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Level Structure of Sn^{118} and Sn^{120} from the Decay of Sb Isotopes*

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The decay of 5-hr Sb^{118} and 6-day Sb^{120} were studied. The spins, parities, and multipole orders of the transitions in both Sn isotopes are characterized by $7-(E2)5-(E1)4+(E2)2+(E2)0+$. Level ordering in both isotopes was determined to differ from the previously accepted order. The spins and multipole order assignments were determined from angular correlation and internal conversion measurements in Sn^{118} and from a reinterpretation of similar experimental results by Ikegami for Sn^{120}. All β decay is directly to the 7− states. The levels are at 2.57, 2.32, 2.28, and 1.23 Mev in Sn^{118} and 2.50, 2.30, 2.21, and 1.18 Mev in Sn^{120}. Half-lives determined using delayed coincidence techniques were as follows: (7−), $(2.3\pm0.1)\times10^{-7}$ sec; (5−), $(2.0\pm0.3)\times10^{-8}$ sec in Sn^{118}; and (7−), $(1.12\pm0.10)\times10^{-6}$ sec; (5−), $(5.2\pm0.4)\times10^{-9}$ sec in Sn^{120}. Reduced transition probabilities are compared with current theories. No crossover transitions were found in either decay except for a weak 1.090-Mev $E3$ transition from the 5− to 2+ levels in Sn^{118}, which has a reduced transition probability close to single-particle speed. Triple coincidence experiments determined a β^+ to capture ratio of $(1.6\pm0.1)\times10^{-3}$ in the Sb^{118} decay yielding an inferred transition energy of 1.32 Mev.

I. INTRODUCTION

THE tin isotopes are magic in proton number ($Z=50$), and it might be expected that the low-lying excited states can be characterized to a large extent by shell-model wave functions. However, the number of neutrons is far from magic (68 or 70), and in this region of atomic weight other nuclear models such as Davydov and Fillipov's asymmetric rotor model[1] or, in some cases, the near-vibrational model of Goldhaber and Weneser,[2] are capable of giving reasonably successful descriptions of the low-lying excited states of some even-even nuclei (e.g., Cd^{110}, Cd^{112}, Cd^{114}, Te^{122}, Te^{124}). It is reasonable to assume, therefore, that the tin isotopes may display characteristics that involve both shell-model and collective effects. Indeed, the first-excited states of Sn^{118} and Sn^{120}, 2+ states with lifetimes ten times shorter than single-particle speed,[3] have been interpreted as collective levels.

Kisslinger and Sorensen[4] have calculated the pairing correlation effects of two-particle excitation in even nuclei with a single closed shell, contributing to the interpretation and understanding of levels in this class of nuclei. These authors have made detailed calculations on the levels of the Sn isotopes.

The levels of Sn^{118} and Sn^{120} populated in radioactive decay have been studied by a number of investigators over the past few years.[5–12] In particular, the results of the investigation of the levels of Sn^{118} from the decay of Sb^{118} by Ramaswamy *et al.*[5] suggested that there might be certain inconsistencies in the proposed decay scheme and assignments. It was therefore felt that a careful reexamination of these states was warranted, and it was for this reason that the present work was undertaken.[13]

The previous works reported that the decay of the 5.1-hr Sb^{118} populates the levels in Sn^{118} by electron capture. These investigators are in agreement that four radiative transitions follow the electron capture, all transitions being in cascade with no observed crossovers, and sequentially ordered in time in the order 0.040, 0.254, 1.05, and 1.23 Mev. In addition, the branching of the electron decay was reported[6] to be 90 and 10% to the third and fourth excited states, respectively. Assignments of spins and parities for all levels were made, and the multipolarities of the transitions assigned.[5,8] The work on Sn^{120} proposed a decay scheme very similar to that of Sn^{118}.[12]

Our measurements began with a careful examination of the decay of Sb^{118}. After our determination of the level scheme of Sn^{118}, the report of the study of Ikegami on the decay of Sb^{120} appeared in the literature.[12] It became apparent that the level scheme of Sn^{120} might be identical in level sequence, spin, and parity, if the ordering of two γ-ray transitions presented by Ikegami were interchanged. Measurements of the time order were performed and it was found that indeed Ikegami's

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[1] A. S. Davydov and G. F. Fillipov, Nuclear Phys. **8**, 237 (1958); A. S. Davydov and V. S. Rostovsky, *ibid.* **12**, 58 (1959).

[2] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).

[3] P. H. Stelson and F. K. McGowan, Bull. Am. Phys. Soc. **2**, 69 (1957).

[4] L. S. Kisslinger and R. A. Sorensen, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **32**, No. 9 (1960).

[5] M. K. Ramaswamy, W. L. Skeel, D. L. Hutchins, and P. S. Jastram, Phys. Rev. **121**, 553 (1961) (Sn^{118}).

[6] C. L. McGinnis and D. N. Kundu, Bull. Am. Phys. Soc. **3**, 62 (1958) (Sn^{118}).

[7] C. E. Gleit and C. D. Coryell, Phys. Rev. **122**, 229 (1961).

[8] B. Skytte Jensen, O. B. Nielsen, and O. Skilbreid, Nuclear Phys. **19**, 654 (1960) (Sn^{118} and Sn^{120}).

[9] R. W. Fink, thesis, University of Rochester, 1953 (unpublished).

[10] C. L. McGinnis, Phys. Rev. **98**, 1172(A) (1955); **109**, 888 (1958) (Sn^{120}).

[11] M. Linder and I. Perlman, Phys. Rev. **73**, 1124 (1948) (Sn^{120}).

[12] H. Ikegami, Phys. Rev. **120**, 2185 (1960) (Sn^{120}).

[13] A preliminary report of this work was given in abstract form [Bull. Am. Phys. Soc. **6**, 50 (1961)] and our final decay scheme for Sn^{118} was presented at the 1961 Annual Physical Society meeting.

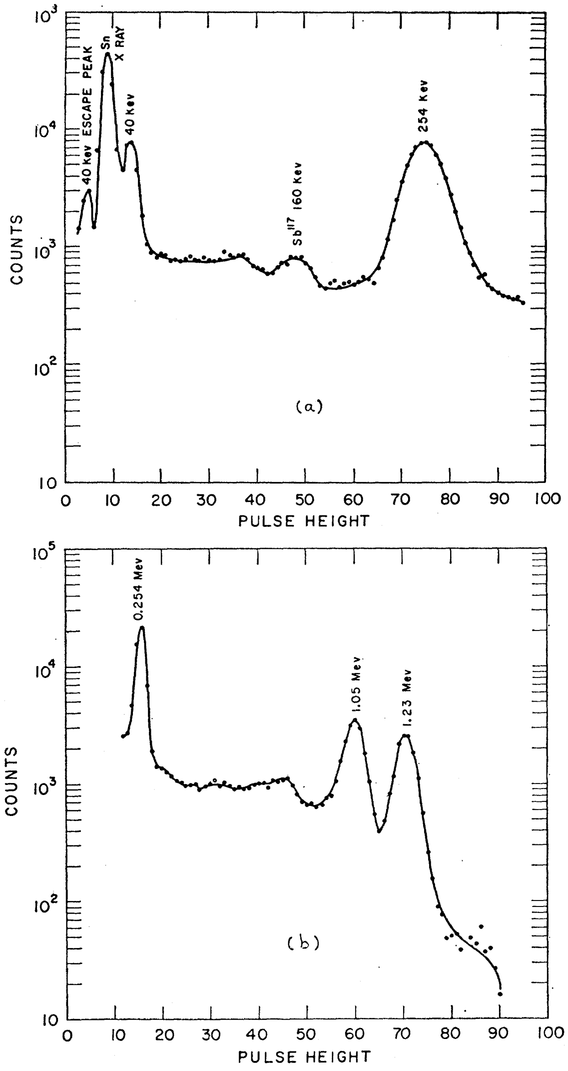

FIG. 1. NaI pulse height spectra: (a) low-energy region, (b) high-energy region.

ordering was in error, making the schemes of Sn^{118} and Sn^{120} very similar. The results of the experiments determining the ordering are presented in an Appendix of this paper. Knowledge of the detailed character of the decay is derived from a reinterpretation of the experimental work of Ikegami, utilizing our new level ordering. The body of this paper is concerned with our detailed study of the properties of the $Sb^{118} \rightarrow Sn^{118}$ decay.

Scintillation γ-ray and magnetic β-ray spectroscopy techniques were employed in this work to investigate the transitions present in the decay. Of considerable importance and significance, as it relates to detailed model predictions, were the measurements of the lifetimes of various excited states by delayed coincidence techniques. The observation of these lifetimes has not been previously reported. These results, in addition to those obtained for the angular correlations of three pairs of cascade gamma rays, the internal conversion coefficients of the transitions, the K/L internal conversion ratio and L subshell internal conversion studies, electron capture-to-positron ratio, and the relative intensities of the gamma-ray transitions are presented. A new revised decay scheme is proposed which differs significantly from those reported previously, and the assignments of the spins and parities of all levels, as well as the multipolarities of all transitions, consistent with the above mentioned experimental results, have been obtained.

II. SOURCE PREPARATION

Samples of 5.1-hr Sn^{118} were produced by the reaction $In^{115}(\alpha,n)Sb^{118}$ using $\sim$15-Mev α particles from the Brookhaven National Laboratory 60-in. cyclotron and a natural In foil-target. The activity was separated from the target material by means of an ether extraction from a 7.5N HCl solution. Weak HCl solutions prepared from the source material were used for the scintillation spectroscopy. Sources for the internal conversion measurements were prepared by back-extracting the activity from ether into H_2O. The water solution was dried on a thin gold backing.

The α bombardment of natural In produces no other long-lived activities except for 2.8-hr Sb^{117} [$In^{115}(\alpha,2n)Sb^{117}$]. The details of this decay are well known[14] and present no difficulties in the present work.

III. γ-RAY INTENSITIES

We have investigated the radiative transitions following the decay of Sb^{118} by scintillation means. The singles spectrum obtained with a 3 in.×3 in. NaI detector is shown in Fig. 1, which presents the low-

TABLE I. Relative intensities.

Transition energy (Mev)	Measured γ-ray intensities	Expected γ intensities derived from decay scheme[a]	Final total transition intensities[b]
0.041	0.29 ± 0.02^c	0.30	0.98
0.254	0.93 ± 0.06^c	0.94	1
(0.294)	$<3\times10^{-3\,d}$	···	$<3\times10^{-3}$
1.049	1.0 ± 0.1^c	0.98	0.98
1.090	0.024 ± 0.004^d	0.024	0.024 ± 0.004
1.229	1^c	1	1
K x ray	1.45 ± 0.15^c	1.3^e	
Annihilation	$(3.2\pm0.2)\times10^{-3\,f}$		

[a] Derived from Fig. 11 using theoretical conversion coefficients (pure multipoles).
[b] Unless otherwise indicated, errors are less than 1%. These small errors are a result of the small experimental limits set on β-decay branching to levels other than 2.57 Mev.
[c] Determined from singles scintillation spectroscopy.
[d] Determined from measured internal conversion intensities and assumed theoretical $E3$ conversion coefficients.
[e] Assuming theoretical conversion coefficients, K/L capture ratio, and a fluorescence yield of 0.84.
[f] From triple coincidence measurements.

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[14] *Nuclear Data Sheets*, edited by C. L. McGinnis, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C., 1960).

and high-energy portions of the spectrum. The four γ rays of 0.040, 0.254, 1.05, and 1.23 Mev are easily seen. In addition, the 40-kev line is well resolved from that of the 25-kev Sn *K* x ray. The rather weak transition at 160 kev is due to the presence of Sb^{117}.

The relative intensities of the γ rays determined from the singles spectrum are presented in the second column of Table I. The x-ray intensity was corrected for the presence of Sb^{117}. Coincidence studies ($2\tau \sim 2 \times 10^{-7}$ sec) showed that all γ rays were in simple cascade and revealed no crossover transitions.

IV. LIFETIME MEASUREMENTS

Delayed coincidence studies were made between the 1.23 and 0.254-Mev γ rays using NaI detectors and time-to-pulse-height conversion.[15] The results are given in Fig. 2. The "prompt" response curve was obtained by channelling on the 1.33-Mev γ-ray full-energy peak and the Compton electron spectrum in the region of 0.254 Mev due to the 1.17-Mev γ ray from a Co^{60} source, thus simulating the pulse-height conditions of the 1.23–0.254-Mev cascade. From the slope of the delayed coincidence spectrum, the 1.23-Mev transition was found to be delayed relative to the 254-kev transition with a half-life of $(2.0 \pm 0.3) \times 10^{-8}$ sec.

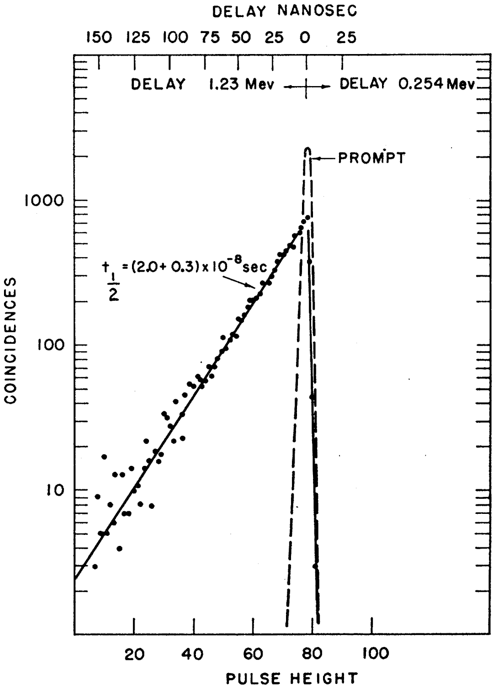

FIG. 2. Time spectrum of coincidences between the 0.254- and 1.23-Mev γ rays. Prompt spectrum was obtained using Co^{60} source.

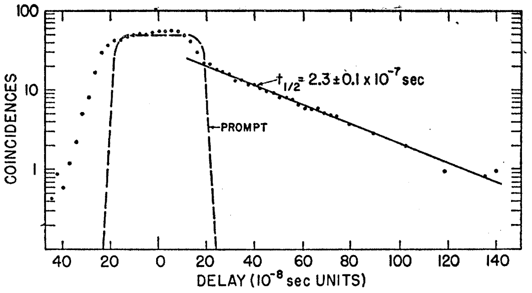

FIG. 3. Time delay curve of the x-ray–0.254-Mev coincidences.

A conventional delayed coincidence experiment (using a resolving time of $\sim 4 \times 10^{-7}$ sec) between the *K* x rays and the 254-kev transition, shown in Fig. 3, yielded a half-life of $(2.3 \pm 0.1) \times 10^{-7}$ sec for the delay of the 254-kev γ ray with respect to the x rays resulting from electron capture. Evident also, on the left side of this figure, is the delayed slope due to the x rays following internal conversion of the 40-kev transition being delayed over that of the 254-kev transition with the 20-nanosecond half-life found in Fig. 2. The prompt component of this curve is due to contributions of Compton events of prompt γ rays entering the energy channels used. Here the "prompt" curve was

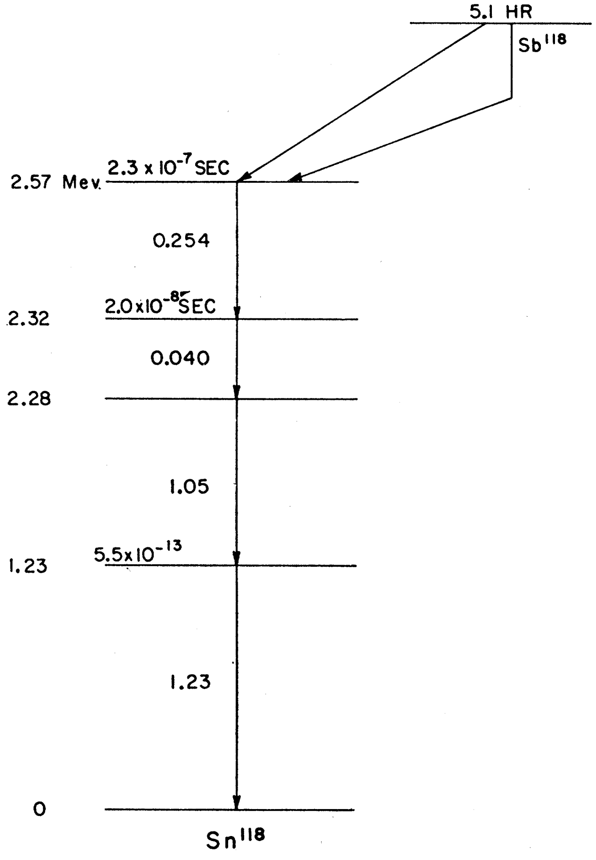

FIG. 4. Time order of prominent transitions in Sn^{118}.

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[15] J. V. Kane, R. E. Pixley, R. B. Schwartz, and A. Schwarzchild, Phys. Rev. **120**, 162 (1960); R. E. Green and R. E. Bell, Nuclear Instr. **3**, 127 (1958).

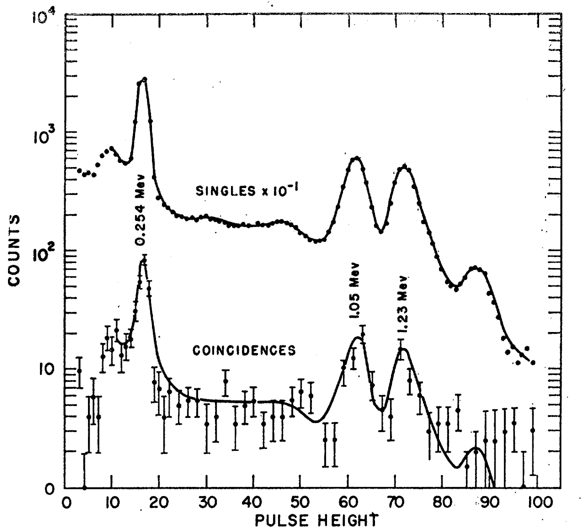

FIG. 5. Triple coincidence spectrum with annihilation radiation. The singles spectrum is shown for comparison. The low-energy portion of the spectrum below channel 10 was suppressed by a discriminator.

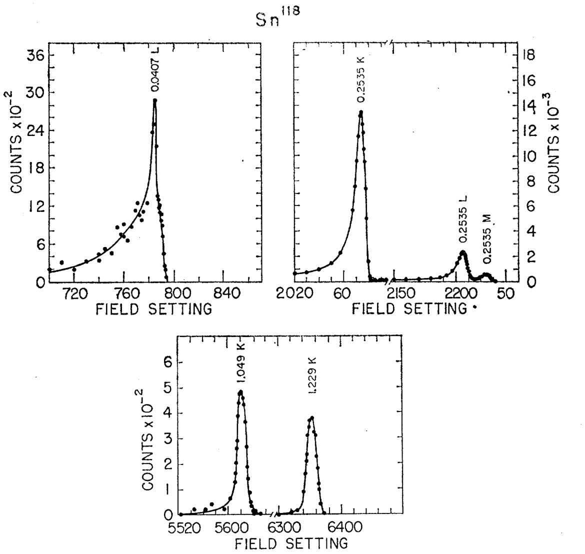

FIG. 6. Internal conversion line spectrum obtained with a $\pi\sqrt{2}$ magnetic spectrometer. Only selected regions are shown. Careful observation of the 0.040-Mev L line reveals that $L_{\text{I}}/(L_{\text{II}}+L_{\text{III}})=1.5\pm0.5$, indicative of the $E1$ character of this transition.

taken using the 160-kev γ ray and the 25-kev Sn K x ray from a separate Sb^{117} source, again simulating the conditions of the cascade under investigation. Other studies showed the 0.040-, 1.05-, and 1.23-Mev γ rays to be in prompt coincidence with each other within $<5\times10^{-9}$ sec. The 1.23-Mev γ ray has been shown, from studies of the decay of the 3.5-min isomer of Sn^{118},[9] and from Coulomb excitation studies,[3] to be the transition from the 5.5×10^{-13}-sec first excited state to the ground state. The presence of two measurable lifetimes and the prompt character of the 1.05–1.23-Mev coincidence uniquely determines the time ordering of the transitions shown in Fig. 4. This scheme is in serious disagreement with previously proposed schemes in the ordering of the 40- and 254-kev transitions.[5,6,8]

V. ELECTRON CAPTURE AND β^+ EMISSION

The intensities of the 1.23- and 0.254-Mev transitions, as observed in the singles spectrum, impose a limit of $<10\%$ for direct population from Sb^{118} of any state below the 2.57-Mev level. In order to determine conversion coefficients accurately, it is necessary to determine the β branching more precisely.

In order to determine the branching ratio and energy release of the β decay from the 5.1-hr state of Sb^{118}, triple coincidence measurements were made between the two annihilation quanta (511 kev) and the nuclear gamma rays. Since K/β^+ ratios vary very rapidly with decay energy, the triple coincidence experiment is very sensitive to weak branches to lower levels. Due to the nature of the annihilation process, the efficiency for their coincident detection at 180°, at large source-to-detector distance, is sufficiently enhanced relative to other coincidences to see β^+ emission that is considerably less than 1% of the decay. In these measurements, each of two 3×3-in. NaI scintillation detectors was set to accept only the full energy peak of the 511-kev quanta at 180° to each other at a distance of 10 cm from the source. A 4×5-in. NaI detector at ~2 cm from the source was used to record the triple coincidence spectrum of the 0.254-, 1.05-, and 1.23-Mev γ rays coincident with the annihilation radiation.

The electronics was arranged so that pulses from the 511–511-kev detectors were mixed in fast coincidence with a resolving time of 2×10^{-8} sec. The pulses from the third detector (4-in.×5-in.) were mixed with the 511–511 coincidence signal using a resolving time of 2×10^{-6} sec. This slow resolving time must be used in order to obtain high efficiency because of the long lifetime of the 2.57-Mev state.

The spectrum obtained is shown in the lower portion of Fig. 5. The upper curve is the singles spectrum obtained in the 4×5-in. crystal. The highest energy peak is that due to the coincident summing of the 1.23- and 0.254-Mev γ rays. The curve drawn through the observed experimental points of the triple coincidence spectrum is the singles spectrum normalized to the 254-kev γ-ray peak. It is seen that the triple coincidence spectrum has the same shape as the singles spectrum, indicating that β^+ emission goes rather exclusively to the 2.57-Mev level as shown in Fig. 4.

Detailed analysis using these data and the triple-coincidence detection efficiencies determined experimentally using a Na^{22} source yielded the following results. The decay proceeds entirely to the 2.57-Mev level with an upper limit of 0.9% for the decay going to the 2.32 Mev or lower level. The value obtained for

TABLE II. Internal conversion results of Sn^{118}.

Transition energy (Mev)	Experimental[a] coefficient or ratio	Theoretical[b]				Assignment
		$E1$	$E2$	$M1$	$M2$	
0.0407 ± 0.0010	$\alpha_T=2.42\pm0.25$[c]	2.2	>31	7.3		$E1$
0.2535 ± 0.0005	$\alpha_K=(4.9\pm0.4)\times10^{-2}$	1.2×10^{-2}	5.0×10^{-2}	3.8×10^{-2}	1.8×10^{-1}	$E2$
	$\alpha_L=(8.4\pm0.8)\times10^{-3}$	1.4×10^{-3}	8.3×10^{-3}	4.8×10^{-3}	2.7×10^{-2}	
	$\alpha_M=(2.0\pm0.3)\times10^{-3}$	...	...	...	...	
	$\alpha_K/\alpha_L=6.0\pm0.1$	8.4	6.1	7.9	6.7	
1.049 ± 0.002	$\alpha_K=(9.7\pm0.5)\times10^{-4}$	4.4×10^{-4}	1.0×10^{-3}	1.3×10^{-3}	3.0×10^{-3}	$E2$
1.229 ± 0.002			7.25×10^{-4}			$E2$
1.090 ± 0.003[d]		Theoretical $\alpha_K(E3)=2.05\times10^{-3}$				$E3$

[a] Calculated using indicated theoretical conversion coefficient for 1.229-Mev transition.
[b] References 17 and 18.
[c] Determined from scintillation spectroscopy.
[d] Gamma transition not observed. Multipolarity assignment from decay scheme.

the fraction of the decay proceeding by positron emission is $(1.6\pm0.1)\times10^{-3}$. This result is well within the upper limit estimates previously reported.[5] From the known functional relationship between the positron-to-capture ratio and the energy release involved for allowed β-decay transitions,[16] one obtains quite sensitively that the energy of the decay populating the 2.57-Mev level is 1.32 ± 0.01 Mev. Using the 5.1-hr parent half-life and these results, a logft of 5.0 is obtained for this decay, a value corresponding with that expected for allowed decay.

VI. INTERNAL CONVERSION STUDIES

The internal conversion electron spectrum of the transitions was studied using a double-focusing $\pi\sqrt{2}$ iron β-ray spectrometer operated at approximately 0.25% resolution. The results, for those regions which are of interest, are shown in Fig. 6. Included are the 0.0407-Mev L subshell conversion lines, the 0.2535-Mev K, L, and M internal conversion lines, and the 1.049- and 1.229-Mev K conversion lines, corrected for source decay. In addition, a search was made for the possible presence of crossover transitions which were unobserved in the scintillation γ-ray studies. A single crossover transition, previously unreported, was observed in the form of a weak K internal conversion line at 1.090 Mev, shown in Fig. 7. The energy of this transition substantiates the level order given in the proposed decay scheme of Fig. 4. An upper limit for the intensity of the possible 294-kev crossover transition, which was not observed, is $I_K(294)/I_K(254)<6.4\times10^{-3}$. Listed in Table II are the various internal

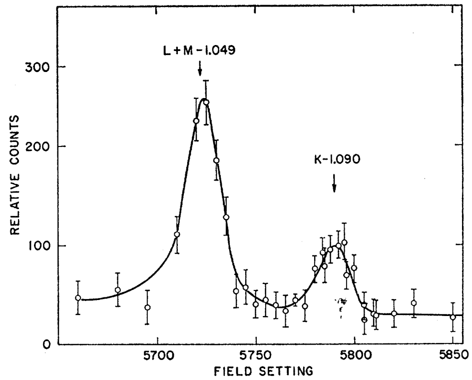

FIG. 7. Internal conversion of the weak K line of the 1.090-Mev crossover transition. This is shown well resolved from the $L+M$ line of the 1.049-Mev transition.

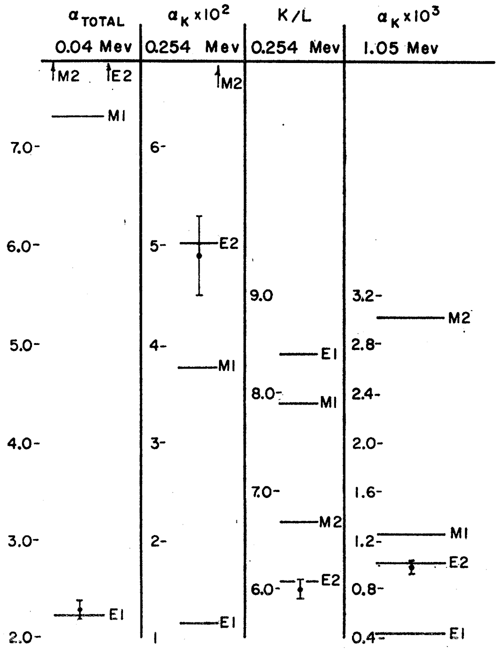

FIG. 8. Schematic representation of the observed and theoretical conversion coefficients and K/L ratio for the 0.040-, 0.254-, and 1.049-Mev transitions.

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[16] M. L. Perlman and M. Wolfsberg, Brookhaven National Laboratory Report, BNL-485, 1958 (unpublished). Additional references are given in this report.

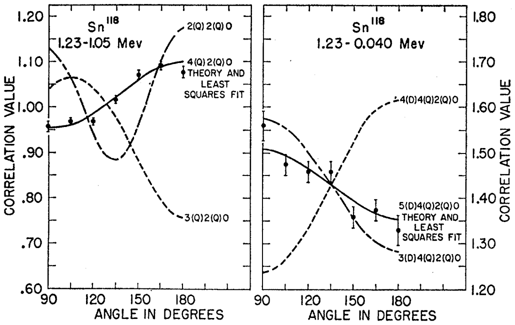

FIG. 9. Results of angular correlations between the 1.23–1.05-Mev and the 1.23–0.040-Mev γ-ray cascades. Some theoretical correlations are shown for comparison.

conversion coefficients and ratios obtained from a comparison of these intensities and that of the pure $E2$ 1.23-Mev transition, utilizing the relative intensities of the transitions given in Table I. The values obtained for the K-conversion coefficients of the 0.254- and 1.05-Mev transitions are in good agreement with the values quoted by Skytte Jensen *et al.*[8]

Although no attempt was made to derive the L-conversion coefficient of the 40-kev transition due to counter-window absorption uncertainties at this energy, the relative L-subshell structure observed can be used to assign the nature of this transition. Assuming that the K-conversion coefficient of the 40-kev transition has the theoretical value for an $E1$ transition, the observed total L-conversion intensity agrees with the theoretical $E1$ value if a transmission of ~60% is assumed for our 0.9-mg/cm^2 counter window, which is reasonable. In addition, from the relative intensities of the γ rays obtained from the scintillation spectrum and the exclusive electron capture decay to the 2.57-Mev level, the total internal conversion coefficient of the 40-kev transition was obtained. This value is listed in Table II. The theoretically expected values for the conversion coefficients for various electric and magnetic multipolarities[17,18] are presented for comparison. Most of these data are also given in Fig. 8, in a semigraphical form allowing a somewhat clearer presentation of the multipole designations. These results are consistent with the following pure multipole assignments: 0.040 Mev, $E1$; 0.254 Mev, $E2$; 1.05 Mev, $E2$. These assignments are in agreement with those of Skytte Jensen *et al.*[8] The assignment of the 1.090-Mev crossover is taken to be $E3$ from the spin and parity assignments described in a later section.

VII. γ-γ ANGULAR CORRELATIONS

Coupling the multipolarity assignments of the transitions obtained from internal conversion studies with the results of γ-γ angular correlation measurements may lead to unique spin assignments for the levels populated in the decay. γ-γ angular correlation measurements were made on three pairs of cascade γ rays. In these studies, the data were obtained at 15-degree intervals from 90° to 270° and were taken and recorded automatically. The two 3×3-in. NaI detectors (for the 40-kev correlation a 1.5×0.125-in.-thick NaI) were placed 15 cm from the centered source with each of the two channels sensitive to the full energy peak of one γ ray of the pair under investigation. A fast coincidence resolving time of $\sim 2\times 10^{-8}$ sec was used. The data so obtained were corrected for accidental coincidences which were less than a few percent. The time spent in completing one 90°–270° cycle was such as to make correction for source decay very small. The coincidence rate at each angle was normalized to the singles counting rate in the movable counter. The correlation coefficients were obtained from a least-squares analysis of the data[19] and then corrected for the finite solid angle of the detectors. All correlations were performed relative to the 1.23-Mev γ ray. Thus the possibility of Compton contributions of higher energy γ rays in one of the detectors is removed. The skipped and double-skipped correlations are sufficiently sensitive to determine all the spins involved.

A. 1.23–1.05-Mev Correlation

As these two γ rays are the most energetic observed in the scintillation spectrum, no other coincident radiations contribute to the observed correlation. The results are presented in Fig. 9 in addition to being listed in Table III. The solid line is a least-squares fit to the data and is indistinguishable, in this plot, from the theoretical correlation[20] corrected for finite solid angle, for the sequence $4(Q)2(Q)0$. Presented for comparison are the theoretical correlations for some spin sequences which are consistent with the pure quadrupole character of both transitions. Clearly, the data correspond to the $4(Q)2(Q)0$ assignment, in agreement with the results of Skytte Jensen *et al.*[8] and

TABLE III. Angular correlation results.

γ-ray energies (Mev)	Experimental coefficients $P_2(\cos\theta)$	Experimental coefficients $P_4(\cos\theta)$	Theoretical coefficients for indicated cascades $P_2(\cos\theta)$	Theoretical coefficients for indicated cascades $P_4(\cos\theta)$
1.229–1.049	0.099±0.009	0.011±0.012	0.102	0.0091
			$4(Q)2(Q)0$	
0.041–1.229	−(0.080±0.014)	···	−0.071	0
			$5(D)4(Q)2(Q)0$	
0.254–1.229				
Prompt	0.106±0.011	0.020±0.014	0.102	0.0091
Delayed	0.103±0.009	0.014±0.013	$7(Q)5(D)4(Q)2(Q)0$	

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[17] *Internal Conversion Coefficients*, edited by M. E. Rose (North-Holland Publishing Company, Amsterdam, 1958).

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

[19] M. E. Rose, Phys. Rev. **91**, 610 (1953).

[20] L. C. Biedenharn and M. E. Rose, Revs. Modern Phys. **25**, 729 (1953).

in disagreement with the results of Ramaswamy *et al.*[5] who obtained a somewhat higher coefficient for the P_2 term, prompting their assignment of the 1.05-Mev transition to contain a small admixture of $M3$ radiation. Taken together with the present K-internal conversion results, the correlation we obtained does not allow any mixed multipole assignment for this transition.

B. 1.23–0.040-Mev Correlation

In this correlation measurement, the thin scintillator used to register the 40-kev γ ray was covered with three mils of Cu foil to selectively absorb the 25-kev Sn K x ray. The 40-kev detector was stationary. Present here is the possibility of underlying Compton distributions of the 1.05- and 0.254-Mev γ rays also coincident with the 1.23-Mev transition. To measure the extent of this effect, 30 mils of Cu were interposed on the 40-kev detector side of the source, which effectively absorbed the 40-kev γ ray completely, while not affecting the higher energy gamma rays. The angular correlation was measured with and without the absorber. The effect of the Compton distributions was found to be negligible.

The results are presented in Fig. 9 and Table III. The least-squares fit to the data (solid line) is indistinguishable from the theoretical correlation corrected for finite solid angle, for the sequence $5(D)4(Q)2(Q)0$. This is a case of a skipped correlation with the intermediate transition unobserved.[21] Again, for comparison, the theoretical correlations consistent with the multipole assignments obtained from the conversion studies are plotted. It is seen that the $5(D)4(Q)2(Q)0$ sequence is clearly most consistent with the data. As in the 1.23–1.05-Mev correlation, correlation functions involving other spins and including multipole mixing would not admit to a fit of the data with multipole mixtures in any reasonable agreement with the internal conversion results or the observed lifetimes of the 40-kev transition.

C. 1.23–0.254-Mev Correlation

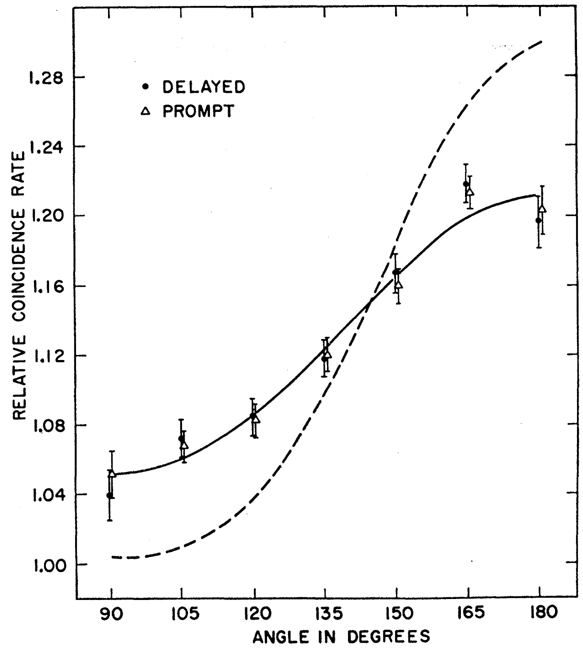

FIG. 10. Angular correlation between the 0.254- and 1.23-Mev γ rays. Correlations using a resolving time of $\sim 1.5\times 10^{-8}$ sec were obtained with and without a 30-mμsec delay of the 0.254-Mev radiation. The points shown have been slightly displaced from the designated angle for clarity of presentation. The solid line is the least-squares fit to the data. The dashed curve is the only other possible correlation [$3(Q)5(D)4(Q)2(Q)0$] with positive $P_2(\cos\theta)$ coefficient, assuming pure multipoles.

This is a case of a double-skipped correlation with the two intermediate radiations unobserved. The theoretical treatment of this correlation is a natural and simple extension of the single-skipped case.[22] There exists the possibility that the lifetime of the 2.32-Mev level (2×10^{-8} sec) might be sufficiently long to allow the spin orientation of this level to precess about any existing internal fields due to the coupling of the nuclear magnetic dipole or electric quadrupole moments to those fields. This effect would manifest itself in a decrease in the measured anisotropy from the unperturbed value. This possibility was explored by performing delayed angular correlation measurements with delay times from zero to 30 mμsec, using a weak HCl solution for the source. It was found that within experimental error, no evidence for such a diminution of the measured correlation was observed.

In addition, there is a contribution to the measured correlation from the 1.23–1.05-Mev correlation due to the 1.05-Mev Compton distribution underlying the 0.254-Mev full-energy peak. Since the 1.17- and 1.33-Mev γ rays from Co^{60} are so close in energy to the 1.05- and 1.23-Mev transitions in Sn^{118} and give rise to the same angular correlation function, this source was used to measure the extent of this contribution. This was accomplished with one channel set the same as for the 0.254-Mev peak and the other on the 1.33-Mev line. The results were used to correct the 1.23–0.254-Mev correlation observed. Since the 1.23–1.05-Mev cascade is prompt, the delayed angular correlation measurements did not contain this "background" correlation.

The results are given in Fig. 10 and Table III.

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[21] L. C. Biedenharn, *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press, Inc., New York, 1960), Part B, Chap. V, p. 732.

[22] Using the notation and formula numbering of reference 21 for the cascade $j_0(L_0,L_0')J_1(L_1,L_1')J_2(L_2,L_2')J_3(L_3,L_3')j_4$, the correlation function is given by a modified form of Eq. (66), where $W_L(\theta)=\sum_\nu A_\nu(0)A_\nu(3)C_\nu(1)C_\nu(2)P_\nu(\cos\theta)$. The calculations then proceed in a straightforward manner. However, it should be noted that the δ^2 which appears in the incoherent sum of Eq. (66) is the intensity ratio of the primed and unprimed decay modes of the unobserved intermediate transition and not of the gamma-ray intensities, this distinction being important where the intermediate transition is reasonably highly converted and is composed of a mixture of multipoles.

TABLE IV. Transition probabilities in Sn^{118} and Sn^{120}.

Transition and multipole order	Sn^{118}			Sn^{120}		
	E (Mev)	$\tau_{\frac{1}{2}}$ (sec)	$\tau_\gamma/\tau_{\gamma(\mathrm{S.P.})}$[a]	E (Mev)	$\tau_{\frac{1}{2}}$ (sec)	$\tau_\gamma/\tau_{\gamma(\mathrm{S.P.})}$
$2+ \xrightarrow{E2^{b}} 0+$	1.229	5.6×10^{-13}	0.097	1.175	6.9×10^{-13}	0.097
$5- \xrightarrow{E1} 4+$	0.041	2.0×10^{-8}	1.5×10^{4}	0.090	5.2×10^{-9}	1.6×10^{4}
$7- \xrightarrow{E2} 5-$	0.254	2.3×10^{-7}	16	0.200	1.1×10^{-5}	250
$5- \xrightarrow{E3} 2+$	1.090	8.7×10^{-7}	1.1	1.12 (not observed)		>0.3[c]

[a] $\tau_{\gamma(\mathrm{S.P.})}$ calculated according to Weisskopf estimate given by A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout [*Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959), p. 71], including internal conversion.

[b] From Coulomb excitation.[3]

[c] A search for the internal conversion line of this transition resulted in this lower limit.

They are consistent only with the sequence $7(Q)5(D)$-$4(Q)2(Q)0$. The possibilities of spins 6, 5, or 4 for the 2.57-Mev state give negative P_2 coefficients assuming a pure multipole nature for the 254-kev radiation. (If one allows for a small multipole admixture then only spin 6 might be fit, but this predicts a negative P_4 coefficient of 0.04, which is outside our error. Also, consideration of transition probabilities shows that if the state had spin 6, the possible $6 \rightarrow 5$ $M1$ transition would be retarded by a factor of 2×10^{6}, which seems unreasonable.)

Summarizing the results of the present angular correlation measurements and those obtained from the other studies reported in this paper, the spin and parities so determined are shown in the decay scheme of Fig. 11 for mass 118.

The decay scheme of 6-day Sb^{120} is also presented in Fig. 11, and is discussed in the Appendix.

VIII. DISCUSSION

The similarity between the level schemes of Sn^{118} and Sn^{120} is apparent. This discussion concerns both level schemes. Table IV presents the known lifetimes of levels in both nuclei and a comparison of the partial γ-ray lifetimes to the Weisskopf estimates.

As mentioned previously, the first-excited 2+ states have enhanced transitions which are 10 times faster than single-particle speed.[3] The enhancement of these $E2$ radiations is discussed in detail by Kisslinger and Sorensen[4] and predicted rather well by their model. The 4+ states might either be interpreted as members of the two-phonon triplet which could be expected at this energy, or they may be due to an even neutron configuration, which from the work of Kisslinger and Sorenson would also be expected to be present in this energy region. Proceeding higher in energy, it is evident that the pairing is broken, in order to account for the negative parity states.

The possible neutron orbitals available in this region are $h_{11/2}$, $s_{1/2}$, and $d_{3/2}$. The $h_{11/2}$ must be present in all odd parity states. It is obvious that within this scheme the 7− states must be characterized by $(h_{11/2},d_{3/2})_{7-}$. The 5− states may have contributions from the two configurations $(h_{11/2},d_{3/2})_{5-}$ and $(h_{11/2},s_{1/2})_{5-}$. It is suggested by the rules of Glaubman and Talmi[23] for the coupling of two identical particles, that 7− is the lowest state of the $(h_{11/2},d_{3/2})$ configuration. Since the 5− state lies lower than the 7− state, one therefore concludes that it is predominantly $(h_{11/2},s_{1/2})_{5-}$.

The $E2$ transitions from the 7− to 5− states are most interesting. These are retarded in both nuclei, and the retardation differs by a factor of 16 between Sn^{118} and Sn^{120}. It would seem that a simple shell-model calculation (which ascribes an effective neutron charge of the order of the proton charge) would lead to an

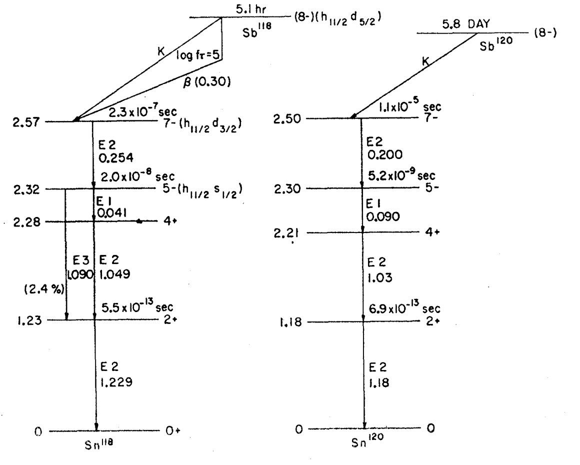

FIG. 11. Delay scheme of Sb^{118} and Sb^{120}. All energies are in Mev.

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[23] M. J. Glaubman, Phys. Rev. **90**, 1000 (1953); I. Talmi, *ibid.* **90**, 1001 (1953).

allowed transition in both nuclei or at least a similar retardation. The work of Kisslinger and Sorensen[4] provides formulas for calculation of the expected retardation factors for this transition in Sn^{118} and Sn^{120}, according to their model. Using their formulation and the parameters for Sn presented in their paper for the states in question, the speeds of these two transitions should, indeed, be significantly reduced from single-particle speed. However, the values so obtained differ considerably from the experimental results. However, these predictions should not be taken too seriously because the parameters describing population and vacancy of the states between which the transitions proceed are such that the population parameters of Sn^{118} are very nearly equal to the vacancy parameters in Sn^{120}, and vice versa. In other words, an inversion in values of these parameters is undergone between Sn^{118} and Sn^{120}. The transition probability depends upon the small difference of these two similar quantities. A very slight modification in these parameters might result in lifetimes in agreement with experiment, while having little or no effect upon other characteristics of the level schemes of these nuclides. To say the least, on the basis of the work of Kisslinger and Sorensen, the lifetimes of the $E2$ $7-$ to $5-$ transitions may be expected to show variations as large as observed, indicating that no other effects need be incorporated to explain these results.

The $5-$ level decays with a retardation factor of $\sim 1.5\times 10^4$ for the $E1$ transitions to the $4+$ state in both nuclei. Both the $(h_{11/2},s_{1/2})$ or the $(h_{11/2},d_{3/2})$ configuration of the $5-$ level absolutely forbid the observed transitions, in agreement with the large $E1$ retardation factors present. To allow the transition to proceed, small admixtures of either other shell model configurations or of collective effects could be invoked. The $E1$ transition from the $5-$ state can be ascribed to some admixture of the giant dipole excitation as a collective effect built up on the $4+$ state. It seems rather striking to us that the retardation factors for the $E1$ transitions in both Sn^{118} and Sn^{120}, listed in Table IV, are essentially identical although no reason for the similarity is apparent.

Similarly, although the $E3$ transition from the $5-$ to $2+$ states in Sn^{118} proceeds with about single-particle speed, both possible shell model configurations ascribed to the $5-$ levels forbid an $E3$ transition. The emission of the 1.090-Mev transition in Sn^{118} can be ascribed to only a small admixture of the collective octopole excitation built on the $2+$ core state, resulting in an $E3$ transition of about single-particle speed, since the octopole part itself would result in an enhanced transition. The observation of the corresponding $E3$ in Sn^{120} is more difficult experimentally because of the faster speed of the competing $E1$ transition, and was not observed in this work.

Since the 5.1-hr parent level in Sb^{118} and the 6-day level in Sb^{120} decay by an allowed β transition only to the $7-$ levels in Sn, the spin and parity of these states would either be $6-$, $7-$, or $8-$. The odd proton, exceeding the closed shell at 50 by one proton, would presumably be in the $d_{5/2}$ orbital. The negative parity of these levels again requires the odd neutron to occupy the $h_{11/2}$ orbital. Using the coupling rules for odd-odd nuclei of Brennan and Bernstein[24] and de-Shalit and Walecka,[25] the highest spin, $8-$, possible from the $(h_{11/2},d_{5/2})$ configuration should lie lowest. This $(h_{11/2},d_{5/2})_{8-}$ assignment is quite consistent with the β decay going exclusively to the $(h_{11/2},d_{3/2})_{7-}$ levels, being the transition of the $d_{5/2}$ proton to the $d_{3/2}$ neutron orbital.

Short-lived isomers of Sb^{118} and Sb^{120} are known. In both cases, the isomers decay by positron emission to the $0+$ and $2+$ states in Sn^{118} and Sn^{120}. The isomers have therefore been assigned spin $1+$. These can be ascribed to the configuration $(d_{3/2},d_{5/2})_{1+}$. The position of these isomers relative to the long-lived isomers are uncertain. For Sb^{120} the decay energy of the long-lived isomers is unknown since no positron emission has been observed. For Sb^{118} two measurements of the decay energy of the short-lived isomers exist in the literature.[9,14,26] These report 4.12 Mev[9,14] and 3.72 Mev,[26] which are in disagreement. The long-lived isomer of Sb^{118} lies 3.89 Mev above the Sn^{118} ground state. The position of the $1+$ level thus remains ambiguous. A remeasurement of the decays of the short-lived isomers, including a serach for decay to a possible state of spin $0+$ or $2+$ near the known $4+$ states, would be of great value.

Another interesting measurement which is in progress, suggested from the results of our lifetime and angular correlation measurements, would be a measurement of the magnetic moment of the $5-$ states by precession of the angular correlations.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge helpful and stimulating discussions with L. S. Kisslinger, R. A. Sorensen, A. de-Shalit, and G. Emery on some of the theoretical aspects of this problem. We are also indebted to M. Perlman for the use of the double-focusing beta-ray spectrometer; to G. Emery for use of a lens spectrometer in the preliminary internal conversion studies; and to C. Baker and the Brookhaven cyclotron crew for the many bombardments.

APPENDIX. ORDER AND LIFETIMES OF STATES IN Sn^{120}

The lifetimes of the third and fourth excited states in Sn^{120} have been measured by Ikegami.[12] As discussed in the Introduction, the possibility of error in the

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[24] M. H. Brennan and A. M. Bernstein, Phys. Rev. **120**, 927 (1960).

[25] A. de-Shalit and J. D. Walecka, Phys. Rev. **120**, 1790 (1960).

[26] A. A. Sorokin *et al.*, Izvest. Akad. Nauk SSSR, Ser. Fiz **24**, 1484 (1960).

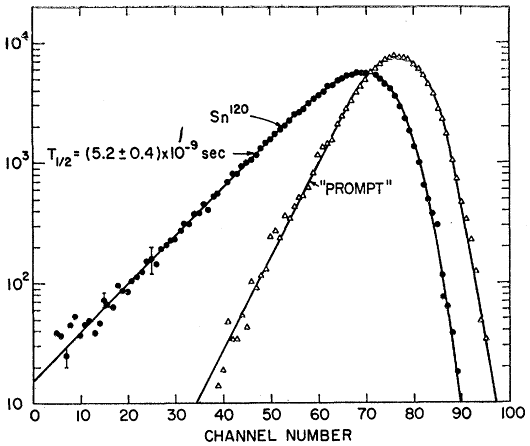

FIG. 12. Time spectrum of coincidences between the 0.200- and 0.090-Mev γ rays of Sn^{120}. The lifetime appears on the side corresponding to the late arrival of the 0.090-Mev γ ray.

ordering of the transitions was considered, and for that reason we remeasured these lifetimes.

Sources of 6-day Sb^{120} were produced by deuteron bombardment of natural Sn metal. A thick target was used and the bombarding particles were 20-Mev deuterons from the Brookhaven 60-in. cyclotron. The targets were allowed to decay for about 5 days and the Sb activities were separated using an ether extraction from 7.5*N* HCl. The sources so obtained were sufficiently intense and free of disturbing contaminants.

Lifetime of the Third Excited State

It was possible to use two 2×2-in. NaI(Tl) detectors in the measurements, thus essentially removing any ambiguity as to the energy of the transitions observed. For the lifetime of the third excited state a time-to-pulse-height converter of the Green and Bell[15] type was employed. Time spectra were obtained using energy selection of the photopeaks of the scintillation spectra for several pairs of γ rays.

Figure 12 shows one of the time spectra obtained by channeling on the 0.090-Mev and 0.200-Mev transitions. The prompt curve was obtained using an Na^{22} source and identical energy channels as for the Sn measurements.[27] This spectrum indicates that the 0.200-Mev transition does precede the 0.090-Mev transition, in contradiction to Ikegami's ordering. In order to check this point further, time spectra were measured by channeling on the different sets of γ rays as indicated in Table V. These results show unambiguously that the time order of the transitions is indeed as given in our decay scheme of Fig. 11. We take as the half-life of the third excited state $(5.2 \pm 0.4) \times 10^{-9}$ sec. This value is somewhat in disagreement with the value $(6.05 \pm 0.20) \times 10^{-9}$ sec obtained by Ikegami.[12] Our time scale was determined by observation of the prompt time spectra of Na^{22} with appropriate delays, and was linear over more than 60 channels.

TABLE V. Lifetime measurements Sn^{120}.

γ-ray energies used in delay measurement. Early radiation listed first (Mev)	Observed $\tau_{\frac{1}{2}}$ (sec)
x ray–0.20	$(11.2 \pm 1.0)^{a} \times 10^{-6}$
x ray–0.09	$(11.2 \pm 1.0)^{a} \times 10^{-6}$
0.20–0.09	$(5.2 \pm 0.4) \times 10^{-9}$
0.20–(1.0+1.2)[b]	$(5.3 \pm 0.6) \times 10^{-9}$
0.09–1.2	prompt $<3 \times 10^{-9}$

[a] Error due to uncertainty in time calibration.
[b] Composite peak accepted in late channel.

Lifetime of the Fourth Excited State and Instrumentation for Measurement of Microsecond Lifetimes

The lifetime of the fourth excited state was remeasured using a transistorized 400-channel Radiation Instrument Development Laboratory pulse-height analyzer as a direct time-delay analyzer. A schematic of the electronic arrangements is shown in Fig. 13. The address advance oscillator in the standard analyzer has a frequency of 2 Mc/sec, thus resulting in ½-μsec time intervals for each channel. The pulse height of the output of the single-channel analyzer which is set on the earlier radiation (Sn *K* x ray) is adjusted so that this pulse would normally store in channels 390 to 400 of the pulse-height analyzer. The pulse from the second detector is passed through a single-channel analyzer and delayed by ~20 μsec. This pulse is then fed[28] to the analyzer to a point which stops the address advance oscillator. If a pulse appears in the early detector, and no pulse appears in the second channel

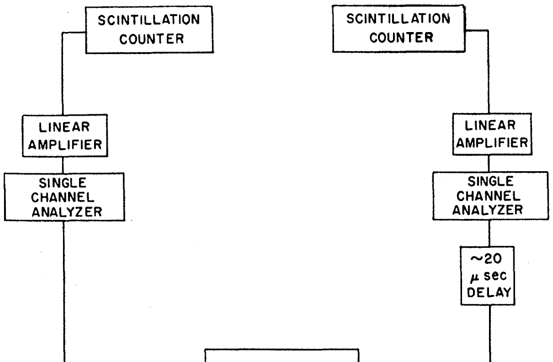

FIG. 13. Block diagram of electronics for microsecond life-time determinations.

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[27] Positrons from this source were annihilated in Al; for the purposes of this measurement this source may be considered prompt.

[28] A 10-volt negative pulse is imposed on pin 8 of connector P4(RA) of the R.I.D.L. model 34-8 or 34-12 analyzer.

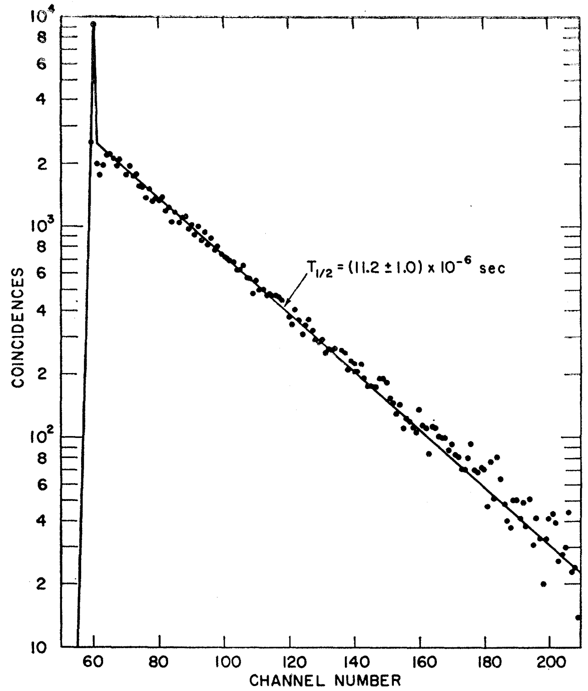

FIG. 14. Time spectrum of coincidences between K x rays and the 0.200-Mev radiation in Sn^{120}. A small accidental contribution of 42 counts per channel has been subtracted from each channel.

for ~200 μsec thereafter, the analyzer stores in channels 390–400. If a pulse appears within this time interval in the "late" detector, a pulse is stored in the analyzer in a channel appropriate to the time delay.

Because of the long effective "resolving time" of this system, very weak sources must be used for these experiments to maximize the "true-to-chance" coincidence rate. The probability of obtaining an "accidental" pulse from the *delayed* single channel analyzer within an arbitrary 200-μsec interval must be appreciably smaller than unity. If this is not the case, the accidental spectrum obtained will not contain an equal number of pulses per channel but will be heavily weighted at low channels, and evaluation of the accidental coincidence contribution to the measured time spectrum will be difficult.

To detect the Sn K x rays, a thin window 1×1-in. NaI detector was used. The second (late) detector was a 2×2-in. NaI scintillator. The "late" channel was set on the full energy peak of either the 0.090- or 0.200-Mev radiation. The time spectrum shown in Fig. 14 was obtained by channeling on the 0.200-Mev radiation. The curve shows a "prompt" contribution due to coincidences between the 200-kev radiation and the K x rays from internal conversion of the 0.090-Mev transition. The ratio of intensities of the prompt and delayed parts are in quantitative agreement (within $<10\%$) with the known K-conversion coefficient of the 0.090-Mev transition and the theoretical allowed K-to-L capture ratio for the Sb decay. The observed half-lives are given in Table V and are in good agreement with the value of $\tau_{\frac{1}{2}} = (1.18 \pm 0.05) \times 10^{-5}$ sec obtained by Ikegami.[12]

Decay Scheme and Spin Assignments

The spin and multipolarity assignments indicated in Fig. 11 for the levels of Sn^{120} are obtained from the internal conversion results of Ikegami[12] and from a reinterpretation of his many angular correlation experiments, using the new level ordering. It can be shown that if all transitions are pure multipoles, all angular correlations for the cascade $7(\gamma_1 Q)5(\gamma_2 D)$-$4(\gamma_3 Q)2(\gamma_4 Q)0$ are identical with the cascade $7(\gamma_2 D)$-$6(\gamma_1 Q)4(\gamma_3 Q)2(\gamma_4 Q)0$ suggested by Ikegami. The notation (γ_i), above, refers to the energy of the transition. The angular correlation measurements of Ikegami are not completely consistent with the assumption of pure multipoles. In several of his correlations, some $P_4(\cos\theta)$ terms appear which must be zero for the pure multipole assignments. However, we feel that not too much significance should be placed upon the very small errors Ikegami puts on the small $P_4(\cos\theta)$ coefficients, since several of his measurements are internally inconsistent if one interprets the errors literally.