Decay of Sb^{125}

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Eleven gamma rays between 0.100 and 0.637 Mev have been identified in the decay of Sb^{125}. From their relative intensities as measured with a sodium iodide crystal 3 inches in diameter and 3 inches high, and with the assistance of coincidence spectrometry, a decay scheme may be constructed which is consistent with all the data. The half-life for Sb^{125} was determined as 2.0 ± 0.2 years.

INTRODUCTION

DESPITE the fact that many investigators have studied the radiations from Sb^{125},[1] its complete decay scheme is still uncertain. Some features of the decay, however, are fairly well established. It is known, for example, that some of the beta transitions feed an isomeric level in the daughter whose half-life has been measured as 58 ± 4 days.[2] The work of Hill, Scharff-Goldhaber, and Friedlander,[2] Siegbahn and Forsling,[3] and Bowe and Axel[4] gave conclusive evidence for the existence of two cascading transitions of 0.110 and 0.035 Mev in the isomeric decay and the assignment $h_{11/2}-d_{3/2}-s_{1/2}$ was established for the three states involved.

The electron spectrum from the decay of Sb^{125} has been studied with magnetic spectrometers and found to be complex. Kern *et al.*[5] identified gamma rays of 0.110, 0.125, 0.174, 0.431, 0.466, 0.609, and 0.646 Mev and from an examination of the continuous beta spectrum obtained beta-ray transitions of 0.621 and 0.288 Mev. Further analysis was made difficult by the presence of the intense conversion lines. Siegbahn and Forsling[3] found evidence for gamma rays of 0.035, 0.175, 0.425, 0.465, 0.601, and 0.637 Mev and analyzed the beta spectrum into three groups with end points at 0.616, 0.299, and 0.128 Mev with intensities of 18%, 49%, and 33%, respectively. Both groups admitted to the possibility of other, weaker, beta groups, particularly at low energy.

More recently, coincidences between the gamma and beta rays have been obtained with scintillation spectrometers by Johansson[6] and by Moreau.[7] Unfortunately, their conclusions were contradictory, especially with respect to the location of the 0.175-Mev gamma ray. Thus, this work was projected in an attempt to find a consistent decay scheme for Sb^{125} with some hope of success in view of the statisfactory operation of the large crystal coincidence spectrometer for the solution of other complicated problems in the past.

EXPERIMENTAL TECHNIQUES

The Sb^{125} used in this work was obtained as the daughter activity of Sn^{125} which was made by neutron irradiation of tin. The Sb^{125} was separated by the Isotopes Division at ORNL in the spring of 1953. Spectra were obtained in October, 1954 and coincidence data were taken in April, 1955 and again in October, 1955, yielding essentially the same results. Sources were prepared by evaporating a drop of a solution of Sb_2Cl_3 on Scotch tape. Two cylindrical NaI(Tl) crystals 3 inches in diameter and 3 inches tall were used in the coincidence spectrometer. They were mounted with their axes at an angle of 90° and with at least a half-inch of lead placed between them to prevent Compton-scattered radiation from one crystal from entering the other and causing spurious peaks.[8] Additional lead shielding was used to absorb radiation which might scatter off one crystal and then again scatter off the table or supports for the crystal and be detected in the second crystal. Sources were mounted at the intersection of the axes of the crystals in such a way that the entire face of each detector was illuminated by the source. The standard fast-slow coincidence circuit was used with a single-channel analyzer in one channel and a multichannel analyzer to record the coincidence spectra.[9] As a check of the efficiency of the shielding, a sample of Be^7 was placed in the same geometry as was used in the Sb^{125} experiment, and the window in the single channel was set to include all of the spectrum from the 0.479-Mev gamma ray except the full-energy peak. The spectrum in coincidence with this window was determined and no counts were obtained in any part of the spectrum which could not be explained by random coincidences or cosmic-ray background.

SINGLE-CRYSTAL RESULTS

The pulse-height distribution obtained from a source of Sb^{125} placed on the axis of a crystal three inches in

[1] See Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953), for a complete listing of references on the early work with this nucleus.
[2] Hill, Scharff-Goldhaber, and Friedlander, Phys. Rev. **75**, 324 (1949).
[3] K. Siegbahn and W. Forsling, Arkiv Fysik **1**, 505 (1950).
[4] J. C. Bowe and P. Axel, Phys. Rev. **85**, 858 (1952).
[5] Kern, Mitchell, and Zaffarano, Phys. Rev. **76**, 94 (1949).
[6] S. A. E. Johansson, U. S. Atomic Energy Commission Report AECU-ISC 432, Dec. 7, 1953 (unpublished).
[7] J. Moreau, Arkiv Fysik **7**, 391 (1954).
[8] P. R. Bell, in *Beta and Gamma Ray Spectroscopy*, edited by K. Siegbahn (North Holland Publishing Company, Amsterdam, 1955).
[9] For a discussion of this arrangement, see N. H. Lazar and E. D. Klema, Phys. Rev. **98**, 710 (1955).

diameter and three inches tall, at a distance of 9.3 cm from the face of the cylinder, is shown in Fig. 1. Because of the change of pulse height of the three-inch photomultipliers with variations in counting rate,[10] energy calibration was obtained by placing the antimony sample together with two known radiations whose energies straddle an unknown peak and measuring their pulse height simultaneously. In this way, the energy of the gamma rays at 0.175 and 0.427 Mev were determined. From these values, the energies of other transitions were determined by interpolation or linear extrapolation. Satisfactory agreement was obtained between these values and magnetic measurements of electron conversion lines.

The intensities of some of the gamma rays in the decay were determined as a result of the analysis shown in Fig. 1. The full-energy peaks from single gamma rays have been observed in the past to be very nearly Gaussian in shape. Two peaks having this shape were found to fit the observed distribution in the region from 800 to 1100 pulse height. It is clear from the figure that one Gaussian having the proper width could not account for the entire observed peak in this region. The Compton distributions associated with these gamma rays were drawn in by using, as a guide for the shape, the pulse-height distribution obtained from the 0.661-Mev gamma ray from Cs^{137} placed in the same geometry. These curves were subtracted, point by point, from the observed spectrum and the resultant curve was then analyzed in a similar manner. Two peaks were found in the region from 600 to 800 pulse heights and were attributed to gamma rays of 0.427 and 0.463 Mev. Again, the Compton distribution was drawn in for these gamma rays to determine the intensity of the gamma rays at lower energy. For this purpose, the spectrum shape observed from the 0.479-Mev gamma ray in the decay of Be^7 was used as a guide. The shape of the curve in the region of the "back-scatter" peak (180° Compton scattering of the photon from the surroundings into the crystal) was taken literally because of the similarity in energies between the Cs^{137} and Be^7 gamma rays and those from Sb^{125}. In any event, the intensity of the 0.175-Mev gamma ray is the only one which would be greatly affected by this structure in the Compton distribution. By carrying out the appropriate subtractions, weak peaks were found at 0.377 and 0.113 Mev. The relative intensities of all gamma rays were then determined from the measured peak areas.

To calculate the intensities of some of the gamma rays, certain assumptions about the decay scheme of Sb^{125} were required to properly take into account possible coincident summing of cascading transitions. It was assumed that the 0.427- and 0.595-Mev gamma rays fed the level at 0.035 Mev and that their radiation could sum with the x-rays following the conversion of the low-energy transition. This summing was fairly small in any case, since the solid angle subtended by the crystal at the source was less than 5% of the total solid angle. The intensities which were determined, by making these assumptions and using the peak efficiencies measured at this laboratory for the crystal size and geometry used in this experiment, are shown in third column of Table I. The efficiencies are felt to be accurate to 5% and the uncertainties quoted are primarily due to the uncertainties in the analysis. As will be discussed below, all these gamma rays were found in coincidence with other transitions and the

TABLE I. Energies and relative intensities of gamma rays from Sb^{125}.

	Measured energy (Mev)	Relative intensity of γ-rays from single-crystal data	Relative intensity of γ rays from coincidence data
γ_1	0.637	0.23 ±0.02	
γ_2	0.595	0.88 ±0.09	
γ_3	0.463	0.31 ±0.03	
γ_4	0.427	1.0	
γ_5	0.377	0.038±0.008	
γ_6	0.320		0.0088±0.0020
γ_7	0.214		0.006 ±0.003
γ_8	0.205		0.008 ±0.002
γ_9	0.175	0.19 ±0.02	
γ_{10}	0.175		0.006 ±0.003
γ_{11}	0.113	0.014±0.007	

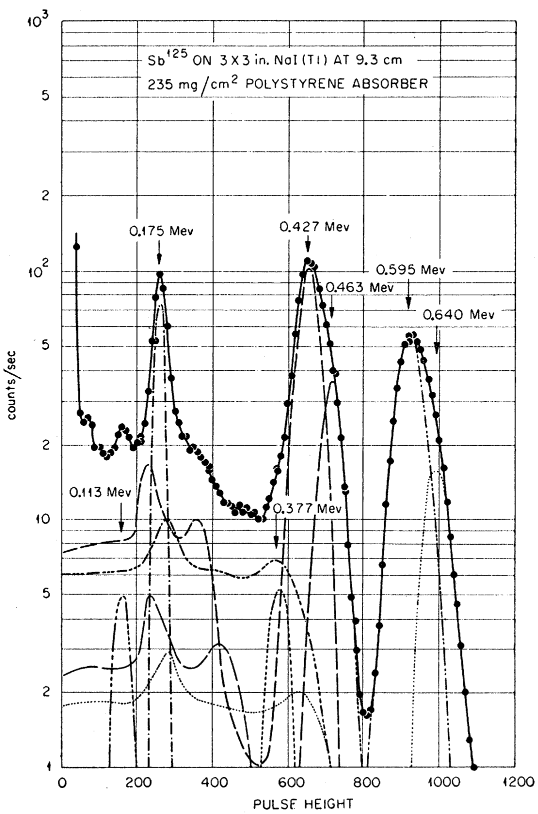

FIG. 1. Pulse-height spectrum from gamma rays from Sb^{125} on 3-in.×3-in. NaI(Tl) crystal.

[10] Bell, Davis, and Bernstein, Rev. Sci. Instr. **26**, 726 (1955).

reality of the weak gamma rays at 0.113 and 0.377 Mev was further established by those measurements.

A value for the half-life of Sb^{125} was obtained by measuring the area under the 0.595- and 0.637-Mev peaks in November, 1954 and again in November, 1955. The value obtained was 2.0 ± 0.2 years. The source, in both these measurements, was placed 9.3 cm from the face of the crystal. The assigned error of 10% is primarily due to the uncertainty in the solid geometry—especially because of the uncertainty in the radius of one of the two crystals used for the two measurements. More care was taken to determine the geometry during the later measurement and possibly a lower limit on the probable error may be made by further measurement at a later date. This value is somewhat lower than the one previously reported in the literature.[1]

COINCIDENCE RESULTS

Coincidences were recorded with all the prominent gamma rays selected individually in the single channel window. The results of some of these runs are shown in Figs. 2–5. Data were also taken in coincidence with the highest energy pair of gamma rays, and a counting rate equal to the random plus background rate in the region 0.1–0.3 Mev was obtained. Previous investigators have shown that x-rays are in coincidence with the 0.427- and 0.595-Mev transitions and this was confirmed.

The spectrum in coincidence with the window set over the 0.427- 0.463-Mev region yielded rather surprising results (see Fig. 2). Aside from coincidences with x-rays (not shown in Fig. 2), peaks at 0.113, 0.175, and 0.214 Mev are evident. To determine if these peaks might be caused by coincidences with weak gamma rays of very nearly the same energy as that of the 0.427- or 0.463-Mev transitions, the window was placed across the high-energy end of this pair of lines. This reduced the 0.113-Mev peak markedly but the 0.175- and 0.214-Mev peaks decreased in counting rate about as much as would be expected from the lower single rates. Moving the window to the lower-energy side of the 0.427-Mev peak enhanced the 0.113-Mev peak, but again the 0.175- and 0.214-Mev peaks were reduced only in the same ratio as the singles rates. It was concluded that the 0.113-Mev transition was in coincidence with a weaker gamma ray at somewhat lower energy while the 0.175- and 0.214-Mev transitions were both in coincidence with both the 0.427- and 0.463-Mev gamma rays.

Corroborative evidence for this conclusion was obtained by setting the window over the region of 0.113 Mev (Fig. 3). The peak at 0.37 ± 0.01 Mev definitely

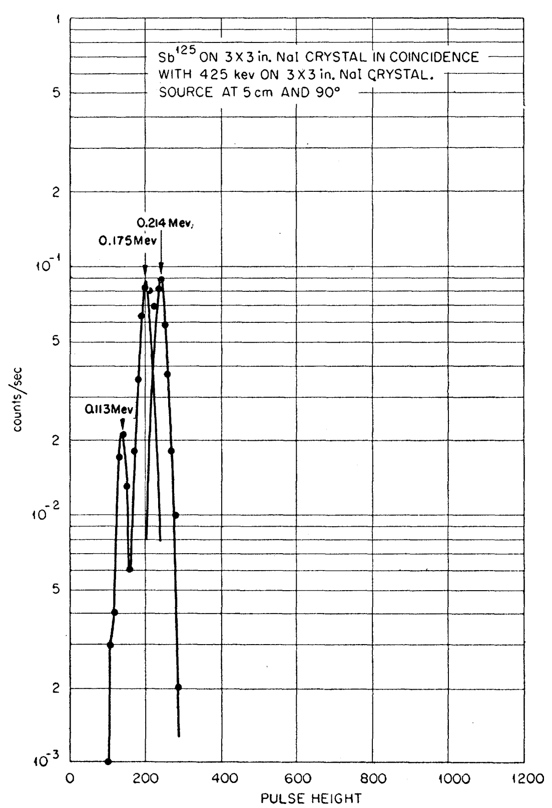

FIG. 2. Pulse-height spectrum from gamma rays from Sb^{125} in coincidence with single-channel window set at 425 kev.

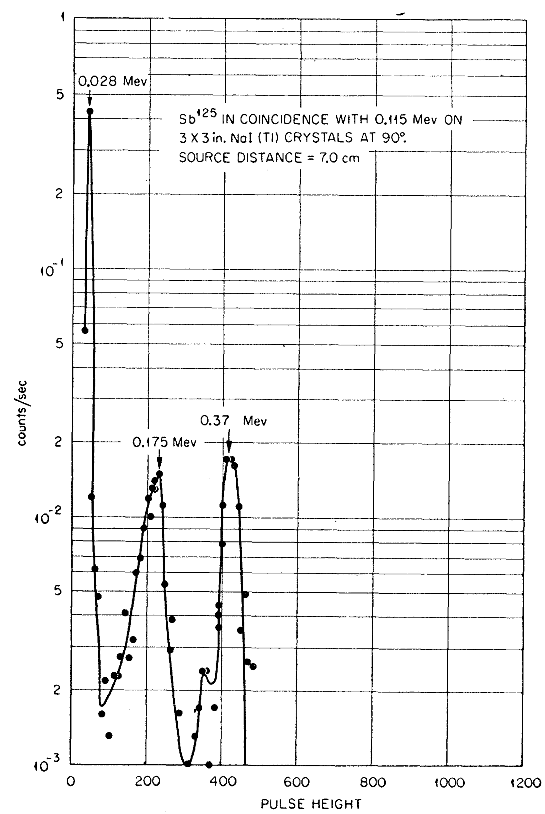

FIG. 3. Pulse-height spectrum from gamma rays from Sb^{125} in coincidence with single-channel window set at 115 kev.

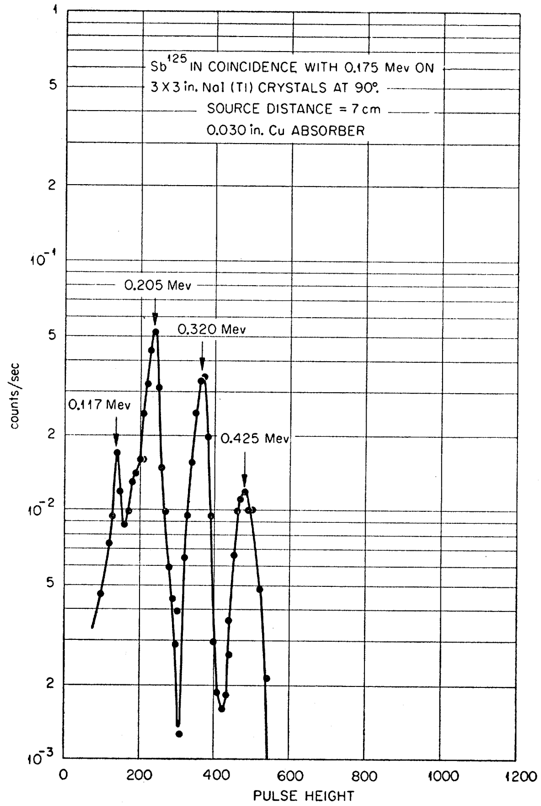

FIG. 4. Pulse-height spectrum from gamma rays from Sb^{125} in coincidence with single-channel window set at 175 kev.

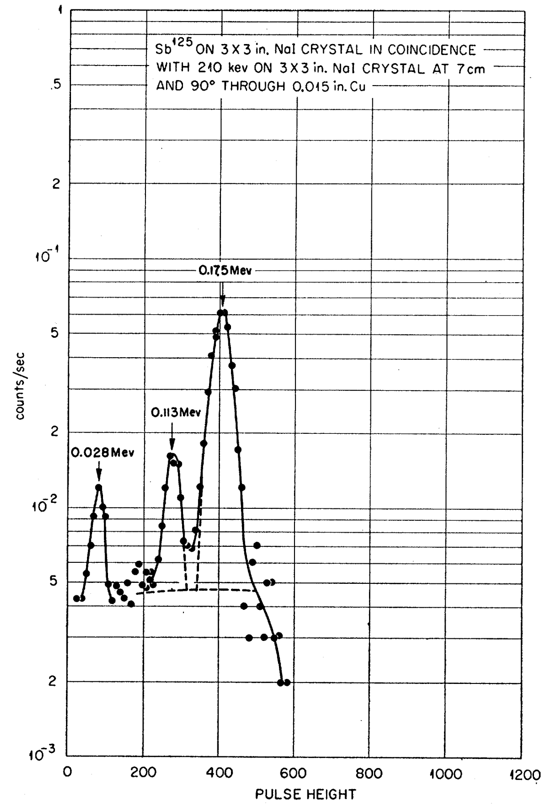

FIG. 5. Pulse-height spectrum from gamma rays from Sb^{125} in coincidence with single-channel window set at 210 kev.

established a 0.37–0.113-Mev cascade. The large asymmetrical peak at ~0.175 Mev indicates coincidences between the 0.113-Mev transition and at least two other gamma rays. These were confirmed by setting the window of the single-channel analyzer across the regions of 0.175 Mev and 0.220 Mev separately (Figs. 4 and 5). Coincidences with both regions showed peaks at ~0.113 Mev. Coincidences with the 0.175-Mev peak also gave evidence for a gamma ray of 0.320 Mev, as well as confirming the coincidences with the 0.427-Mev transition. In addition, the prominent peak at 0.205 Mev appeared. These latter coincidences were confirmed by the appearance of the 0.175-Mev peak in the spectrum coincident with a window set across the region of ~0.200 Mev.

If one sets the single-channel analyzer window across γ_2, the second gamma ray in a cascade, and determines $P(\gamma_1)$, the area under the peak obtained in coincidence with this gamma ray, one may determine the relative intensity of the two gamma rays from the equation

$$P(\gamma_1)=C_w(\gamma_2)\epsilon_{p1}\Omega_1 f,$$

where $C_w(\gamma_2)$ is the counting rate in the window due to γ_2, ϵ_{p1} and Ω_1 are the peak efficiency and solid angle for the counter detecting γ_1, and f is the intensity of γ_1 relative to γ_2. For example consider the 0.205–0.175-Mev cascade. $C_w(0.175)$ was determined from the "singles" rate in the single channel after subtracting a value obtained by extrapolating the Compton level due to the higher energy gamma rays back under the 0.175-Mev peak observed in the singles spectrum. Although there may be an uncertainty in this Compton level of as much as 20%, such an effect would cause an error of less than 10% in $C_w(0.175)$. Because of poor statistics the estimated over-all uncertainty in the relative intensity in this case is set at 25%. The figures in the last column of Table I were determined from this type of argument after normalization to the intensity of γ_4 using the relative intensities determined from the single-crystal data.

DISCUSSION

The decay scheme of Sb^{125} may now be constructed (Fig. 6). The two levels at 0.463 and 0.637 Mev may be deduced from the gamma rays having these energies. It is apparent, from x-ray coincidences, that the two gamma rays of 0.427 and 0.595 Mev originate at these states and cascade to the ground state through the 0.035-Mev level. The weak gamma ray (γ_{10}) of 0.175 Mev which was found in coincidence with the 0.427–0.463-Mev region is probably a transition between the 0.463- and 0.637-Mev states. But the intensity of γ_{10} is much too weak to account for the 0.175-Mev peak

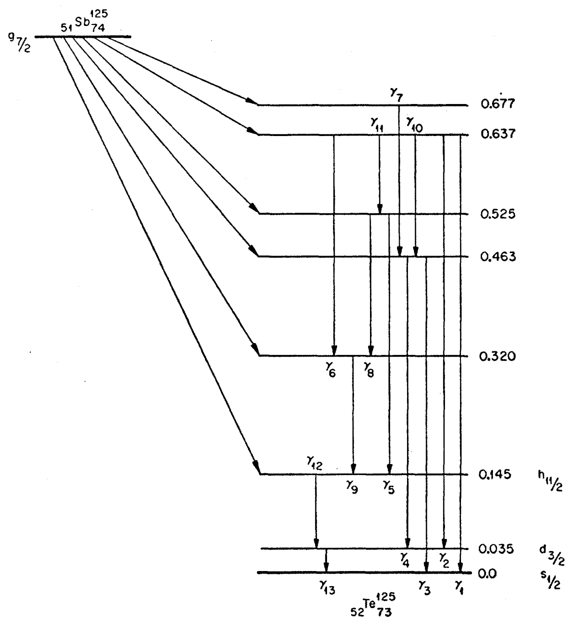

FIG. 6. Decay scheme of Sb^{125}. Level energies are in Mev. The gamma-ray energies are given in Table I.

observed in the single crystal spectrum (Fig. 1). Thus γ_9, a second gamma ray of 0.175 Mev, must be postulated and, since no other gamma rays are of comparable intensity, it must be fed primarily by beta transitions. There appears to be no peak with an energy less than 0.175 Mev by 0.035 Mev. One would expect to find such a transition, which would decay through the 0.035-Mev state, in analogy with γ_2 and γ_4, if γ_9 decays directly to the ground state. Thus, one must assume that there is a level at 0.320 Mev and that γ_9 feeds the isomeric 0.145-Mev state. This conclusion would agree with Moreau's[7] beta-gamma coincidence measurements. The existence of γ_6 in coincidence with γ_9 strengthens the argument for the existence of the 0.320-Mev state, since such a transition could logically be expected from the 0.637-Mev state. The gamma ray at 0.214-Mev (γ_7) found in coincidence with the region of 0.427–0.463 Mev seems to originate from a level at 0.677 Mev. However, a gamma ray similar in energy is found in coincidence with the 0.175-Mev region. Clearly, γ_7 cannot be in coincidence with γ_{10} since there isn't enough energy in the decay, nor can it be in coincidence with γ_3 and γ_4 and also with γ_9 if the above arguments are

TABLE II. Intensity of β-ray groups from Sb^{125} computed from γ-ray intensities. $\beta_{0.145}$ is assumed to have an intensity of 0.14.

Beta-ray group	Intensity	Log*ft*
$\beta_{0.145}$	0.14	9.3
$\beta_{0.320}$	0.055	9.4
$\beta_{0.463}$	0.42	7.8
$\beta_{0.525}$	0.012	9.2
$\beta_{0.637}$	0.37	6.7
$\beta_{0.677}$	0.0017	8.7

valid. Thus, a second gamma ray of this energy must be postulated. γ_8, in cascade with γ_9, defines a level at 0.525 Mev. There seems to be further confirmation for this level from the cascade of 0.113–0.377 Mev. γ_5 is not in coincidence with γ_9 and, from the absence of a gamma ray 0.035 Mev lower in energy, it appears to decay through the isomeric state. Simple addition indicates the 0.377-Mev gamma ray originates at the 0.525-Mev level and the 0.113-Mev transition occurs between the 0.637- and 0.525-Mev states.

One may now proceed to calculate β-ray intensities and comparative half-lives for all the transitions (Table II) using the new value for the half-life of 2.0 ± 0.2 years. In making the calculation, the internal conversion of the gamma rays were neglected since although the amount of conversion is not known, it should not affect, appreciably, the logarithm of the *ft* value. Unfortunately, spin and parity assignments based on these values and single-particle considerations are extremely tenuous since for nuclei in this region, it is almost certain that large configuration interactions occur and thus that transition probabilities may easily be orders of magnitude different from single-particle predictions. However, the ground state of Sb^{125} is probably predominantly a single-particle $g_{7/2}$ state since the odd proton is the 51st. If one believes the comparative half-lives enough to predict the order of forbiddenness, all the states except, possibly, the level at 0.637 Mev, would have even parity. The possibility of other selection rules applying, however, leaves even this statement open to question.

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