UCRL 3488

UNIVERSITY OF
CALIFORNIA

Radiation
Laboratory

RADIOACTIVITY OF TIN-110, TIN-108, AND INDIUM-108

DISCLAIMER

UCRL-3488
Physics Distribution

UNIVERSITY OF CALIFORNIA
Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

RADIOACTIVITY OF TIN-110, TIN-108, AND INDIUM-108

Warren Mead

(Thesis)

August 6, 1956

Printed for the U. S. Atomic Energy Commission

RADIOACTIVITY OF TIN-110, TIN-108, AND INDIUM-108

Contents

RADIOACTIVITY OF TIN-110, TIN-108, AND INDIUM-108

Warren Mead

Radiation Laboratory and Department of Physics
University of California, Berkeley, California

August 6, 1956

ABSTRACT

An attempt has been made to extend the knowledge of the disintegration behavior of the tin and indium isotopes of mass numbers 108 and 110. Observations made with tin sources obtained by alpha bombardment of enriched cadmium isotopes indicate that the 4-hour tin activity should be assigned to Sn^{110}, rather than to Sn^{108} as previously reported.[4, 5] The decay of In^{108} has been investigated, directly with the aid of enriched $Ag^{107}Cl$, and also as the daughter activity of Sn^{108}. The evidence obtained suggests a decay scheme for In^{108} which closely parallels that of In^{110}. The growth of a 3.5-Mev positron activity identified with the ground state of In^{108} has been interpreted in terms of an approximately 9-minute parent, and this half life has been tentatively assigned to Sn^{108}. Suggested decay schemes for these isotopes are presented in Figs. 1 and 17.

RADIOACTIVITY OF TIN-110, TIN-108, AND INDIUM-108

Introduction

The evolution within the last several years of relatively satisfactory nuclear models with which to associate low-energy experimental data has resulted in a gradual shift of emphasis in the field of beta and gamma spectroscopy. In contrast to the earlier preoccupation with the determination of half lives and transition energies as ends in themselves, recent experimental works have been frequently concerned with providing evidence that may be of assistance in evaluating some aspect of a nuclear model. The investigation of isomerism, for example, has progressed from the determination of half lives to more selective and detailed experiments whose purpose is to provide experimental estimates of the matrix elements for various transition types. These empirical matrix elements can then be compared with theoretical estimates that have been calculated on the basis of a particular nuclear model. Such an analysis provides a very useful check on the applicability of the model under consideration.

Among the most significant predictions of the shell model[1,2] are those relating to the special nuclear characteristics to be expected in the region of closed neutron or proton shells. It seemed worth while, therefore, to attempt to extend the knowledge of disintegration behavior in such a closed-shell region, and to evaluate the new information in terms of the shell model and the trends encountered by other investigators. The closed-proton-shell isotopes chosen for investigation, and for which disintegration information has been missing or incomplete, are Sn^{110}, Sn^{108}, and In^{108}.

It is interesting to notice that the nuclear properties that make studies in a closed-shell region of particular importance often result in certain characteristic difficulties in connection with such an investigation. The prevalence of isomerism, for example, complicates the proper identification of the radiations encountered. The assignment of tin activities to the proper mass number is further complicated by the relatively large number of stable cadmium isotopes from which tin may

be produced by alpha bombardment. Such difficulties appear to be partly responsible for the confusion that has existed with regard to the radioactive isotopes in this region.

Tin-110

The half lives of the neutron-deficient isotopes of tin down through Sn^{108} are listed in the current literature, with the exception of Sn^{110}. In attempting to determine the half life of Sn^{110}, it is helpful to consider the decay scheme of In^{110}[3] because when Sn^{110} is produced a growth of the In^{110} radiations is expected. (Fig. 1.) Since it appears likely that the decay from Sn^{110} to In^{110} takes place primarily in such a way as to involve the ground state of In^{110}, rather than the 5+ isomeric state, both the 660-kev gamma ray and the 2.25-Mev positrons should be present in the radiations resulting from Sn^{110}.* A growth and decay of these radiations should be interpretable in terms of the decay period of Sn^{110}.

Sn^{110} was produced by bombarding cadmium enriched in Cd^{108} with alpha particles of about 30 Mev: The (α, 2n) reaction, leading to Sn^{110}, should predominate at this energy. After separation of indium, sources were prepared from the tin fraction and were observed with a magentic-lens beta-ray spectrometer, and with a scintillation counter and continuous recording pulse-height analyzer. (A brief description of the apparatus and of chemical techniques will be found in the Appendix.)

A gamma ray of approximately 660 kev, identified with In^{110}, was observed with the spectrometer and with the scintillation counter and pulse-height analyzer. This gamma ray was followed for about 35 hours with the scintillation counter, and was observed to grow in intensity for about 1.5 hours, followed by a decay with a half life of about 4 hours. (Fig. 2.) Subtraction of the initial activity from the extrapolated 4-hour period yields a decay with a half life of about 65 minutes (Fig. 3), which has been identified with the period of the ground state of In^{110}.

---

* Bleuler et al.[3] have not made definite spin assignments for the In^{110} isomers; the values referred to in this discussion represent possible assignments suggested by these investigators.

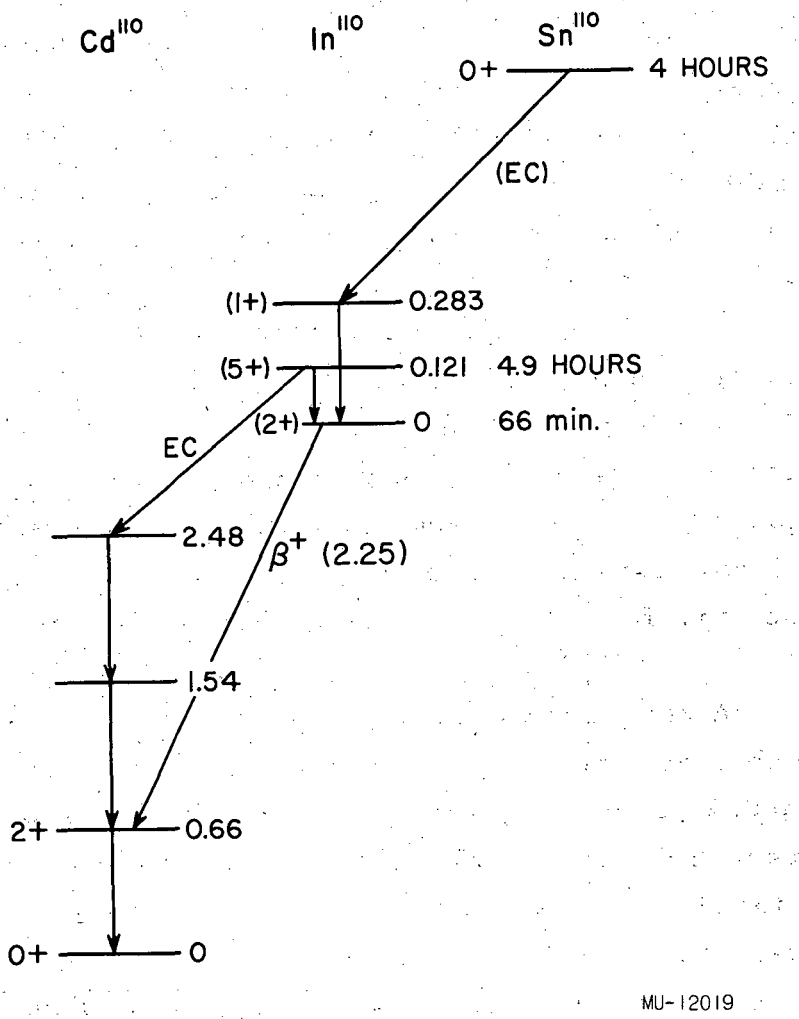

Fig. 1. Suggested decay scheme of Sn^{110} and the previously reported decay scheme of In^{110}.[3]

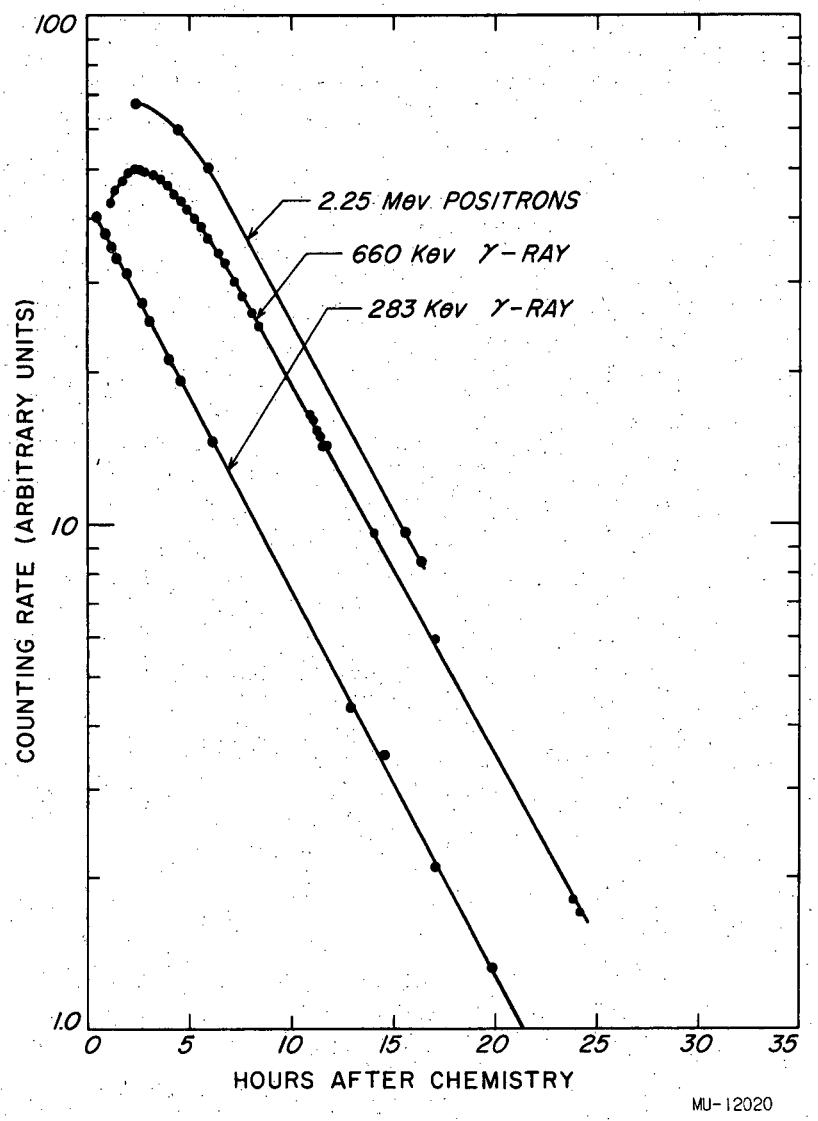

Fig. 2. The decay of radiations utilized in assigning the 4-hour period to Sn^{110}.

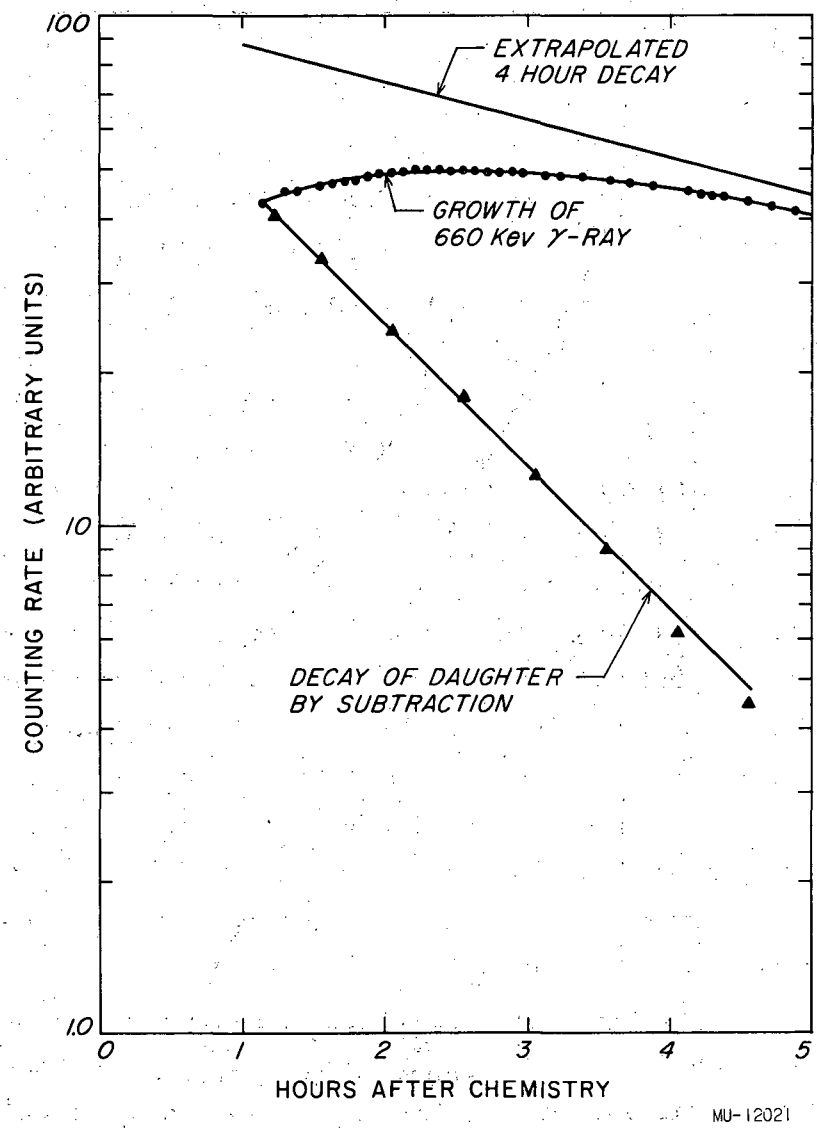

Fig. 3. Analysis of the growth of the 660-kev gamma ray.

A positron spectrum was also obtained (Figs. 4 and 5) and appears to consist primarily of positrons having an end-point energy of about 2.25 Mev. This is in agreement with the energy previously assigned to the positrons of In^{110}.[3] A plot of the positrons of maximum intensity (Fig. 2) also shows the effect of an initial growth, followed by a decay of about 4 hours. A value of 4.0 ± 0.2 hours has been assigned to the decay period exhibited by the 660-kev line and the 2.25-Mev positrons.

The assignment of this 4-hour period to Sn^{110} depends upon the assumption that these decays neither result from the 4.9-hour isomeric level of In^{110}, nor are appreciably altered by its presence. The possibility that this isomeric level is involved in producing the observed pattern of growth and decay appears to be excluded for several reasons. Bleuler et al.[3] have estimated that the isomeric transition to the ground state represents only about 0.6% of the total decay, the remainder taking place by electron capture to high-energy excited states of Cd^{110}. Therefore, the isomeric state could not of itself produce the growth and decay observed. Furthermore, neither the 121-kev isomeric transition nor either of the high-energy gamma rays of In^{110} was observed. This is in agreement with the assumption that the decay from the 0+ ground state of Sn^{110} would be unlikely to take place in such a way as to involve the 5+ isomeric state of indium in preference to the 2+ ground state. Finally, when silver was bombarded to produce indium directly, the 121- and 660-kev lines were found to have half lives of about 5 hours, which appeared to be clearly distinguishable from the 4-hour period observed when tin is produced.

It is of interest to notice that the time after the chemical separation at which the maximum activity of the 660-kev gamma ray occurs is in approximate agreement with that predicted by calculations for a 4-hour activity decaying into an initially absent 66-minute daughter. This indicates that the chemical separation of the indium was reasonably effective.

Another question that arises in connection with the assignment of the 4-hour period to Sn^{110} concerns the possible effect of the presence

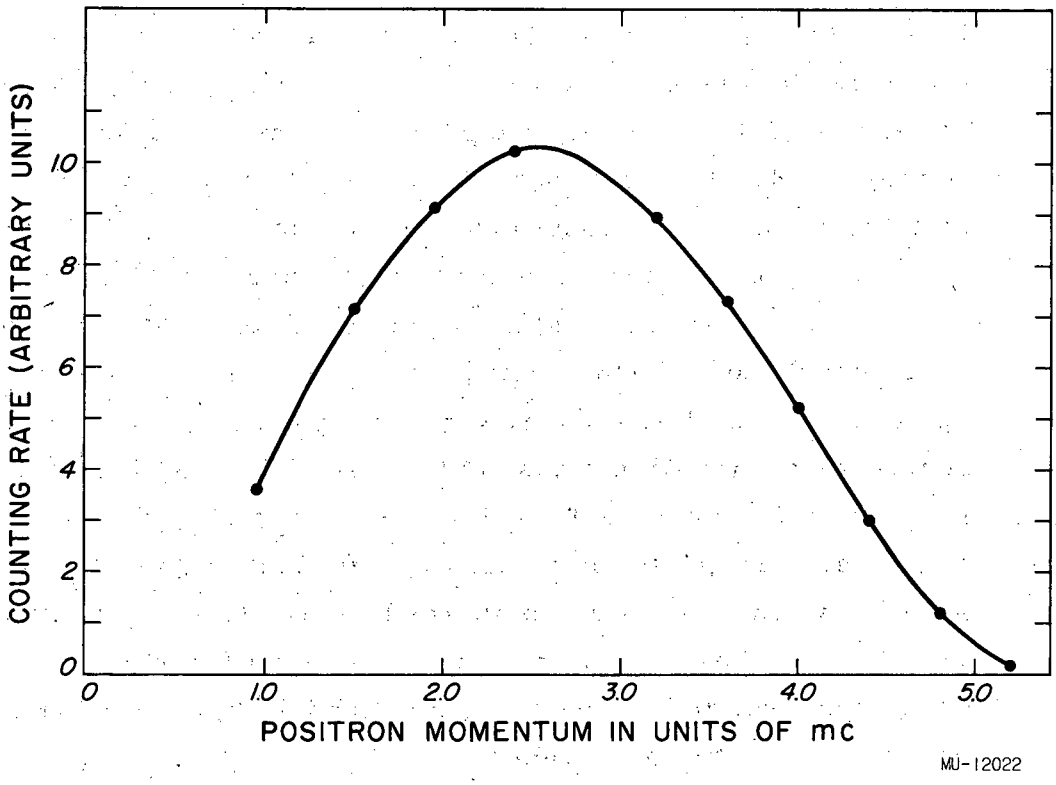

Fig. 4. Positron spectrum of In^{110}.

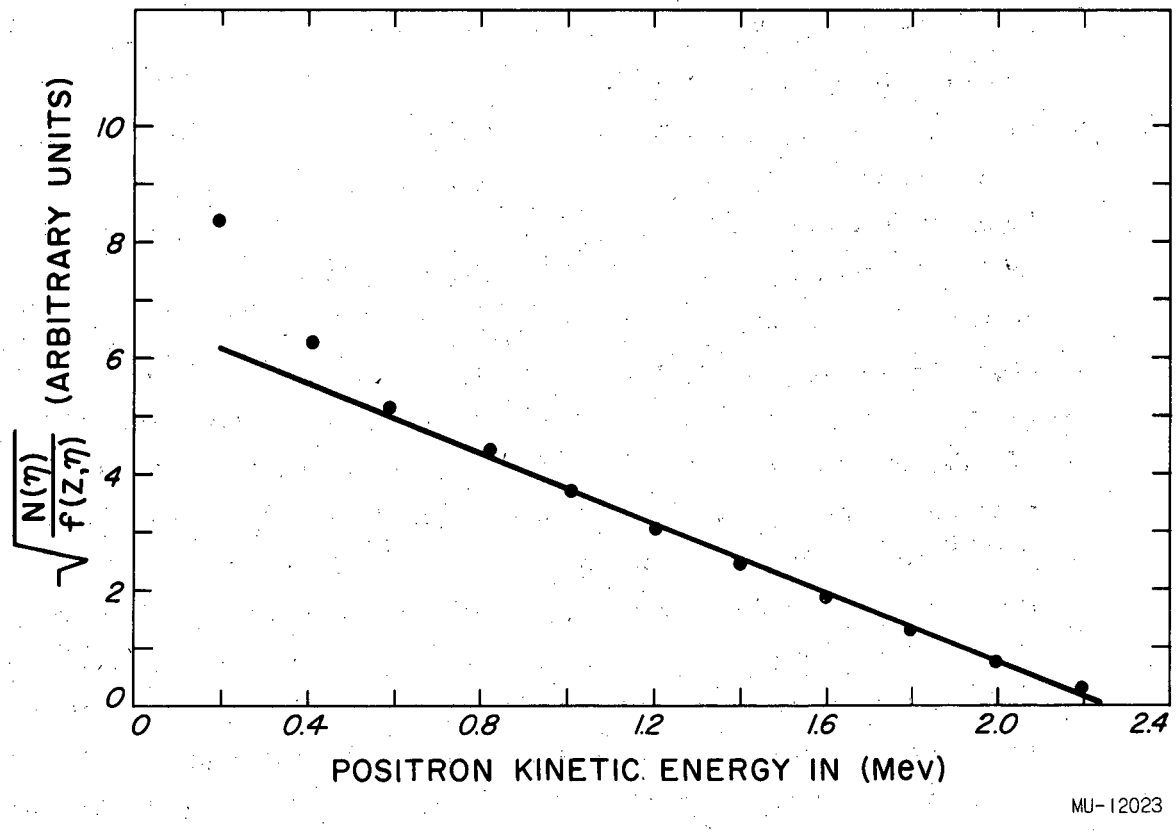

Fig. 5. Kurie plot of In^{110} positrons.

of Cd^{106} in the samples of enriched Cd^{108}. The (α, 2n) reaction with Cd^{106} yields Sn^{108}. Two previous investigators[4, 5] have assigned a period of about 4 hours to Sn^{108}, and a 55-minute positron activity of about 2 Mev to In^{108}. Since it seemed quite possible that In^{108} might also contain a gamma ray in the 650-kev region, these similarities in the two pairs of isotopes appear to cast doubt on the assignment of the observed 4-hour activity to Sn^{110}. Therefore, a series of experiments was undertaken in which enriched Cd^{106} was bombarded, and which involved experimental procedures similar to those described above.

Observations of the tin sources obtained by bombarding enriched Cd^{106} included a decay curve of the positron annihilation radiation. These data were obtained by means of a coincidence arrangement consisting of two scintillation counters placed at 180°, each leading to a pulse-height analyzer set to observe pulses in the annihilation region. The curve obtained is similar to that reported by Mallory and Pool[4]--an initial growth followed by a decay having a half life of about 4 hours. A positron spectrum was also obtained with the beta spectrometer, and appeared to consist primarily of positrons of about 2 Mev. However, the intensity of these positrons was generally less by factors of 10 to 100 than when enriched Cd^{108} was bombarded. It appears, therefore, that they result from the small amount of Cd^{108} present in the enriched Cd^{106}, and that the 4-hour period should be assigned to Sn^{110}, rather than Sn^{108}. Further investigation has served to confirm this conclusion.

The positron decay curves obtained with the sources prepared from the bombarded Cd^{106} contained, in addition to the 4-hour half life referred to above, indications of additional activities with half lifes of roughly 2 hours and 43 hours. Neither of these periods has been positively identified.

An internal conversion line was seen at about 660 kev. It appeared to result in part from In^{110} and in part from the 650-kev line previously identified with Sn^{109}. Other conversion peaks observed were generally identified with known tin or indium isotopes, and none was seen that could be assigned to Sn^{108} or In^{108}. However, in order to eliminate short-lived activities, these tin sources were not prepared until about 2 hours after the end of the bombardment.

Therefore, the failure to see radiations that could be identified with Sn^{108} or In^{108} suggested that the half life of Sn^{108} might be relatively short compared with the 4-hour period previously assigned to it.

In the tin sources obtained from the bombardment of enriched Cd^{108}, a strong internal-conversion peak was found corresponding to a gamma ray of 283 kev. A gamma ray of 285 kev was observed by McGinnis and assigned to In^{108}. McGinnis's tin sources were obtained by alpha bombardment of natural cadmium. With enriched isotopes, however, it has been found that this gamma ray is always much weaker when Cd^{106} is bombarded, so it appears to belong to the 110 decay sequence. Its decay has been followed for periods up to 61 hours and the half life observed is the same, within experimental error, as that assigned to Sn^{110}. Although both the 2.25-Mev positrons and the 283-kev gamma ray are much lower in intensity when Cd^{106} is bombarded, the ratio of the 283-kev line to the positrons is the same as in the sources obtained from enriched Cd^{108}. Finally, since no growth of the 283-kev line was observed when observations were begun 24 minutes after the chemical separation of indium, this gamma ray has been assigned to the decay of Sn^{110}. A portion of the decay curve of the 283-kev line is shown in Fig. 2.

Because of the relatively high intensity of the 283-kev gamma ray, it seems reasonable that the decay of Sn^{110} may consist primarily of electron capture to a 283-kev excited state of In^{110}. A value of 8.0 ± 1.0 has been obtained for the K/L ratio of the 283-kev line. An examination of the empirical curves of Goldhaber and Sunyar[6] suggests the possible transition types M1, M2, M3, or E2, where the transition types in closest agreement with the measured K/L ratio are listed first. These empirical curves do not yield a decisive answer in this case, partly because of the necessity of extrapolating the curves in order to apply them to a gamma ray of this energy. An approximate value of the K-conversion coefficient has also been obtained with the aid of a gold converter standardized in terms of the 172- and 247-kev gamma rays of In^{111}. A conversion coefficient of about 6% is obtained when the values of the In^{111} conversion coefficients obtained by McGinnis[5] are used, and about 3% with the values of Boehm et al.[7] The theoretical

conversion coefficients for a gamma ray of this energy taken from the curves of Rose et al.[8] are 2.5% and 3.25% for M1 and E2 transitions, and 11% and 12% for M2 and E3 transitions. A consideration of both the K/L ratio and the conversion coefficient suggests an M1 transition as being somewhat more likely than the other possibilities mentioned.

A spin of 2 with even parity has been suggested for the ground state of In^{110} by Bleuler et al.[3] in consideration of the fact that less than 3% of the 2.25-Mev positron (an allowed transition with log (ft) about 5.5) decays go to the ground state of Cd^{110} (and the remainder to the 2+ excited state). If this 2+ value is assumed for the ground state of In^{110}, a direct decay from the 0+ ground state of Sn^{110} to the ground state of indium would represent a second-forbidden transition. If we assume, then, that all transitions from Sn^{110} to In^{110} involve the 283-kev gamma ray, we can obtain an estimate of the conversion coefficient by comparing the areas under the curves of the 2.25-Mev positron spectrum and the 283-kev internal-conversion peak. The ratio of electron capture to positrons for the 2.25-Mev transition can be estimated from the theoretical values given by Zweifel,[9] and is approximately 0.33. The value obtained in this way for the conversion coefficient of the 283-kev line is about 2%. This is in agreement with the assumption of an M1 transition as suggested by the K/L value and the conversion coefficient as measured directly. More significantly, the above considerations tend to confirm the assignment of a 2+ value to the ground state of In^{110}.

An interpretation of the 283-kev line of Sn^{110} in terms of an M1 transition to the ground state of indium suggests a spin of 1 and even parity for the excited state. Since spins of 1+ have been assigned to the ground states of at least three even-A isotopes of indium, the occurrence of this level as an excited state in In^{110} appears reasonable. A possible decay scheme is suggested in Fig. 1.

Tin-108 and Indium-108

Because the 4-hour period previously assigned to Sn^{108} by Mallory and Pool[4] could not be confirmed, a further investigation of this isotope seemed indicated. When enriched Cd^{106} was bombarded, no activities were observed that could definitely be assigned to Sn^{108} or In^{108}. However, because of the presence in the enriched Cd^{106} of considerable amounts of the other stable cadmium isotopes, and also because of the overlapping of the alpha-reaction curves, it seemed likely that activities resulting from Sn^{108} might have been overlooked in the presence of the numerous gamma rays and positron spectra resulting from other tin and indium isotopes.

An alternative approach to the investigation of Sn^{108} is to begin by studying the decay of In^{108}. An important advantage of this approach is that silver, from which indium may be produced by alpha bombardment, has only two stable isotopes. It is therefore possible to produce the desired indium isotopes much more selectively than those of tin. An investigation of In^{108} is also of direct interest because of the possibility that isomerism may be involved, as it is for at least four of the other even-A isotopes of indium.

Since the 283-kev gamma ray previously assigned to In^{108} by McGinnis[5] has been reassigned to Sn^{110}, there were no known gamma rays with which to identify In^{108}. When silver foil was bombarded with 40-Mev alpha particles, the conversion peaks observed were generally identified with those expected from other known indium isotopes. The positron activity, followed by means of the annihilation radiation, showed an initial 55- to 60-minute decay, followed by a decay with a half life of 4 to 5 hours. Both of these periods could be identified with In^{110}.

A more helpful approach was provided by a consideration of the decay scheme of Ag^{108},[10] which beta-decays to both Cd^{108} and Pd^{108}. About 0.8% of the β-decays take place to an excited state of Cd^{108} of about 620 kev. This transition may also occur in the decay of In^{108} into cadmium. To check this possibility, a 0.3-mil silver foil was bombarded with alpha particles of about 40 Mev. The $(\alpha, 3n)$ reaction

leads to both In^{110} and In^{108}, therefore the 660-kev gamma ray of In^{110} is expected to be present, and perhaps an additional line at about 620 kev which could be identified with In^{108}. Because a chemical separation did not seem essential, a source for the beta-spectrometer was made directly from the silver foil. In this way it was possible to obtain the first readings 10 minutes after the end of the bombardment.

The region from 500 to 700 kev was carefully examined with the spectrometer for a period of 12 hours following the bombardment. Two converted gamma rays were observed at about 637 and 660 kev. (Fig. 6.) Although the two lines are not completely resolved, the difference in half lives makes it clear that two separate gamma rays exist. The decay of the 660-kev line consists principally of a half life of about 5 hours, since it is fed primarily by the 4.9-hour isomeric state of In^{110}. The 637-kev line decays with an initial half life of about 57 minutes into the 5-hour background resulting from the presence of the 660-kev line. After subtraction of this 5-hour background, the 637-kev line shows a decay of about 52 minutes (Fig. 7), in approximate agreement with the 50- to 55-minute half life assigned to In^{108} by the previous investigators.[4,5] This gamma ray was therefore tentatively assigned to In^{108}, and is believed to represent the same transition as occurs in the decay of Ag^{108}. It is of interest to notice that the decay of the 637-kev line appears to involve only the 52-minute period.

An attempt to utilize the 637-kev line of In^{108} to determine the half life of Sn^{108} was unsuccessful because of the presence of the strong gamma ray of Sn^{109} that occurs at about 650 kev. Therefore, a more extensive investigation of In^{108} was undertaken with the aid of silver chloride enriched (about 97%) in Ag^{107}.

A number of bombardments of the $Ag^{107}Cl$ was made, using alpha particles of about 40 Mev. The bombarding energy and the energy range in the target material were varied in some cases in an attempt to reduce unwanted activities. The bombardment times were usually somewhat less than 1 hour. Since the chemical procedure employed was more complicated than was required for preparing the tin sources, the first readings were not obtained until about 1 hour after the end of the bombardment. In addition to the (α, 3n) reaction, which leads to In^{108}, the

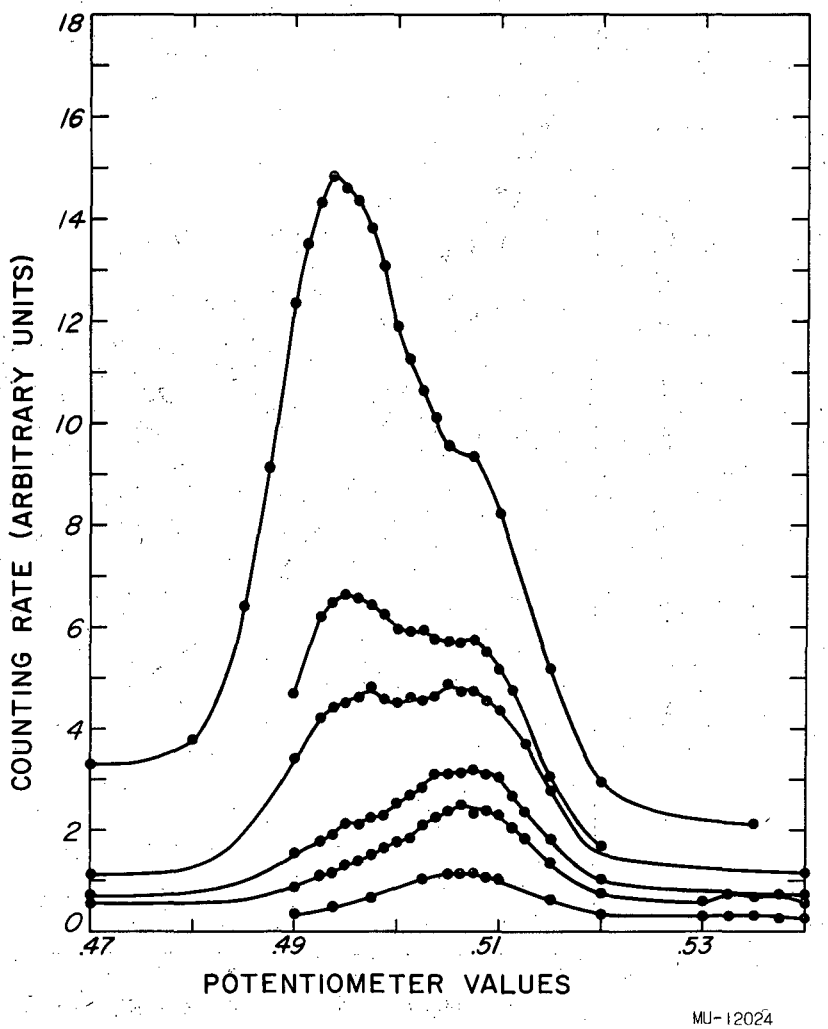

Fig. 6. The 637- and 660-kev gamma rays.

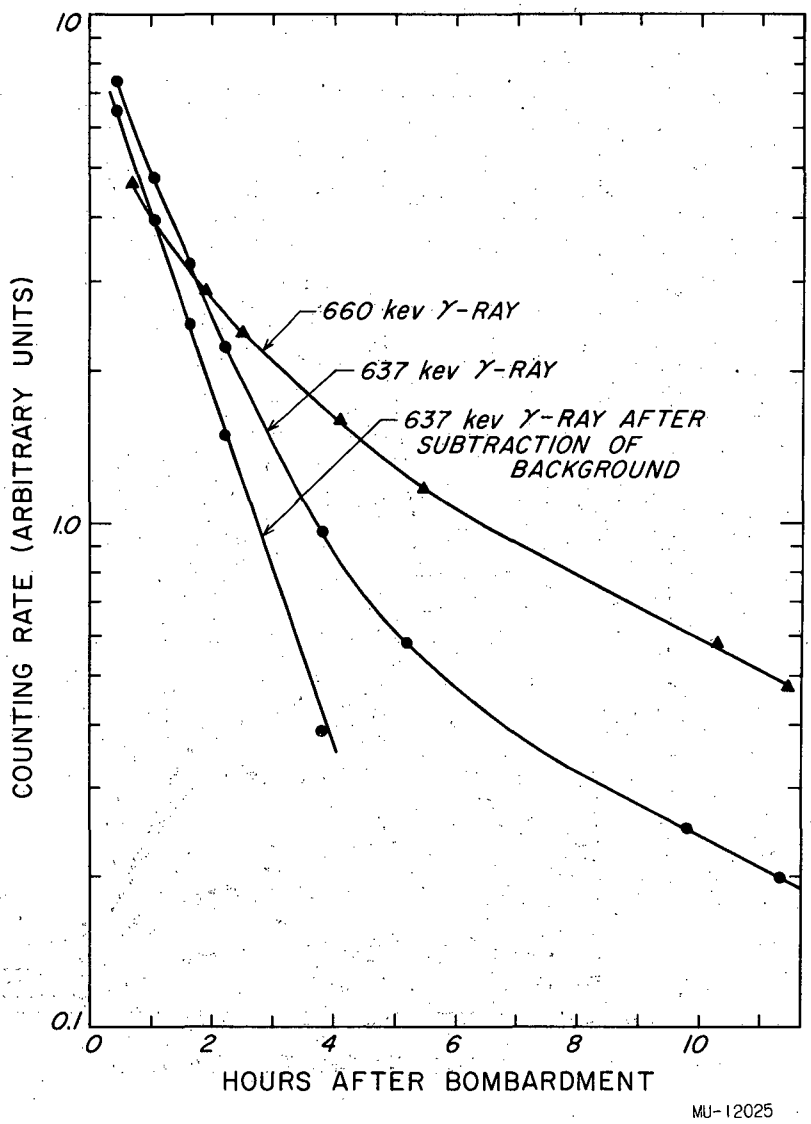

Fig. 7. Decay of the 637- and 660-kev gamma rays.

adjacent reactions (α, 2n) and (α, 4n) also took place, so that the converted gamma rays of In^{109} and the In^{107} daughter, Cd^{107}, were present to an appreciable extent.

The following gamma rays were observed to decay with periods of about 55 minutes, and have been assigned to In^{108}.

Photon Energy (Mev)	Relative internal conversion intensity	K/L
1.05	3	
0.878	10	
0.637	32	
0.330	22	4
0.246	100	3.7 ± 0.5

A source prepared from the bombarded $Ag^{107}Cl$ was also examined with a scintillation counter and continuous recording pulse-height analyzer. Gamma rays were observed with energies of about 1.07, 0.89, and 0.63 Mev. The lower-energy lines were not separated from the 205-kev line of In^{109}.

The 637-kev line, which also occurs in the decay of Ag^{108}, appears to be the first excited state of Cd^{108}. The level that leads to this transition in the decay of Ag^{108} has been assigned a spin of 2 and even parity by Perlman et al.[10] A value of 2+ for the first excited states of even-even nuclei has been found to occur in at least 80% of the cases investigated.[11] The energy of the 637-kev line agrees roughly with the energies of the first excited states of the other known even-even cadmium isotopes, although the expected trend[11] of increasing energy with decreasing neutron number suggests a somewhat higher energy of about 680 kev.

In attempting to understand the decay scheme of In^{108}, it is of particular importance to consider the possibility that an isomeric state of indium may be involved. Isomerism occurs for the even-A indium isotopes from In^{110} through In^{116}. The similarities in the characteristics of these four known isomeric transitions should be of assistance in

suggesting the nature of the suspected isomer of In^{108}. With the exception of In^{110}, the ground states of these even-A indium isotopes have all been assigned spins of 1 with even parity. As has been noted, the ground state of In^{110} appears to be 2+. The spins of the isomeric states, two of which have been recently measured,[12] are 4 or 5 with even parity. The transitions are therefore M3 or E4 with no change of parity. In all cases the isomeric state has the higher spin and a longer half life than the ground state.

These characteristics of the known even-A indium isomers indicate that the 55-minute period of the gamma rays identified with In^{108} might result from an isomeric state of indium, rather than the ground state. This possibility is suggested by an extrapolation of the spin characteristics of the even-A indium isotopes, and of the general tendencies with regard to the spins of excited states of even-even nuclei. That is, if the ground state of In^{108} has a low spin, as is suggested by the situation for the other even-A indium isotopes, then the decay to cadmium would take place primarily to low spin states. It seems unlikely, however, that all the gamma rays assigned to In^{108} would result from levels with sufficiently low spin to be fed by the presumably low-spin ground state of In^{108}. The ground states of the other even-A indium isotopes, for example, feed, at most, one excited state of the cadmium daughter. These considerations suggest that the In^{108} state that gives rise to the observed gamma rays has a spin greater than 1 or 2, and may therefore be an isomeric state.

Further evidence for the interpretation of the 55-minute period in terms of an In^{108} isomer was suggested by subsequent observations of the radiations resulting from Sn^{108}, from which at least some of the In^{108} gamma rays appeared to be absent. Such a situation would be consistent with the assumption that the decay from the zero-spin ground state of Sn^{108} takes place in such a way as to involve the ground state of In^{108}, rather than the isomeric state which alone feeds all the levels attributed to the In^{108} decay.

In considering the possibility of isomerism in connection with In^{108}, the two lower-energy gamma rays observed are of particular interest, since they might result from isomeric transitions. A portion

of the internal conversion spectrum which includes these two gamma rays is shown in Fig. 8. The K/L ratio of 3.7 obtained for the 246-kev line may be used to obtain an estimate of the transition type by means of a comparison with the empirical curves of Goldhaber and Sunyar.[6] The K/L values suggested by these curves for a gamma ray of this energy are indicated in the following table:

Transition type	E4	E3	M4	E2	M3
K/L	1.7	3.2	3.7	5.2	6.4

In utilizing the measured K/L ratio of the 246-kev line to obtain an estimate of the transition type, it is important to consider a possible source of error which may have affected the value obtained. A gamma ray of 220 kev with a half life of about 30 minutes has been assigned to In^{107} by Cassatt and Meinke.[13] Since the conversion lines of Cd^{107} were observed, this 220-kev line must have been present. Its K/L ratio has not been reported, but the L-conversion peak would coincide approximately with the K peak of the 246-kev line assigned to In^{108}. Although the decay of the 246-kev line appeared to show no evidence of a shorter-lived component, it is possible that the 220-kev line was present to a sufficient extent to alter the apparent K/L ratio.

The empirical curves suggest that the 246-kev line represents an M4 transition. An examination of the known M4 transitions in this energy range indicates a half life of roughly 2 days. This would require that only a small proportion of the decays take place to the ground state, and this situation appears to be compatible with information obtained from an analysis of the relative number of conversion electrons and positrons. A difficulty in connection with the interpretation of the 246-kev line as an M4 isomeric transition of In^{108} is that M4 transitions do not seem to occur in odd-odd isotopes.[14] Furthermore, an M4 transition requires a negative parity level, none of which are found among the known even-A isomers of indium.

The two transition types adjacent of M4 in the above table, whose K/L values are close to the measured value, should also be considered. An E2 transition could not lead to isomerism. The E3 possibility, which

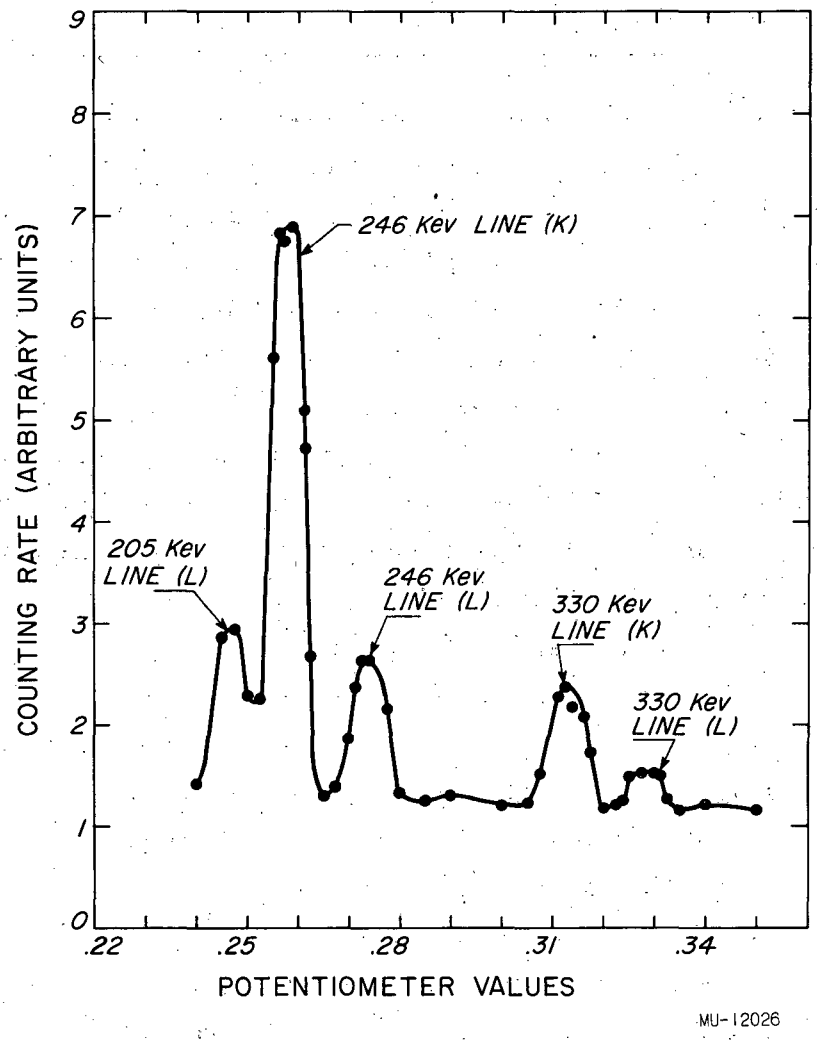

Fig. 8. A portion of the In^{108} internal conversion spectrum.

also requires a negative parity state, is probably too fast a transition at this energy to account for a 55-minute isomer.

An approximate K/L ratio of 4 has been measured for the 330-kev gamma ray. The empirical curves suggest an E3 transition, which is unlikely to account for a 55-minute isomer. The possibility of an M4 transition cannot be excluded, and such a transition would be compatible with a 55-minute half life. It should be noticed that the K line of the 347-kev gamma ray of In^{109} falls at approximately the same position as does the L line of the 330-kev gamma ray of In^{108}. The measured K/L ratio may therefore be lower than the correct value.

It is of interest to notice that the energies of the isomeric states of the three even-A indium isotopes with known transition energies are closely proportional to the numbers of neutrons of the respective isotopes. An extrapolation of this trend suggests an energy of about 85 kev for the isomeric state of In^{108}. A careful search of the low-energy region failed to reveal any additional gamma rays that could be assigned to In^{108}. However, the presence of the K and L conversion peaks of both the 58-kev line of In^{109} and the 94-kev line of Cd^{107} may have masked a gamma ray of low intensity. It is also possible, of course, that an isomeric state may exist from which transitions to the ground state of indium are negligible.

A different interpretation of the 246-kev line, in terms of excited states of Cd^{108}, is suggested by the fact that the sum of the energies of the 246- and 637-kev lines is equal to that of the 878-kev line, within better than 1%. This suggests the possibility that the first two excited states of Cd^{108} may be 637 and 878 Mev, with the 878-kev gamma ray representing a cross-over transition from the second excited state to the ground state. Such an arrangement, however, presents several difficulties, particularly if the first excited state of 637 kev is 2+ as expected. Both isomerism and negative parity states, required by the assumption of an E3 or M4 transition type for the 246-kev line, are extremely rare among even-even nuclei.[11,15] Furthermore, it is difficult to explain the required competition between the two modes of decay from the 878-kev level. Transition probabilities calculated by means of the single-particle formula[16] appear to indicate that the 878- and 246-kev

transitions from the 878-kev level would not compete sufficiently to account for their observed intensities. Since the single-particle formula cannot properly be applied to an even-even nucleus, this arrangement of excited levels cannot be rejected on the basis of such calculations alone. Some further evidence relating to this interpretation of the 246-kev line has been suggested by an analysis of the In^{108} positron spectrum.

Mallory and Pool[4] report an energy of about 2 Mev for the positrons that they identified with the decay of In^{108}. More recently, McGinnis[5] obtained the value 2.31 Mev. As mentioned previously, McGinnis obtained his sources from the bombardment of natural cadmium, so it is possible that his value was influenced by the presence of the In^{110} positrons. A positron spectrum obtained with a source prepared from bombarded $Ag^{107}Cl$ is shown in Fig. 9. The points represent the measured intensities, divided by quantities proportional to the momentum, about 1.5 hours after the end of bombardment. The high-energy portion of the spectrum is incomplete, since the upper limit of the spectrometer is about 2.5 Mev. Repeated observations of the spectrum indicate that the positrons in the region of maximum intensity decay with a half life of about 55 minutes, while the higher-energy portion of the spectrum decays, at first, with a shorter period of 30 to 45 minutes.

An analysis of the positron spectrum is complicated by the presence of the 750-kev positrons of In^{109}, the approximately 2-Mev positrons of In^{107}, and possibly the 2.25-Mev positrons of In^{110}, in addition to the In^{108} positrons. A Kurie plot is shown in Fig. 10. The high-energy points are particularly interesting because they suggest a positron component having an end-point energy greater than 3 Mev. Such an energy appears to be too high to be identified with the positrons of In^{107}. With the aid of subsequent data, an attempt has been made to subtract out this high-energy component. The resulting Kurie plot shows a low-intensity component of about 2.2 Mev. When this component is subtracted, the Kurie plot (Fig. 11) is still complex, but appears to consist largely of a component--the majority of the positrons observed--having an end-point energy of 1.4 ± 0.1 Mev. The upward deviation at low energies may be partly due to the presence of the 750-kev positrons of In^{109}. The 1.4-

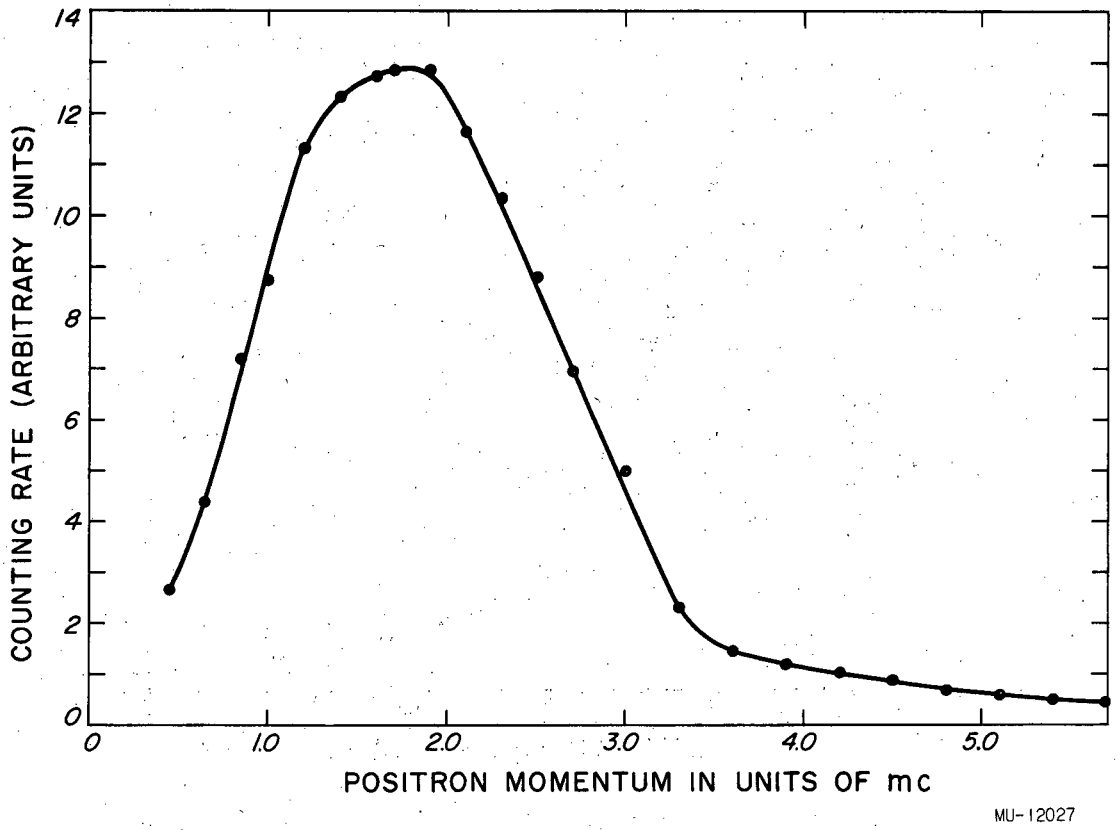

Fig. 9. In^{108} positron spectrum.

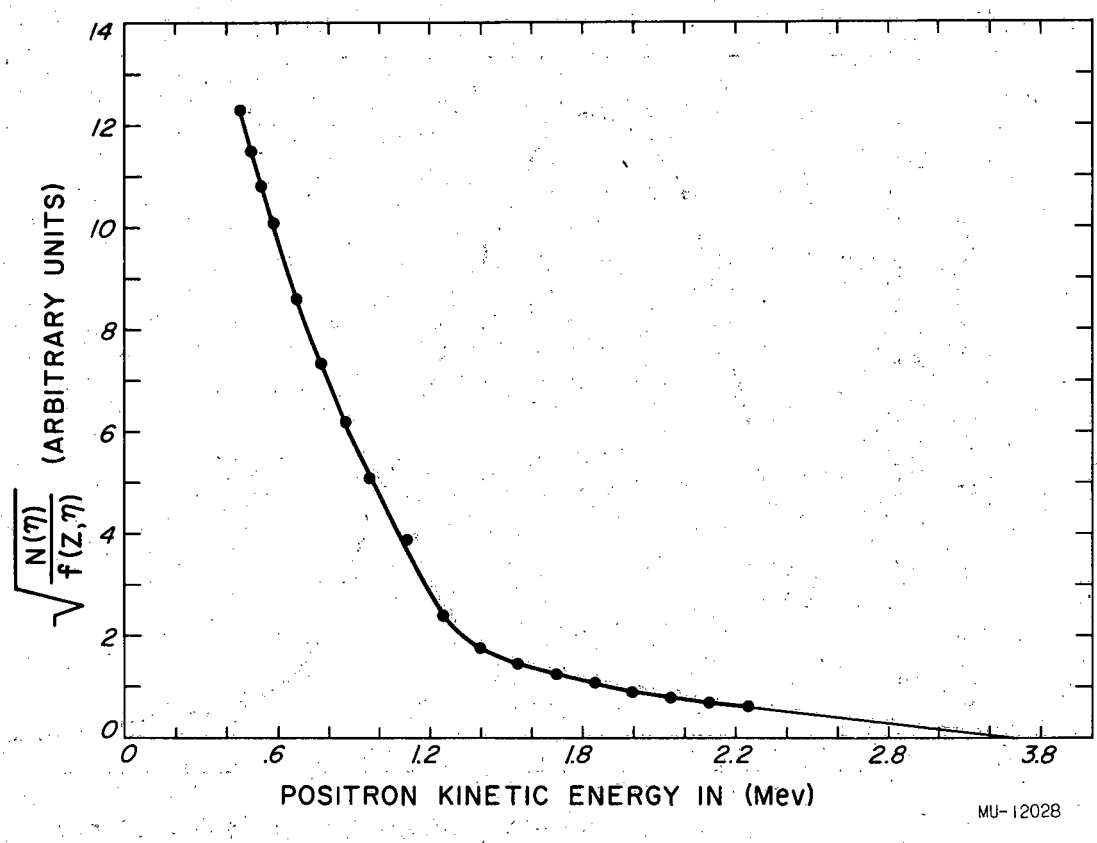

Fig. 10. Kurie plot of In^{108} positrons.

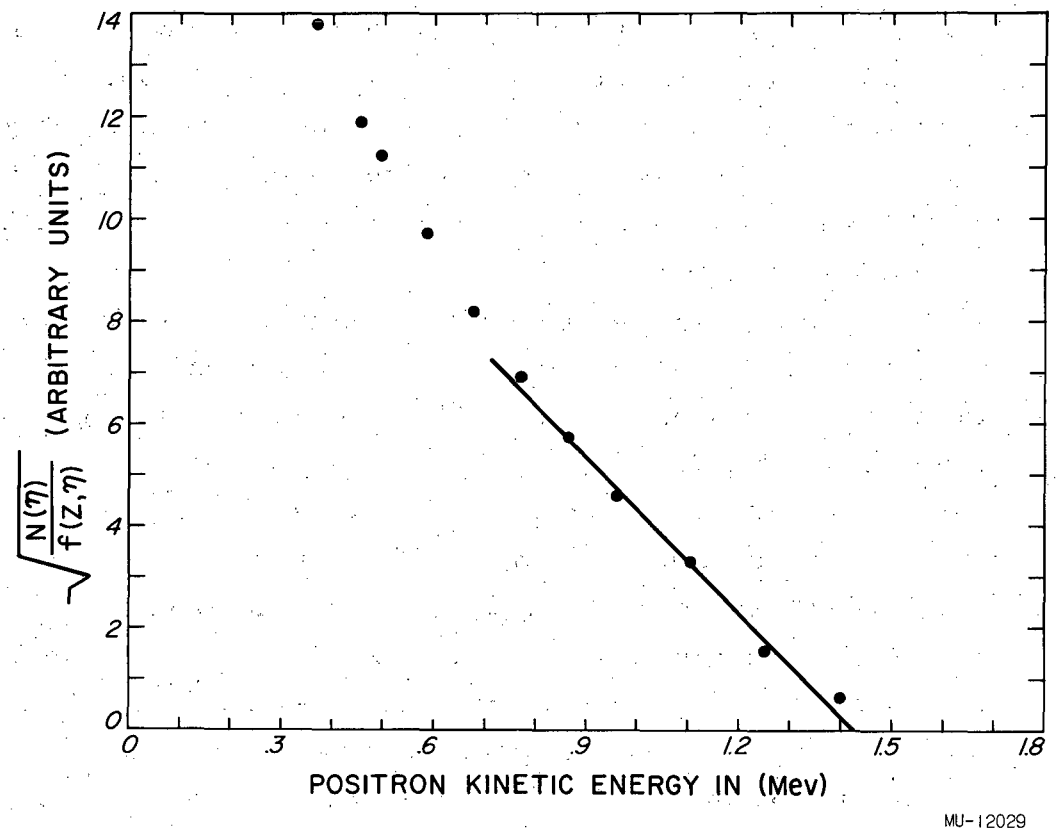

Fig. 11. Kurie plot of In^{108} positrons after subtraction of high-energy components.

Mev positrons decay with a period of approximately 55 minutes and are assumed to represent a primary mode of beta decay from the 55-minute state of In^{108}.

In order to obtain further information concerning the high-energy positrons, an additional bombardment was made using enriched $Ag^{107}Cl$. In this case, the target material contained less than 1% Ag^{109}. With a source obtained from this bombardment, the decay of five points of the high-energy positron spectrum was followed for a period of about 12 hours. (Fig. 12.) These points all decay initially with half lives of approximately 45 minutes. Subtraction of background activity suggests a half life for this positron component of about 42 minutes. The Kurie plot obtained from these points is shown in Fig. 13, and again appears to contain a component having and end-point energy of roughly 3.5 Mev. The deviation, from the straight line suggested by the highest-energy points, appears to be due to positrons of about 2.2 Mev, which may result from the presence of In^{107}.

Since the high-energy positrons have an end-point energy and half life which suggest that they do not belong to In^{107} or In^{109}, an interpretation in terms of the In^{108} decay scheme is suggested. If the 55-minute state of In^{108} is an isomeric state, then these positrons may represent the transition from the ground state of In^{108} to the ground state, or first excited state, of Cd^{108}. In this case, these positrons should be present among the activities resulting from Sn^{108}. Since they are of higher energy than the other known tin and indium positrons in this region, they should be distinguishable even in the presence of the many activities that result from the bombardment of enriched Cd^{106}. To test this possibility, Cd^{106} was bombarded and a source prepared from the separated tin fraction. The positron spectrum, particularly the high-energy region, was observed for more than 12 hours beginning about 1 hour after the end of the bombardment. The decay of the point on the positron spectrum corresponding to an energy of 2.3 Mev is shown in Fig. 14. Its half life appears to be 40 ± 2 minutes. The decays of points on the spectrum representing lower energies were also followed and were observed to decay into a longer half life of about 4 hours. This background has been subtracted from the values used to obtain the Kurie

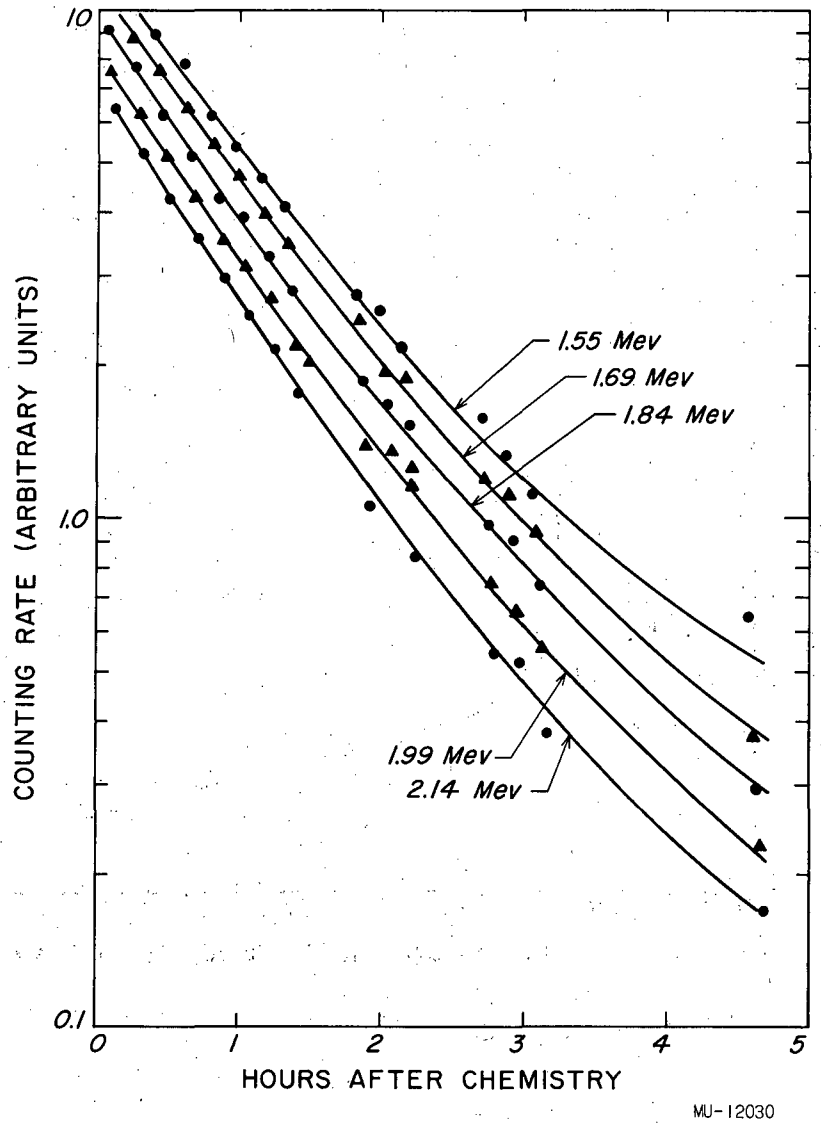

Fig. 12. Decay of five points of the In^{108} positron spectrum.

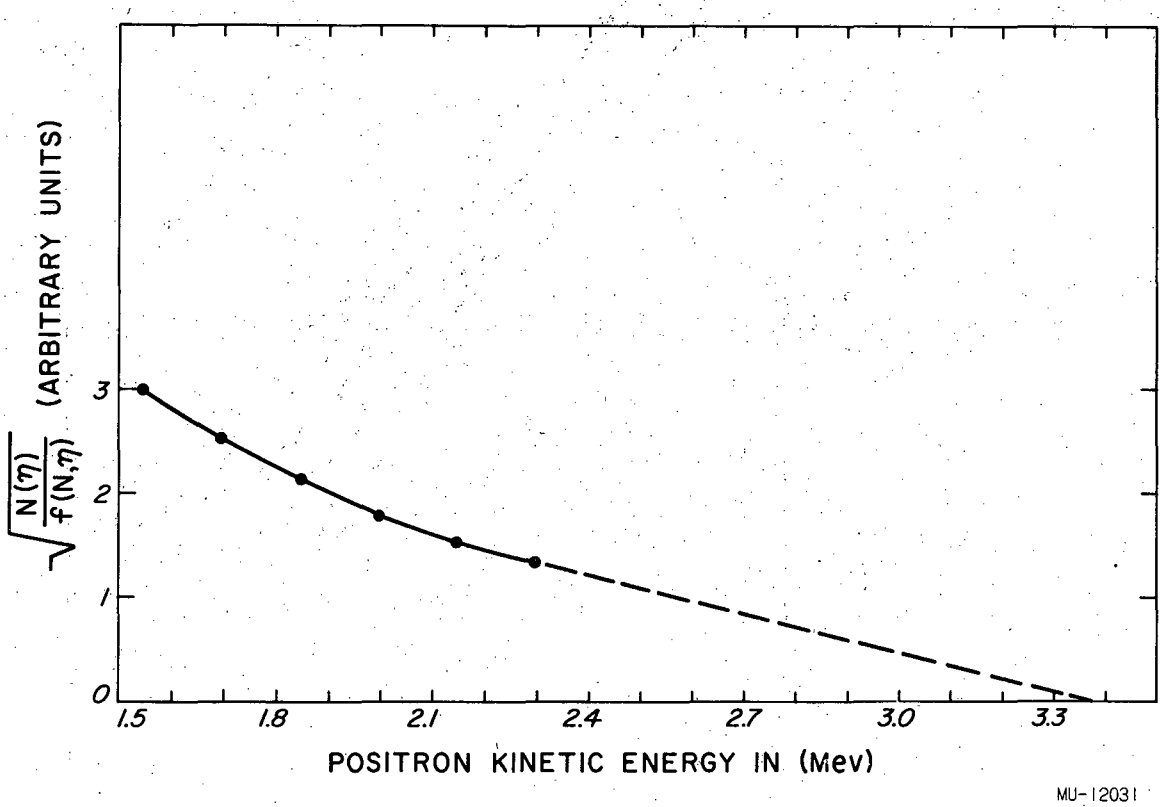

Fig. 13. Kurie plot of the high-energy portion of the In^{108} positron spectrum.

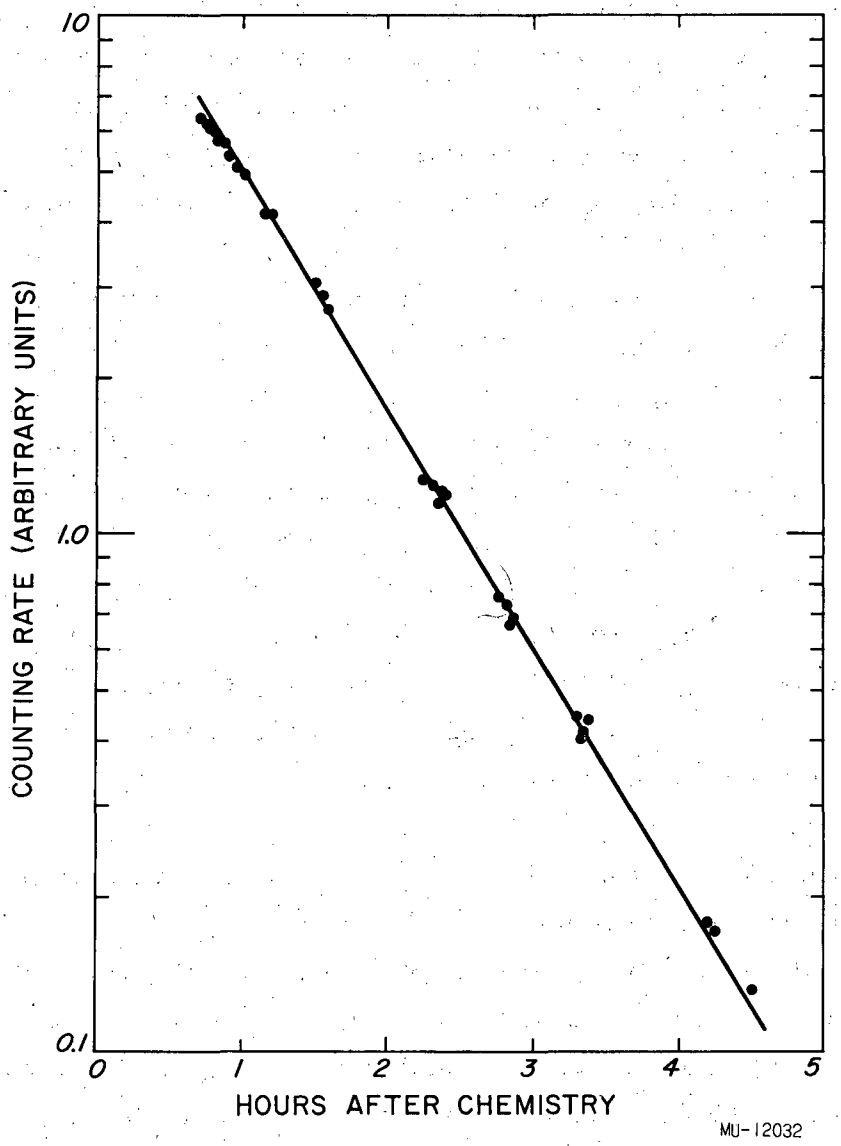

Fig. 14. Decay of the 40-minute positron activity.

plot shown in Fig. 15. An extrapolation of the line indicated by the highest-energy points of the Kurie plot suggests an end-point energy of 3.5 ± 0.1 Mev. This is believed to represent a more accurate value than was obtainable from the Kurie plots referred to previously. The log(ft) value for positrons with this energy and half life is approximately 6; that is, near the upper limit for an allowed transition. Because of the agreement in energy and half life, it has been assumed that these positrons are the same as those observed when indium is produced directly. In addition to the 40-minute and 4-hour half lives, there was some indication of a lower-energy positron activity with a half life of roughly 2 hours. No definite assignment of this activity has been made.

The initial points in the decay of the positrons of 2.3 Mev seem to indicate that a growth of the 40-minute activity has taken place. To investigate this growth, another tin source was prepared with which it was possible to obtain the first readings of the high-energy positrons 13 minutes after the chemical separation and 20 minutes after the end of the bombardment. The decay of the positrons at 2.3 Mev was followed for about 6 hours. Figure 16 shows the initial growth and the extrapolated 40-minute decay. Subtraction yields a half life of approximately 9.5 minutes, which has been tentatively assigned to Sn^{108}.

In order to obtain further evidence to aid in the proper assignment of the 3.5-Mev positron activity, an additional set of two bombardments was carried out. The intention was to compare the high-energy positron intensities of sources that had been similarly prepared except for the bombardment energy. To do this, two "compound targets" were prepared. In the first target, two quantities of about 3.4 milligrams of $Cd^{106}O$ were placed in small platinum "hats" and assembled into a single target in such a way as to be separated by 1.5 mils of platinum. The purpose of this arrangement was to obtain an alpha energy of approximately 28 Mev on the first quantity of $Cd^{106}O$ and about 16 Mev on the second. These energies were chosen with the intention of permitting a comparison between the source activities resulting from (α, n) and $(\alpha, 2n)$ reactions. Following the bombardment, almost simultaneous chemical separations were performed on both quantities of $Cd^{106}O$. The chemical procedures were chosen so as to yield two sources as nearly the same

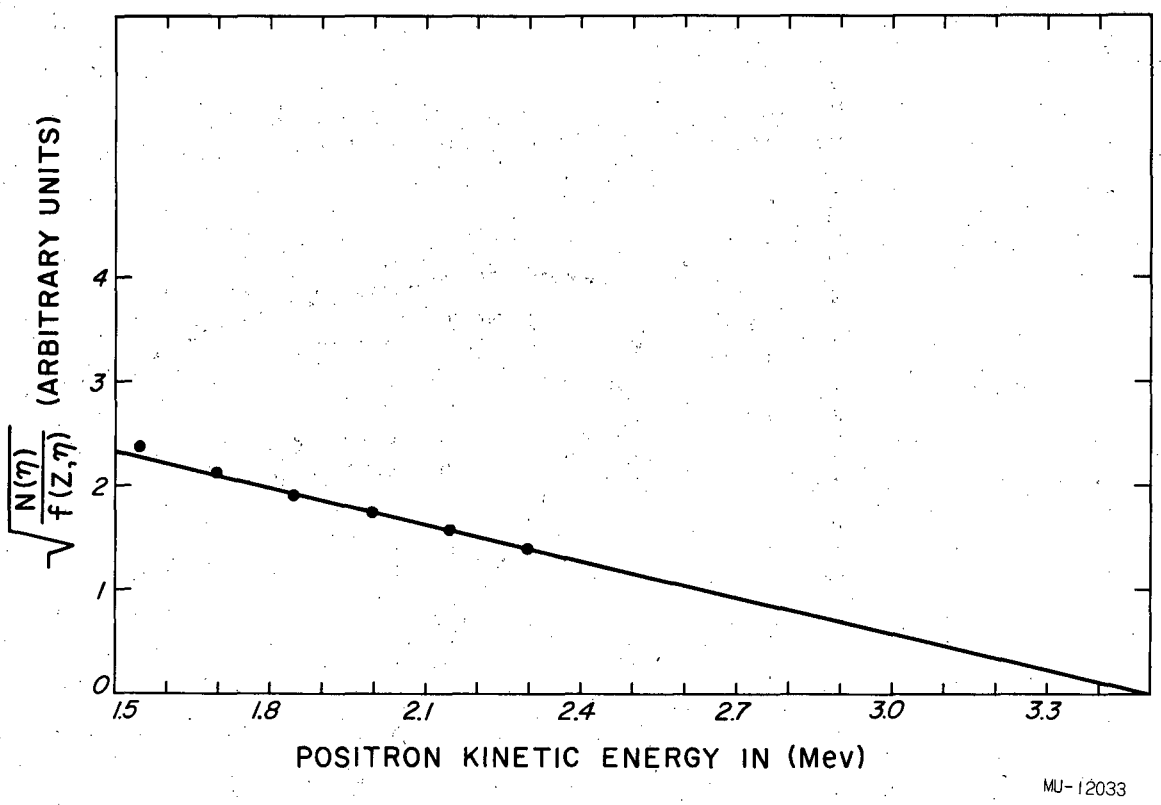

Fig. 15. Kurie plot of the high-energy portion of the 40-minute positron activity.

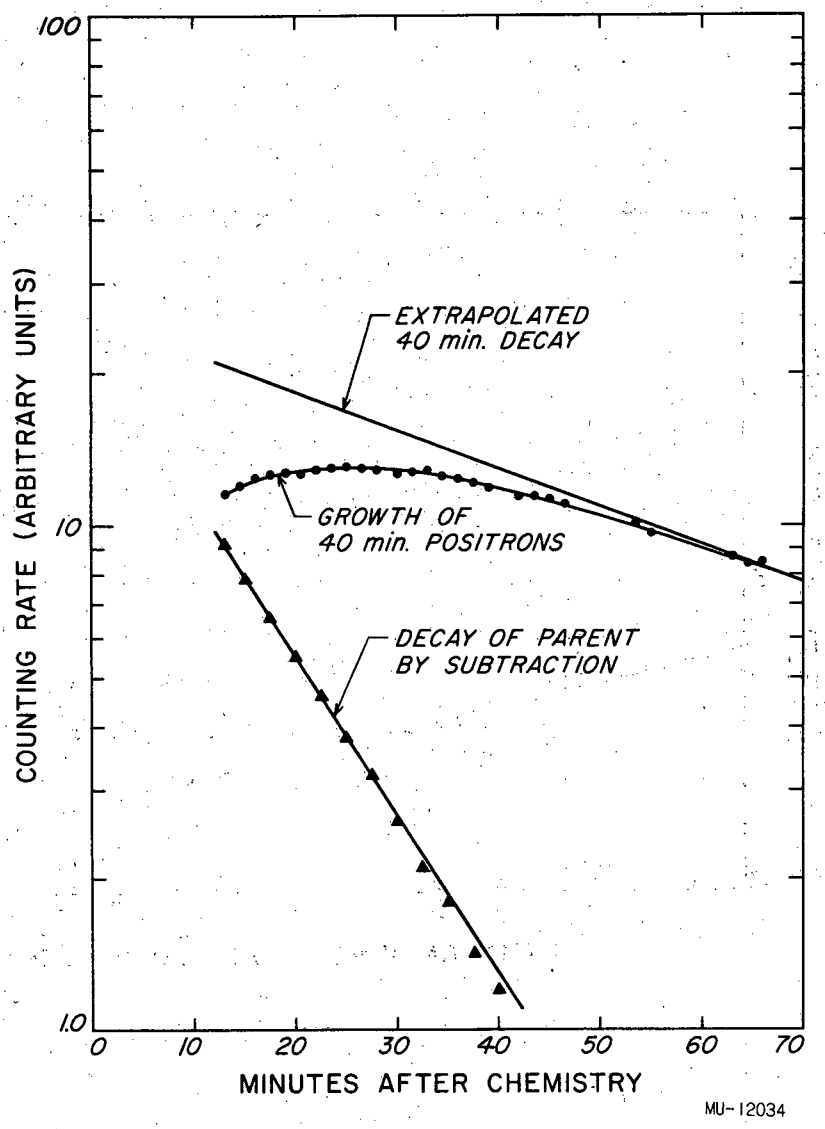

Fig. 16. Analysis of the growth of the 40-minute positrons.

as possible. The positron activity at 2.3 Mev and several internal conversion peaks were observed alternately with the two sources. (Each source was inserted separately into the beta-ray spectrometer.) Approximately 3 minutes elapsed between the end of a reading with one source and the beginning of a reading with the other. The first readings were obtained about 20 minutes after the end of the bombardment. With the source obtained from the (α, 2n) reaction (which should produce primarily Sn^{108}) the high-energy positrons were more intense than those observed with the other source and showed a decay of about 45 minutes. The positrons at 2.3 Mev observed with the (α, n) source decayed with a half life of about 19 minutes.* The intensity of the 205 kev gamma-ray of In^{109} was greater by a factor of about 2.5 in the (α, n) source.

In the second bombardment the (α, 2n) and (α, 3n) reactions were to be compared, and the energies chosen were approximately 22 Mev and 40 Mev. The same procedure as outlined above was followed in preparing the two sources. In this case, the high-energy positrons in the (α, 2n) source were only slightly more intense than with the (α, 3n) source. However, their intensity in the latter source was expected to be approximately 10 times as great as in the former if they had resulted from an (α, 3n) reaction. These two sets of observations tend to confirm the assignment of the 3.5-Mev positrons to an isotope of mass number 108.

The relatively high end-point energy of the 40-minute positrons suggests that they result from a transition from the ground state of In^{108} to the ground state or first excited state of Cd^{108}. An estimate of the transition energy available for the decay from In^{108} into Cd^{108} can be obtained by reference to the empirical curves of Way and Wood.[18] The value suggested for the decay of In^{108} to Cd^{108} is approximately 4 Mev. If the energy of the first excited level of Cd^{108} (637 kev) is subtracted from this total transition energy, a value of 3.36 Mev is obtained. The agreement with the measured positron energy suggests that the positrons

---

* For a discussion of the 18-minute activities observed, refer to M. D. Petroff,[17] who collaborated in this part of the investigation.

observed represent a decay to the 637-kev level of Cd^{108}. The internal conversion spectrum in the region of 650 kev was examined with the tin source with which the high-energy positrons were followed. Although several gamma rays are expected in this region, the maximum intensity 2 hours after bombardment occurred at approximately 637 kev. Since the half life at that time was roughly 40 minutes, it seems likely that the activity consisted primarily of the 637-kev line of In^{108}. Assuming that this gamma ray results from an E2 transition, and estimating the area under the extrapolated curve representing the 3.5-Mev positrons, one can compare these two activities. The result of this crude estimate is consistent with the interpretation of the 3.5-Mev positrons in terms of a decay that takes place primarily to the first excited state of Cd^{108}.

It is interesting to notice that the energy of the 40-minute positrons helps to distinguish them from positrons belonging to the adjacent odd-A isotopes. That is, the transition energies available to the odd-A isotopes in this region appear to be at least 1 Mev less than for the even-A isotopes.

The approximate energies of the two positron activities attributed to In^{108} provide some evidence as to the general characteristics of the In^{108} decay scheme. The sum of the lower-energy positrons and the two highest-energy gamma rays is 3.33 Mev--the same, within 200 kev, as the end-point energy of the high-energy positrons. If the 3.5-Mev positron decay takes place primarily to the 637-kev level, this suggests that the three high-energy gamma rays of In^{108} are in cascade, with the highest level, or one close to it, being fed by the 1.4-Mev positrons. Such an arrangement would be inconsistent with the possibility, mentioned earlier, that the 878-kev line arises from a level just 246 kev above the first excited state. This suggests a further consideration of the possibility that the 246-kev line may represent the isomeric transition. If it is an M4 transition, its half life is expected to be long compared with 55 minutes. However, the energy of the 1.4-Mev positrons appears to be compatible with a 55-minute half life, as the corresponding log(ft) value is about 4.8. This implies a branching ratio from the isomeric level such that only a few percent of the decays take place to the ground state of indium. The observed ratio of the 1.4-Mev positrons to

the 246-kev conversion electrons is not inconsistent with the assumption that the 246-kev line is an M4 isomeric transition of In^{108}. In this connection, it will be noticed that if the energy of the 330-kev gamma ray is added to the value of 3.33 Mev referred to above, and 246 kev is added to the 3.5-Mev positrons, the agreement between the two final energies is somewhat better than before. These speculations, however, are not considered sufficient justification for definite assignment of either of the two low-energy lines of In^{108}.

The assumption that the positron decay from the ground state of In^{108} takes place primarily to the first excited state of Cd^{108} suggests that the ground state of In^{108} may have a spin of 2 and even parity, as has been assumed for In^{110}. In this case, the beta-decay from Sn^{108} is not expected to take place directly to the ground state of indium; and therefore one or more Sn^{108} gamma rays may be observed. In a rapid survey of the internal conversion spectrum of a tin source, Petroff[16] observed three gamma rays which appeared to decay with half lifes of approximately 12 minutes. It may be that these gamma rays should be identified with Sn^{108}.

Some aspects of a possible decay scheme for Sn^{108} and In^{108} are indicated in Fig. 17.

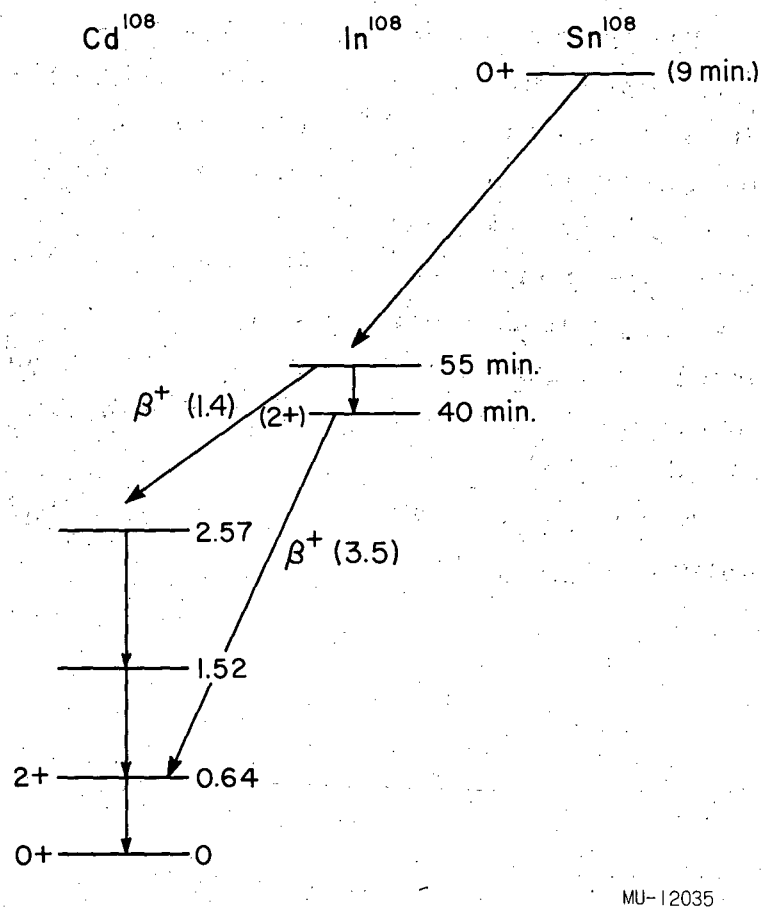

Fig. 17. Suggested decay scheme for Sn^{108} and In^{108}.

Conclusions

In the consideration of the possible decay schemes of the Sn^{110}, Sn^{108}, and In^{108}, it has been assumed that the ground states of the even-A isotopes of tin and cadmium have spins of zero with even parity. This assumption of 0+ ground states for the even-even nuclei appears to be consistent with the experimental evidence, and is one of the primary predictions of the shell model.

The similarities in the known isomers of the even-A indium isotopes have been utilized as a guide in suggesting the characteristics of the isomers of In^{108}. The even-A indium isotopes previously investigated have ground states of low spin, and isomeric states of relatively high spin. The 1+ ground states of the 112, 114, and 116 isotopes can be readily understood in terms of the shell model. The spin of the odd neutron (or hole) in the $g_{7/2}$ level subtracts, according to Nordheim's rule,[19] from the spin of the odd proton in the $g_{9/2}$ level to yield a spin of 1. A correct shell-model interpretation of the 2+ ground state, which has been suggested for In^{110}, and possibly In^{108}, is less obvious. A possible explanation is that the 3 or 5 neutrons in the $g_{7/2}$ level combine to give a spin of 5/2, which, with the odd $g_{9/2}$ proton, could result in a spin of 2. However, such a coupling of spins to yield a resultant spin that is one less than that of the odd nucleon is generally encountered only in light nuclei.

Of the two gamma rays considered as possible isomeric transitions of In^{108}, the 246-kev gamma ray appears to be a somewhat more reasonable choice. However, no definite evidence was obtained to permit making this assignment with certainty. The gamma rays and positron spectra assigned to In^{108} suggest that isomerism is involved, and appear to be compatible with the assumption of an isomeric state of higher spin than the ground state, as for the other even-A indium isotopes.

Acknowledgments

It is a pleasure to thank Professor A. C. Helmholz for suggesting this problem and for helpful discussions and suggestions throughout the course of the investigation. Michael D. Petroff, who collaborated in certain phases of this work, and Wesley O. Doggett were of considerable assistance. The successful production of the required isotopes was facilitated by the assistance and cooperation of William B. Jones, Peter F. McWalters, and the members of the crew of the 60-inch cyclotron. This investigation was made possible by the financial assistance of the Atomic Energy Commission and the facilities of the University of California Radiation Laboratory.

Appendix

The principal piece of apparatus used in these investigations was the magnetic-lens beta-ray spectrometer. It was constructed by Raymond W. Hayward, Jr.,[20] and is similar to the spectrometer described by Siegbahn.[21] Its special feature is a magnetic field that is about 30% stronger at the two foci than at a point halfway between. A magnetic field of this form reduces spherical aberration and results in a greater transmission factor for a given resolution. Changes in the associated equipment made during these investigations include an improved current regulator,[22] a redesigned Geiger tube,[17] and a ring baffle.[22] This additional baffle was used in obtaining most of the internal conversion spectra that have been discussed, and in some cases permitted a resolution of better than 2%.

The pulse-height analysis equipment used in some phases of the work was designed by William Goldsworthy.[23]

In the alpha bombardments, the choice of bombarding energy was, in most cases, based on an examination of the excitation curves for alphas on silver as reported by Ghoshal.[24] The alpha-particle energy and the energy range in the target material were varied somewhat during the course of the experiments in an effort to achieve maximum production of the desired isotopes, or to reduce unwanted activities.

The tin sources were prepared by dissolving the target material in concentrated nitric acid containing tin and indium carriers. The tin was separated from this solution, presumably in the form of SnO_2, with the aid of a centrifuge. More elaborate separations were employed in some cases, but the increase in purity of the sources did not appear to be sufficient to warrant the additional time required. Especially for the tin sources, the chemistry was continually simplified in order to obtain readings as soon as possible. The observed growth of the indium daughter activities could usually be interpreted as evidence that the separation was reasonably effective.

The AgCl targets were dissolved by boiling in concentrated HCl containing indium carrier. The AgCl was then precipitated by the addition of water. After the AgCl was removed, the solution was boiled to

near dryness. Water was added, and sufficient NH_4OH to precipitate the indium selectively as indium hydroxide. In order to speed drying of the sources, which were deposited on tygon films, the source material was sometimes washed with dilute acetone.

The enriched cadmium was in the form of CdO and CdS. Some of the $Cd^{106}O$ was known to contain 19.94% Cd^{106} and 0.65% Cd^{108}. The concentrations of the other enriched cadmium samples are not known with certainty, but are believed to have been more highly enriched in the desired isotope than the $Cd^{106}O$ referred to above.

Bibliography

1. M. G. Mayer and J. H. Jensen, Elementary Theory of Nuclear Shell Structure, Wiley, New York, 1955.
2. Eugene Feenberg, Shell Theory of the Nucleus, Princeton University Press, 1955.
3. Bleuler, Blue, Chowdary, Johnson, and Tendam, Phys. Rev. 90, 464 (1953).
4. E. C. Mallary and M. L. Pool, Phys. Rev. 76, 1454 (1949).
5. C. L. McGinnis, Phys. Rev. 81, 734 (1951).
6. M. Goldhaber and A. W. Sunyar, Phys. Rev. 83, 906 (1951).
7. Boehm, Huber, Marmier, Preiswerk, and Steffen, Helv. Phys. Acta 22, 69 (1949).
8. M. E. Rose, G. H. Goertzel, and C. L. Perry, K-Shell Internal Conversion Coefficients; Revised Tables, Oak Ridge National Laboratory Report No. ORNL-1023, June 1951.
9. P. F. Zweifel, Phys. Rev. 96, 1572 (1954).
10. Perlman, Berstein, Schwartz, Phys. Rev. 92, 1236 (1953).
11. Gertrude Scharff-Goldhaber, Phys. Rev. 90, 587 (1953).
12. L. S. Goodman and S. Wexler, Phys. Rev. 100, 1245(a), 1796(a) (1955).
13. Wayne A. Cassatt, Jr., and W. Wayne Meinke, Phys. Rev. 100, 1372 (1955).
14. Eugene Feenberg, Shell Theory of the Nucleus, Princeton University Press, 1955, p. 73.
15. M. G. Mayer and J. H. Jensen, Elementary Theory of Nuclear Shell Structure, Wiley, New York, 1955, p. 188.
16. J. M. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics, Wiley, New York, 1952, p. 627.
17. Michael D. Petroff (Thesis), University of California Radiation Laboratory (to be published).
18. Katherine Way and Marion Wood, Phys. Rev. 94, 119 (1954).
19. L. A. Nordheim, Revs. Modern Phys. 23, 322 (1951).
20. Raymond W. Hayward, Jr., Studies in Beta- and Gamma-Ray Spectroscopy (Thesis), UCRL-582, Jan. 1950.

21. K. Siegbahn, Phil. Mag. 37, 181 (1946).
22. Wesley O. Doggett, Radioactivity of Neutron-Deficient Rubidium Isotopes (Thesis), UCRL-3438, June 1956.
23. W. Goldsworthy, Recording Pulse-Height Analyzer, UCRL-2083, Jan. 1953.
24. S. N. Ghoshal, Phys. Rev. 73, 417 (1948).