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Michael D. Petroff

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ABSTRACT

An investigation of the beta and gamma radiations from the 4.3-hour radioactive isotope In^{109} has been made with a magnetic-lens beta-ray spectrometer. On the basis of the observed positron spectrum and the measurement of the conversion coefficients of the more intense gamma rays a decay scheme for In^{109} is proposed. The spins and parities of the levels of Cd^{109} that are involved in the decay scheme are discussed in relation to the known levels of Cd^{111}. The investigation included the measurement of the half life of a 58-kev isomeric transition in Cd^{109} which yielded a value of $12 \pm 3 \times 10^{-6}$ second.

The investigation of the products of alpha-particle bombardment of cadmium enriched in Cd^{106} has resulted in the assignment of an 18-minute electron capture and positron and gamma activity to the isotope Sn^{109}. The information obtained on the radioactivity of this isotope is discussed with reference to the occurrence of isomerism among odd-nucleon-number indium isotopes.

INTRODUCTION

The extensive information accumulated on nuclei since the discovery of the means of artificially producing radioactive isotopes consists principally of life times, spins of ground states, disintegration energies, and energies of the observed particles and γ rays that are emitted. Despite the wealth of such information, the conversion coefficients and K/L ratios of γ transitions observed in the decay of a particular isotope have been measured only in relatively few cases. Consequently, assignments of spin and parity to the excited states of nuclei have been done for only a small part of all the nuclei that can be produced artificially. Still fewer are cases where the spins and parities of the excited states of two or more neighboring odd- or even-A nuclei have been thoroughly investigated. The information from such groups of neighboring isotopes is of considerable value to the refinement of theoretical models for which evidence is otherwise drawn almost exclusively from the properties of the ground states of nuclei. If one considers that the evidence for strong interactions found in nuclear reactions is derived from the properties of the compound nucleus, which is always formed in a state of high excitation energy, one would then expect that the energies of the first few excited states of a nucleus can be described by a refinement of the shell model, which appropriately considers the effect of interactions between the nucleons of an intermediate character. In particular, when we consider neighboring odd-A nuclei in the region of magic numbers, a refinement of the shell model by inclusion of the interactions between protons and neutrons has been used with some success to explain the energy trends of certain levels when the nucleon number of the nuclei being considered changes by two protons or two neutrons.[1] In this connection, the information on the levels of Cd^{109} obtained from the study of the radioactivity of In^{109} may be of importance, as the levels of the neighboring Cd^{111} have been thoroughly studied through the decay of In^{111} and Ag^{111}. A possible theoretical approach consists of fitting the parameters of a given model to the experimental levels of Cd^{111} and checking the validity of the model by comparing with the observed levels of Cd^{109} the theoretical levels predicted upon consideration of the effect of deleting two neutrons from the Cd^{111} nucleus.

The study of the radioactivity of Sn^{109} has not been carried out to the same extent as that of In^{109} because of the short half life with which it decays. Nevertheless, information obtained in this work is of significance in that it indicates an isomeric state of In^{109} with a half life less than two minutes. This isomer appears to be of the same type as occurs in In^{113} and In^{115}.

The investigation of In^{109} and Sn^{109} has yielded important information on two more 109 isobars in addition to what is known about the decay of Cd^{109}, Ag^{109}, and Pd^{109}.

RADIOACTIVITY OF INDIUM-109

Brief Summary of Earlier Experiments

The 4.3-hour In^{109} activity was first observed by Bradt and Tendam[2] as a product of α-particle bombardment of silver. Mallary and Poole[3] produced In^{109} by proton and deuteron bombardment of cadmium enriched in Cd^{106} and Cd^{108}. As a result of their experiments the mass number 109 assigned to this indium activity was definitely established. The positron and conversion-electron spectra of In^{109} were also observed by McGinnis[4] in the course of his investigation of In^{111}. The work of the observers mentioned above served to determine that In^{109} decays to Cd^{109} by electron capture and positron emission with a maximum positron energy of 0.75 Mev and that γ transitions, with the energies 0.058, 0.205, 0.347 and 0.427 Mev are involved in the decay. In the course of investigation of other In and Sn isotopes some results different from those of McGinnis were obtained.[5] A further study of In^{109} was undertaken to augment and to check the information obtained in the earlier experiments with the aim of establishing the decay scheme.

General Experimental Procedure and Apparatus

In^{109} was produced by bombarding silver foil with α particles from the University of California 60-inch cyclotron. The 48-Mev alpha beam was degraded by means of copper foil to approximately 26 Mev so as to maximize the (α, 2n) yield in accordance with Ghoshal's cross-section measurements of the (α, 2n) reaction for silver.[6] Since natural silver consists of an approximately equal mixture of Ag^{107} and Ag^{109}, both In^{109} and In^{111} are produced by the (α, 2n) reaction. In order to study weak γ transitions in the decay of In^{109}, which would otherwise be obscured by the In^{111} spectrum, targets of AgCl, with the silver enriched in Ag^{107} to 99%, were also used to produce In^{109}.

The indium activities produced in the bombardments were chemically separated with the aid of indium carrier.[5] In several bombardments the chemical separation was completed less than 40 minutes after the end of the bombardment to look for the possibility that In^{109} may have an isomeric state with a half life shorter than the ground state.

The principal piece of equipment used to study the radiations from In^{109} was a magnetic-lens β-ray spectrometer of the type described by Siegbahn.[7] This spectrometer was constructed by Hayward[8] and subsequently improved with the introduction of a ring baffle near the detector,[9] giving a resolution of 1.5%. A Geiger tube detector, designed to maintain uniform characteristics over long periods of time and high counting rates, was a modification that appreciably raised the performance of the spectrometer. The γ spectrum was studied with NaI(Tl) crystals mounted on 6292 photomultiplier tubes and a unit consisting of two pulse-height analyzer circuits with a coincidence output. A special 1.5-mm-thick NaI crystal was used for x-ray detection and pulse-height analysis. The γ spectrum was also measured by means of an external gold converter placed over the source in the β-ray spectrometer. β-γ coincidence experiments were done with stilbene and anthracene crystals mounted on 6292 photomultiplier tubes.

Experimental Results

The Positron Spectrum of Indium-109

A Fermi plot of the positron spectrum is shown in Fig. 1. After subtraction of background and the 2.25-Mev component due to the 5-hour In^{110m}, the maximum energy of In^{109} positrons is 0.795 ± 0.010 Mev (see Fig. 2). In^{110m} is also present, since at the optimum bombarding energy for an (α, 2n) reaction, the (α, n) cross section is of the order of 1/4 of the (α, 2n) cross section.

The fraction of In^{109} decays associated with positron emission was evaluated by a comparison of two areas derived from data obtained with the same source in the β-ray spectrometer. One was the area under the momentum distribution of the positron spectrum, and the other was the area calculated from the K and L conversion electron lines of the 0.087-Mev transition in the decay of the 470-day Cd^{109} daughter of In^{109}. Both areas were evaluated from curves obtained by dividing the points of the observed spectrum by their momentum positions. Since Cd^{109} is known to decay by electron capture to the first excited 7/2(+) state of Ag^{109} at 0.087 Mev above the 1/2(-) ground state,[10] and the conversion coefficient has been measured as 6, the area under momentum distribution of the K and L conversion electrons after all the In^{109} nuclei had decayed can be used to evaluate the number of Cd^{109} nuclei in the source. This number is equal to the number of In^{109} nuclei in the source immediately after the chemical separation. If A_1 and A_2 are the positron and the 0.087-Mev transition areas respectively, corrected for decay to the time of the chemical separation, t_1 and t_2 the corresponding half lives of In^{109} and Cd^{109}, and α the conversion coefficient of the 0.087-Mev transition, then the fraction of In^{109} decays occurring through positron emission is given by

$$\frac{A_1 t_1 \alpha}{A_2 t_2 (\alpha + 1)}$$

Such an analysis gives a value of 0.063 ± 0.006 for the positron decay fraction. With this value, the 4.3-hour half life and the 0.795-Mev maximum positron energy, log ft is equal to 4.95 ± 0.01 and hence the decay is in the class of allowed β transitions.

Theoretical calculations including the screening effect,[11] which have proved to coincide with experimental results within a margin of 5%, indicate that for a 0.795-Mev allowed β decay of indium the ratio of electron capture to positron emission should be 8.9. Comparison of this theoretical value with the positron decay fraction suggests

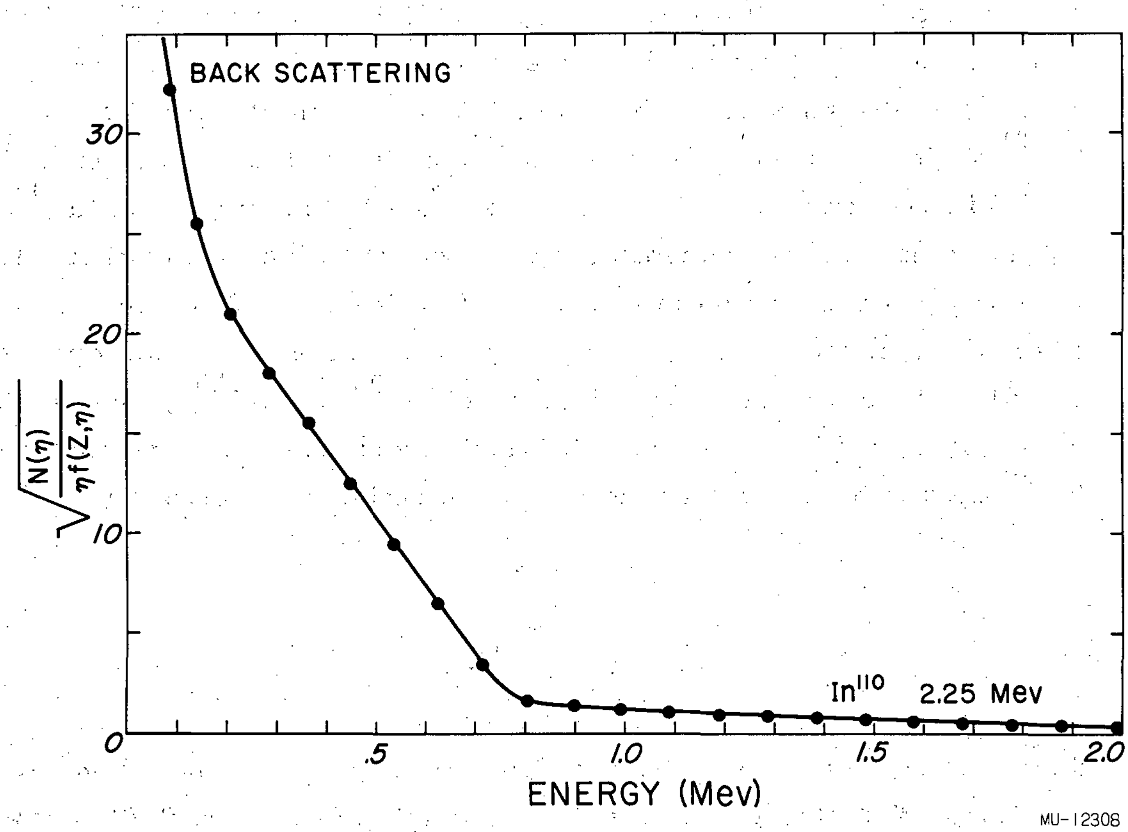

Fig. 1. Fermi analysis of the positron spectrum of In^{109}. The data were taken 4.5 hours after the chemical separation of indium and 6 hours after the end of the bombardment.

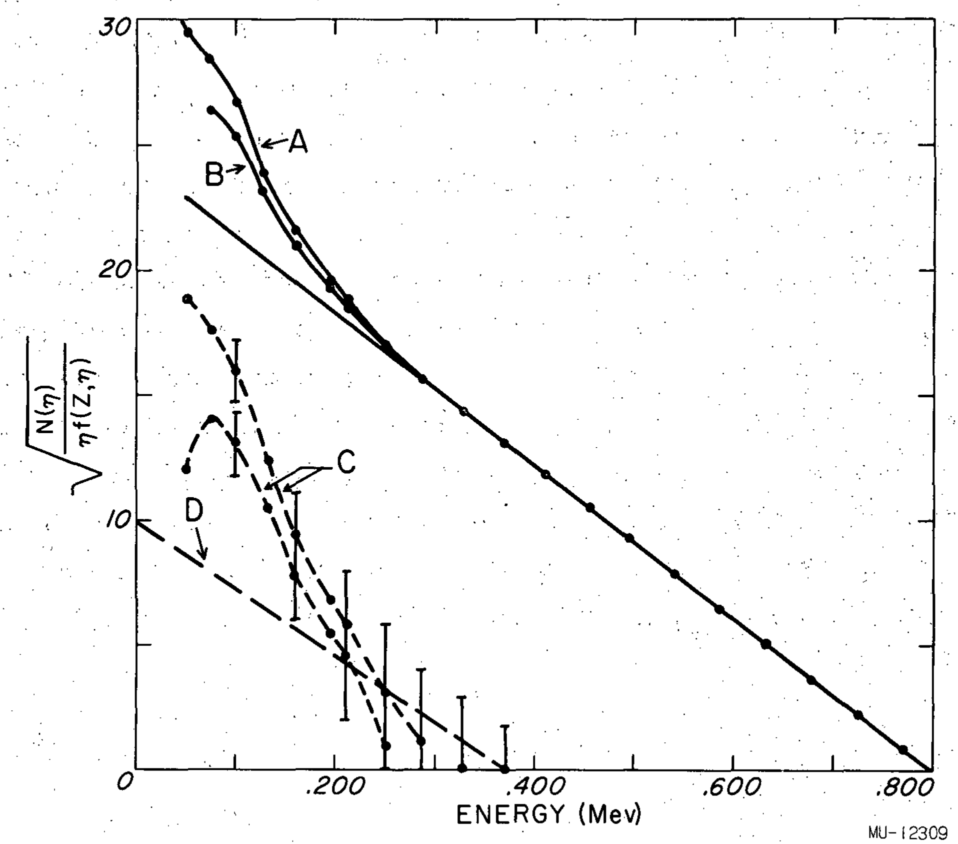

Fig. 2. Fermi plot of the In^{109} positron spectrum after subtraction of the In^{110} 2.25-Mev positron spectrum:

A. Without correction for the screening effect;
B. With correction for screening;
C. After subtraction of the extrapolated 0.795-Mev positron contribution;
D. Contribution of a 0.368-Mev positron spectrum for a branching ratio $\beta^+(0.795)/\beta^+(0.368) = 50$.

that there may be branching in the β decay of In^{109}. The Fermi analysis given in Fig. 2 shows that after subtraction of the 0.795-Mev component the resulting curve could be interpreted as due to an additional positron spectrum with a maximum energy of approximately 0.30 Mev. However, if theoretical values of ratios of electron capture to positron emission for a 0.3-Mev β decay are considered, the points on this resultant curve appear at least four times too high. One must conclude that most of the remainder curve is due to backscattering as a result of source thickness and backing. If the indicated statistical error is kept in mind, it is not difficult to see that the experimental curve is consistent with appreciable electron-capture decay to any levels in Cd^{109} about 0.40 Mev above the level to which the 0.795-Mev positron decays take place. On the basis of these considerations it is entirely possible that in addition to the allowed β decay, which is readily observed, there are other allowed electron-capture branches, with ratios of electron capture to positron emission greater than 200, to higher excited states of Cd^{109} in the region 0.4 Mev above the level populated by the observed positron decay. To illustrate this point, and with a view of the later discussion of the decay scheme of In^{109}, the positron contribution of an electron capture and positron decay to a level 0.427 Mev above the level populated by the observed positron decay is shown in Fig. 2. This contribution was calculated assuming a theoretical branching ratio for allowed positron decays $\beta_{(0.795)}/\beta_{(0.368)}$ approximately equal to 50.

Gamma Transitions in the Decay of Indium-109

Figures 3 and 4 show the conversion-electron spectrum of indium sources made from $Ag^{107}Cl$ bombarded with α particles. The assignment of observed lines to the decay of In^{109} is based primarily on the 4.3-hour half life with which they were observed to decay. Table I summarizes the information obtained from the conversion-electron spectrum, the γ-ray spectrum shown in Fig. 5, the electron spectrum (see Figs. 6 and 7) obtained when an external gold converter was used, and other experiments designed to study the individual transitions in more detail. The experiments pertaining to the results presented in Table I are discussed in Appendix I.

In addition to the γ transitions shown in Table I a number of other transitions were observed. From the strongest source prepared after the bombardment of Ag^{107} the conversion electron spectrum indicated the presence of very weak transitions with the following energies: 0.516, 0.530, 0.618, 0.710, 0.805, and 1.15 Mev. Since these transitions do not appear in the known decay of In^{110m} and their half life is of the order of 4 hours, they must belong to the decay of In^{109}. A more detailed and accurate study of these transitions would require source strengths beyond the limit imposed by the maximum beam current of the cyclotron; hence no information as to their multipolarities was obtained.

The 0.058-Mev transition was found to have a $12 \pm 3 \times 10^{-6}$-second half life associated with it. The experimental arrangement used in the half-life determination is described in detail in Appendix I.

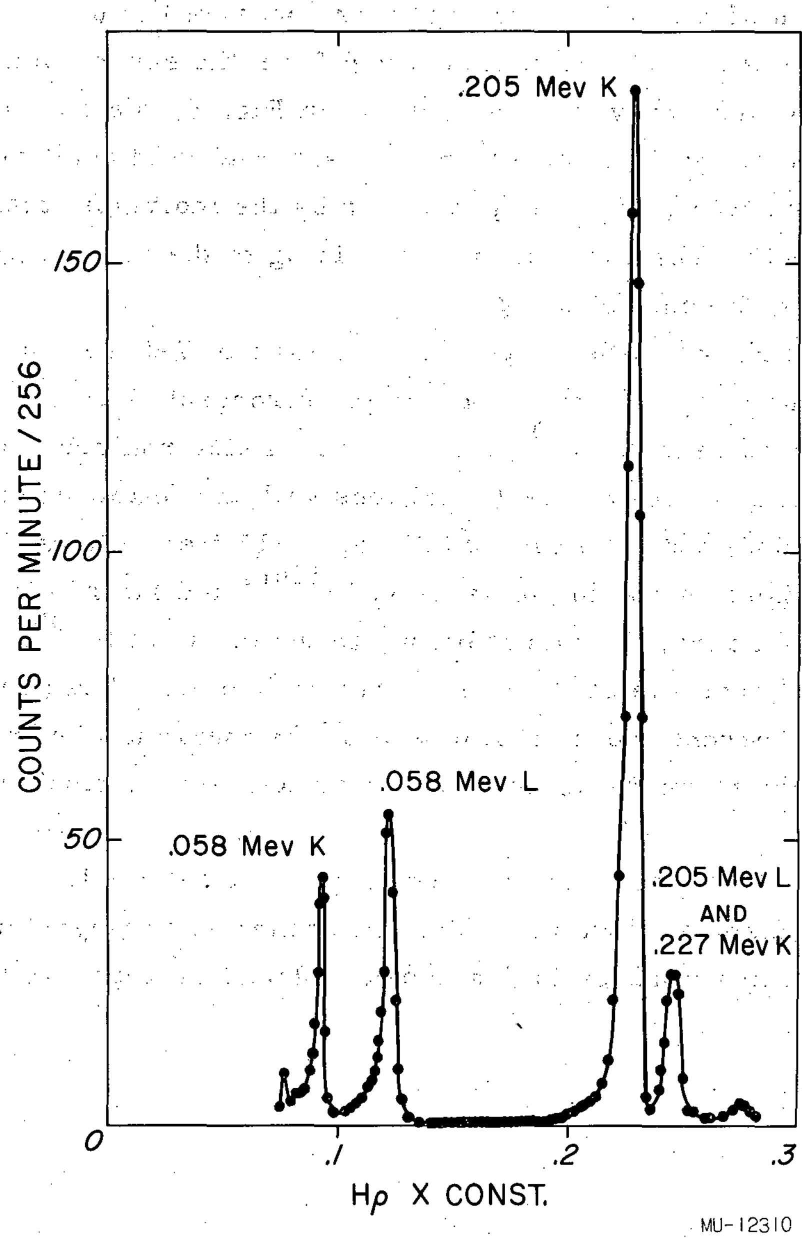

Fig. 3. Conversion-electron spectrum of the 0.058-Mev and the 0.205-Mev transitions in the decay of In^{109}.

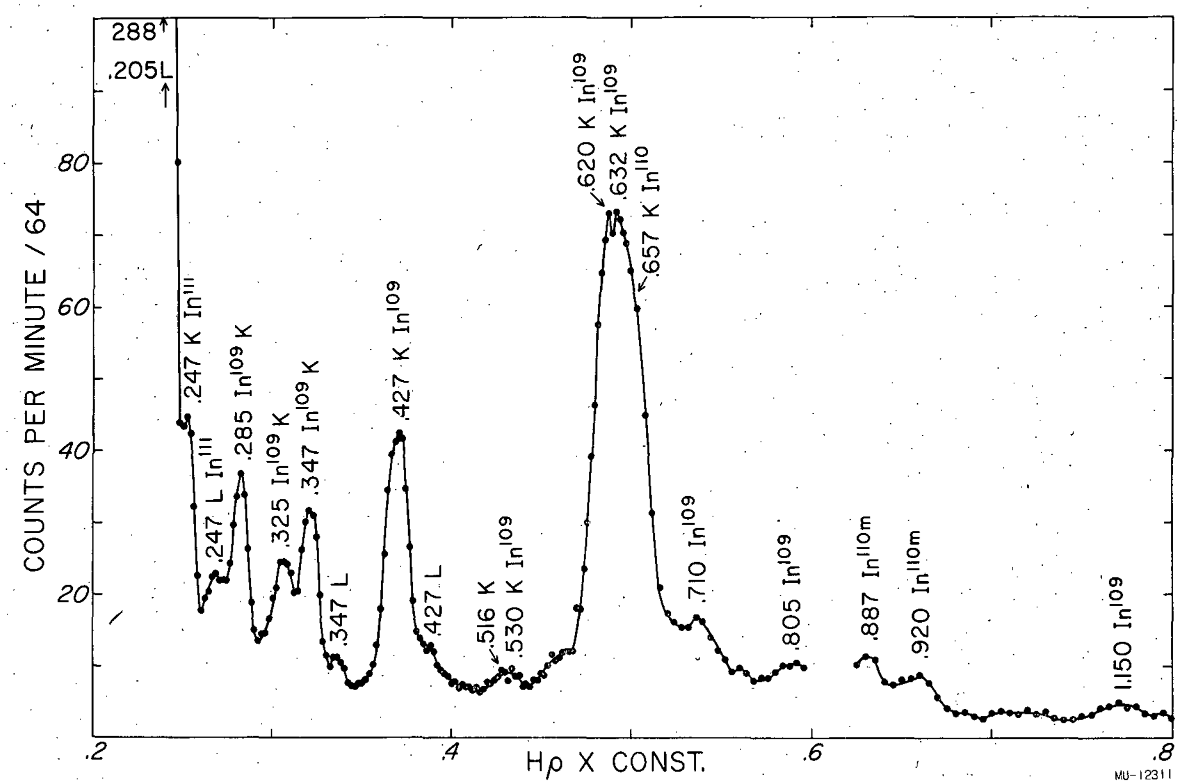

Fig. 4. Conversion-electron spectrum of the transitions with energies above 0.205 Mev in the decay of In^{109}.

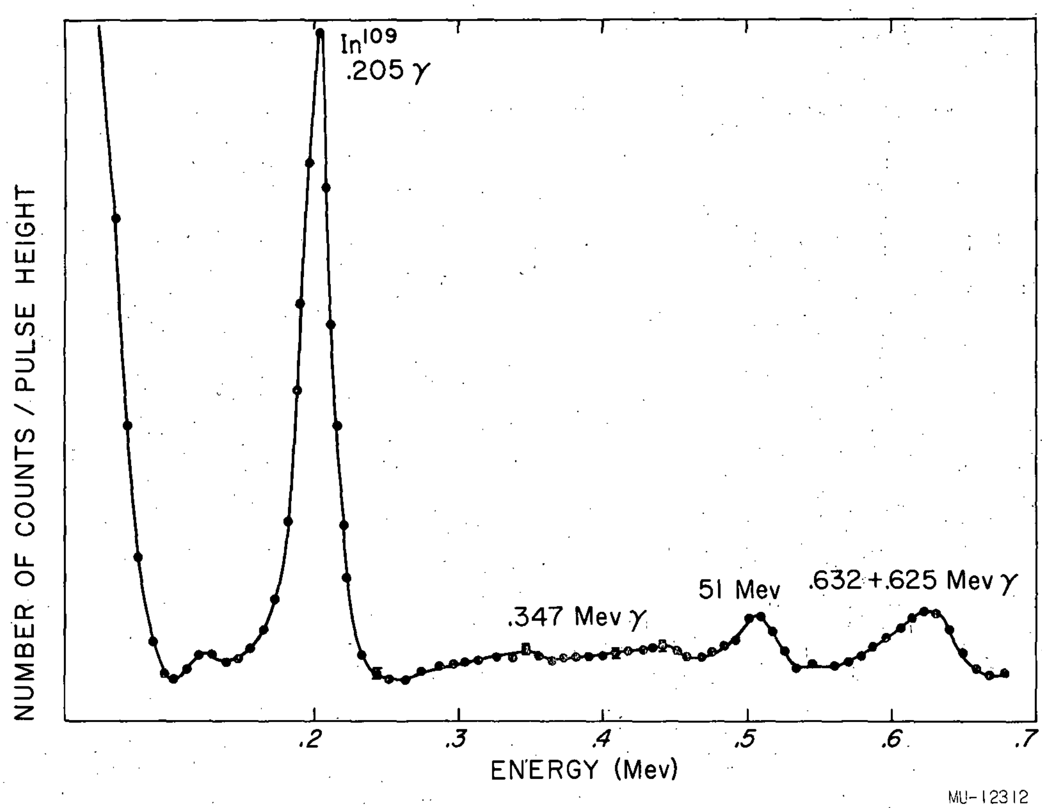

Fig. 5. The gamma-ray spectrum of In^{109} obtained with a 1.5-by-1-in. NaI (Tl) crystal.

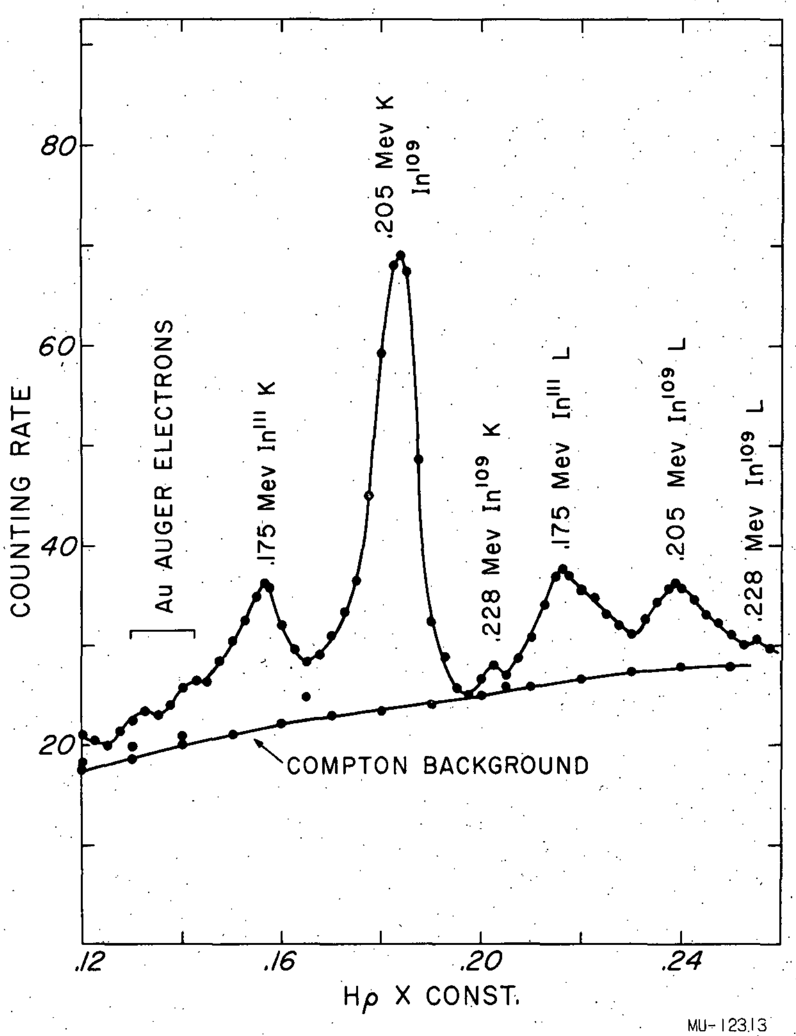

Fig. 6. The gamma-ray spectrum of In^{109} obtained with a 2-mg/cm^2 gold radiator.

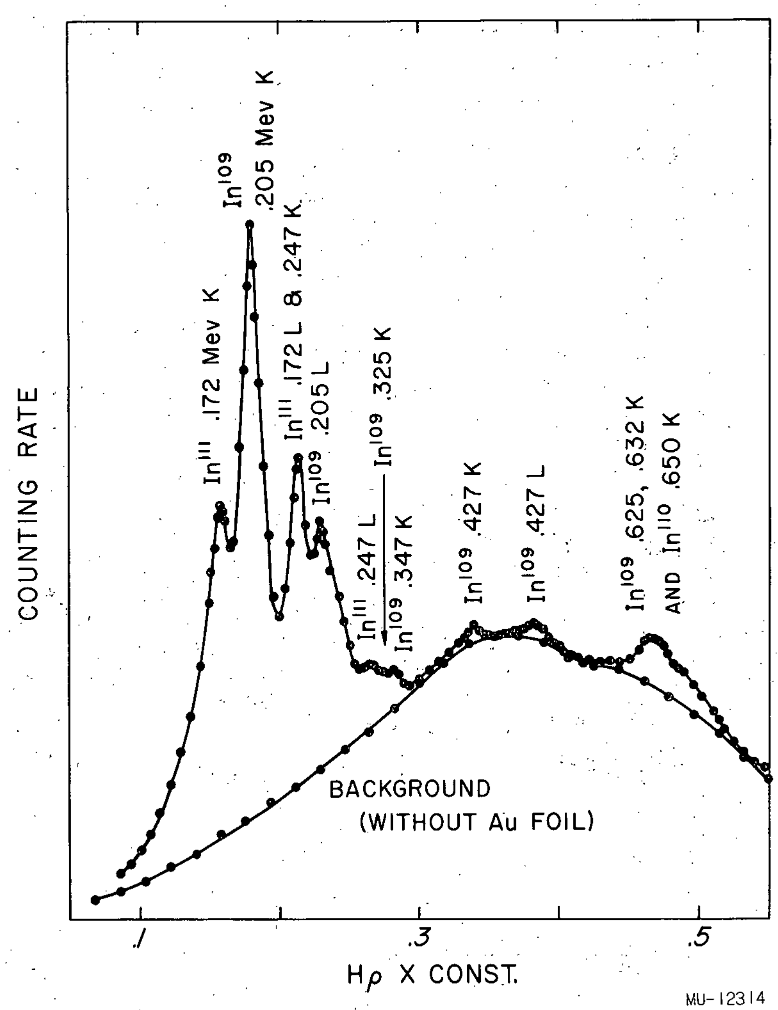

Fig. 7. The gamma-ray spectrum of In^{109} obtained with an 8-mg/cm^2 gold radiator.

Table I

Summary of the analysis of the γ and conversion-electron spectrum of Indium-109

Transition energy (Mev)	Relative intensity of conversion electrons	Relative intensity of gamma rays	Conversion coefficient	K/L ratio	Multipolarity
0.0580 ±.0005	0.49 ± .03	<0.01	>5	0.85 ±.08	E2
0.205 ± .001	1.0	1.0	0.07 ± .01	7.6 ±0.4	M1
0.227 ± .001	0.02 ±0.007	0.038 ± .020	0.04 ± .02	---	M1 or E2
0.285 ± .002	0.0145 ±.003	------	------	5.0	M1 or E2
0.325 ± .003	0.0065 ±.002	------	------	---	----
0.347 ± .003	0.0135 ±.002	0.04 ± .01	0.020 ± .008	5.1 ±0.5	E2
0.427 ± .003	0.017 ± .002	0.09 ± .02	0.014 ± .005	8.0 ±1.0	M1
0.632 ± .005	0.018 ± .004	0.42 ± .20	0.0032 ±.0015	---	M1 or E2

The Decay Scheme of Indium-109

The present knowledge of the spins of the levels of odd-A indium and cadmium isotopes provides sufficient material to predict that the ground state of In^{109} has a spin of 9/2(+) and that the spin of the ground state of Cd^{109} is, in the order of likelihood, 5/2(+) or 7/2(+) (see Appendix II). Consistent with this, the experimental information obtained in the study of the positron spectrum of In^{109} and the γ transitions as summarized in Table I permits the proposal of a decay scheme which assumes that the ground state of In^{109} has a spin of 9/2(+) and the spin of the ground state of Cd^{109} is 5/2(+). This decay scheme is shown in Fig. 8, from which it is clear that the first excited state of Cd^{109} is an isomeric state which decays with the 12×10^{-6}-sec half life. For the first two excited states of Cd^{109} the experimental data were sufficiently accurate to allow the assignment of energies, spins, and parities with certainty. The next two levels in the decay scheme are based on measurements that have a large margin of error. However, as all other alternatives either were in conflict with even a broad interpretation of the shell model or led to greater disagreement with theoretical transition probabilities, the assignments are believed to be quite reliable. A discussion of the considerations leading to the decay scheme in Fig. 8 is contained in Appendix III.

It is of considerable interest to compare the spins and energies of the levels of Cd^{109}, as indicated in Fig. 10 with what is known about the levels of Cd^{111}.

The decay schemes of In^{111} and Ag^{111} have been studied by several investigators.[4, 12, 13] As a consequence of their work the spins and parities of the first five levels of Cd^{111} are well established (see Fig. 9). All the spins of the first four levels of Cd^{109}, as proposed in Fig. 8, are also found among the first five levels of Cd^{111}. The relative energy variation of corresponding levels in Cd^{109} and Cd^{111} is not larger than changes observed in other neighboring pairs of odd A isotopes.[14] The Cd^{111} 11/2(-) level may have as its counterpart the 0.530-Mev level of Cd^{109}. Unfortunately the spin of this level could not be inferred because the transitions associated with this level are very weak.

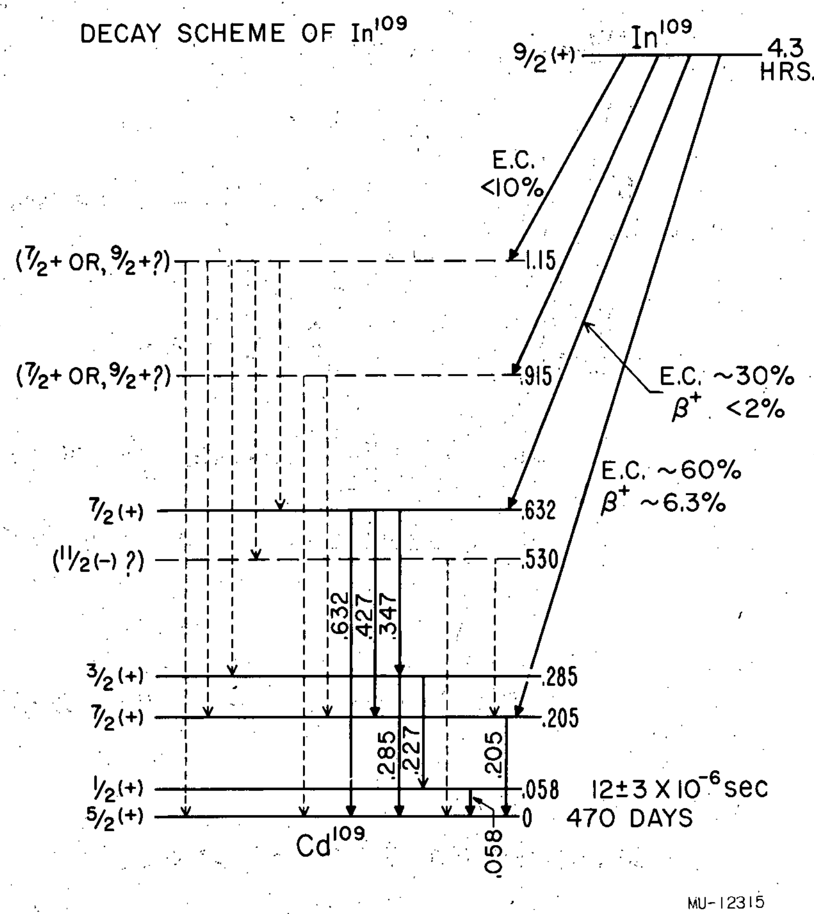

Fig. 8. The decay scheme of In^{109}.
The levels and transitions indicated with dotted lines are based on inconclusive or marginal data.

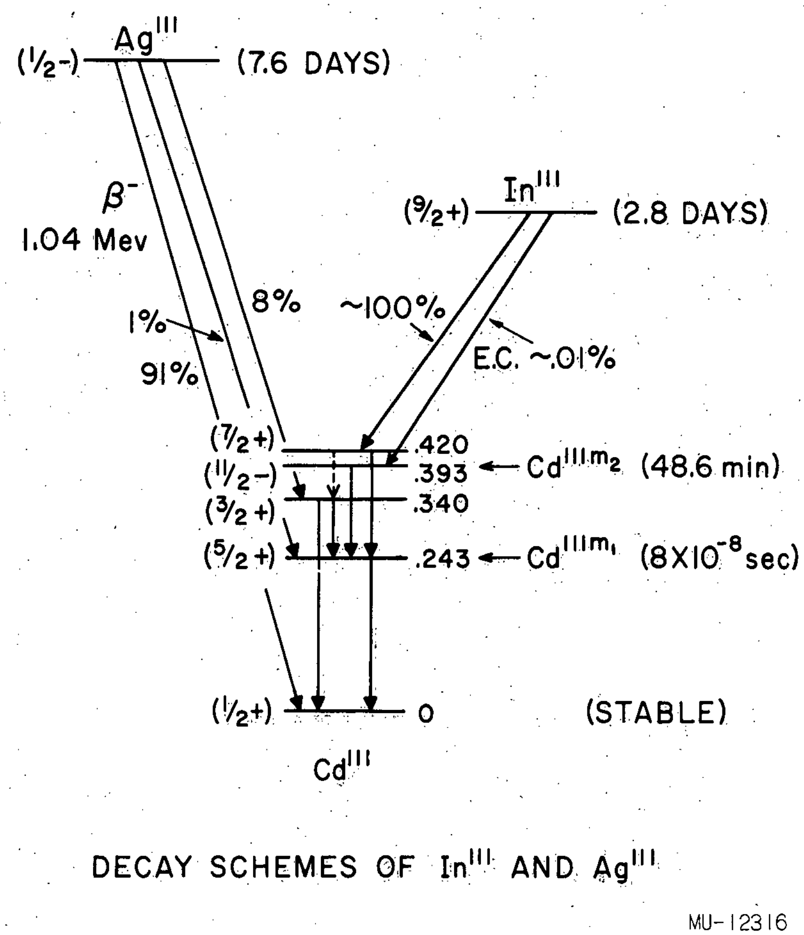

Fig. 9. The decay schemes of In^{111} and Ag^{111}.

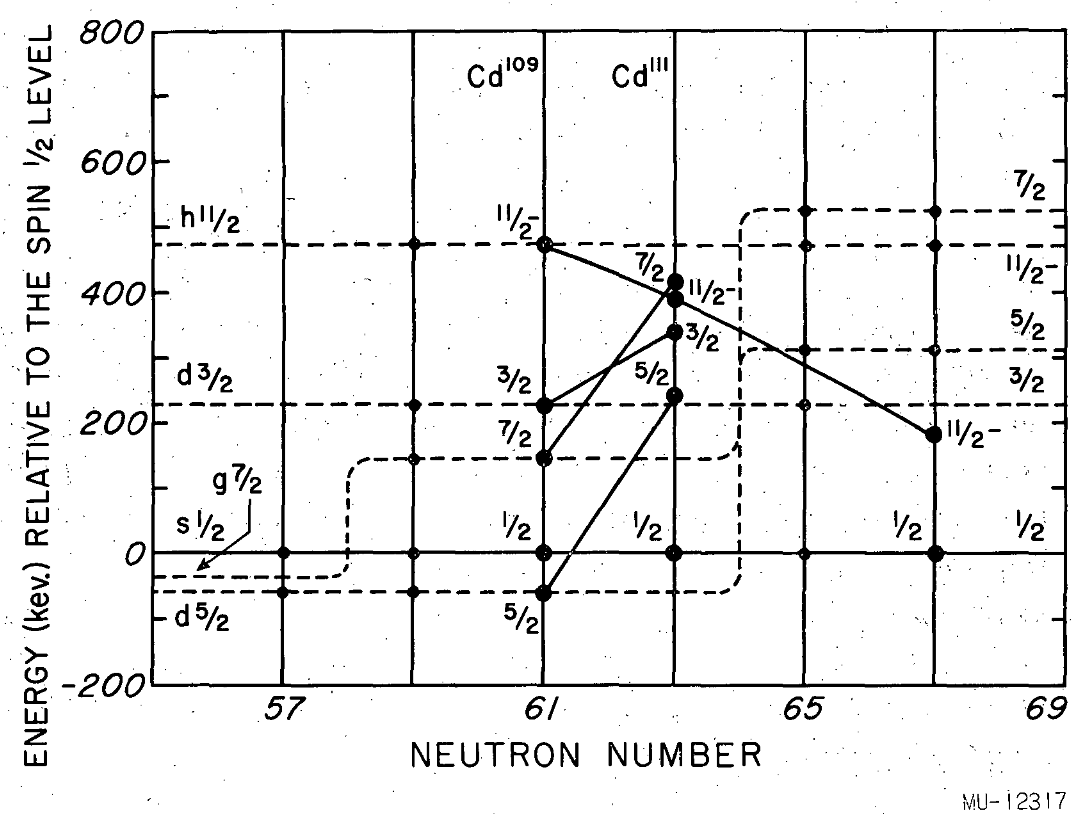

Fig. 10. The energy levels of Cd^{109} and Cd^{111}.

Transitions involving the second 7/2(+) state (0.632 Mev) in Cd^{109}, which are readily observed in the decay of In^{109}, are not necessarily expected to have their analog in the decay of In^{111} and Ag^{111}. If there is a second 7/2(+) state in Cd^{111} it should be, as in Cd^{109}, on the order of 0.43 Mev above the first 7/2(+) state. Electron-capture decay of In^{111} to this state would either be energetically impossible or extremely weak, since the 2.8-day half life for an allowed transition indicates that the energy available for electron capture to the first 7/2(+) state is about 0.40 Mev. Similarly, the decay of Ag^{111} to this level requires a third-forbidden β^- transition to compete with a first-forbidden transition; hence, the effects of the possible second 7/2(+) state would not be observed. In view of these considerations, the spins assigned to the levels of Cd^{109} are qualitatively consistent with what is known about the levels of Cd^{111}.

The energy behavior of the levels of Cd^{109} and Cd^{111} appears to be in rough agreement with the configurations for the levels of Cd^{109} suggested by the shell model (see Appendix III). In Fig. 10 the energies of the observed states of Cd^{109} and Cd^{111} are plotted relative to the 1/2(+) state. As a first approximation to the expected behavior of the various levels, the dotted lines in Fig. 10 represent the energy behavior of independent particle states with an additional interaction existing only between pairs of neutrons which can couple to give a total spin of zero. A delta-function attractive potential has been effectively used to explain such coupling properties,[15] with the result that the pairing energy varies with the angular momenta of the coupled particles according to the relation

$$\Delta E = -\frac{2j+1}{2A} C,$$

where A is the number of nucleons and C has an empirical value on the order of 25 Mev. The energy of a given configuration is then equal to the sum of the single-particle energies of the nucleons in the configuration and the coupling energies of the paired nucleons. The single-particle energies were chosen so as to yield a best fit the Cd^{109} levels. For neutron numbers below 59 the order of the levels indicated in Fig. 10 is just the single-particle level order, and it is in reasonable agreement with the Suess, Haxel, and Jensen level scheme.[16] The energy behavior represented by the dotted lines in Fig. 10 predicts that the level order of Cd^{109} and Cd^{111} should be the same, whereas in Cd^{113} the 5/2 and 7/2 levels should experience a considerable energy change away from the spin 1/2 ground state. A more realistic model must include interactions between all the nucleons, although the greatest lowering of the energy of a given state is still expected to be associated with the interaction between pairs of particles with the same angular momentum coupling to a total spin of zero. Furthermore, the average potential experienced by a given nucleon is not spherically symmetrical; consequently, the wave function of a certain spin state is a linear combination of wave functions of particles in a spherically symmetric potential well corresponding to different configurations with the same spin. A consideration of these effects has been used to explain the experimentally observed smooth movement of energy levels with changes in nucleon number. In line with this and with regard to Fig. 10, a more realistic behavior should be one in which the sudden discontinuities in the 5/2 and 7/2 lines between Cd^{111} and Cd^{113} are smoothened out over a greater range of odd neutron numbers. The experimental points for the spin 5/2 and 7/2 levels are in agreement with such a behavior. Figure 10 merely explains the relative energy trend with increasing neutron number of the spin-5/2, 7/2, and 1/2 levels in the immediate region of 61 and 63 neutrons. Very little significance can be attached to the dotted lines outside this region, which predict, for instance, that the spin 3/2 and 11/2 levels should lie on a horizontal line. Nevertheless, it is encouraging that the lines connecting the two 3/2 states and the 11/2 states are closer to being horizontal than the lines connecting the 5/2 and 7/2 states.

The above discussion suggests the following conclusions:

1. The spins of the levels of Cd^{109} and Cd^{111} are in agreement with the general shell-model level scheme and the strong pairing effect,

which has overwhelming empirical evidence to support it.

2. The states of Cd^{109} and Cd^{111} involve considerable configuration mixing as expected for odd neutron numbers between magic numbers. In line with this the observed transition probabilities are not expected to follow single-particle estimates closely.

3. The 11/2 level of Cd^{109} is expected to have an energy about 0.50 Mev above the ground state, indicating that the 0.530-Mev level in Fig. 8 has a spin of 11/2(-).

RADIOACTIVITY OF TIN-109

Beta-decay systematics[17] of Sn and In isotopes predict that the disintegration energy associated with the decay of Sn^{109} to In^{109} should be on the order of 3.5 Mev. Guided by the assumption that the decay in question is allowed, as in Sn^{111}, a search for Sn^{109} was undertaken with the expectation that the half life would be on the order of 10 minutes. The reaction chosen for the production of this isotope was $Cd^{106}(\alpha, n)Sn^{109}$. Since Cd^{106} has a natural abundance of only 1.2%, it was necessary to use cadmium enriched in Cd^{106}. The targets were bombarded for 15-minute periods and chemical separations of the tin activities were completed about 12 minutes after the end of the bombardment. The tin sources were studied with the beta-ray spectrometer and in most cases the first readings were taken about 10 minutes after the chemical separation had been completed. An analysis of the conversion electron spectra (Fig. 11) of several sources established that Sn^{109} has a half life of 18 minutes and that the following γ rays must be attributed to the decay of Sn^{109}:

γ-ray energy	Relative intensity of conversion electron
1.12	0.027
0.887	0.012
0.658	1.000
0.521	0.014
0.335	0.098

The assignment of these γ rays to Sn^{109} follows from the agreement between the 18-minute half life associated with these γ rays and the observed 18-minute growth of the 0.205-Mev conversion-electron peak of In^{109} (Fig. 12.) The conversion electrons of a 0.078-Mev transition were also observed to have a half life of 18 minutes, and it was at first believed that this transition occurred in the decay of Sn^{109}.

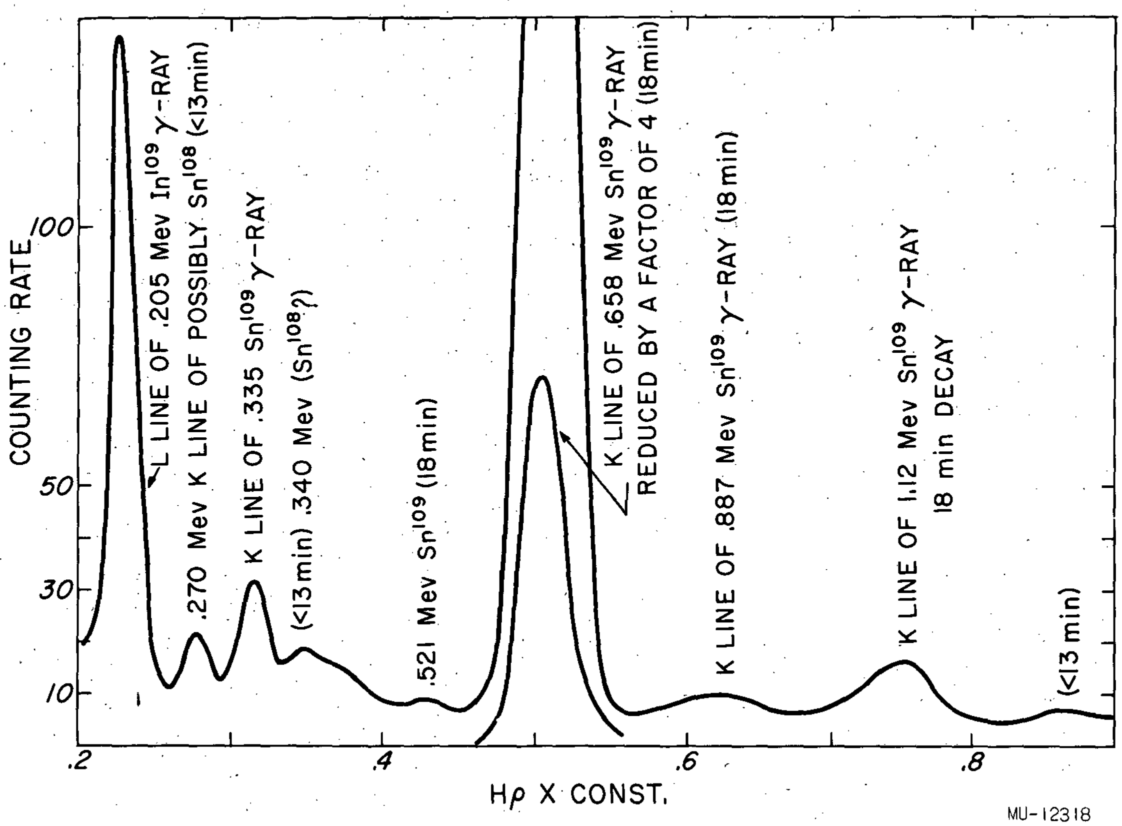

Fig. 11. The conversion-electron spectrum of tin sources taken approximately 20 minutes after the chemical separation.

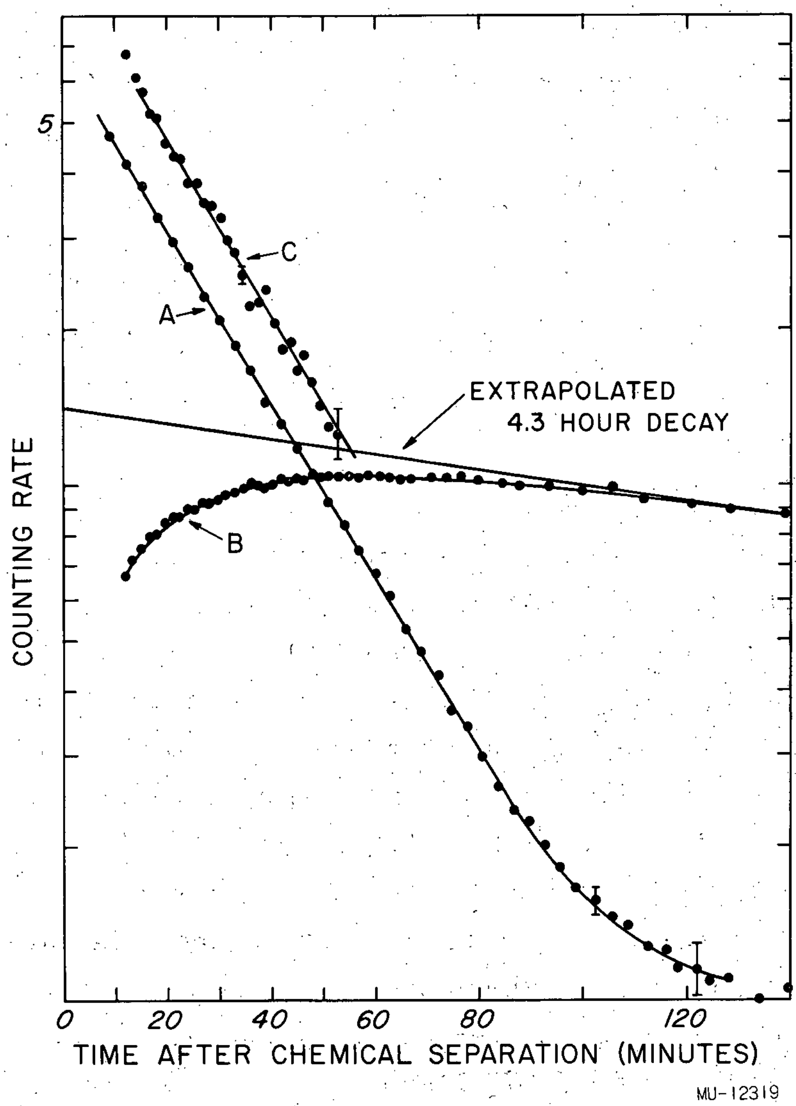

Fig. 12. The decay of Sn^{109} and the growth of In^{109}:
A. The decay of the 0.658-Mev gamma rays of Sn^{109};
B. The growth and the decay of the K-conversion line of the 0.205-Mev transition of In^{109};
C. The decay of Sn^{109} calculated from the growth of In^{109}.

However, further experiments cast serious doubt on the assignment of the 0.078-Mev transition to the decay of Sn^{109} in spite of the apparent equality of its half life to that of the other transitions. In the course of the study of Sn^{109} two different qualities of cadmium enriched in Cd^{106} were used. One consisted of about 60% Cd^{106} and 15% Cd^{108}, with the remaining 25% made up of the other isotopes of cadmium in approximately the ratio of their natural abundance. The other cadmium had the following composition:

Isotope	Percentage
106	19.94
108	0.65
110	7.21
111	39.16
112	11.85
113	4.14
114	15.25
116	1.80

The experiments on the basis of which the activity of Sn^{109} was first reported were done with the cadmium enriched in Cd^{106} to 60%. It was found that the intensity of the conversion electrons of the 0.078-Mev transition was about equal to the intensity of the conversion electrons of the 0.658-Mev transition. But when the latter type of cadmium was bombarded, the ratio of the conversion-electron intensity of the 0.078-Mev transition to that of the 0.658-Mev transition was approximately 20. For both types of cadmium the conversion-electron ratios of the 0.658-Mev transition to the 0.205-Mev transition in the decay of In^{109} were in all cases the same. Furthermore, when the targets were bombarded with higher-energy α particles, so that the $(\alpha, 2n)$ reaction predominated, the intensity of the 0.078-Mev transition relative to the 0.658-Mev transition was higher by a factor of about 5 than when the bombardment energy was such that the (α, n) reaction was predominant. These results indicate that the 0.078-Mev transition does not belong to the decay of Sn^{109}. The fact that the yield of the activity giving rise to the 0.078-Mev transition is largest when cadmium having the relatively large amounts of isotopes with mass numbers above 108 is used suggests the possibility that it is due to an isomeric state in one of the tin isotopes with mass numbers above 111. The existence of such an isomeric state has further corroboration in a previously reported 18-minute activity induced when tin is exposed to slow neutrons.[18] This activity was reported in 1939, however, and no further mention of it has appeared in the literature since then. Also the observation was made with a Geiger counter; hence, aside from the 18-minute half life, there is no additional evidence to identify it with the 0.078-Mev transition. An attempt to detect the difference between the half life of Sn^{109} and the activity related to the 0.078-Mev transition indicated that Sn^{109} has a slightly shorter half life. The best determination of the half life of Sn^{109} was done with a NaI(Tl) crystal and pulse-height analyzer set to count γ rays above 0.60 Mev, and yielded a value of 18.1 ± 0.3 minutes. The observation of the decay of the L conversion electron peak of the 0.078-Mev transition in the β-ray spectrometer resulted in a value of 19 ± 1 minutes.

The study of the positron spectrum of Sn^{109} (Fig. 13) was complicated by several factors. Owing to the presence of appreciable amounts of Cd^{108} in the target material the 35-minute Sn^{111} was also produced in the bombardments. At the optimum energy for the production of Sn^{109} the (α, 2n) cross section is of the order of 1/4 of the (α, n) cross section hence Sn^{108} is also produced.[5] When we take into account the time that elapses between the end of the bombardment and the first spectrometer readings, which was usually about 25 minutes, the Sn^{109} activity is further reduced relative to the conflicting Sn^{111} activity. Thus, together with the Sn^{109} positrons we observe, Sn^{111} positrons with the maximum energy of 1.5 Mev, the growth of In^{108} positrons corresponding to the 9 minute decay of Sn^{108} and their subsequent decay with 40 minute and 55 minute periods, the associated maximum positron energies being 3.5 and 1.4 Mev.[5]

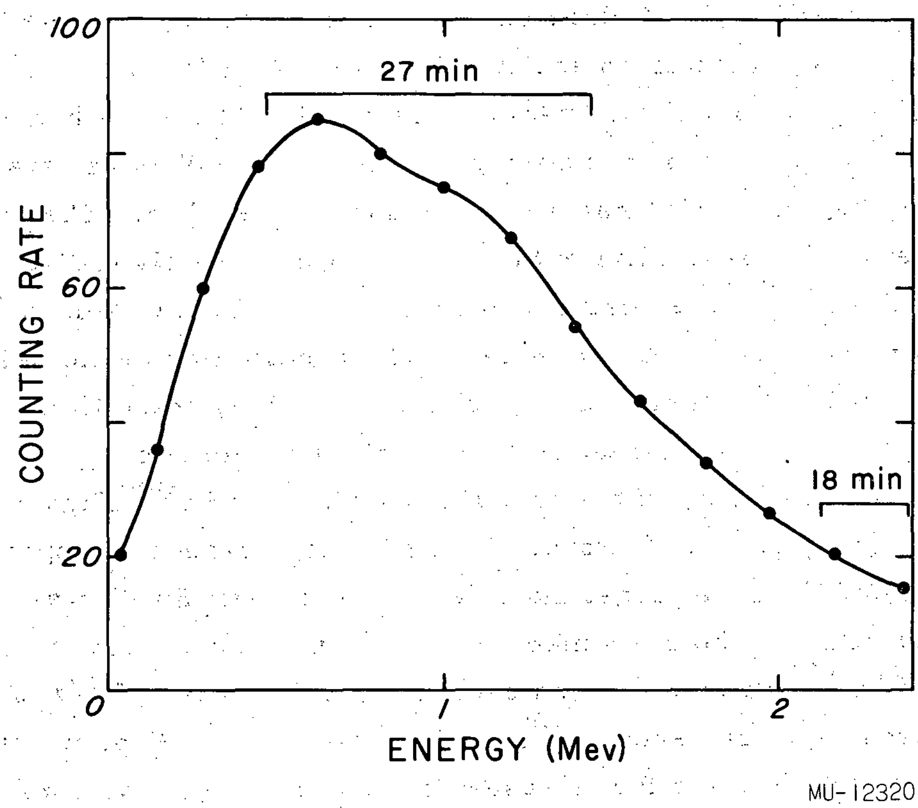

Fig. 13. The positron spectrum of tin sources taken approximately 25 minutes after the end of the bombardment. The approximate initial decay rates of the different regions of the spectrum are indicated.

In view of these difficulties it was not possible to determine the positron spectrum of Sn^{109}. Nevertheless, the following conclusions can be drawn: The maximum energy of the positron spectrum is greater than 2.5 Mev. There is a lower-energy component with a maximum energy between 1.3 and 1.8 Mev. The ratio of electron capture to positron emission is between 3 and 6. The log ft value associated with the higher-energy positrons must be greater than 5.7, whereas the log ft value of the lower-energy positrons can be as low as 4.8.

The intensity of the conversion electrons of the 0.658-Mev transition when compared with the intensity of the conversion electrons of the 0.205-Mev transition in the decay of In^{109} indicates that the conversion coefficient of the 0.658-Mev transition is greater than 0.02. The lower limit of 0.02 corresponds to the case in which every Sn^{109} decay is accompanied by the emission of one 0.658-Mev γ ray. The γ-ray spectrum of Sn^{109} (Fig. 14) obtained with a 1" by 1.5" NaI(Tl) crystal and a continuously recording pulse-height analyzer shows that the ratio of the number of 0.658-Mev γ rays to the number of Sn^{109} decays is $0.30 \pm .10$. This value is based on a consideration of the efficiency of the crystal and the height of the 0.658-Mev peak relative to the height of the 0.205-Mev. In^{109} peak that remains after most of the Sn^{109} has decayed. When this value is taken into account the conversion coefficient of the 0.658-Mev transition is $0.07 \pm .02$. Theoretical conversion coefficients of an M4 and an E5 transition fit this value. The E5 transition is unlikely because the theoretical single-particle estimate of the half life associated with such a transition is much greater than 18 minutes.[19] The single-particle estimate of the M4 transition half life is 10 seconds. An empirical estimate on the basis of the known M4 transitions of In^{113} and In^{115} indicates a half life of 1 minute. An attempt to measure the half life of the 0.658-Mev transition by performing chemical separations of the indium from the tin activity and observing the decay of γ rays in the region of 0.658 Mev showed that the half life is shorter than 2 minutes. Analysis of the γ and conversion-electron spectrum of Sn^{109} also indicates that the 0.335-Mev transition is either an M1 or an E2 transition. Since the γ-ray intensity of the other transitions of Sn^{109} was not obtained, nothing can be said about their multipolarity.

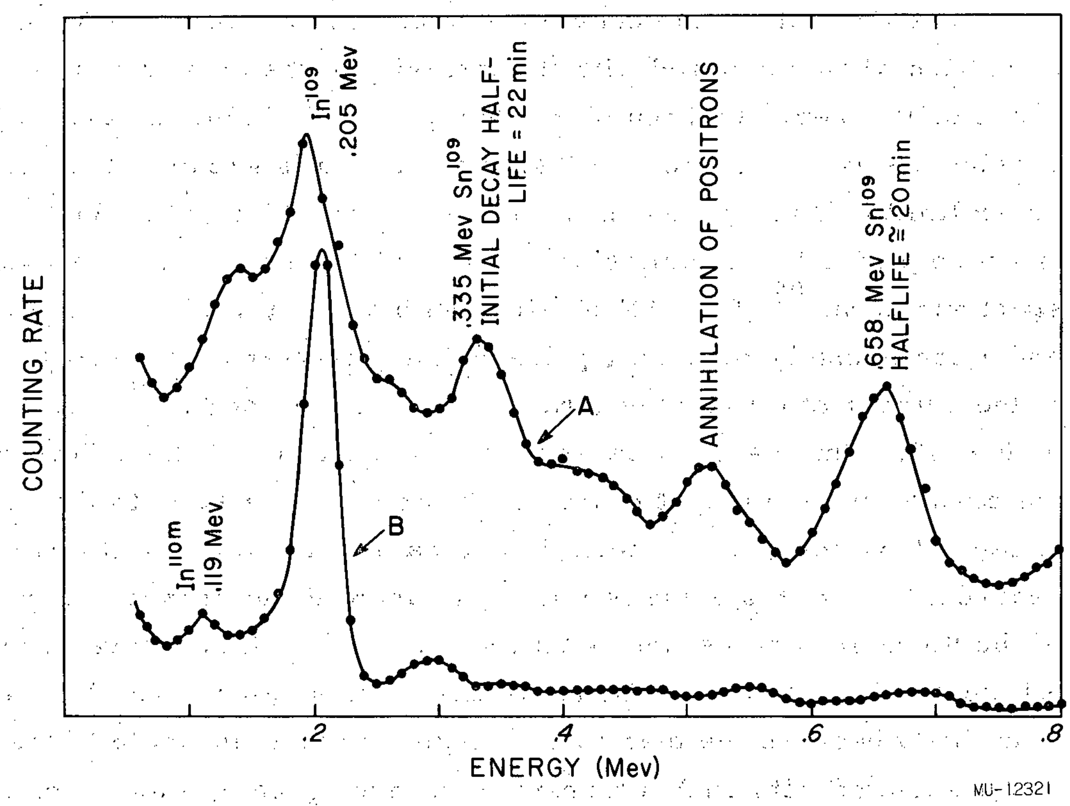

Fig. 14. The gamma-ray spectra of a tin source obtained with a NaI(Tl) crystal;
A. 15 minutes after chemical separation of tin;
B. 5 hours after the chemical separation.

The experimental information presented above is far from sufficient to establish the decay scheme of Sn^{109}. However, some useful conclusions can be reached when it is compared with the experimental information on other isotopes of tin and indium. The ground states of Sn^{113}, Sn^{115}, Sn^{117}, and Sn^{119} all have a spin of 1/2,[20] whereas Sn^{111} has a ground-state spin of 7/2(+). The assignment of the spin to Sn^{111} and Sn^{113} is based on the observed log ft values and shell-model considerations. In this connection it is helpful to refer to Fig. 12, which depicts a similar trend of the ground-state spins of cadmium. One would not expect the behavior of the levels of odd-A tin isotopes to be very different from the behavior of the levels of odd-A cadmium isotopes when the comparison is made between tin and cadmium isotopes with the same neutron number. Thus, the change of spin from 1/2 to 7/2 in tin and from 1/2 to 5/2 in cadmium occurs between the neutron number 63 and 61 in both cases. The spin of 7/2 for Sn^{111} in contrast to 5/2 for Cd^{109} is not unreasonable, since in Cd^{109} the 7/2 level is only 0.205 Mev above the spin 5/2 ground state. Extending this discussion to Sn^{109}, one would expect a ground-state spin of 7/2(+) or possibly 5/2(+). Here, a comparison of the radioactivities of Sn^{109} and Sn^{111} can be used to decide between the two possibilities. The work of McGinnis[4] establishes that Sn^{111} decays directly to the ground state of In^{111} by electron capture and the emission of positrons with a maximum energy of 1.5 Mev, and the log ft value for this decay is 4.8. McGinnis also reported that no conversion-electron lines could be identified with the decay of Sn^{111}. His failure to observe conversion-electron lines does not rule out the possibility of some electron-capture and positron-emission branching to excited states with spins 5/2(+), 7/2(+), and 9/2(+) which are expected to be more than 0.50 Mev above the ground state. The γ rays associated with the above possibility would be relatively high-energy M1 or E2 transitions with very small conversion coefficients. In view of the difficulty of taking a conversion-electron spectrum of a 35-minute activity with a β-ray spectrometer, they could easily have escaped detection. Admitting appreciable decay of Sn^{111} to the above-mentioned excited states of In^{111}, one would not expect this decay to measurably involve the 1/2(-) state of In^{111}--which is very probably the first excited state, as in In^{113} and In^{115}. These considerations on the decay of Sn^{111} permit prediction of what one would expect to observe in the decay of Sn^{109} if the spin of the ground state of Sn^{109} were 7/2(+). Owing to the greater disintegration energy, β-decay branching to the higher excited states of In^{109} would be enhanced so that the conversion-electron spectrum resulting from the decay of these excited states would be stronger than in Sn^{111}. The 1/2(-) state of In^{109} would still not be expected to be measurably involved in the decay. The log ft value of the highest-energy positron decay mode would be, as in Sn^{111}, about 4.8. The observed decay of Sn^{109} is significantly different from the expected decay with the spin of 7/2(+) for the ground state. A strong conversion-electron line corresponding to a 0.658-Mev M4 transition is observed in the decay of Sn^{109}, and the log ft value of the higher-energy β-decay mode is greater than 5.7. The presence of an M4 transition indicates that the 1/2(-) state of In^{109} is involved in the decay to a large extent, and the log ft value greater than 5.7 suggests that the decay of Sn^{109} to the ground state of In^{109} is forbidden. When a spin of 5/2(+) for the ground state of Sn^{109} is considered it is possible to fit the information obtained for Sn^{109} into a decay scheme (Fig. 15). This decay scheme represents one way of accounting for the observed M4 transition and the log ft value greater than 5.7 for the high-energy component of the positron spectrum. One is led to conclude that of the two possibilities for the ground-state spin of Sn^{109}, 5/2(+) is the proper choice. The change in the ground-state spin in going from Sn^{111} to Sn^{109} indicates that the energy difference between the 5/2 and the 7/2 levels is very small in both Sn^{109} and Sn^{111}, as the change in the energy difference between the two levels in Cd^{109} and Cd^{111} is small (Fig. 10). The decay scheme (Fig. 15) requires that the first excited state of In^{109} be 1/2(-) and be 0.658 Mev above the ground state. If we examine the energies of the spin 1/2(-) states above the 9/2(+) ground states in In^{113} and In^{115}, we find that the presence of the 1/2(-) state 0.658 Mev above the ground state is not unreasonable.

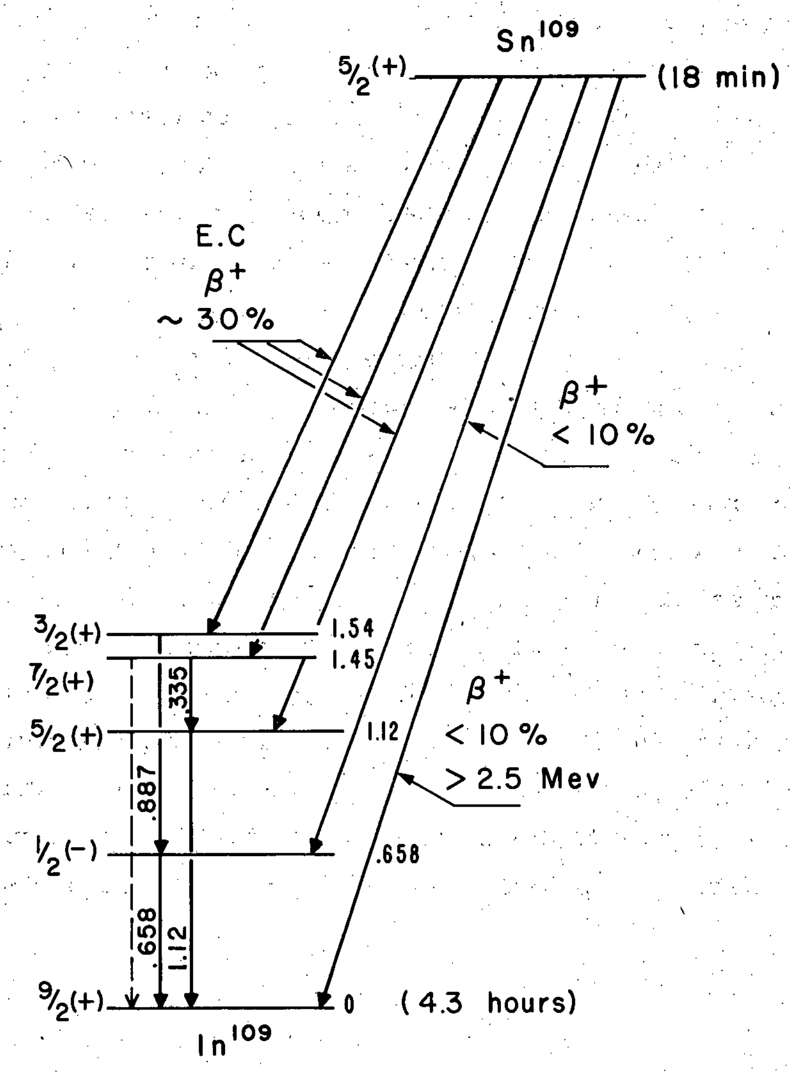

Fig. 15. Tentative decay scheme of Sn^{109}

Isotope	Energy of the 1/2(-) state (Mev)
In^{109}	0.658
In^{111}	----
In^{113}	0.392
In^{115}	0.335

A possible explanation of the above trend is in the interaction between protons and neutrons. The interaction energy is expected to be largest when the orbital angular momenta of the proton and the neutron are equal. The mixed neutron configurations of the indium isotopes are expected, on the basis of the shell model, to include progressively stronger admixtures of configurations containing paired $1h_{11/2}$ neutrons as the neutron number increases. The $1h_{11/2}$ neutrons will interact more strongly with the $1g_{9/2}$ protons than with the $2p_{1/2}$ protons. Consequently, the 1/2(-) state, which contains more $g_{9/2}$ protons than the 9/2(+) ground state, is depressed relative to the 9/2(+) as the neutron number increases. With these considerations in mind, the observed decay of Sn^{109} suggests that In^{111} has an M4 isomer with a half life of several minutes. Some explanations for the absence of information on this possible isomer are mentioned in Appendix II in connection with the discussion of the ground-state spin of In^{109}. The foregoing discussion lends further support to the assignment of a spin of 9/2(+) to the ground state of In^{109}, and indicates that it would be worth while to investigate the possibility that the isomeric state of In^{111} may have been overlooked because of the shortness of its half life.

SUMMARY AND CONCLUSIONS

The positron, conversion-electron, and γ-ray spectra of In^{109} and Sn^{109} were studied with a β-ray spectrometer and NaI(Tl) crystal spectrometer with the following results:

1. In^{109} decays by electron capture and positron emission with the maximum energy of 0.795 Mev. The associated log ft value is 4.95 and the branching ratio β^+/E. C. is 0.068 ± .006. In addition to the four previously reported γ transitions, ten more were assigned to the decay of In^{109}. The energies, intensities, conversion coefficients, and K/L ratios were measured where it was possible, and the results are given in Table I. The energies of the transitions not listed in Table I are given on page 12.

2. A $12 \pm 3 \times 10^{-6}$-sec isomeric state of Cd^{109} was observed in the decay of In^{109}. The energy of the transition is 0.058 Mev, and its multipolarity is probably E2.

3. Sn^{109} decays with a half life of 18 minutes by electron capture and positron emission. The positron spectrum is complex, and the high-energy component has a maximum energy greater than 2.35 Mev. Five γ rays were observed in the decay of Sn^{109} (page 26). The conversion coefficient of the 0.658-Mev γ ray is 0.07 ± .02.

4. A 0.078-Mev γ transition with a half life of 18 min, which is also produced from cadmium by an (α, n) or an (α, 2n) reaction, must be assigned to a tin isotope other than Sn^{109} in the region of mass numbers greater than 112.

The well-established theoretical calculations of conversion coefficients, K/L ratios, single-particle transition probabilities, and shell-model considerations were used in the analysis of the experimental results. It was found that In^{109} must be assigned a ground-state of 9/2(+) and the ground state of Cd^{109} a spin of 5/2(+). The energies and spins of some of the excited states of Cd^{109} were also established and are presented in the decay scheme of In^{109} (Fig. 8). The most reasonable spin assignment to the ground state of Sn^{109} is 5/2(+).

The spins assigned to the ground states of In^{109} and Sn^{109} and to the levels of Cd^{109} appear to be consistent with the present experimental information on the spins of the other isotopes of indium, cadmium, and tin.

ACKNOWLEDGMENTS

It is a pleasure to thank Professor A. C. Helmholz for the support of this work and for the helpful discussions during its course. S. Warren Mead and Wesley O. Doggett, who collaborated in certain phases of the investigation were of considerable assistance. The successful production of the activities was facilitated by the assistance of William B. Jones, Peter F. McWalters, and the members of the operating crew of the University of California 60-inch cyclotron.

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APPENDIX

I. The Gamma Transitions in the Decay of Indium-109

The experimental information on the γ transitions occurring in the decay of In^{109} from which most of the results presented in Table I are derived is discussed below. Each subtitle gives the energy of the transition under consideration.

0.205 Mev. The conversion coefficient of the 0.205-Mev transition was measured by means of a 2-mg/cm^2 gold converter calibrated for efficiency in terms of the known conversion coefficient of the 0.172-Mev transition in the decay of In^{111}.[4] This measurement yielded a value of 0.070 ± .010. The determination of the K/L ratio of this transition was complicated by the presence of a weak K-conversion line of the 0.227-Mev transition in In^{109}, which cannot be resolved from the L-conversion line of the 0.205-Mev transition. A careful analysis of the conversion-electron spectrum resulted in a K/L ratio of 7.6 ± 0.4. Theoretical values of the internal conversion coefficient for M1 and E2 transitions are 0.06 and 0.095 respectively.[21] The experimental value is in close agreement with an M1 transition. If one uses empirical curves of K/L ratios,[14] the observed K/L ratio of 7 agrees more closely with an M1 transition for which K/L is 8. The curves give 4.7 for an E2 transition. One can conclude that the 0.205-Mev transition is predominantly M1 with a possible mixture of E2.

The fraction of In^{109} decays resulting in the 0.205-Mev transition was measured by the same method as used for evaluating the positron decay ratio. It was found that 75% of In^{109} decays involved this transition. From coincidence measurements utilizing the positron annihilation radiation and from a β-γ coincidence spectrum obtained with a stilbene crystal mounted on a photomultiplier tube, the positrons of In^{109} were found to be in coincidence with the 0.205-Mev γ rays. From these results it appears that the Cd^{109} level that decays by the 0.205-Mev transition is populated through the 0.795-Mev positron and electron-capture decay mode. If the theoretical electron capture to positron branching ratio of 8.9 is accurate, then 83% of the 0.205-Mev transitions are connected with this mode of electron capture and positron decay. The remainder must be associated with electron capture to higher excited states of Cd^{109}, which decay to the level giving rise to the 0.205-Mev transition.

<u>0.058 Mev.</u> The conversion-electron spectrum due to this transition is about 0.49 ± .03 in intensity relative to the strong 0.205-Mev conversion-electron spectrum. However, attempts to observe γ rays of this transition with a NaI crystal were not successful, indicating that the conversion coefficient is very large. An estimate of the maximum conversion coefficient for which a γ peak could be detected above the high Compton background is approximately 5. Since no peak due to a 0.058-Mev γ ray was observed, the conversion coefficient must be greater than 5. The percentage of In^{109} decays resulting in this transition is on the order of 2.5%.

The K/L ratio of the 0.058-Mev transition was found to be 0.85 ± .08. Empirical curves of K/L ratios[14] give the following values for this energy:

Transition	K/L ratio
M1	7.5
M2	5.5
M3	1.6
M4	0.3
E1	3.3
E2	0.8
E3	0.4
E4	0.1

The E2 transition is the closest to the experimental value. However, an M3 or an E3 transition is still within the distribution of the empirical points from which the curves are derived. The theoretical conversion coefficient for all these transitions is larger than 5. A consideration of the expected lifetimes for these transitions can be used to determine the multipolarity of the 0.058-Mev transition. Theoretical transition probabilities,[19] conversion coefficients,[22] and lifetimes associated with the possible multipolarities for the 0.058-Mev transition are listed below.

Multi-polarity	γ Transition probability	Conversion coefficient	Mean life (sec)
E2	5×10^{4}	14	1.4×10^{-6}
E3	6×10^{-3}	15	1.1
M3	2×10^{-4}	400	12.2

The mean lives quoted above are expected to coincide with experimental values only within a factor of 100. However, they are sufficient to reliably distinguish an E2 transition from an E3 or an M3 transition if the half life is measured.

This transition was expected to be in delayed coincidence with K x-rays and very probably with one or more of the γ rays observed in the decay of In^{109}. A γ- or x-ray detector and pulse-height analyzer was connected to the trigger input of a Tektronix 514D oscilloscope. The deflection input of the oscilloscope was coupled to a pulse-height analyzer receiving pulses originating in the detection of 0.030- and 0.055-Mev K and L conversion electrons of the 0.058-Mev transition. To accomplish this a special detector was designed in order to insure sufficient discrimination between the low-energy conversion electrons and all other more intense radiations, including the conversion electrons from the 0.205-Mev transition, positrons, and all the x- and γ-rays accompanying the decay of In^{109}. An anthracene crystal of a thickness of approximately 0.1 mm was mounted on the face of a 6292 Dumont photomultiplier. A weak source was deposited on an 8-mg/cm^2 aluminum foil, which was placed about 3 mm above the face of the photomultiplier. Opposite this detector were placed a NaI crystal and photomultiplier, serving as the detector for the other channel, and making a lighttight seal over the chamber containing the source and anthracene crystal. The effectiveness of the low-energy electron detector is demonstrated in the curves of Fig. 16. The upper curve gives the pulse-height distribution with the source facing the anthracene crystal, the low-energy electrons free to impinge upon it. When the foil holding the source was turned over so that 8 mg/cm^2 of aluminum intervened between the source and the detector, the pulse-height distribution had a greatly diminished low-energy component, since this amount of aluminum is sufficient to stop 0.065-Mev electrons. It was hoped that this arrangement would permit observation of the L conversion electrons as a peak in the pulse-height spectrum, but it is not difficult to see from Fig. 16 that this was too optimistic. The pulse height corresponding to the small light yield from most organic scintillators for 0.055-Mev electrons is barely above the pulse height of noise pulses at room temperature, which can be as high as 20 kev from anthracene. An estimate of an average number of 15 initial photoelectrons from the sensitive cathode reaching the first dynode of the photomultiplier per 55-kev electron would indicate that the resolution of the pulse-height spectrum cannot be better than 50%. Furthermore, the 0.058-Mev transition occurs in only 2.5% of In^{109} decays, so that K and lower-energy x rays make a comparatively large contribution to the low-energy part of the pulse-height spectrum even though the efficiency of their detection is greatly reduced by the thinness of the crystal. In spite of these difficulties it is clear that the area between the two curves in Fig. 16 represents detection of the 0.058-Mev transition. With the pulse-height analyzer set to admit to the scope input pulses whose heights fall within this area, it was found that the pulses appearing on the scope were distributed in time with decreasing intensity from the origin of the sweep. The distribution was measured by counting visually the number of pulses occurring in 10-microsecond intervals at different positions along the x axis of the oscilloscope picture. The results are presented in Fig. 17, where the three sets of experimental points correspond to three different

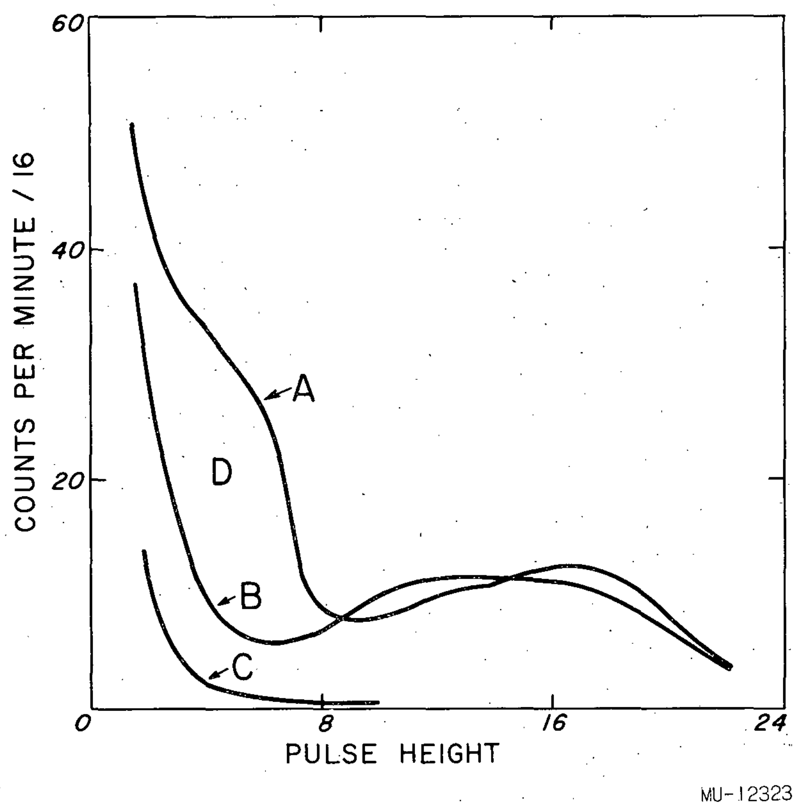

Fig. 16. The detection of the conversion electrons of the 0.058-Mev transition of In^{109} with an anthracene crystal:

A. Pulse-height spectrum with no absorber between source and crystal;

B. Pulse-height spectrum with 8 mg/cm^2 aluminum absorber between source and detector;

C. Background without source;

D. Area representing detection of the 0.055- and 0.032-Mev conversion electrons.

regions of the x- and γ-ray spectrum that were set to trigger the oscilloscope sweep. The half life of the 0.058-Mev transition thus obtained is $12 \pm 3 \times 10^{-6}$ sec. The upper set of points on Fig. 9 shows that the 0.058-Mev transition is in delayed coincidence with one or more of the γ rays with energies above 0.205 Mev. Since electron capture is the principal mode of the decay of In^{109}, a positive result is also obtained when x-rays are made to trigger the oscilloscope sweep. The ratio of counting rates of delayed pulses for the γ-ray and the x-ray parts of the experiment are consistent with the results mentioned before, i.e., that 2.5% of In^{109} decays involve the 0.058-Mev transition, if the 0.058-Mev transition is in delayed coincidence with about 8% of the γ rays above 0.205 Mev in energy. This indicates that the ratio of the number of γ decays with energies above 0.205 Mev to the number of In^{109} decays is on the order of 1/3. The greatly reduced ratio of the delayed counting rate to trigger rate when the γ pulse-height analyzer is set on the peak of the 0.205 Mev γ ray indicates that the 0.058-Mev transition is not in delayed coincidence with the 0.205-Mev transition. The counts that are nevertheless observed can be partly explained by the Compton background due to the higher-energy γ rays with which the 0.058-Mev transition is in delayed coincidence but it is more likely that the transition is in delayed coincidence with the weak 0.227-Mev γ rays, which are partially detected since the resolution of the crystal γ spectrometer was not better than 15%. It is significant that almost no delayed counts were observed with 0.8 mg/cm^2 of aluminum between the source and the detector or when the pulse-height analyzer was set to integrate the region of pulse heights above the low-energy component.

For the purpose of establishing the multipolarity of the 0.058-Mev transition, the method used in the half-life determination is entirely adequate, since the result obtained definitely eliminates from consideration the E3 and M3 transitions. The 0.058-Mev transition is therefore an E2 transition.

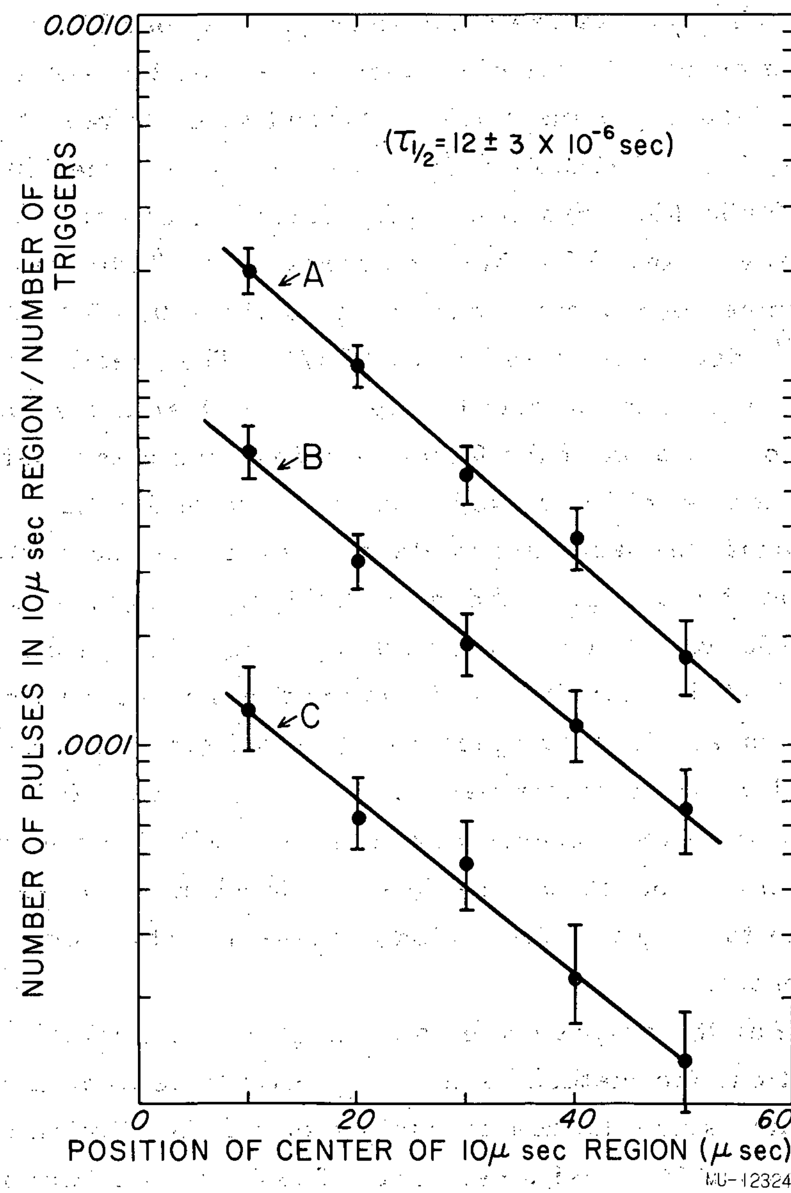

Fig. 17. The half life of the 0.058-Mev transition in the decay of In^{109}:

A. Oscilloscope sweep triggered by the gamma rays with energies above 0.250 Mev;

B. Scope triggered by K x-rays;

C. Scope triggered by the 0.205-Mev gamma rays.

0.227 Mev. Although this transition is not seen as a line in the conversion electron spectrum of In^{109}, its presence is revealed when an external gold converter is used (see Fig. 5). The existence of this line also solves an apparent paradox in earlier measurements of the K/L ratio of the 0.205-Mev transition. The K/L ratio of this transition measured from spectra of the many sources prepared in the course of the investigation of In^{109} varied from source to source, sometimes by as much as 20%. Such a variation was much larger than the probable error calculated from a consideration of statistics, Geiger-tube dead time, and other intrinsic errors in the method used to evaluate the K/L ratio. For a given source the K/L ratio did not vary as a function of time, thus eliminating the possibility of a weak conversion line due to coincidence of some other activity having a different half life, with either the K or L peak of the 0.205-Mev transition. The presence of the 0.227-Mev transition in the decay of In^{109} solves the apparent inconsistency in the K/L ratio measurements. The K-conversion electrons of this transition are only 0.0025 Mev lower in energy than the L-conversion electrons of the 0.205-Mev transition. It is clear that the height of the composite curve of two lines separated by a distance corresponding to this energy difference would be a function of the width of the lines. The width of observed lines depends on the thickness and area of the source in addition to the intrinsic resolution of the spectrometer. With sources that were relatively thick and spread over a large area the composite peak due to the L line of the 0.205-Mev transition and the K line of the 0.227-Mev transition was necessarily higher, relative to the K line of the 0.205-Mev transition, than for smaller and thinner sources for which the resolution was on the order of 1.5%. The best source showed a marked deviation of the composite peak from the expected shape of a single L line. The deviation was consistent with the energy of 0.227 Mev. With these considerations in mind a quantitative analysis of the spectra gives the result that the intensity of K-conversion electrons in the 0.227-Mev transition relative to the intensity of the K-conversion electrons of the 0.205-Mev transition is 0.020 ± .007. From this result, the conversion coefficient of the 0.227-Mev transition is 0.04 ± .02. For a transition of this energy, theoretical values[21] of conversion coefficients of only M1 and E2 transitions are within 0.04 ± .02.

0.285 Mev. Conclusive evidence for this transition in the decay of In^{109} is found only in the conversion-electron spectrum where the K-conversion line is well resolved from the neighboring lines. When an external gold converter is used the K peak due to this transition falls on the slope of the L peak of the much stronger 0.205-Mev transition. The K/L ratio of this transition could not be established accurately because of the presence of a 0.325-Mev transition. It appears, however, to be greater than 7, indicating an M1 or an E2 transition.

0.347 Mev. From the conversion electron spectrum the K/L ratio for this transition is 5.1 ± 0.5, which falls in the region of empirical K/L ratios of E2, E3, or M4 transitions. The conversion coefficient has been estimated as 0.020 ± .008, which is consistent with theoretical values for either an E2 or an M1 transition. When both the K/L ratio and the conversion coefficient are considered the multipolarity of this transition is E2.

0.427 Mev. The K/L ratio of 8 ± 1 and the estimated conversion coefficient of 0.014 ± .005 are consistent only with an M1 transition when theoretical values for conversion coefficients and K/L ratios are considered.

0.632 Mev. When indium sources were made from the α bombardment of silver, a peak at about 0.625 Mev was observed. The half life of this peak appeared to be 5 hours; hence it was believed that it was due to the 5-hour In^{110m} activity, in which there is a 0.650-Mev transition.[23] Unless the shape of the line at 0.625 Mev is studied very carefully it is easy to overlook the effects of the 0.632-Mev transition in In^{109}. This is a probable reason for McGinnis's failure to report this transition.[4] With the expected shape of single lines in mind, a study of the shape of this line and its change with time revealed that it is composed of three conversion-electron lines, two with the energies 0.620 Mev and 0.632 Mev and a half life of 4.2 ± .04 hours, and the other at 0.657 Mev with a half life of 5.1 ± .03 hours. The former were therefore assigned to In^{109}, and the latter to In^{110m}. The conversion-electron intensity of the 0.632-Mev transition relative to the K-conversion electrons of the 0.205-Mev transition was evaluated as 0.018 ± .004. The 0.620-Mev conversion line is weaker than the 0.632-Mev line by a factor of 4. For the same reason as mentioned above the intensity of the 0.632-Mev transition could not be accurately determined from the spectrum obtained with an 8-mg/cm^2 gold converter or with the NaI crystal spectrometer. When the shape of the composite peak in the Au converter spectrum, was taken into account, the value of the conversion coefficient of the 0.632-Mev transition was nevertheless estimated as 0.0032 ± .0015. This would place the transition in the class of M1 or E2 transitions since theoretical conversion coefficients for a 0.632-Mev transition in Cd are as follows:

Multipolarity	Conversion coefficient
E1	0.001
M1	0.0033
E2	0.0027
M2	0.0086
E3	0.0066

II. The Spins of the Ground States of Indium-109 and Cadmium-109

The experimental information on the spins of levels of other odd-A indium isotopes provides sufficient material to predict the spin of the ground state of In^{109}. The spins of In^{113} and In^{115} have been established as 9/2.[20] In^{111} has been assigned a spin of 9/2 with even parity as a consequence of its well-established decay scheme.[10] Studies of isomerism in indium have shown that both In^{113} and In^{115} have states with the spin 1/2 and odd parity as the first excited state.[10] The energy of this 1/2(-) state above ground state is 0.392 Mev for In^{113} and 0.335 Mev for In^{115}. The ground-state spins of 9/2(+) and first-excited-level spins of 1/2(-) for nuclei with 49 protons and an even number of neutrons comply remarkably well with the shell-model level scheme for protons that was proposed by Haxel, Suess, and Jensen.[16] In this scheme a closed shell occurs at 50 protons; the $p_{1/2}$ and the $g_{9/2}$ levels are filled last. The spin of 9/2 and even parity result when one proton is missing from among the ten possible $g_{9/2}$ protons and the two $p_{1/2}$ levels are occupied. The spin 1/2 and odd-parity first excited state is formed when one of the $p_{1/2}$ protons changes to the tenth available $g_{9/2}$ orbit. Other excited states are expected to occur at energies considerably higher than the ground state, since such states would either require filling the $g_{9/2}$ or $p_{1/2}$ levels with a proton already occupying the lower $p_{3/2}$ or $f_{5/2}$ levels or by exciting the odd proton in the $p_{1/2}$ level to a state in the next shell. On the basis of these considerations only 9/2(+) or 1/2(-) spins and parities for the ground state of In^{109} need to be considered. Of these two possible spins, 9/2(+) is the more appropriate choice for the ground state of In^{109}. The energy difference between the two levels is expected to vary as a smooth function of the even neutron number. If the 1/2(-) level is 0.335 Mev above the 9/2(+) ground state in In^{115} and is 0.392 Mev above the ground state in In^{113}, then it would be expected to be even higher above ground state in both In^{111} and In^{109}. The absence of information on the possible isomer of In^{111} may be connected with the estimated short half life of less than 10 min if the 1/2(-)level is more than 0.5 Mev above the ground state with a spin of 9/2(+). However, the experiments of Lawson and Cork[24] and Bradt and Tendam[25] were such that an isomeric state in In^{111} would have been detected even if its half life was less than 10 min. An explanation for the nonexistence of an M4 isomer of In^{111} is suggested by the order of levels in In^{115}, which is known from the decay scheme of Cd^{115}. In^{115} has a 5/2(+) state at 0.500 Mev above its ground state. It is possible that in In^{111} the 5/2(+) state is below the 1/2(-) state, allowing the decay of the 1/2(-) state by a cascade of M2 and E2 transitions to the 9/2(+) ground state. Thus, the absence of isomerism in In^{111} tends to show that the 1/2(-) state is higher in energy than the 9/2(+) state and that this energy difference increases with decreasing neutron number. On the basis of these considerations the ground state of In^{109} must have a spin of 9/2 and even parity.

We now consider the ground state of Cd^{109}, the daughter of In^{109}. Cd^{109} decays to the stable isotope Ag^{109}, which has a 7/2(+) isomeric state 0.087 Mev above the 1/2(-) ground state.[10] The spin of 1/2 has been measured directly and the 7/2(+) spin of the isomeric state was assigned on the basis of the agreement of the 39.2-sec half life, the K/(L + M) ratio, and the conversion coefficient with those for the 0.087-Mev E3 transition. There is no electron-capture branching to 1/2(-) ground state of Ag^{109} in decay of Cd^{109}. The $Q_{E.C.}$ value has been measured as 0.16 Mev by a reaction threshold method.[26] When the 470-day half life of Cd^{109} is considered, log ft for this decay is on the order of 6.2. This value is still in the region of log ft values for allowed transitions. The value of 6.2 also suggests that it may be an ℓ-forbidden allowed transition,[27] since the allowed transitions involving the same orbital angular momentum in the parent and daughter have log ft values closer to 5. The possible lowest states of Cd^{109} can be limited to 1/2(+), 5/2(+), 7/2(+), 3/2(+) and 11/2(-) when the lowest states of Cd^{111} are considered. Of these, 5/2(+) and 7/2(+) for the ground state of Cd^{109} are consistent with an allowed transition. Of the latter two, the choice of 5/2(+) agrees with the ℓ-forbidden allowed transition indicated by the log ft value. When the shell model is invoked, the 7/2(+) state in Ag^{109} can be explained only as a $(g_{9/2})^3$ J = 7/2 state resulting from the coupling of the three "holes" in the $g_{9/2}$ proton shell,[14] and the 5/2(+) state is a $d_{5/2}$ state. The choice of 7/2(+), which is due to a single proton in a $g_{7/2}$ state according to the shell model, would give rise to a strictly allowed transition with no change in orbital angular momentum. The ground state of Cd^{109} is therefore, in the order of likelihood, 5/2(+) or 7/2(+); all other spins suggested by those of Cd^{111} are inconsistent with the decay scheme of Cd^{109}.

III. Some Considerations Used in Deriving the Decay Scheme of Indium-109

The discussion in Appendix II requires that the information on the decay of In^{109} (Fig. 8) must be fitted together with a ground-state spin of 9/2(+) for In^{109} and either a $\frac{5}{2}$(+) or $\frac{7}{2}$(+) spin for the ground state of Cd^{109}. Accordingly, the arguments presented below show that the data on the decay of In^{109} are entirely consistent with a ground-state spin of $\frac{5}{2}$(+) for Cd^{109}, as against 7/2(+). The decay scheme in Fig. 8 is then derived as follows.

Since the 0.205-Mev transition is more intense than all others combined, there must be a level 0.205 Mev above the ground state. Coincidence experiments show that the observed positron decay takes place to this level. The multipolarity of the 0.205-Mev transition is M1 and the β decay is allowed, requiring the assignment of a spin of 7/2(+) to the 0.205-Mev level. The shell-model interpretation of the 9/2(+) In^{109} ground state and the 7/2(+) Cd^{109} excited state as single-particle $g_{9/2}$ proton and $g_{7/2}$ neutron states respectively implies that the β decay is not ℓ-forbidden. The log ft value less than 5.5 is consistent with this interpretation.

The level that decays through the 0.058-Mev transition must be located 0.058 Mev above the ground state and must be assigned a spin of 1/2(+) according to the following reasoning. The 0.058-Mev transition is E2 and occurs in about 2.5% of the In^{109} decays, and its half life is 12×10^{-6} sec. If the level in question is placed 0.058 Mev above the 5/2(+) ground state its spin must be either 1/2(+) or 9/2(+). A spin of 9/2(+) must be ruled out as unlikely on the basis of the shell model, and also because an allowed β decay to this level would take place in contradiction to the fact that the transition occurs in only 2.5% of the In^{109} decays. If the level giving rise to the 0.058-Mev transitions is placed elsewhere, it must be above the 0.205-Mev level and its spin must be greater than 9/2. Any other lower spins for the level would allow it to decay by E1, M1, E2, or M2 transitions to the 5/2(+) ground state with a half life shorter than 10^{-6} sec. According to the shell model the only spin greater than 9/2 that could possibly be among the spins of the first few excited states of Cd^{109} is 11/2(-). An E2 transition from a state with this spin would require a final state with a spin of 7/2(-). The presence of such a state among the first excited levels of Cd^{109} is in gross contradiction with the shell model. On the other hand, a 1/2(+) state 0.058 Mev above the ground state is consistent with the fact that no 0.147-Mev transition is observed in the conversion-electron spectrum of In^{109}, since the expected branching ratio of the possible 0.147-Mev M3 transition to the 0.205-Mev M1 transition is on the order of 10^{-10}.

The 0.632-Mev transition, which occurs in about 30% of In^{109} decays, requires an allowed β-decay branch in addition to the one that populates the 0.205-Mev level. Furthermore, this level must be 0.632 Mev above the ground state, as required by the presence of the observed 0.427-Mev transition, indicating that the 0.632-Mev level also decays to the 0.205-Mev level with the emission of a 0.427-Mev γ ray. When the 0.347-Mev the 0.285-Mev, and the 0.227-Mev transitions are considered, a level at 0.285 Mev above the ground state becomes necessary. The multipolarities M1 or E2 assigned to the 0.227-Mev and 0.285-Mev transitions require that the spin and parity of the 0.285-Mev level be 1/2, 3/2, or 5/2 even. The decay scheme of In^{111} suggests that 3/2(+) is the most reasonable choice. This choice implies that both the 0.227- and 0.285-Mev transitions are M1, and hence their branching ratio should be on the order of 1, which is in agreement with the observed intensities of the two conversion lines. An assignment of 5/2(+) or 1/2(+) to this level would be in conflict with the theoretical branching ratio (E2)/(M1) on the order of 10^{-3} as calculated from Weisskopf's formulas for the transition probabilities for γ emission. The level 0.632 Mev above ground state must then be assigned a spin of 7/2 and even parity, since the 0.347-Mev transition was found to E2, the 427-Mev transition M1, and the 632-Mev transition either M1 or E2. The experimental branching ratio γ(632): γ(427): γ(347) is approximately 10:4:1. Weisskopf's transition probabilities indicate the ratio M1(632): M1(427): E2(347) should be $12{:}4{:}10^{-3}$ if the transitions are to be explained on the basis of the single-particle model. Experimental lifetimes for

Ml transitions are scarce; there are, however, several examples in which observed transitions are slower than the theoretical estimates.[14] So far as E2 transitions are concerned there is a large amount of information from lifetime measurements and Coulomb excitation cross sections indicating that the theoretical transition probabilities for single-particle transitions are much smaller than the experimental values for transitions not expected to be single-particle transitions.[14] Since the transitions under consideration are not single-particle transitions, the discrepancy between the observed branching ratio and the theoretical single-particle estimate is not sufficiently serious to render the spin and parity assignments invalid. It was mentioned above that the transitions are not single-particle transitions. This is clear if we assume the following configurations for the ground state and the first three excited states as suggested by the shell model:

Energy (in Mev)	Spin and parity	Configuration
0	5/2(+)	$g^8{}_{7/2}, d^3{}_{5/2}$
0.058	1/2(+)	$g^8{}_{7/2}, d^2{}_{5/2}, s_{1/2}$
0.205	7/2(+)	$g^7{}_{7/2}, d^4{}_{5/2}$
0.285	3/2(+)	$g^8{}_{7/2}\, d^2{}_{5/2}\, d_{3/2}$

The second 7/2(+) state at 0.632 Mev above ground state could be any one or a combination of the following possible configurations: $g^5{}_{7/2}, d^6{}_{5/2}$, $g^7{}_{7/2} d^2{}_{5/2} s^2{}_{1/2}$, $g^7{}_{7/2} d^2{}_{1/2} h^2{}_{11/2}$. The transition from these configurations involves at least two particles when the final state is the ground state, the 0.205-Mev state, or the 0.285-Mev state.

If the 0.632-Mev level has a spin of 7/2 and even parity, electron capture and positron emission to this level are allowed. The observed intensity of the 0.632-Mev γ rays relative to the 0.205-Mev γ rays is 0.42 ± .20, and the ratio of 0.205-Mev transitions to In^{109} decays is 0.75 ± .10. This estimates the fraction of In^{109} decays to the 0.632-Mev level as 0.35 ± .20. The log ft value that follows from the above estimates is between 5.0 and 5.5. If theoretical ratios of electron capture to positron emission[11] are used, the expected branching ratio $\beta^+(0.795)/\beta^+(0.368)$ can be estimated as 32. Figure 2 shows the effect of a positron spectrum with the maximum energy of 0.368 Mev in addition to the readily observed 0.795-Mev spectrum. Due to the large statistical error in the points obtained after subtraction of the 0.795-Mev component it is difficult to verify the presence of the lower-energy positron spectrum.

The weak γ transitions having the energies 0.325, 0.516, 0.530 0.618, 0.710, 0.805, and 1.15 Mev can be fitted into the decay scheme in several ways. One of the possible ways is shown in Fig. 8. This would require another allowed electron-capture decay mode to a state 1.15 Mev above the ground state. The total intensity of the assumed transitions from this level indicate that not more than 10% of the In^{109} decays take place to this level.

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