Isomeric Transition in Sb^{122}†

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An investigation of the two previously reported gamma radiations (61 kev and 75 kev) of Sb^{122m} (3.5 min) revealed that the 75-kev transition has a K conversion coefficient which agrees with that of an $E2$ transition but a half-life in agreement with that of an $L=3$ transition. Delayed coincidence measurements disclosed a state with a 1.8-μsec half-life which is populated by the 75-kev transition. This decays through the emission of a 61-kev gamma ray. This transition exhibits a K conversion coefficient in agreement with that of an $E1$ transition although the lifetime is more compatible with an $L=2$ assignment. These transitions are delayed by factors of $\geq 10^6$.

INTRODUCTION

THE 3.5-min activity in Sb^{122} was first observed in 1947 by der Mateosian, Goldhaber, Muehlhause, and McKeown.[1] der Mateosian and Goldhaber[2] reported a 0.068-Mev gamma ray associated with this isomer and Kahn[3] reported the existence of a two-step transition, giving 0.059 and 0.074 Mev as the energies of the two transitions. This was confirmed by LeBlanc, Cork, and Burson,[4] who gave 0.0607 and 0.0753 Mev as their measured values.

GAMMA-RAY STUDIES

The gamma-ray spectrum of Sb^{122m} (3.5 min) was studied with a scintillation spectrometer and is shown in Fig. 1. Sources were prepared by irradiating samples[5] of Sb enriched in Sb^{121} in the Brookhaven reactor. A K x-ray peak (27 kev) and a peak composed of the partially resolved, unconverted 61- and 75-kev gamma rays are seen. A 58.8-kev gamma ray from the decay of Co^{60m} (10.47 min) which is also shown (slightly displaced in position), was used to construct the shape of the 61-kev peak so that the composite peak could be decomposed into its two components. From the areas under the two peaks the ratio of the unconverted 61-kev gamma ray to the unconverted 75-kev gamma ray was determined and found to be 2.9. The ratio of the K x-ray intensity relative to the sum of the intensities of the two unconverted gamma rays was also determined, 1.37 ± 0.1, after correcting for absorption and crystal efficiencies and multiplying by the fluorescent yield.[6] The ratio is taken to be equal to $e_K/(\gamma_1+\gamma_2)$ where e_K is the intensity of the K conversion electron, γ_1, γ_2 are the unconverted 61- and 75-kev gamma-ray intensities. Tables I and II show calculated values for these ratios as a function of the nature and multipolarity of the two transitions.

A search was made with an intense source of Sb^{122m} (3.5 min) for the cross-over gamma ray (136 kev). Only a long-lived background of Compton radiations due to higher energy gamma rays was seen in the 136-kev region. In order to set a low upper limit on this transition, a 3014-mg/cm² thick Cu absorber was used, reducing the intensity of the mixed 61 kev–75 kev peak

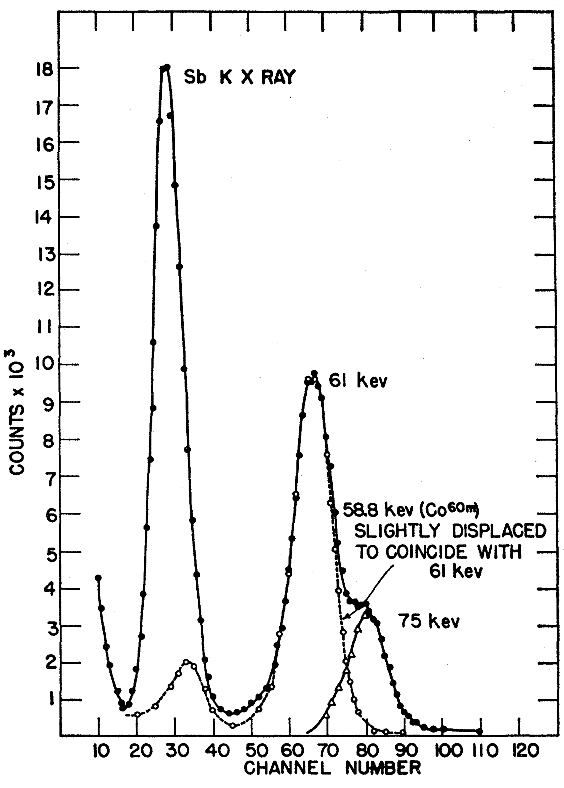

FIG. 1. Spectrum of gamma rays observed in the decay of Sb^{122m} (3.5 min) with a scintillation spectrometer. The detector was a 1×1 in. NaI(Tl) crystal. Two partially resolved unconverted gamma rays of 61- and 75-kev energies are seen as well as the K x ray of Sb. The 58.8-kev gamma ray of Co^{60m} (10.47 min) was also run and is shown slightly displaced in energy so that it coincides with the 61-kev peak. The shape of this gamma-ray peak was used to resolve the 61- and 75-kev gamma rays.

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[1] E. der Mateosian, M. Goldhaber, C. O. Muehlhause, and M. McKeown, Phys. Rev. **72**, 1271 (1947).

[2] E. der Mateosian and M. Goldhaber, Phys. Rev. **82**, 115 (1951).

[3] J. H. Kahn, Oak Ridge National Laboratory Report ORNL-1089, 1951 (unpublished).

[4] J. M. Le Blanc, J. M. Cork and S. B. Burson, Phys. Rev. **98**, 39 (1955).

[5] Obtained from Oak Ridge National Laboratory.

[6] A. H. Wapstra, G. J. Nijgh, and R. Van Lieshout, *Nuclear Spectroscopy Tables* (Interscience Publishers, Inc., New York), p. 81.

TABLE I. Ratio of unconverted 61-kev gamma ray to unconverted 75-kev gamma ray for various assumptions of multipolarity.

75 kev \ 61 kev	$E1$	$E2$	$M1$	$M2$
$E1$	0.81	0.14	0.41	0.036
$E2$	3.0	0.52	1.51	0.13
$E3$	39.1	6.8	19.7	1.7
$E4$	733	128	370	32.5
$M1$	1.34	0.23	0.67	0.06
$M2$	10.4	1.83	5.3	0.46
$M3$	106.6	18.6	53.8	4.7
$M4$	130.4	228	660	57.8

with which the 136-kev gamma ray was to be compared. Readings were repeated as a function of time and a 3.5-min component was sought for in the two energy regions that were compared. After subtracting the long-lived components from the 136-kev region, the residual counts were taken to be the upper limit to the crossover. Correcting for efficiencies of detection, absorption in copper, and the relative amounts of 61- and 75-kev gamma rays in the combined 61 kev–75 kev peak, the ratio of the unconverted 75-kev gamma ray to the 136-kev gamma ray was found to be 60. This implies that if the crossover is an $E3$, it is $>6\times10^4$ times slower than the Weisskopf estimate for a single-particle transition.

A search for high-energy gamma rays or beta rays from the 3.5-min level was unsuccessful, an upper limit of 0.5% being established. The apparent contradiction between half-life and conversion data might be resolved if the 3.5-min lifetime were associated with a third transition preceding the 75-kev transition. A search was made for soft gamma rays and electrons but no new gamma rays and no electrons of energies greater than 15 kev other than those associated with the 75- and 61-kev transitions were observed. Triple concidences between K and L x rays and gamma rays were performed with negative results. These results seem to rule out the possibility of a transition with an energy greater than 15 kev preceding the 75-kev transition.

COINCIDENCE STUDIES

Coincidence measurements were made with a conventional coincidence circuit of the fast-slow type having a resolving time of 0.24 μsec. Prompt $e^-{-}\gamma$ coincidences in Sn^{117m} (14 day) were used as a control to test the circuit. When $e^-{-}\gamma$ coincidences were observed in Sb^{122m} (3.5 min) a reduced efficiency ($\sim$0.1$\times$efficiency for prompt coincidences) was obtained. An oscilloscope triggered with electrons and displaying gamma rays of Sb^{122m} (3.5 min) showed delayed coincidences with a half-life of a few microseconds. Coincidences were counted as a function of delay time and the curve in Fig. 2 was observed. The 2.6-μsec half-life in Tm^{171} is shown for comparison. Sb^{122m} shows a half-life of 1.8$\pm$0.2 μsec. The curve in Fig. 2 was obtained by delaying the 75-kev gamma ray, indicating that the 75-kev transition precedes the 61-kev transition.

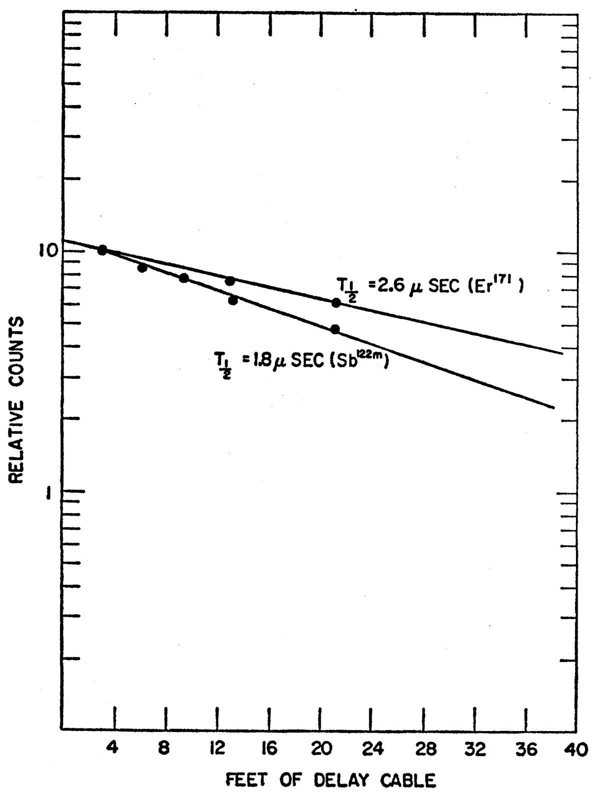

FIG. 2. Delayed coincidences in Sb^{122m} (3.5 min) as a function of time. HR 2000 cable was used to effect the delays. Each foot of cable is equivalent to 0.11 μsec. Er^{171} (7.8 hr) was run as a control showing the 2.6-μsec state which exists in Tm^{171}.

TABLE II. Ratio of K x-ray relative to total unconverted gamma rays (75 kev and 61 kev) for various assumptions of multipolarity.

75 kev \ 61 kev	$E1$	$E2$	$M1$	$M2$
$E1$	0.46	0.92	0.85	1.40
$E2$	1.14	3.48	2.33	5.88
$E3$	1.0	6.4	2.8	25
$M1$	0.85	1.9	1.52	2.77
$M2$	1.75	8.0	3.92	1.87
$M3$	1.66	10.48	4.1	44.5

Gamma-gamma delayed coincidences (75-kev γ ray delayed 0.4 μsec) were measured with a channel in the triggering input set first on the 75-kev gamma ray and then the 61-kev gamma ray. Figures 3 and 4 were obtained in this way. In Fig. 3, K x rays and the unconverted 61-kev gamma ray are seen in delayed coincidence with the 75-kev gamma ray triggering. Chance coincidence corrections were made both by following the single counts in each channel and computing the chances and also by delaying the 61-kev gamma ray instead of the 75-kev gamma ray and counting

coincidences for a length of time equivalent to the above runs. After making the proper corrections for chances, K x-ray fluorescence yield and absorption, the ratio of the area under the K x-ray peak relative to the area under the 61-kev peak was taken. This ratio is precisely α_K, the K conversion coefficient for the 61-kev gamma ray. The value obtained for this coefficient is 0.88 ± 0.10. Similarly, from Fig. 4, the K conversion coefficient for the 75-kev gamma rays was obtained and its value is 3.1 ± 0.5. These measured conversion coefficients are compared in Table III with calculated values taken from Rose.[7]

NEUTRON ACTIVATION CROSS SECTIONS

The thermal-neutron activation cross section of the Sb^{122m} 3.5-min isomer was measured by irradiating a sample of enriched Sb^{121} in the thermal column of the Brookhaven reactor and comparing the 3.5-min activity with the 2.8-day ground-state activity. The cross section for producing the 2.8-day activity was checked against that of a gold sample and a cross section of 6 b was obtained, essentially in agreement with the Seren, Friedlander, and Turkel[8] value of 6.8 b. The thermal neutron activation cross section of the Sb^{122m} 3.5-min isomer was calculated to be 0.057 ± 0.010 b on the assumption that the 75-kev γ ray is an $E2$ transition and the 61-kev, an $E1$ (see below). The isomeric ratio[9] ($\sim$105) is in agreement with the isomeric ratio rule.

TABLE III. K conversion coefficients of the 61-kev and 75-kev transitions of Sb^{122m} (3.5 min) for various assumptions of multipolarity.

Energy of gamma ray	61 kev		75 kev	
Nature of transition	Calculated value	Experimental value	Calculated value	Experimental value
		0.88 ± 0.10		3.1 ± 0.5
$E1$	0.62		0.344	
$E2$	5.00		2.69	
$E3$	30.00		16.4	
$E4$	...		96.7	
$M1$	2.10		1.15	
$M2$	30		13.6	
$M3$	270		113	
$M4$			862	

DISCUSSION

Experimentally determined values for the K-conversion coefficients of the 75- and 61-kev gamma rays, the intensity ratio of the unconverted 61- and 75-kev gamma rays, and the ratio of the K x-ray peak to the unconverted gamma ray peaks were compared in Tables I–III with theoretical values. All conversion

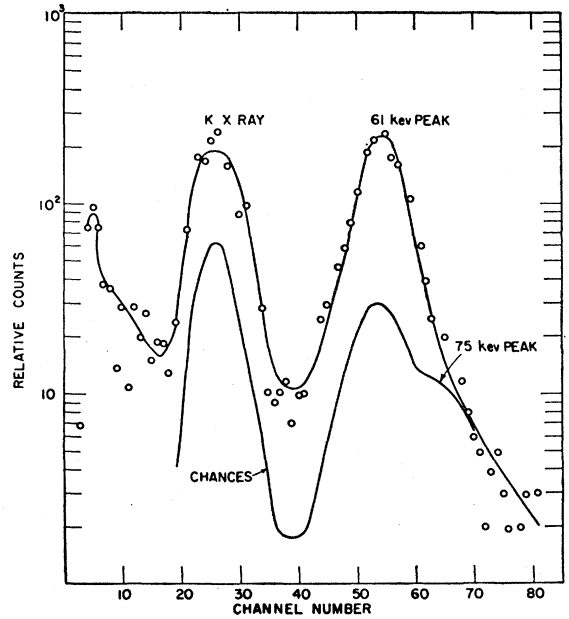

FIG. 3. Spectrum of gamma rays coinciding with the 75-kev gamma ray of Sb^{122m} (3.5 min) in delayed coincidence. A 0.4-μsec delay was used in the triggering channel, which was set on the 75-kev gamma-ray peak. Chance coincidences were determined both by counting singles and calculating the chance coincidences and by making a similar run with the 61-kev gamma ray delayed instead of the 75-kev.

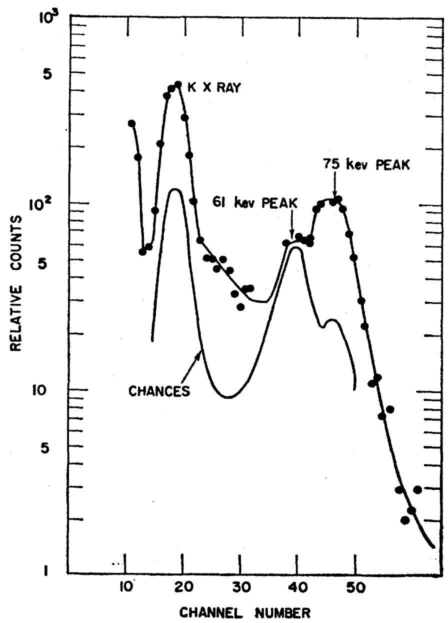

FIG. 4. Spectrum of gamma rays coinciding with the 61-kev gamma ray of Sb^{122m} (3.5 min). The triggering channel was set on the 61-kev peak of Sb^{122m} and the display channel was delayed 0.4 μsec. Chance coincidences were both calculated from the singles counts and determined experimentally by repeating the run with the delay in the 61-kev channel.

[7] M. E. Rose, *Internal Conversion Coefficients* (Interscience Publishers, Inc., New York, 1958).
[8] L. Seren, H. N. Friedlander, and S. H. Turkel, Phys. Rev. **72**, 888 (1947).
[9] E. Segrè and A. C. Helmholz, Revs. Modern Phys. **21**, 271 (1949); E. der Mateosian and M. Goldhaber, Phys. Rev. **108**, 766 (1957).

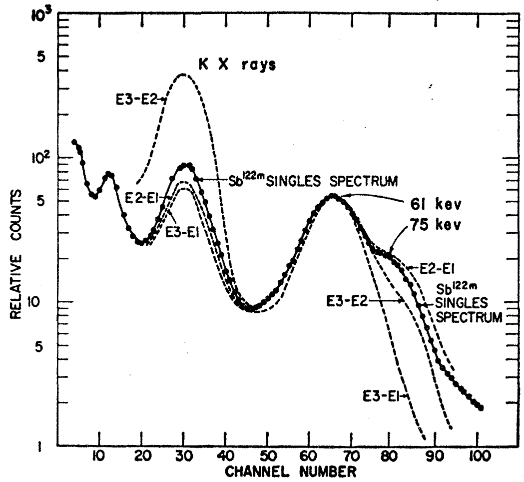

FIG. 5. Comparison of singles spectrum of Sb^{122m} (3.5 min) with constructed curves based on various assumptions of multipolarity for the two gamma-ray transitions involved. The best fit ($E2$-$E1$) for the 75- and 61-kev gamma rays is in agreement with conversion data.

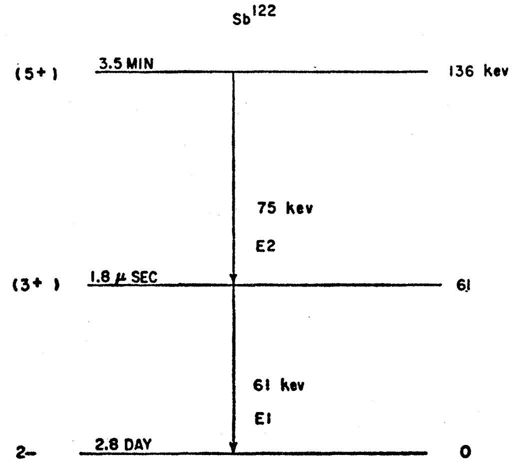

FIG. 6. Proposed decay scheme of Sb^{122m} (3.5 min).

data are in agreement with an $E2$ assignment to the 75-kev and an $E1$ assignment to the 61-kev transitions. These assignments, however, require that the transition from the second-excited state (3.5 min) be about 10^8 times retarded, and that from the first-excited state (1.8 μsec) be about 10^6 times retarded over the Weisskopf estimates. The 3.5-min half-life agrees with that expected for a spin change[10] of 3 and the 1.8-μsec half-life with that expected for a spin change of 2. In Fig. 5, constructed singles spectra for various assumptions for the multipolarities of the transitions are compared with a typical experimentally determined singles spectrum. The large K x-ray intensity required by the $E3$-$E2$ assignment for the multipolarities of the 75- and 61-kev gamma rays makes this assignment most unlikely.[11]

The decay scheme of Sb^{122m} is shown in Fig. 6. The ground-state spin has been measured[12]; the rest of the spins and parities have been assigned tentatively on the basis of the multipolarities derived from the conversion data.

All of the spins assigned to the levels in Sb^{122} are allowable spins on the basis of the shell model. Since the spins of the stable antimony isotopes, Sb^{121} and Sb^{123}, have been measured and are $\frac{5}{2}$ and $\frac{7}{2}$, one may assume that the odd proton has low-lying $d_{5/2}$ and $g_{7/2}$ states. In the Sn isotopes both experimental data[10] and theoretical calculations[13] suggest low-lying $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, $g_{7/2}$, and $h_{11/2}$ levels for the odd neutron. These nucleon configurations may combine in various ways to give the measured ground-state spin and the spins assigned to the excited level. Since the ground state (2−) has negative parity it must involve an $h_{11/2}$ state. A proton in a $g_{7/2}$ state and a neutron in an $h_{11/2}$ state could give the ground state ($g_{7/2}$,$h_{11/2}$). The first-excited state (3+) would be obtained if the neutron were in an $s_{1/2}$ state, the proton again in the $g_{7/2}$ state ($g_{7/2}$,$s_{1/2}$). The second-excited level (5+) may be a ($g_{7/2}$,$d_{3/2}$) or a ($d_{5/2}$,$d_{5/2}$) configuration. The last assignment might explain the delayed $E2$ transition since two nucleons would be involved in the transition. The following $E1$ transition would involve a neutron transition from an $s_{1/2}$ state to an $h_{11/2}$ state which should make the $E1$ transition highly forbidden.

ACKNOWLEDGMENTS

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[10] *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C.).

[11] Recently, C. J. Gallagher, Jr., and H. L. Nielson have reported a similar case in W^{183} (5.3 sec) [Nuclear Phys. **24**, 422 (1961)] of an isomer with an $M2$ conversion coefficient and an $E3$ lifetime. Whereas they may be able to explain the situation in W^{183} by ascribing the delayed transition to K forbiddenness, such an explanation is unlikely in Sb^{122}.

[12] P. C. B. Fernando, G. K. Rochester, and K. F. Smith, Phil. Mag. **5**, 1309 (1960).

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