PHYSICAL REVIEW VOLUME 149, NUMBER 3 23 SEPTEMBER 1966

Decay Schemes of 43-Day ^{115m}Cd and 2.3-Day ^{115g}Cd†

G. GRAEFFE,* C.-W. TANG,‡ C. D. CORYELL, AND G. E. GORDON
Department of Chemistry and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received 8 April 1966)

The decay schemes of 43-day ^{115m}Cd and 2.3-day ^{115g}Cd were studied using Ge(Li) γ-ray detectors and coincidence techniques. Gamma rays of the following energies (in keV) and relative intensities (in parentheses) were observed in the decay of ^{115g}Cd: 35 (1.4), 232 (2.4), 261 (6.5), 267 (0.13), 336 (178, ^{115m}In I.T.), 493 (26), and 528 (100). The energies and relative intensities of γ rays observed in the decay of ^{115m}Cd are: 106 (0.45), 158 (0.9), 336 (0.25, ^{115m}In I.T.), 485 (13.6), 493 (0.45), 934 (100), 1133 (4.2), 1291 (46), 1419 (0.11), and 1450 (0.85). Upper limits of 0.03 and 0.10 are placed on the relative intensities of 130- and 292-keV γ rays, respectively, that have previously been reported for ^{115m}Cd decay. The 106-, 336-, 493-, and 1450-keV γ rays have not been previously observed in ^{115m}Cd decay, although the 336- (^{115m}In I.T.) and 493-keV γ rays are well known to occur in the decay of ^{115g}Cd. Excited states in ^{115}In are established at 336 (4.4-h ^{115m}In), 597, 829, 864, 934, 1078 (from previous electromagnetic excitation studies), 1133, 1291, 1419, and 1450 keV. The first four of these levels are fed directly by β decay of ^{115g}Cd, and the ground state plus levels at 934, 1133, 1291, 1419, and 1450 are fed by that of ^{115m}Cd. We have found that ^{115m}In is formed in about 0.009% of the ^{115m}Cd decays as a result of the 106-keV γ transition from the 934-keV level to that at 829 keV, followed by the 493-keV γ transition to ^{115m}In. The conversion coefficient α_K of the 35-keV transition was measured as 9.6±1.2. For the 336-keV ^{115m}In I.T. we found $\alpha_K=0.91\pm0.06$ and $\alpha_K/(\alpha_L+\alpha_M)=3.75\pm0.10$. A decay scheme consistent with all of our observations was constructed. Arguments for assignments of spins and parities are given. In particular, observation of the 106-keV transition indicates the assignments $\frac{5}{2}-$ and $\frac{7}{2}+$ for the levels at 829 and 934 keV, respectively. Implications of the results for current nuclear models are discussed.

I. INTRODUCTION

THE recent extensive study of the decay of the ^{117}Cd isomers by Tang *et al.*[1] revealed some very interesting features among the low-lying levels of $_{49}{}^{117}$In. Previous studies of nuclides having 45 and 47 protons have given evidence for collective excitations that couple with single quasiparticles to produce low-lying excited states. In particular, ^{103}Rh, ^{107}Ag, and ^{109}Ag have $\frac{1}{2}-$ ground states.[2] Each of these has $\frac{3}{2}-$ and $\frac{5}{2}-$ excited states in the range 290 to 430 keV which are strongly produced in Coulomb excitation.[3] The $\frac{1}{2}-$, $\frac{3}{2}-$, and $\frac{5}{2}-$ levels have been interpreted as members of a $K=\frac{1}{2}-$ rotational band[4] and, in other works, it has been suggested that the $\frac{3}{2}-$ and $\frac{5}{2}-$ excited states may represent the coupling of the $\frac{1}{2}-$ state with a 2+ vibrational phonon.[3,5] By contrast, in ^{117}In levels at 273, 345, and 434 keV above $\frac{1}{2}-$ ^{117m}In decay to the $\frac{1}{2}-$ state with half-lives of 0.17, 59.7, and 4.55 nsec.[1,6] If two of these states correspond to the $\frac{3}{2}-$ and $\frac{5}{2}-$ excited states of ^{103}Rh, ^{107}Ag, and ^{109}Ag discussed above, the transition probabilities to the $\frac{1}{2}-$ state are much less in ^{117}In than in the 45- and 47-proton nuclei. This result suggests that collective effects are much less applicable in describing the 49-proton nuclei than for those with 45 and 47 protons.

Because of the similar and rather short half-lives of the ^{117}Cd isomers (2.4 and 3.4 h) and the complexity of their γ-ray spectra, details of the low-lying ^{117}In levels are very difficult to study. Therefore, we have chosen to investigate the levels of ^{115}In by observing the decay of the ^{115}Cd isomers which have more convenient half-lives for separate studies of the two isomers and much less complex spectra. Our aim was to find out if some of the interesting features of the ^{117}In levels were also present in ^{115}In.

The decay schemes of the ^{115}Cd isomers initially appear to be rather simple and they have been studied many times previously.[2,7,8] In spite of the simplicity of the spectra and the ease of source preparation, considerable confusion exists in the literature. For example, some of the lines previously reported for ^{115m}Cd are, in fact, those of ^{110m}Ag (an impurity in some ^{115}Cd sources). In this work, we have studied the radiations from chemically separated ^{115}Cd sources with high-resolution Ge(Li) γ-ray detectors and Si(Li) detectors, and associated electronics. A decay scheme that accounts for all of our observations has been constructed, and its nuclear-model implications are discussed below.

† This work was in part supported by the U. S. Atomic Energy Commission under Contract No. AT(30-1)-905.
* Permanent address: Department of Physics, University of Helsinki, Helsinki, Finland.
‡ Present address: Department of Chemistry, McMaster University, Hamilton, Ontario, Canada.
[1] C.-W. Tang, G. Chilosi, C. D. Coryell, and A. H. Wapstra, MIT, Instituut voor Kernphysisch Onderzoek, and Oak Ridge National Laboratory (unpublished data); see also, C.-W. Tang, thesis, MIT, 1965 (unpublished).
[2] *Nuclear Data Sheets*, compiled by K. Way, *et al.* (National Academy of Sciences—National Research Council, Washington D.C., 1964).
[3] F. K. McGowan and P. H. Stelson, Phys. Rev. **109**, 901 (1958).
[4] G. Alaga, K. Alder, A. Bohr, and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **29**, No. 9 (1955); G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956); T. Huus and A. Lundén, Phil. Mag. **45**, 966 (1954).
[5] N. L. Lark, P. F. A. Goudsmit, J. F. W. Jansen, J. E. J. Oberski, and A. H. Wapstra, Nucl. Phys. **35**, 582 (1961).
[6] J. R. Van Hise, G. Chilosi, and C.-W. Tang, Bull. Am. Phys. Soc. **11**, 67 (1966).
[7] J. B. Van der Kooi, H. J. Van den Bold, and P. M. Endt, Physica **29**, 140 (1963).
[8] V. R. Pandharipande, K. G. Prasad, R. M. Singru, and R. P. Sharma, Phys. Rev. **143**, 740 (1966).

II. EXPERIMENTAL PROCEDURES

A. Production of Sources

For most of the work with 43-day ^{115m}Cd, sources were obtained from Oak Ridge.[9] They were found to be contaminated with 1.3-yr ^{109}Cd and 240-day ^{110m}Ag. The ^{109}Cd decays by emission of only an 88-keV γ ray and silver x rays, and thus did not interfere critically with the study of ^{115m}Cd γ rays. Silver was removed by twice stirring freshly precipitated AgCl into the source solution (in HNO_3) and centrifuging the mixture. The AgCl collected showed the characteristic ^{110m}Ag γ-ray spectrum. The supernatant solution containing the ^{115m}Cd was made $2N$ in HCl and adsorbed on a 3-cm column of Dowex 1-X2 anion-exchange resin. Elution with $0.5N$ HCl removed most indium impurities. The γ-ray spectra of the eluant from the column showed peaks of 160 and 192 keV associated with long-lived species, in addition to the weak 336-keV peak identified as the isomeric transition (I.T.) of 4.4-h ^{115m}In. The 192-keV γ ray is ascribed to 50-day ^{114m}In and the 160-keV to 104-day ^{123m}Te. For γ-ray studies the ^{115m}Cd was conveniently counted on the column.

For a few of the final experiments, ^{115m}Cd was obtained from a commercial supplier.[10] As the ^{115m}Cd was made by neutron irradiation of cadmium enriched in ^{114}Cd, the source contained negligible amounts of ^{109}Cd, but some 47-day ^{203}Hg contamination was present which was easily removed by an anion-exchange separation.

Sources of 2.3-day ^{115g}Cd were prepared by irradiating CdO powder enriched in ^{114}Cd (99.1%) in the MIT reactor at a thermal-neutron flux of $2\times10^{13}\,n$ cm^{-2} sec^{-1}. The CdO was dissolved in concentrated HCl, diluted to $2N$, and absorbed on a Dowex 1–X2 anion-exchange column. In order to minimize the intensity of the 336-keV γ ray of ^{115m}In, indium was periodically removed by elution with $0.5N$ HCl.

For the study of electron and low energy γ- and x-ray spectra, thin sources of ^{115}Cd were prepared as follows: The ^{115}Cd, after being cleaned from ^{115}In, was eluted from the column with water. The eluant was made basic with NH_4OH and ^{115}Cd extracted into a small volume of $CHCl_3$ containing a small amount of diphenylthiocarbazone. The $CHCl_3$ solution was evaporated to dryness on a 0.009-mm aluminum foil.

The 4.4-h ^{115m}In sources were obtained from the $0.5N$ HCl washings from the resin columns. These $0.5N$ HCl solutions were further purified from ^{115}Cd by passage through a second column. The pH of the eluant was adjusted to $\sim$3.5 with NH_4OH. A $CHCl_3$ solution of 8-hydroxyquinoline was used to extract the ^{115}In from the aqueous solution. The source for counting was prepared by evaporating the $CHCl_3$ solution to dryness on a small watch glass. For measurement of the conversion coefficient of the 336-keV transition, the purified solution of ^{115m}In in $0.5N$ HCl was concentrated by evaporation and mixed with appropriate amounts of ^{113}Sn and ^{203}Hg standards. The mixed solution was evaporated to dryness on a piece of polyvinylchloride film.

[9] Isotopes Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[10] New England Nuclear Corporation, Boston, Massachusetts.

B. Counting Equipment and Methods

Both Ge(Li) γ-ray detectors and NaI(Tl) crystals were used to determine γ-ray spectra. The Ge(Li) detector had a surface area of 1.5 cm^2 and an 8-mm intrinsic-layer thickness and under optimum conditions gave a full width at half-maximum (FWHM) of 3.0 keV for the 662-keV line from a ^{137}Cs source with the use of a commercial amplifier system.[11] The detector was housed in the cold-finger chamber[12] shown in Fig. 1. The detector was positioned 0.4 cm from the thin (0.75-mm) aluminum window of the chamber. The configuration maximized the solid angle subtended by the detector relative to the source and the window minimized absorption of radiations entering the chamber, allowing us to observe photons of energies as low as 20 keV. The NaI(Tl) detectors used were integrally mounted 7.6×7.6-cm and 5.1×0.64-cm crystals, the latter having a 0.025-mm aluminum entrance window for use particularly with low-energy radiations.

For β-ray and conversion-electron spectra, Si(Li) detectors, one of 0.5 cm^2 area and 0.5 mm thickness and

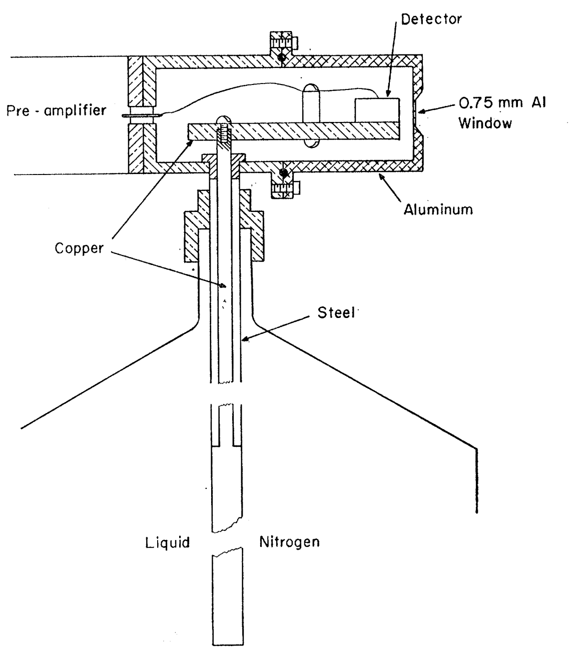

FIG. 1. Schematic drawing of the cold-finger chamber for semiconductor detectors. The entire assembly is mounted on a standard Dewar vessel. The signal is passed to the preamplifier, mounted on the chamber, via a Kovar seal. Outlets to a diffusion pump and an ion pump are on either side of the chamber near the top of the cold finger.

[11] Tennelec, Inc. Model 100C preamplifier and 200C main amplifier.

[12] G. Graeffe, MIT Laboratory for Nuclear Science, Chemistry Progress Report No. MIT-905-52, 1965 (unpublished).

another of 2 cm^2 area and 3 mm thickness, were used. Measurements were made at dry-ice temperature with the detector housed in a chamber similar to that shown in Fig. 1 with sources placed inside of the chamber. The FWHM of the peaks produced by low-energy electron groups (308 keV) was about 6 keV for the smaller detector and 13 keV for the larger one when used with commercial amplifiers.[11]

Various combinations of the detectors described above were employed in coincidence experiments. Coincidences were detected with the use of DD2-type amplifiers and coincidence units operating in the "zero-crossover" mode.[13] In order to avoid the loss of coincidences by variations of crossover times, we always used resolving times, 2τ, of 60 nsec or greater, generally in the range 60 to 100 nsec. A 4096-channel pulse-height analyzer with two 1024-channel analog-to-digital converters was used to record and store singles and coincidence spectra. The analyzer was equipped with a digital-gate unit which made it possible to obtain eight 512-channel or four 1024-channel coincidence spectra simultaneously.

Gamma-ray energies were determined by internal calibration, i.e., the spectrum of the source of interest was taken simultaneously with those of well-known standards. The center of gravity was calculated for each peak and energies computed by a linear interpolation between neighboring peaks of standards. Energy values listed in Table I were used for the standards.

Relative intensities of γ rays were obtained from photopeak areas with the use of a relative photopeak efficiency curve established by observing the spectra of sources that emit γ rays of several different energies with well-determined intensity ratios. For the region from 20 to 90 keV, the efficiency curve was determined from the ratios of the x-ray photopeak areas to the areas for γ rays emitted by ^{115m}In, ^{137}Cs, ^{139}Ce, and ^{203}Hg sources. Conversion coefficients for the γ rays emitted by the latter three sources are well known,[2] and that of ^{115m}In was determined in this work.

The conversion coefficient for the 336-keV ^{115m}In isomeric transition was measured using a source that contained ^{115m}In, ^{113}Sn, and ^{203}Hg. By measuring the relative γ-ray intensities with the Ge(Li) detector and the relative electron intensities with a Si(Li) detector, we could obtain the conversion coefficient, α_K, for ^{115m}In from the well-known values for the 279-keV ^{203}Hg transition (0.163)[2] and the 393-keV ^{113}Sn transition (0.438).[14]

TABLE I. Gamma-ray standards used for energy calibration.

Source	Energy (keV)[a]
^{241}Am	59.568±0.017
^{57}Co	122.05 ±0.05
	136.50 ±0.06
^{139}Ce	165.84 ±0.03
^{203}Hg	279.15 ±0.02
^{22}Na	511.006±0.005
	1274.4 ±1.3
^{207}Bi	569.69 ±0.07
	1063.89 ±0.20
^{137}Cs	661.595±0.076
^{54}Mn	835.50 ±0.15
^{88}Y	898.2 ±0.4
	1836.7 ±0.9
^{60}Co	1173.21 ±0.030
	1332.48 ±0.034

[a] Energies taken from compilations, e.g., Ref. 2, plus recent published and unpublished measurements.

[13] R. L. Chase, Rev. Sci. Instr. 31, 945 (1960).

III. RESULTS

A. ^{115g}Cd Decay

In Fig. 2 is shown a singles γ-ray spectrum of 2.3-day ^{115g}Cd obtained with the Ge(Li) detector. The source consisted of ^{115g}Cd adsorbed on an ion-exchange column which was eluted at about 20-min intervals with 0.5N HCl to remove 4.4-h ^{115m}In. The FWHM of the 261-keV line is 3.0 keV making it possible to resolve a very weak line at 267 keV. The thin window of the detector made it possible to observe clearly the 35-keV γ ray and indium x rays. In Table II are listed the γ-ray energies and their intensities relative to the 528-keV line. For comparison we have also listed the intensities obtained with the use of NaI(Tl) by Varma and Mandeville[15] and by Hans and Rao.[16] All intensity values from this study were obtained from direct spectra. The intensity of the 35-keV γ ray was measured from thin sources. The relative γ-ray intensity of the 336-keV isomeric transition was measured with a source in which ^{115m}In was in transient equilibrium with ^{115g}Cd. Coincidence measurements showed that the 35-keV line is in coincidence with the 232- and 493-keV γ rays and that the 267- and 232-keV lines are coincident with the 261-keV γ ray.

In Fig. 3 is shown a γ-ray spectrum taken of a thin ^{115g}Cd source with a Ge(Li) detector in coincidence with

TABLE II. Gamma rays observed in the decay of 2.3-day ^{115g}Cd.

This work [Ge(Li)]		Literature [NaI(Tl)] Relative intensities	
Energy (keV)	Relative intensity	Varma and Mandeville[a]	Hans and Rao[b]
35.3±0.6	1.4 ±0.3	...	2
231.5±0.4	2.4 ±0.3	2.3	2.2
260.8±0.4	6.5 ±0.4	7	7.6
267.1±0.6	0.13±0.02	0.7	<0.2
336.3±0.4	178 ±7[c]	...	...
492.6±0.3	26 ±1	51	39
527.9±0.3	(100)	(100)	(100)

[a] Reference 15.
[b] Reference 16.
[c] ^{115m}In I.T. γ ray, measured in transient equilibrium.

[14] J. H. Hamilton, in *Nuclear Spin-Parity Assignments*, edited by N. B. Gove and R. L. Robinson (Academic Press, Inc., New York, 1966), p. 31.
[15] J. Varma and C. E. Mandeville, Phys. Rev. 97, 977 (1955).
[16] H. S. Hans and G. N. Rao, Nucl. Phys. 44, 320 (1963).

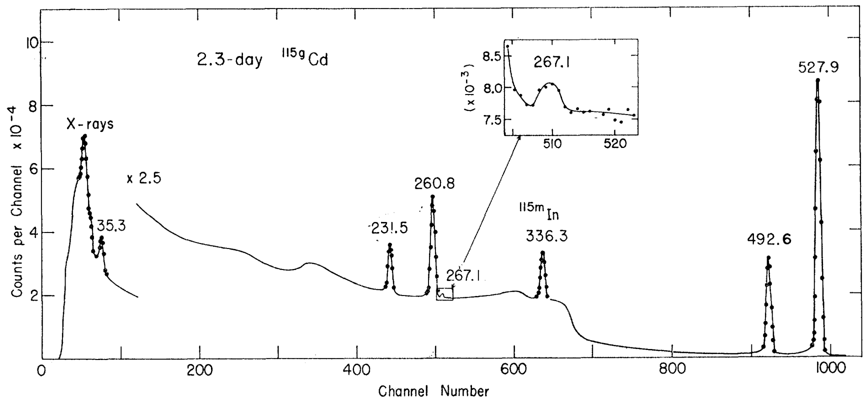

FIG. 2. Spectrum of γ rays from 2.3-day ^{115g}Cd observed with the Ge(Li) detector. For clarity the region around the 267-keV line is expanded in the inset. Numbers above the peaks represent the corresponding γ-ray energies in keV.

the 493-keV region observed with a NaI(Tl) detector. By comparison of the x-ray intensity to that of the 35-keV γ ray and correction for fluorescence yield we obtained the value of the conversion coefficient, α_K, of 9.6 ± 1.2 for the 35-keV transition. As can be seen from the decay scheme given below (see Fig. 7), the only other possible source of x rays in the spectrum is random coincidence events in which some other transition is converted. Corrections for the contribution from random events were small as determined by delaying pulses from one side of the coincidence by 400 nsec. Shapes for the response functions were determined by observing the indium x rays from a pure thin ^{115m}In source and lanthanum x rays from a thin ^{139}Ce source. The values of α_K obtained previously with the use of NaI(Tl) are 7.6 ± 0.8 by Hans and Rao,[16] 3.43 ± 0.12 by Bornemeier *et al.*,[17] and 4.2 ± 0.6 by Tandon and Devare.[18] In all of those earlier measurements, the x- and γ-ray photopeaks were not separated.

In Fig. 4 is shown the electron spectrum of a ^{115g}Cd source observed with the 3-mm thick Si(Li) detector. The only lines observed result from conversion of the 336-keV ^{115m}In isomeric transition. From this spectrum we obtained the value 3.75 ± 0.10 for the ratio $\alpha_K/(\alpha_L+\alpha_M)$ in good agreement with previously measured values of 3.85[15] and 3.76.[19] For the K-shell conversion coefficient, α_K, of the 336-keV isomeric transition, a value of 0.91 ± 0.06 was obtained via the technique described in Sec. II B. Scintillation-counting measurements have given the slightly smaller values 0.83[15] and 0.84.[16]

Beta spectra from pure ^{115m}In sources were obtained with the 3-mm thick Si(Li) detector. Indium-115*m* decays both by isomeric transition and a direct β-ray transition to ^{115}Sn. By comparing the intensity of the β-ray continuum with that of the conversion electrons, a value of $(3.7\pm0.8)\%$ was obtained for the β-branching fraction. Values of about 6% have previously been reported.[19,20]

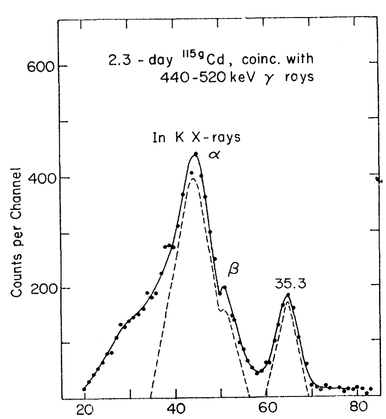

FIG. 3. Indium K x rays and the 35-keV γ ray observed with the Ge(Li) detector in coincidence with the 440- to 520-keV region of the spectrum observed with a NaI(Tl) crystal. Peaks of the response functions are sketched. The response functions were determined by observing the indium x rays from a pure ^{115m}In source and 34-keV lanthanum x rays from a ^{139}Ce source.

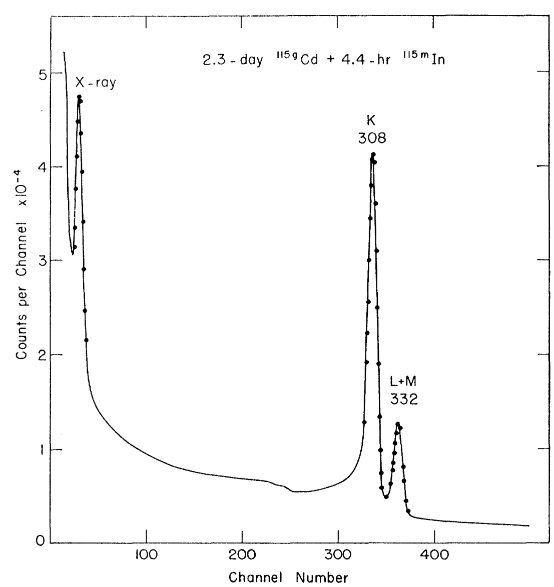

FIG. 4. Electron spectrum of 2.3-day ^{115g}Cd with a 4.4-h ^{115m}In in equilibrium observed with the 50 mm^2 area, 0.5-mm thick Si(Li) detector. Conversion lines are associated with the 336-keV ^{115m}In isomeric transition.

[17] D. D. Bornemeier, L. D. Ellsworth, C. E. Mandeville, and V. R. Potnis, Phys. Rev. **134**, B740 (1964).
[18] P. N. Tandon and H. G. Devare, Phys. Letters **10**, 113 (1963).
[19] G. A. Graves, L. M. Langer, and R. D. Moffat, Phys. Rev. **88**, 344 (1952); L. M. Langer, R. D. Moffat, and G. A. Graves, *ibid.* **86**, 632 (1952).
[20] P. R. Bell, B. H. Ketelle, and J. M. Cassidy, Phys. Rev. **76**, 574 (1949).

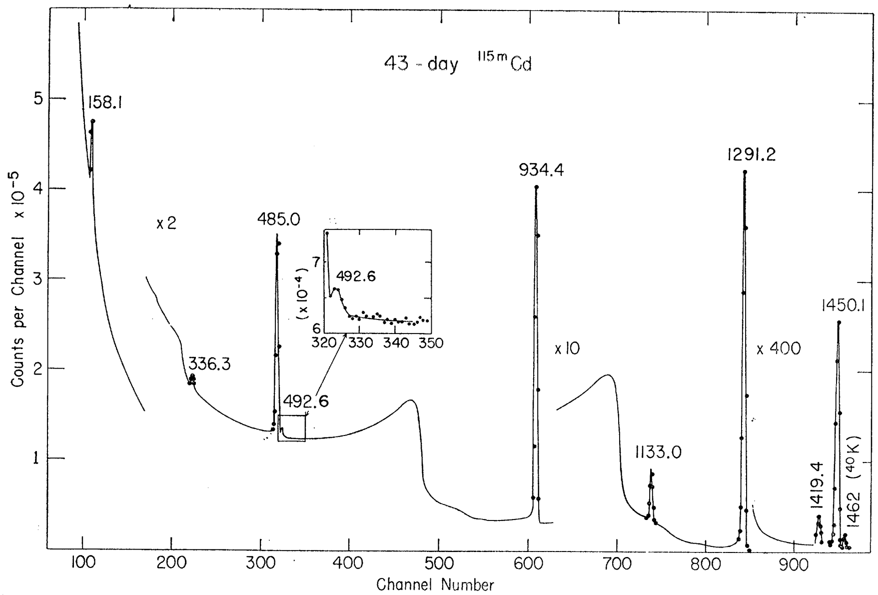

FIG. 5. Spectrum of γ rays from 43-day ^{115m}Cd observed with the Ge(Li) detector. Source obtained from Oak Ridge[9] and further chemically purified. The region around the 493-keV line is expanded in the inset for clarity. Numbers above the peaks represent the energies of the corresponding γ rays in keV. The small amount of ^{40}K observed is associated with the surroundings.

B. ^{115m}Cd Decay

A γ-ray spectrum taken with an old source (i.e., one from which 2.3-day ^{115}Cd had completely decayed) is shown in Fig. 5. The region up to 150 keV is not shown because of the very high activity of the 88-keV line of ^{109}Cd also present in the source. In addition to the γ rays previously known for ^{115m}Cd decay, γ rays at 336, 493, and 1450 keV are clearly observable. The former two are well known in the decay of ^{115g}Cd, but had not previously been seen in the spectrum of ^{115m}Cd. This result agrees with our finding of 336-keV ^{115m}In γ rays in the indium fraction milked from old ^{115m}Cd samples as mentioned above.

In Fig. 6 are shown three γ-ray spectra observed with the Ge(Li) detector in coincidence with three different energy regions of the γ-ray spectrum taken with a NaI(Tl) detector. The three coincidence spectra were taken simultaneously with the 4096-channel analyzer and digital-gate unit. These and other data show that the 485-keV γ ray is coincident with the 934 keV and that the 158-keV γ ray is coincident with that of 1133 keV. The 106-keV γ ray that clearly stands out in the spectrum coincident with the 490-keV region has not previously been observed in the ^{115m}Cd decay. As discussed below, the 106-keV line is coincident with both the 485- and 493-keV γ rays and the spectrum of Fig. 6(c) includes both contributions.

In Table III are listed the energies and intensities of the γ rays we have observed in the decay of ^{115m}Cd and upper limits for some lines previously reported but not apparent in our spectra. The intensity of the 106-keV γ ray was obtained by comparison of its photopeak with that of the 934-keV in the spectrum coincident with the 490-keV region [see Fig. 6(c)]. The other intensities were obtained from the Ge(Li) singles γ-ray spectrum.

Van der Kooi *et al.*, have reported γ rays at 130, 206, and 292 keV.[7] Two of these, the 130- and 292-keV, would fit nicely into the decay scheme, but we saw no evidence for them and have set upper limits on their intensities that are somewhat below the intensities reported by Van der Kooi and co-workers (see Table III). In Fig. 6(a) we see a broad peak at ~206 keV (about channel 90) that results from backscattering.

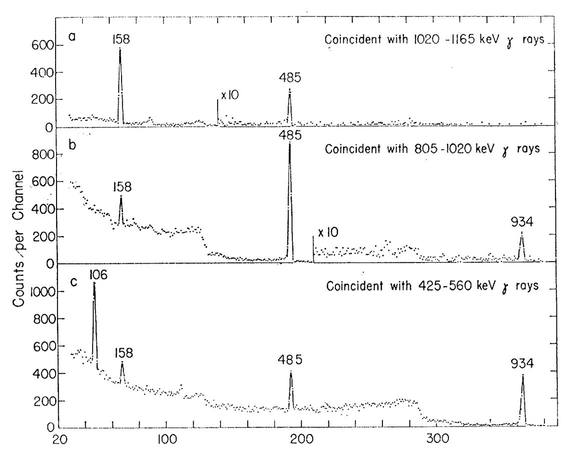

FIG. 6. Gamma-ray spectra of ^{115m}Cd observed with Ge(Li) in coincidence with three different regions of the spectrum observed with NaI(Tl). Numbers above the peaks are energies of the corresponding γ rays. Unlabeled small apparent peaks (e.g., that at channel 90 in (a)) are thought to arise from scattering events (a) Coincidences with 1020- to 1165-keV region. The peak at 485 keV arises from random events. (b) Coincidences with 805- to 1020-keV region. The peak at 158 keV arises from random events plus true coincidences with Compton events from the 1133-keV γ ray in the gate. (c) Coincidences with 425- to 560-keV region. The peak at 158 keV arises from random events plus true coincidences with Compton events from the 1133-keV γ ray in the gate. The 485-keV peak includes true coincidences with 493 keV and with Compton events of the 934-keV γ ray in the gate.

TABLE III. Gamma rays observed in the decay of 43-day ^{115m}Cd.

This work		Van der Kooi *et al.*[a]
Energy (keV)	Relative intensity	Relative intensity
105.6±0.8	0.45±0.15	...
(130 ±5)	<0.03	0.07±0.04
158.1±0.04	0.9 ±0.2	1.3 ±0.4
(292 ±5)	<0.1	0.20±0.10
336.3±0.4	0.25±0.10[b]	...
485.0±0.6	13.6 ±1.0	16 ±1.5
492.6±0.3	0.45±0.10	...
934.4±0.6	(100)	(100)
1133.0±0.6	4.2 ±0.3	5.2 ±1.0
1291.2±0.6	46 ±2	45 ±2
1419.4±1.0	0.11±0.02	2.0 ±1.5
1450.1±1.0	0.85±0.10	...

[a] Reference 7.
[b] Intensity of 4.4-h ^{115m}In I.T. γ ray measured in transient equilibrium.

We assume that the 206-keV peak seen by Van der Kooi *et al.*,[7] has a similar origin as those authors have suggested. Peaks reported by Sharma and Devare[21] at 650 and 850 keV are associated with ^{110m}Ag decay. These workers observed a peak at 310 keV in coincidence with ~1130-keV γ rays. This peak probably corresponds to that at 292 keV as observed by Van der Kooi *et al.*,[7] under similar conditions. In Fig. 6(a) a broad peak occurs at 310 keV (about channel 125). We believe that the peak arises from 485–934 coincidences by scattering in the following way: 934- and 485-keV γ rays both interact with the NaI(Tl) crystal, the former being absorbed completely and the latter undergoing backscattering, with the backscattered photon being absorbed in the Ge(Li) detector. Events of this type would simultaneously deposit about 300 keV in the Ge(Li) detector and 1120 keV in the NaI(Tl) crystal, thus explaining the event. The dependence of the energies upon the scattering angles permitted would also explain why 292 keV was observed in one experiment[7] and 310 keV in another.[21]

IV. ANALYSIS OF THE RESULTS

A. Decay Schemes

The proposed decay schemes for the ^{115}Cd isomers are shown in Fig. 7. To illustrate clearly the genetic origin of the various levels, the β and γ transitions resulting from decay of ^{115g}Cd are grouped together on the left and those from ^{115m}Cd on the right. The conventions adopted in Fig. 7 are those used in the Nuclear Data Sheets.[2]

Energies of the β groups were obtained by differences from Q_β of ^{115}Cd and the energies of the ^{115}In levels. The value of Q_β for ^{115}Cd was determined from accurately measured masses[22] of ^{114}Cd and ^{115}In and the Q value of the ^{114}Cd$(d,p)^{115}$Cd reaction.[23] The energy difference ^{115m}Cd-^{115g}Cd was also obtained from the (d,p) reaction data.[23] The energies of the β transitions agree well with the best values obtained by direct β-ray measurements.[2]

2.3-Day ^{115g}Cd

Cadmium-115*g* decays by β- and γ-ray transitions to 4.4-h ^{115m}In which subsequently decays 96.3% by a 336-keV isomeric transition to the ground state and 3.7% by β decay to ^{115}Sn. No production of ^{115g}In in the decay of ^{115g}Cd except via ^{115m}In has been observed in this or previous studies. The percentages of the various β groups and the log*ft* values are based on the measurements of γ-ray intensities, conversion coefficients, and the β branching of ^{115m}In of this study. In particular, the intensity of the 1.01-MeV β group from ^{115g}Cd directly to ^{115m}In is based on the intensity of the 366-keV ^{115m}In γ ray (I.T.) relative to that of the other γ rays in the spectrum obtained from a source containing ^{115m}In in transient equilibrium with ^{115g}Cd. Internal conversion of the transitions other than the 35- and 336-keV ones were neglected in the calculations for β-ray abundances. It was not possible to establish from our work any meaningful limits for the conversion coefficients of the transitions in the 250-keV region because of their low intensities. However, the conversion of the 493- and 528-keV γ rays may be safely assumed to be negligible.

Tang *et al.* found in the decay of ^{117}Cd that levels in ^{117}In at 659 and 748 keV have half-lives of 59.7 and 4.55 nsec, respectively.[1,6] One might expect to find similar half-lives for corresponding levels in ^{115}In, the most likely candidates being the 829- and 864-keV levels. Tandon and Devare found a half-life of 5.5 nsec for the 829-keV level by β-γ coincidence and time-to-amplitude conversion.[18] From careful examination of the time spectrum obtained by them with ~520-keV γ rays in the gate, we note the possibility of a short-lived component of half-life ≤1 nsec for the 864-keV level, but perhaps measurable under better conditions. By study of delayed β-γ coincidences, with Si(Li) and Ge(Li) detectors, we have been unable to find any ^{115}In levels of half-life >5.5 nsec other than 4.4-h ^{115m}In.

43-Day ^{115m}Cd

The levels at 934, 1133, 1291, and 1419 keV are well-known from many previous works involving both decay and nuclear excitation studies. From the discrepancy in the intensity ratios of the 485- to 1420-keV γ rays observed in inelastic-neutron scattering and in β-decay studies, Lind and Day suggested that the 1420-keV level might be a doublet.[24] We have resolved the doublet by observing low-intensity γ rays of 1419 and 1450 keV, whose relative intensities remained constant throughout chemical purification and decay of several months. The 1450-keV line, which has not previously

[21] R. P. Sharma and H. G. Devare, Phys. Rev. **131**, 384 (1963).
[22] R. A. Damerow, R. R. Ries, and W. H. Johnson, Jr., Phys. Rev. **132**, 1673 (1963).
[23] R. J. Silva and G. E. Gordon, Phys. Rev. **136**, B618 (1964).
[24] D. A. Lind and R. B. Day, Ann. Phys. **12**, 485 (1961).

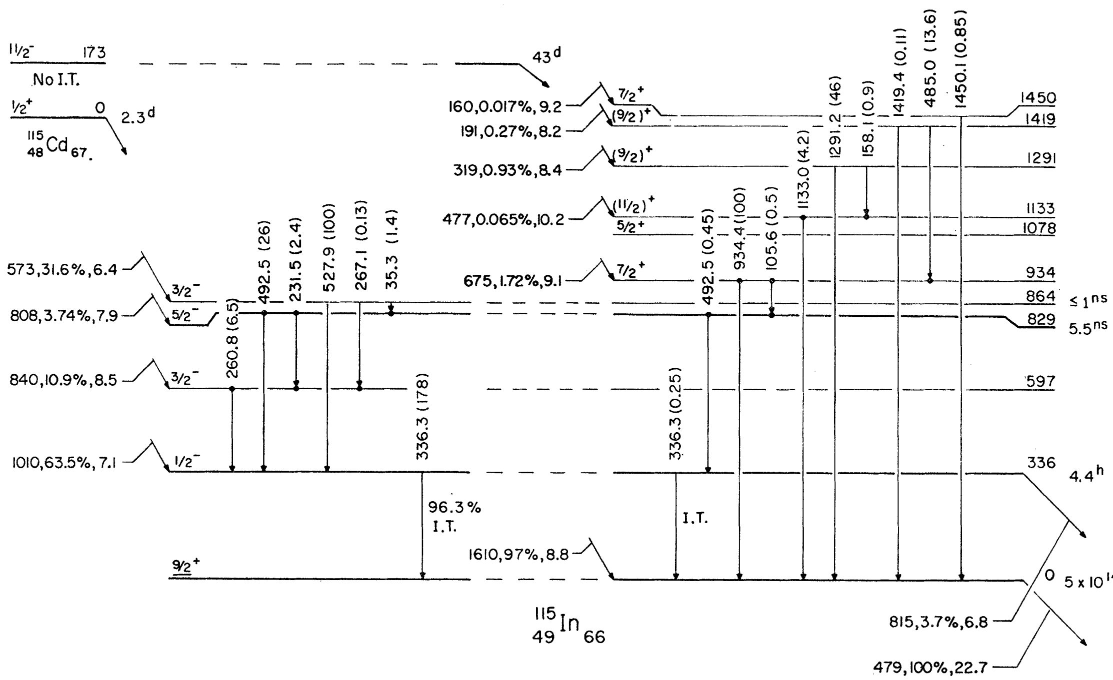

FIG. 7. Decay scheme of the ^{115}Cd isomers. Conventions used are those of the Nuclear Data Sheets[2] except that all energies are given in keV.

been observed, is not coincident with other γ rays and thus a level is established at that energy. The existence of this level is supported by electron-excitation studies on ^{115}In by Chertok and Booth, who found a level at 1460±20 keV.[25]

The 1078-keV level is not observed in decay of the ^{115}Cd isomers but is based entirely on evidence from nuclear excitation studies such as inelastic proton scattering,[26] and electron,[25] x-ray,[25] and Coulomb excitations.[27] The energy of the level is adopted from the (p,p') work on ^{115}In by Sharp and Buechner.[26]

The 106-keV γ ray is coincident with γ rays of about 490 keV. Within limits of error, the energy of this line is equal to the difference in energies of the levels at 934 and 829 keV; therefore, the transition is placed between those levels. This transition explains the production of ^{115m}In in the decay of ^{115m}Cd as evidenced by the presence of 336- and 493-keV peaks in the singles γ-ray spectrum. Further support for the proposed path from ^{115m}Cd to ^{115m}In is given by the work of Chertok and Booth, who have found that some ^{115m}In is formed following excitation of the 935-, 1078-, and 1460±20-keV levels.[25] If the last is the same as seen by us at 1450 keV, we should see additional transitions from that level to one or more of those on the left of Fig. 7; however, the 1450-keV level is so weakly populated in the decay of ^{115m}Cd that we would not observe these weak branchings.

The relative intensity of the 106-keV γ ray was obtained from coincidence experiments, as in Fig. 6(c). Note that the coincidence events arise from gate pulses produced by both the 485- and 493-keV γ rays, with the latter being substantially the larger contributor. Within limits of error the intensities of the 106- and 336- (after correction for conversion), and 493-keV transitions are equal for ^{115m}Cd sources with ^{115m}In in equilibrium. This suggests that the indicated path is the major source of ^{115m}In from ^{115m}Cd although we cannot rule out other weak paths. Note that, as we observe the 493-keV γ ray, the lines at 232 and 261 keV should also occur in ^{115m}Cd decay; however, their expected intensities (0.04) are too small to be observed because of Compton interference. From the ratio of intensities 336/934 for transient-equilibrium sources, we calculate a branching of ^{115m}Cd decay to ^{115m}In of 0.009% in good agreement with the very early measurement of 0.007% by Engelkemeier.[28]

B. Assignments of Spins and Parities

The spins and parities of ^{115g}Cd and the isomeric level at 173 keV, ^{115m}Cd, are $\frac{1}{2}+$ and $11/2-$, respectively.[23,29] The spin of ^{115}In has been measured[30] as $\frac{9}{2}$

[25] B. T. Chertok and E. C. Booth, Nucl. Phys. **66**, 230 (1965); also, E. C. Booth (private communication).

[26] R. D. Sharp and W. W. Buechner, Phys. Rev. **112**, 897 (1958).

[27] D. G. Alkhazov, K. I. Erokhina, and I. Kh. Lemberg, Izv. Akad. Nauk SSSR, Ser. Fiz. **28**, 1667 (1964); V. D. Vasilev, K. I. Erokhina, and I. Kh. Lemberg, *ibid.* **26**, 992 (1962); D. C. Andreev, V. D. Vasilev, G. M. Gusinsky, K. I. Erokhina, and I. Kh. Lemberg, *ibid.* **25**, 832 (1961).

[28] D. W. Engelkemeier, Argonne National Laboratory Report, ANL-4525, 1950 (unpublished).

[29] M. N. McDermott, R. Novick, W. Perry, and E. B. Saloman, Phys. Rev. **134**, B25 (1964).

[30] J. E. Mack, Rev. Mod. Phys. **22**, 64 (1958).

and the logft for the β group to it from ^{115m}Cd suggests even parity. From the shell model, $g_{9/2}$ is expected. The isomeric state at 336-keV decays to the ground state by a transition that is mostly $M4$ according to α_K and $\alpha_K/(\alpha_L+\alpha_M)$ measurements. Theoretical values of α_K from Sliv and Band are 0.88 and 0.69 for $M4$ and $E5$, respectively,[31] and our experimental value is 0.91 ± 0.06. The logft of the β transition from ^{115m}In is typical of first-forbidden transitions. Thus, the assignment of $\frac{1}{2}-$ to ^{115m}In is established, as expected from the shell model.

The logft value for β decay to the 597-keV level is 8.5. This suggests negative parity for this state and $\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ as possible spin assignments. Angular-correlation experiments have indicated the assignments $\frac{3}{2}-$ and $\frac{5}{2}-$ for the state.[8,16] We believe the former is less subject to error in interpretation (a β-γ correlation, $^{115g}\text{Cd}-\beta\rightarrow 597-\gamma_{261}\rightarrow {}^{115m}\text{In}$), and assign the level as $\frac{3}{2}-$. This assignment is supported by the existence of a $\frac{3}{2}-$ second excited state in ^{113}In at 648 keV.[2,32] This level has also been observed in neutron inelastic scattering.

The β feeding from ^{115g}Cd to the 829-keV level is 3.7% and the logft value is 7.9 which suggests a first-forbidden transition. However, we cannot rule out an allowed transition in the region as large amounts of phonon mixing can apparently seriously hinder allowed β decay.[33] Therefore, the possible assignments are $\frac{1}{2}\pm$, $\frac{3}{2}\pm$, and $\frac{5}{2}-$. Because of the observation of the 106-keV transition from the 934- to the 829-keV level, we can limit the assignments to $\frac{3}{2}+$ or $\frac{5}{2}-$. The 934-keV level must have spin $\frac{7}{2}$ or greater and positive parity as a result of the β feeding to it from ^{115m}Cd. This spin cannot be higher than $\frac{7}{2}$ because of the 106-keV transition to a level of spin $\leq\frac{5}{2}$. The 934-keV level has been formed by Coulomb excitation of the $\frac{9}{2}+$ ground state[27]; therefore, the 934-keV transition has some $E2$ character.

From the above considerations we see that the assignment of the 934-keV level is $\frac{7}{2}+$, that of the 829-keV, $\frac{3}{2}+$ or $\frac{5}{2}-$, and the multipolarity of the 106-keV transition, $E1$ or $E2$. To determine which of these is correct, we compared the observed 106/934 intensity ratios with ratios based on calculated single-proton rates[34] and the measured[27] $E2$ partial half-life (4×10^{-12} sec) of the 934-keV transition. The 106-keV transition cannot be $E2$: the observed intensity ratio 106/934 is a factor of $\sim$200 greater than the calculated single-proton $106(E2)/934(E2)$ ratio and the 934-keV $E2$ rate is known to be about the same order as the calculated rate. Any $M1$ mixing in the 934-keV transition would require the 106-keV transition, if $E2$, to be enhanced even more. By similar arguments, the 106-keV transition, if $E1$, is hindered by a factor of between 2×10^4 and 4×10^6, depending on the amount of $M1$ mixing in the 934-keV transition. Hindrance factors in this range are found to be quite common for $E1$ transitions.[35] Therefore, we conclude that the 106-keV transition is $E1$ and the assignment of the 829-keV level is $\frac{5}{2}-$.

The assignment $\frac{3}{2}-$ for the 864-keV level is most likely. The measured α_K value for the 35-keV transition is 9.6 ± 1.2 and the theoretical values extrapolated from Sliv and Band[31] are 2.0, 7.1, 18, and 130 for $E1$, $M1$, $E2$, and $M2$, respectively. Thus, the transition is apparently $M1$ with some mixing of $E2$ and the assignment of the level is $\frac{3}{2}-$ or $\frac{5}{2}-$. The logft value for the transition from ^{115g}Cd is very low for a unique first-forbidden transition, but reasonable for nonunique first-forbidden.[36] Therefore, the assignment $\frac{3}{2}-$ is the most likely, although $\frac{5}{2}-$ is not completely ruled out.

All of the excited states above 864 keV in Fig. 7 except the one at 1078 keV are weakly populated by β decay of ^{115m}Cd. The logft values for those transitions correspond to unique or nonunique first forbidden. Therefore, these levels have positive parities and spins in the range $\frac{7}{2}$ to 15/2. Above we have established the assignment of the 934-keV level as $\frac{7}{2}+$, in agreement with many previous works. The 1078-keV level is undoubtedly $\frac{5}{2}+$ as it is not populated in the decay of the ^{115}Cd isomers, yet some ^{115m}In is formed as a result of excitation of the level by electrons or bremsstrahlung.[25] It is also observed[27] in Coulomb excitation of ^{115}In. The levels at 934, 1133, and 1291 keV appear to be quite similar in that they are all weakly populated in β decay of ^{115m}Cd, they de-excite strongly by transitions to the ground state, and they are formed in Coulomb excitation.[27] From γ-γ angular correlations, the assignments $11/2+$ and $\frac{9}{2}+$ have been made for the levels at 1133 and 1291 keV, respectively.[37] Although these assignments are consistent with all of the information known on these levels, we do not feel that the angular correlations are definitive as they involve small differences between large spin values.

The level at 1419 keV has previously been assigned[7,15,37] spin and parity $\frac{9}{2}+$. If this assignment is correct, the large ratio of intensity of the 485-keV transition to the $\frac{7}{2}+$ level at 934 keV to that of the 1419-keV γ ray to the ground state is difficult to explain. Also, the level is not formed in Coulomb excitation.[27]

The 1450-keV level probably has spin and parity $\frac{7}{2}+$. Chertok and Booth[25] find that ^{115m}In is produced following electron or bremsstrahlung excitation of a level at 1460 ± 20 keV which we take as the same level.

---

[31] L. A. Sliv and I. M. Band, in *Alpha- Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), Vol. 2, Appendix 5.

[32] H. A. Grench, in *Nuclear Spin-Parity Assignments*, edited by N. B. Gove and R. L. Robinson (Academic Press Inc., New York, 1966), p. 297.

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

[34] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, Inc., New York, 1952), p. 627.

[35] C. F. Perdrisat, Rev. Mod. Phys. **38**, 41 (1966).

[36] C. E. Gleit, C.-W. Tang, and C. D. Coryell, Ref. 2, pages 5-5-109 to 5-5-148, 1963.

[37] V. R. Pandharipande, R. P. Sharma, and G. Chandra, Phys. Rev. **136**, B346 (1964).

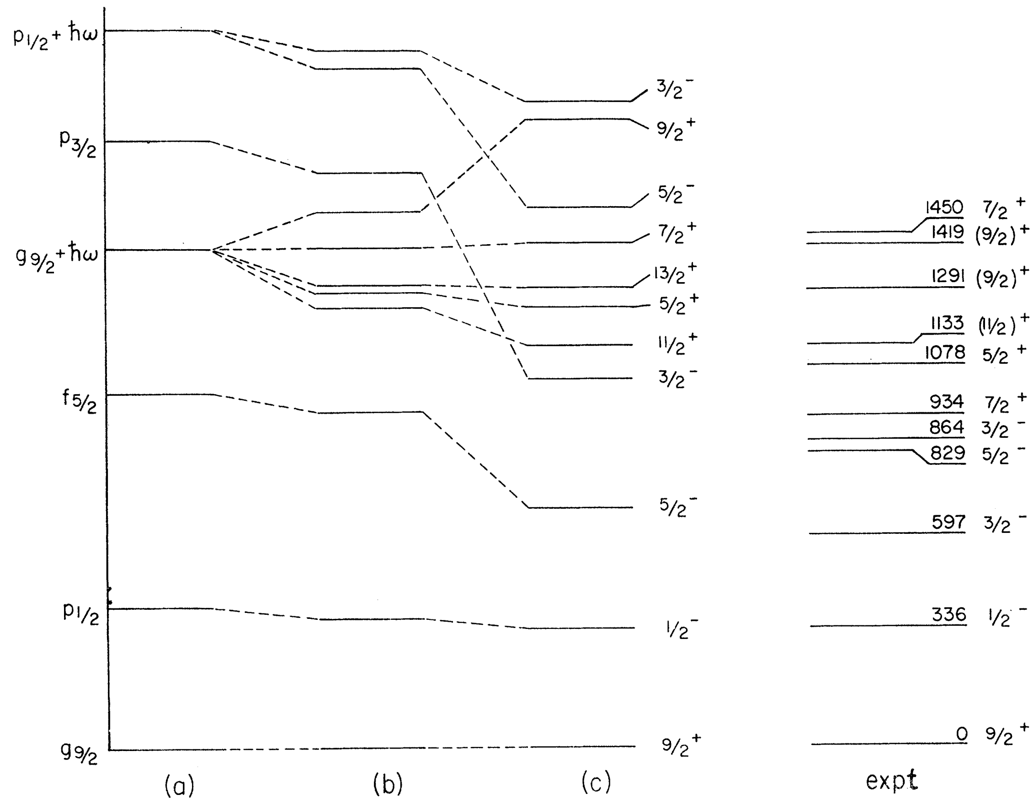

FIG. 8. Comparison of ^{115}In levels predicted by Silverberg[38] (a, b, and c) with those observed in this work (expt). See text for explanation of the predicted levels.

The most likely path for formation of ^{115m}In is via a 621-keV transition to the 829-keV level. We have not observed such a γ ray as the 1450-keV level is very weakly populated and the 621-keV region is covered by Compton events from the 934-keV γ ray in singles and coincidence spectra in which one might hope to observe the 621-keV line.

V. CONCLUSIONS

There are no detailed theoretical calculations available in the literature with which the properties of the ^{115}In levels can be compared. Silverberg[38] has estimated the positions of the ^{115}In levels by methods similar to those of Kisslinger and Sorensen.[39] The single-proton hole levels $g_{9/2}$, $p_{1/2}$, $f_{5/2}$, and $p_{3/2}$ were considered as well as the levels constructed by coupling a 2+ vibrational phonon ($\hbar\omega$) of the core to the lowest two single-hole states as shown in column (a) of Fig. 8. Column (b) shows the levels as calculated by a first-order perturbation treatment of the interaction between the phonon and single holes under conditions for which the perturbation treatment should be valid. The levels of column (c) represent Silverberg's extrapolation from column (b).[38] In the fourth column, labeled "expt," are shown the levels of ^{115}In from Fig. 7.

Although there is some correlation between the predicted and experimental level positions, closer examination shows that treatments involving the coupling of core-vibrational phonons to the single-hole states cannot be even a good first approximation. For example, it is tempting to describe at least the lowest four of the levels above 900 keV as members of a quintuplet formed by coupling a phonon with the $\frac{9}{2}+$ proton hole. However, the $E2$ rates for transitions to the ground state are much slower than expected from a simple phonon-coupling picture. According to that description, the $B(E2)$ values for transitions from members of multiplet to the particle state are about equal to those for the phonon transition in neighboring even-even nuclei.[40] But from Coulomb excitation of the levels between 934 and 1291 keV,[27] one finds that the value of the ratio $B(E2)/B(E2)_{sp}$, where $B(E2)_{sp}$ is calculated for single-proton transitions, ranges from 0.6 to 5.8. The corresponding ratio for transitions from the first excited states to ground states in ^{114}Cd and ^{116}Sn are about 35 and 12, respectively.[41] Similarly, among the low-spin

[38] L. Silverberg, Arkiv Fysik **20**, 341 (1961).
[39] L. S. Kisslinger and R. A. Sorensen, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **32**, No. 9 (1960).
[40] A. de-Shalit, Phys. Rev. **122**, 1530 (1961).
[41] P. H. Stelson and F. K. McGowan, Phys. Rev. **110**, 489 (1958).

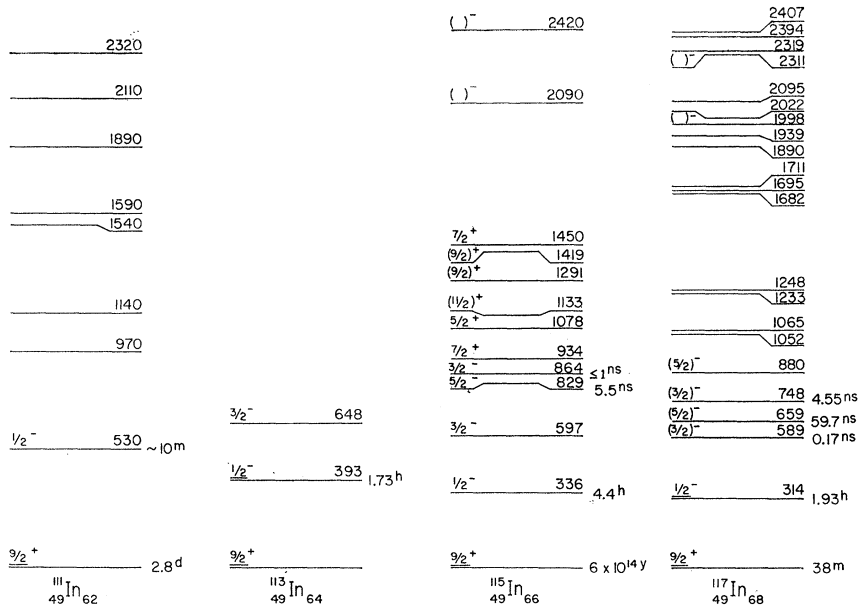

FIG. 9. Summary of observed low-lying levels of odd-A indium isotopes. Based on Refs. 1, 2, J. W. Snyder and M. I. Pool, Phys. Rev. **138**, B770 (1965); R. K. Jolly, E. K. Lin, and B. L. Cohen, *ibid.* **128**, 2292 (1962); and this work.

levels, we know that the 829-keV ($\frac{5}{2}-$) to 336-keV ($\frac{1}{2}-$) transition is much too slow for a phonon-mixed transition as the ratio $B(E2)/B(E2)_{sp}$ is approximately 0.1 based on the 5.5-nsec half-life of the 829-keV level.[18] The $E2$ part of the 864-keV($\frac{3}{2}-$) to 336-keV($\frac{1}{2}-$) transition is probably also slow as evidenced by the large competition from the 35-keV transition to the 829-keV level. As noted in the Introduction, $_{45}{}^{103}$Rh, $_{47}{}^{107}$Ag, and $_{47}{}^{109}$Ag have $\frac{1}{2}-$ ground states and $\frac{3}{2}-$ and $\frac{5}{2}-$ excited states at about 300 and 400 keV, respectively. By contrast with the slow $E2$ transitions in ^{115}In, the values of $B(E2)/B(E2)_{sp}$ for transitions from the $\frac{3}{2}-$ and $\frac{5}{2}-$ states to the $\frac{1}{2}-$ ground states of ^{103}Rh, ^{107}Ag, and ^{109}Ag range[3] from 35 to 45. Collective effects, vibrational or rotational, are definitely indicated by these fast $E2$ rates in the structures involving 45 or 47 protons. The picture, thus, changes dramatically between ^{109}Ag and ^{115}In upon addition of the 2 protons and 4 neutrons.

It should be noted that slow $E2$ rates are predicted for some transitions from the superconductor model and the agreement with experimental observations is rather good.[42] However, these occur when the transition involves the jump of a quasiparticle between two single-particle levels approximately equidistant from the "Fermi energy" λ, with one level above and the other below λ. This situation cannot arise in the 49-proton case of ^{115}In, as λ is above all of the single-proton levels in the 28-to-50 shell region.[39]

Thus, it would appear that no theoretical treatment involving vibrational coupling can describe the levels of ^{115}In. For a better theoretical approach it would probably be necessary to construct the states of $_{50}{}^{116}$Sn by a rather detailed treatment of the interactions among the neutrons, such as that by Arvieu *et al.*,[43] and to couple the resulting states, especially the lowest 2+, with the proton hole in ^{115}In.

There are some interesting trends among the odd-A indium levels as shown in Fig. 9 that should be investigated further. One of the most striking features is the presence of excited states of measurable half-lives above 600 keV: the 59.7- and 4.5-nsec levels[6,8] at 659 and 748 keV, respectively, in ^{117}In and the 5.5-nsec at 829 keV in ^{115}In.[18] The positions of the lowest $\frac{1}{2}-$ and $\frac{3}{2}-$ levels seem to vary smoothly across the series. Recently, Demin and Kushakevich reported the production of a 210-msec very-high-spin ($\geq 21/2$) level at 2.73 MeV in ^{109}In by the ^{107}Ag$(\alpha,2n)$ reaction.[44] Isomers of this type might well exist in other members of the series and should be investigated.

[42] R. A. Sorensen, Phys. Rev. **133**, B281 (1964).

[43] R. Arvieu, E. Baranger, M. Veneroni, M. Baranger, and V. Gillet, Phys. Letters **4**, 119 (1963).

[44] A. G. Demin and Yu. P. Kushakevich, Soviet J. Nucl. Phys. **1**, 138 (1965).