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HIGH ANGULAR MOMENTUM STATES IN ^{110}Cd FROM THE DECAY OF 4.9 h ^{110m}In

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Abstract: The high angular momentum states in ^{110}Cd have been studied from the decay of 4.9 h ^{110m}In. Singles γ-ray spectra were taken with a high resolution and high efficiency Ge(Li) detector. Singles conversion electron spectra were taken with a Si(Li) detector. Extensive $\gamma\gamma$-coincidence measurements were taken with both NaI(Tl)-Ge(Li) and Ge(Li)-Ge(Li) arrangements. From these data it was concluded that levels at 657.73, 1476.60, 1542.45, 2004.24, 2124.55, 2219.76, 2479.94, 2561.2, 3063.90, 3121.46, 3187.3, 3239.5, 3338.2, 3345.0 and 3525.1 keV in ^{110}Cd are populated in the decay of 4.9 h ^{110m}In. In addition, possible population of known levels at 2078.4, 2162.58 and 2926.58 keV in ^{110}Cd from the decay of ^{110m}In is discussed. From $\log ft$ values determined in this work, from α_K values from this work and previously published results and from γ-ray intensity information limits have been placed for the J^π values of many levels.

E | RADIOACTIVITY ^{110m}In; measured E_γ, I_γ, $\gamma\gamma$-coin; deduced $\log ft$. ^{110}Cd deduced levels, J, π, cc, γ-multipolarity. NaI(Tl), Ge(Li) and Si(Li) detectors.

1. Introduction

Most of the recent studies of the levels in ^{110}Cd by the methods of nuclear reaction spectroscopy have been summarized recently by Sarantites *et al.* ^{1}). The study of the decay of the 69 min ^{110g}In has revealed ^{1}) many of the low angular momentum states in ^{110}Cd which lie below 3770 keV of excitation. The high angular momentum states in ^{110}Cd, however, are not easily accessible by means of excitations induced by nuclear reactions, since such processes involve high orbital angular momentum transfer and these are usually of low probability. Some of the high angular momentum states in ^{110}Cd are populated by means of the decay of (6$^+$) 250 d ^{110m}Ag. Thus, from several internal conversion studies $^{2-5}$) and the directional correlation work of Munnich *et al.* ^{6}) levels at 657.7(2$^+$), 1475.6(2$^+$), 1542.4(4$^+$), 2162.6(3$^+$), 2219.84(4$^+$), 2479.9(6$^+$) and 2926.6(5$^+$) keV, with the J^π values in parentheses, have been well established. Recently, Brahmavar *et al.* ^{7}) have carefully measured the energies and intensities of the γ-rays from ^{110m}Ag decay with the use of Ge(Li) detectors and have proposed their values for energy and intensity standards. The transitions in ^{110}Cd have further been studied by Krane and Steffen ^{8}) who

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reported preliminary results on the E2/M1 multipole mixing ratios for the 677, 706, 818, 1384 and 1505 keV transitions in ^{110}Cd (using a $^{110\text{m}}$Ag source) from $\gamma\gamma$-directional correlation measurements employing two Ge(Li) detectors.

The study of the high angular momentum states in ^{110}Cd can be better accomplished from the decay of (7^+) 4.9 h $^{110\text{m}}$In than from the decay of (6^+) 250 d $^{110\text{m}}$Ag, because of the higher J-value of the parent and the higher available decay energy.

The decay of 4.9 h $^{110\text{m}}$In has been studied in recent years by means of NaI(Tl) scintillation spectroscopy and conversion electron spectroscopy by a number of workers [9-13]). Although some of these works were rather thorough, these studies suffered from lack of resolution in the γ-ray measurements and as a result many inconsistencies remained in the proposed decay schemes.

This investigation was undertaken because it was thought that a substantial contribution toward the identification and characterization of the properties of the high J^π value states in ^{110}Cd could be made by means of high resolution Ge(Li) γ-ray spectrometry in singles and in $\gamma\gamma$-coincidence measurements employing high efficiency Ge(Li) detectors. Thus in this work many new γ-rays were observed and six new levels in ^{110}Cd have been established. Many J^π value assignments have been made from previously reported and present conversion electron measurements, from presently determined $\log ft$ values and from γ-ray intensity information.

2. Experimental procedures

2.1. PREPARATION OF $^{110\text{m}}$In SAMPLES

The samples of 4.9 h $^{110\text{m}}$In were prepared by the ^{107}Ag(^{4}He, n)$^{110\text{m, g}}$In reaction using a 14 MeV ^{4}He ion beam from the Washington University cyclotron. The targets employed were 10 mg/cm^2 natural silver foils. In all of the experiments the In activity was purified radiochemically using the In purification procedure outlined in ref. [1]). The counting of the samples began about 10 h after the end of bombardment to allow for decay of the 69 min $^{110\text{g}}$In which is produced in significant amounts. In all of the experiments the beam energy was kept below the threshold for the ^{109}Ag(^{4}He, 2n)^{109}In reaction. The absence of the 4.3 h ^{109}In from the samples was confirmed by the lack of observation of the most intense 205 keV γ-ray from ^{109}In decay.

2.2. DETECTION EQUIPMENT AND METHODS OF COUNTING

For singles γ-ray measurements only Ge(Li) detectors were employed. The detectors used had active nominal volumes 3.5, 20 and 30 cm^3 with system resolution (FWHM) for the 662 keV γ-ray of ^{137}Cs of 3.0, 2.4, and 4.0 keV, respectively.

For conversion electron measurements a Si(Li) detector with an area of 2.0 cm^2 and a depletion depth of 3.0 mm was employed.

Several coincidence experiments were performed employing a 7.6 × 7.6 cm NaI(Tl) detector and 20 or 30 cm^3 Ge(Li) detectors. The coincidence spectra displayed in the

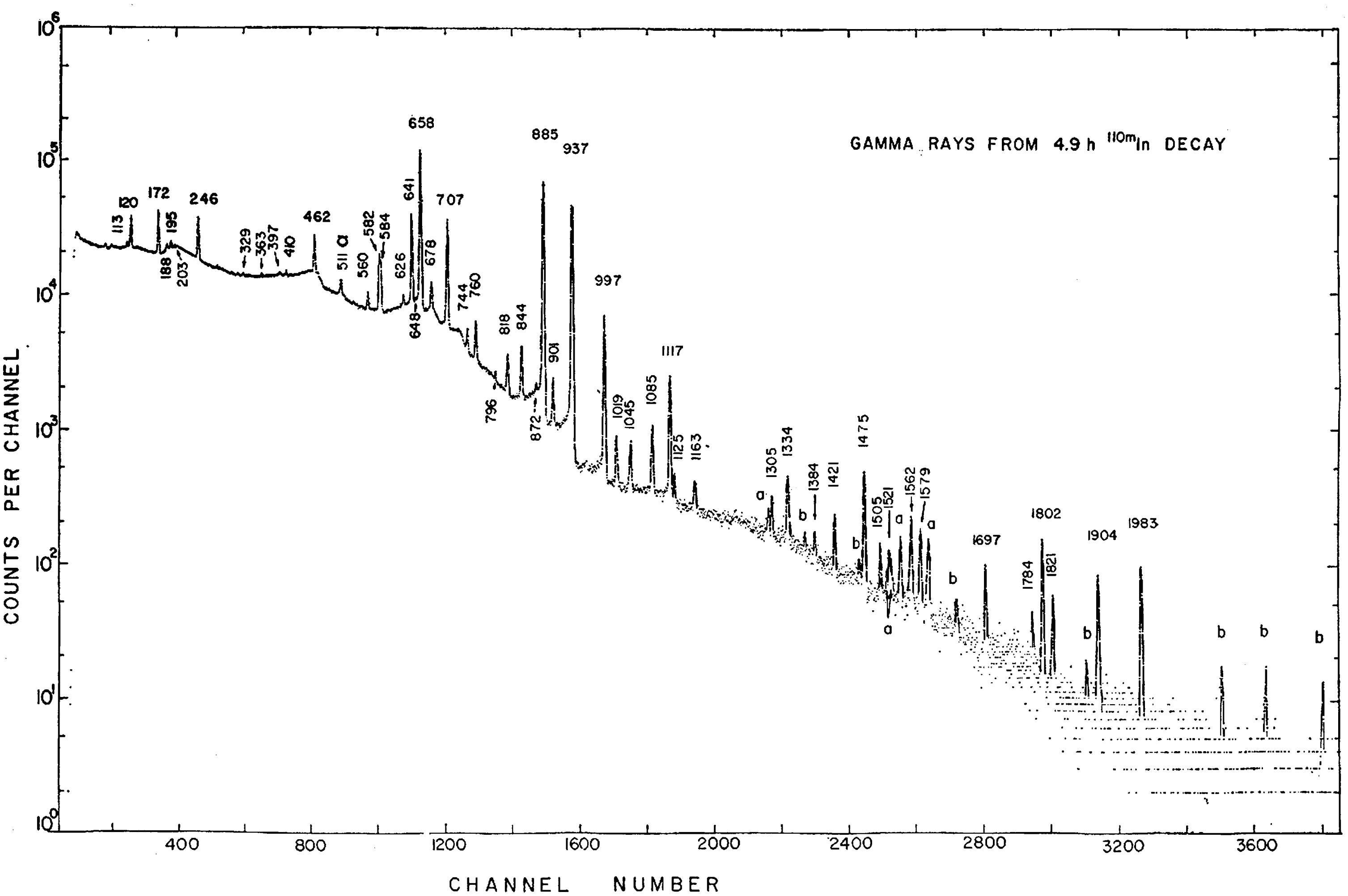

Fig. 1. Typical singles γ-ray spectrum from ^{110m}In decay obtained 20 h after bombardment. Peaks labeled *a* are associated with a half-life longer than 4.9 h and peaks labeled *b* could not be characterized by half-life as they are very weak.

illustrations were obtained in an experiment employing a 20 and a 30 cm^3 Ge(Li) detector. The properties of the two Ge(Li) detectors used and the two parameter pulse-height analysis system used have been described elsewhere [14]). The two Ge(Li)

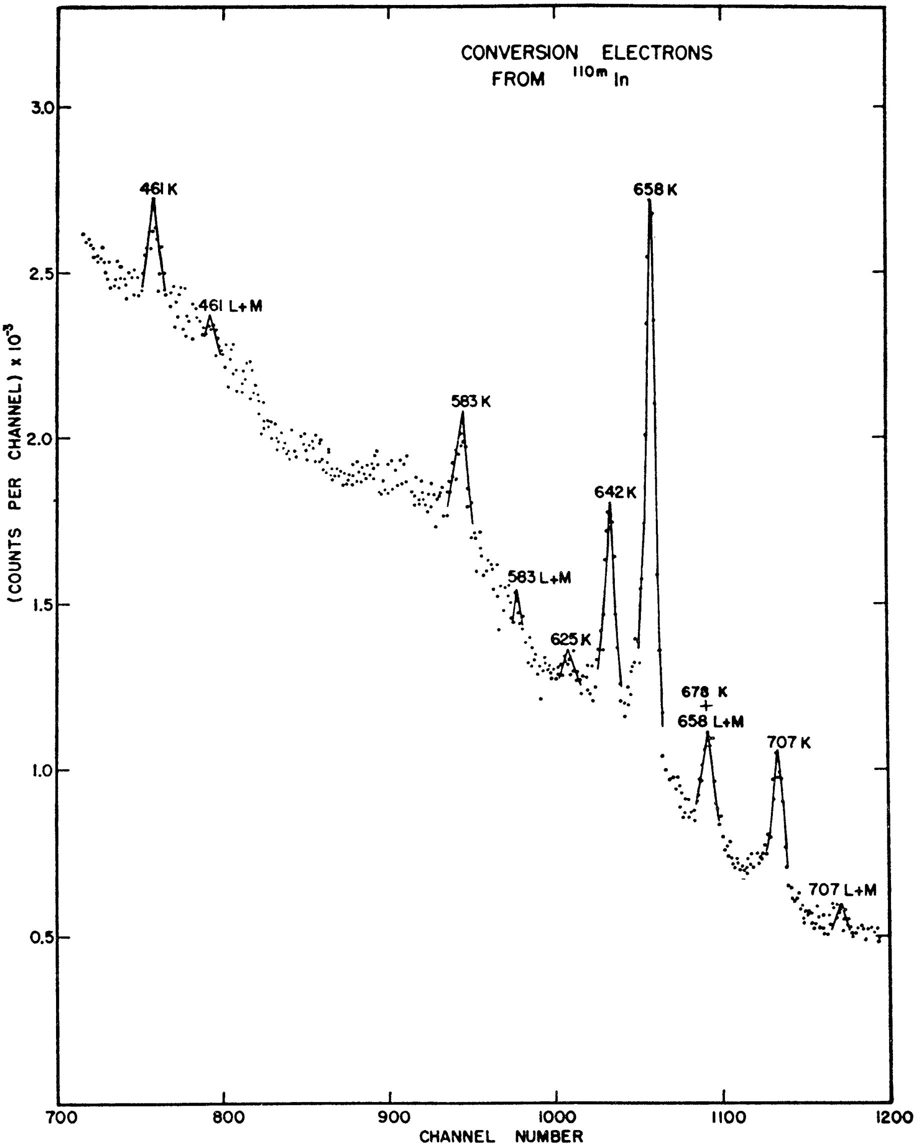

Fig. 2. Typical spectrum of the conversion electrons from transitions in the energy range 430–730 keV obtained with a Si(Li) detector. The high background is due to the Compton distributions of the γ-rays recorded in the detector.

detectors were placed at an angle of ≈ 100° at ≈ 3.0 cm from the source and were shielded from each other by 1.2 cm of Pb absorber to reduce the crystal-to-crystal

TABLE 1

Energy and relative intensity of γ-ray following 4.9 h ^{110m}In decay from singles measurements

γ-ray energy (keV) a)		Relative γ-ray intensity a)		E_γ from the scheme b)
113.5	*1*	0.27	*2*	
120.42	*7*	1.86	*9*	120.31
187.8	*1*	0.69	*5*	
195.3	*1*	0.89	*9*	
202.6	*5*	0.22	*3*	
328.6	*2*	0.13	*2*	
363.2	*2*	0.14	*4*	
397.4	*2*	0.32	*5*	
409.8	*2*	0.58	*4*	
461.79	*6*	7.4	*4*	461.79
560.34	*6*	2.04	*16*	560.26
582.0	*2*	9.2	*5*	582.10
584.0	*2*	6.7	*5*	593.96
626.34	*6*	1.35	*9*	
641.70	*10*	27.2	*7*	641.52
648.6	*2*	1.2	*2*	
657.73	*6*	100.00		657.73
677.7	*2*	5.94	*31*	677.31
707.38	*6*	31.6	*5*	707.40
744.2	*1*	1.7	*1*	744.16
759.7	*1*	3.40	*15*	759.56
795.7	*1*	0.29	*6*	
818.03	*7*	2.29	*7*	817.87
844.3	*1*	3.34	*8*	814.14
871.7	*1*	0.57	*14*	
884.72	*6*	96.2	*26*	884.72
901.60	*8*	2.02	*15*	901.70
937.49	*6*	70.5	*25*	937.49
997.23	*16*	10.5	*3*	996.91
1019.4	*2*	1.01	*5*	1019.74
1045.22	*11*	0.85	*5*	1045.16
1085.37	*15*	1.46	*8*	1085.60
1117.20	*9*	4.18	*12*	1117.22
1125.5	*2*	0.39	*2*	1125.24
1163.3	*2*	0.36	*2*	
1304.9	*2*	0.34	*5*	1305.34
1334.0	*1*	1.58	*7*	1334.0
1383.9	*2*	0.17	*4*	1384.13
1420.7	*2*	0.42	*3*	1420.67
1475.4	*2*	1.25	*4*	1475.60
1504.6	*2*	0.21	*4*	1504.85
1521.1	*2*	0.17	*3*	1521.45
1561.8	*2*	0.54	*3*	1562.03
1578.6	*2*	0.34	*4*	1579.01
1697.2	*2*	0.25	*2*	1697.05
1783.5	*4*	0.10	*1*	
1802.2	*2*	0.53	*3*	1802.55
1821.4	*2*	0.17	*3*	
1903.6	*2*	0.30	*4*	1903.47
1982.9	*2*	0.36	*4*	1982.65

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a) Energies and intensities from at least 7 independent measurements.

b) This is the transition energy deduced from the proposed level scheme for ^{110}Cd. The level energies are weighted averages of energy sums. If no value is indicated in this column it means that the present data were not sufficient to locate this transition in the level scheme.

TABLE 2

Summary of K-shell conversion coefficients from singles conversion electron measurements $\alpha_K(\times 10^3)$

γ-ray energy (keV)	Ref. 4)	Ref. 9)	Ref. 10)	Ref. 11)	Ref. 13)	This work	Adopted value	Probable multi-polarity
113.5				196			196	M1, E2
120.4		116	227	160			110 *30*	E1; M1, E2
461.79				2.9	2.3 *4*	4.2 7	4.2 *7*	M1, E2
560.34					2.9 *7*		2.9 *7*	M1, E2
582.0 584.0 a)				1.5	2.2 *4*	2.8 3	2.6 *3*	M1, E2 E1?
641.7				3.9	3.2 *3*	3.4 *4*	3.5 *3*	M1, E2
657.73	2.64 *10*	2.64 *10*	2.64 *10*	2.64 *10*	2.64 *10*	2.64 *10*	2.64 *10*	M1, E2
707.38				2.9	2.3 *2*	2.3 *3*	2.5 *3*	M1, E2
744.2					1.7 *6*		1.7 *6*	M1, E2
759.7					1.9 *4*		1.9 *4*	M1, E2
818.03	1.3 *2*				2.1 *6*		2.1 *6*	M1, E2
844.3					1.6 *3*		1.6 *3*	M1, E2
884.72	1.30 *7*	0.35	1.15	1.23	1.34 *11*		1.30 *6*	E2
937.49	1.18 *7*	0.49	1.01	1.12	1.09 *11*		1.14 *6*	E2
997.23					0.45 *13*		0.45 *13*	E1?
1085.37					1.1 *9*		1.1 *9*	
1117.20					0.5 *3*		0.5 *3*	
1475.38	0.44 *10*						0.44 *10*	M1, E2

a) The conversion coefficient reported refers to the unresolved doublet.

Compton scattering. With this arrangement coincidences were recorded at a rate of ≈ 500 c/sec. The resolving times employed were typically ≈ 100 nsec and the random coincidence rate was < 5 % of the total coincidence rate in all experiments.

3. Results and construction of the decay scheme

Singles γ-ray spectra from ^{110m}In were recorded as a function of time for a period of at least four half-lives. This allowed a clear identification of the γ-rays with a half-life of 4.9 h which were attributed to ^{110m}In decay. A typical singles spectrum recorded with the 20 cm^3 Ge(Li) detector for a period of 160 min is shown in fig. 1. This spectrum was obtained 20 h after bombardment and in addition to the ^{110m}In γ-peaks it displays γ-peaks with a half-life longer than 4.9 h (labeled a) and some very weak peaks (labeled b) that could not be characterized by half-life.

The energies and relative intensities of the γ-rays are listed in columns 1 and 2 of table 1 and were determined from peak centroids and areas as described elsewhere [15]).

Fig. 2 shows the portion of interest of a typical conversion electron spectrum from ^{110m}In obtained with the 3.0 mm deep Si(Li) detector. The large background seen is due to events from Compton scattered γ-rays. The measured values for the K-shell conversion coefficients for five of the strongest transitions in the decay of ^{110m}In are listed in column 7 of table 2. The α_K values were obtained from the relative conversion

TABLE 3

Summary of the observed coincidence relationships of the γ-rays from ^{110m}In decay

Fig. [a])	γ-ray in gate (keV)	γ-rays observed in coincidence (keV)
3a	113, 120	462, 997
4a	462	120, 658, 885, 1117, 1334
5a	532	568, 885, 997
5b	584	658, 885, 937
6a	658	120, 397, 410, 462, 582, 584, 642, 678, 707, 744, 579, 818, 844, 885, 901, 937, 997, 1019, 1045, 1085, 1117, 1163, 1305, 1334, 1421, 1521
6b, 6c	678	658,844, 885, 902
7a	707	658, 885, 937
8a, 8b	818	113, 560, 744, 844, 1085
9a	885	120, 462, 582, 584, 642, 658, 678, 707, 759, 844, 902, 937, 997, 1019, 1117, 1334
9b	937	584, 642, 658, 707, 759, 885, 1045
10a	997	120, 402, 582, 658, 885
10b	1019	658, 678, 885
10d	1085	560, 658, 818
11a	1117	462, 658, 885
11a	1125	658, 678, 744, 855

[a]) The data shown in figs. 3-11 are from the Ge(Li) × Ge(Li) experiments.

electron and γ-ray intensities and are based on the value of $(2.64 \pm 0.10) \times 10^{-3}$ for the 657.73 keV transition [4]. Column 2 in table 2 gives the K-shell conversion coefficients for the transitions in ^{110}Cd as reported by Newbolt and Hamilton [4]. Columns 3, 4, 5 and 6 give the α_K values calculated using the relative electron intensities from refs. [9-11,13], respectively. Column 8 gives the adopted α_K values.

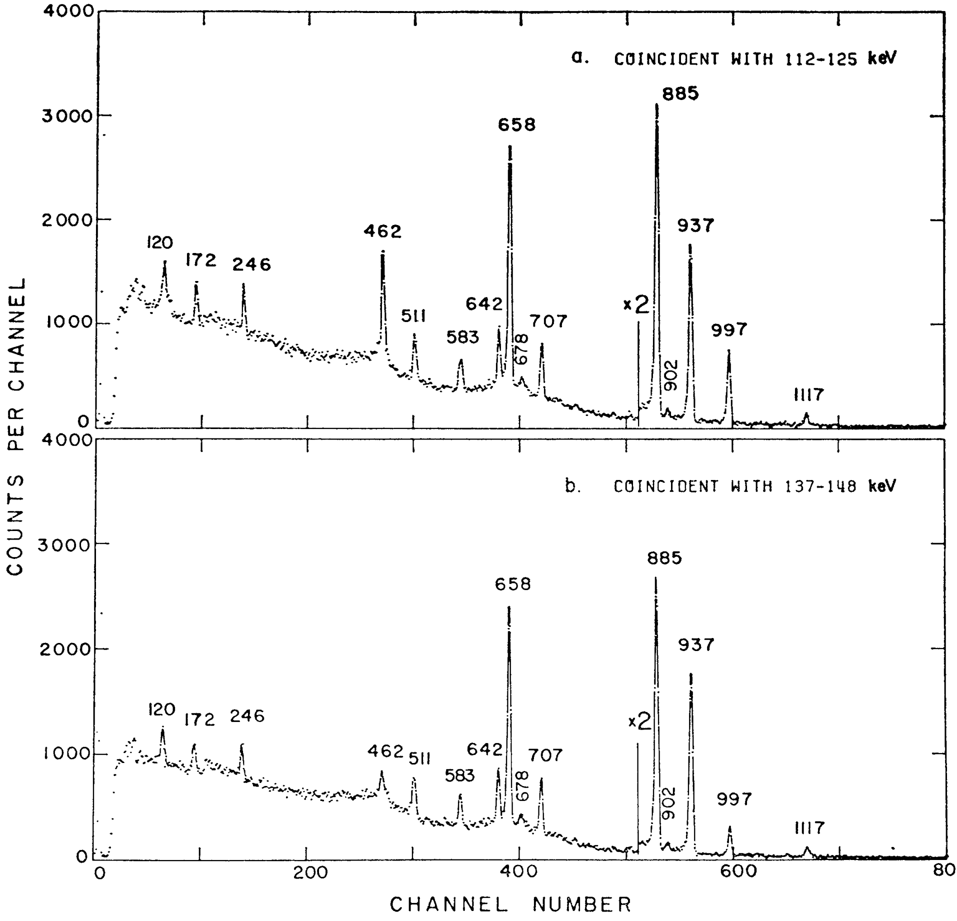

Fig. 3. Spectra of the γ-rays from ^{110m}In decay observed with the 20 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30 cm^3 Ge(Li) detector. The gate in part a contains the 120 keV γ-ray, while part b displays the contribution from Compton scattered higher energy γ-rays. Note that the vertical scales are the same in both spectra.

The $\gamma\gamma$-coincidence relationships were established by recording the coincidence spectra in a 256 × 1024 channel two-parameter configuration employing a NaI(Tl) and a Ge(Li) detector or two Ge(Li) detectors. The coincidence relationships are summarized in table 3 and the corresponding spectra are shown in figs. 3–11. Although the NaI × Ge(Li) coincidence spectra suffer from poor resolution in the gating NaI axis, they are of good statistical quality and therefore serve as corroborative evidence for the measurements with Ge(Li) × Ge(Li), and in a few cases illustrate features not prominent in the high resolution data.

On the basis of the above evidence a decay scheme shown in fig. 12 was constructed and arguments for the proposed scheme are presented below.

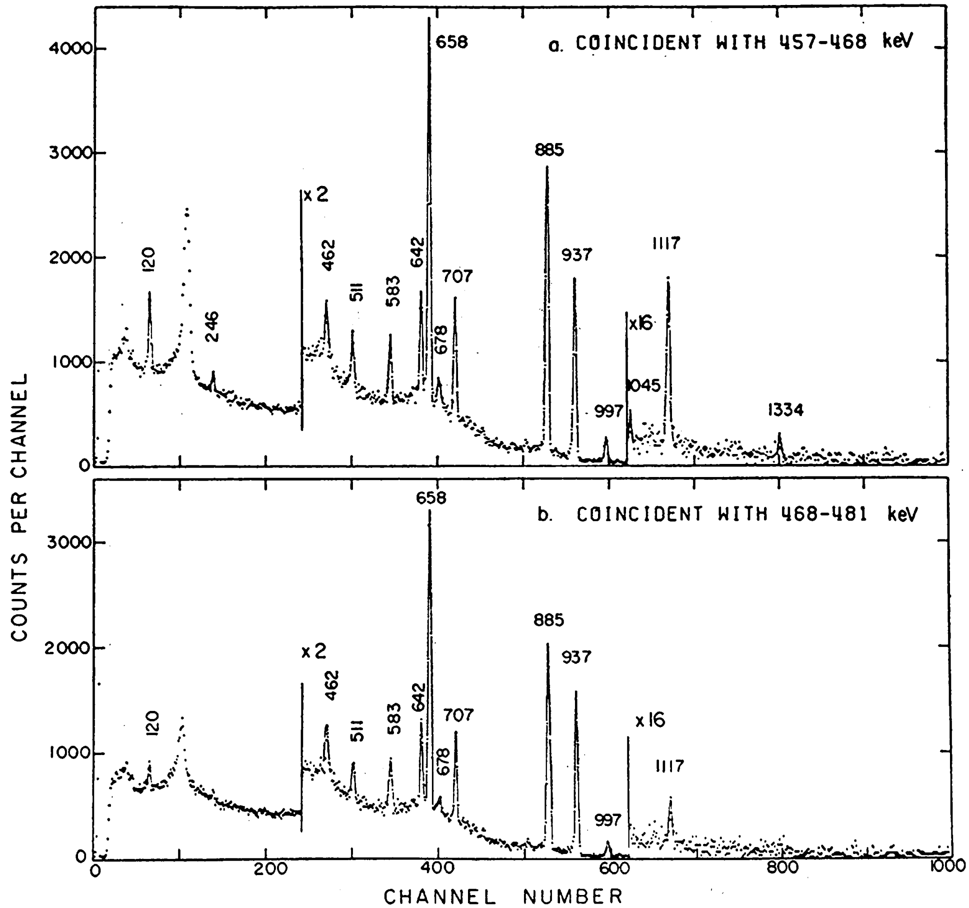

Fig. 4. Spectra of the γ-rays from ^{110m}In decay observed with 20 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30 cm^3 Ge(Li) detector. The gate in part a contains the 462 keV γ-ray, while part b displays the corresponding Compton background. Note that the vertical scales are the same in both spectra.

3.1. DEFINITIVE LEVELS

The definitive levels discussed below are based on at least one observed coincidence relationship and are further supported by energy sums.

The 657.73 keV *level.* This level is well characterized [1,7]) from the decays of ^{110g}In and ^{110m}Ag and populates the ground state.

The 1476.6 keV *level.* This level is also well established from the decay [7]) of ^{110m}Ag and from the fact that the 818.0 keV γ-ray was observed in strong coincidence with the

657.73 keV γ-ray and not with any of the other intense γ-rays. The 1475.4 keV γ-ray populates the ground state on energy considerations and from the fact that it is not in coincidence with the 657.73 keV γ-ray.

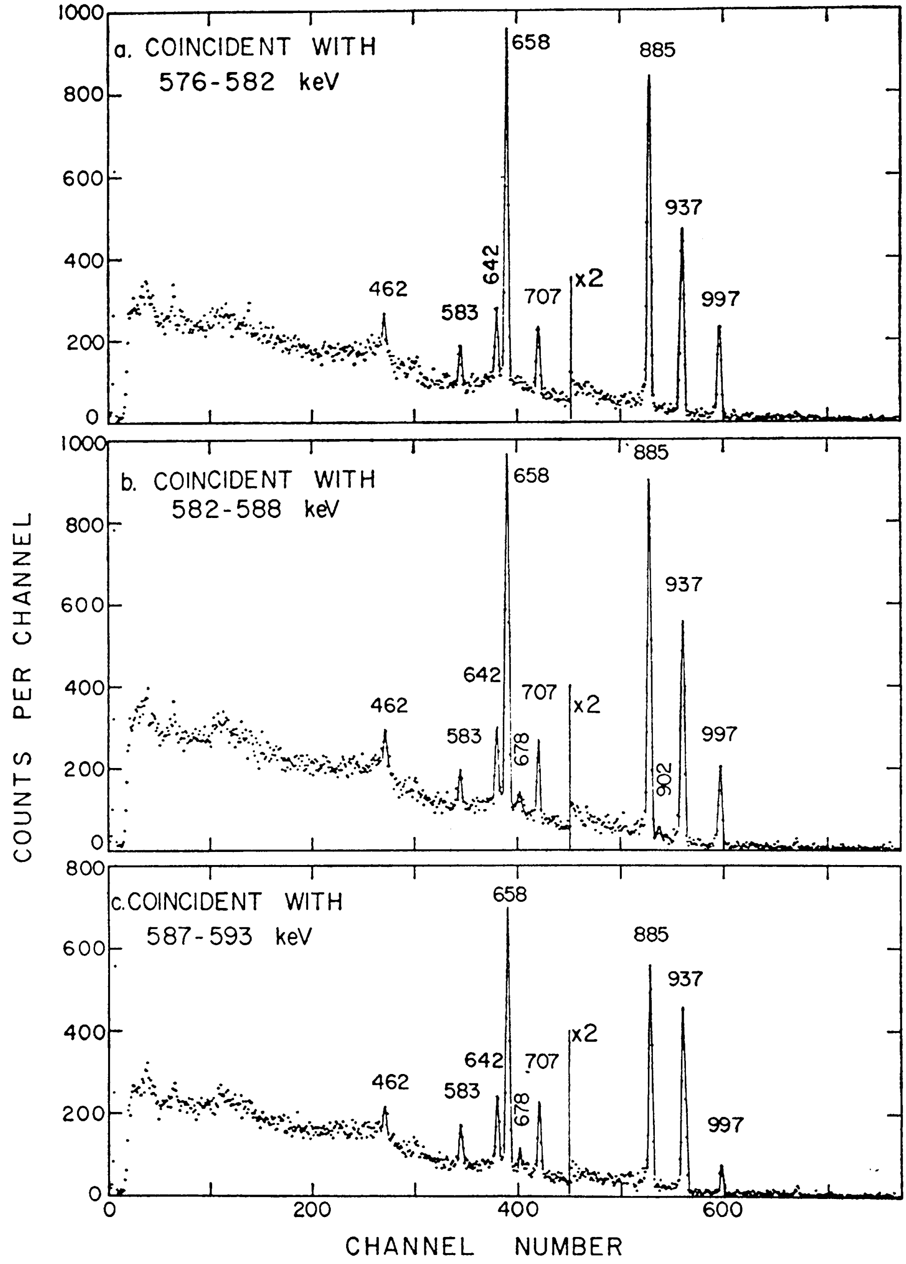

Fig. 5. Spectra of the γ-rays from ^{110m}In decay observed with the 20 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30 cm^3 Ge(Li) detector. Parts a and b display the spectra coincident with the 582 and 584 keV γ-rays, and c the corresponding Compton background.

The 1542.45 keV *level.* The 884.72 keV γ-ray is the second most intense and it is seen in strong coincidence with the 657.73 keV γ-ray (fig. 6a). This confirms the well-known level [7]) at 1542.45 keV.

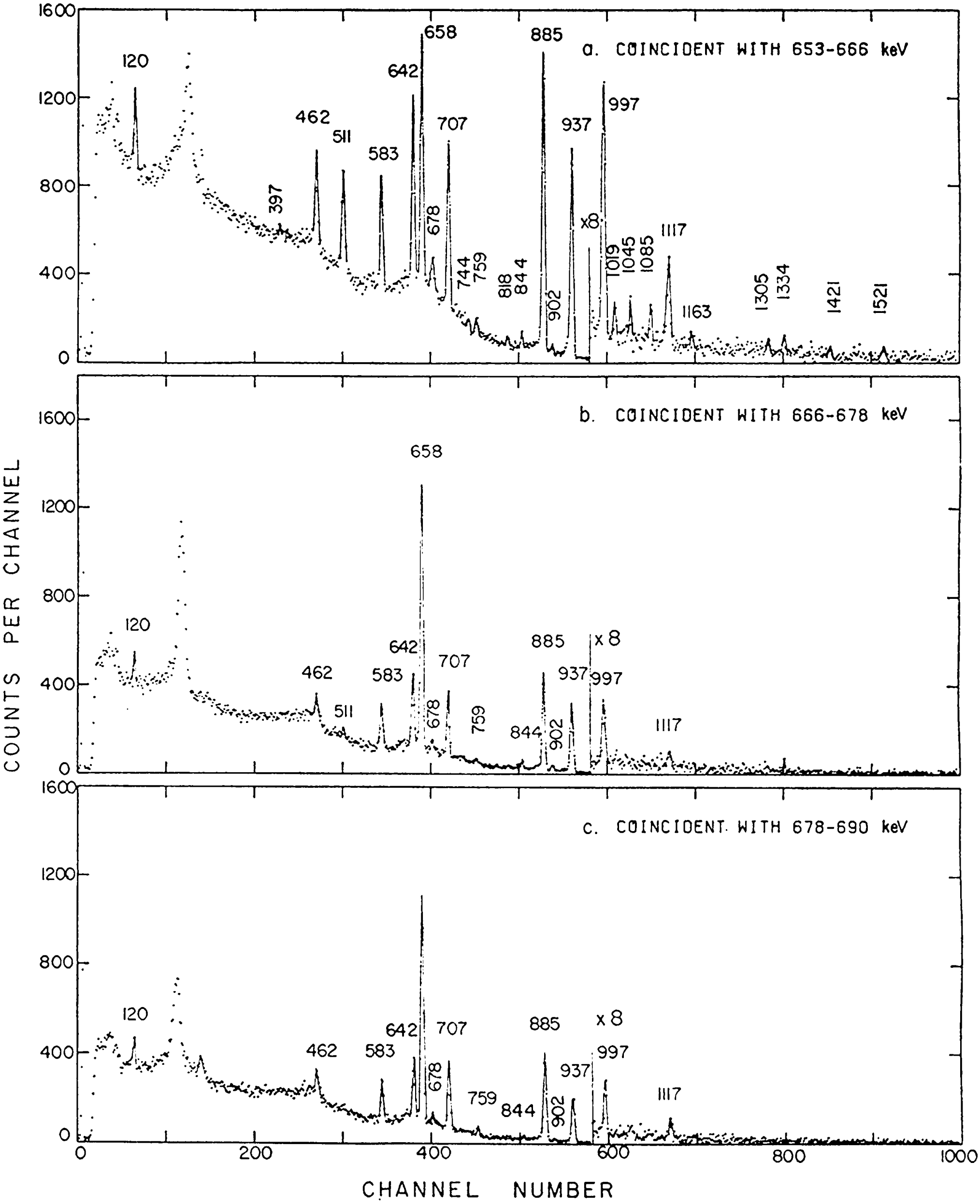

Fig. 6. Spectra of the γ-rays from ^{110m}In decay observed with the 20 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30 cm^3 Ge(Li) detector. Part a displays the spectrum coincident with the 658 keV γ-ray, while b and c show the spectrum coincident with the 678 keV γ-ray.

The 2479.94 keV *level.* The 937.49 keV γ-ray is the third most intense and it is seen in coincidence with both the 657.73 and 884.72 keV γ-rays (figs. 6a, 9a). This information strongly suggests a level at 2479.94 keV and thus confirms the assignment of this level from the decay [7]) of ^{110m}Ag.

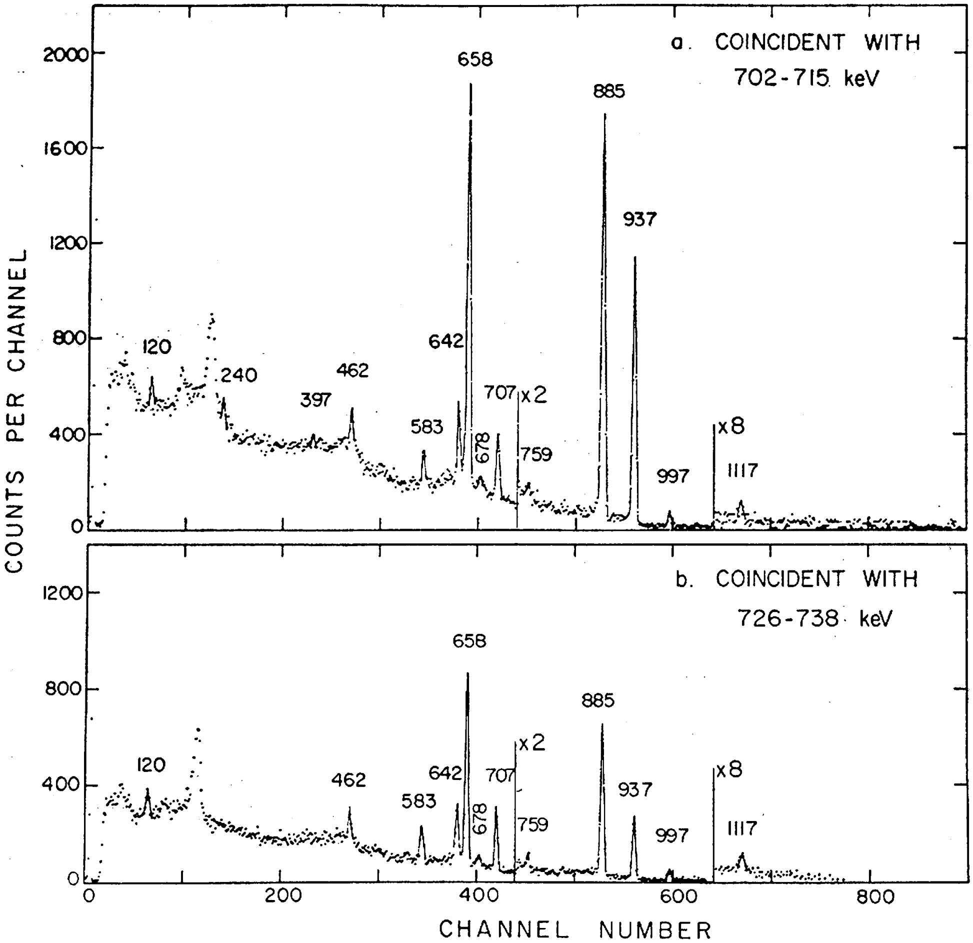

Fig. 7. Spectra of the γ-rays from ^{110m}In decay observed with the 20 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30 cm^3 Ge(Li) detector. Part a displays the spectrum coincident with the 707 keV γ-ray and part b the corresponding Compton background plotted in the same vertical scale.

The 2219.76 keV *level.* The 677.7 and 744.2 keV γ-rays are in coincidence with the 884.72 and 818.0 keV γ-rays, respectively (figs. 9a, 8a and 8b). This information firmly establishes the level at 2219.76 keV. The 1561.8 keV γ-ray is assigned to populate the 657.73 keV level on the basis of energy sums.

The 2124.55 and 3063.90 keV *levels.* The γ-ray doublet at 583 keV was resolved from the singles measurements to the 582.0 and 584.0 keV γ-rays. The 584.0 keV γ-ray is in coincidence with both the 884.72 and 937.49 keV γ-rays, while the 582.0 keV

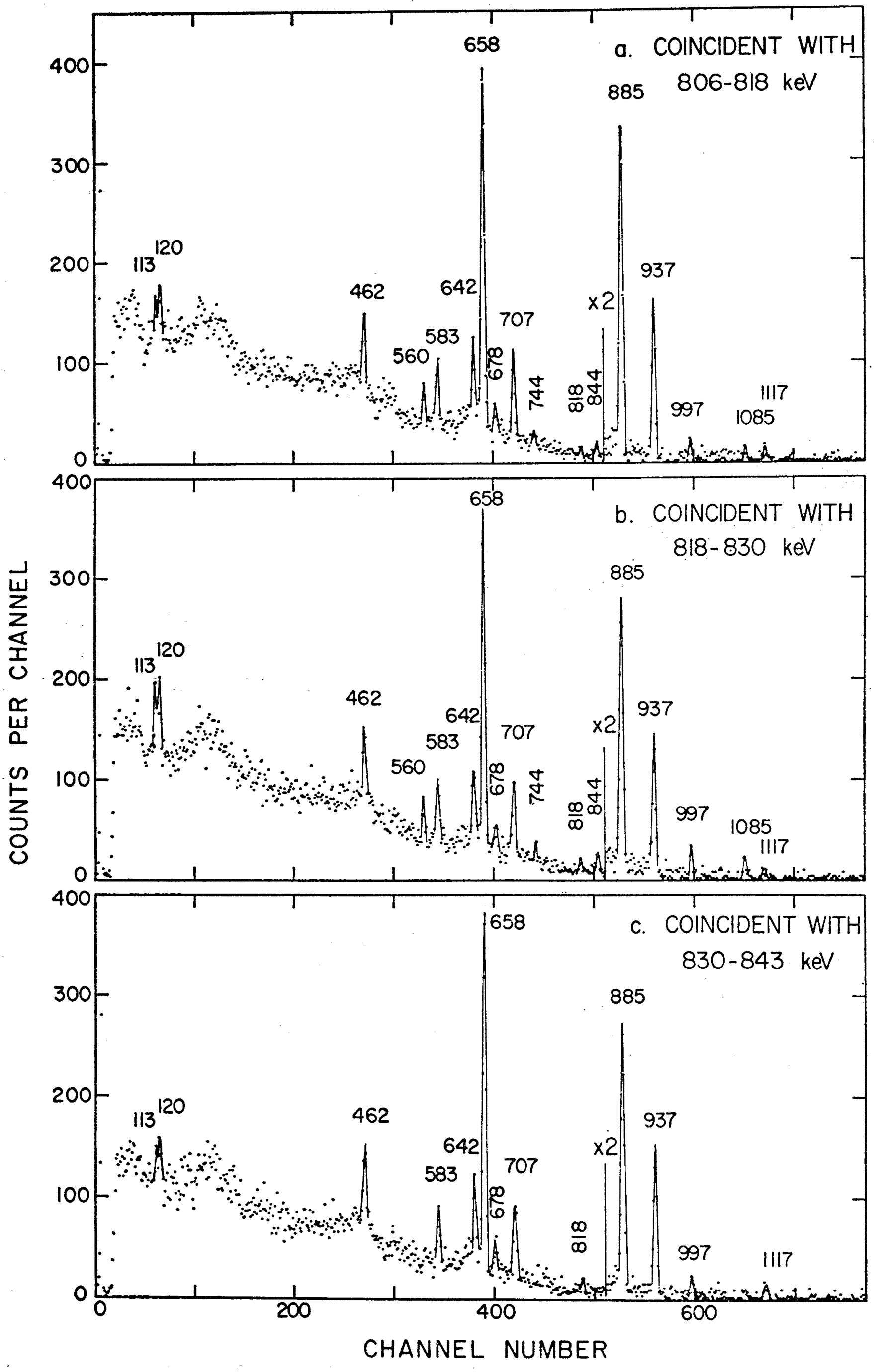

Fig. 8. Spectra of the γ-rays from ^{110m}In decay observed with the 20 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30 cm^3 Ge(Li) detector. Parts a and b show the spectra coincident with the 818 keV γ-ray and part c the spectrum coincident with the 844 keV γ-ray.

γ-ray is in coincidence with only the 884.72 keV γ-ray (figs. 9a and 9b). This is substantiated (i) by an observed higher energy by $\approx$ 1 keV of the 583 peak in the coincidence spectrum with the 937.49 keV γ-ray (fig. 9b) when compared with that in

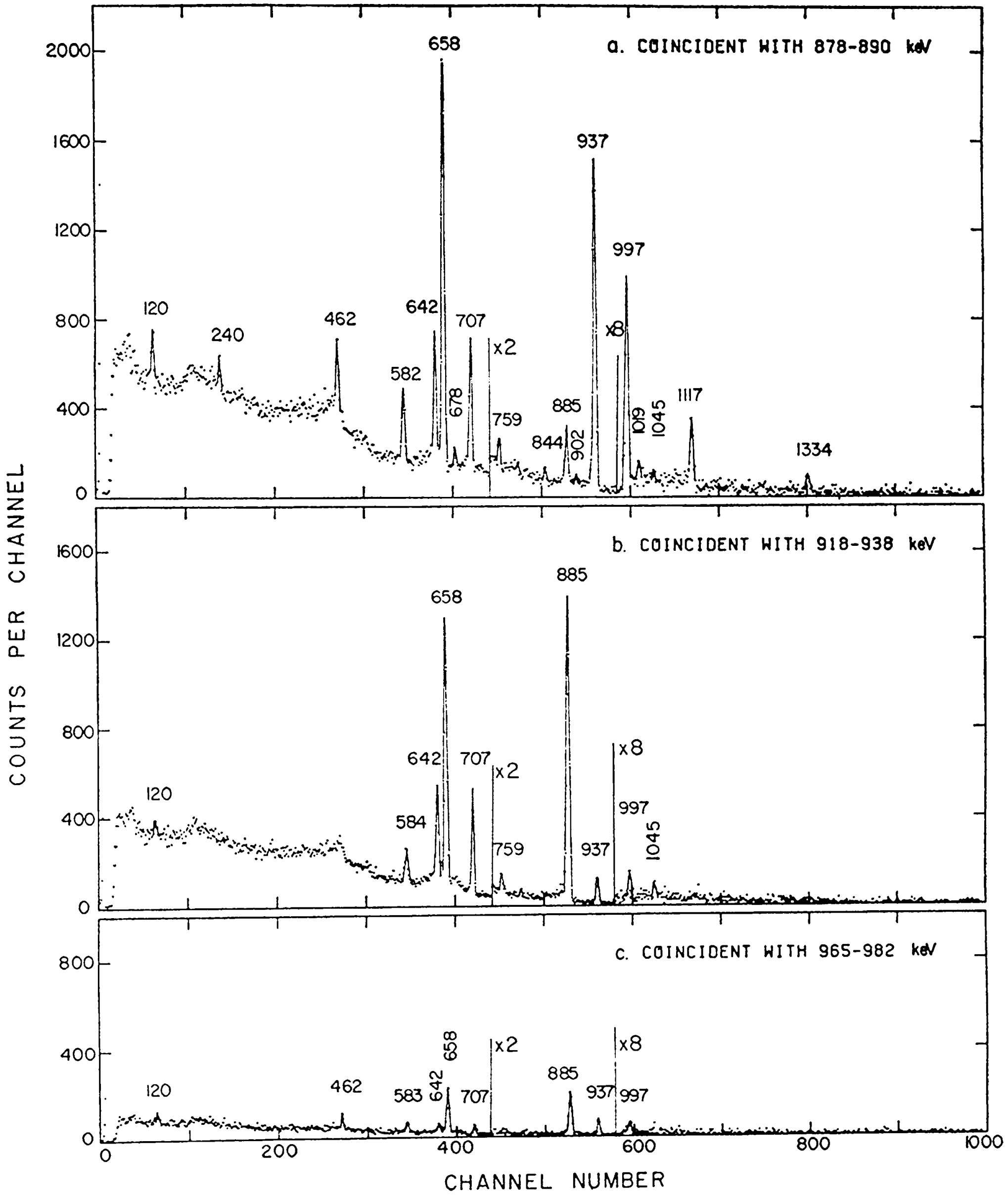

Fig. 9. Spectra of the γ-rays from $^{110\mathrm{m}}$In decay observed with the 20 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30 cm^3 Ge(Li) detector. Parts a and b display the spectra coincident with the 885 and 937 keV γ-rays, respectively, while part c shows the corresponding Compton background in the same energy scale.

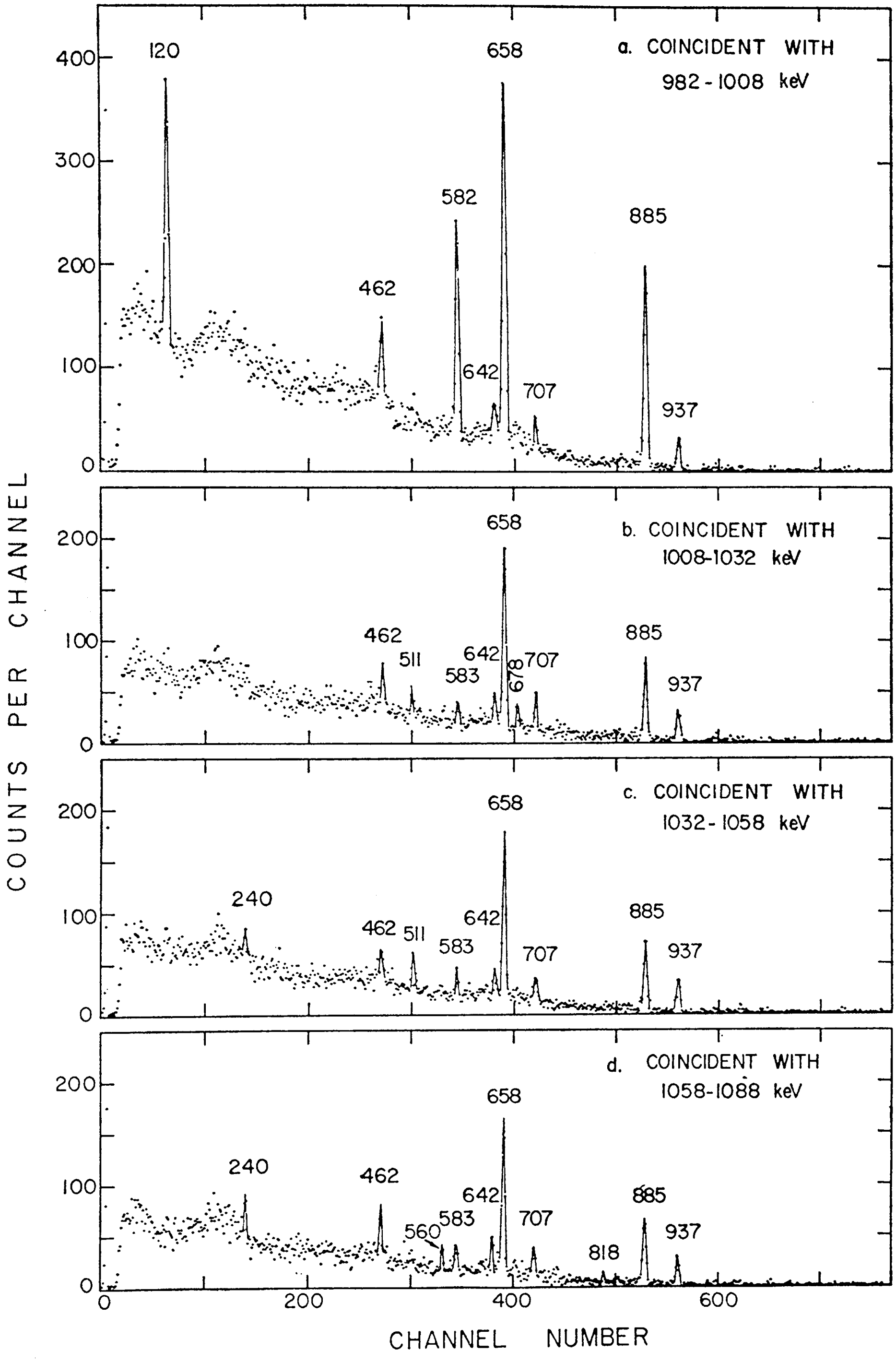

Fig. 10. Spectra of the γ-rays from ^{110m}In decay observed with the 20 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30 cm^3 Ge(Li) detector. Parts a, b, c and d show the spectra coincident with the 997, 1019, 1045 and 1085 keV γ-rays, respectively.

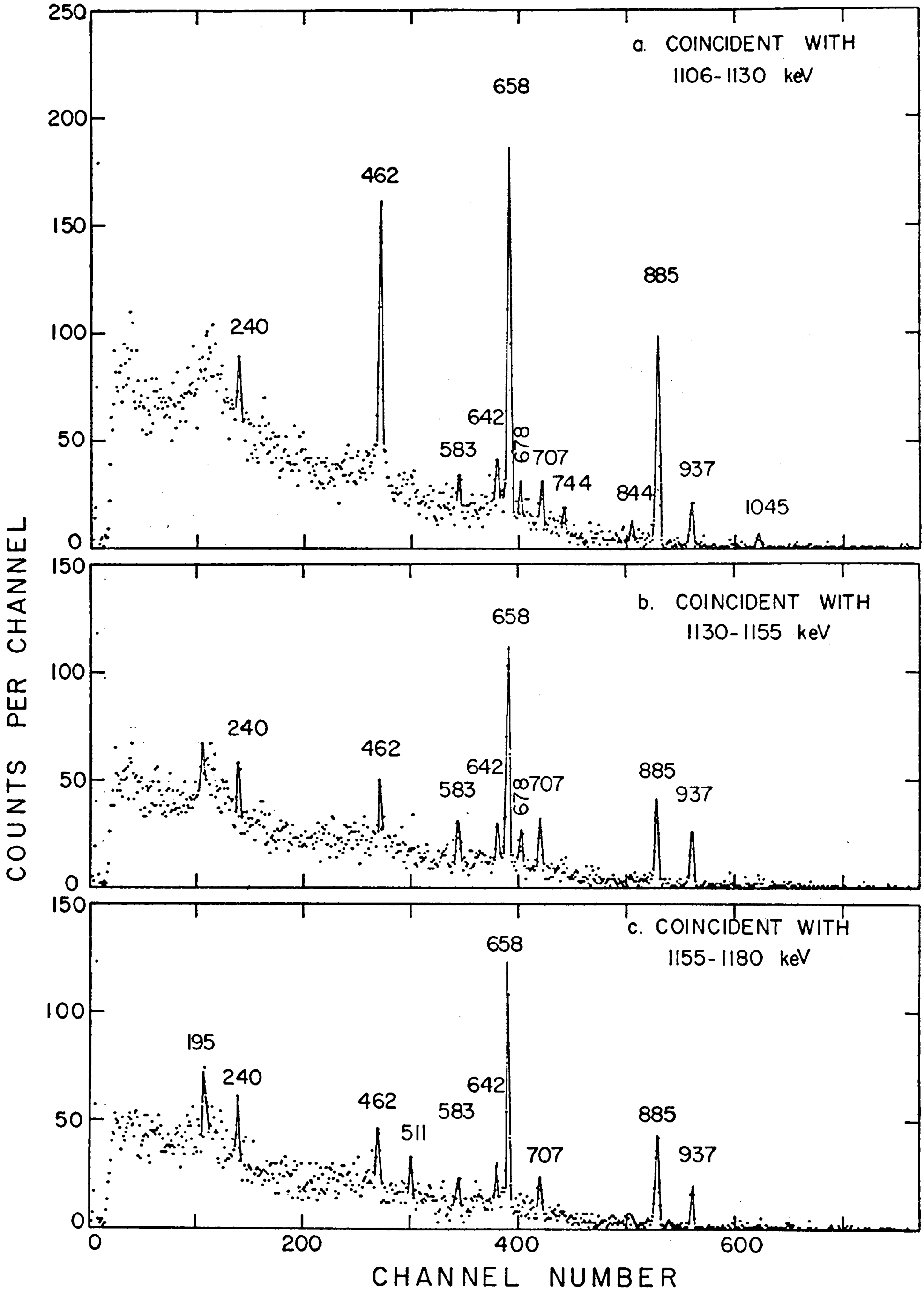

Fig. 11. Spectra of the γ-ray from ^{110m}In decay observed with the 20 cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30 cm^3 Ge(Li) detector. Parts a and c show the spectra coincident with the 1117 and 1163 keV γ-rays, respectively, and part b shows the corresponding Compton background.

coincidence with the 884.72 keV γ-ray (fig. 9a), and (ii) by the ratio of the observed coincidences in these two spectra. This information suggests the presence of levels at 2124.55 and 3063.90 keV. The level at 3063.90 keV is further supported by the observed coincidence of the 844.3 keV γ-ray with the 677.7 keV γ-ray (figs. 6b and 6c), with the 1521.1 keV γ-ray assigned to de-excited this level on energy considerations. The level at 2124.55 keV is further supported by the observed coincidence of the 997.2 keV γ-ray with the 582.0 and 120.4 keV γ-rays (fig. 10a).

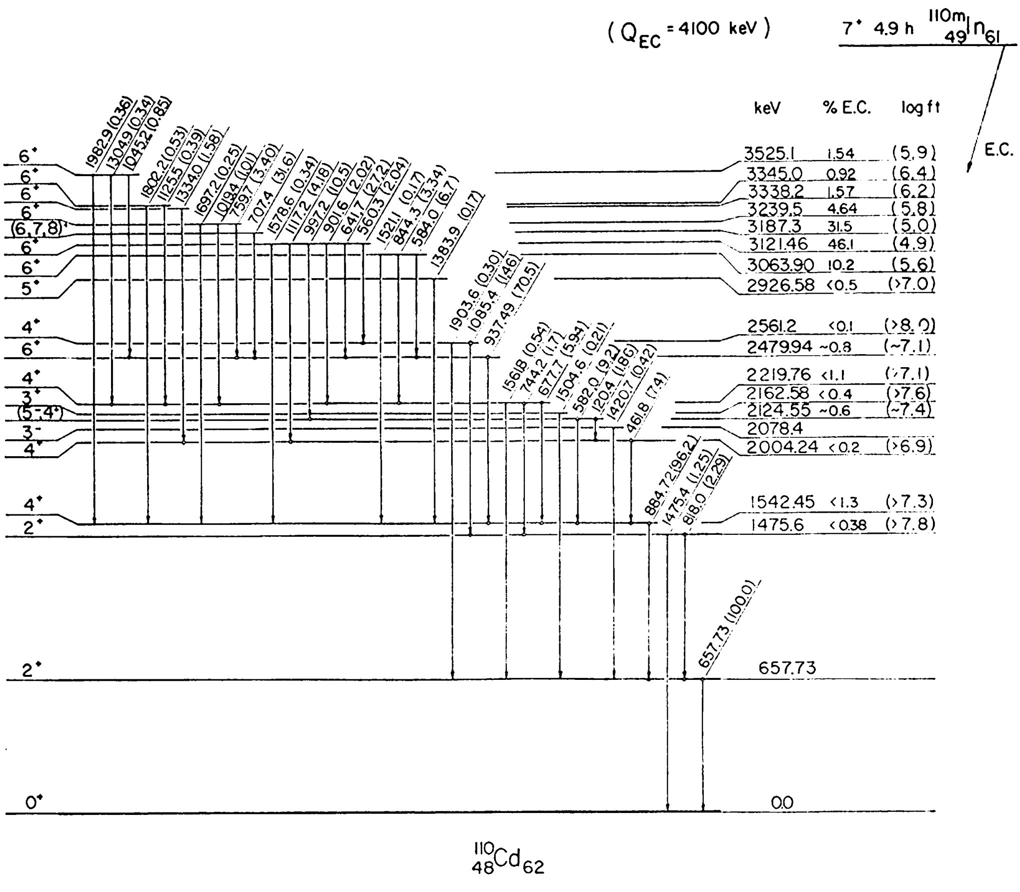

Fig. 12. Proposed decay scheme for 4.9 h ^{110m}In. The energies are given in keV and the γ-ray intensities given in parentheses are relative to the intensity of the 657.73 keV γ-ray taken as 100.

The 3121.46 keV *level.* The rather intense 641.7 keV γ-ray is in coincidence with the 937.49 keV γ-ray suggesting a level at 3121.46 keV. This is further firmly established by the following observed coincidences: 560.3 with 1085.4 keV (fig. 10d), 901.6 with 677.7 keV (figs. 6b and 6c), 997.2 with 582.0 keV (figs. 5a and 10a) and 1117.2 with 461.8 keV (figs. 4a and 11a). Finally, the 1578.6 keV γ-ray is assigned by energy difference to de-excite the 3121.46 keV level.

The 2004.24 keV *level.* This level is established on the basis of the observed coincidences of the 461.8 keV γ-ray with the 120.4 and 1117.2 keV γ-rays (fig. 4a). The latter two γ-rays originate from two levels established from other evidence and this information establishes a level at 2004.24 keV.

The 2561.2 keV *level.* The 1085.4 keV γ-ray is in coincidence with the 818.0 keV γ-ray (figs. 8a and 8b). This suggests a level at 2561.2 keV, which is further supported by the observed 1903.6 keV γ-ray assigned on the basis of excellent energy agreement to populate the 657.73 keV level. This level is further supported by the observed coincidence of the 1085.4 keV γ-ray with the 560.3 keV γ-ray (fig. 10d).

The 3187.3 keV *level.* The rather intense 707.4 keV γ-ray is in coincidence only with the 657.73, 884.72 and 937.49 keV γ-rays (figs. 7a, 6a, 9a and 9b). This information strongly suggests a level at 3187.3 keV. No other transition from this level was observed.

The 3239. 5 keV *level.* The 759.7 and 1019.4 keV γ-rays were observed in coincidence with the 937.49 and 766.7 keV γ-rays, respectively (figs. 9b and 6c). This establishes a level at 3239.5 keV and accommodates the 1697.2 keV γ-ray which is assigned to de-excite this level and populate the 1542.45 keV level.

The 3338.2 keV *level.* The 1334.0 keV γ-ray was observed in coincidence only with the 461.8, 657.73 and 884.72 keV γ-rays (figs. 4a, 6a and 9a). This evidence suggests that the 1334.0 keV γ-ray populates the 2004.24 keV level directly, thus establishing a level at 3338.2 keV. No other transition was observed to de-excite this level.

The 3345.0 keV *level.* The 1125.5 keV γ-ray appears to be in coincidence with the 677.7 and 744.2 keV γ-rays, since the 1125.5 keV γ-ray is included in the gate of fig. 11a and the 1117.2 keV γ-ray is not in coincidence with either of these γ-rays (see fig. 12). This suggests a level at 3345.0 keV which is supported also by the observed 1802.2 keV γ-ray assigned on energy grounds to de-excite this level.

The 3525.1 keV *level.* The 1045.2 keV γ-ray is in coincidence with the 657.73, 884.72 and 937.49 keV γ-rays (figs. 6a, 9a and 9b). This suggests a level at 3525.1 keV, which is confirmed by the observed 1304.9 and 1982.9 keV γ-rays that were assigned to de-excite this level on energy grounds. The assignment of the 1304.9 keV γ-ray is also supported by coincidence information with the 657.73 keV γ-ray.

3.2. TENTATIVE LEVELS

The 2078.4 keV *level.* A level at this energy is known from ^{110g}In decay to de-excite by a 1421.4 keV γ-ray [1]). Since the 1420.7 keV γ-ray has an energy lying within the experimental error of the two measurements it is tentatively assigned to de-excite a level at 2078.4 keV.

The 2162.58 keV *level.* This level is known to be populated by the ^{110m}Ag decay [7]) via a 763.88 keV transition from the 2926.58 keV level. This level de-excites by emitting a 1504.90 keV γ-ray [7]). In view of the good energy agreement between this and the observed 1504.6±0.2 keV γ-ray the 2162.58 keV level is tentatively assigned to be populated in the ^{110m}In decay via de-excitation of the 2926.58 keV level. The connecting 763.88 keV transition is expected on the basis of the branching ratio I_{1384}/I_{764} from ^{110m}Ag and the present intensity of the 1384 keV γ-ray to be too weak to be observed in the spectrum of fig. 1.

The 2926.58 keV *level*. This level is known to be populated in the ^{110m}Ag decay [7]) and de-excites by emitting a 1384.22±0.04 keV γ-ray. As the energy of the 1383.9± 0.2 keV γ-ray agrees with this within experimental error, the 2926.58 keV level is tentatively assigned to be populated in the decay of ^{110m}In. It should be mentioned that the 763.88 keV γ-ray, the second most intense to de-excite the 2926.58 keV level from ^{110m}Ag decay [7]), is not expected to be seen here because this level is only very weakly populated in the ^{110m}In decay.

4. Assignment of J^{π} values

An upper limit of 0.1 % was estimated for the total positon emission in the ^{110m}In decay from lack of observation of the annihilation radiation. The small amount of the annihilation radiation that is seen in fig. 1 is due to the longer-lived impurity of that sample. Other spectra, however, were recorded where no annihilation radiation could be observed. The log ft values given in fig. 12 are based on the fraction of electron capture to the levels in ^{110}Cd obtained from the transition intensity balances using the γ-ray and conversion electron intensities from this work. As the proposed decay scheme accommodates 98.2 % of the total γ-ray intensity, it may be assumed that the unassigned γ-rays would not affect significantly the log ft values. The log ft values were calculated using Moszkowski's nomographs [16]) in an expanded form [17]). For this purpose the Q_{EC} value of 4.10 MeV was used based on an estimate from level systematics of 170 keV for the energy of the isomeric state in ^{110}In. The discussion of the character of the electron-capture decay is given below, together with the assignment of the J^{π} values from the internal conversion data. The K-shell conversion coefficients presented in table 2, when compared to the values of Sliv and Band [18]), suggest the most probable multipolarities for some of the transitions involved, as shown in the last column of table 2.

The angular momentum of the metastable state in ^{110m}In has been determined from atomic beam experiments to be 7 [see, e.g. ref. [19])], and from level systematics its parity is expected to be positive.

The J^{π} values of the first three excited states 657.73(2^+), 1475.6(2^+) and 1542.45 (4^+) keV have been well characterized and a brief discussion of their nature has been given in ref. [1]). These J^{π} assignments are also consistent with the multipolarities based on the K-shell conversion coefficients given in table 2.

From the directional correlation data of Munnich *et al.* [6]) it has been well established that the 1542.45 and 2479.9 keV levels have J-values of 4 and 6, respectively. The α_K results (table 2) for the corresponding 884.72 and 937.49 keV transitions suggest an E2 character thus establishing the 2479.9 keV level as 6^+.

The level at 2219.76 keV is not substantially populated by electron capture (log ft

> 7.1). The 744.2 keV transition populates the 2^+ level at 1475.6 keV and its α_K value suggests an M1 or E2 character. This limits the J^π assignment for the 2219.76 keV level to less than or equal to 4^+. The fact that this level was not populated in the decay of the 69 min 2^+ ^{110g}In helps eliminate the values $\leqq 2^+$ for this level. Finally, a 3^+ assignment may be eliminated as a possibility because this level is rather strongly populated by transitions from several higher lying 6^+ levels. This leaves the 4^+ as the most probable assignment for the 2219.76 keV level.

The level at 3069.9 keV is strongly populated by electron capture by an allowed transition ($\log ft = 5.6$) and this limits its J^π value to $(6,7,8)^+$. This level de-excites to populate the 4^+ level at 1542.45 keV and this eliminates the $(7,8)^+$ values as possibilities leaving the 6^+ as the most probable J^π assignment.

Similarly the levels at 3121.46, 3239.5, 3345.0 and 3525.1 keV are strongly populated by allowed electron capture ($\log ft \leqq 6.4$) and this again limits the J^π value to $(6,7,8)^+$ for these levels. All four of these levels de-excite to populate significantly the 4^+ level at 1542.25 keV and this eliminates $(7,8)^+$ as possibilities leaving the 6^+ assignment as the most probable one for all these levels.

The level at 2561.2 keV is not populated by electron capture. The 6^+ level at 3121.46 keV de-excites via the 560.3 keV γ-ray to populate the 2561.2 keV level. Since the 560.3 keV γ-ray has an α_K value suggesting an M1 or E2 transition the J^π value for the 2561.2 keV level can be limited to $(4, 5, 6, 7 \text{ or } 8)^+$. Of these, the values other than 4^+ can be eliminated on the basis of the fact that this level de-excites to populate only 2^+ levels below, and that the 1085.37 keV transition appears from the α_K value to be M1 or E2 in character.

The level at 2004.24 keV is not populated significantly by electron capture and de-excites by the 461.8 keV γ-ray to populate only the 4^+ level at 1542.45 keV. The 461.8 keV γ-ray has an α_K consistent with an M1 or E2 transition. This information limits the J^π value for this level to $(2, 3, 4, 5 \text{ or } 6)^+$. Since the 6^+ level at 3121.46 keV de-excites the populate substantially the 2004.24 keV level the values $(2,3)^+$ can be eliminated as a possibility. Furthermore the values $(5 \text{ or } 6)^+$ for this level can be eliminated because such a level should be populated substantially the β^- decay of the 6^+ ^{110m}As and this is not observed [7]). This leaves the value 4^+ as the most probable for the 2004.24 keV level.

The level at 2124.55 keV should be discussed in more detail in view of the fact that the published conversion electron results are conflicting. At first the α_K values obtained from the conversion electron intensities from refs. [9-11,13]) are in serious disagreement with each other. The adopted value (0.14 ± 0.05) is an equal weight average and it suggests an E1 or possibly and M1 assignment. The value from Katoh *et al.* [13]) is too low even for an E1 transition while the highest value of Bleuler *et al.* [10]) agrees with an M1 transition. The K/L ratio of 6 ± 1 reported by Smith [11]) and by Katoh *et al.* [13]) is consistent with either an M2 or a 40 % M1+60 % E2 transition [11]). The M2 assignment must be excluded on the basis of the α_K value. Although the low value of α_K for the 120.4 keV transition suggests a negative parity assignment for the 2124.55

keV level, the conflicting evidence from the K/L ratio makes the assignment uncertain. The data of Katoh *et al.* [13]) suggest further that the 997.2 keV transition may be an E1 and this would support a negative parity assignment for the 2124.55 keV level. Furthermore, the α_K value for the unresolved doublet at 583 keV is compatible with one of the transitions, say the 582.0 keV one, being an E1 and the other M1, thus corroborating toward the negative parity assignment for the 2124.55 keV level. From the above evidence if the parity were indeed negative then the J^π value is limited to 5^-. On the other hand, for a positive parity the J^π would be limited to 4^+ on the basis of absence of population of this level from β^- decay of ^{110m}Ag.

The 3338.2 keV level is populated by electron capture in an allowed transition ($\log ft = 6.2$) and it appears to decay exclusively to the 4^+ level at 2004.24 keV. This information is sufficient to limit the J^π for this level to 6^+.

The 3187.3 keV level is populated by electron capture in an allowed transition ($\log ft = 5.0$) and since it was observed to decay only to the 6^+ level at 2479.94 keV the J^π value for this level can only be limited to $(6, 7, 8)^+$.

Finally, the levels at 2078.4, 2162.58 and 2926.58 keV were assigned as 3^-, 3^+ and 5^+, respectively, on the basis of previous knowledge [1,7]) from the decays of ^{110g}In and ^{110m}Ag.

5. Discussion

The proposed decay scheme of fig. 12 is in good agreement with the compilation in ref. [17]) with the exception of an assigned level at 2249 keV for which no evidence is found in this work. Two additional levels at 2688 and 3093 keV in ^{110}Cd and an isomeric transition in ^{110}In including the 121 keV γ-ray have been proposed by Katoh *et al.* [13]) for which no evidence is found in this work. The 120.4 keV γ-ray corresponds to a transition in ^{110}Cd as it was observed in coincidence with the 884.7, 461.8 and 997.2 keV γ-rays. This is also consistent with the findings of Smith [11]) and of Hamilton and Sattler [20]) who placed an upper limit of 0.008% for the isomeric transition in ^{110}In. The level at 3093 proposed by Katoh *et al.* [13]) is actually located at 3063.9 keV but no 411 keV γ-ray was observed to de-excite it.

The energy levels of ^{110}Cd that have been well characterized are summarized in table 4. The properties of the low-lying states at 657.73 (2_1^+), 1475.6 (2_2^+) and 1542.45 (4_1^+) keV have been studied by means of Coulomb excitation by McGowan *et al.* [21]) and by Milner *et al.* [22]). From B(E2) values thus determined for the $4_1^+ \to 2_1^+$, $2_2^+ \to 2_1^+$ and $2_2^+ \to 0$ transitions, serious questions are raised about the validity of the vibrational model [see also ref. [1])]. This fact makes pointless any attempt to characterize the high spin states as members of a three-phonon quadrupole quintet. However, Koike *et al.* [23]) have interpreted the 2219.76 keV 4^+ state as due to single-phonon 2^4 pole vibration on the basis of an $l = 4$ angular distribution of inelastically scattered 55 MeV protons on ^{110}Cd. The other two states at high excitation that are excited with substantial cross section by the (p, p′) reaction at 55 MeV are located at 2479.94 and 2926.58 keV. Both of these states are excited in the β^- decay of ^{110m}Ag.

TABLE 4
Summary of energy levels in ^{110}Cd

Energy level (keV)	J^π	Energy level (keV)	J^π
g.s.	0^+	2974.1	$(1,2)^+$
657.73	2_1^+	3063.90	6_2^+
1473.4	0^+	3077.9	2^+
1475.6	2_2^+	3101.4	2^+
1542.45	4_1^+	3121.46	6_3^+
1731.5		3187.3	$(6,7,8)^+$
1783.3	$(1,2)^+$	3193.8	$(2,3)^+$
1809.0		3239.5	6_4^+
2004.24	4_2^+	3313.3	2^+
2078.4	3^-	3338.2	6_5^+
2124.55	$(4^+,5^-)$	3345.0	6_6^+
2162.58	3^+	3401.2	$(1,2)^+$
2219.76	4_3^+	3451.1	$(2,3)^+$
2355.5	$(1,2,3)^+$	3464.3	$(1,2)^+$
2463.1	$(1,2,3)^+$	3474	$(1,2)^+$
2479.94	6_1^+	3525.1	6_7^+
2561.2	4_4^+	3596	$(1,2)^+$
2786.5	$(1,2)^+$	3701	$(1,2)^+$
2878.3	$(1,2)^+$	3770	2^+
2926.58	5^+		

The 4^+ states at 2004.24, 2561.12 and possibly at 2124.55 keV have not been observed earlier as they are not expected to be populated directly in the $^{110\mathrm{m}}$Ag decay. As these 4^+ states and the 6^+ states assigned to ^{110}Cd are at energy higher than 2.0 MeV it is reasonable to assume that many of them are two quasiparticle neutron or proton states. The information available from the present work for the characterization of the high spin states in ^{110}Cd includes γ-ray branching ratios and $\log ft$ values. The branching ratios have been used to calculate B(E2) ratios for transitions of the type $(J+2)^+ \rightarrow J^+$ with $J = 2$ and 4 and the results are summarized in table 5.

The 4_3^+ and 4_4^+ states in ^{110}Cd decay to the 2_1^+ and 2_2^+ states at 657.73 and 1475.6 keV, respectively, with B(E2) ratios which are similar. These enhancements of the E2 transitions to the 2_2^+ state, however, are consistent either with substantial one-phonon or three-phonon admixtures in the wave function for the 4_3^+ and 4_4^+ states. Similar relative enhancements of about two orders of magnitude are seen for the transitions from the 6_2^+, 6_3^+, and 6_4^+ levels to the 4_3^+ and 4_1^+ levels (see table 5).

TABLE 5

Relative B(E2) values in ^{110}Cd

From level (keV)	To levels (keV)	E_γ (keV)	$B(\mathrm{E2})_n/B(\mathrm{E2})_1$
2219.76(4^+_3)	657.73(2^+_1)	1561.8	128 ± 10
	1475.6 (2^+_2)	744.2	
2561.2 (4^+_4)	657.73(2^+_1)	1903.6	81 ± 12
	1475.6 (2^+_2)	1085.4	
3063.9 (6^+_2)	1542.45(4^+_1)	1521.1	296 ± 53
	2219.76(4^+_3)	844.3	
3121.46(6^+_3)	1542.45(4^+_1)	1578.6	98 ± 14
	2219.76(4^+_3)	901.6	
3239.5 (6^+_4)	1542.45(4^+_1)	1697.2	52 ± 5
	2219.76(4^+_3)	1019.4	
3345.0 (6^+_6)	1542.45(4^+_1)	1802.2	6.2 ± 0.5
	2219.76(4^+_3)	1125.5	
3525.1 (6^+_7)	1542.45(4^+_1)	1982.9	7.6 ± 1.4
	2219.76(4^+_3)	1304.9	
3121.46(6^+_3)	1542.45(4^+_1)	1578.6	69 ± 8
	2004.24(4^+_1)	1117.2	
3121.46(6^+_3)	1542.45(4^+_1)	1578.6	1070 ±103
	2561.2 (4^+_4)	560.3	

This should be contrasted with the ratios from the 6^+_7 and 6^+_3 levels to the same 4^+ levels, which are 6.2 and 7.6, respectively.

Another source of information which is useful in an attempt to shed some light in the structure of the 6^+ states in ^{110}Cd are the logft values for the EC decay of ^{110m}In. It seems interesting to point out that the first 6^+ state in ^{110}Cd is only very weakly populated by electron capture with a logft value estimated to ≈ 7.1. This is to be contrasted with the strong population of the higher lying 6^+ states in ^{110}Cd (logft $\geqq$ 4.9). At excitation energies of 3 MeV and higher, the number of two-quasiparticle configurations that lead to 6^+ states is significant. Such configurations could account for the observed logft values for the 6^+ states other than the one at 2479.94 keV. The logft value for the population of the 2479.94 keV state is rather high and it seems unlikely that this hindrance is due to pairing correlation effects or to l-forbiddenness. This suggests a significant collective character for this 6^+ state. This is also suggested by the log*ft* value of 8.2 for the decay of the 6^+ $^{110\text{m}}_{47}\text{Ag}_{63}$ to the same 6^+ state in ^{110}Cd.

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