The disintegration constant computed by the above method is

$$\lambda = (1.73 \pm 0.6) \times 10^{-21} \text{ sec.},$$

the average life is

$$\theta = 1.83 \times 10^{13} \text{ years}$$

and the half-life is

$$T = (12.8 \pm 3.0) \times 10^{12} \text{ years}.$$

The principal sources of error in the above values appear to enter through the method employed in determining the thickness of the layer from which rays reach the counter and through the estimation of the counter efficiency. In so far as can be told from the data at hand, these errors lie within the limits given. The present value of $13 \times 10^{12}$ is to be compared with the previous values of $15 \times 10^{12}$ obtained by Mühlhoff and $5 \times 10^{12}$ years given by Orban.

It is now known that potassium is composed of three isotopes with mass numbers 39, 40 and 41.[9, 10] Smythe and Hemmendinger[11] have recently shown that of these only $K^{40}$ is radioactive. Since the abundance[10] of $K^{40}$ is given by the ratio $K/K^{40} = 9000$, the disintegration constant for $K^{40}$ is obtained by multiplying the values given above by 9000. The radioactive constants for $K^{40}$ then become:

$$\lambda = (1.56 \pm 0.6) \times 10^{-17} \text{ sec.}^{-1},$$
$$\theta = 20.3 \times 10^{8} \text{ yr.},$$
$$T = (14.2 \pm 3.0) \times 10^{8} \text{ yr.}$$

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[9] A. O. Nier, Phys. Rev. **48**, 283 (1935).
[10] A. Keith Brewer, Phys. Rev. **48**, 640 (1935).
[11] Smythe and Hemmendinger, Phys. Rev. **51**, 178 (1937).

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# The Nuclear Isomers of $In^{116}$

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The isomeric periods of $In^{116}$ (13 seconds and 54 minutes), produced by the capture of slow neutrons by $In^{115}$, have been studied with the purpose of determining the energy level scheme for $In^{116}$. The $\gamma$-ray of energy 1.4 Mev previously measured by the authors has been shown to have a period of 54 minutes. No $\gamma$-ray of 13 second period could be found. The percentage transmission by boron of resonance neutrons which effect the two periods has been measured and found to be the same within the experimental error, for both periods. The value obtained for the percentage transmission of 0.0252 g/cm² $B$ (uncorrected for obliquity) is $73.5 \pm 3.0$. The branching ratio $R$(13 sec.)/$R$(54 min.) has been shown to be independent of the method of excitation and has the value $1.12 \pm 0.06$. From the known beta-ray end points and the energy of the gamma-ray an energy level diagram has been drawn up which accounts for all the experimental facts. The two excited levels of $In^{116}$ from which disintegration takes place are separated by 0.3 Mev, the level corresponding to the 13 second period lying higher. Gamma-ray transitions between these two levels can be forbidden by choosing quantum numbers which differ by 5 units.

## INTRODUCTION

THE element indium, when subjected to neutron bombardment, becomes radioactive and shows several periods. The most prominent periods are those of 13 seconds and 54 minutes discovered by Amaldi, d'Agostino and Segrè[1, 2] which were shown to result from the capture of slow neutrons by indium. Szillard and Chalmers[3] also found a period of 3.5 hours which they attributed to the action of fast neutrons on indium, since they obtained it when the neutrons were not slowed down by paraffin. They pointed out that, since indium has only two known isotopes, one of the isotopes must be responsible for two periods.

[1] E. Amaldi, O. d'Agostino, E. Segrè, Ricerca Scient. **5**, 2 (1934).
[2] E. Amaldi, O. d'Agostino, E. Fermi, B. Pontecorvo, F. Rasetti, and E. Segrè, Proc. Roy. Soc. **149**, 522 (1935).
[3] L. Szillard and T. A. Chalmers, Nature **135**, 98 (1935).

Recent investigations have added materially to our knowledge of the indium periods. From the work of Lawson and Cork,[4] who have made a thorough investigation of the indium periods which are obtained when this and neighboring elements are bombarded by various types of particles, it is clear that the 13 second and 54 minutes periods are to be attributed to $In^{116}$. In the present experiment indium was bombarded with slow neutrons, and under these conditions only two periods are observable;[5] namely 13 seconds, and 54 minutes due to $In^{116}$. In the present work we shall investigate the isomeric periods of $In^{116}$ and shall show that a nuclear energy level scheme can be drawn up which will account satisfactorily for all of the experimental data.

## The Beta-Ray Spectrum

The spectrum of the beta-rays associated with the two periods of indium has been studied in a cloud chamber by several investigators. Gaerttner, Turin and Crane[6] found, from the Konopinski-Uhlenbeck theory of beta-ray emission, an extrapolated end point of 3.2 Mev for the beta-ray associated with the 13 second period. The end point obtained by inspection appears to be about 3.1 Mev.

For the 54-minute period Gaerttner, Turin, and Crane obtained an extrapolated end point of 1.3 Mev while Brown and Mitchell,[7] using the same method found an extrapolated end point of 1.45 Mev. The end point obtained by inspection of the curves of the two sets of investigators is certainly not less than 1.3 Mev.

It is interesting to note that, although in some cases the K-U extrapolated end points are considerably higher than those obtained by inspection,[8] in the present case they appear to agree with the end points obtained by inspection to about 0.1 Mev. From all the data it seems that the best values for the end points are: for the 13 second period, $3.1\pm0.1$ Mev; for the 54 minute period $1.4\pm0.1$ Mev.

## The Gamma-Rays

Mitchell and Langer[9] measured the gamma-rays associated with the 54-minute period of indium. The method they used was that of measuring the stopping power of aluminum for Compton electrons ejected from a light metal by the gamma-rays. The ejected electrons were allowed to pass through two thin walled counters arranged to count coincidences. The decrease in the number of coincidences per minute was measured as a function of the thickness of aluminum placed between the counters. The authors also showed, from straight absorption experiments, that the gamma-ray was monochromatic. From this fact and the results of the coincidence method they showed that the energy of the gamma-ray was $1.39\pm0.10$ Mev.

## The Period of the Gamma-Ray Activity

We have performed a number of experiments in which we have measured the period of the gamma-rays. To do this we used two identical thin walled glass counters lined with a thin coating of silver. One counter was wrapped with lead foil to a thickness of 1.44 g/cm$^2$ (which stops beta-rays of energies up to 3.2 Mev) and was used to measure the gamma-rays. The other counter was used to measure the beta-rays. The counters were attached to a high speed amplifier and a thyratron scale of 4 or 8 recording mechanism. Indium foils were irradiated with neutrons from a radium beryllium source, containing 200 milligrams of radium salt. The neutron source was placed in a large paraffin cylinder, 4 cm below the top surface, and the indium samples were placed on top. In certain experiments an additional 5 cm of paraffin was placed behind the detector. The irradiation times varied from 1 to 15 minutes.

Since preliminary experiments showed that the period of the gamma-ray was about an hour, we irradiated samples of indium for periods of time ranging from 5 to 15 minutes, and started count-

[4] J. L. Lawson and J. M. Cork, Phys. Rev. **52**, 531 (1937).
[5] Mitchell (Phys. Rev. **53**, 269 (1938)) has shown that slow neutrons will produce an activity in indium with a 45-day period. This activity is due to $In^{114}$ and does not appear in these experiments since the irradiation time is too short.
[6] E. R. Gaerttner, J. J. Turin and H. R. Crane, Phys. Rev. **49**, 793 (1936).
[7] M. V. Brown and A. C. G. Mitchell, Phys. Rev. **50**, 593 (1936).
[8] L. M. Langer and M. D. Whitaker, Phys. Rev. **51** 713 (1937).
[9] A. C. G. Mitchell and L. M. Langer, Phys. Rev. **52**, 137 (1937).

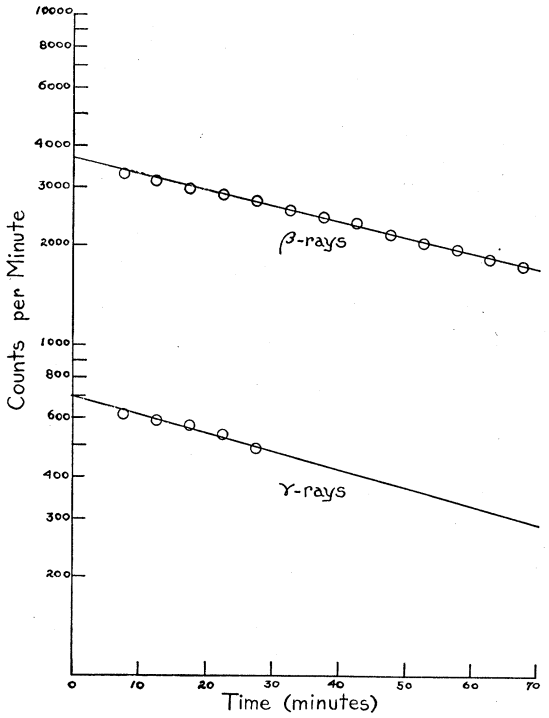


FIG. 1. Decay curves for the beta- and gamma-radiation of the 54-minute activity of indium (116).

ing 5 minutes after the end of the irradiation. With this procedure, any effect due to the 13 second period would be entirely negligible. Measurements on the beta-rays with the beta-ray counter, and on the gamma-rays with the gamma-ray counter, showed that the two periods were the same to within the experimental error, and had the value $55\pm5$ minutes. Fig. 1 shows decay curves for the beta- and gamma-rays taken with identical indium samples irradiated in the same manner. The samples were irradiated for 15 minutes. It will be seen that the initial intensity of the beta-ray count was 3700 per minute while that for the gamma-rays was 700 per minute. The ratio of the two is therefore

$$I(\gamma)/I(\beta)=700/3700=0.189.$$

This value, of course, has nothing to do with the number of gamma-ray quanta per disintegration since the gamma-ray counter was not calibrated in terms of quanta.

Experiments were now performed to see if there were any gamma-rays connected with the 13-second period. In these experiments the indium was irradiated for 1 minute on the paraffin cylinder and paraffin was placed behind the sample to increase the intensity. The sample was placed on the counter and readings were taken as soon after irradiation as possible, the first readings being taken in from 10–20 seconds after irradiation. Readings were taken every 10 seconds.

A typical set of data on the beta- and gamma-ray counters is shown in Table I. The first column shows the time after irradiation, the second the beta-ray count and the third the gamma-ray count. A scale-of-eight counter was used for recording the beta-ray count while a scale of four was used for the gamma-rays. Since the gamma-ray count was small and a scale of four counter was used the fluctuations are large. It will be seen at once from the table that the beta-ray activity decreases by a factor of ten, in the time interval under consideration, whereas the gamma-ray activity decreases but slightly. In the table the activity due to the 54-minute period has not been subtracted. Readings on the above experiments were carried on for 30 minutes after the end of the irradiation. The gamma-ray count showed a period of 54 minutes and the activity for the earlier times extrapolated from the complete decay curves, shows that the gamma-ray activity given in column 3 of the table is due to the gamma-rays of the longer period. Runs were taken with longer irradiation times to increase the accuracy, and a calculation shows that any gamma-ray activity obtained in the early part of the run can be attributed to the 54-minute activity.

## EFFECT OF BORON ABSORPTION ON THE TWO ACTIVITIES

It is of interest to see whether the two isomeric periods of indium have the same resonance energy. In the case of the bromine isomers, of 18 minutes and 4 hour periods, Fleishmann[10] has shown that the resonance neutrons which excite the two isomeric periods show the same absorption coefficient in boron, from which it follows that the resonance state in which the neutron is captured by the bromine nucleus is the same for both isomeric periods. Moreover, he has

[10] R. Fleishmann, Zeits. f. Physik **107**, 205 (1937).

TABLE I. *Comparison of beta- and gamma-ray intensity for 13 second period of indium.* (1 *minute irradiation.*)

| TIME AFTER IRRADIATION (SEC.) | BETA-RAYS (COUNTS/MIN.) | GAMMA-RAYS (COUNTS/MIN.) |
|---|---|---|
| 0 | — | — |
| 10 | — | — |
| 20 | — | — |
| 30 | 5341 | 88 |
| 40 | 4381 | 40 |
| 50 | 3037 | 88 |
| 60 | 2221 | 88 |
| 70 | 1549 | 88 |
| 80 | 1021 | 88 |
| 90 | 781 | 40 |
| 100 | 637 | 88 |
| 110 | 397 | 40 |
| 120 | 493 | 40 |

shown that the ratio of the two activities is independent of whether the neutrons have been filtered through cadmium or not. In the case of indium there exists a set of measurements by Goldsmith and Rasetti[11] which appears to show that the two isomeric periods do not have the same resonance energy. In order to test this point we have measured the percentage of the resonance neutrons transmitted by boron for both periods.

To carry out these measurements the neutron source was situated in the paraffin cylinder, described above. Across the top of the paraffin was placed a cadmium sheet, 0.218 g/cm² thickness, and measurements were taken with and without a Pyrex sheet containing 0.0252 g/cm² of boron as absorber. In order to make as good measurements as possible on the 13-second period activity, arrangements were made to photograph the recording meter and the stop watch at frequent intervals during the early part of the run with a Sept camera. The procedure, therefore, was as follows: An indium detector was irradiated, with or without the Pyrex filter, for a period of either 5 or 10 minutes. It was placed on the beta-ray counter as soon after irradiation as possible and instantaneous pictures of the meter and stop watch were taken every two seconds until the count became to small in this time interval for accurate measurement. Counting was continued, by reading the meter visually, until the end of the fortieth minute. The initial activity of the 54-minute period was obtained by extrapolating back to zero time the observations taken at the later times, and the activity of the 13-second period was obtained in the same way from the data of the films, due account being taken of the activity arising from the 54-minute period during the earlier times.

The results are shown in Table II, in which the percentage of the activity due to neutrons transmitted through boron is shown in the last two columns. It will be seen that the transmission is the same, to within the limit of experimental error, for both periods.[12] It appears, therefore, that the neutron resonance energy is the same for both isomeric periods.

## THE BRANCHING RATIO

We have measured the branching ratio for the process, *viz.*, the activity of the 13-second period to that of the 54-minute period, under various conditions of irradiation. This ratio is independent of the method of excitation of the sample, as is shown in Table III. Column 1 shows the method of irradiation. Thus, for example, the notation "paraffin only" indicates that the sample was placed directly on top of the paraffin cylinder containing the neutron source; Cd indicates that 0.218 g/cm² of cadmium was placed between the detector and the paraffin; and Cd+B, that 0.218 g/cm² of cadmium and 0.0252 g/cm² of boron (Pyrex plate) were interposed between source and paraffin. Column 2 shows the length of time of irradiation. In columns 3 and 4 are given the corrected initial rates of decay of the 13 second and 54 minute periods, respectively, in counts per second. These

TABLE II. *Boron absorption.*

| CONDITIONS | IRRADIATION TIME (MIN.) | ACTIVITY (COUNTS PER MIN.) | | PERCENT TRANSMISSION | |
|---|---|---|---|---|---|
| | | 13 SEC. | 54 MIN. | 13 SEC. | 54 MIN. |
| 0.218 g/cm² Cd | 5 | 3850 | 225 | | |
| 0.218 g/cm² Cd+0.0252 g/cm² B | 5 | 2850 | 155 | 74.0 | 69.0 |
| 0.218 g/cm² Cd | 10 | 4000 | 420 | | |
| 0.218 g/cm² Cd+0.0252 g/cm² B | 10 | 3000 | 312 | 75.0 | 74.5 |
| | | | | 74.5 ±0.5 | 72.0 ±3.0 |

[11] H. H. Goldsmith and F. Rasetti, Phys. Rev. **50**, 328 (1936).

[12] Since the angular distribution of the neutrons is not particularly well known for the experimental arrangement we have used, we have not attempted to calculate the absorption coefficient or the absolute value of the resonance energy.

data were obtained in the manner usually employed in radioactive work, i.e., the initial activities were found by extrapolating the various decay curves to zero time after irradiation and then correcting these for irradiation time, so that all figures are given on the basis of infinite irradiation time for both periods. The ratio of these two results, called the branching ratio $R$ (13 sec.)/$R$ (54 min.), is shown in column 5 of Table III. It will be seen at once that the branching ratio is independent of the method of excitation and that it has the value $1.12\pm0.06$.

From the branching ratio one can calculate the number of radioactive atoms present in each isomeric state at zero time after infinite irradiation. Since the branching ratio has to do with the initial rate, the ratio of the number of atoms present in the two states will be given by

$$1.12=\frac{\lambda_{13}N_{13}}{\lambda_{54}N_{54}};$$

$$\frac{N_{13}}{N_{54}}=1.12\times\frac{2.14\times10^{-4}}{5.32\times10^{-2}}=0.446\times10^{-2}$$

using the values for $\lambda_{13}$ and $\lambda_{54}$ of $5.32\times10^{-2}$ sec.$^{-1}$ and $2.14\times10^{-4}$ sec.$^{-1}$, respectively.

## The Energy Level Scheme

It has been suggested by Weizsäcker[13] that the nuclear isomers may be considered as metastable states in the excited parent nucleus. Transitions may occur from both excited states of the parent nucleus to various states in the product but, because of selection rules, transitions between the excited states of the parent either do not occur or the lives of these states are long compared to the lifetime for decay into the product. With this hypothesis as a basis we now have enough data to draw up a tentative energy level scheme for $In^{116}$.

Table III. *Determination of the branching ratio.*

| Method of Excitation | Time of Irradiation (Min.) | Corrected Initial Rates $R$ (counts/sec.) | | $\frac{R\ (13)}{R\ (54)}$ |
|---|---|---|---|---|
| | | 13 sec. | 54 min. | |
| Paraffin only | 5 | 133 | 135 | 0.99 |
| Paraffin only | 5 | 192 | 151 | 1.27 |
| Paraffin only | 5 | 166 | 148 | 1.12 |
| Cd | 5 | 64.1 | 58.3 | 1.10 |
| Cd | 10 | 66.6 | 58.3 | 1.14 |
| Cd+B | 5 | 47.5 | 40.1 | 1.18 |
| Cd+B | 5 | 50.0 | 48.0 | 1.04 |
| Cd+B | 10 | 50.0 | 43.3 | 1.15 |
| | | | Average | $1.12\pm0.06$ |

[13] C. F. v. Weizsäcker, Naturwiss. **24**, 813 (1936).

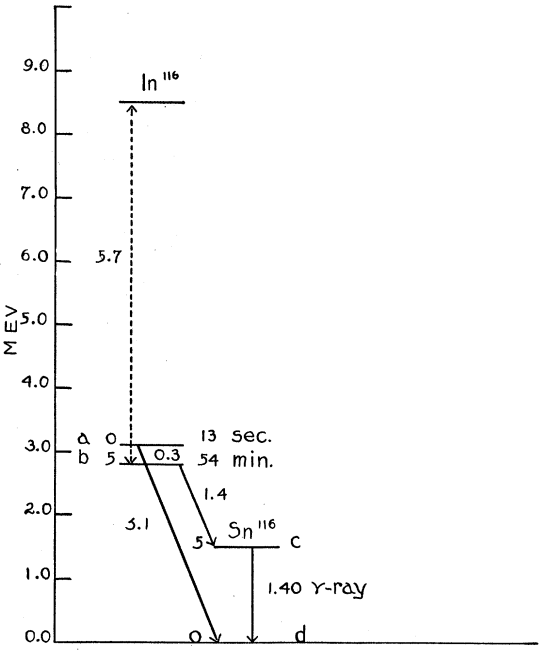


FIG. 2. Energy level system of indium (116).

Figure 2 shows the energy level scheme for the process. The states to the left of the diagram represent the parent nucleus $In^{116}$ while those to the right represent the product $Sn^{116}$. Since the sum of the beta- and gamma-ray energies (2.8 Mev) connected with the 54-minute period is less than the beta-ray energy of the 13-second period, the energy level for the 54-minute period must lie lower than that of the 13-second period. Moreover, we have been unable to detect any gamma radiation of 13-second period. We have shown that the observed gamma-ray must be attributed to the 54-minute period. Furthermore, we have attributed the gamma-ray of 1.4 Mev energy to a transition in the product nucleus $Sn^{116}$. Although we have no proof at present that this is correct, it follows by analogy from the situation in the natural radioactive elements where it can be shown that the gamma-ray follows the disintegration and is attributed to a transition in the product.

One now has to explain why there is no observed gamma-ray transition between the levels $a$ and $b$. The mean life for a gamma-ray depends on the angular momentum change for the transition and the energy of the gamma-ray according to the formula,[14] $\tau = 5\times10^{-21}(l!)^2(20/\hbar\omega)^{2l+1}$ seconds, where $\hbar\omega$ is the energy of the gamma-ray in millions of volts and $l$ is the change in angular momentum during the process of emission. With the available energy taken as 0.3 Mev, one must choose an $l$ which will make the mean life for the gamma-ray transition $a\rightarrow b$ long compared to the beta-ray transition $a\rightarrow d$. If one takes $l=5$ one obtains $\tau_\gamma = 139$ min. ($\lambda_\gamma = 0.83\times10^{-4}$ sec.$^{-1}$). Now, when one measures the period of the beta-rays from state $a$ from the relation $e^{-\lambda t}$, the value of $\lambda$ obtained is the sum of all the transition probabilities to all possible lower states. Hence

$$\lambda_{13} = \lambda_\gamma + \lambda_\beta = 5.32\times10^{-2} \text{ sec.}^{-1}$$

so that with the value of $\lambda_\gamma$ given above for $l=5$, the ratio of the intensity of gamma-ray transition to the total is given by

$$\frac{I_\gamma}{I_{\text{total}}} = \frac{\lambda_\gamma}{\lambda_\gamma+\lambda_\beta} = \frac{0.0083\times10^{-2}}{5.32\times10^{-2}} = 0.0016 = 0.16 \text{ percent}$$

Thus, the gamma-ray emission would be undetectable in agreement with experiment. On the other hand, if one takes $l=4$ one obtains $\tau_\gamma = 7.57\times10^{-2}$ sec. ($\lambda_\gamma = 9.15$ sec.$^{-1}$). With this small value for $\tau_\gamma$ it will be seen that the total activity of the state $a$ would decay in a time which is short compared to 13 seconds by gamma-ray emission so that no beta-ray emission with a period of 13 seconds would be observed. However, since a strong beta-ray emission of 13-second period is observed it follows that $l$ cannot be less than 5.

The assignment of quantum numbers to the various levels cannot be made on a very sound basis. Some progress can be made, however, if one makes use of certain assumptions. In the first place the level $d$, ground state of $Sn^{116}$, probably has zero spin since the nucleus contains $4n$ particles. Furthermore, the beta-ray end points of both the 13 second and the 54 minute activities lie on the first Sargent curve for which $\Delta i = 0$. This suggests assigning the quantum number 0 to level $a$ so that it will have the same quantum number as $d$. Similarly the levels $b$ and $c$ should have the same quantum numbers. Since the transition $a\rightarrow b$ is to be forbidden, it follows from the above calculation that the level $b$ must be assigned the quantum number 5, and hence level $c$ should also be given the quantum number 5. Finally, the assignment of the quantum number 5 to level $c$ does not forbid the gamma-ray transition $c\rightarrow d$. A short calculation shows that, on account of the high energy of the gamma-ray (1.4 Mev), the mean life for the transition $c\rightarrow d$ is about $10^{-6}$ seconds.

Unfortunately, the energy of the gamma-radiation occuring in the process of the capture of slow neutrons by $In^{115}$ to form $In^{116}$ has not been measured. In this region of the periodic table the binding energy of the neutron is about 8.5 Mev, so that if the nucleus made a transition from the capture state to one of the states $a$ or $b$ with the emission of one quantum of radiation, one would expect a gamma-ray of 5.4 to 5.7 Mev energy. Now the branching ratio has been shown to be approximately unity, i.e. the rates at which nuclei are leaving states $a$ and $b$ are about the same. At equilibrium, therefore, the rates at which they are arriving in states $a$ and $b$ are also equal. If the states $a$ and $b$ are fed from the capture state by single transitions, one would expect large differences in the rates at which the states are populated on account of selection rules governing the gamma-ray transitions which depend on the quantum numbers of the state $a$ and $b$ as well as that of the capture state.[15] If cascade transitions occurred the effect of selection rules would be more or less obliterated so that the rates of arriving in states $a$ and $b$ would be approximately equal. It would be of interest, therefore, to make a measurement of the energy of the capture gamma-rays as it would elucidate the mechanism of the transitions between the capture state and the states $a$ and $b$.

The authors wish to acknowledge their indebtedness to the American Philosophical Society for a grant from the Penrose Fund which made this work possible. They are also grateful to Dr. M. H. Johnson, Jr. for many helpful discussions.

[14] See H. A. Bethe, Rev. Mod. Phys. **9**, 226 (1937).

[15] The quantum number of the capture state is probably 4 or 5, since $In^{115}$ has a spin of 9/2 and the neutron is so slow that most of the capture occurs from the $S$ wave.