Capture-Gamma-Ray Spectrum of $Cd^{113}(n,\gamma)Cd^{114}$ and the Associated Energy Levels in Cd^{114}†

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The capture gamma-ray spectrum of $Cd^{113}(n,\gamma)Cd^{114}$ was investigated with the Argonne 7.7-m bent-crystal spectrometer. The observed spectrum consisted of 119 gamma rays with energies below 2 Mev. These precision energy measurements were combined with a series of coincidence experiments to modify and extend the level scheme of Cd^{114}. The errors in the energy values of five previously observed levels are reduced by a factor of 10. Their new values are found to be 557.8±0.1, 1208.4±0.2, 1282.2±0.2, 1304.9±0.3, and 1362.9±0.3 kev. Five new levels are established at 1133.1±0.2, 1730.3±0.2, 1839.9±0.3, 1958.3±0.3, and 2202.4±0.3 Mev. Eight more levels are suggested at 1607.8±0.3, 2048.3±0.4, 2225.1±0.4, 2392.5±0.4, 2573.8±0.5, 2868.0±0.7, 3216.8±0.8, and 3484.7±0.8 kev. The limits placed on the spins and parities of these levels by the observed capture gamma rays are discussed.

I. INTRODUCTION

CADMIUM-114 is a spherical or near spherical nucleus which would be expected to exhibit a vibrational energy level scheme for low excitation energies. Basically, this model consists of a 0^+ ground state, a 2^+ first excited state, and a triplet of 0^+, 2^+, and 4^+ states at twice the energy of the 2^+ first excited state. The 2^+ first excited state is associated with a one-phonon vibrational state of the nucleus, while the triplet corresponds to a two-phonon excitation. The energy level structure of Cd^{114} is unique in that it is the only nucleus in which states with all three spins (0^+, 2^+, 4^+) have been observed in the energy region of the two-phonon vibrational triplet. In Cd^{114} the first 2^+ state occurs at 557.8 kev and the energy levels associated with the triplet have energies between 1.1 and 1.4 Mev. In the simple vibrational theory, this triplet is degenerate.[1] Recently, a number of more refined theories have been suggested to explain the splitting of this degenerate triplet.[2–6] Although all of these theories predict energies for the triplet states at about twice that of the first 2^+ state, the energy differences between the triplet states (20–200 kev for Cd^{114}) are quite varied, as is their sequence of spin assignments. The difficulty in the interpretation of the level scheme of Cd^{114} is that two extra states have been found in the triplet energy region. The selection of a particular model or theory cannot be made until it is decided which, if any, of the five possible states are associated with the collective motion of the nucleons. In addition to the two-phonon triplet at 1.1 Mev, the vibrational theory predicts a three-phonon quintet at 3 times the energy of the first 2^+ state. This would be about 1.7 Mev above the ground state. The quintet should consist of 0^+, 2^+, 3^+, 4^+, and 6^+ states. In the same energy region the asymmetric rotor model of Davydov and Filippov[7] predicts a 3^+ state at an energy above the ground state equal to the sum of the energies of the first and second 2^+ states (1.76 Mev for Cd^{114}) and a 4^+ state at 1.6 Mev. The $E2$ gamma-ray transitions from these upper collective states to the collective states in the triplet energy region are enhanced in the collective model. Their presence should therefore be observable in the spectrum of capture gamma rays.

The precision of the bent-crystal spectrometer allows one to check and extend the present level scheme of Cd^{114} through the comparison of capture gamma-ray energies. The presence of known low-energy levels having a wide range of known spins (0^+,2^+,4^+) make Cd^{114} a favorable case for locating new levels and for determining the spins of these new levels through the investigation of gamma-ray transitions. The gamma-ray coincidence experiments reported in this paper were used to provide the necessary checks on the level scheme to guard against the possibility of generating false levels.

II. EXPERIMENTAL METHOD

A. Capture-Gamma-Ray Spectrum

The spectrum of capture gamma rays from neutron capture in Cd^{113} was investigated with the Argonne 7.7-m bent-crystal spectrometer.[8] The observed spectrum consisted of 119 gamma rays below 2 Mev, with intensities which varied from 88 to 0.0033 photons per 100 neutron captures in Cd^{113}. The precision of the energy measurements for these gamma rays varied between 1 part in 1000 and 1 part in 20 000, depending on the energy and intensity of the gamma ray. The full width at half maximum of a gamma-ray diffraction peak in this spectrometer is 0.5% for a 500-kev gamma

† This work performed under the auspices of the U. S. Atomic Energy Commission.
[1] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).
[2] L. Willets and M. Jean, Phys. Rev. **102**, 788 (1956).
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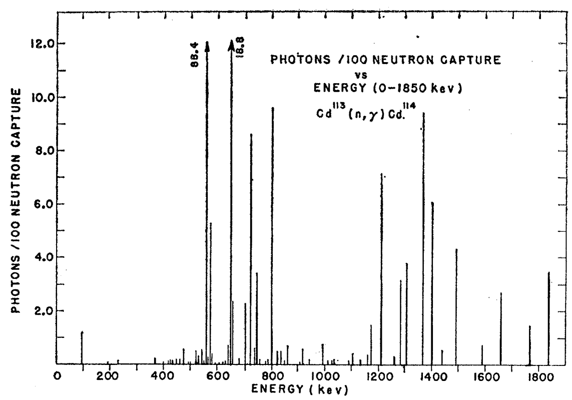

FIG. 1. Spectrum of capture gamma rays from $Cd^{113}(n,\gamma)Cd^{114}$ as observed with the bent-crystal spectrometer. Fifty-five of the gamma rays listed in Table I are too weak to be seen in this graph.

ray and is proportional to the energy of the gamma ray. Approximately half of the observed gamma rays have energies below 500 kev. Most of these are weak, having intensities below 1 photon per 1000 neutron captures. Their average intensity is about 3 photons per 10 000 neutron captures. A line graph of the observed spectrum appears in Fig. 1. Since many of the low-energy lines are too weak to show on this graph, a line graph of the low-energy region with an appropriate scale for the weak lines is given in Fig. 2. The source of capture gamma rays was a 0.003-in. foil of cadmium metal. It was mounted in the center of a beam hole extending completely through the Argonne research reactor, CP-5. Because of the high neutron-capture cross section of Cd^{113} (about 2000 bars) no attempt was made to use the separated isotope as a source. During the course of the experiment, neutron capture converted approximately 80% of the Cd^{113} atoms in the source to Cd^{114}. This resulted in a decrease in the rate of neutron capture in Cd^{113} to 20% of the initial value. By comparing the

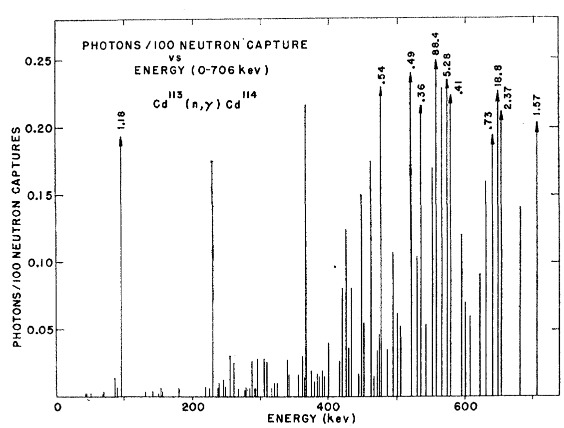

FIG. 2. Spectrum of capture gamma rays from $Cd^{113}(n,\gamma)Cd^{114}$ from 40 to 710 kev. The numbers next to the arrows indicate the intensities of the associated gamma rays in units of photons per 100 neutron captures in Cd^{113}. A number of the close doublets appear as single lines in this graph.

intensity of a gamma ray at the beginning of the experiment with that observed at the end of the experiment, it was possible to determine which gamma rays resulted from neutron capture in Cd^{113}. A list of these gamma rays, their errors, and their intensities is given in the first three columns of Table I. The 16 gamma rays that were found to be associated with neutron capture in other isotopes of Cd and in impurities are not listed in Table I. The question marks which appear under "remarks" indicate that the assignment of this gamma ray to neutron capture in Cd^{113} is uncertain. In order to convert the relative gamma-ray intensities obtained from the analysis of the bent-crystal data to absolute intensities, it is necessary to know the rate of neutron capture in the source. The number of neutrons captured per second per cubic centimeter of source material is often very difficult to determine in capture-gamma-ray work. This is because of the difficulty in measuring the energy dependence and absolute magnitude of the neutron spectrum at the source (in this case near the core of a reactor). What is needed for the intensity determination is the integral of the product of the neutron flux and the cross section, integrated over neutron energy. The value of this product was determined from the observed rate of decrease in the intensities of gamma rays known to result from neutron capture in Cd^{113}. The errors in the absolute values of the intensities are estimated to be between 10% and 20%. The average error for relative intensities is $\approx 5\%$ for gamma rays separated by less than 500 kev. Relative intensities for gamma rays with energies separated by more than 1 Mev may be in error by as much as 15% because of uncertainties in the self-absorption in the source at the low energies and uncertainties in the detector efficiency at the high energies. The errors given for the gamma-ray energies in Table I are probable errors which include the statistics of the experiment and an estimated systematic error. Because of the cancellation of systematic errors, the energy difference between two gamma rays whose energies differ by 10% or less has half the error that the square root of the sums of the squares of the absolute errors would predict. An extra significant figure is given for the higher energies in Table I to facilitate the comparison of energy differences.

B. Gamma-Ray Coincidence Measurements

A series of coincidence experiments was performed to determine which of the capture gamma rays were in coincidence with each other. A piece of Cd was placed in the thermal beam of the Argonne chopper and the resulting capture gamma rays were detected by two NaI crystals. Whenever two gamma rays were detected in coincidence, their pulse heights were separately recorded on magnetic tape. The magnetic tape was then run through a 3-dimensional analyzer.[9] (Only two

[9] Argonne National Laboratory Rept. ANL-6275 (unpublished).

TABLE I. Spectrum of capture gamma rays associated with $Cd^{113}(n,\gamma)Cd^{114}$ observed with the Argonne 7.7-m bent-crystal. spectrometer. The checks in columns 4 and 5 denote the occurrence of the gamma ray in Figs. 3 and 4, respectively. The question marks which occur in column 6 denote uncertainty in the assignment of the gamma ray to neutron capture in Cd^{113}. The errors given in column 2 are probable errors.

Energy (kev)	(2) Error (kev)	(3) Photons per 100 neutron captures	(4) Fig. 3	(5) Fig. 4	(6) Remarks
1829.2	2.5	3.51			possible doublet
1766.0	3.1	1.38			possible doublet
1659.2	1.0	2.67		√	possible doublet
1589.9	2.1	0.68			
1490.6	0.8	4.35		√	
1440.1	2.3	0.56		√	
1400.3	0.7	6.05	√	√	
1365.9	0.7	9.40		√	
1305.1	0.7	3.79	√	√	
1283.8	0.7	3.19		√	
1258.5	1.2	0.27		√ √ √	doublet
1210.5	0.5	7.16		√	
1175.6	0.5	1.43			
1161.7	2.0	0.26			
1137.7	4.8	0.16			
1107.5	0.5	0.38			
1092.0	0.9	0.13		√ √	
1068.6	0.8	0.18		√	
1029.4	1.1	0.12		√ √	
1015.6	0.8	0.13		√ √	
995.14	0.4	0.74			possible doublet
945.66	0.5	0.17			doublet
920.19	0.3	0.56	√	√ √	possible doublet
910.52	0.6	0.13		√ √	
865.00	0.3	0.71			possible doublet
853.65	0.3	0.08			possible doublet
839.58	±0.3	0.51	√	√ √	possible doublet
825.36	0.25	0.49	√	√	
805.17	0.24	7.00	√	√	
789.33	0.46	0.18			
760.38	0.43	0.13			
747.13	0.21	2.36	√	√	
741.43	0.40	0.43			
724.44	0.19	5.82	√	√	
706.72	0.18	1.57	√	√	
683.21	0.34	0.14			
653.53	0.50	2.37	√	√	
650.68	0.16	18.75	√	√	
642.11	0.45	0.73		√ √	possible doublet
631.41	0.29	0.16	√	√	
622.22	0.43	0.09			doublet
608.71	0.41	0.06			
601.07	0.40	0.07			
595.33	0.26	0.12	√	√	doublet
579.50	0.20	0.41			
575.36	0.15	5.28	√	√	
566.72	0.20	0.28			
557.78	0.12	88.42	√	√	
552.70	0.22	0.17		√	
543.42	0.43	0.05			
535.75	0.17	0.36			
531.44	±0.21	0.10			
521.80	0.10	0.49	√	√	
510.17	0.30	0.09			ann. rad.+γ ray
506.28	0.28	0.05			
501.40	0.38	0.062			doublet
494.91	0.18	0.108		√	doublet
485.70	0.17	0.035			possible doublet
476.96	0.08	0.538	√	√	
474.23	0.25	0.047			
472.04	0.13	0.034	√	√	
466.42	0.24	0.015			
462.05	0.12	0.175			
451.33	0.15	0.055			doublet
448.07	0.12	0.152	√	√	
444.65	0.29	0.017			
433.67	0.11	0.081			
430.62	0.14	0.037			
426.17	0.07	0.124			
419.49	0.10	0.080			
417.30	0.13	0.027			
399.42	0.12	0.042		√	
394.16	0.17	0.016			
391.34	0.17	0.020			
383.68	0.22	0.018			
379.62	0.11	0.011			
375.30	0.10	0.020			
367.42	0.07	0.215	√	√	
363.42	±0.14	0.014			
362.09	0.10	0.031			
356.05	0.09	0.016			
341.54	0.09	0.017			
340.05	0.09	0.028			
324.32	0.08	0.010			
321.31	0.11	0.010			doublet
309.98	0.06	0.025			
306.21	0.07	0.028			
295.98	0.05	0.028			
292.15	0.09	0.006			
289.70	0.09	0.006			
287.69	0.05	0.028			
285.26	0.09	0.006			
280.76	0.12	0.006			
275.58	0.11	0.005			
267.77	0.11	0.005			
261.58	0.04	0.024			
255.91	0.04	0.029		√	
248.63	0.04	0.007			
246.16	0.04	0.012			
240.05	0.04	0.010			
239.23	0.06	0.007			
229.63	0.03	0.165	√	√	possible doublet
225.87	0.06	0.006			
219.93	0.05	0.007			
181.37	0.05	0.006		√	
156.45	0.04	0.004			
155.99	±0.04	0.003			
154.50	0.04	0.006	√	√	
151.20	0.03	0.002			
142.32	0.04	0.003			?
131.43	0.03	0.003			?
95.90	0.006	1.18			
89.97	0.012	0.006		√	?
85.95	0.016	0.013			?
69.73	0.007	0.003			?
69.44	0.010	0.002			?
54.72	0.004	0.002			?
46.55	0.003	0.003			?
45.68	0.003	0.002			?

of the channels were used.) Each run yielded the complete energy spectrum of the gamma rays in one crystal that were in coincidence with the gamma rays whose energies fell in a particular 5-kev range in the other crystal. In this way the spectrum of gamma rays in coincidence with each of 51 such ranges was obtained for each crystal. From these, the coincident gamma rays could be identified if their intensities were at least

1 photon per 100 neutron captures; and the approximate energies could be found for many weaker gamma rays in coincidence.

III. LEVEL SCHEME

The precision capture-gamma-ray measurements were combined with the coincidence experiments to modify and extend the energy level scheme of Cd^{114}. The new level scheme appears in Fig. 3. The width of the line in Fig. 3 reflects the intensity of the corresponding γ-ray transition. The filled circles represent coincidence events in which the gamma rays involved are identified. The filled squares denote coincidence events in which only the approximate energies of the gamma rays were determined. Five of these levels (557.8, 1208.4, 1282.2, 1304.9, and 1362.9 kev) were known previously. Five new levels were found at 1133.1, 1730.3, 1839.9, 1958.3, and 2202.4 kev. The energies of the levels below 1.4 Mev are determined with errors of 0.1–0.3 kev. The error associated with the difference between two closely spaced levels in the triplet region is between 0.05 and 0.15 kev. The energies of the new states above 1.4 Mev are determined from the sum of three gamma-ray energies and have errors of 0.2–0.4 kev. The average energy difference between the gamma-ray energy given in Table I and the transition energy as given by the energy levels in Fig. 3 is 0.05 kev. This low average error results from the cancellation of systematic errors which arise in the calculations of absolute energy values.

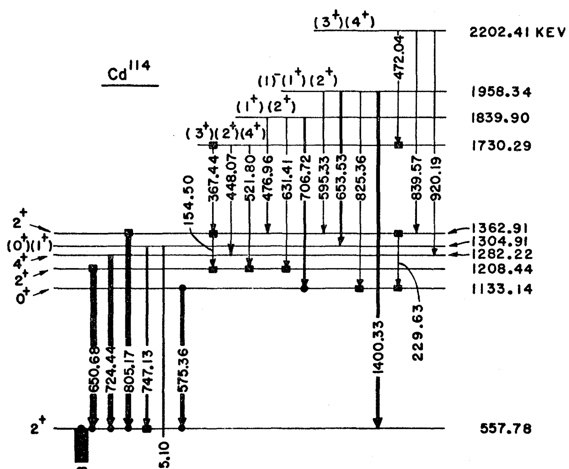

FIG. 3. Energy levels in Cd^{114} as determined from the precision energy measurements of capture gamma rays from $Cd^{113}(n,\gamma)Cd^{114}$ and coincidence measurements of associated gamma rays. The width of the line corresponds to the intensity of the gamma-ray transition. The filled circles denote a coincidence in which both gamma rays were identified. The filled squares denote coincident events in which only the approximate energies of the gamma rays were identified.

IV. REMARKS ON INDIVIDUAL LEVELS

A. 557.78-kev Level

The accuracy of the 557.78-kev level is essentially that of the gamma-ray measurement (0.12 kev). The intensity of 88 photons per 100 neutron captures for the 557.78-kev gamma ray agrees well with the work of Groshev[10] and Motz.[11] The strength of this transition suggests that strong selection rules favor gamma-ray transitions to this level rather than to the ground state. The 2^+ spin and parity assignment comes from Coulomb excitation experiments.[12–15] The reduced transition probability $B(E2)$ of this transition as found in Coulomb excitation experiments is enhanced by a factor of 35 over what would be predicted from single-particle estimates.[15] This strong enhancement of the $B(E2)$ transition probability is predicted by the collective model and is the best evidence available for the collective nature of this state.[15,16]

B. 1133.14-kev Level

The coincidence experiments described in Sec. IIB indicated that the 575.36-kev gamma ray and the 557.78-kev gamma ray were strongly correlated. The strength of the coincidence rate observed between the two gamma rays required that the 575.36-kev gamma ray should feed the 557.78-kev level directly. This information was used to predict a level at 1133.1 kev. The transitions found to connect this level with the higher energy levels tend to confirm its existence. This level has also been seen by Groshev[10] and by Cohen.[17] Groshev observed a very weak high-energy transition from the 1^+ neutron-capture state to a level at 1135 ± 5 kev. He also observed an internal-conversion line of approximately 1135 kev. From this information he concluded that there was a 0^+ level at 1135 kev. Cohen observed a level at 1.14 Mev in the reaction $Cd^{113}(d,p)Cd^{114}$. The relative cross section for the proton group associated with the formation of the 1.14-Mev level was found to decrease by a factor of 8 when the angle of observation was varied from 8° to 14° relative to the deuteron beam. Cohen states that this could only result from an $l_n=0$ neutron capture. Since the ground state of the Cd^{113} nucleus is $(\frac{1}{2})^+$, this would result in the formation of a 0^+ or 1^+ state.

[10] L. V. Groshev, *Proceedings of the International Conference on Nuclear Structure* (University of Toronto Press, Toronto, Canada, 1960), p. 568.
[11] H. T. Motz, Phys. Rev. **104**, 1353 (1956).
[12] F. K. McGowan and P. H. Stelson, Phys. Rev. **106**, 522 (1957); **110**, 489 (1958).
[13] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).
[14] H. Mark, C. McClelland, and C. Goodman, Phys. Rev. **98**, 1245 (1955).
[15] P. H. Stelson and F. K. McGowan, Phys. Rev. **121**, 209 (1961).
[16] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winthe Revs. Modern Phys. **28**, 432 (1956).
[17] B. Cohen and R. Price, Phys. Rev. **118**, 1582 (1960).

The formation of a 0^+ state is favored because the configuration needed to form a 1^+ state is considerably more complicated than for a 0^+ state. The crossover transition from the 1133.1-kev level to the 0^+ ground state was not observed with the bent-crystal spectrometer. An upper limit of 0.15 gamma rays per 100 neutron captures can be set for the intensity of this transition. Combining this with the electron internal-conversion work of Groshev,[10] one obtains a lower limit on the internal conversion coefficient $\alpha \geqslant 0.05$.[18] The tables of Rose[19] predict $\alpha_4=0.002$ for an $E4$ transition, $\beta_5=0.011$ for an $M5$ transition, and $\alpha_5=0.010$ from an $E5$ transition of the appropriate energy. From this, one concludes that if the spin of this state is not zero then it is $\geqslant 5$. The vibrational model predicts that the cascade transition (575.4 kev) from this 0^+ state to the first 2^+ state (557.8 kev) should be enhanced if the 1133.1-kev level is assumed to be part of the two-phonon triplet. This enhancement should be visible in double Coulomb excitation experiments similar to those of Stelson and McGowan[15] if the chance coincidences between the 557.8-kev gamma rays from the excitation of the first 2^+ level could be eliminated. Such an experiment might allow one to decide which of the two 0^+ states in the triplet region corresponds more closely to the 0^+ level predicted by the collective model.

C. 1208.44-kev Level

This level was first suggested by the external- and internal-conversion experiments of Motz.[11] The value of the conversion coefficient obtained by Motz suggested an $E2$ or $M1$ transition for the 650.7-kev cascade gamma ray. This led to a 1^+ or 2^+ assignment for this level. The 2^+ assignment has been confirmed by the recent Coulomb-excitation work of Stelson and McGowan.[15]

The energy of the 1208.44-kev state as reported in this paper, is obtained from the sum of the two cascade gamma rays (557.78 kev+650.68 kev) plus a slight modification to improve the fits of the upper cascades. An error of 0.17 kev is assigned to this level. In previous work[10,11,15] it has been assumed that the 1210-kev gamma ray was the crossover transition from this level to the ground state. The energy difference between the sum of the cascade gammas and the 1210.5-kev gamma as determined from the bent-crystal data[20] is 2.1 ± 0.6 kev. The 2.1-kev discrepancy in the energy fit is 14% of the full linewidth at half the peak height and is too large to be explained by systematic errors. For this reason it does not appear in Fig. 3.[21] The energy mismatch does not rule out the existence of a crossover transition but only sets an upper limit of 2 photons per 100 neutron captures for its intensity. The ratio of the cascade to crossover gamma-ray intensities becomes $\geqslant 9.4$. Stelson and McGowan[15] used a ratio of 3.6 in their calculation of the reduced transition probabilities for the Coulomb excitation of the 1208.4-kev level and 650.7-kev gamma transition. The new limit on the cascade-to-crossover ratio lowers their value of $B(E2, 2'\rightarrow 0)$ by 13% to $\leqslant 0.16\times10^{-50}$ cm^4 and raises the lower limit of $B(E2, 2'\rightarrow 2)$ by a factor of 2.4 to $B(E2, 2'\rightarrow 2)\geqslant 3.3\times10^{-49}$ cm^4. It also sets a lower limit of $R=B(E2, 2'\rightarrow 2)/B(E2, 2\rightarrow 0)\geqslant 2.9\pm0.5$.[22] This is quite close to the value of $R=2.7\pm1.2$ found in the case of Te^{122} but is double the value of similar ratios in many of the other vibrational nuclei. The increase in the value of $B(E2, 2'\rightarrow 2)$ will result in a similar increase in the cross section of double Coulomb excitation of this level. Because of this increase, the double $E2$ cross section might account for 20% of the total Coulomb excitation cross section for this level.

D. 1282.22-kev Level

The position of this level is given by the sum of the two cascade gamma rays (724.4 kev+557.8 kev), modified slightly by the energy differences of the upper cascades. The error associated with this determination is ±0.23 kev. A coincidence is seen between the 724.4-kev and the 557.8-kev gamma ray. The 4^+ spin assignment of this level was determined by Brazos and Steffen[23] from the angular correlation of the two cascade gamma rays resulting from the β decay of the 5^+ isomeric state in In^{114}. This level was observed through double Coulomb excitation by Stelson and McGowan.[15] The observed cross section for double Coulomb excitation of this level requires a strong enhancement of the $E2$ transition from the first 2^+ level at 557.8 kev to this 4^+ level. This enhancement supports a collective model interpretation for the state. A (1283.8 ± 0.7)-kev gamma ray was observed with the bent-crystal spectrometer in the gamma-ray spectrum associated with $Cd^{113}(n,\gamma)Cd^{114}$. This energy is 1.6 ± 0.7 kev higher than the sum of the two cascade gamma rays. This difference is too large to be accounted for by systematic errors and the 1283.8-kev gamma ray is therefore not assigned to this transition. Its presence, however, raises the upper limit that can be set for the crossover gamma (1282.2 kev) to 1 photon per hundred neutron captures.

[18] The ratio of the intensity of the 1305-kev electron-conversion line to that of the 557.8-kev conversion line obtained by Groshev (reference 10) is three times the value obtained by Motz (reference 11). If Groshev's work is used to obtain the intensity of the 1135-kev internal-conversion line relative to the 1305-kev one and the work of Motz is used to obtain a lower limit on the ratio of the intensity of the 1305-kev to that of the 557.8 kev internal conversion, then $\alpha\geq 0.016$. This is still large for an $E4$ transition of 1135 kev.

[19] M. E. Rose, *Internal Conversion Coefficients* (Interscience Publishers, Inc., New York, 1958).

[20] The term "bent-crystal data" will always refer to the precision gamma-ray energy measurements reported in this paper.

[21] The 1210.5-kev gamma ray was found to fit higher up in the level scheme (see general discussion).

[22] The $B(E2, 2'\rightarrow 2)$ and $B(E2, 2\rightarrow 0)$ are the reduced transition probabilities for the upper and lower cascade gammas, while the $B(E2, 2'\rightarrow 0)$ refers to the crossover transition. The values given for the $B(E2)$'s are in units of e^2 and refer to the gamma-ray decay process.

[23] J. N. Brazos and R. M. Steffen, Phys. Rev. **102**, 753 (1956).

If this gamma-ray transition were to exist, the most likely assignment for the 1282.2-kev level would be 2^+.

E. 1304.91-kev Level

Motz[11] has observed a strong internal-conversion line of 1305 ± 8 kev following neutron capture in Cd. He ascribed this conversion line to a transition from a 0^+ state at 1305 kev to the 0^+ ground state. The energy of this level, as determined by the bent-crystal spectrometer measurements, is (1304.91 ± 0.26) kev. This is based on the assumption that the 747.13-kev gamma ray is the transition from this level to the 2^+ state at 557.8 kev. The coincidence experiments, which were complicated by the presence of the 724.4-kev gamma, gave only qualitative agreement with this assumption. A strong gamma ray with an energy of 1305.1 kev was observed in the spectrum of capture gamma rays associated with neutron capture in Cd^{113}. This is too close an energy fit to be ruled out on this basis. If the level at 1304.9 kev is a 0^+ level, then the $0^+\rightarrow0^+$ gamma-ray transition to the ground state should be forbidden and the 1305.1-kev gamma ray is located somewhere else in the scheme. However, the chance of finding a gamma ray in Table I whose energy accidentally comes within 0.2 kev of a particular energy value between 1.0 and 1.5 Mev is only 1 in 100. If the 1304.9-kev level is assumed to have a spin other than zero, it is possible to estimate its internal-conversion coefficient. Using the relative internal-conversion intensities obtained by Motz[9] and the gamma-ray intensities obtained with the bent-crystal spectrometer, and assuming that the 557.78-kev gamma ray is a pure $E2$ transition, one obtains 0.034 for the internal-conversion coefficient of the 1304.9-kev gamma ray. This internal-conversion coefficient would require a large spin change (5 or 6). If this level had a spin of 5 or 6, it is not likely that the level would be fed heavily enough to sustain the strong gamma rays that deplete it. The most reasonable assumption is that either the internal-conversion transition or the gamma-ray transition depletes the 1304.9-kev level, but not both. An alternative solution to this problem would be to assume the presence of two closely spaced levels with the 741.4-kev gamma ray appearing as the cascade gamma from the lower of the two levels to the 2^+ level at 557.8 kev. This would further complicate the level scheme in the triplet region and make its interpretation even more difficult.

F. 1362.91-kev Level

The presence of this level was first suggested by the conversion-electron work of Motz.[11] The 2^+ spin assignment has been confirmed by the Coulomb-excitation work of Stelson and McGowan.[12] The error associated with the 1362.9-kev energy value assigned to this level by the bent-crystal data is 0.32 kev. It is fed by four cascade gamma rays from the upper four levels in Fig. 3. The gamma-ray transition from the 2^+ state at 1362.9 kev to the 2^+ state at 1208.5 kev was observed with the bent-crystal spectrometer. The ratio of the intensity of this 154.50-kev gamma ray to the competing 805.17-kev gamma ray is 8.8×10^{-4}. Both of these gamma rays are believed to be $2^+\rightarrow2^+$ transitions. If both transitions are assumed to be $E2$, the single-particle model predicts an intensity ratio of 2.0×10^{-4}, which is in reasonable agreement with the observed value of 8.8×10^{-4} and suggests that the 154.50-kev transition is enhanced over the 805.17-kev transition. The ratio $B(E2,2''\rightarrow2')/B(E2,2''\rightarrow2)$ is equal to 4.4, where 2, 2′, and 2″ refer to the 2^+ levels at 557.8 kev, 1208.4 kev, and 1362.9 kev, respectively. The 229.63-kev gamma ray appears to be the transition from the 2^+ level at 1362.9 kev to the 0^+ level at 1133.1 kev. The difference between the energy of the 229.63-kev gamma ray and the level spacing is 0.14 kev. This energy fit is poor when compared to the other energy differences. The determination of the energy of this gamma ray was complicated by the presence of a capture gamma ray from an impurity and may account for this discrepancy. The coincidence experiments give conflicting evidence. A (230 ± 10)-kev gamma ray appears to be in coincidence with both a (150 ± 10)-kev gamma ray and a (370 ± 10)-kev gamma ray. It has been assumed in this paper that this conflict of information is due to the inability to resolve the gamma-ray spectrum in the coincidence experiments. The ratio of the intensity of the 229.63-kev transition to that of the 154.50-kev transition is 27 to 1. If both transitions are assumed to be $E2$, the single-particle estimate of the ratio of their intensities is 7.3 to 1. This suggests an enhancement of the 229.67-kev transition over both the 154.50-kev and 805.17-kev transitions; $B(E2,2''\rightarrow0')/B(E2,2''\rightarrow2')=3.7$ and $B(E2,2''\rightarrow0')/B(E2,2''\rightarrow2)=16$. The $B(E2,2''\rightarrow0')$ refers to the transition from the 2^+ state at 1362.9 kev to the 0^+ state at 1133.1 kev.

The Coulomb-excitation experiments of Stelson and McGowan[15] give a value for the reduced transition probability of the 805.2-kev gamma ray, $B(E2,2''\rightarrow2)$, which is six times as large as the single-particle model would predict. This enhancement is only one sixth that found for the similar cascade transition (650.7 kev) associated with the 2^+ level at 1208.4 kev. The calculation of this enhancement depends on the ratio of the intensity of the cascade gamma ray to that of the assumed crossover gamma ray whose energy is 1365.9 ± 0.7 kev as measured with the bent-crystal spectrometer. The energy difference between the sum of the cascade gamma rays and the assumed crossover gamma ray as measured by the bent-crystal spectrometer is 3.0 ± 0.8 kev. This discrepancy is believed to be too large to be explained by an accumulation of errors. For this reason the gamma ray has been omitted from Fig. 3. This energy mismatch does not rule out the existence of a crossover transition but it does set an upper limit of 3 photons per 100 neutron captures on

its intensity. The ratio of cascade to crossover gamma-ray intensities becomes $\geqslant 2$. Correcting Stelson's values of the $B(E2)$'s for this new limit, one obtains $0.09\times10^{-50} \leqslant B(E2, 2''\to 0)\leqslant 0.13\times10^{-50}$ cm^4, $B(E2, 2''\to 2) \geqslant 4.1\times10^{-50}$ cm^4 and $B(E2, 2''\to 2)/B(E2, 2\to 0) \geqslant 0.33$. A lower limit can also be set for the ratio of the $B(E2)$'s of the 229.62-kev cascade transition to the crossover transition to the ground state, namely, $B(E2, 2''\to 0')/B(E2, 2''\to 0)\geqslant 520$. Both of the cascade transitions (650.68 kev and 805.17 kev) appear to be enhanced compared to single-particle estimates by at least a factor of 10. This experiment cannot determine which enhancement is greater because only lower limits are obtained for the $B(E2)$'s.

G. 1730.29 kev Level

Three conditions were required for the acceptance of a new level above 1.4 Mev. First, it must be connected to three previously established levels through observed gamma rays. Second, at least two of these gamma rays must have errors which are less than 0.5 kev. Third, there must be some supporting evidence for this level in the coincidence experiments. The 1730.3-kev level was connected to the established level scheme by three low-energy gamma rays whose errors ranged from 0.12 kev to 0.07 kev. Coincidence support was found for two of these gamma rays.

A spin assignment of 2, 3, or 4 is suggested for this level by the presence of gamma-ray transitions to 2^+ and 4^+ states. The spin assignments of 0 and 1 were ruled out because of the transition to the 4^+ state at 1282.2 kev. The 2^+ assignment may be ruled out for this level because no transition was observed to a 0^+ state. No selection rules are known that would prohibit such a transition. The energy of this level differs by only 2% from the energy at which the asymmetric-rotor model of Davydov and Filippov[7] predicts a 3^+ level. This prediction is based on the assumption that the 2^+ level at 1208.4 kev is the 2^+ collective state in the triplet energy region. The asymmetric-rotor model also predicts a 4^+ state at 1560 kev, which is not seen. The "+" assignment for the parity of this level and of the uppermost level comes from the work of M. Rozkos[11] who investigated the related $In^{115}(\gamma,p)Cd^{114}$ reaction at gamma-ray energies of 14.8 and 17.6 Mev. No proton groups were observed that would correspond to an energy level in Cd^{114} below 4 Mev. Since the 0^+, 2^+, and 4^+ levels were not observed in this experiment, Rozkos concludes that the levels that he observed have odd parity resulting from $E1$ gamma-ray absorption and s-wave proton emission. The ground state of In^{115} is $(9/2)^+$. This implies that there are no negative-parity states below 4 Mev with a spin greater than 2. The 3^+ or 4^+ spin assignment for this level is further substantiated by the lack of evidence of this level in the high-energy capture-gamma-ray work of Groshev[10] and the similar gamma-ray work of Motz and Carter[24] as well as the (d,p) work of Cohen.[17]

H. 1839.87-kev Level

The spins of 1 and 2 are suggested for this level by the gamma-ray transitions from it to 2^+ and 0^+ levels. Spin assignments of 0, 3, and 4 were ruled out on the basis of the 706.7-kev transition to the 0^+ level at 1133.1 kev. A strong coincidence was observed between the 706.7-kev gamma ray and the 575.4-kev gamma ray. The presence of a 557.65-kev transition from this level to the 4^+ level at 1282.22 kev was masked by the existence of a strong gamma ray at 557.78 kev. The 535.75-kev gamma ray comes within 1.8 kev of matching the energy difference between this level and the 0^+ level at 1304.9 kev. The error in this level spacing is believed to be less than 0.5 kev. This is small enough to rule out the assignment of the 535.75-kev gamma ray to this transition. An upper limit of 0.03 photons per 100 neutron captures can be set for the transition from the 1839.9-kev level to the 1304.9-kev level. The comparison of this upper limit with the intensity of the strong 706.7-kev transition to the 0^+ level at 1133.1-kev demonstrates the radically different nature of these two levels. The 1283.9-kev gamma ray comes within 1.9 ± 0.7 kev of matching the energy of a transition from the 1839.9-kev level to the 557.8-kev level. The 1829.2-kev gamma ray listed in Table I is the first peak in a group of unresolved gamma rays which could contain the transition from the 1839.9-kev level to the 0^+ ground state. The Compton spectrometer work of Motz and Carter[24] suggests an 1836-kev gamma ray, while the work of Groshev[10] suggests 1840 kev for the energy of the gamma ray. Groshev also observes a high-energy gamma ray which may connect this level with the 1^+ capture state. These experiments support the 1^+ or 2^+ spin assignment. Cohen observes a proton group in the $Cd^{113}(d,p)Cd^{114}$ reaction which corresponds to a level at 1.86 Mev.[17] From relative cross-section measurements at 8° and 14° he concludes that $l_n=0$ for the captured neutron which forms this level. This indicates a spin of 0^+ or 1^+ for this state. Since the 0^+, 3^+, and 4^+ assignments have been ruled out, the most likely spin assignment is 1^+. None of the present collective models predict a 1^+ state at this energy.

Although the method of gamma comparison is quite effective in locating 1^+, 2^+ 3^+, and 4^+ states, it may not find 0^+ or 6^+ states. This comes about because three gamma connections to the existing level scheme were required for the establishment of a level. States with 6^+ assignments would only exhibit one transition to the lone 4^+ state; and if crossover transitions are forbidden, then 0^+ states would have only two connecting transitions to the two 2^+ states at 1208.44 kev and 1362.91 kev. If one accepts pairs of gamma rays whose

[24] H. Motz and R. Carter (private communication, June, 1960).

energy difference is the difference between the two 2^+ levels as evidence for a 0^+ level, then 0^+ levels are suggested at energies of 1607.84±0.12, 1652.8±0.4, 1703.2±0.3, 1715.5±0.4, 2648.3±2.5, and 2800.1±3.1 kev.

A large number of energy differences are possible with 119 gamma rays. The statistics are such that three of the six possible 0^+ levels given above probably result from accidental energy matches. The level at 1607.84 ±0.12 kev is the only 0^+ level suggested in this manner that has sufficient accuracy to make an accidental interpretation unlikely. None of the possible 0^+ levels agree with the 1.86-Mev energy predicted by Cohen. If a 0^+ does exist, it is connected to the lower levels between 1.1 and 1.4 Mev by only one gamma ray whose intensity is equal to or greater than 0.03 photons per 100 neutron captures.

I. 1958.34-kev Level

Four gamma rays were found to connect this level with the lower states. The spins of these lower states (only 0^+ and 2^+) suggest a 1^+, 2^+, or 1^- assignment for this level. The 0^+, 3^+, and 4^+ assignments are eliminated by the presence of two transitions to 0^+ states. The 2^+ assignment might be ruled out by the absence of a transition to the 4^+ state at 1282.22 kev. If the 1958.3-kev level is not connected with the collective motion of the nucleons, then there is no reason to assume that the E2 transitions would be enhanced to compete with the $M1$ transitions. If the spin of the 1958.3-kev level is 2, then it must be 2^+ if transitions to 0^+ states are to compete with transitions to 2^+ states. The error in the energy match of the 1400.3-kev crossover transition to the 2^+ state at 557.78 kev is 0.23±0.7 kev. This crossover is forbidden in the collective model if the 1958.3-kev level is considered as a member of the three-phonon vibrational quintet. Although this model is inadequate for this case, the intensity of the 1400.3-kev transition is large for a collective-model interpretation of this level. The 1^- assignment for this level may be ruled out by the absence of a strong gamma-ray transition to the ground state.

J. 2202.41-kev Level

This state was added after establishing a state at 1730.29 kev. Its existence is therefore less certain than that of the other states. Three gamma rays connect it with the rest of the level scheme. The 920.19-kev transition to the 4^+ level at 1282.22 kev eliminates a 0^+, 1^+, 1^-, and 2^- spin assignment for the 2202.41-kev level. The lack of a transition to a 0^+ state would rule out the possibility of a 2^+ state. The 1068.6-kev gamma ray comes within 0.7±0.9 kev of matching the energy of the transition from this level to the 0^+ level at 1133.14 kev. This is a poor fit, but the equally large error resulting from the low intensity (0.18 photons per 100 neutron captures) of this gamma ray makes the fit a possible one. Because of uncertainty in the energy of this gamma ray, it does not appear in Fig. 3. Its presence in the scheme would eliminate the 3^+ and 4^+ spin assignments for this level. In this case the spin assignment would have to be 2^+.

V. GENERAL DISCUSSION

The level scheme of Cd^{114}, as modified and extended in this paper, supports and confirms much of the previous work on this isotope. In particular, the enhancement of $E2$ transitions appears to be even stronger than previously supposed, and most of the competing $M1$ or $E2$ crossover transitions are either absent or too weak to be seen. The two low-energy transitions observed in the energy region where the triplet vibrational band is predicted are enhanced as well.

If the accuracy and coincidence requirements for the acceptance of new levels are relaxed, many more energy levels can be suggested. The level scheme in Fig. 4 is an extension of the level scheme for Cd^{114} in which no confirming evidence from the coincidence experiments was required. The scheme was constructed by accepting all levels that made three or more transitions to the existing scheme, starting with the level scheme in Fig. 3. The energy of a gamma ray was required to match the final level spacing within two probable errors. In the final scheme only two levels have less than four gamma-ray connections to the rest of the level scheme. If these two levels are removed from the scheme, all the rest of the new levels have four or more connections. The two levels in question (1607.8 kev and 2048.3 kev) are believed to be 0^+ levels. The level at 1607.8 kev has only two connections to the level scheme but it is included because the errors of the gamma rays are small and the energy fit is good. The chance of this fit occurring by accident is 1 in 30. The three dashed levels directly above the 1607.8-kev level are also connected to the scheme by two similar gamma rays but the errors are larger and the energy fits are poorer. These four levels exhaust all the possibilities for a 0^+ level below 2.6 Mev that is only connected to the two 2^+ levels at 1208.4 kev and 1362.9 kev. If one considers pairs of gamma rays that cascade to only one of the above levels and to the 2^+ level at 557.8 kev, then it is possible to find several more candidates for 0^+ levels but the errors are too large to rule out chance occurrences of this type (see discussion in Sec. IV, H).

The gamma rays that appear in Figs. 3 and 4 are indicated by checks in columns 4 and 5, respectively, of Table I. The multiple checks indicate that the gamma ray occurs in more than one place in Fig. 4. In four out of the eight such cases, the gamma ray is observed as a close doublet in the bent-crystal data. The remaining four cases are about what is expected to occur by accident in a level scheme of this type. The average probable error for the gamma rays involved in these duplicate cases is 0.8 kev. A level scheme consisting of 18 randomly spaced levels between 1.1 and 3.5 Mev

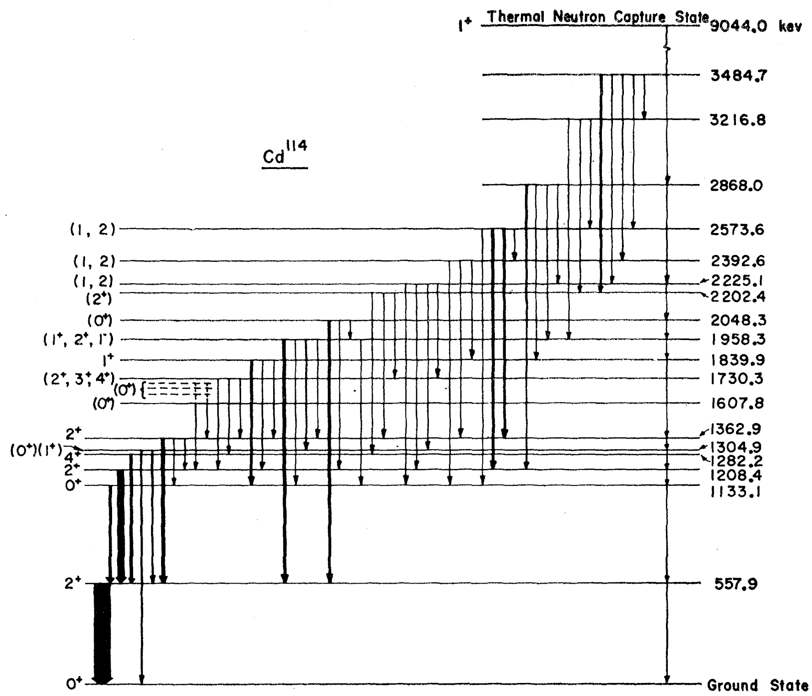

FIG. 4. Energy levels in Cd^{114} as determined from the comparison of gamma-ray energies. This level diagram, an extension of Fig. 3, requires only that all gamma-ray energies agree with the level spacing within two probable errors. The series of arrows at the right-hand side of Fig. 3 proceeding from from the thermal-neutron-capture state to the levels in the decay scheme indicate high-energy gamma-ray transitions (references 10 and 24).

would be expected to exhibit six pairs of gamma-ray transitions whose energies agreed within 1.6 kev and were greater than 800 kev. The detection of four of the twelve probable transitions of this type is a highly probable event. In a complicated level scheme such as the one shown in Fig. 4, one would expect that four or five out of the 44 gamma rays in the scheme might be due to an accidental energy fit and really belong higher up in the level scheme. The 1210.5- and 1365.9-kev gamma rays that were rejected as crossover transitions from the 1208.4- and 1362.7-kev levels to the ground state appear in Fig. 4 as transitions from a level at 2573.8 kev to the levels at 1362.7 and 1208.4 kev, respectively. The coincidence experiments appear to support this assignment for the 1210.5- and 1365.9-kev gamma rays but the statistics were too poor to confirm it.

The existence of the upper levels in Fig. 4 is less certain than the rest of the level scheme because they themselves depend on the existence of new levels. Some corroborating evidence for existence of these upper levels has recently been published by Cohen and Price.[17] Although their $Cd^{113}(d,p)Cd^{114}$ work could not resolve the levels above 2 Mev, prominent proton peaks were observed corresponding to energy levels in Cd^{114} at 2.53, 2.90, 3.23, and 3.45 Mev. If one allows errors of 40 kev for these energy determinations because of the complicated nature of the proton spectrum, then they agree quite well with the values of 2573.5, 2868.0, 3216.8 and 3484.7 kev obtained from the bent-crystal data. A summary of the energy levels in Cd^{114}, as determined from the bent-crystal data, appears in Table II.

In Fig. 4 there are 160 level spacings with energy within the limits of measurement by the bent-crystal spectrometer. If the spins of the observed levels are distributed evenly between 0^+, 1^+, 2^+, 3^+, and 4^+, then 100 of the measurable gamma-ray transitions would require a spin change of 2 or less and would be either $M1$ or $E2$ in nature. A further reduction in the number of observable gamma-ray transitions is expected from the competition between high- and low-energy transitions as well as from additional selection rules. Fifty gamma rays appear in Fig. 4. The intensity balance between the gamma rays that feed a level in Fig. 4 and those that deplete it appear in columns (6) and (7) of Table II. Most of the levels exhibit quite reasonable intensity balances. The slight excess of radiation feeding the level at 1362.9 kev is accounted for by assuming that small amounts of the intensities of the 1365.9- and 1210.5-kev gamma rays are due to the presence of the missing crossover gamma rays from the levels at 1362.7 and 1208.4 kev to the ground state. If the intensities of these two transitions are assumed to be 0.5 photon per 100 neutron captures, the intensity balance is restored. This is quite consistent with the upper limit of 2 photons per 100 neutron captures set by the analysis of the bent-crystal data. The intensity balance for the 4^+ level at 1282.2 kev is quite poor. It is difficult to understand why more gamma rays are not observed to feed this level. The other noticeable imbalance occurs at the 2202.4-kev level. Most of the

TABLE II. Energy levels in Cd^{114} as determined from the capture-gamma-ray data and the coincidence experiments. The errors given in column 2 are probable errors.

(1) Energy (kev)	(2) Error (kev)	(3) Spin	(4) In Fig. 3	(5) In Fig. 4	(6) Percent of cascades that feed	(7) Percent of cascades that deplete	(8) Remarks
0.0	±0.0	0^+	√	√	92.2		Ground state
557.8	0.1	2^+	√	√	49.7	88.4	
1133.1	0.2	0^+	√	√	3.9	5.3	
1208.4	0.2	2^+	√	√	13.3	18.8	
1282.2	0.2	4^+	√	√	0.7	5.8	
1304.9	0.3	$(0^+,1^+)$	√	√	2.6	6.1	Conflicting evidence
1362.9	0.3	2^+	√	√	8.4	7.2	
1607.8	0.3	(0^+)		√	0.0	0.07	Very tentative
1730.3	0.2	$(2^+,3^+,4^+)$	√	√	0.14	0.86	
1839.9	0.3	1^+	√	√	0.23	1.76	
1958.3	0.3	$(1^+,2^+,1^-)$	√	√	0.35	7.0	
2048.3	0.4	(0^+)		√	0.0	4.6	Tentative
2202.4	0.3	(2^+)	√	√	3.2	0.74	
2225.1	0.4	(1,2)		√	0.47	0.49	Tentative
2392.5	0.4	(1,2)		√	0.20	0.33	Tentative
2573.8	0.5	(1,2)		√	0.46	17.1	Tentative
2868.0	0.7			√	0.0	3.2	Tentative
3216.8	0.8			√	0.005	0.5	Tentative
3484.7	0.8			√	0.0	3.4	Tentative

difficulty results from the presence of the 1283.8-kev gamma ray. The energy fit of this gamma ray is borderline and its placement in the level scheme may be in error.

Most of the strong gamma-ray transitions observed with the bent-crystal spectrometer appear in Fig. 4. A notable exception is the 1.2% line at 95.90 kev. This energy is close to the level spacing between the 1304.9-kev level and the 1208.4-kev level. The 0.6-kev discrepancy was considered large enough to eliminate this assignment. It would have been considered as an $E2$ transition and its intensity of 1.2 photons per 100 neutron captures would require an unreasonable enhancement of this transition.

A striking feature of the level scheme in Fig. 4 is the lack of crossover transitions from the levels above 1.4 Mev to the 2^+ level at 557.8 kev and to the 0^+ ground state. Out of the 19 possible transitions, only 3 occur. This suggests that most of the states above 1.4 Mev are composed mainly of excitations involving more than two phonons. Another interesting feature of this level is that there are no level spacings larger than 240 kev above 1.4 Mev. This tends to make the recognition of the three-phonon quintet, if it exists, quite difficult.