Study of the Gamma-Ray and Inner Bremsstrahlung Transitions in the Decay of Tin-113*

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A fast-slow coincidence spectrometer was used to study the decay of Sn^{113}. A 650-kev gamma ray found in the single-channel spectrum was shown to be in coincidence with the InK x ray both in the fast and in the slow coincidence spectra. This confirmed the existence of a 650-kev level in In^{113} fed by a weak orbital capture branching. From the relative intensities of the 257-kev gamma rays and the 650-kev gamma rays (16.4±1.9:1), it was determined that the spin of the 650-kev level is $\frac{5}{2}$ and the parity is odd. The absence of positrons and arguments from log(ft) classifications indicate a spin of $\frac{3}{2}$ and even parity for the ground level of Sn^{113} and a decay energy in the range of 0.8 to 1.6 Mev. The shape of the corrected inner bremsstrahlung spectrum indicated a decay energy of 1.3±0.3 Mev.

INTRODUCTION

THE decay of Sn^{113} has been widely studied.[1–20] It is presently believed that Sn^{113}, of uncertain spin, parity, and energy, decays by orbital electron capture to two excited levels of In^{113} at 650 and 393 kev, that the 650-kev level is short-lived and of uncertain spin and parity, that the 393-kev level is $p_{\frac{1}{2}}$ of half-life 1.7 hours, and that the ground level is $g_{9/2}$. The experimental findings reported here, especially in the energy range above 400 kev, provide evidence to reduce these uncertainties.

EXPERIMENTAL PROCEDURE

Equipment

A fast-slow coincidence scintillation spectrometer was used. For the coincidence spectra, an x-ray channel was adjusted to accept photons in the energy range of 18 to 30 kev, and the gamma-ray channel was scanned over the range of energies up to about 2.5 Mev.

The x-ray detector was a 2 mm by 1-inch diameter NaI(T1) x-ray crystal covered with a $\frac{1}{4}$-mil aluminum foil and optically coupled with Canada balsam to a magnetically shielded Dumont 6292 photomultiplier tube operated at a potential of 1100 volts.

The gamma-ray detector was a 12R4, 3-inch diameter by 1-inch thick, Harshaw NaI(T1) crystal covered by a 40-mil aluminum housing and optically coupled with 60 000 viscosity silicone fluid to a magnetically shielded 5-inch Dumont 6364 photomultiplier tube operated at 850 volts potential.

Each photomultiplier output was fed to an Atomic Instrument Company A1D amplifier system consisting of a 219A preamplifier and a model 218 linear amplifier. The amplified pulses were analyzed by Francis-Bell No. 5 differential pulse-height analyzers whose outputs were fed to the slow inputs of an ORNL C-4 fast-slow coincidence analyzer. The discriminator outputs of the amplifiers were fed to the fast inputs of the coincidence analyzer.

The single-channel count rates were recorded on a binary scaler with a dead time of 1 microsecond and the coincidence count rates were recorded on a binary scaler with a dead time of 5 microseconds.

The source and detectors were shielded with 1.5 tons of iron at a minimum distance of 18 inches on all sides and the top in addition to the shielding afforded by the concrete floors above and directly below.

The source was placed at the center of the face of the gamma-ray crystal for 47.4% geometry and the x-ray crystal was placed with coinciding horizontal axis at a distance of $\frac{7}{16}$ inch for a 16.3% geometry. A $\frac{1}{16}$-inch lead anti-Compton shield with a $\frac{3}{8}$-inch hole separated the crystals.

Sources

About two milligrams of SnO_2, enriched to about 72.5% of Sn^{112}, were irradiated for three weeks in the LITR at ORNL. The SnO_2 was aged for six weeks then treated with 4N HCl which dissolved a portion of the

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[1] W. T. Achor *et al.*, Phys. Rev. **114**, 137 (1959).
[2] Paul Avignon, Ann. phys. **1** 10 (1956).
[3] R. F. Bacher and D. H. Tomboulian, Phys. Rev. **52**, 836 (1937).
[4] S. W. Barnes, Phys. Rev **56** 414 (1939).
[5] K. S. Bhatki, R. K. Gupta, S. Jha, and B. K. Medan, Nuovo cimento **6**, 1461 (1957).
[6] C. D. Broyles, D. A. Thomas, and S. K. Haynes, Phys. Rev. **89**, 715 (1953).
[7] S. B. Burson, H. A. Grench, and L. C. Schmid, Phys. Rev. **115**, 188 (1959).
[8] J. Childs and L. S. Goodman, Bull. Am. Phys. Soc. **1**, 342 (1956).
[9] K. D. Coleman and M. L. Pool. Phys. Rev. **72**, 1070 (1947).
[10] T. B. Cook, Jr., and S. K. Haynes, Phys. Rev. **86**, 190 (1952).
[11] J. M. Cork, A. E. Stoddard, C. E. Branyan, W. J. Childs, D. W. Martin, and J. M. LeBlanc, Phys. Rev. **84**, 596 (1951).
[12] G. Gardner and J. I. Hopkins, Phys. Rev. **101**, 999 (1956).
[13] Ted M. George, Master's thesis, Vanderbilt University, 1957 (unpublished).
[14] R. K. Girgis and R. van Lieshout, Physica **24**, 672 (1958).
[15] G. A. Graves, L. M. Langer, and R. D. Moffat, Phys. Rev. **88**, 344 (1952).
[16] T. C. Hardy and S. Millman, Phys. Rev. **61**, 459 (1942).
[17] R. G. Jung and M. L. Pool, Bull Am. Phys. Soc. **1**, 172 (1956).
[18] J. L. Lawson and J. M. Cork, Phys. Rev. **57**, 982 (1940).
[19] J. J. Livingood and G. T. Seaborg, Phys. Rev. **55**, 667 (1939).
[20] D. A. Thomas, S. K. Haynes, C. D. Broyles, and H. C. Thomas, Phys. Rev. **82**, 961 (L) (1951).

SnO_2 as alpha-stannic acid which was removed and used as a beta-ray spectrometer source by Achor.[1] The remaining SnO_2 was dissolved in NaOH. Dilute HCl was added drop by drop until the SnO_2 began to precipitate. The mixture was allowed to stand overnight and the top half of the supernatant liquid was then decanted. Distilled water was added; the mixture was stirred and allowed to stand overnight again. After a series of such washings, the precipitated SnO_2 was spread upon a thin Saran film, dried under a heat lamp, and covered with a second film of Saran. The source was aged for about a year and a half.

A second source was prepared from fresh Sn^{113} Cl_2 obtained from the Isotopes Division of ORNL. A drop of the liquid, of 0.77 mC/ml specific activity, was placed on a tin foil for about 15 minutes, then upon nickel foil for about 15 minutes, upon a second foil for about 10 minutes, then upon Saran. This procedure was performed to free the source of contaminants of a greater chemical activity than tin. The removed activity was essentially a pure Sb^{125} contamination. Part of the solution was placed upon a thin Saran film, dried under a heat lamp, and covered with a Saran film. Its activity was very nearly that of the SnO_2 source.

Similarly constructed calibration sources of Co^{60}, Cs^{137}, Cr^{51}, and Tl^{204} were already available.

Spectra

Coincidence spectra were obtained of those photons which were in time coincidence with the indium K x rays (window from 18 to 30 kev) at two resolving times. The fast coincidence resolving time was determined to be 80×10^{-9} sec by the use of two independent but equal Sn^{113} sources. The slow coincidence resolving time was similarly measured to be 1 microsecond. This was the value expected since the pulse-shaping stubs were designed to produce pulses of this duration. The resolving times were also checked under the operating geometry conditions by delaying one channel. The slow resolving time was confirmed thereby, but the fast coincidence circuit was sensitive to the slight distortion of the delayed pulse so that its resolving time was changed.

A single-channel spectrum of the SnO_2 source (47.4% geometry) was obtained simultaneously with the coincidence spectrum. In addition, the gamma-ray channel was operated in isolation to obtain the same spectrum and to obtain a spectrum at reduced (25%) geometry as a quick means of investigating accidental summing effects. Summing peaks would be decreased relative to the remaining spectrum by a factor of two approximately.

As a check on contaminants in the source, a single-channel spectrum of the $SnCl_2$ source was obtained at 47.4% geometry. Single-channel spectra of the calibration sources and of a weak Co^{60} standard source were obtained. Background spectra were obtained for the coincidence arrangement and for the single-channel arrangement.

DATA AND ANALYSIS

Instrument Calibration and Linearity

A calibration curve for the spectrometer was made by plotting the pulse-height setting corresponding to the median point of the monoenergetic gamma-ray photopeak of each of the calibration sources versus its known energy. The relationship was linear throughout the range of energies investigated and at all amplifier gains used. Energies were reproducible to within 2 kev over a period of a few weeks. However, the over-all uncertainty of absolute energy may be high as 10 kev below 1 Mev and perhaps greater above 1 Mev.

Single-Channel Spectra

The single-channel spectrum and the slow coincidence spectrum of the SnO_2 source are shown in Fig. 1. The intensity scale of the single-channel spectrum was chosen (1:727) so that it would also indicate the chance coincidence rate which was subtracted from the gross coincidence spectrum (not shown). The shape and intensity of this theoretical coincidence spectrum was confirmed by the method of independent sources. Both spectra have been corrected for background and have been corrected for decay to the activity with time.

The lowest energy peak seen is the 24-kev In-K-x-ray peak. The 4-kev In L x rays are obscured by the low-energy instrument noise which has been subtracted as background. The shoulder on the high-energy side of the 24-kev peak is an 83-kev peak which was resolved distinctly in the spectrum (not shown) taken with the

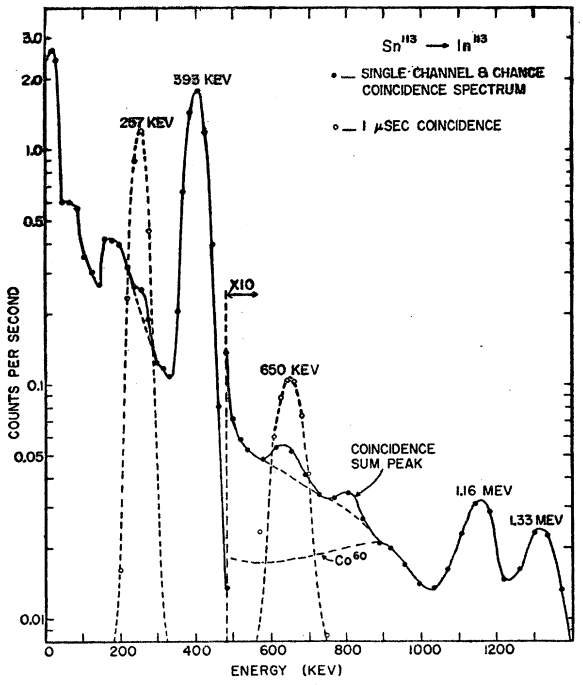

FIG. 1. Gamma-ray spectra.

amplifier gain doubled. Since the 83-kev peak was not present in the spectrum of the $SnCl_2$ source, it was attributed to contamination.

The next peak was produced by the Compton distribution and the backscattering of 393-kev gamma rays. The shoulder was due to the 257-kev gamma-ray transition. The intensity of this transition was determined by plotting the double-gain spectrum, corrected for dead-time losses and background, on 50-cm by 50-cm linear graph paper and subtracting Gaussian curves of various amplitudes and of proper standard deviation (discussed below) from the curve until the shoulder was removed. This process was guided by a knowledge of the usual shape of the Compton distribution in the spectra of Au^{198} and Cr^{51} which have about the same energy. The peak intensity was judged to be 114 ± 26 counts per second per window, or 67 ± 16 counts per second after 1.7 window normalization factor was applied.

The peak at 393 kev corresponded to the isomeric transition from the metastable level of In^{113}. This was the principal gamma ray of the Sn^{113} decay and fitted well a Gaussian curve of area 1930 ± 60 counts per second and of 56.3-kev width at half height. This corresponded to a standard deviation of 23.9 kev for this Gaussian distribution. The Gaussian widths for all the peaks were computed from that of the 393-kev peak by use of dependence of this width upon the square root of energy.

The next peak on the single-channel spectrum is at 650 ± 10 kev. This peak has not been reported previously. Its intensity was measured to be 2.8 ± 0.6 counts per second. Burson *et al.*[7] failed to find the 650-kev peak and estimated the upper limit at about a third of the relative intensity found here. Girgis and van Lieshout[14] also failed to find a 650-kev peak and fixed an upper limit of a sixth of the value reported here. They found, however, a 605-kev peak which they were reluctant to assign to the Sn^{113} activity because of its variation of intensity by a factor of two in the two sources as well as because of its energy value. A 605-kev activity was observed in the second source used in the work reported here, but it was extracted as described above and identified by the shape and energies of the entire spectrum as belonging to Sb^{125}.

The peak at 786 kev was attributed to accidental summing of two 393-kev gamma rays. Its intensity was measured to be 1.7 ± 0.6 counts per second. For a detector resolving time, t, the coincidence rate should be $2tN^2$, where N is the count rate in the 393-kev peak. This relationship gives a detector resolving time of 0.23 ± 0.08 microsecond, which is reasonable for the equipment used.

The remaining two peaks of the single-channel spectrum are at 1.16 and 1.33 Mev. The same peaks were present in the $SnCl_2$ source but with a relative intensity of 1.7 times that of the SnO_2 source. All the other peaks of the $SnCl_2$ source, except the 83-kev peak which was absent, had the intensities reported above. Therefore, it was postulated that the 1.16 and 1.33-Mev peaks were due to some contaminant. The energy location of the peaks, their shape, and the age of the better source made Co^{60} a leading suspect. The weak Co^{60} spectrum was normalized to the peaks and the fit was found to be good. The Compton distribution of the corrected Co^{60} spectrum is indicated down to the edge of the 393-kev peak.

The residual spectrum in the energy range above the 393-kev peak, after the cobalt spectrum and the other peaks were subtracted, has been attributed to inner bremsstrahlung (IB) photons from the electron capture to the $p_{\frac{1}{2}}$ level.

Coincidence Spectra

The slow coincidence (resolution time of 1 microsecond) spectrum shows peaks at 257 kev with intensity of 1.5 counts per second and at 650 kev with an intensity of 0.025 count per second. The coincidence spectrum below 140 kev (the Compton distribution) is not shown since it was determined only approximately.

The fast coincidence (resolving time of 80 nanoseconds) spectrum (not shown, but of the same shape as the slow coincidence spectrum) had intensities of 0.210 count per second for the 257-kev peak and 0.00324 count per second for the 650-kev peak.

Since all of the above mentioned peaks were produced by monoenergetic photons (the continuous IB spectrum will be treated subsequently), the procedure for correlating them with the intensities of the photons actually emitted from the source is rather straightforward. However, a preliminary correction must be considered.

Alternative Interpretations of the 650-kev Peak

Despite the desirability, from the point of view of simplicity of nuclear theory, of the interpretation of the 650-kev photon as the gamma-ray cross-over transition, two other possibilities exist. The peak could be due to contamination, or it could be a coincidence summing of the 393-kev and 257-kev gamma rays. The coincidence summing intensity would be the sum of the genuine coincidences and the accidental coincidences. The genuine coincidences would be those in which the metastable state decayed within the resolution time of one microsecond and could be ignored. Therefore, the summing intensity was computed from the $2tN(257)N(393)$ accidental relationship, and for t of $\frac{1}{4}$ microsecond, the predicted intensity was found to be 0.065 ± 0.015 count per second. Since these counts were due to the summation of light photons in the scintillator, the probabilities of the simultaneous photons being counted in the peak were those of the individual photons; hence, no energy-difference correction was necessary. Of the 2.8 counts per second in the 650-kev peak, only 0.065 ± 0.015 were due to coincidence summing. The correction

for the loss by "washout" of these counts from the 257-kev peak and for augmentation of the 650-kev peak was insignificant.

The possibility of contamination, however, could not be eliminated completely. The coincidence of the 650-kev counts with counts in the 18- to 30-kev window was a very helpful restriction. But coincidence *per se* would not eliminate the possibility of bremsstrahlung from beta rays or conversion electrons or degradation of other gamma rays. However, the agreement of the slow and fast coincidence ratios and the rough agreement of the less accurate single-channel ratio is good evidence that the coincidence is nearly 100% detected. The low probability for bremsstrahlung or Compton scattering into the energy range of the window would eliminate these possibilities. A list of isotopes containing transitions in the energy range of 650±100 kev was compiled. Most of the members of the list could be discarded because of their short half-lives. Many others could be marked off because of the presence of other prominent gamma rays which were not observed in the spectra. The energy resolution was adequate to cast serious doubt upon or to eliminate others. Practically all were rejected on more than one count. What remained was a null set. However, the initial list was not a closed set and for that reason, the possibility of contamination must be acknowledged.

Peak Efficiencies

To obtain the number of monoenergetic radiations emitted by the source per unit of time, the count rate of the Gaussian peak is divided by the absolute peak efficiency, which is the probability that an emanation will deliver all its energy into the scintillator. The absolute peak efficiency is the product of the geometry factor, G (fractional part of 4π steradians which is subtended by the crystal), and the intrinsic peak efficiency. The geometry factor for the 3-inch diameter crystal at a source distance of 2 mm is 0.474. The intrinsic peak efficiency is the product of the intrinsic total efficiency (probability that an incident photon will be counted) and the peak-to-total ratio, p. Since the intrinsic total efficiency is a function of both geometry and energy, it can be multiplied by G to obtain the absolute total efficiency, f, thereby consolidating the geometry dependence. The desired absolute peak efficiency is fp, which is known.

Corrected Data

By means of the fp relationships, the gamma-ray intensities of the single-channel spectra (in counts per second) were computed to be:

$$N(257)=179\pm41,$$
$$N(393)=9272\pm288,$$
$$N(650)=27\pm6,$$
$$R=N(257)/N(650)=6.6\pm2.1.$$

The indicated uncertainty is the statistical uncertainty only and does not include the large additional uncertainty due to the lack of knowledge of the exact shape of the subtracted spectrum due to the Compton distribution and backscattering of the intense 393-kev gamma rays.

If it is assumed that the half-lives of the coincidence events are short enough to prevent appreciable loss of coincidence counts, and if the uncertainty in absorption coefficients of the crystal produces a 10% uncertainty in fp, the slow coincidence rates (in counts per second per K x ray) and their ratio can be computed to be:

$$C_sN(257)=4.0\pm0.4,$$
$$C_sN(650)=0.24\pm0.02,$$
$$R=16.7\pm2.4,$$

and from the fast coincidence spectrum,

$$C_fN(257)=0.56\pm0.056,$$
$$C_fN(650)=0.031\pm0.003,$$
$$R=18\pm2.5.$$

The weighted value for the ratio is 16.4±1.9. The lack of agreement of the value from the single-channel spectrum is attributed to its inherent uncertainty.

Implications

The comparison of experimental values with theoretical values of the ratio of the probability of a 257-kev transition between the second excited level of In^{113} and the assumed $p_{\frac{1}{2}}$ first excited level to the probability of

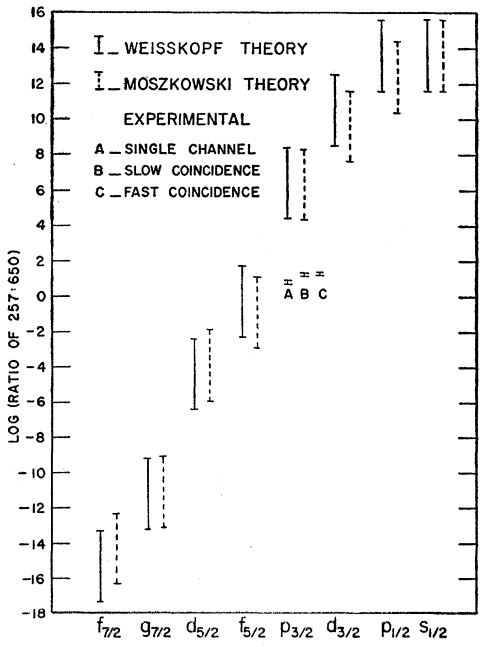

FIG. 2. Theoretical and experimental ratios of 257- to 650-kev gamma-ray transitions.

the 650-kev transition between the second excited level and the assumed $g_{9/2}$ ground level is made in Fig. 2. The theoretical values are those of Weisskopf[21] and Moszkowski[22] and are plotted against the assignment of the 650-kev level for all the reasonably possible assignments. The experimental ratios are plotted without respect to abscissa. It can be seen that these ratios are consistent with $f_{\frac{5}{2}}$ so that the second excited level has spin $\frac{5}{2}$ and odd parity. This assignment is in agreement with theory and with the assignment of the similar level in In^{115} made by Varma and Mandeville,[23] but not with previous In^{115} assignments[24] nor with previous In^{113} assignments.

The K-conversion coefficient of the 257-kev transition can be computed to be 0.068 ± 0.029 from the ratio of K-conversion electrons from the 257-kev transition to K-conversion electrons from the 393-kev transition of 0.0028 ± 0.001 obtained by Achor,[1] from the ratio of intensities of the 257-kev to the 393-kev gamma rays of 0.019 ± 0.0044, and from the K-conversion coefficient of the 393-kev transition interpolated from Rose's tables[25] as 0.46. This probable range of values embraces only the coefficient for $E2$ transitions as can be seen from Table I. However, $M1$ is possible, and mixtures of $M1$ plus $E2$ and $E1$ plus $M2$ are consistent with the experimental range of values of 0.039 to 0.097. These further possible multipolarities correspond to assignments of $p_{\frac{1}{2}}$, $p_{\frac{3}{2}}$, and $d_{\frac{3}{2}}$. Hence, while the conversion coefficient is consistent with the $f_{\frac{5}{2}}$ assignment of the 650-kev level, the conversion coefficient data are ambiguous.

Inner Bremsstrahlung (IB) Data

End point energies of 1200, 900, and 600 kev were assumed for the IB spectrum. The theoretical distribution[26,27] of $x(1-x)^2$, where x is the energy in end-point energy units, was plotted on semilogarithmic paper as a function of energy (plotted linearly). On the same graph, the product of absolute peak efficiency and the relativistic correction[26] were plotted. These three functions were multiplied together by graphical addition. The resulting spectra were the spectra to be expected if detectors were available which had perfect resolution and no photon degradation.

TABLE I. K-conversion coefficients for 257-kev transitions in indium.[a]

Multipolarity	$E1$	$M1$	$E2$	$M2$	$E3$	$E4$	$M3$	$E5$	$M4$	$M5$
αK	0.011	0.034	0.048	0.16	0.18	0.67	0.69	2.5	2.9	12

[a] From reference 25.

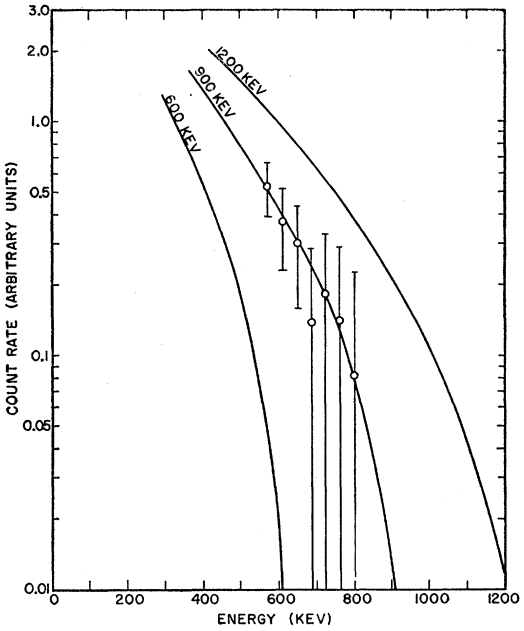

FIG. 3. Inner bremsstrahlung spectra.

Further corrections were necessary to allow for the imperfections of NaI(Tl) scintillators. For a fraction p counts in the peak, there were a fraction $1-p$ counts in the Compton distribution which could be approximated with good accuracy to be a uniform distribution from zero energy up to the maximum energy (in kev) of $E'=E/(1+2E/511)$.

Each peak curve was replotted on a large linear graph and the energy abscissa was divided into a number of convenient elements. The area under the curve in each element was measured by a planimeter, multiplied by the factor $(1-p)/p$ for the median energy of that element, and the resulting area was distributed uniformly over the energy range below E'. The summation of these areas from all the elements was drawn as a smooth curve representing the Compton distribution which should be detected, and it was added graphically to the peak curve.

Corrections for iodine-x-ray escape effects[28] were made, but were found to be negligible above 300 kev. The resulting curve then represented the response expected for a crystal of ideal resolution.

The smearing effect of finite resolution was introduced by dividing each of the above spectra into units of 30.5 kev (the width of the spectrometer window), measuring the area in each window, representing this

[21] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons, New York, 1952), Chap. XII.
[22] S. A. Moszkowski, in *Beta- and Gamma-ray Spectroscopy*, edited by Kai Siegbahn (Interscience Publishers, New York, 1955), Chap. XIII.
[23] J. Varma and C. E. Mandeville, Phys. Rev. **97**, 977 (1955).
[24] J. M. Hollander, I. Perlman, and G. T. Seaborg, Revs. Modern Phys. **25**, 613 (1953).
[25] M. E. Rose, *Internal Conversion Coefficients* (Interscience Publishers, New York, 1958).
[26] P. C. Martin and R. J. Glauber, Phys. Rev. **109**, 1307 (1958), and previous papers.
[27] T. Lindquist and C. S. Wu, Phys. Rev. **101**, 905 (1956).
[28] F. K. McGowan, Phys. Rev. **93**, 163 (1954).

area by a Gaussian peak of proper standard deviation, and adding the Gaussian peaks.

The three curves obtained in this way were the spectra to be experimentally measured in the absence of background counts and after corrections had been made for the dead time losses, if the bremsstrahlung photons had the assumed end point energy. These curves as well as the experimentally determined spectral points attributed to IB are shown in Fig. 3. The end-point energy was indicated to be about 900±300 kev by the probable slope of the IB spectrum. Such an end-point energy corresponds to a Q of 1.3±0.3 Mev. Lack of knowledge of the K/L capture ratios prevented quantitative use of the intensity of the IB spectrum. Qualitatively, the intensity was that expected to accompany the orbital capture to the first excited level of In^{113} and giving rise to the observed intensity of the 393-kev gamma-ray transition. The dependence of the expected IB intensity upon the end point energy is depicted in Fig. 3, but the scale of the experimental points is arbitrary. The large uncertainties of the experimental points at the upper end are due to the Co^{60} contamination.

These large uncertainties negated results of a Kurie-type plot to find the end-point energy.

CONCLUSIONS

Coincidence Study

A 650-kev gamma ray was found in the decay of Sn^{113} in the single-channel spectrum and it was found to be in coincidence with the In K x ray in the fast and in the slow coincidence spectra. This confirmed the existence of a 650-kev level in In^{113} fed by a weak electron capture branching.

From the relative intensities of the 257-kev gamma rays and of the 650-kev gamma rays (16.4±1.9:1) it was indicated that the spin of the 650-kev level is $\frac{5}{2}$ and the parity is odd.

This assignment was supported by the K-conversion coefficient of the 257-kev transition which was computed from experimental data as 0.068±0.029 which indicates an electric quadrupole transition, but not unambiguously.

The existence of the 650-kev In^{113} level and of captures to it indicates that the ground level of Sn^{113} lies more than 257 kev above the first excited level at 393 kev. The absence of reports in the literature of detected positron emission indicates that the Sn^{113} ground level lies below or near the positron threshold of 1.02 Mev above the 393-kev level in In^{113}. By means of log (ft) classifications[29] and the Moszkowski calculation method,[30] the capture energy for allowed transitions was computed to be 50 to 120 kev; for first forbidden transitions, 400 to 1200 kev; for unique first forbidden transitions, 2 to 8 Mev; and for higher order transitions, greater than 8 Mev. A first forbidden transition was indicated. Therefore, the ground level of Sn^{113} appears to be $s_{\frac{1}{2}}$ or $d_{\frac{3}{2}}$ (or $D_{\frac{3}{2}}$). If it is $s_{\frac{1}{2}}$, decays to the $f_{\frac{5}{2}}$ level of the intensity observed would require that Sn^{113} lie more than 1.3 Mev above this level. The absence of positrons of 1% of the 393-kev gamma-ray intensity refutes this; therefore, the Sn^{113} ground level seems to have spin $\frac{3}{2}$ and even parity. The possibility of the presence of both levels closely spaced is merely acknowledged.

The discrepancy of the relative intensity of the 650-kev gamma peak reported here as compared with the lower limits set by other investigators is serious. The superiority of their data is evident. However, the coincidence method should be more reliable. The work should be repeated with better equipment and with improved chemistry.

Inner Bremsstrahlung Study

An inner bremsstrahlung spectrum was taken in the energy range above the 393-kev gamma peak. The spectrum was corrected only for counter dead time and for background and was compared with the spectra to be expected experimentally as were determined by correcting the theoretical $x(1-x)^2$ shape for relativistic effects, photopeak efficiencies, Compton distribution, iodine-x-ray escape, crystal resolution, and crystal housing absorption at varoius end point energies. The experimental shape indicated a probable end point energy of 900±300 kev. The observed intensity was appropriate for radiation accompanying orbital electron capture from the ground level of Sn^{113} to the first excited level of In^{113}, but lack of knowledge of K/L capture ratios prevented a quantitative use of the intensity. The indicated Q of the Sn^{113} decay was 1.3±0.3 Mev which is consistent with the Q of 1.35±0.25 Mev computed from mass data and is consistent with the 0.8- to 1.6-Mev range for a first forbidden transition to the first excited level.

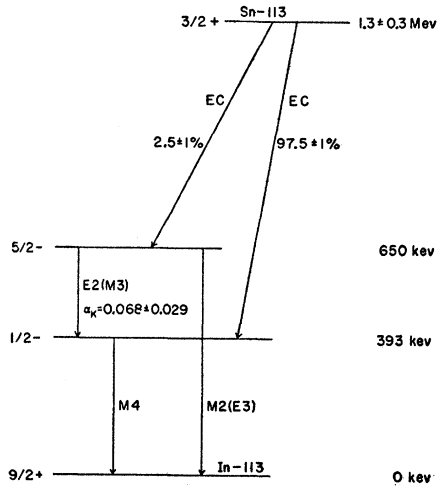

FIG. 4. A proposed decay scheme for Sn^{113}.

[29] M. G. Mayer, S. A. Moszkowski, and L. W. Nordheim, Revs. Modern Phys. **23**, 315 (1951).

[30] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).

The energy uncertainty could be reduced by better chemistry, such as cupferron-solvent methods, and by the use of a multichannel coincidence analyzer.

A proposed decay scheme for Sn^{113} is shown in Fig. 4.

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Internal Conversion Electrons Following Coulomb Excitation of Highly Deformed Odd-A Nuclei*

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The internal conversion electrons emitted following Coulomb excitation of Eu^{153}, Dy^{161}, Dy^{163}, Ho^{165}, Tm^{169}, Lu^{175}, and Ta^{181} have been measured. The relative intensities of the decay transitions from the first two rotational states of these isotopes have been compared with the predictions of the rotational model of Bohr and Mottelson. In general, there is good agreement between the experiment and theory; however, the results for the Dy isotopes indicate some disagreement which is outside the experimental uncertainty. For Eu^{153}, Dy^{163}, and Lu^{175} transitions involving intrinsic states were observed in addition to the rotational transitions. The reduced $E2$ transition probabilities for these intrinsic transitions are appreciably larger than single-particle estimates. The first rotational state in Lu^{176} was observed with a natural Lu target. The data indicate that this transition is predominantly $M1$.

I. INTRODUCTION

IT has been pointed out previously[1–3] that Coulomb excitation of highly deformed odd-A nuclei is an excellent method for checking the predictions of the rotational model of Bohr and Mottelson. The most accurate experiments of this type up to the present time have been the measurements[4] of the inelastically scattered particles. The inelastic scattering experiments, however, only measure the $E2$ transition probabilities between the ground state and the excited states. In order to obtain information concerning the $M1$ transition probabilities and the $E2$ transition probabilities between the excited states, one must measure the decay radiations—gamma rays or internal conversion electrons.

The advantages and disadvantages associated with measuring the internal conversion electrons rather than the gamma rays have been discussed in detail elsewhere.[1–3] In principle the same information can be obtained from the observation of the gamma rays or the internal conversion electrons; however, at the present time a more complete and more accurate check of the model can be obtained from the internal conversion measurements.

In the present experiment the internal conversion electron spectra emitted following Coulomb excitation of Eu^{153}, Dy^{161}, Dy^{163}, Ho^{165}, Tm^{169}, Lu^{175}, and Ta^{181} have been measured. With electric quadrupole excitation of these odd-A nuclei one excites the first two rotational states above the ground state. There are, therefore, three transitions from the decay of these states: the transition from the first rotational state to the ground state, the cascade transition from the second rotational state to the first, and the crossover transition from the second rotational state to the ground state.

The basic techniques used in the present experiment are essentially the same as those used in previous experiments.[2,3,5,6] However, these techniques have been greatly improved with the result that the experimental uncertainties have been significantly reduced. Also, in the earlier experiments the weak conversion lines of

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[1] K. Alder, A. Bohr, T. Huus, B. Mottelson, and A. Winther, Revs. Modern Phys. **28**, 432 (1956).

[2] E. M. Bernstein and H. W. Lewis, Phys. Rev. **105**, 1524 (1957).

[3] T. Huus, J. Bjerregaard, and B. Elbek, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **30**, No. 17 (1956).

[4] M. C. Olesen and B. Elbek, Nuclear Phys. **15**, 134 (1960). See also B. Elbek, K. O. Nielsen, and M. C. Olesen, Phys. Rev. **108**, 406 (1957); V. Ramsak, M. C. Olesen, and B. Elbek, Nuclear Phys. **6**, 451 (1958); B. Elbek, M. C. Olesen, and O. Skilbreid, Nuclear Phys. **10**, 294 (1959).

[5] E. M. Bernstein and H. W. Lewis, Phys. Rev. **100**, 1345 (1955).

[6] E. M. Bernstein, Phys. Rev. **112**, 2026 (1958).