Decay Scheme of Sn^{113}†

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The electron capture decay of Sn^{113} has been investigated using scintillation detectors and coincidence circuitry. Decay was found to occur to the 650- and 393-kev states of In^{113} with branching ratios of $(1.8\pm0.1)\%$ and $(98.2\pm0.1)\%$, respectively. The 650-kev state decayed by the emission of a 255-kev gamma ray to the 393-kev state. No evidence was found for the existence of a 648-kev crossover transition. An upper limit for the intensity of this transition was placed as 0.1% of that of the 255-kev transition. The orbital electron capture ratio to the 648-kev state was determined to be $(P_{LMN}.../P_K)<0.19$. From this value, a minimum decay energy to the 648-kev state was assigned as 150 kev. It was determined that transitions to the 393-kev state of In^{113} were first forbidden by considering log ft values; this is consistent with a spin and parity of $\frac{1}{2}+$ or $\frac{3}{2}+$ for the ground state of Sn^{113}. The 648-kev state was assigned a spin and parity of $\frac{1}{2}-$ or $\frac{3}{2}-$ on the basis of possible log ft values and the absence of the 648-kev crossover transition.

INTRODUCTION

THE decay of Sn^{113} has been shown to occur by orbital electron capture, with a half-life of approximately 119 days. Decay occurs to excited states of In^{113} at 393 and 646 kev,[1–5] the 393-kev state being predominantly populated. The references quoted above are those of the more recent investigations; a comprehensive listing of earlier references is given by Phillips *et al.*[5] The ground-state spin of In^{113} has been measured to be 9/2,[6] which is consistent with a single-particle shell model assignment of $g_{9/2}$ to this level. The 393-kev isomeric state decays to the ground state with a half-life of 104 min. Its spin has been measured as $\frac{1}{2}$,[7] which is consistent with a shell-model assignment of $p_{\frac{1}{2}}$ for this state. Although there is reasonable agreement on the relative probability of population of the 648-kev state, disagreement has arisen over the exact mode of decay of this state and consequently its spin and parity. This state decays predominantly by a 255-kev transition to the 393-kev state. The disagreement arises over the question of the existence of a 648-kev transition. Grigis *et al.*[2] placed an upper limit on the intensity of this 648-kev transition of 0.05% that of the 393-kev transition, and likewise Burson *et al.*[4] put this upper limit as 0.1%. However, Phillips *et al.*[5] found a 648-kev gamma ray in both "singles" and coincidence spectra having an intensity of 0.24% that of the 393-kev gamma-ray intensity. Dependent on the existence of this 648-kev transition is the spin and parity assignment to the 648-kev state, although the internal conversion coefficients obtained by Burson *et al.*[4] would indicate that the 255-kev transition is $M1$ or $(M1+E2)$ in nature, i.e., the 648-kev state has a $\frac{1}{2}-$ or $\frac{3}{2}-$ spin and parity.

Bhatki *et al.*[1] obtained a value for the ratio of the probability of electron capture occurring from the L, M, $N\cdots$ shells to that occurring from the K shell in transitions to the 648-kev state of In^{113} as $(P_{LMN}.../P_K)=2.23_{-0.88}{}^{+1.12}$, which would indicate a decay energy to this level of $36_{+4}{}^{-1}$ kev. As they point out, since capture to this state is expected to be first forbidden and such a decay energy would indicate a log ft value of 5, this presents an anomaly. This study of the Sn^{113} decay scheme was undertaken in order to help remove these remaining inconsistencies.

EXPERIMENTAL

A. Gamma-Ray Scintillation Spectra

A source of Sn^{113} was produced by a neutron irradiation of 2 mg of tin, enriched in Sn^{112} up to 72%, in the NRX reactor at Chalk River for three weeks. The source was allowed to sit for three months after irradiation to allow most of the Sn^{125} activity to decay to Sb^{125} before chemistry was performed. The active tin was dissolved in hot 6N HCl, and in that portion of the source used to look for the 648-kev transition, traces of antimony and tellurium were removed by electrodepositing on iron in the acidified solution.

The gamma-ray spectra were studied with a scintillation detector consisting of either a $1\frac{1}{2}\times1$ in. NaI(Tl) crystal mounted on a DuMont 6292 photomultiplier tube or a 5×4 in. NaI(Tl) crystal mounted on a DuMont 6364 photomultiplier tube. Pulse-height analysis was accomplished with a 20-channel pulse-height analyzer.

A typical spectrum, obtained with the $1\frac{1}{2}\times1$ in. NaI(Tl) crystal is shown in Fig. 1. In this spectrum, the 255-kev gamma ray is unresolved from the Compton edge of the 393-kev gamma ray at 238 kev. The only

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[1] K. S. Bhatki, R. K. Gupta, S. Jha, and B. K. Madan, Nuovo cimento **6**, 1461 (1957).
[2] R. K. Girgis and R. Van Lieshout, Physica **24**, 672 (1958).
[3] W. T. Achor, W. E. Phillips, J. I. Hopkins, and S. K. Haynes. Phys. Rev. **114**, 137 (1959).
[4] S. B. Burson, H. A. Grench, and L. C. Schmid, Phys. Rev. **115**, 188 (1959).
[5] W. E. Phillips and J. I. Hopkins (private communication); and Phys. Rev. **119**, 1315 (1960).
[6] R. F. Bacher and D. H. Tomboulian, Phys. Rev. **52**, 836 (1937).
[7] W. J. Childs and L, S, Goodman, Bull. Am. Phys. Soc. **1**, 342 (1956).

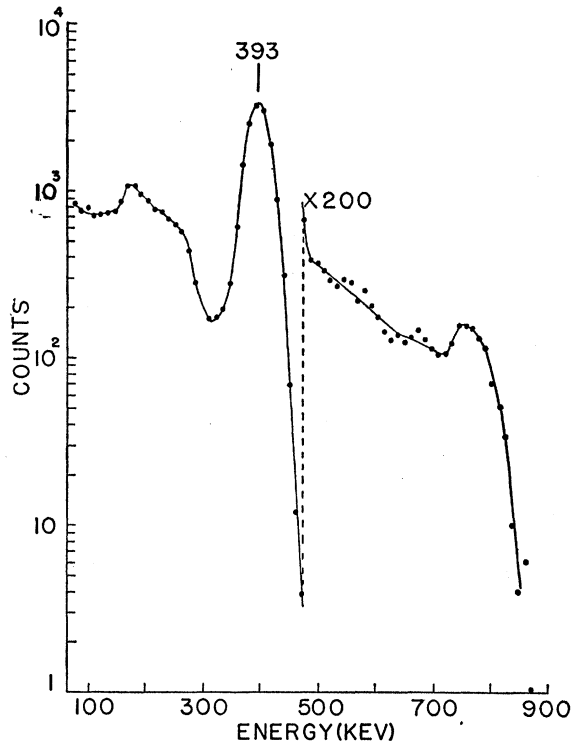

FIG. 1. Singles gamma-ray spectrum of Sn^{113} measured with a $1\frac{1}{2}$ in.$\times$1 in. NaI(Tl) crystal.

high-energy peak in this spectrum can be attributed to a random 393-kev coincidence summing peak. From this spectrum an upper limit for the intensity of 648-kev gamma radiation can be placed at 0.05% that of the 393-kev gamma-ray intensity. In the unpurified Sn^{113} samples, the spectra showed a definite peak in the region of 615 kev; this was attributed to the 601-kev and 637-kev gamma rays of Sb^{125}.[8]

The continuous part of the spectrum in Fig. 1 above the 393-kev photopeak cannot be attributed to the internal bremsstrahlung spectrum associated with electron capture to the 393-kev state, since it is about twenty times as intense as would be expected. For this spectrum to be internal bremsstrahlung would require approximately 5×10^{-3} internal bremsstrahlung quanta for every K orbital capture to the 393-kev state, with a decay energy of approximately 800 kev. The same objection would also apply to the continuous spectrum interpreted by Phillips *et al.*[5] to be the internal bremsstrahlung spectrum.

Experiments were performed to obtain an accurate value for the ratio of the intensity of the 258-kev gamma radiation to the 393-kev gamma radiation. In these experiments the indium, and hence the 393-kev In^{113} isomer, was chemically separated rapidly from the Sn^{113}. The 255-kev gamma radiation, now no longer obscured by the 393-kev gamma radiation in these spectra, was observed and its absolute intensity measured. The 393-kev gamma ray was seen to grown back to its equilibrium value within a day, after which time its absolute intensity was measured. Chemical separation was very easily performed since indium chloride in excess sodium hydroxide forms insoluble indium hydroxide, whereas both stannic and stannous chlorides form compounds soluble in sodium hydroxide. Using this technique the separation could be completed in less than 5 min. Spectra were taken using the 5$\times$4 in. NaI(Tl) crystal. A spectrum taken shortly after such a separation is shown in Fig. 2. Part A of this spectrum, containing the 255-kev photopeak, was taken within the time interval 6.5 to 9.5 min after commencement of the separation, whereas part B, containing the 393-kev photopeak, was taken from 19.7 to 13.7 min after separation. After correcting for the differences in detection efficiencies, and the probabilities of producing the full energy peaks, the 255-kev gamma ray intensity was determined to be (2.8$\pm$0.1)% of the 393-kev gamma-ray intensity.

B. Coincidence Experiments

Using a "singles" scintillation detector, the upper limit which could be placed upon the possibility of a 648-kev crossover transition was the same as that obtained by Grigis *et al.*[2] This upper limit is five times

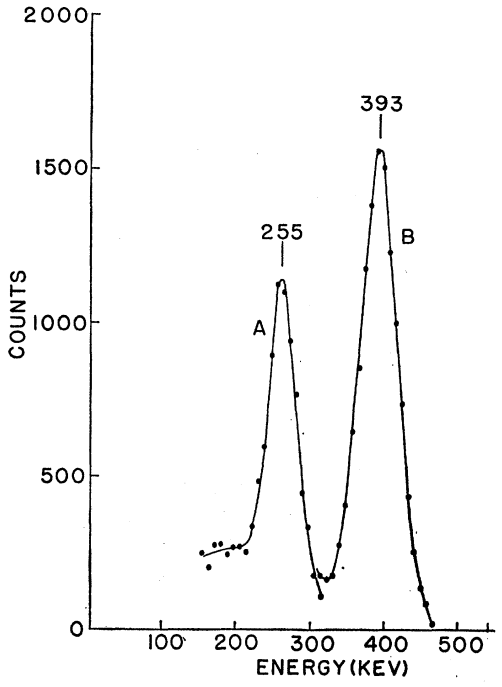

FIG. 2. Singles gamma-ray spectrum of Sn^{113} measured with a 5 in.$\times$4 in. NaI(Tl) crystal after the 104-min 393-kev isomer of In^{113} had been removed by chemical separation. Curve A was taken in a time interval 6.5 min to 9.5 min after the commencement of the separation and curve B was taken in the time interval 10.7 to 13.7 min.

[8] N. H. Lazar, Phys. Rev. **102**, 1058 (1956).

less than the intensity of the 648 kev seen by Phillips *et al.*[5] However, the latter authors also found the 648-kev gamma radiation in coincidence with In K x rays. It was therefore decided to obtain such coincidence spectra in this investigation. The detectors consisted of a $1\frac{1}{2}\times1$ in. and a $1\frac{1}{2}\times\frac{1}{2}$ in. NaI(Tl) crystals mounted on DuMont 6292 photomultiplier tubes. The coincidence circuit used had a resolving time of 10^{-7} sec. A 20-channel pulse-height analyzer was used in conjunction with this coincidence circuit. Spectra were observed in the energy region 550 to 750 kev in coincidence with In K x rays. No evidence of a 648-kev gamma radiation was observed in the spectra obtained. An upper limit for the intensity of the 648-kev transition was placed as $3\times10^{-3}\%$ that of the 393-kev gamma-ray intensity. A series of coincidence experiments was undertaken to determine the relative probabilities of K orbital electron capture to L, M, N, $\cdots$ orbital electron capture in decay to the 648-kev state of In^{113}. Coincidence spectra, using the previously described coincidence circuitry, were taken with the "fixed" channel set to accept all the In K x rays. The 255-kev gamma ray was found to be in "real" coincidence with the In K x rays. Such a spectrum is shown in Fig. 3. The ratio of the intensity of the 255-kev gamma rays observed in the "free" channel, denoted by C_2, to the intensity of the 255-kev gamma rays observed in the same crystal, denoted by N_2, with exactly the same geometry in both spectra, can be related to the probability, P_K, of K orbital electron capture occurring to the 648-kev state. The relationship can be expressed as

$$P_K=(C_2/N_2)\frac{1}{\omega_K d_x(\omega_2 T_x)P_x},$$

where P_x is the probability that a detected In K x ray will give a full energy peak; ω_K is the fluorescence yield; d_x is the detection efficiency of the In K x ray in the crystal of the "fixed" channel, and $(\omega_2 T_x)$ is the probability that a In K x ray emitted by the source will enter the crystal of the "fixed" channel. Although the intensity of the 255-kev gamma ray cannot be obtained directly from the "singles" spectrum, it can be calculated from the intensity of 393-kev gamma rays in the spectrum. Spectra were taken with several different sized crystals in experimental arrangements with and without anti-Compton shielding. Account was taken of the possibility of a 255-kev gamma ray being detected in the crystal in the "free" channel with an iodine K x ray escaping and being detected in the crystal in the "fixed" channel by interposing a Cu absorber between the two crystals in some of the spectra. From these experiments, a value of $P_K=1.01\pm0.17$ was obtained; this error assignment is the maximum possible error. Consequently, the minimum value P_K can have is 0.83 and therefore, an upper limit can be placed on the ratio of the probability of L, M, N, $\cdots$ orbital electron capture to the probability of K orbital capture to the 648-kev state of $(P_{LMN}.../P_K)<0.19$.

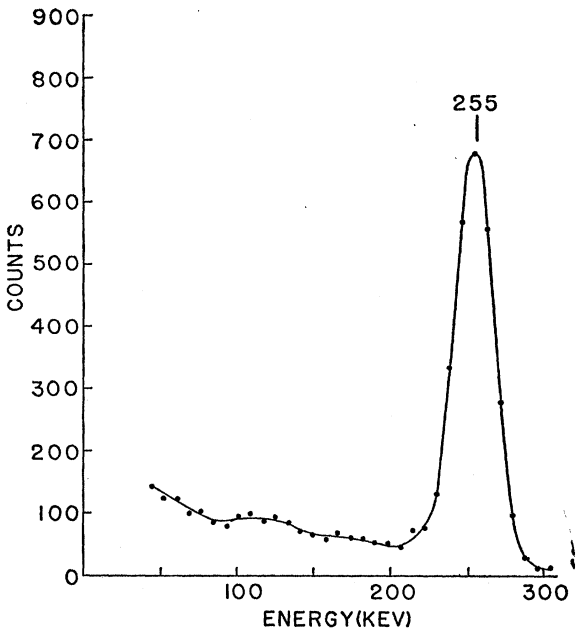

FIG. 3. The gamma-ray spectrum in coincidence with In K x rays.

INTERPRETATION

The value obtained for $(P_{LMN.../P_K})$ can be related to the decay energy using the theoretical results of Brysk and Rose[9] on the relative probabilities of L and K orbital electron capture together with Robinson and Fink's[10] calculations of the ratios of electron densities of M, N, $\cdots$ shells at the nuclear radius to those in the $L_{\rm I}$ and $L_{\rm II}$ shells. Since only an upper limit, $(P_{LMN.../P_K})<0.19$, was obtained in this investigation, only an estimate of the minimum decay energy can therefore be made. The decay energy to the 648-kev state was determined to be greater than 150 kev.

From the coincidence experiments, an upper limit for the intensity of the 648-kev transition was placed as 0.1% that of the 255-kev transition intensity. Because of the absence of 648-kev gamma radiation, the only possible spin assignments to the 648-kev state are $\frac{1}{2}$ and $\frac{3}{2}$. Internal conversion data for the 255-kev transition obtained by Burson *et al.*[4] suggest that this transition is $M1$ or $(M1+E2)$ in nature. Thus the spin and parity assignment to the 648-kev state would be $\frac{1}{2}-$ or $\frac{3}{2}-$. On a shell-model interpretation this is possibly the $p_{\frac{3}{2}}$ state which is found close to the $g_{9/2}$ and the $p_{\frac{1}{2}}$ levels. Further confirmation that this state

[9] H. Brysk and M. E. Rose, Revs. Modern Phys. **30**, 1169 (1958).

[10] B. L. Robinson and R. W. Fink, Revs. Modern Phys. **32**, 117 (1960).

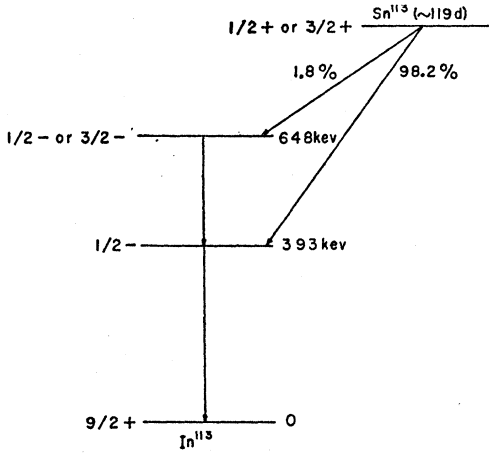

FIG. 4. Decay scheme of Sn^{113}.

indeed has a negative parity can be obtained from log ft values.

On a shell model picture, the ground state of Sn^{113} would be a $d_{\frac{5}{2}}$ state, in which case transitions to the 393-kev state of In^{113} would be unique first forbidden. Such an assignment for this transition would require, on the basis of log ft values, a transition energy to the 393-kev state of greater then approximately 2 Mev. Because of the absence of positron emission such a large decay energy can be ruled out. Since the decay energy to the 393-kev state is greater than 400 kev, possible log ft values for this transition are greater than 6.6 which suggests a first forbidden assignment for this transition. This would require that the ground state of Sn^{113} be a $\frac{1}{2}+$ or a $\frac{3}{2}+$ state. Such an assignment is consistent with the ground state assignments of the other odd neutron nuclei in this region which have $s_{\frac{1}{2}}$ ground state. This suggests strongly that the ground state of Sn^{113} is $s_{\frac{1}{2}}$ but an assignment of $\frac{3}{2}+$ cannot be eliminated on the basis of these experiments. This is especially the case since the adjoining level to the $s_{\frac{1}{2}}$ state on the shell model is a $d_{\frac{3}{2}}$ state.

Consider transitions to the 648-kev state of In^{113}; for a decay energy to this state greater than 150 kev, the corresponding log ft values would have values greater than 7.3. Therefore, transitions to the 648-kev state can only be first forbidden, which in turn requires that the 648-kev state have negative parity. This confirms the assignment of Burson *et al.*[4] made on the basis of the internal conversion coefficients of the 255-kev transition.

Since first forbidden transitions normally have log ft values less than 8.0, it might be expected that the decay energy to the 648-kev state is less than approximately 350 kev. This would indicate that the total decay energy of Sn^{113} to the In^{113} ground state is in the range 800 to 1000 kev.

It has been determined that the 255-kev gamma radiation is 2.8% as intense as the 393-kev gamma radiation. To obtain the branching ratios to the 648 and 393-kev states, it is necessary to know the total internal conversion coefficients of the 255-kev transition and the 393-kev transition. Since the 393-kev transition is $M4$ in nature, the theoretical K conversion coefficient of this transition is 0.49[11] which, when combined with the $K/(L+M)$ conversion ratio of 4.3 ± 0.1, obtained by Burson *et al.*,[4] gives a total conversion coefficient of 0.60. Both the theoretical conversion coefficients for an $M1$ transition and the experimental conversion coefficients obtained by Burson *et al.*[4] would indicate a conversion coefficient of approximately 0.04 for the 255-kev transition. Using these values, the branching ratio to the 648 kev was determined as $(1.8\pm0.1)\%$. The decay scheme, which is shown in Fig. 4, is consistent with that obtained by Burson *et al.*[4]

[11] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Report Part I, 1956 [translation: Report 57 ICC K1 issued by Physics Department, University of Illinois, Urbana, Illinois (unpublished)].