Radioactivity of In^{120} and Sb^{120}

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An investigation of the radiations from the mass-120 isobars has been made using magnetic lens, scintillation pulse-height, and coincidence counting techniques. Sb^{120m} decays with a 5.8-day half-life by electron capture, positron emission if any $<0.03\%$, to an 11-μsec level of Sn^{120} which then decays by the emission of the following gamma rays (energies in Mev): 0.089 ($E1$), 0.199 ($E2$), 1.04 ($E2$), and 1.18 ($E2$). The 1.18-Mev gamma ray also occurs in the decay of the 16-min Sb^{120}, where the number of gamma rays per positron is 0.03. An activity of $\sim$55 sec is assigned to In^{120m}. A decay scheme is proposed.

INTRODUCTION

THE radioactivity of the long-lived Sb^{120m} has been investigated previously by Lindner and Perlman.[1] A 6-day half-life found in the Sb fraction from an 18-Mev deuteron bombardment of enriched Sn^{120} was assigned to Sb^{120}. By absorption methods the radiations were determined to be Sn K x-rays, 1-Mev gammas, and weak conversion electrons. No positrons were found.

EXPERIMENTAL RESULTS

All the experimental results of the present investigation, a preliminary report of which has been published previously,[2] are summarized in Tables I to V. Most of the data reported were obtained from the deuteron bombardment of Sn^{119} (enriched to 80%). This material was supplied by the Stable Isotopes Division, Oak Ridge National Laboratory. The conversion electron spectrum was measured with a thin-lens magnetic spectrometer. The photon spectrum was examined with a NaI(Tl) scintillation pulse-height spectrometer with a single channel differential discriminator. All gamma-gamma coincidences were measured by using pulse-height analyzers in both channels. To measure the delay of the 0.089-Mev gamma ray with respect to the K x-rays an electronic time-delay generator was also used. Measurements were made for delay times from 3 μsec to 60 μsec. With a delay of 3 μsec, 90 coincidences per min were obtained. The random coincidence rate was 2.5 per minute.

DECAY SCHEME

The gamma-gamma coincidence data (Table IV) establish that all four gamma rays are in series. No crossover transitions were observed. The appearance of the 1.18-Mev gamma ray in the decay of the 16-min Sb^{120} fixes the first excited level of Sn^{120} at 1.18 Mev. The observation of a gamma ray of 1.155-Mev energy and half-life of 0.69 $\mu\mu$sec by Coulomb excitation[3] confirms the location of this level. The second level is placed at 2.22 Mev to agree with the systematics[4] of the second excited states of even-even medium-weight nuclei. The x-γ and γ-γ delay experiments show that the 2.51-Mev

TABLE I. Summary of all experimental information on 5.8-day Sb^{120}. The estimated errors are based on two or more measurements.

$T_{\frac{1}{2}}=5.8\pm0.2$ day	Method of production: Sn(18-Mev d,n), Sn^{119}(18-Mev d,n) chem.[a] Sb($\leq$ 50-Mev γ,n) no chem.			
Total conversion electron intensity (relative)	Transition energy (Mev)	$K/(L+M)$		Method
2740±340	0.089±0.001	8±1	$M2/E1=0.001$	Scintillation and magnetic lens spectrometer
1370±100	0.199±0.001	4.6±0.2	$E2=100\%$	
13.5±1.5	1.040±0.010		$E2=100\%$	
10	1.180±0.010		$E2=100\%$	
(0.089-Mev γ)/(0.199-Mev γ)$=0.9\pm0.1$				Scin.
(1.040-Mev γ)/(1.180-Mev γ)$=1.0\pm0.1$				Scin.
No 0.288-Mev γ (<0.001 of 0.199-Mev γ)				Scin.
No annihilation radiation; therefore $\beta^+<0.3\%$				Scin.
Coincidence measurements:				
Gamma rays in fourfold coincidence.				
Each gamma ray is delayed 11±1 μsec with respect to K x-rays.				
No other delays were found.				
Coinc. ratio $\frac{(K\text{ x-ray})(0.089\text{-Mev }\gamma)}{(K\text{ x-ray})(0.199\text{-Mev }\gamma)}=0.85\pm0.10$				

[a] Precipitate Sb_2S_3 in hot 3N HCl. See Radiochemical Procedures AECD-2738, W. W. Meinke, editor.

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TABLE II. Summary of experimental information on 16-min Sb^{120}.

Method of production:		Sb($\leq$50-Mev γ,n) no chem.
1.18-Mev γ/total $\beta^+=0.03$	scin.	
1.04-Mev γ/total $\beta^+<0.004$	scin.	

level has the 11-μsec half-life. From the coincidence ratio (K x-ray)(0.089γ)/(K x-ray)(0.199γ)=0.85 it is concluded that electron capture to a level at either 2.42 or 2.31 Mev is less than 10% of that to the 2.51-Mev level. Based on the agreement between the experimental and theoretical internal conversion coefficients (see Table VI) the 0.089- and 0.199-Mev gamma rays are given the assignments $E1$ and $E2$, respectively, but the order of emission has not been determined.

However, from the following considerations the 11-μsec half-life is associated with the 0.089-Mev $E1$ gamma ray. With this assignment the half-life is

TABLE III. Summary of experimental information on 55-sec In^{120m}. This work was done in collaboration with D. N. Kundu.

Method of production:	Sn(20-Mev n,p) no chem.
$T_{\frac{1}{2}}\approx 55$ sec from the decay of $\sim$1-Mev γ's	scin.

4×10^7 times longer than the single proton estimate.[5] In the medium-weight nuclei the $E1$ transitions in Ag^{107} and Ag^{109} are the only others available for comparison. In these nuclei the 0.32-Mev cascade transition from the 0.41-Mev $5/2^-$ level to the 40-sec $7/2^+$ level has a half-life of 9×10^{-9} sec based on 45 $\mu\mu$sec[6] for the half-life of the 0.41-Mev level and a branching of 0.5%.[7] These $E1$ transitions are 10^6 times slower than the single-proton estimate. If the 11-μsec half-life were assigned to the 0.199-Mev $E2$ gamma ray, the transition would be 300 times slower than the single-proton estimate. The only other slow $E2$ gamma rays occur in Ni^{61}, Zn^{67}, Cd^{111}, and Pr^{141}. These are about 4 times

TABLE IV. Summary of coincidences found in the decay of 5.8-day Sb^{120}. Circuit resolving time: $2\tau=1.2$ μsec. NaI scintillation counters were used. Y=coincidences observed; N=coincidences not observed. Gamma-ray energies in Mev.

Gating radiation	Coincident radiation: K x-ray	0.089γ	0.199γ	1.04γ	1.18γ
K x-ray	Y	Y	Y	Y	Y
0.089γ	Y	N	Y	Y	Y
0.199γ	Y	Y	N	Y	Y
1.04γ	Y	Y	Y		
1.18γ	Y	Y		Y	N

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TABLE V. Summary of results on γ-γ angular correlations. Circuit resolving time: $2\tau=1.2$ μsec. NaI scintillation counters were used. Gamma-ray energies in Mev.

	$\left(\frac{W(\pi)-W(\pi/2)}{W(\pi/2)}\right)$	Interpretation
(1.04γ)(1.18γ)(θ)	$+0.16\pm0.02$	$J=4, 2, 0$
(0.20γ)($\sim$1.1γ's)(θ)	$+0.16\pm0.02$	$\Delta J=2(Q), 2(Q)$
(0.09γ)(0.20γ)(θ)	-0.12 ± 0.02	$\Delta J=1(D), 2(Q)$

slower, whereas the other 90 $E2$ transitions in medium-nuclei are about 25 times faster[8] than the single-proton estimate. Hence, it seems reasonable to associate the 11-μsec half-life with the 0.089-Mev $E1$ gamma ray. The third level in Sn^{120} is placed at 2.42-Mev.

From the internal conversion coefficient data $E2/M1 > 3$ for the 1.04-Mev gamma ray. Thus for the 1.04-, 1.18-Mev cascade the spin sequence could be 2^+, 2^+, 0^+. For three other even-even medium-weight nuclei the $E2/M1$ ratio for the first transition in this type of spin sequence has been determined[9–11] by γ-γ angular correlation measurements, i.e., Se^{76} 5.5, Sn^{116} 9, and Te^{122} 10 (references 9, 10, and 11 respectively). However, the angular correlation data (see Table V) limit the $E2/M1$ ratio for the 1.04-Mev gamma ray to less than 0.04. It turns out that a 2^+, 2^+, 0^+ sequence with $E2/M1 = 0.0376$ is indistinguishable from the 4^+, 2^+, 0^+ pure quadrupole-quadrupole sequence. As this limit is incompatible with the above measurement and the expected ratio of $\sim$9 for a 2^+, 2^+, 0^+ cascade, the 1.04-Mev gamma ray is designated pure $E2$. For similar reasons the 0.199-Mev gamma ray is also pure $E2$. Hence the spin sequence for the first three Sn^{120} levels is 2^+, 4^+, and 6^+.

TABLE VI. Multipolarity assignments to 5.8-day Sb^{120} γ's. The experimental internal conversion coefficients are derived from the relative intensities of the conversion electrons assuming $\alpha(E2) = 0.000872$ for the 1.18-Mev transition. The theoretical values are taken from the privately circulated tables of Rose *et al.* (1956). To take account of screening, only one-half of the value of the M conversion coefficients was used.

E_γ (Mev)	Expt. α	Theoretical internal conversion coefficients: $E1$	$E2$	$M1$	$M2$		Assignment
0.089	0.29 ± 0.05	0.24	2.30	0.80	8.9	$\times10^{-3}$	$E1$
0.199	0.13 ± 0.01	0.025	0.12	0.093	0.52	$\times10^{-3}$	$E2$
1.040	$1.2\ \pm0.1$	0.50	1.19	1.56	3.57	$\times10^{-3}$	$E2$
E_γ (Mev)	Expt. $K/(L+M)$	Theoretical $K/(L+M)$ ratio: $E1$	$E2$	$M1$	$M2$		Assignment
0.089	8.0 ± 1	6.5	2.4	6.8	4.2		$E1$, $M1$
0.199	4.6 ± 0.2	6.8	4.6	6.6	5.4		$E2$

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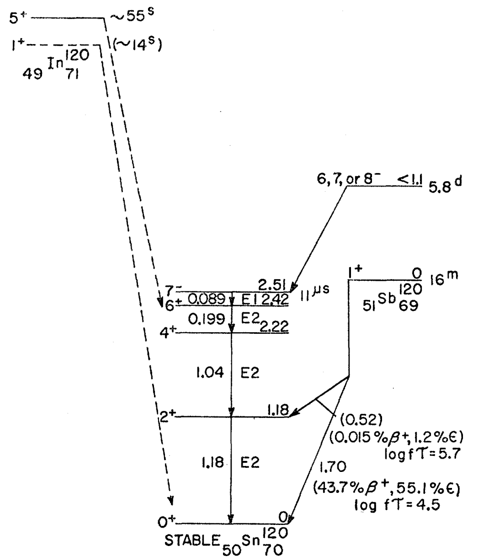

FIG. 1. Proposed decay scheme for In^{120} and Sb^{120}. The Sb^{120} ground state half-life and positron energy are taken from reference 14. The disintegration energy of In^{120} is taken from the beta-decay energy systematics of reference 13. The theoretical electron capture to positron ratios have been used in calculating the 16-min Sb^{120} branching ratios. The remainder is the result of this work.

For the 0.089-Mev gamma ray the internal conversion coefficient data show that $M2/E1$ is less than 0.01. The (0.089γ)–(0.199γ) angular correlation results may be fitted with the spin sequence 7^-, 6^+, 4^+ with $M2/E1 = 0.001$ or 5^-, 6^+, 4^+ with $M2/E1 = 0.02$. No mixture will fit the sequence 6^-, 6^+, 4^+. Thus the only compatible assignment for the 2.51-Mev 11-μsec level is 7^- with $M2/E1 = 0.001$ for the 0.089-Mev gamma ray. The partial $M2$ half-life is then 0.006 sec. This gives a comparative half-life, $\log_{10}[\tau_\gamma A^{\frac{2}{3}} E_\gamma{}^5] = -6.1$. The expected range for $M2$ transitions[12] is -4.5 to -6.5.

The order of the 5.8-day and 16-min Sb^{120} levels is not known. The beta-decay energy systematics[13] predict 2.7 Mev for the total decay energy of Sb^{120}. 1.7-Mev positrons[14] follow the decay of the 16-min Sb^{120} and hence this activity most likely belongs to the ground state. The limit on positron emission of the 5.8-day Sb^{120} ($\lesssim 0.3\%$) implies that its decay energy to the 2.51-Mev Sn^{120} level is less than 1.3 Mev. The $\log ft$ for this activity then lies between 5.0 and 6.3 which is compatible with an allowed transition. A spin of 6^-, 7^-, or 8^- is therefore assigned to this level.

A 20-Mev neutron bombardment of natural tin is expected to produce short-lived ~1-Mev gamma rays which may originate only from the decay of In^{116}, In^{118}, or In^{120}. In^{116} and In^{118m} are known to have half-lives of 13 sec and 4.5 min, respectively. The data of Table VII are the basis for assigning the ~55-sec activity to In^{120m}. The metastable levels of both In^{114} and In^{116} are both known to have spin 5, and hence In^{120m} is assumed to have spin 5. A comparison between the measured and expected half-lives would allow branching to both the (4^+) 2.22-Mev and (6^+) 2.42-Mev levels in Sn^{120}.

The high spin assigned to the 5.8-day Sb^{120} would account for the fact that this activity was not observed in the following reactions: Sn(6.8-Mev p,n),[15] and Sb($\leq$18-Mev γ,n).[16]

The proposed decay scheme is shown in Fig. 1.

TABLE VII. Expected half-lives for In^{118} and In^{120}.

Nucleus	In^{118}	In^{120}	In^{120m}
β decay energy (Mev)	4.2[a]	5.4±0.4[a]	3.2±0.4[a]
Final Sn level (Mev)	ground state	ground state	2.22
Assumed log ft	4.60[b]	4.60[b]	5.25[c]
Calculated $T_{\frac{1}{2}}$(sec)	6	14_{-13}^{+6}	70_{-30}^{+50}

[a] See reference 13.
[b] Log ft for 3.3-Mev β of 13-sec In^{116}.
[c] Log ft for 0.87- and 1.00-Mev γ's of 54-min In^{116m}.

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