correlations are often influenced by interactions of extranuclear fields with the nuclear moments in the intermediate state of the gamma-gamma cascade.[18] External fields do exist in most radioactive sources as a result of the charge and current distribution of the electron shell of the decaying nucleus and, of other atoms in the immediate neighborhood. However, the directional correlation is disturbed only if enough time is available in the intermediate nuclear state. A discussion of this effect shows that, in general, no disturbing influence is to be expected if the lifetime of the intermediate state is less than 10^{-10} sec. Intermediate states of shorter lifetimes are affected in extraordinary cases only (e.g., an atom strongly disturbed by a preceding alpha-decay process, strong magnetic hyperfine coupling in the paramagnetic ions of the transition elements, etc.).

The intermediate state involved in the Cd^{114} gamma-gamma cascade has a lifetime τ_N of less than 2.3×10^{-10} sec.[14] Hence, the possibility of a perturbation of the directional correlation, although not very probable, cannot be excluded *a priori*, and the environment of the decaying Cd^{114} nucleus must be chosen with this consideration in mind.

In general, the attenuation, if any, of directional correlations displayed by nonviscous liquid sources is very small. Furthermore, the use of a metal in the liquid phase also eliminates possible after-effects of the preceding K-capture decay by virtue of the fast recovery of the excited atom in metals. In view of these considerations, the directional correlation measurements on the Cd^{114} gamma-gamma cascade were performed on In^{114} sources in the form of liquid indium metal.

2.2 Preparation of the Source

The 50-day In^{114} was obtained in metallic form from the Isotopes Division of the Oak Ridge National Laboratory. A small amount of the metal was sealed into a thin Pyrex tube of 1-mm inside diameter and 5-mm length, which was heated electrically to a temperature of 165°C to keep the indium metal in the liquid phase.

2.3 Directional Correlation Apparatus

The experimental arrangement consisted of two scintillation detectors with NaI(Tl) crystals mounted on Dumont 6292 photomultipliers. A coincidence analyzer of over-all resolving time $\tau_0=9.6\times10^{-8}$ sec, with differential pulse-height selection in the two

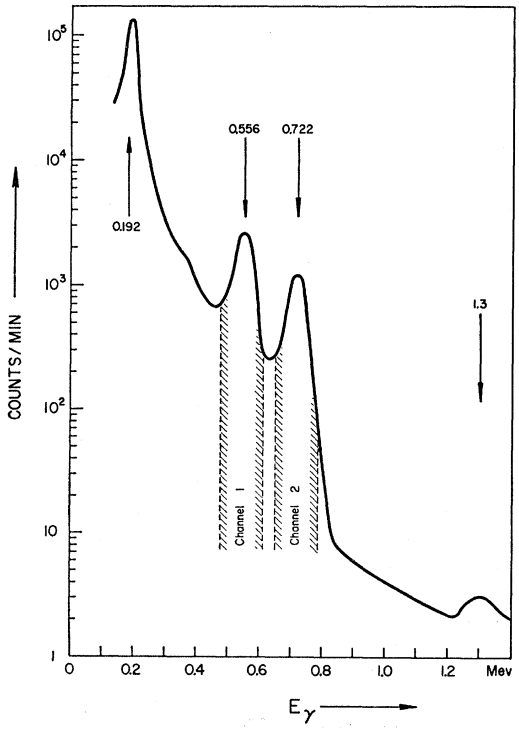

FIG. 1. Energy spectrum of the gamma radiation emitted during the decay of the 50-day In^{114} isomer.

[12] J. N. Brazos, M. S. thesis, Purdue University, January, 1954 (unpublished).
[13] J. N. Brazos and R. M. Steffen, Phys. Rev. **99**, 1645 (1955).
[14] J. C. Daubin and D. R. Hamilton, Phys. Rev. **99**, 683 (1955).
[15] L. Grodzins and H. T. Motz, Phys. Rev. **100**, 1236 (1955).
[16] L. Grodzins and H. T. Motz, following paper [Phys. Rev. **102**, 761 (1956)].
[17] R. M. Steffen and J. N. Brazos, Phys. Rev. **99**, 1646 (1955).
[18] R. M. Steffen, Advances in Phys. Phil. Mag. Suppl. **4**, 293 (1955).

channels was used in all the experiments. The coincidence circuit which was of the fast-slow type allowed one to measure the coincidence counting rate $C_{\gamma\gamma}$ simultaneously with differential pulse-height selection and with integral pulse-height discrimination. A more detailed description of the apparatus and the electronics will be published soon.[19]

The energy resolution of the two scintillation detectors was between 8% and 9% for the Cs^{137} gamma-ray photopeak.

The angle between the axes of the two detectors was changed automatically every 15 or 60 minutes and the accumulated data recorded by means of a camera.

2.4 Measurement of the Cd^{114} Directional Correlation

The spectrum of the In^{114}-Cd^{114} gamma radiation measured with one of the two scintillation detector channels is shown in Fig. 1. The width of the energy band accepted by the two differential channels in all directional correlation measurements is indicated in this figure. In order to prevent overloading of the amplifiers by the pulses from the strong 0.192-Mev radiation, lead absorbers of 3-mm thickness were placed in front of the scintillation detectors. These lead absorbers also served the purpose of reducing the number of coincidence counts due to Compton scattered radiation. The latter is, of course, only of significance for the correlation measurements where no differential pulse-height selection was employed.

Figure 2 shows a plot of the coincidence counting rate (with differential pulse-height selection) divided by the product of the single counting rates in the two channels and corrected for the decay of the source *versus* the angle Θ. A least-squares fit of the data to a function of the form $W''(\Theta)=A_0''+A_2''P_2(\cos\Theta)+A_4''P_4(\cos\Theta)$ yields the following result for the normalized experimental correlation function $W'(\Theta)$ which is not yet corrected for the finite angular resolution of the equipment:

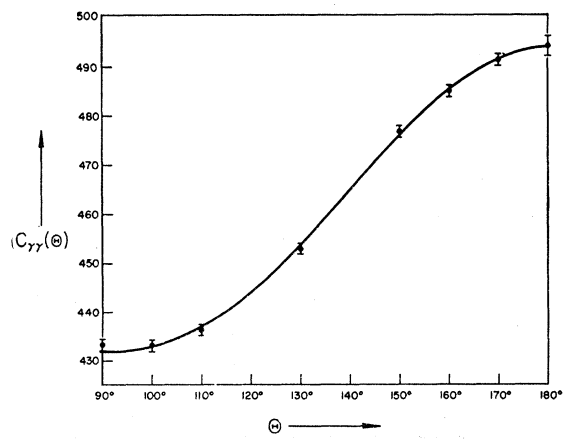

FIG. 2. Directional correlation of the Cd^{114} gamma rays displayed by sources of In^{114} in the form of liquid indium metal and measured with differential pulse-height selection.

[19] H. Paul and R. M. Steffen (to be published).

$$W'(\Theta)=1+(0.0912\pm0.0045)P_2(\cos\Theta)+(0.0075\pm0.0053)P_4(\cos\Theta). \quad (1)$$

It has been shown by Frankel[20,21] that in the case of a point source the experimental correlation function $W'(\Theta)=1+\sum A_{2k}'P_{2k}(\cos\Theta)$ differs from the theoretical (point-point) function

$$W(\Theta)=1+\sum_{k=1}^{k_{\max}} A_{2k}P_{2k}(\cos\Theta), \quad (2)$$

insofar as each of the coefficients A_{2k}' is equal to the theoretical coefficient A_{2k} multiplied with a geometrical correction factor $Q_{2k}(Q_{2k}<1)$. For the case of cylindrical symmetry of the detectors, Rose[22] has given the following expression for these correction factors:

$$Q_{2k}=\frac{I_{2k}^{(1)}(\mu_1)I_{2k}^{(2)}(\mu_2)}{I_0^{(1)}(\mu_1)I_0^{(2)}(\mu_2)}, \quad (3a)$$

where

$$I_{2k}^{(i)}(\mu_i)=\int_{\text{Detector } i}(1-e^{-\mu_i x(\theta_i)})P_{2k}(\cos\theta_i)\sin\theta_i d\theta_i. \quad (3b)$$

$x(\theta_i)$ is the distance traveled by the gamma ray in the ith detector crystal, μ_i is the absorption coefficient of the crystal for this gamma radiation, and θ_i is the angle between the propagation direction of the gamma ray and the axis of the detector i. Rose's correction factors give satisfactory results if differential pulse height selection is employed, and if the photoelectric absorption factor is used for μ_i.

When one takes into account this geometrical correction, the directional correlation of the Cd^{114} gamma rays as measured with differential pulse-height selection is then represented by the following function:

$$W^{\text{diff}}(\Theta)=1+(0.099\pm0.005)P_2(\cos\Theta)+(0.010\pm0.007)P_4(\cos\Theta). \quad (4)$$

For purpose of comparison, there is shown in Fig. 3 the directional correlation as measured with integral pulse-height discrimination accepting in both channels all gamma radiation above 0.2 Mev. The large coincidence counting rate at $\Theta=180°$ is caused by annihilation radiation due to the low-intensity positron spectrum in the In^{114} decay. An independent measurement of the directional correlation of annihilation radiation verified that the angular resolution of our equipment is good enough to make the contribution of annihilation radiation negligible, except for the angular interval from $\Theta=162°$ to $\Theta=198°$. Hence the points at $\Theta=180°$ and $\Theta=170°$ were not used for the following computa-

[20] S. Frankel, Phys. Rev. **83**, 673 (1951).
[21] A. M. Feingold and S. Frankel, Phys. Rev. **97**, 1025 (1955).
[22] M. E. Rose, Phys. Rev. **91**, 610 (1953).

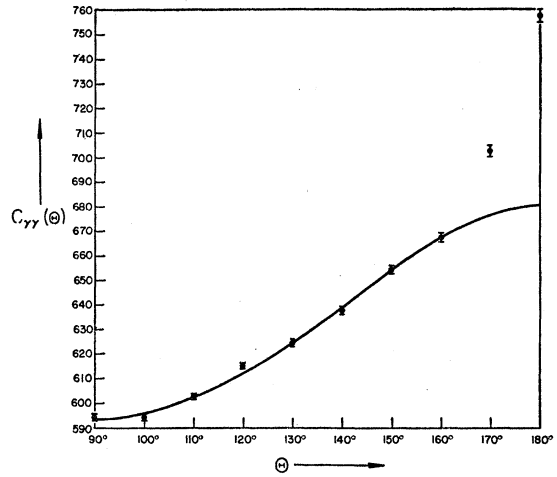

FIG. 3. Directional correlation of the Cd^{114} gamma rays displayed by liquid indium metal sources and measured with integral energy discrimination. All gamma radiation above 0.2 Mev was accepted by the detectors.

tion. The normalized experimental correlation function obtained from the data of Fig. 3 by a least-squares fit is

$$W'(\Theta)=1+(0.0873\pm0.0025)P_2(\cos\Theta)+(0.0092\pm0.0036)P_4(\cos\Theta). \quad (5)$$

The finite-geometry correction which must be applied to this experimental correlation function requires again the calculation of $I_{2k}{}^{(i)}(\mu_i)$. For this case, where the directional correlation was observed with integral pulse-height selection, Rose's approximation for the counter efficiency $\epsilon(\theta_i)=1-e^{-\mu_i x(\theta_i)}$ is not satisfactory and must be replaced by an experimentally determined efficiency function $\epsilon(\theta_i)$.[23] The directional correlation corrected in this way as determined with integral pulse-height discrimination, is represented by

$$W^{\text{int}}(\Theta)=1+(0.098\pm0.003)P_2(\cos\Theta)+(0.013\pm0.005)P_4(\cos\Theta). \quad (6)$$

The agreement of this correlation function with that obtained using differential energy selection is satisfactory and implies that there is no necessity to assume a competing cascade which interferes with the 0.722-Mev—0.556-Mev gamma-gamma correlation.

Table I summarizes the experimental results for the directional correlation coefficients A_2 and A_4 with their root-mean-square errors. The theoretical values[24] of A_2 and A_4 for a quadrupole-quadrupole cascade between states of angular momentum 4, 2 and 0, as well as for a cascade of a mixed 96% dipole+4% quadrupole transition (with phase change, $\delta=-0.195$) followed by a pure quadrupole transition between states of angular momentum 2, 2 and 0, are included in this table. A comparison of the experimental and theoretical results shows that the observed directional correlation is characteristic for a sequence of two pure quadrupole transitions between states of angular momentum quantum number 4, 2 and 0. Thus the original angular momentum assignment of one of the authors[1] seems to be confirmed.

From a comparison of the gamma-gamma coincidence rate at $\Theta=180°$, extrapolated from Eq. (5), with the experimentally observed value at this angle (Fig. 3), the relative intensity of the In^{114} positron radiation can be estimated. After applying the corrections for solid angle, relative gamma efficiency, etc., a value of 10^{-3} positron per gamma cascade is obtained.

2.5 Extranuclear Effects and the Cd^{114} Gamma-Gamma Directional Correlation

Recently a rather pronounced effect of the chemical and physical structure of the In^{114} source on the Cd^{114} gamma-gamma directional correlation has been reported,[14] and conclusions have been drawn therefrom regarding the electric quadrupole moment of the first excited state of Cd^{114}. Since no such effect was found earlier in this laboratory,[18] a more accurate investigation of the influence of extranuclear fields on the Cd^{114} cascade was started.

Using differential pulse-height selection, the Cd^{114} directional correlation was measured with ten sources of widely differing chemical composition and physical structure. The result of this investigation is summarized in Table II, where the correlation coefficients $\bar{A}_2$ and $\bar{A}^4$ obtained on the basis of a least-squares fit and/or the directly measured anisotropy values, $\bar{A}=[W(180°)-W(90°)]/W(90°)$, are given. The latter were corrected for the finite angular resolution of the equipment.

A directional correlation function which, if unperturbed, is of the form (2) is modified to[25,26]

$$\bar{W}=1+\sum_{k=1}^{k_{\max}}\bar{A}_{2k}P_{2k}(\cos\Theta)=1+\sum_{k=1}^{k_{\max}}G_{2k}A_{2k}P_{2k}(\cos\Theta), \quad (7)$$

if an extranuclear interaction is present due to atomic or crystalline fields in a source which, as a whole, is isotropic, e.g., polycrystalline powder, liquid, etc. The

TABLE I. The directional correlation of the Cd^{114} gamma rays.

Coefficient	Experimental values: differential energy selection	Experimental values: integral energy discrimination	Theoretical values: 4(Q)2(Q)0	Theoretical values: 2(96% D +4%(Q)2)-2(Q)0 ($\delta=-0.195$)
A_2	0.099±0.005	0.098±0.003	0.102	0.100
A_4	0.010±0.007	0.013±0.005	0.009	0.119

[23] J. S. Lawson, Jr., and H. Frauenfelder, Phys. Rev. **91**, 649 (1953).
[24] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).
[25] A. Abragam and R. V. Pound, Phys. Rev. **92**, 943 (1953).
[26] K. Alder, Helv. Phys. Acta **25**, 235 (1952).

TABLE II. The Cd^{114} gamma-gamma correlation displayed by various In^{114} sources.

In^{114} source	$\bar{A}_2$	$\bar{A}_4$	$\bar{A}$	G_2	G^*
Indium metal, liquid	0.099±0.005	0.010±0.007	0.165±0.003		
Indium metal, solid	0.096±0.007	0.016±0.010	0.160±0.004	0.97±0.11	0.97±0.03
$InCl_3$, polycrystalline	0.109±0.007	0.005±0.009	0.168±0.004	1.10±0.10	1.02±0.03
Dilute aqueous solution of $InCl_3$	0.097±0.010	0.007±0.015	0.158±0.007	0.98±0.14	0.96±0.04
Dilute aqueous solution of $InCl_3$ and glycerine, viscosity $\eta=0.5$ cgs units	0.100±0.010	0.009±0.013	0.160±0.006	1.01±0.11	0.96±0.04
In_2O_3			0.173±0.010		1.05±0.06
$In(OH)_3$, dry			0.165±0.010		1.00±0.05
$In(OH)_3$, gelatinous			0.179±0.009		1.09±0.05
InI_3			0.167±0.011		1.01±0.07
In imbedded in Ag			0.16 ±0.01		0.97±0.06

attenuation coefficients G_{2k} ($G_{2k}\leq 1$) characterize the influence of the interaction on the directional correlation. They depend upon the coupling of the nuclear moments to the external fields as well as on the lifetime of the nuclear state.

We identify the "true" coefficients A_2 and A_4 of the Cd^{114} directional correlation with the values which were obtained on the basis of measurements on the liquid indium metal source, which were described above. A justification of this assumption follows from a consideration of the extranuclear interaction in the same source material of the 0.247-Mev state of Cd^{111}. The lifetime of this nuclear state, $\tau_N(Cd^{111})=1.2\times10^{-7}$ sec, is much larger than that of the first excited state of Cd^{114}, $\tau_N(Cd^{114})<2.3\times10^{-10}$ sec.

For a liquid, where the extranuclear coupling is due to the time-dependent interaction between the nuclear electric quadrupole moment Q and the rapidly fluctuating electric gradients of mean square value $\langle(\partial E_z/\partial z)^2\rangle$, the attenuation coefficients are of the form

$$G_{2k}=1/(1+\lambda_{2k}\tau_N), \tag{8a}$$

where the interaction parameter λ_{2k} is given by[25]

$$\lambda_{2k}=\frac{3}{80}\left(\frac{eQ}{\hbar}\right)^2\left\langle\left(\frac{\partial E_z}{\partial z}\right)^2\right\rangle \times\frac{2k(2k+1)[4I(I+1)-2k(2k+1)-1]}{I^2(2I-1)^2}\tau_c. \tag{8b}$$

I is the angular momentum of the intermediate nuclear state. The correlation time of the liquid, τ_c, is related to the characteristic time of Debye's theory of dielectric dispersion in polar liquids,[27] and can be defined as the average time-interval during which the local configuration around a nucleus can be considered as constant. Equation (8a) is correct if the correlation is observed by means of a coincidence analyzer of resolving time $\tau_0\gg\tau_N$. Delay measurements on the Cd^{111} gamma-gamma directional correlation displayed by sources of liquid indium metal[28] have shown that the time-dependent quadrupole interaction in sources of this kind is negligibly small: $\lambda_2(Cd^{111})\cdot\tau_N(Cd^{111})<0.006$. From this upper limit for Cd^{111}, we obtain for the interaction in the case of Cd^{114},

$$\lambda_2(Cd^{114})\cdot\tau_N(Cd^{114})<2\times10^{-5}\left(\frac{Q(Cd^{114})}{Q(Cd^{111})}\right)^2. \tag{9}$$

Even in the unlikely case that the electric quadrupole moment of the first excited state of Cd^{114} should exceed the one of the corresponding Cd^{111} state by an order of magnitude,[29] the time-dependent quadrupole interaction in liquid indium metal sources would still have a negligible effect on the Cd^{114} directional correlation.

The attenuation coefficients $G_2=\bar{A}_2/A_2$ for the various sources investigated are listed in Table II. Since the accuracy of the determination of these coefficients is somewhat limited, a reduction factor $G^*=\bar{A}/A$, ($G^*\leq1$), which characterizes the reduction in the anisotropy A due to extranuclear influences in the various sources has been computed and is included in Table II. These reduction factors, as well as the attenuation coefficients are all, within the limits of error, equal to unity. Thus, on the basis of our experiments, no indication of the presence of an extranuclear influence on the Cd^{114} directional correlation was observed.

3. POLARIZATION-DIRECTIONAL CORRELATION OF THE Cd^{114} GAMMA RAYS

In order to determine the parities of the Cd^{114} levels and, possibly, to give further support to the 4-2-0 assignment, polarization-directional correlation experiments were carried out on the Cd^{114} gamma-gamma cascade.[12,13]

3.1 Polarization-Directional Correlation Apparatus

The polarization of one gamma ray is measured as a function of the angle between the two cascade gamma rays. The arrangement which is shown in Fig. 4 is

[27] P. Debye, *Polar Molecules* (Dover Publications, New York, 1945).

[28] R. M. Steffen (to be published).

[29] M. Goeppert Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley and Sons, Inc., New York, 1945).

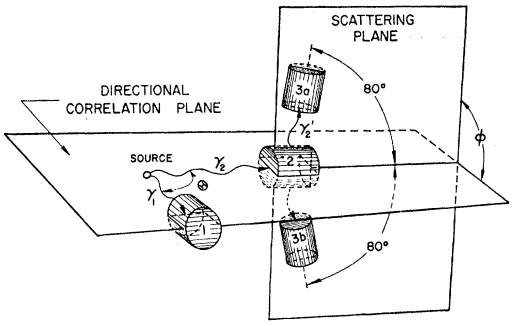

FIG. 4. Geometry of the polarization-directional correlation arrangement.

similar to that described by Metzger and Deutsch.[30] It consists of a polarization-sensitive detector arrangement (the analyzer) and a polarization-insensitive directional detector (1), which, together with the source, determine the so-called "correlation plane" and the angle Θ between the two detector axes. The analyzer makes use of the fact that the Compton scattering process, according to the Klein-Nishina formula, is sensitive to the polarization of the incoming radiation. It is made up of three coplanar detectors, the scatterer-detector (2) and two detectors (3a) and (3b) connected in parallel and placed in such a position that they will detect rays scattered through angles of about 80°. This analyzer is rotated automatically about an axis through the scatterer and source once every hour so that slow electronic fluctuations will produce little effect on the measured polarization-directional correlation. The position of the analyzer is given by the angle ϕ between the scattering and correlation planes. A lead shield is placed in such a position as to limit the gamma rays entering detectors (3a) and (3b) to those coming from the scatterer only.

The experiment involves the measurement of the triple coincidence counting rates $N_{\parallel}$ and $N_{\perp}$ between detectors (1), (2), and (3a)+(3b) at angles $\phi=0°$ (parallel position) and $\phi=90°$ (perpendicular position), respectively, for different positions Θ of the directional detector (1). The ratio $N_{\parallel}(\Theta)/N_{\perp}(\Theta)$ of corrected triple coincidence counting rates is computed, and the quantity $p(\Theta)=J_{\parallel}(\Theta)/J_{\perp}(\Theta)$, were $J_{\parallel}(\Theta)$ and $J_{\perp}(\Theta)$ are the intensities of the radiation components linearly polarized parallel and perpendicular to the plane defined by the two gamma rays, is then determined by the following expression:

$$p(\Theta)=\frac{R-N_{\parallel}(\Theta)/N_{\perp}(\Theta)}{RN_{\parallel}(\Theta)/N_{\perp}(\Theta)-1}, \qquad (10)$$

where R is the asymmetry ratio of the apparatus, a measure of the polarization sensitivity of the analyzer. R depends upon the solid angles of the detectors and also upon the initial energy of the scattered gamma ray, as seen by the energy dependence of the Klein-Nishina formula. The asymmetry ratio R is found empirically by a polarization correlation measurement on a gamma-gamma cascade of known polarization character [i.e., known $p(\Theta)$; e.g., Ni^{60}]. The asymmetry ratio of this arrangement varies from $R=2.2\pm0.3$ for $E_{\gamma}\cong1.28$ Mev to $R=2.6\pm0.3$ for $E_{\gamma}\cong0.65$ Mev.[31]

The $p(\Theta)$ so determined experimentally may be compared with that calculated theoretically for various angular momenta and parity assignments.

3.2 Experimental Procedure for Cd^{114}

Measurements were made on Cd^{114} after which many alterations on the apparatus, including changes in geometry, were carried out. Following this, a second set of data was taken such that the two sets carried about equal weight. They agreed within the experimental error and are hence presented in combined form in this report.

Since no extranuclear effects were observed in the Cd^{114} directional correlation, the choice of chemical and physical state of the source is irrelevant. Metallic In sources (a few mC) were used. Lead absorbers were used to prevent overloading of the amplifiers by the pulses from gamma rays of the 0.192-Mev isomeric transition. The integral discriminators were set so as to accept each of the cascade gamma rays in both the analyzer and directional detector.

3.3 Results

The polarization-directional correlation measurements were made at angles $\Theta=90°$, 270°; 120°, 240°; 150°, 210°; and 180°. The results are shown in Table III and in Fig. 5. The function $p(\Theta)$ computed from Eq. (10) was plotted in preference to the conventional $N_{\parallel}(\Theta)/N_{\perp}(\Theta)$ ratio, since the theoretical curves for $N_{\parallel}(\Theta)/N_{\perp}(\Theta)$ calculated for different parity assignments depend upon the apparative constant R, which is determined experimentally. It is, therefore, not possible to combine data taken with different R values unless the results are given in terms of $p(\Theta)$.

Together with the experimental results the theoretical polarization-directional correlation ratio $p(\Theta)$ of the pure quadrupole-pure quadrupole 4-2-0 cascade and of the mixed 96% dipole+4% quadrupole-pure quadrupole 2-2-0 cascade ($\delta=-0.195$) is included in Fig. 5. for all possible parity combinations. Numerical values are given in Table IV.

TABLE III. Experimental polarization-directional correlation data for the Cd^{114} gamma-gamma cascade.

Θ	90°	120°	150°	180°
$p(\Theta)_{exp}$	1.32 ±0.05	1.125 ±0.06	1.165 ±0.065	1.000 ±0.035

[30] F. Metzger and M. Deutsch, Phys. Rev. 78, 551 (1950).

[31] D. M. Roberts, Ph.D. thesis, Purdue University, 1952, (unpublished).

The calculation of $p(\Theta)$ for the pure-pure 4-2-0 cascade is straight-forward. Explicit expressions of $p(\Theta)$ for cascades of pure multipoles have been given by Hamilton,[32] e.g., for the $4(E2)2(E2)0$ cascade:

$$p(\Theta)=\frac{1.166-0.021\sin^2 2\Theta}{1+0.166\cos 2\Theta}. \quad (11)$$

The theoretical polarization-directional correlation curves for the 2-2-0 cascade involving a mixed dipole-quadrupole radiation field in the first transition were calculated using the procedure outlined by Biedenharn and Rose.[24]

The average polarization-directional correlation function is

$$\langle \bar{W}(\Theta,\Phi)\rangle_{Av}=\eta_{12}\bar{W}_1(\Theta,\Phi)+\eta_{21}\bar{W}_2(\Theta,\Phi), \quad (12)$$

where η_{12} is the over-all efficiency when photon 1 enters the polarization detector, and η_{21} is the over-all efficiency when photon 2 enters this detector. The $\bar{W}$'s are functions of Θ and Φ. Here, Φ is the angle between the normal to the correlation plane and the direction of polarization, given by the electric vector $\mathbf{E}$. $\bar{W}_1$ is the polarization-directional correlation function when only the polarization of the pure radiation is measured, and $\bar{W}_2$ is the correlation function when only the polarization of the mixed radiation is measured. Therefore, in the case of 2-2-0 cascades, "photon 1" refers to the second transition and "photon 2" to the first. For cases involving mixtures, these two functions must be written as follows:

$$\bar{W}_1=\bar{w}_{\rm I}+\delta^2\bar{w}_{\rm II}+2\delta\bar{w}_{\rm III},$$

and

$$\bar{W}_2=\bar{w}_{\rm I}'+\delta^2\bar{w}_{\rm II}'+2\delta\bar{w}_{\rm III}',$$

where δ^2 is the intensity ratio $I(\text{quad.})/I(\text{dip.})$. The functions $\bar{w}_{\rm I}$, $\bar{w}_{\rm I}'$, $\bar{w}_{\rm II}$, and $\bar{w}_{\rm II}'$ are the polarization correlation functions for the corresponding pure–pure transitions, e.g., for the particular case of a $2(M1+E2)$-$2(E2)0$ cascade $\bar{w}_{\rm I}$, $\bar{w}_{\rm I}'$, $\bar{w}_{\rm II}$, and $\bar{w}_{\rm II}'$ correspond to the following pure–pure transitions $(E2,M1)$, $(M1,E2)$, $(E2,E2)$ and $(E2,E2)$, respectively, where in each the multipole transition indicated first in the parentheses is observed by the polarization sensitive detector. $\bar{w}_{\rm III}$ and $\bar{w}_{\rm III}'$ are the interference terms.

TABLE IV. Theoretical values of the polarization-directional correlation ratio $p(\Theta)$ for various cascades. The calculations for the cases of mixed transitions refer to 96% dipole—4% quadrupole mixtures with phase change ($\delta=-0.195$).

Cascade	$p(\Theta)$ calculated 90°	120°	150°	180°
$4(E2)2(E2)0$	1.40	1.256	1.061	1.00
$4(M2)2(E2)0$	1.00	1.00	1.00	1.00
$4(M2)2(M2)0$	0.715	0.815	0.943	1.00
$4(E2)2(M2)0$	1.00	1.00	1.00	1.00
$2(M1+E2)2(E2)0$	1.89	1.54	1.126	1.00
$2(E1+M2)2(E2)0$	0.74	0.81	0.94	1.00
$2(M1+E2)2(M2)0$	1.35	1.24	1.065	1.00
$2(E1+M2)2(M2)0$	0.53	0.65	0.89	1.00

[32] D. R. Hamilton, Phys. Rev. 74, 782 (1948).

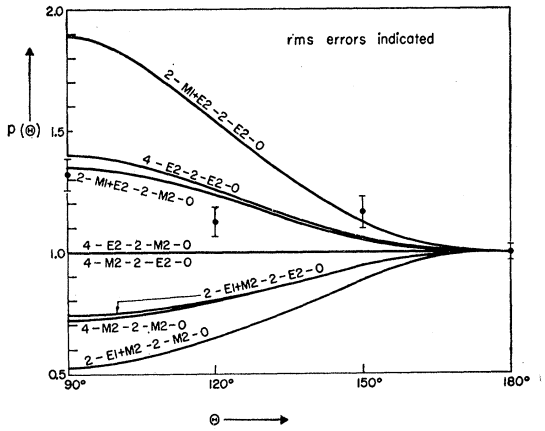

FIG. 5. Polarization-directional correlation of the Cd^{114} gamma-gamma cascade.

Since all cascade gamma rays were accepted in the counters, and since the energies do not differ radically, the assumption that η_{12} and η_{21} are equal seems justified. Dropping the multiplicative efficiency constant, one can write

$$\langle \bar{W}(\Theta,\Phi)\rangle_{Av}=\bar{W}_1+\bar{W}_2=\bar{w}_{\rm I}+\bar{w}_{\rm I}'+\delta^2(\bar{w}_{\rm II}+\bar{w}_{\rm II}')+2\delta(\bar{w}_{\rm III}+\bar{w}_{\rm III}').$$

The separate terms of $\bar{W}$ may be evaluated in terms of Legendre polynomials and associated Legendre polynomials with the aid of the tables given by Biedenharn and Rose.[24] The function $\langle \bar{W}(\Theta,\Phi)\rangle_{Av}$ is evaluated for $\Phi=90°$ and $\Phi=0°$ and the theoretical polarization ratio $p(\Theta)$ is obtained:

$$p(\Theta)=J_{\rm II}(\Theta)/J_{\perp}(\Theta)=\langle \bar{W}(\Theta,90°)\rangle_{Av}/\langle \bar{W}(\Theta,0°)\rangle_{Av}. \quad (13)$$

As an example, the explicit expression of $\langle \bar{W}(\Theta,\Phi)\rangle_{Av}$ for the $2(M1+E2)2(E2)0$ cascade may be given $(\eta_{12}=\eta_{21})$:

$$\langle \bar{W}(\Theta,\Phi)\rangle_{Av}=2+2\delta^2+[0.5000-0.1532\delta^2+1.465\delta]P_2(\cos\Theta)+[-0.2500+0.07654\delta^2-0.2440\delta]P_2^2(\cos\Theta)\times\cos 2\Phi+0.653\delta^2P_4(\cos\Theta)+0.0544\delta^2P_4^2(\cos\Theta)\cos 2\Phi. \quad (14)$$

A comparison of the experimental and the theoretical polarization–correlation data (Tables III and IV, Fig. 5.) shows that only the $4(E2)2(E2)0$ and the $2(M1+E2)2(M2)0$ cascades are compatible with the observed polarization-directional correlation. The latter cascade, however, can be excluded on the basis of lifetime considerations, since the lifetime of the first excited Cd^{114} state, $\tau_N<2.3\times10^{-10}$ sec, is too short

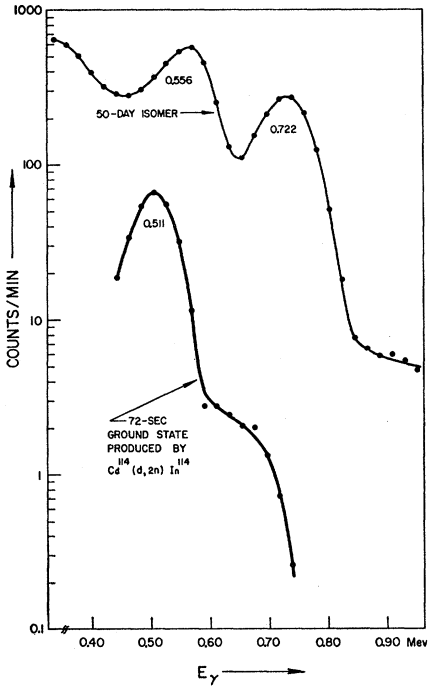

FIG. 6. Energy spectrum of the gamma radiation emitted in the decay of the 72-sec In^{114} ground state. For purpose of comparison the gamma-ray spectrum of the 50-day isomer is included.

to be compatible with an $M2$ transition by several orders of magnitude.[33]

Thus the polarization-directional correlation experiments show that all three states involved in the Cd^{114} cascade have the same parity, and furthermore, strongly favor the $4^+(E2)2^+(E2)0^+$ angular momenta and parity assignment.

4. MEASUREMENTS ON THE 72-SEC In^{114} GROUND STATE

In order to show directly that the 0.722-Mev—0.556-Mev cascade does not follow the decay of the In^{114} ground state, this 72-sec state was produced by deuteron bombardment of cadmium foils in the Purdue cyclotron resulting in the reactions $Cd^{114}(d,2n)In^{114}$, and $Cd^{113}(d,n)$-In^{114}. The decay of the gamma spectrum was followed in a 20-channel analyzer. The initial spectrum with background subtracted is shown in Fig. 6. When compared with the 50-day equilibrium spectrum it is seen that the spectra are quite different. The 0.722- and 0.556-Mev photopeaks do not appear, while the 0.511-Mev photopeak is identified as the annihilation radiation originating with the β^+ decay from the 72-sec In^{114} to the Cd^{114} ground state. That this peak is truly connected with the In^{114} ground state is seen by the fact that it was observed to decay with exactly a 72-sec half-life. The apparent peak at about 0.7 Mev should probably not be taken as being real, since in this energy region some difficulty was encountered in subtracting off a mixture of rather strong residual contaminant activities. It is therefore seen that the 0.722-Mev and 0.556-Mev gamma radiations must originate mainly with the 50-day isomeric state, and the $I=4$ angular momentum assignment for the second excited state of Cd^{114} is confirmed. These results are in very good agreement with the more comprehensive and conclusive experiments which the Brookhaven group performed with separated isotopes.[15,16]

5. ANGULAR MOMENTA AND PARITIES OF THE Cd^{114} STATES AND THE DECAY OF In^{114}

The directional correlation experiments and the polarization-directional correlation results strongly favor the $4^+(E2)2^+(E2)0^+$ assignment to the Cd^{114} states. Since the ground state of In^{114} has even parity and angular momentum $I=1$, one is forced to conclude that the K-capture decay arises from the 50-day isomer ($I=5$, even parity) of In^{114} instead of from the ground state. The measurements on the 72-sec In^{114} ground state in this laboratory and at Brookhaven[16] confirm this conclusion. On the basis of these experiments the decay scheme shown in Fig. 7 is proposed. The information that the 1.300-Mev gamma ray does not originate in a 1.856-Mev third excited state of Cd^{114},[12] but follows a β^- transition, a result which was obtained independently by Johns *et al.*[11] and the Brookhaven group, has greatly contributed to the understanding of this decay scheme. The dismissal of a 1.856-Mev Cd^{114} state is in agreement with neutron capture—gamma ray studies,[34] and with the results of Lu, Kelly and Wiedenbeck.[35]

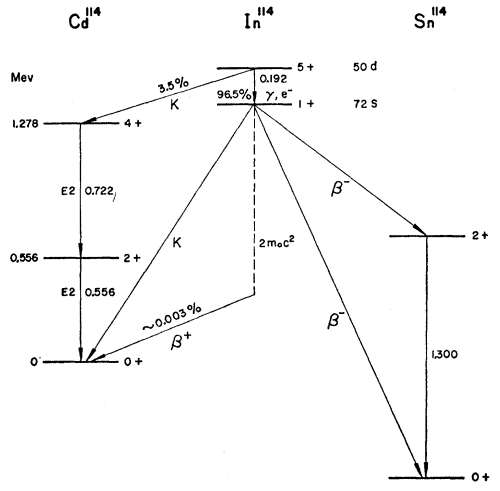

FIG. 7. The angular momenta and parities of the Cd^{114} states and the decay scheme of the 50-day In^{114} isomer.

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Decay of In^{114m} and In^{114}†

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Scintillation counter experiments have been performed on the 72-second activity of In^{114} produced by (p,n) and $(d,2n)$ cyclotron bombardment of enriched Cd^{114} and on the 49-day activity of In^{114m} produced by neutron activation. The well-known 556–722-kev cascade radiation of Cd^{114} is shown to be excited by a K-capture transition from the 49-day isomeric level. The weak 1300-kev gamma ray previously assigned to Cd^{114} is shown to come from the first excited state of Sn^{114} and is in coincidence with a low-energy beta spectrum having an end point of 675±40 kev. No gamma rays in Cd^{114} other than the 556- and 722-kev lines have been observed from the decay of In^{114m} or In^{114}. A 1.9% K-capture branch from In^{114} to the ground state of Cd^{114} has been found. A positron branch of ~0.004% between these two states is shown to have an end point of 400±25 kev.

I. INTRODUCTION

IN recent years several investigations have been conducted on the radiations from the 72-second ground state and the 49-day isomeric state of In^{114}.[1–10] The results of Brazos and Steffen[7–9] on the polarization-directional correlation of the well-known 556–722-kev cascade in Cd^{114} indicate that the spin of the state at 1278 kev is probably 4^+ and that of the 556-kev state 2^+. It is known that the isomeric state of In^{114} has a spin 5,[10] and thus it would be expected that this cascade would be excited by electron capture from this state only and not from the 72-second ground state of spin 1 as has been reported.[2] Gamma rays of weak intensity having energies of 576±3, 1271±6, 1300±3 have been reported and were also assigned to the K-capture branch.[4–6] The reported observation of 556–1300 kev coincidences indicated the existence of a state in Cd^{114} at 1856 kev.[4,6]

Kinsey and Bartholomew[11] did not observe a high-energy gamma ray from the $Cd^{113}(n\gamma)Cd^{114}$ reaction which would correspond to the reported level at 1856 kev, although their data do suggest the existence of levels in Cd^{114} at 563±8, 1205±14, 1320±11 and 1381±11 kev. Preliminary coincidence measurements by Bernstein[12] at Brookhaven National Laboratory failed to verify the existence of 556–1300 kev coincidences. The 556–1300 kev coincidences were also reported to be much weaker than previously suggested by the work of Lu *et al.*[13] Because of these discrepancies and the necessity of knowing the energy level scheme of Cd^{114} in arranging the many gamma rays from the reaction $Cd^{113}(n\gamma)Cd^{114}$ [14] into a reliable decay scheme, the present work on In^{114} was undertaken. Scintillation counter experiments were performed on the 72-second activity produced by (p,n) and $(d,2n)$ cyclotron bombardment of 83% enriched Cd^{114} and on the 49-day In^{114m} produced by neutron capture in 65% enriched

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