last pair of protons in Mo^{91} (which is probably a $g_{9/2}$ pair) would continue the trend of making the $g_{9/2}$ neutron state more stable.

Table I also shows the agreement between the relative lifetimes of isomeric transitions. The experimentally observed lifetimes, corrected for branching ratio and statistical weight, are compared with the theoretical lifetimes given by Blatt and Weisskopf.[16] The significant part of the comparison is that the ratio of experimental to theoretical value is almost the same for all four examples. If the ground state of Mo^{91} were assumed to have a spin of $\frac{1}{2}$, the Mo^{91m} lifetime would disagree essentially by the statistical weight factor of 5. The absolute agreement between experimental and theoretical values is probably fortuitous. The theory is only an approximate one which is, as yet, only useful for determining dependences of the lifetime on the energy and on the nuclear size. For example, an alternative theoretical formula given by Moszkowski[17] predicts a lifetime which is shorter by a constant factor of 10.7.

We wish to thank Mr. T. Keegan, engineer of the 22-Mev betatron, and his operating crews for their efficient assistance in making the irradiations. We are also indebted to R. B. Duffield for making available to us the unpublished data he had on the gamma rays in molybdenum.

[16] Reference 14, p. 627.

[17] S. A. Moszkowski, Phys. Rev. **83**, 1071 (1951) and private communication.

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Level Scheme of In^{115}†

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The disintegration of the 2.3-day Cd^{115} and its isomer, the 43-day Cd^{115}, have been studied with thallium-activated sodium iodide counters, anthracene counters, and coincidence methods. The levels of In^{115} have been shown to have excitation energies of 0.335 ($T_{\frac{1}{2}}=4.5$ hr), 0.595, 0.825, 0.858, 0.935, 1.30, and 1.42 Mev, the first four levels being excited in the decay of the 2.3-day period alone and the latter three in decay of the 43-day activity only. The gamma transitions from the 1.3-Mev level proceed directly to the ground state of In^{115} while all the transitions from the 1.42-Mev level terminate at the 0.935-Mev level. The gamma transitions from the 0.595, 0.825, and 0.858-Mev levels lead to the metastable state at 0.335 Mev. About three percent of the transitions from the 0.858-Mev level terminate at the 0.825-Mev level which in turn de-excites by way of a 0.230 Mev–0.260 Mev gamma-ray cascade or by emission of a 0.490-Mev quantum in the crossover transition. The angular correlation function for the 0.485 Mev–0.935 Mev cascade in the decay of the 43-day Cd^{115} is found to be essentially isotropic. A level scheme for In^{115} has been established by these measurements.

INTRODUCTION

THE radiations of the 43-day activity have been previously studied by several groups of investigators.[1–4] It has been suggested[4] that In^{115*} de-excite with the emission of a 0.950-Mev gamma ray or by the emission of a 0.45 Mev–0.50 Mev cascade. Other measurements[3] showed that the 43-day activity emits a complex beta spectrum such that de-excitation of In^{115*} occurs with the emission of a 0.94-Mev gamma ray or a 1.30-Mev gamma ray or a 0.48 Mev–0.94 Mev cascade.

The 2.3-day activity has also been investigated[5–7] and shown to emit a complex beta spectrum and gamma rays at 0.335 Mev and 0.52 Mev. Hayward[4] has reported gamma rays of quantum energies 0.335, 0.360, 0.500, and 0.525 Mev, the 0.360- and 0.500-gamma rays being in cascade. He has also suggested that a 0.500-Mev level in In^{115} is excited in the decay of both activities.

Since the above quoted results are not in good agreement, it was decided to investigate further the radiation characteristics of the cadmium activities. NaI(Tl) and anthracene spectrometers were employed in coincidence as was a thin-lens magnetic spectrometer.

To obtain sources of the 2.3-day activity, elemental metallic cadmium was irradiated by slow neutrons for 72 hours in the Brookhaven pile. Chemical separations were performed for removal of Sb, Sn, and other impurities. It was noted that the relative intensities of the several gamma rays present remained unchanged by the purifications. The source of 43-day cadmium was first processed at Oak Ridge National Laboratory and later additionally purified at Bartol for removal of Sb^{124}.

In the course of studying the 2.3-day activity, the

† Assisted by the Joint Program of the Office of Naval Research and the U. S. Atomic Energy Commission.

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[1] Gill, Mandeville, and Shapiro, Phys. Rev. **80**, 284 (1950).
[2] A. C. Wahl and N. A. Bonner, Phys. Rev. **85**, 570 (1952).
[3] D. W. Engelkemeier, Argonne National Laboratory Report ANL-4717, April, 1952 (unpublished).
[4] R. W. Hayward, Phys. Rev. **87**, 202 (1952).
[5] Mandeville, Scherb, and Keighton, Phys. Rev. **75**, 221 (1949).
[6] R. W. Hayward and A. C. Helmholz, Phys. Rev. **75**, 1469 (1949).
[7] E. B. Dale and J. D. Kurbatov, Phys. Rev. **80**, 126 (1950).

4.5-hour isomer of In^{115} was frequently separated from the parent Cd^{115} by a hydroxide precipitation using gallium as carrier.

43-DAY Cd^{115}

In Fig. 1 is shown the pulse-height spectrum generated in a 3.5-cm thick crystal of NaI(Tl) by the gamma radiation from a source of the 43-day Cd^{115}. The quantum energies are clearly 0.485, 0.935, and 1.30 Mev. The photopeak at 87 kev is associated with the gamma radiation of the 400-day Cd^{109}. The slight contribution at 1.42 Mev was noticeable only when the source was near the crystal showing it to arise from the simultaneous detection of coincident gamma rays. The sharp rise in counting rate below 0.450 Mev is caused by bremsstrahlung produced by the intense high-energy beta rays which lead to the ground state of In^{115}. From the areas under the photopeaks of the various gamma rays and the measured efficiency for full energy absorption of NaI(Tl), the relative intensities of the 0.485, 0.935, and 1.30-Mev radiations were estimated to be 1.0:7.4:3.1.

The various sequential relationships between the gamma rays were determined by coincidence studies. A source of Cd^{115m} was placed between the NaI(Tl) crystals of two scintillation spectrometers in coincidence. The channel of one spectrometer was fixed at the photopeak of the 0.935-Mev gamma ray; the channel of the other was moved through the region of lower energies. Figure 2 shows the coincidence and single counting rates for each position of the moving channel. It is evident that the 0.935-Mev quanta are coincident with the 0.485-Mev gamma ray. The coincidence peak has the full width at half-maximum to be expected for a monoenergic gamma ray of energy 0.485 Mev. If the contribution due to bremsstrahlung and higher-energy radiations is subtracted (as shown by the broken curve) from the single counting rate in the region of 0.485 Mev, the singles peak at 0.485 Mev is found to have identically the same shape and half-width as does the peak of coincidences, showing that the peak at 0.485 Mev arises from a single gamma ray and is not composed of contributions from two gamma rays at 0.450 and 0.500 Mev as previously reported.[4]

The absence of the two coincident gamma rays at 0.450 and 0.500 Mev was further established by the coincidence data of Fig. 3. To obtain these curves, the channel of one spectrometer was fixed at ~0.500 Mev (the exact position is indicated on the figure), and the channel of the second scintillation spectrometer was used to scan the region about 0.485 Mev. The coincidence rate as well as the single counting rate was recorded for each position of the second channel as shown. Were the two gamma rays present as previously reported, the peak in the coincidence rate would have been at 0.450 Mev or at least shifted toward 0.450 Mev and away from the peak of single counts. As is clear from the figure, the coincidence curve follows closely in shape the curve of single counts showing the absence of the two gamma rays reported.[4] The same conclusion was drawn from a similar set of curves obtained when the channel of the one spectrometer was fixed at 0.450 Mev. It should, perhaps, be mentioned that part of the coincidences of these measurements arise from detection of the Compton recoils of the 0.935-Mev gamma ray in the moving channel and the photopeak of the 0.485-Mev gamma ray in the fixed channel, so that a slowly changing "background" of coincidences results. The

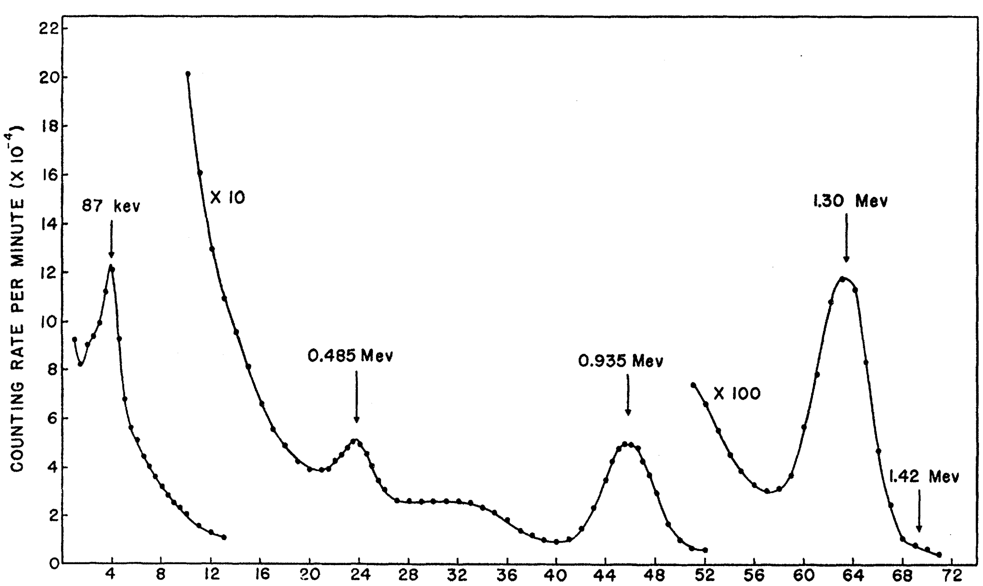

FIG. 1. Pulse-height distribution from gamma rays of the 43-day Cd^{115} on NaI(Tl).

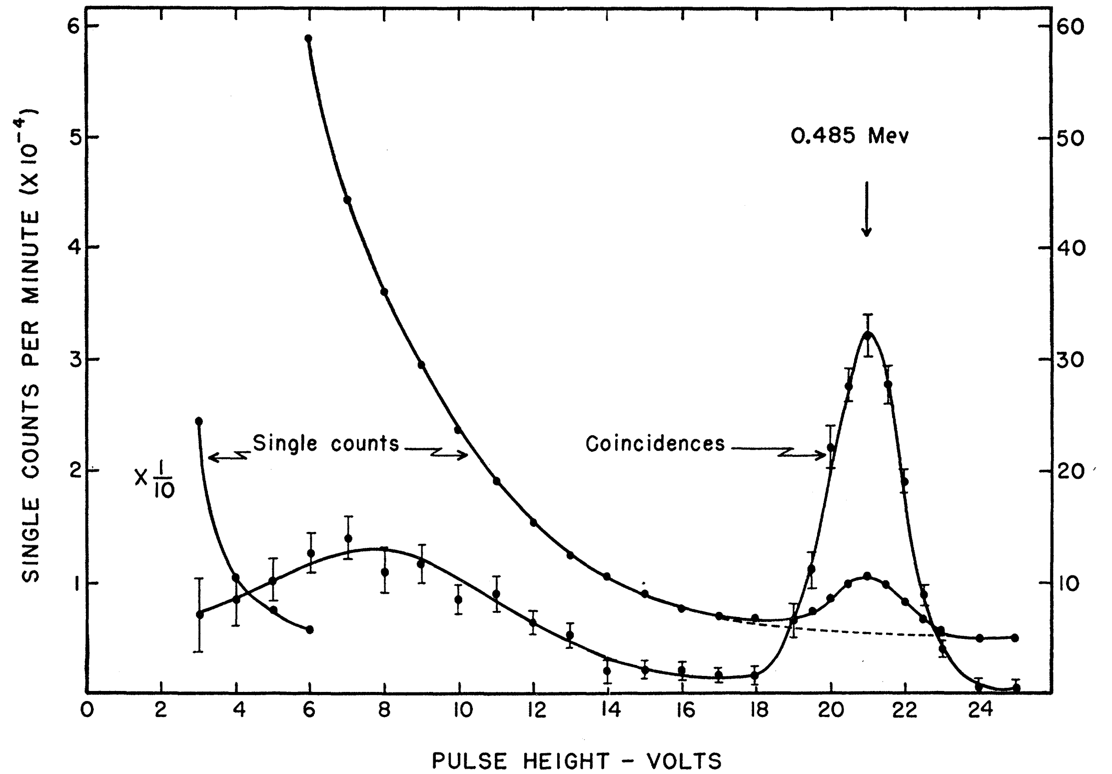

FIG. 2. Coincidences between pulses from the 0.485-Mev gamma ray of the 43-day Cd^{115} and pulses in photopeak of the 0.935-Mev quantum.

peaked shape of the coincidence curve of Fig. 3 is produced by detection of the photo-peak of the 0.485-Mev gamma ray in the moving channel and Compton recoils of the 0.935-Mev quanta in the fixed channel.

The various gamma-gamma coincidence measurements indicate the presence of an excited state of In^{115} at 1.42 Mev. The 1.30-Mev radiation shown in Fig. 1 was found to be noncoincident with any other gamma rays. The relative intensities of the gamma rays suggests that the 0.485-Mev gamma ray is emitted from a level at 1.42 Mev which is fed by a soft beta spectrum of low intensity. The softer gamma ray is, of course, followed by the gamma rays of energy 0.935 Mev. It can also be concluded that beta spectra terminate at all levels of Cd^{115m}. The foregoing results are interpreted in the level diagram of Fig. 9 and are in agreement with the data of Engelkemeier.[3]

A study of the spatial correlation of the two coincident gamma rays of Cd^{115m} was carried out in a coincidence counter arrangement of half-angle 9°. A solid source gave the result that

$$\left[\frac{W(\pi)}{W(\pi/2)}-1\right]=0.016\pm0.010,$$

$$\left[\frac{W(3\pi/4)}{W(\pi/2)}-1\right]=-0.026\pm0.015.$$

Thus, the correlation function is essentially isotropic. Liquid sources gave the same result. This measurement favors the occurrence of $9/2 \xrightarrow{D} 7/2 \xrightarrow{D} 9/2$ transitions, but because of the possibility of mixture in both transitions, little of a definite nature can be concluded.

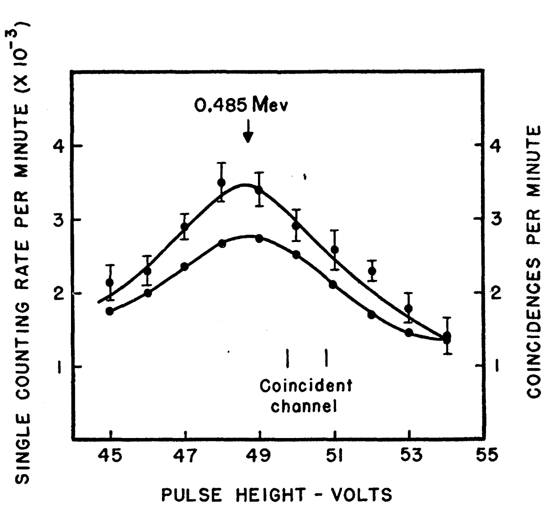

FIG. 3. Coincidence rate with channel of one spectrometer fixed at 0.500 Mev, showing absence of a 0.45 Mev–0.50 Mev cascade.

2.3 DAY Cd^{115}

In Fig. 4 is plotted the pulse-height spectrum generated in a 3.5-cm thick crystal of NaI(Tl) by the gamma rays of the 2.3-day Cd^{115}. Photopeaks are in evidence which correspond to quantum energies of 230, 260, 335, and 520 kev. From the unduly large width and asymmetrical shape of the peak of highest energy, it was concluded that it must be composed of contributions from more than one gamma ray. This spectrum was observed several times over a decay time of six half-periods, and all the gamma rays were found to decay with the same half-life. Taking into account the efficiency of the crystal for absorption of the full energy of the gamma quanta, an analysis of the spectrum of Fig. 4 gave the relative intensities of the 230, 260, and ~520-kev gamma rays as 1:3.3:65. The spectrum of Fig. 4 was taken almost immediately after separation of Cd^{115} from the 4.5-hour isomer of In^{115}, so that the intensity of the 335-kev radiation was greatly reduced and thus did not interfere with the peaks of the softer gamma rays.

To obtain information regarding the excitation of nuclear energy levels of In^{115} in the decay of the 2.3-day Cd^{115}, coincidences between pairs of the several gamma rays were studied.

A coincidence study, shown in Fig. 5, revealed that the 230- and 260-kev gamma rays are in cascade. To obtain the data of Fig. 5, a source of Cd^{115} was placed before two crystals of NaI(Tl) so located that the angle included between their axes was about 60°. To eliminate coincidences which might arise from scattering of the 520-kev radiation, a thickness of 10 g/cm^2 of lead was placed between the two crystals. The channel of one spectrometer was fixed at the full energy peak of the 230-kev gamma ray while that of the other was moved over an interval of energy about 230 kev. A pronounced photopeak of coincidences appears at 260 kev. Because of the instrumental resolution, a few pulses from the

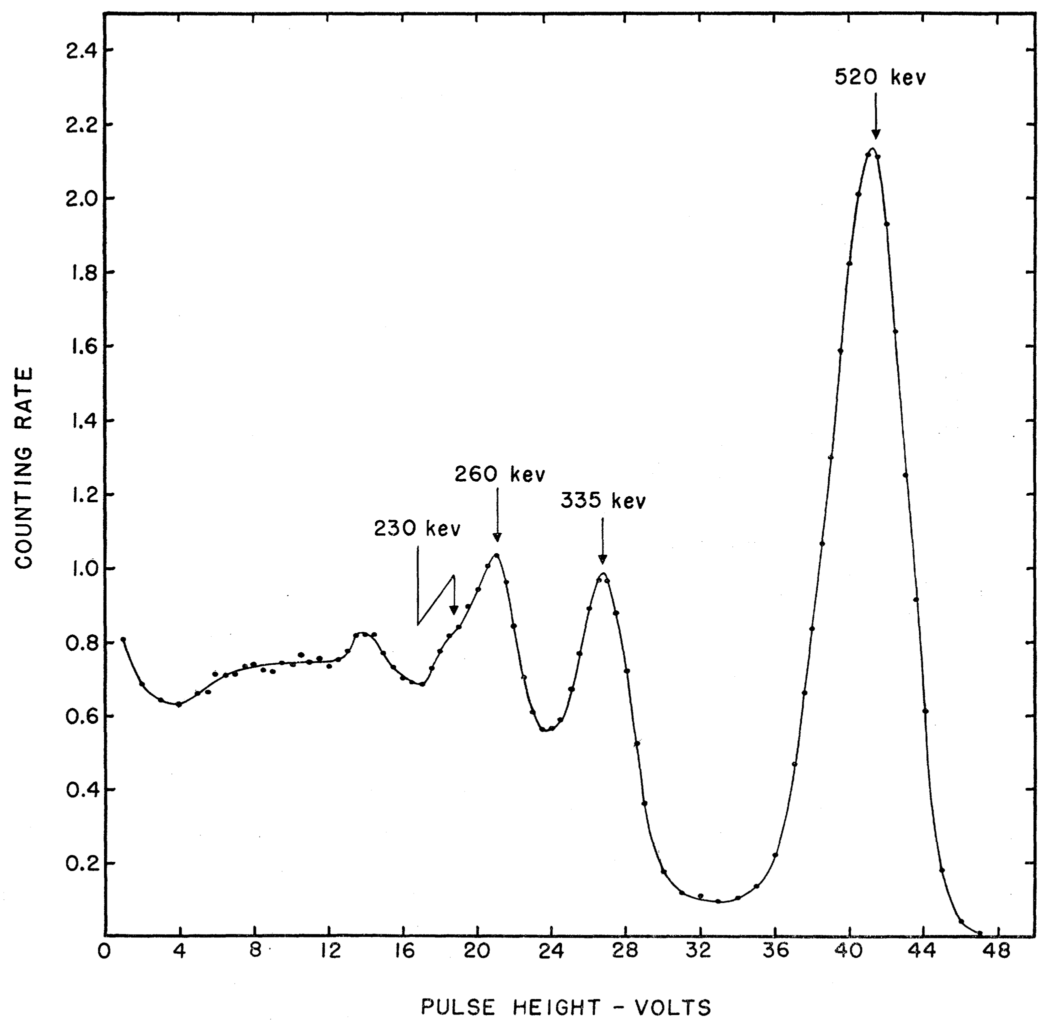

FIG. 4. Pulse-height distribution in NaI(Tl) of the gamma rays from the 2.3-day Cd^{115}. The amount of In^{115*} present was greatly reduced by chemical separation.

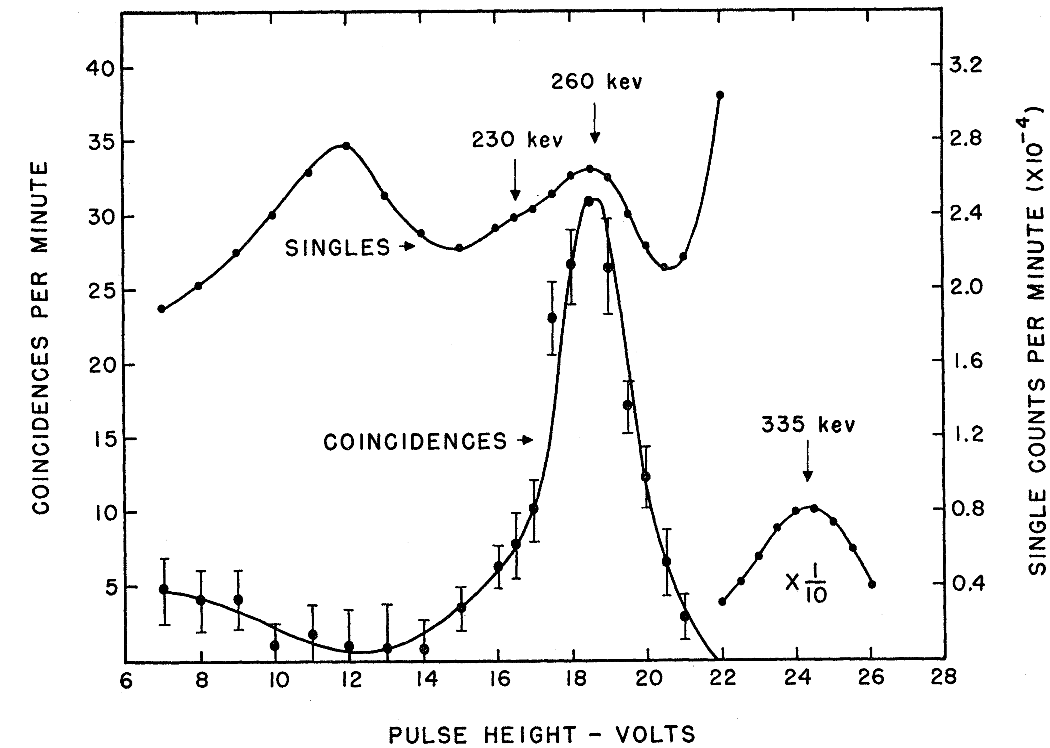

FIG. 5. Coincidences of the 230 kev–260 kev cascade in the decay of the 2.3-day cadmium. The channel of one spectrometer was fixed at 230 kev.

260-kev peak are detected in the fixed channel, giving rise to a somewhat higher coincidence rate on the low-energy side of the 260-kev peak. A similar set of curves is shown in Fig. 6 where the fixed channel was located at the high-energy side, ~270 kev, of the 260-kev photopeak. The coincidence rate was recorded as a function of the position in pulse-height of the moving channel. It is clear from the figure that a strong asymmetry, far greater than that of Fig. 5, was present in the coincidence rate, appearing in this case at a quantum energy of about 260 kev. This result suggests that in addition to coincidences between gamma rays of energies 230 and 260 kev, some were also present because of a 263 kev–260 kev cascade as well. If the intensity of the 260-kev gamma ray is taken arbitrarily as 3, it can be estimated from Figs. 4 and 6, that the relative intensities of the 263-kev quantum and the 230-kev gamma ray are respectively 0.3 and 1.0. Because the 260-kev gamma ray is more intense, and because it is coincident with no other radiations except the x-rays and those gamma rays just indicated, it must be concluded that the level from which it is emitted is fed in part by a beta-ray spectrum and in part by a 230-kev gamma ray or a 263-kev gamma ray. Using an anthracene beta-ray spectrometer and an NaI(Tl) gamma-ray spectrometer, beta-gamma coincidences were observed between beta-ray pulses and the pulses of the high-energy side of the 260-kev photopeak. The beta-gamma coincidence data are plotted in Fig. 7 where the inner spectrum coincident with the 260-kev gamma ray is shown to have an end point at 860 kev, indicating that the intense 260-kev transition terminates at the 4.5-hour isomeric level of In^{115}. The anthracene counter was calibrated by the conversion electrons of the gamma ray of Cs^{137}. The *K-L*

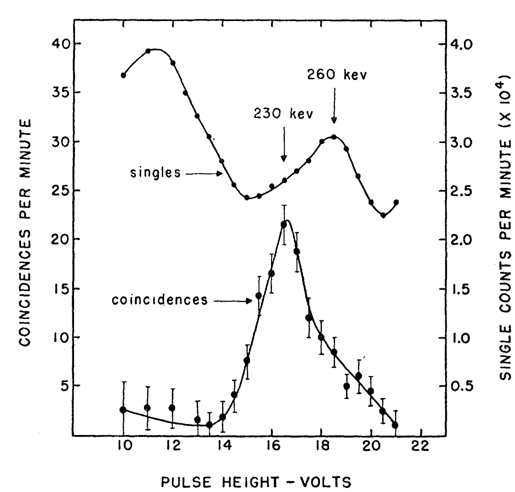

FIG. 6. Coincidences of the 230 kev–260 kev cascade and of the 263 kev–260 kev cascade in the decay of the 2.3-day cadmium. The channel of one spectrometer was fixed at 270 kev.

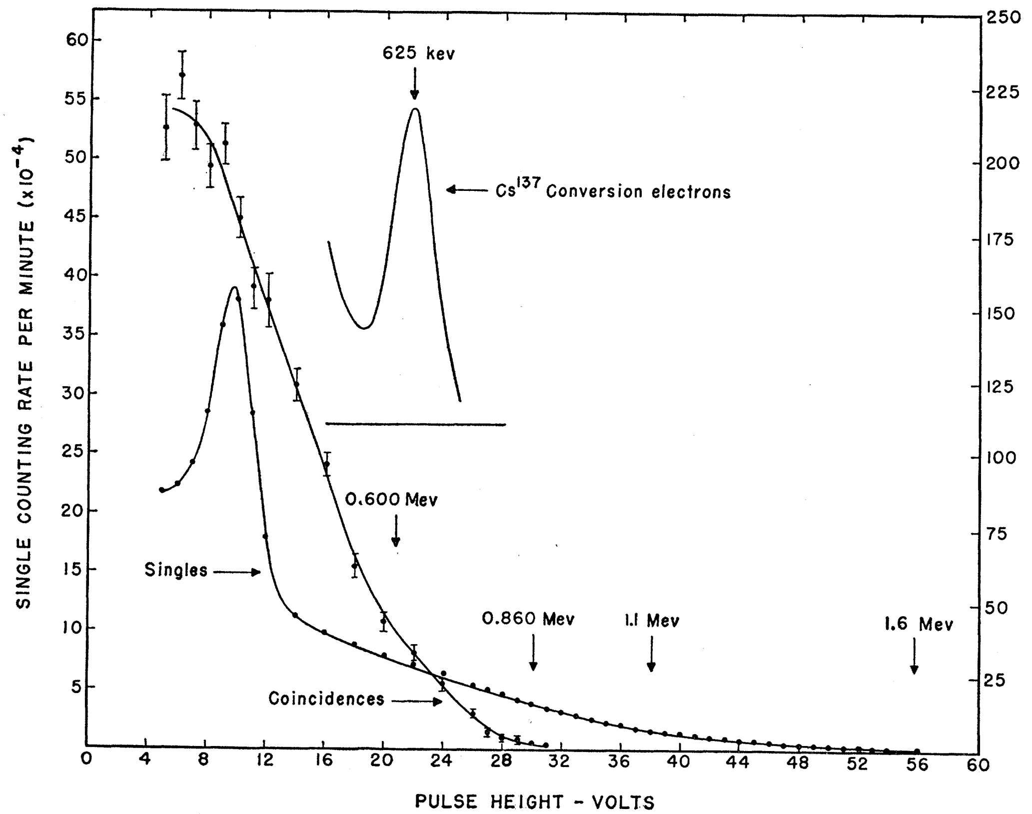

FIG. 7. Beta-gamma coincidences in the disintegration of the 2.3-day Cd^{115}. The channel of the gamma spectrometer was fixed at 260 kev while that of the anthracene counter was moved over the β-ray spectrum.

conversion electron peak is shown as an insert in Fig. 7. These beta-gamma coincidence data and the previously described gamma-gamma coincidence studies show that energy levels are present in In^{115} which are, respectively, 260, 490, and ~520 kev above the 4.5-hour isomeric level.

It was noted that the radiations giving rise to the peak at ~520 kev are in coincidence with the x-rays of indium. A source of Cd^{115} was placed between the NaI(Tl) crystals of two scintillation spectrometers in coincidence. The channel of one spectrometer was fixed at the photopeak of the x-rays while that of the other spectrometer was moved across the peak at ~520 kev. In Fig. 8 are presented the single and coincidence counting rates for each position of the second spectrometer. In these measurements, a copper absorber of thickness 2 g/cm^2 was placed just before the high-energy gamma-ray counter to eliminate any coincidences which might result from escape of iodine x-rays from the surface of the crystal and their subsequent detection in the spectrometer at the indium x-ray peak. Chemical separations of indium from cadmium were also performed to reduce in intensity unwanted x-rays arising from the conversion of the 335-kev gamma ray of the 4.5-hour isomer of In^{115}. From the curves of Fig. 8 it is clear that the 25-kev x-rays are coincident only with a gamma ray at 490 kev. These measurements suggest that the 490-kev gamma ray is in cascade with a gamma ray which is very nearly totally converted or with one of energy 25 kev, indistinguishable from the indium x-rays. Using the width of the 490-kev radiation as determined in the coincidence measurements, the peak of single counts was analyzed into two components as shown by the dashed curves corresponding to

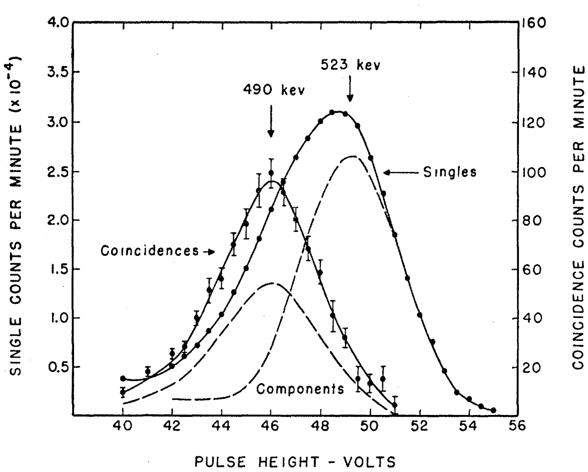

FIG. 8. Coincidences between indium x-rays and gamma rays in the vicinity of 520 kev.

quantum energies of 490, and 523 kev with relative intensities of 1:1.95, so that the intensity ratios of the 230-, 260-, 263-, 490-, and 523-kev gamma rays now become 1:3.0:0.3:22:43.

From the calculated efficiency of the low-energy counter for detection of the x-rays, it is shown that the data of Fig. 8 indicate only three percent of the 490-kev quanta to be in sequence with the x-rays. A beta-gamma coincidence study similar to that of Fig. 7 showed that the 490- and 523-kev gamma rays are coincident with no beta rays of energy greater than 620 kev. Thus, the 490- and 523-kev quanta are emitted in crossover transitions corresponding to the 230 kev–260 kev and the 263 kev–260 kev cascade. The above described level arrangement and the presence of x-rays coincident with the 490-kev gamma ray and the beta-gamma coincidence measurements show that some of the 490-kev quanta are preceded in time by a heavily converted gamma ray of energy 33 kev, whereas others are immediately preceded by beta rays.

The results of the foregoing measurements on the 2.3-day Cd^{115} are summarized in Fig. 9 where the decay of the 43-day isomeric level is likewise depicted.

Since no 858-kev gamma rays are observed in decay of the 2.3-day period, and taking into account the spins of the ground and isomeric levels of In^{115}, it is concluded that the multipolarity of the 523-kev gamma ray must be $E1$, $M1$, or $E2$. In order for the 33-kev quantum to compete as it does in intensity ($\sim$1 percent) with the 523-kev gamma, it must be dipole in character. Since it was not possible to detect any unconverted gamma quanta at 33 kev in counting of single photons or coincidence studies, the conversion coefficient must be very large, favoring an $M1$ assignment.

The K-shell conversion coefficient of the 335-kev gamma ray emitted in the decay of the 4.5-hour In^{115} was measured by comparing its intensity with that of the indium K-radiation which results from conversion. A source was prepared for this measurement by separating In^{115*} from its parent element by a hydroxide precipitation and mounted on Scotch Tape. This source was placed at distances from a 4 cm thick NaI(Tl) crystal which varied from 5 to 8 cm. To obtain relative intensities from the areas under the photopeaks of the 335-kev gamma ray and the x-radiation, several factors were taken into account such as the fluorescence yield of the K-radiation of indium (0.82), the absorption of the x-rays in the Al-MgO housing of the crystal of NaI(Tl), and the efficiency of the crystal for full energy absorption of the 335-kev quanta. From the data and their associated corrections, the K-shell conversion coefficient was calculated to be 0.83. In addition, the $K/(L+M)$ ratio for the 335-kev gamma ray was measured in a thin magnetic lens spectrometer. In Fig. 10 is given the momentum distribution. From the areas of the two peaks, the $K/(L+M)$ ratio is found to be 3.85. The peak composed of L- and M-shell conversion electrons has the shape and half-width to be expected for monoenergic electrons. It was thus concluded that the L/M ratio must be large (>10). The various conversion coefficient measurements are consistent with the designation of the 335-kev transition as $M4$.[8]

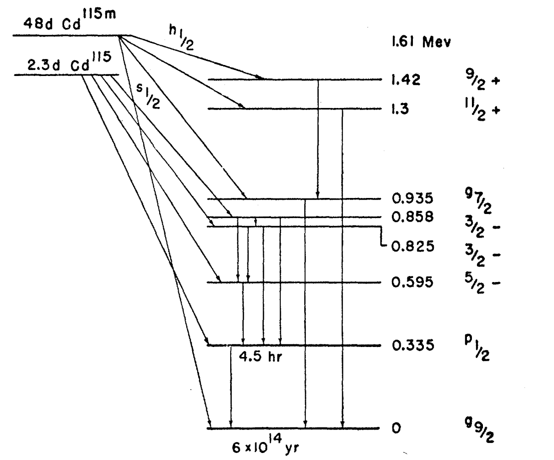

FIG. 9. Level scheme for In^{115}. (The orbital of the 48-day level should have been written as $h_{11/2}$.)

The combined intensities of the 490- and 523-kev gamma rays, when compared with the intensity of the 335-kev isomeric transition, indicate that the two beta spectra feeding the 825- and 858-kev levels in In^{115} have a total intensity of thirty-three percent of all the

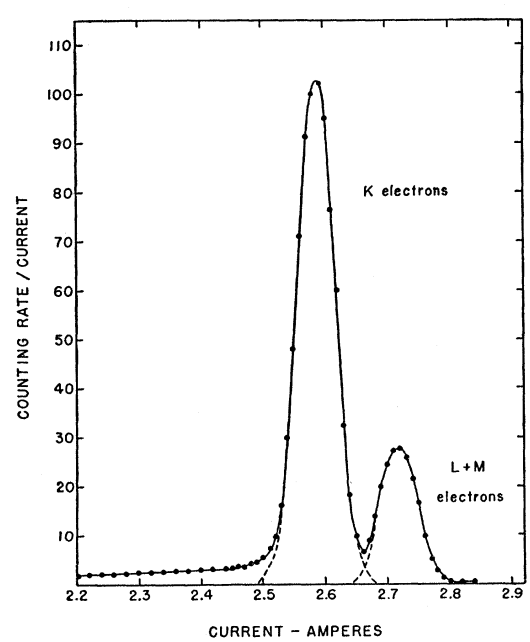

FIG. 10. Conversion electron spectrum of the 335-kev gamma ray of In^{115*} as measured in a thin-lens magnetic spectrometer.

[8] M. Goldhaber and A. W. Sunyar, Phys. Rev. 83, 906 (1951); Rose, Goertzel, and Perry, Oak Ridge National Laboratory Report ORNL-1023, June 25, 1951 (unpublished).

TABLE I. Summary of the characteristics of the β transitions in Cd^{115} leading to In^{115}.

Activity	End-point energy (Mev)	Percent of disintegrations	Logft	Nature of transition
43-day Cd^{115m}	1.61	97	8.86	$\Delta I=1$, yes Anomalous case
	0.68	2	9.15	$\Delta I=2$, yes
	0.31	1	8.1	$\Delta I=0$, yes
	0.19	0.3	8.0	$\Delta I=1$, yes
2.3-day Cd^{115}	1.11	61.5	7.1	$\Delta I=1$, yes
	0.86	1.5	8.3	$\Delta I=2$, yes
	0.63	12	6.8	$\Delta I=1$, yes
	0.59	25	6.5	$\Delta I=1$, yes

beta rays emitted from the 2.3-day level. A value of 37 percent was obtained from direct measurement of the beta-ray spectra in the thin-lens magnetic spectrometer. From the intensity ratio of the 490- and 523-kev gamma rays and the known small intensity of the 33-kev gamma ray, the intensities of the 590- and 623-kev beta spectra, the two innermost spectra, are estimated as 25 percent and 12 percent, respectively. In a similar manner, from the relative intensities of the 230-, 260-, 490-, and 523-kev gamma rays, the beta spectrum terminating at the level just 260 kev above the 4.5-hour level is calculated to contain 1.5 percent of the total beta radiation, leaving 61.5 percent of the beta transitions to lead directly to the metastable level.

DISCUSSION OF RESULTS

The ground state of In^{115} is found to have a spin of measured[9] value 9/2, in agreement with the shell model prediction that the orbital is $g_{9/2}$. The isomeric transition is classified as $M4$ so that the appropriate orbital of the 4.5-hour level is $p_{1/2}$.

The properties of the β spectra of both cadmium activities are given in Table I. In the order of ascending energy of the β-ray end point, the four β spectra of the 43-day activity have values of logft of 8.0, 8.1, 9.1, and 8.9. These values of logft are compatible with spin assignments of 9/2+, 11/2+, and $g_{7/2}$ for the excitation levels in In^{115} at 1.42, 1.30, and 0.935 Mev and with the orbital value of $g_{9/2}$ for the ground state. The orbital assignment of the 43-day level in Cd^{115} is taken to be $h_{11/2}$, according to the shell model.[10] The anomalously large value of logft for the first forbidden ground state transition can be explained by the influence of the nuclear core as discussed by De-Shalit and Goldhaber.[11] The $9/2+\rightarrow g_{7/2}\rightarrow g_{9/2}$ gamma transitions are in accord with the observation of little or no asymmetry in the angular correlation measurements. A peculiar feature of the decay scheme of Fig. 9 is that no intense magnetic dipole transition occurs between the 1.42-Mev level in In^{115} and the ground state $(9/2+\rightarrow 9/2+)$, nor is the other possible transition $9/2+\rightarrow 11/2+$ observed. There is, at present, no obvious explanation for the absence of the above-cited transitions. Their characteristics may in some way be governed by the possibility that the 1.42-Mev state is a rotational level of the $g_{7/2}$ state beneath it.

Values of logft for the four β spectra which initiate at the 2.3-day level of Cd^{115} are in order of ascending energy 6.5, 6.8, 8.3, and 7.1. If the orbital of the 2.3-day level of Cd^{115} is taken to be $s_{1/2}$, the indicated spins of the levels of In^{115} are determined by the various values of logft. These spin values are also consistent with the observed relative intensities of the gamma rays. An $E1$ transition would normally be expected between the $g_{7/2}$ level and the level of orbital 5/2−. That it is not observed may again be related to the presence of rotational levels. For example, the 5/2− state could be a rotational level of the $p_{1/2}$ level.

ACKNOWLEDGMENT

The authors wish to thank Dr. W. F. G. Swann, Director of The Bartol Research Foundation for his continued interest and encouragement in the course of this work. One of the authors (J.V.) is indebted to the Foundation for a research fellowship.

[9] D. A. Jackson, Z. Physik **80**, 59 (1933); F. Paschen and I. S. Campbell, Naturwiss. **22**, 136 (1934); Millman, Rabi, and Zacharias, Phys. Rev. **53**, 385 (1938); T. C. Hardy and S. Millman, Phys. Rev. **61**, 459 (1942).

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

[11] A. De-Shalit and M. Goldhaber, Phys. Rev. **92**, 1211 (1953).