Radioactive Decay of Sn^{111} †

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(Received 12 November, 1964; revised manuscript received 25 January 1965)

Sources of 35-min Sn^{111} were made by the reactions $Sn^{112}(\gamma,n)Sn^{111}$, $Sn^{112}(n,2n)Sn^{111}$ and $Cd^{110}(He^3,2n)Sn^{111}$. The ratio ec/β^+ was determined to be 2.7 ± 0.2. The following gamma rays were observed by scintillation techniques: 750, 970, 1140, 1540, 1590, 1890, 2110, and 2320 keV. The following levels in In^{111} are proposed, based on coincidence studies and transition probabilities: 970, 1140, 1540, 1890, 2110, and 2320 keV.

INTRODUCTION

THE isotope Sn^{111} was reported in 1949 and the half-life of the positron activity was found to be 35 min.[1] This isotope was restudied in 1951 and the ratio of decay by electron capture to decay by positron emission[2,3] was determined to be 2.50 ± 0.25. Enriched isotopes and improved experimental techniques have made it possible to profitably restudy the decay of Sn^{111}.

BOMBARDMENTS AND SAMPLE PREPARATION

Three types of nuclear bombardments were performed during the course of this investigation.

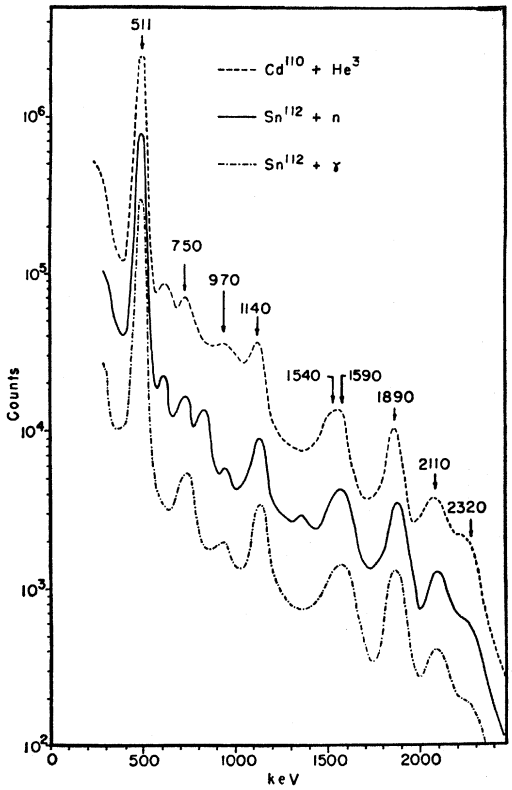

FIG. 1. High-energy portion of gamma-ray spectra showing activities produced in three bombardments.

$Sn^{112}(\gamma,n)Sn^{111}$: Tin oxide enriched to 74.7% in the mass number 112 was bombarded with 23-MeV bremsstrahlung from the OSU betatron.

$Sn^{112}(n,2n)Sn^{111}$: Tin oxide enriched to 74.7% in the mass number 112 was bombarded at the OSU cyclotron with neutrons from the reaction $Be^9(d,n)B^{10}$ produced with 11-MeV deuterons.

$Cd^{110}(He^3,2n)Sn^{111}$: Cadmium metal enriched to 85.66% in the mass number 110 was bombarded with 17-MeV He^3 particles.

For the fast-neutron and He^3 bombardments, the enriched isotopes were pressed into a cavity in an aluminum target holder. After bombardment the activated samples were placed in a gelatin capsule for counting. The gamma-ray bombardment was carried out in a gelatin capsule.

SCINTILLATION SPECTROMETER STUDIES

The gamma-ray scintillation spectra of the activities produced in the three bombardments are shown in Fig. 1, with the energies indicated for those peaks with 35-min half-life. The unmarked peaks are attributed to 4.0-h Sn^{110} which was produced in the fast neutron and He^3 bombardments, and to 2.58-h Mn^{56} and 13.0-h Cu^{64} which were produced in the fast-neutron bombardment because of impurities in the tin sample.

All gamma-ray scintillation spectra were obtained with a 3×3-in. NaI(Tl) crystal. The crystal and photo-

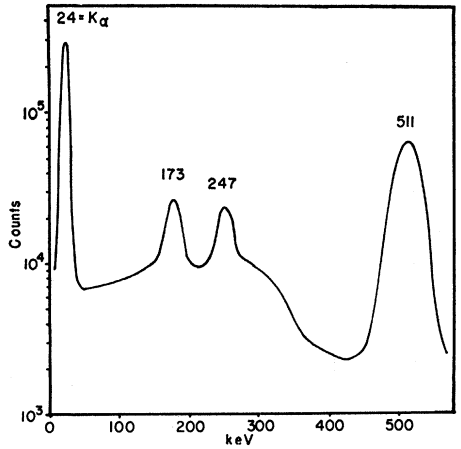

FIG. 2. Low-energy portion of gamma-ray spectrum showing gamma peaks from the decay of Sn^{111} and In^{111}.

† This work supported in part by the U. S. Office of Naval Research.
[1] R. A. Hinshaw and M. L. Pool, Phys. Rev. **76**, 358 (1949).
[2] C. L. McGinnis, Phys. Rev. **81**, 734 (1951).
[3] C. L. McGinnis, Phys. Rev. **83**, 686 (1951).

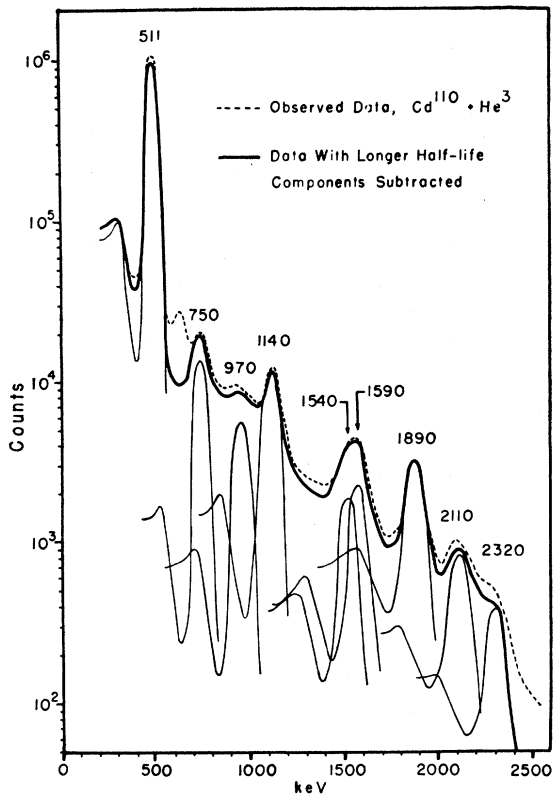

FIG. 3. Gamma-ray spectrum of Sn^{111} showing unscrambled component peaks.

multiplier tube are enclosed in a protective aluminum sheath with aluminum-oxide reflector. A 253 mg/cm² aluminum-equivalent absorption factor is at the crystal face. This detector is located in the center of a lead cave with 4-in.-thick walls and inner dimensions of 32×32×30 in. A graded shielding of 30-mil tin and 15-mil copper lines the inside of the cave.

The low-energy portion of the spectrum is shown in Fig. 2. The 173- and 247-keV peaks and part of the x-ray peak are attributed to 2.8-day In^{111} which is the daughter of Sn^{111}. The x-ray absorption factor of the

TABLE I. Gamma-ray intensities and transition probabilities.

Energy (keV)	N=counts under peak	N/Ep[a]	Transition probability[b]
24.2[c]	1.24×10^6	3.75×10^8	$ec=73\pm11.0$[d]
511	4.42×10^6	3.27×10^{8e}	$\beta^+=27\pm2.1$
750	5.96×10^4	6.40×10^6	1.06 ± 0.21
970	3.22×10^4	4.34×10^6	0.72 ± 0.22
1140	7.02×10^4	1.10×10^7	1.82 ± 0.28
1540	1.43×10^4	2.97×10^6	0.50 ± 0.15
1590	1.58×10^4	3.33×10^6	0.55 ± 0.16
1890	5.77×10^4	5.77×10^6	0.96 ± 0.14
2110	7.28×10^3	1.97×10^6	0.33 ± 0.04
2320	3.31×10^3	9.85×10^5	0.16 ± 0.01

[a] E=detection efficiency; p=peak to total ratio.
[b] Relative number of transitions per 100 decays of Sn^{111}.
[c] Number of counts under x-ray peak corrected for absorption.
[d] Number of ec decays $=4.42\times10^8$ after correcting for fluorescence yield.
[e] Number of β^+ decays $=1.64\times10^8$.

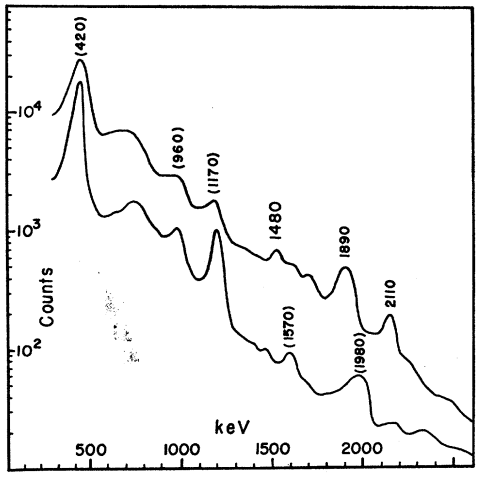

FIG. 4. Sum spectra taken with crystals at 90°. Upper curve was taken 30 min after bombardment while lower curve was taken 5 h after bombardment to differentiate between sum peaks of 35-min Sn^{111} and sum peaks of longer lived activities. Sum peaks at 1480, 1890, and 2110 keV are attributed to the decay of Sn^{111}.

crystal covering material was ascertained by using the x-ray and gamma-ray intensities from the decay scheme of In^{111} which is well known.[4,5] The absorption factor was found to be 7.50. This factor was therefore used in correcting for the number of x rays emitted by Sn^{111}. The ratio of the probability of decay by electron capture to the probability of decay by positron emission was found to be 2.7 ± 0.2 after correcting for a fluorescence yield of 0.838.[6]

Unscrambling was carried out with a library of standard photopeaks. The unscrambled spectrum is shown in Fig. 3. Column 2 in Table I gives the number of counts under the Gaussian part of the distribution for each peak. Column 3 gives the intensity for each gamma. The values in column 4 are arrived at by assuming that each nucleus of Sn^{111} decays either by

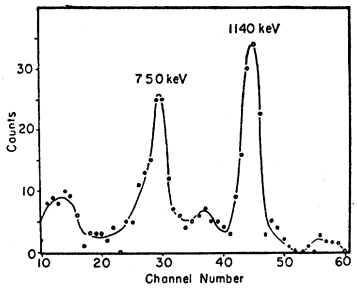

FIG. 5. Spectrum of gamma rays which are in coincidence and sum to form 1890-keV sum peak. The peaks are statistically of equal intensity.

[4] O. Huber, F. Humbel, H. Schneider, and A. de Shalit, Helv. Phys. Acta 25, 3 (1952).
[5] G. A. Graves, L. M. Langer, and R. D. Moffat, Phys. Rev. 88, 344 (1952).
[6] A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959).

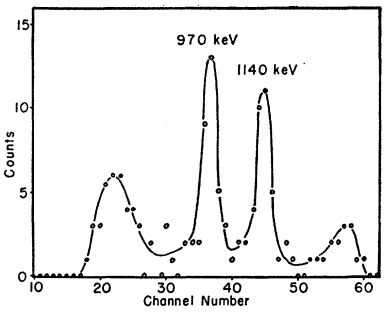

FIG. 6. Spectrum of gamma rays which are in coincidence and sum to form 2110-keV sum peak. The peaks are statistically of equal intensity.

electron capture or positron emission, and that therefore the sum of the number of x rays and positrons should be normalized to 100%. Internal conversion was neglected because of the high energies of the gamma-ray transitions.

COINCIDENCE STUDIES

Coincidence data were taken with 1.75×2-in. NaI(Tl) crystals and analyzed on a 400-channel transitorized analyzer. A four-gate fast coincidence unit with a resolving time $2\tau=30$ nsec was employed. This unit is also equipped to record sum-coincidence data.[7,8]

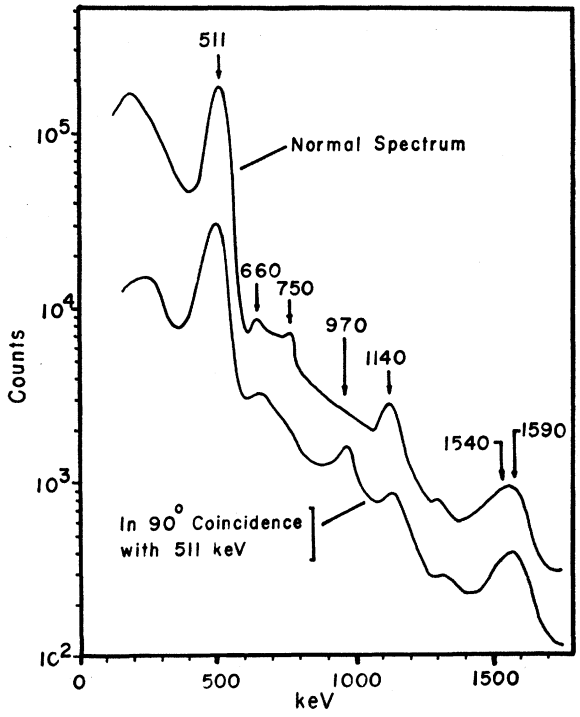

FIG. 7. Spectrum of gamma rays which are in coincidence with 511-keV annihilation radiation.

[7] A. M. Hoogenboom, Nucl. Instr. Methods 3, 57 (1958).

[8] The original Hoogenboom apparatus stored single gamma peaks as well as sums. The unit used in this experiment was modified to store a pure sum spectrum by Paul R. Measel of this laboratory.

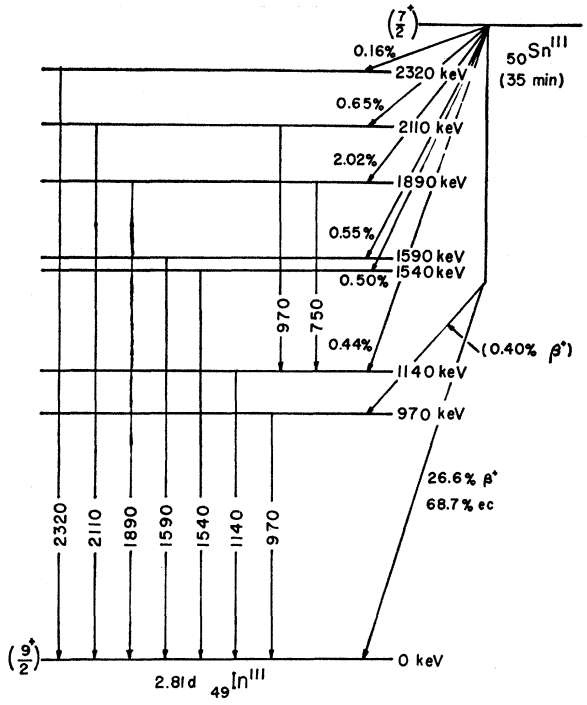

FIG. 8. Proposed decay scheme for Sn^{111}.

Figure 4 is the 90° sum spectrum taken at two different times to differentiate between sums from the decay of the 35-min Sn^{111} activity and sums from the longer lived activities. The peaks with energies in parentheses are attributed to the decay of 2.8-day In^{111} and 4.0-h Sn^{110}. Three sum peaks which are attributed to the decay of Sn^{111} appear in the upper curve of Fig. 4 with energies of 1480, 1890, and 2110 keV.

Figure 5 was obtained by gating on the sum peak at 1890 keV and shows the coincidence of the 750- and 1140-keV gamma rays. Figure 6 was obtained by gating on the sum peak at 2110 keV and shows the coincidence of the 970- and 1140-keV gamma rays. The peaks which are in coincidence in Figs. 5 and 6 are equal to within a statistical deviation.

Figure 7 is a 90° fast-coincidence spectrum obtained by gating on the 511-keV annihilation radiation and it shows the coincidence of the 970-keV gamma ray and the annihilation radiation. The 90° 511–511-keV coincidence in Fig. 7 is within the limits for random coincidence and the other peaks are attributed to random coincidence and to the Compton distributions from higher energy gamma rays. The 1480-keV sum peak in Fig. 4 is also explained by the coincidence of the 970-keV gamma ray and the annihilation radiation.

DISCUSSION OF RESULTS

The proposed decay scheme for Sn^{111} is indicated in Fig. 8. The levels at 1540, 1590, 1890, 2110, and 2320 keV are proposed because no gamma rays were found

to be in coincidence with the gamma rays of these energies. The levels at 970 and 1140 keV are indicated by the coincidence data. A 970-keV and/or an 1140-keV transition from the 2110-keV level to the 1140-keV level or the 970-keV level, respectively, is indicated by the coincidence measurements. In Fig. 8 only, the first of these two possible modes of depopulating the 2110-keV level is shown. The 750-keV transition from the 1890-keV level to the 1140-keV level agrees with the coincidence measurements. The transition probabilities shown on the decay scheme have been calculated in Table I.

Kundu and McGinnis[9] have proposed a 10-min metastable level at 530 keV with spin and parity $\frac{1}{2}^-$ by analogy with In^{113} and In^{115}. A gamma ray of this energy could not be confirmed because of the high intensity of the nearby 511-keV peak.

[9] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C., 1960) NRC 60-2-85.

ACKNOWLEDGMENTS

Our grateful thanks are due to Paul R. Measel for his help with the electronic aspects of this experiment and to P. E. Weiler for his encouragement and aid. Appreciation is also given to T. E. Sopp, OSU Superintendent of Radiation Safety, for his help with the betatron bombardment.

PHYSICAL REVIEW VOLUME 138, NUMBER 4B 24 MAY 1965

Spin, Hyperfine Structure, and Nuclear Magnetic Dipole Moment of 7.7-Min K^{38}†

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(Received 12 January 1965)

The spin and hyperfine structure of 7.7-min K^{38} have been determined by the atomic-beam magnetic-resonance method. In this experiment about 100 mg of K^{39} was placed in an oven in the resonance apparatus and was bombarded with an 0.3 μA beam of 18-MeV protons. K^{38} was produced by the reaction K^{39} (p, d or pn)K^{38}, and the resulting specific activity was high enough so that an adequate atomic beam could be maintained for 2 to 3 h before the oven was empty. Both $\Delta F=0$ and $\Delta F=1$ resonances were observed, and final values are $I=3$, $\Delta\nu=1415.292\pm0.009$ Mc/sec. Comparison with other potassium isotopes yields $\mu_I=+1.3735\pm0.0010$ nm (diamagnetically corrected). The value for the magnetic dipole moment is in good agreement with the prediction based on the coupling of a $d_{3/2}$ neutron hole and a $d_{3/2}$ proton hole to the above spin value.

INTRODUCTION

THIS work represents a continuation of two long-standing programs in this laboratory, a study of the properties of odd-odd nuclei, and spin and moment measurements on short-lived radioactive isotopes.

The nucleus K^{38} is self-conjugate, i.e., $N=Z=19$, and should be a particularly attractive case for nuclear-structure studies since it is just one proton and one neutron short of doubly-magic Ca^{40}. One would expect the ground-state configuration to be predominantly $(d_{3/2})^{-1}$ for both proton and neutron, and in agreement with the predictions of Brennan and Bernstein[1] the lowest two states in this nucleus are 3^+ and 0^+, the sum and the difference of the nucleon spins. The ground state has a 7.7-min half-life, and our measurements show it to have $I=3$ as expected from earlier experiments.[2]

The experiment was carried out with the resonance apparatus used to measure the spin and hyperfine structure in 23-sec Na^{21}, and described in an earlier paper.[3]

The theory of hyperfine structure relevant to this experiment has been frequently described in the recent literature, so we shall not repeat it here. The reader is referred to books by Ramsey[4] or Kopfermann[5] for a detailed discussion.

EXPERIMENTAL DETAILS

The K^{38} was produced by the reaction K^{39}(p, d or pn)K^{38} using the 18-MeV proton beam from the Princeton cyclotron. The oven containing the K^{39} was placed in the resonance apparatus, and the proton beam was brought into the oven chamber and passed through

† This work was supported by the U. S. Atomic Energy Commission and the Higgins Scientific Trust Fund.
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[1] M. H. Brennan and A. M. Bernstein, Phys. Rev. **120**, 927 (1960).
[2] See the Landolt-Börnstein Tables, *Energy Levels of Nuclei: A=5 to A=257*, edited by A. M. Hellwege and K. H. Hellwege (Springer-Verlag, Berlin, 1961).
[3] O. Ames, E. A. Phillips, and S. S. Glickstein, Phys. Rev. **137**, B1157 (1965).
[4] N. F. Ramsey, *Molecular Beams* (Oxford University Press, London, 1956).
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