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Isomerism of In^{110} and In^{112}†

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The decay of In^{110} and In^{112} has been investigated with the aid of beta-ray spectrometer and coincidence measurements. From the half-life 20.7±0.3 min and the $K/(L+M)$ ratio 3.7±0.4, the 155±1-kev isomeric transition in In^{112} is identified as $M3$. The 14.5±1-min ground state emits an allowed negatron spectrum of 656±6 kev and an allowed positron spectrum of 1.52±0.05 Mev. Even parity and spins of 4 and 1 are assigned to the two states. The 66-min ground state of In^{110} decays by emission of an allowed positron spectrum of 2.25±0.02 Mev to the 657-kev level of Cd^{110}. The electron capture from the $4.9\pm0.2-h$ isomeric state is followed by the known 884, 937, and 657-kev gamma-rays in Cd^{110}. Even parity is assigned to both levels. Conversion lines, with $K/(L+M)=4.5\pm1$ indicate an additional gamma-ray of 121 kev which may be the isomeric transition having a branching ratio of about 0.6 percent. It would have to be an $M3$ transition with an abnormally long (factor 10^3) half-life. The existence of the In^{110} isomer is shown to remove several difficulties in the interpretation of the excitation curves of the alpha-particle reactions with silver.

In the course of the measurements of the excitation curves for the (α,n) and $(\alpha,2n)$ reactions with silver,[1] the decay of some of the indium isotopes involved has been reinvestigated. The measurements have been interrupted because of the remodeling of the Purdue cyclotron which was used for the bombardments. Though the decay schemes are still incomplete we wish to summarize the results obtained.

I. In^{112}

A. Previous Measurements

The isomerism of In^{112} was recognized first by Smith.[2] He found a growth curve of the activity, obtained by alpha-bombardment of Ag, from which he derived periods of 16.5 and 17.5 min for the upper and the lower state. Tendam and Bradt,[3] revised the half-lives to 23 and 9 min. Periods of 18 to 23 min for the gross activity were found by earlier workers.[4–7] The energy of the isomeric transition has been given as 0.12[2] and 0.16 Mev.[3,5] The ground-state decays by both positron and negatron emission. Maximum energies of 0.47[2] and 1 Mev[3] have been quoted for the negatron spectrum, 1.3[2] and 1.7 Mev[3,7] for the positrons.

B. Isomeric Transition

In^{112} was produced by bombarding silver, mostly in the form of foils of 10^{-4} in. thickness, with 20-Mev alpha-particles. Since only indium activities are produced in this way, the foil could be used as a source for spectrometer or coincidence measurements without further treatment. A chemical separation was performed in many runs, however, in order to ascertain the assignments, to obtain thinner sources, and to remove a weak activity of Ga^{66} (9.4 hr) which is produced from the copper contamination of the silver foil.

The conversion line was measured in a 180° spectrometer of 10-cm radius and a double-coil lens spectrometer of 75-cm focal length. In the latter positrons and electrons can be distinguished by blocking the annular opening of the baffle system at two places chosen so that the electrons rotate 90° between the obstructions. The particles transmitted by the first shutter will then either be transmitted or stopped by the second shutter, depending on the sign of rotation. The transition has an energy of 155±1 kev, the $K/(L+M)$ conversion ratio is 3.7±0.4. The half-life, obtained by following the decay of the peak intensity of the conversion line (Fig. 1, curve a) as well as by measuring its area several times during a period of 7 half-lives, is 20.7±0.3 min. (The errors quoted are estimated probable errors.)

C. Decay of the Ground State

The half-life of the ground state was determined by setting the spectrometer for electrons of 0.33 Mev and measuring the growth curve (Fig. 1). Since no conversion lines are in the neighborhood of this energy one measures only the disintegration of the ground state. The half-life resulting from the analysis of several runs is 14.5±1 min. The wide variations between the values given for this period by different workers is due to the difficulty of the growth curve analysis for nearly equal half-lives of the parent and daughter activities. The new value is considered to be rather reliable since the longer-lived background has been reduced by at least a factor ten from the earlier measurements.

The negatron spectrum has an upper limit of 656±6 kev. The measurement of the positron spectrum is

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[1] Bleuler, Stebbins, and Tendam, Phys. Rev. 90, 460 (1953).

[2] R. N. Smith, Phys. Rev. 61, 389 (1942).

[3] D. J. Tendam and H. L. Bradt, Phys. Rev. 72, 1118 (1947).

[4] J. L. Lawson and J. M. Cork, Phys. Rev. 52, 531 (1937).

[5] S. W. Barnes, Phys. Rev. 56, 414 (1939).

[6] L. D. P. King and W. J. Henderson, Phys. Rev. 56, 1169 (1939).

[7] J. M. Cork and J. L. Lawson, Phys. Rev. 57, 982 (1940).

complicated by the presence of the strong 2.25-Mev spectrum of the 66-min In^{110}. It was determined by analyzing the decay curves for several settings of the spectrometer. As expected, the positron spectrum shows the same growth curve as the negatrons. The upper limit is 1.52±0.05 Mev. With the measured ratio of 1.94 of the β^- and the β^+ spectra and the theoretical branching ratios for electron capture one obtains $\beta^-:\beta^+:EC=44:24:32$, giving $\log ft=4.05$ and 4.58 for the β^- and β^+ transitions, respectively. It is assumed that the two transitions lead to the ground states of Sn^{112} and Cd^{112} and that the decays are simple (with an estimated upper limit of 25 percent for the probability of transitions to excited states), since the Fermi plots are essentially straight, the gamma-ray intensity in a calibrated arrangement[8] is that expected from the annihilation radiation and the isomeric transition alone, and there are no $\beta\gamma$ coincidences. Also, the calculated threshold for the production of the isomeric state by a (p,n) reaction with Cd^{112}, 3.50 Mev, is in agreement with the value of 3.2±0.3 Mev measured by Blaser *et al.*[9]

D. Discussion

The suggested decay scheme of In^{112} is given in the insert of Fig. 1. The ground state has even parity and probably $I=1$, due to a $g_{9/2}$, $g_{7/2}$ combination of the odd nucleons. (Spin 0, though compatible with the allowed decay, cannot be obtained from the shell model.) From the half-life the isomeric transition seems to be $E3$ or $M3$. The empirical values[10] for the mean life τ_γ vary between 10 and 10^4 sec, while the experimental values are 1.5×10^4 sec for an $M3$, 5×10^3 for an $E3$ transition. Comparison of the experimental $K/(L+M)$ ratio of 3.7±0.4 with the empirical values[10] 4.9 ($M3$), 1.75 ($E3$), 0.6 ($E4$), and 1.9 ($M4$) indicates an $M3$ transition. By comparing the areas of the conversion line and the beta-spectra and correcting for the branching ratios of the ground-state decay and for the parent-daughter relationship it was checked that the 155-kev transition is nearly completely converted, as expected for the $M3$ transition for which the K-conversion coefficient is 5.75.[11] The measurements are too inaccurate for the determination of the actual conversion coefficients.

The isomeric state, then, would have even parity and $I=4$. It could be interpreted as a $g_{9/2}$, $s_{1/2}$ combination of the odd proton and odd neutron, as is the 5+ isomeric state of In^{114}.

II. In^{110}

A. 66-min Ground State

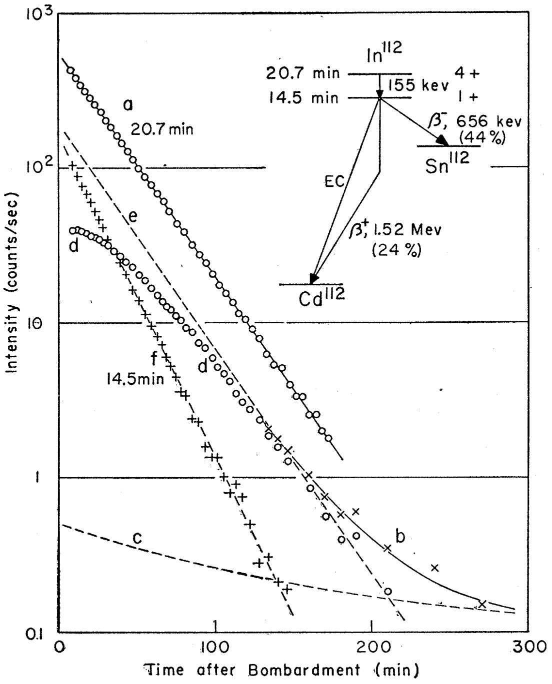

FIG. 1. Determination of the half-lives of the In^{112} isomers. *a* Decay of the conversion peak of the 155-kev isomeric transition; *b* gross decay curve of 330-kev negatrons (not shown at $t<130$ min); *c* long lived background; $d=b-c$ growth curve of the beta-particles emitted from the ground state; *e* 20.7-min equilibrium asymptote; $f=e-d$, gives period of ground state, 14.5 min.

The positron energy has been given as 1.6 Mev[5] and 2.0 Mev.[7] Measurements with both spectrometers yield $E_{max}=2.25\pm0.02$ Mev, the Fermi plot appearing straight down to below 0.4 Mev. With the theoretical branching ratios for an allowed transition, $\beta^+:EC=72:28$, one obtains $\log ft=5.5$.

The negatron spectrum shows the conversion electrons of a gamma-ray of 656±3 kev. Positron-gamma-coincidence absorption measurements, using brass and Bi-cathode gamma-counters, give a $\beta\gamma/\beta$ ratio which is independent of the absorber thickness, indicating that essentially all decays are followed by the gamma-ray. The strength of the gamma-radiation, as determined by gamma-annihilation radiation coincidences and by comparing the intensities of the photoelectrons from a lead radiator, is in agreement with this assumption. It is estimated that less than 3 percent of the positron transitions go to the ground state of Cd^{110}. The total decay energy, 3.93 Mev, is in agreement with that derived from the (p,n) threshold measurement by Blaser *et al.*,[9] 3.7±0.2 Mev.

B. 4.9-hour Isomeric State

The existence of an isomeric state of In^{110} was suggested by the alpha-particle excitation curves of Ag obtained by Ghoshal[12] which are reproduced in Fig. 2. The chief processes are the (α,n), $(\alpha,2n)$, and $(\alpha,3n)$ reactions with the two silver isotopes whose cross

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[8] Hart, Russel, and Steffen, Phys. Rev. **81**, 460 (1951).

[9] Blaser, Boehm, Marmier, and Scherrer, Helv. Phys. Acta **24**, 441 (1951).

[10] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).

[11] Rose, Goertzel, Spinrad, Harr, and Strong, Phys. Rev. **83**, 79 (1951).

[12] S. N. Ghoshal, Phys. Rev. **73**, 417 (1948).

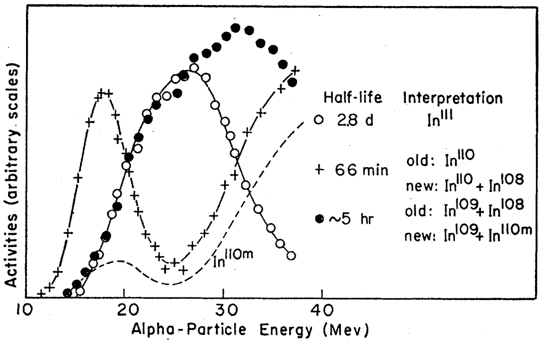

FIG. 2. Excitation curves of (α,n), $(\alpha,2n)$, and $(\alpha,3n)$ reactions with silver, from Ghoshal (reference 12). The broken line has been added to indicate the estimated contribution of In^{110m} to the ~5-hr period.

sections show maxima at about 18, 25, and >30 Mev. The 66-min activity, then, is interpreted as being due to the process $Ag^{107}(\alpha,n)In^{110}$ below 25 Mev, while it is produced by an $(\alpha,3n)$ reaction with Ag^{109} at the higher energies. The 2.8-day In^{111} is produced by an $(\alpha,2n)$ reaction with Ag^{109}. The 5-hr activity, with a similar excitation curve below 25 Mev, is assigned to In^{109} (more recent determinations give half-lives of 4.3[13] and 4.2 hr[14]). At the higher energies it must be the product of an $(\alpha,3n)$ reaction and was therefore assigned to In^{108}, thought to have a period similar to that of In^{109}. Mallary and Pool,[13] however, found a half-life of about 55 min for In^{108}. This activity, expected to be present in the excitation curves above 25 Mev, may not have been distinguishable from the 66-min activity of In^{110}. The 5-hr product of an $(\alpha,3n)$ reaction, then, must be an isomer of either In^{108} or In^{110}. The latter possibility would also explain the behavior of the 5-hr excitation curve near its threshold. The threshold and the initial slope are lower than expected for an $(\alpha,2n)$ reaction and than found for In^{111}, indicating the admixture of a small amount of In^{110m} produced by an (α,n) process.

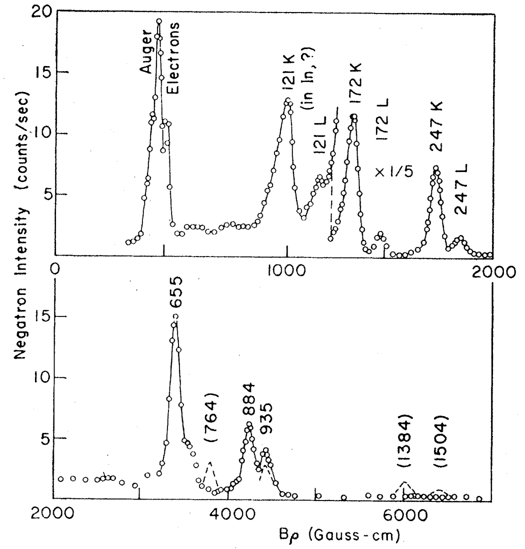

FIG. 3. Conversion lines from In^{110m} and In^{111}. Broken lines indicate strong conversion lines from Ag^{110m} (Siegbahn, reference 16) whose intensities are appreciably different from those found in the decay of In^{110m}.

The assumption has been verified[15] by observing a complex decay of the conversion line of the 656-kev gamma-ray, with periods of 66 min and 4.9 hr, and by identifying in the 4.9-hr activity other gamma-rays emitted from Cd^{110} which are known from the decay of Ag^{110}. The latter results were also obtained by McGinnis.[14]

The negatron spectrum of the 5-hr activity is shown in Fig. 3, together with some of the conversion lines found by Siegbahn[16] in the decay of Ag^{110}. Table I summarizes the gamma-ray energies and relative intensities of the conversion lines found by different authors. The energies given by Cork *et al.*[17] will be used in the discussion. The main difference between the intensities found by McGinnis[14] and us may possibly be due to a residual 66-min component of his 657-kev line. Our intensity of the 121-kev line may be appreciably in error because of scattering and absorption in the sources, most of which had a thickness of 2.5 mg/cm².

TABLE I. Gamma-ray energies (in kev) and relative intensities of conversion lines from Ag^{110m} and In^{110m}.

Ag^{110m} Cork *et al.*[a]	*E*	657	884	937	116 (*I.T.*)
Ag^{110m} Siegbahn[b]	*E*	656	885	935	116
	Int.	100	42	20	350+270[d]
In^{110m} McGinnis[c]	*E*	661	885	935	119 (*I.T.*?)
	Int.	100	13	11	82+18[d]
In^{110m} this work	*E*	656	884	935	121
	Int.	100	42	27	160+35[d]

[a] See reference 17.
[b] See reference 16.
[c] See reference 14.
[d] *K* and *L* conversion lines.

The decay of the different conversion lines is given in Fig. 4. The 657-kev gamma-ray seems to be the only one emitted also from the 66-min ground state. The half-life of the isomeric state is found to be 4.9±0.2 hr, in agreement with the value of 5.0±0.2 hr given by McGinnis.

The 121-kev line is of special interest because it could be the isomeric transition. It appears probable that this line is not observed in the decay of Ag^{110}, although the conversion electrons might possibly be masked by the conversion peaks of the 116-kev isomeric transition. Since the line could belong to In^{109} whose half-life is not too different, the assignment to In^{110m} was confirmed with the aid of a partial excitation curve. A stack of four Ag foils of 2.5 mg/cm² thickness was

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[13] E. C. Mallary and M. L. Pool, Phys. Rev. **76**, 1454 (1949).
[14] C. L. McGinnis, Phys. Rev. **81**, 734 (1951).
[15] Bleuler, Blue, and Johnson, Phys. Rev. **82**, 333 (1951).
[16] K. Siegbahn, Phys. Rev. **77**, 233 (1950).
[17] Cork, Rutledge, Branyan, Stoddard, Childs, and LeBlanc, Phys. Rev. **80**, 286 (1950).

bombarded with a 19-Mev alpha-beam. The intensities of the 121-kev line, the 66-min and the 4.9-hr components of the 657-kev line, and of the conversion lines of In^{111} were measured. Figure 5 shows that the excitation curve for the 121-kev line is identical with that of the 4.9-hr period of the 657-kev gamma-ray. This is evidence that the two lines belong to the same nuclide. If the 121-kev line were emitted by In^{109}, one would expect an excitation curve similar to that of In^{111}, which is considerably steeper, being due to an $(\alpha,2n)$ reaction. While being flatter than that for the $(\alpha,2n)$ process, the excitation curve for In^{110m} is steeper than that for the ground state of In^{110}, indicating that the metastable state has the higher angular momentum.

If the 121-kev line is assumed to be the isomeric transition, the branching ratio between the isomeric transition and the electron capture leading to the emission of the higher energy gamma-rays can be calculated from the ratio of the 121-kev and 657-kev conversion lines. With nearly complete conversion for the former and a conversion coefficient of 2.85×10^{-3} for the latter (for an $E2$ transition, in agreement with the measurements[16]) one obtains a probability of 0.6 percent for the isomeric transition. It should be followed by the emission of the ground-state positron spectrum with an upper limit of 2.25 Mev. A high energy positron spectrum has been found to follow the 4.9-hr period, but the intensity was too weak to determine the energy accurately enough for a definite assignment to the ground state transition.

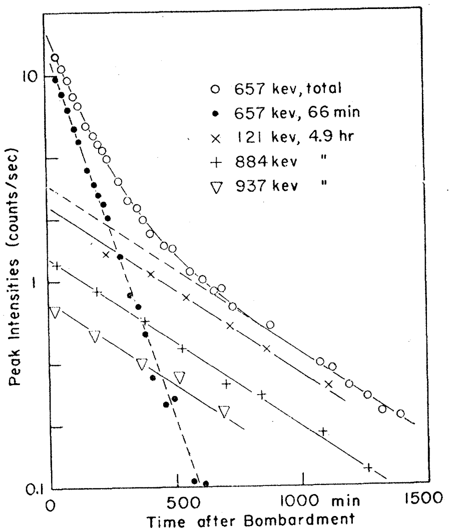

FIG. 4. Decay of the conversion lines from In^{110} (5-hr bombardment). Only the 657-kev gamma-ray is emitted in the decay of both isomeric levels.

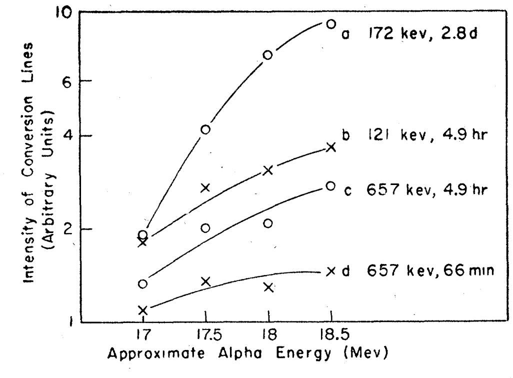

FIG. 5. Partial excitation curves for the reactions $Ag^{109}(\alpha,2n)$-In^{111} (a), $Ag^{107}(\alpha,n)In^{110m}$ (b, c), and $Ag^{107}(\alpha,n)In^{110}$ (d). The ordinate scale is not the same for the different curves. The similarity of curves b and c confirms the assignment of the 121-kev line to In^{110m}. The steeper slope of b and c as compared to d is due to the higher angular momentum of In^{110m}.

C. Discussion

The tentative decay scheme of In^{110} is given in Fig. 6, together with that of Ag^{110}, taken from Cork *et al.*[17] The isomeric transition in Ag^{110} is classified as $M4$, the metastable state as having $I=5$ with odd parity.[18] The 87-kev beta-transition is allowed, which gives odd parity to the 2924-kev level. The 530-kev decay has an ft-value of 10^8, with $(W_0{}^2-1)ft\sim3\times10^8$, indicating even parity and probably $I=4$ to 6 for the 2477-kev level. The assignment of even parity is compatible with the multipole character of the gamma-rays deduced from Siegbahn's conversion coefficients. The 657-kev line may be assumed to be $E2$; the 884 and 937-kev transitions then seem to be $E2$ and $M1$, respectively (or mixtures thereof), leaving the parities of the levels

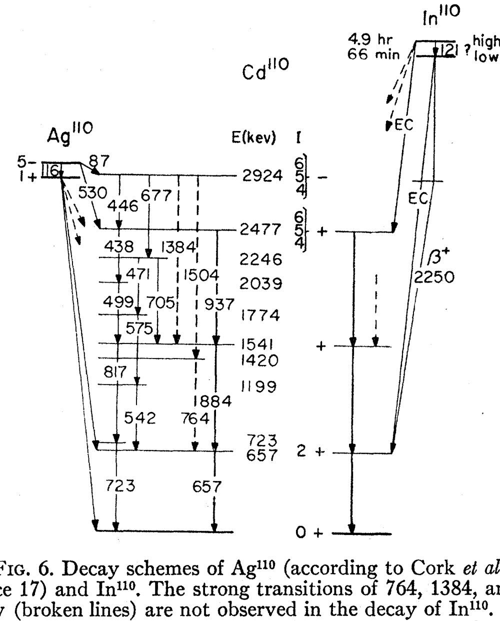

FIG. 6. Decay schemes of Ag^{110} (according to Cork *et al.*, reference 17) and In^{110}. The strong transitions of 764, 1384, and 1504 kev (broken lines) are not observed in the decay of In^{110}. The intensity of the weaker lines, some of which are expected to occur, was insufficient for observation. Additional weak transitions from both In^{110} isomers to higher and intermediate levels of Cd^{110} must be anticipated.

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[18] M. Goldhaber and R. D. Hill, Revs. Modern Phys. 24, 179 (1952).

identical. The ft value of the electron capture from In^{110m} to the 2477-kev level is about 10^5 (this value would not change much if the 121-kev line is not the isomeric transition). This allowed transition requires even parity of In^{110m} and an angular momentum not smaller than $3\hbar$. The transition to the 2924-kev level is at least once forbidden, in agreement with the failure to observe the 764, 1384, and 1504-kev gamma-rays in the decay of In^{110m}. Since the 937-kev transition is no longer bypassed by the 1384-kev line and the 677+705-kev cascade, its relative intensity is expected to be stronger from In^{110m} than from Ag^{110m}, in agreement with the experiment (Fig. 3). The increase is not quite as large as expected from the gamma-ray intensities of Siegbahn; this may be due to additional transitions leading to the 1541-kev level from some higher states.

The parity of the ground state must be even and the angular momentum between $\hbar$ and $3\hbar$. A value of $\hbar$ would be the most natural assumption, as being due to the $g_{9/2}$, $g_{7/2}$ combination of the odd proton and the odd neutron, in analogy to the situation in In^{112} and In^{114}. The apparent absence of the ground state transition (which is observed in both In^{112} and In^{114}), however, might indicate a somewhat different configuration with $I=2$.

If the 121-kev transition is the isomeric transition it would have to be $M3$ or $E4$ according to the above parity assignments. The experimental $K/(L+M)$ ratio is 4.5 ± 1, while the empirical values[10] are: 3.9 ($M3$), 1.4 ($M4$), 1.2 ($E3$), and 0.25 ($E4$). The $M3$ assignment indicated by these values is not very satisfactory because the experimental lifetime for gamma-emission becomes 10^8 sec, whereas the values normally found for $l=3$ range between 10^2 to 10^5 sec for this energy.[10] One thus would be forced to assume a highly anomalous transition probability.

It is quite possible that this line is not the isomeric transition but a mixture of $M1$ and $E2$ (according to the K/L ratio) to be fitted somewhere in the disintegration scheme. Attempts to determine accurately the $K-L$ difference, to identify the coincident x-rays, and to detect the unconverted gamma-ray have failed so far because of the low intensity of the line.

There is a further, though small, possibility that the two electron lines interpreted as the K and L conversion lines of the same gamma-ray, are actually unrelated and that the strong line corresponds to the L conversion of an $E4$ transition of about 97 kev. The K line would be quite weak ($K/L<0.2$) and might be missed unless very thin sources are available.

If there were no observable isomeric transition, as in In^{116}, the low intensity, ~5-hr, positron spectrum may be interpreted as a direct transition from the metastable level to some unidentified intermediate level, with probably negative parity, of Cd^{110}.

Finally, it is possible that the 66-min state is the metastable one, although this would imply a reversal of the order of angular momenta found in the other even In isotopes.

III. CONCLUSION

The isomeric states of both In^{110} and In^{112} are shown to have even parity, i.e., the same parity as the ground state. This behavior appears to be the rule for the even In isotopes since even parity of both states has also been found[19] for In^{114} and made probable for In^{116}.[20] All isotopes with the possible exception of In^{110} have a ground state spin of $\hbar$, while the angular momentum of the metastable states seems to vary between the values $4\hbar$ and $5\hbar$.

The authors wish to thank Mr. G. J. Goldsmith and Miss L. Roth for numerous chemical separations and Mr. D. M. Roberts for his assistance with the cyclotron bombardments.

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[19] Rolf M. Steffen, Phys. Rev. **83**, 166 (1951).

[20] Slätis, du Toit, and Siegbahn, Phys. Rev. **78**, 498 (1950).