Measurement of γ and conversion electron spectra following the decay of ^{125}Sb

M. Sainath and K. Venkataramaniah
Department of Physics, Sri Sathya Sai Institute of Higher Learning, Prashanthinilayam 515134, India

P. C. Sood
Department of Physics, Banaras Hindu University, Varanasi-221005, India
and Department of Physics, Sri Sathya Sai Institute of Higher Learning, Prashanthinilayam 515134, India

(Received 24 December 1997; revised manuscript received 11 June 1998)

Relative intensities of γ rays and conversion electron lines in the decay of ^{125}Sb are measured precisely using an HPGe detector and a miniorange electron spectrometer. These data are used to derive the *K*- and *L*-shell internal conversion coefficients and to deduce the multipolarities of the respective transitions. A revised level scheme is presented for ^{125}Te incorporating 37 transitions between 13 energy levels up to an excitation energy of 675 keV. The newly established levels at 538 and 653 keV complete the hextuplet corresponding to the $(s_{1/2}\otimes 2^+)$ and $(d_{3/2}\otimes 2^+)$ phonon-coupled configurations. [S0556-2813(98)02111-6]

PACS number(s): 23.20.Lv, 23.20.Nx, 27.60.+j

The long-lived ($t_{1/2}=2.76$ yr) β-decaying source $^{125}_{51}$Sb$_{74}$ has been internationally adopted [1,2] as a γ energy and intensity standard for calibration of Ge detectors. Its decay product $^{125}_{52}$Te$_{73}$, has a near-magic proton structure and a half-filled 65–82 neutron configuration space. As such, the ^{125}Sb decay has been extensively studied over the past 50 years [3–14]. The level structures of ^{125}Te have also been investigated by a variety of other techniques [2,14], e.g., ^{125}I electron capture decay, Coulomb excitation, neutron capture, $(\alpha,xn\gamma)$, and particle-transfer reaction studies, etc. However, in spite of this extensive effort, several open questions still remain about the ^{125}Te level scheme. In particular, the possible existence of levels at 402 and 654 keV tentatively proposed in a number of decay studies [4–6,9] and an $l=0$ level around 538 keV indicated in transfer reactions studies [13], still remain to be confirmed. Attention has earlier been focused mainly on the relatively strong transitions in ^{125}Sb decay with a view to provide more precise γ energy and intensity standards. A search for the disputed levels requires specific attention to the weak transitions. The situation with respect to conversion electron measurements [4,6,7,12] also calls for more careful investigations, since earlier studies [7,12] reported significantly large uncertainties even for strong conversion lines. Our present study, using a 60cc HPGe detector for γ ray measurements and a miniorange electron spectrometer for conversion electron measurements, addresses itself to these questions.

The ^{125}Sb source was produced at BARC, Mumbai, by thermal neutron irradiation of ^{125}Sn. The carrier-free sample of ^{125}Sb was obtained in liquid form as antimony chloride in dilute HCl solution. The ^{125}Sb source was allowed to decay for about 8 months, mainly to achieve two purposes. (i) It purified the source of any short lived impurities and (ii) it allowed the $11/2^-$ 144 keV isomeric level in ^{125}Te, with a half life of 58 days, to be reasonably well populated. The latter step ensured that the 109 keV high-multipole ($M4$) transition could be appropriately investigated. The experimental setup and procedure are the same as described in our recent report on ^{147}Nd decay [15].

Our construction of the ^{125}Te level scheme using ^{125}Sb decay data involves two major inputs. Firstly, we apply the energy sum rule in different loops using precise transition energy measurements with the HPGe detector. Secondly, the conversion electron measurements are used to deduce the internal conversion coefficients (ICC's) in the *K* and *L* shells (and also *M* shell for the 109 keV $M4$ transition) and the multipolarities of various transitions. Well established [14] features of the ^{125}Te level scheme are used as a cross check within our procedure.

A portion of the typical γ spectra are shown in Fig. 1. A complete listing of the energies and the relative intensities of the 38 γ transitions, observed in our study, is given in Table I, in comparison with the intensities listed in the latest Nuclear Data Sheets NDS-93 [14]. In accordance with the usual convention, the γ intensities in Table I are quoted relative to the intense 427.88 keV (assumed $I_\gamma=100$) transition. We do not see the 146 keV transition reported in a number of earlier studies [8,10,14]. On the other hand, we observe 13 γ transitions not given in NDS-93; a few of these had earlier been tentatively suggested [4–6,9], but they do not appear in the evaluated data set in NDS-93. A careful comparison of

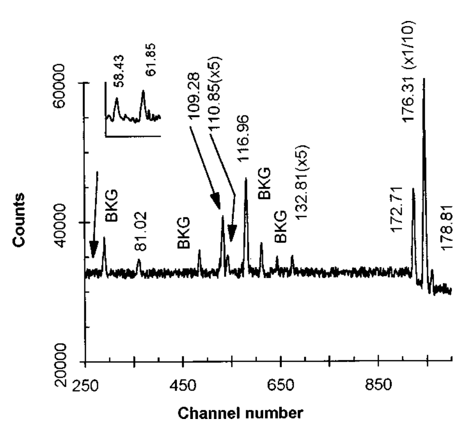

FIG. 1. A portion of the typical single γ-ray spectra observed following the β^- decay of ^{125}Sb recorded by a 60 cc HPGe detector. The peaks labeled BKG arise from other sources.

TABLE I. γ and conversion electron data for transitions observed in the ^{125}Sb decay studies. The successive columns from the left list the γ transition energies in ^{125}Te, relative γ intensities from NDS-93 [14] and present study (SVS), relative K- and L-conversion electron intensities, internal conversion coefficients α_K from NDS-93, and α_K and α_L from the present study, and our deduced multipolarity for the indicated transition.

E_γ (keV)	I_γ		I_{oe} (SVS)		JCC (α_K)		α_L	Multipolarity
	NDS-93	SVS	K	L	NDS-93	SVS	(SVS)	(SVS)
19.80(6)	0.068(2)	0.068(3)						
35.489(4)	14.5(4)	17.7(2)		2264(160)			1.4(1)	$M1+E2$[a]
58.43(5)[b]	0.091(4)	0.0042(20)						
61.85(16)		0.0068(27)						
81.02(4)		0.017(1)	0.70(15)			0.45(10)		$E1$
109.28(4)	0.274(9)	0.232(6)	3514(168)	2450(128)	169(7)	166(11)	116(8)	$M4$
110.85(9)	0.0036(2)	0.0039(3)	0.34(6)			0.96(19)		$(E1)$
116.956(10)	0.961(5)	0.945(15)	6.4(8)		0.074(9)	0.075(10)		$E1$
132.81(14)		0.0029(19)						
172.708(8)	0.67(4)	0.67(4)	5.5(8)		0.092(11)	0.091(14)		$M1+E2$
176.308(2)	23.05(8)	23.09(20)	297(15)	45(3)	0.129(10)	0.142(9)	0.021(2)	$M1+E2$
178.814(7)	0.097(8)	0.121(2)	1.3(2)		0.24(6)	0.12(2)		$M1+E2$
198.631(14)	0.046(5)	0.044(3)						
204.144(8)	1.102(8)	1.014(10)	9.7(6)		0.081(6)	0.105(8)		$M1+E2$
208.074(10)	0.814(11)	0.860(10)	6.1(4)		0.092(5)	0.078(6)		$M1+E2$
209.32(9)		0.152(9)						
227.876(10)	0.440(7)	0.442(9)	4.0(2)		0.086(14)	0.099(7)		$M1+E2$
314.99(11)	0.0132(14)	0.0144(15)	0.051(9)			0.039(8)		$(E1)$
321.101(2)	1.387(9)	1.43(2)	1.34(8)		0.011(3)	0.0103(7)		$E1$
331.82(6)		0.0085(8)						
366.56(11)		0.027(2)						
380.454(8)	5.12(4)	5.17(4)	6.5(3)	0.92(7)	0.0138(8)	0.0138(8)	0.00196(7)	$E2$
401.95(12)		0.021(2)						
408.069(12)	0.621(10)	0.624(7)	0.92(6)		0.0107(19)	0.0164(11)		$M1+E2$
427.880(5)	100	100	100	15.6(6)	0.0111(18)	0.0111(4)	0.00172(9)	$M1+E2$
443.565(7)	1.019(11)	1.051(11)	0.99(7)		0.014(7)	0.0104(9)		$M1+E2$
463.368(4)	35.45(5)	35.12(18)	26.9(10)	3.7(2)	0.0086(4)	0.0084(4)	0.00116(7)	$E2$
489.73(8)		0.0046(23)						
491.29(14)		0.016(8)						
497.41(14)	0.029(13)	0.009(1)						
503.10(6)		0.013(6)						
538.62(12)		0.0047(25)						
600.589(3)	60.35(17)	59.22(18)	22.2(10)	3.1(2)	0.00425(10)	0.0042(2)	0.00058(4)	$E2$
606.700(2)	16.98(7)	16.92(6)	5.8(3)	1.00(8)	0.0037(3)	0.0038(2)	0.00065(6)	$E2$
617.40(14)		0.018(2)						
635.951(3)	38.2(3)	38.32(12)	14.6(7)	2.02(13)	0.0042(2)	0.0042(3)	0.00058(4)	$M1+E2$
652.8(4)		0.009(3)						
671.445(6)	6.06(2)	6.03(2)	1.82(10)		0.0032(3)	0.0033(2)		$E2$

[a]Deduced from α_L value.
[b]Not placed in the level scheme.

our γ energies and their relative intensities for the eight intense γ rays, adopted as a ''benchmark'' for IAEA-95 standardization, with the earlier precise measurements [1,2,14] reveals almost exact agreement, with deviations comparable to the assigned uncertainties. This observation supports the use of ^{125}Sb as a γ-ray energy and intensity standard. It further establishes the desired precision of our energy measurements for reliable application of the energy-sum rule for level placements.

Conversion electron intensities for the K and L shells and the corresponding internal conversion coefficients α's, are also listed in Table I along with the α_K values from NDS-93. We employ the normalized-peak-to-gamma method for determining the conversion coefficients, using the 427.88 keV transition as the standard for normalization with the adopted value of $\alpha_K(427)=0.0111(4)$ and its $M1$-$E2$ mixing ratio of $|\delta|=0.538(11)$ [14]. The multipolarity of each transition is then deduced from a comparison of our α_K values (α_L value for the 35.5 keV transition) with the theoretical predictions for possible multipole transitions interpolated from the

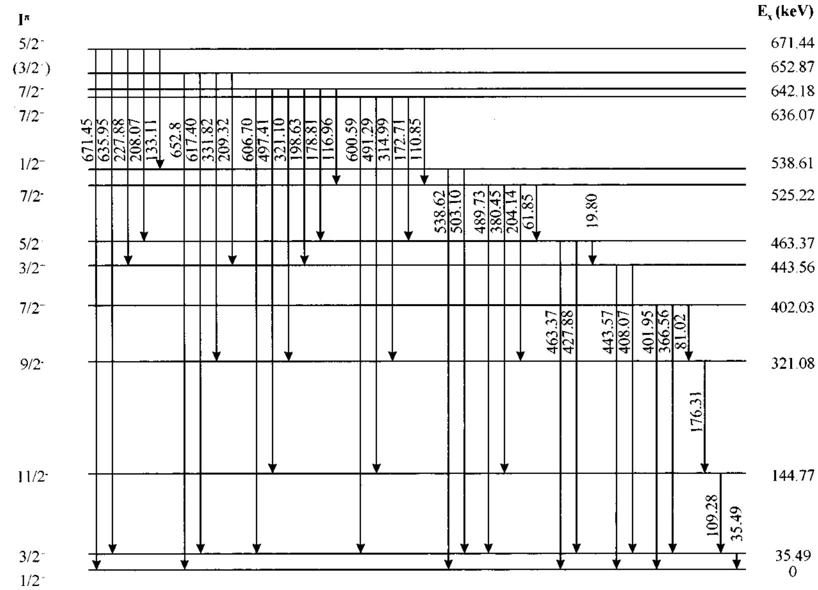

FIG. 2. Level scheme of ^{125}Te deduced from the γ and conversion electron spectra measurement following ^{125}Sb beta decay. The labeling on the left is that of the level spin and its parity, while that on the right is level energy (in keV) deduced from the transition energies listed in Table I and the energy sum rule at each level.

tables of Hager and Seltzer [16]. We not only observe distinct 109 keV K and L lines but the M line is also clearly seen in our electron spectrum. Our value of $\alpha_M = 22.4(18)$ compares well with the theoretical value of 24 for an $M4$ transition from Hager and Seltzer tables [16].

Our level scheme of ^{125}Te, incorporating 37 γ transitions, is shown in Fig. 2; in common with NDS-93, the 58 keV γ is not placed in this level scheme. All seven positive-parity and three negative-parity levels in the adopted set of NDS-93 appear in our level scheme with the spin-parity and energy agreeing in each case. In addition, our level scheme introduces three other levels at 402.03, 538.61, and 652.87 keV, as discussed below, with 10, out of the 13, new γ pertaining to these levels. Further, we deduce $E1$ multipolarity for three transitions (81, 111, and 315 keV) which were assigned no multipolarity earlier.

Level systematics of the neighboring odd-A Te isotopes, and various theoretical predictions [8,17–19] suggest a low-lying $1/2^+$ level in ^{125}Te. Estimating its location around 560 keV, Walters and Meyer [8] searched this neighborhood without success. Later, the single-particle transfer reaction studies of Rodland *et al.* [13] indicated a tentative $l=0$ peak at (538 ± 5) keV in the ^{126}Te (d,t) spectrum. Accordingly, we focused our attention on this proposal and were thus led to place (see Fig. 2) the three newly observed γ with energies 132.81, 503.10, and 538.62 keV, respectively as the decay γ from the 671.44 keV $5/2^+$ level and the decay γ from the newly introduced 538.6 keV levels to the 35.49 keV $3/2^+$ and the $1/2^+$ ground levels. The three energy loops yield its energy as 538.61(2) keV. Our data supports the $I^\pi = 1/2^+$ assignment suggested for this level in the (d,t) reaction study [13]. Next we looked for a level in ^{125}Te in the vicinity of 652 keV suggested in some early studies [4,6]. The four newly observed γ with energies of 652.8, 617.40, 331.82, and 209.32 keV are placed in our level scheme of Fig. 2 as decay transitions from the newly introduced level at 652.87 keV, respectively, to the $1/2^+$ ground state, 35.49 keV $3/2^+$, 321.07 keV $9/2^-$, and 443.56 keV $3/2^+$ levels. All four energy loops add up to the same summed energy, justifying their placement. However, none of these transitions could be assigned a specific multipolarity in the absence of any conversion line seen in our experiment. Thus, the spin-parity assignment for this level may be $3/2^+$ or $5/2^+$; level systematics in neighboring isotopes and theoretical considerations discussed later support a $3/2^+$ assignment.

Following an earlier suggestion by Chandra and Pandharipande [5], Prasad [9] introduced a level at 402 keV in ^{125}Te with the 81, 366, and 402 keV decay transitions, respectively, to the 321 keV $(9/2^-)$, 35.5 keV $(3/2^+)$, and the ground state $(1/2^+)$ levels. None of these transitions have since been confirmed, nor do they appear in the NDS-93 adopted γ's. Our careful investigation of weak transitions identifies all the three γ rays. Our energy sum-rule approach then places this level at 402.03 keV with these three decay γ's. Our evaluation of $\alpha(K)$ for the observed K-conversion line for the 81 keV transition leads to an $E1$ character for it and a possible $I^\pi = 7/2^+$ assignment for the 402 keV level.

The low-lying structures in odd-A Te isotopes involve the $s_{1/2}$, $d_{3/2}$, $h_{11/2}$ particle states, the $g_{7/2}$ and $d_{5/2}$ hole states, and the states arising from the quasiparticle-phonon coupling (QPC) [8,17–19]. In the QPC picture, the 2_1^+ state in the even-mass neighbor is taken as the quadrupole phonon which couples to the $s_{1/2}$ and $d_{3/2}$ quasiparticles, leading to a doublet $(s_{1/2}\otimes 2^+)_{3/2^+,5/2^+}$ and a quartet $(d_{3/2}\otimes 2^+)_{1/2^+,3/2^+,5/2^+,7/2^+}$. The lowest $1/2^+$ and $3/2^+$ states in ^{125}Te are primarily the $s_{1/2}$ and $d_{3/2}$ states. The two $5/2^+$ states at 463 and 671 keV were interpreted [8] to have nearly equal mixing of the two QPC $5/2^+$ structures, while the 636 keV $7/2^+$ and the 642 keV $7/2^+$ were characterized [8] as mainly the QPC $7/2^+$ structure and the $g_{7/2}$ hole configuration, respectively. The other two members, namely $1/2^+$ and $3/2^+$, of the QPC hextuplet had not been identified earlier; our investigations suggest the identification of the 539 keV

$1/2^+$ and the 653 keV $(3/2^+)$ as these two missing states. Our data suggest mixing of the two $3/2^+$ QPC states at 653 and 444 keV, similar to that concluded earlier for the corresponding $5/2^+$ states. The newly added 133 keV γ ray, interconnecting the 671.4 keV $5/2^+$ and 538.6 keV $1/2^+$ states, supports their QPC multiplet inter-relationship. Our data are consistent with the recent QPC model calculations [18,19]. The 402 keV $7/2^+$ level does not fit in the QPC picture. It is also not easily identifiable with the 490 keV $7/2^+$ isomeric level in ^{123}Te. The interacting boson-fermion model (IBFM) calculations by Fawwaz and Stewart [11] place the $7/2^+$ level of the IBFM ground band around this energy. An appropriate characterization of this low-lying $7/2^+$ level is presently an open question.

For the negative parity states, the only available single-particle orbital $h_{11/2}$ is identified with the 144.8 keV 57.4*d* isomer in ^{125}Te. Whereas the higher spin-$15/2^-$ state at 804 keV (not shown here) is seen [8,17] as the QPC $(h_{11/2} \otimes 2^+)_{15/2^-}$ state, the low-lying 321 keV $9/2^-$ and 525 keV $7/2^-$ states cannot be fitted into this simple picture. The low-lying $9/2^-$ state may be viewed as the intruder three-quasiparticle $(h_{11/2})^3$ state and the $7/2^-$ may correspond to five holes in the $h_{11/2}$ shell. Alternatively, Bondarenko *et al.* [20] have recently described these low-lying $9/2^-$ and $7/2^-$ states in ^{123}Te and Te^{125} as the anomalously descended ''antialigned'' states arising from the $h_{11/2}$ neutron orbital coupled to the weakly deformed even-even core.

It is expected that the presently reported more extensive γ ray and conversion electron data and the revised low-energy level scheme of ^{125}Te, taken together with the results from reaction studies, provide a better data base for understanding the level structures in transitional nuclei.

Valuable help from B. Singh during the course of these investigations is gratefully acknowledged.

[1] ''*X-ray and Gamma-Ray Standards for Detector Calibration,*'' Report No. IAEA-TECDOC-619, (1991).
[2] *Table of Isotopes*, 8th ed., edited by R. B. Firestone and V. S. Shirley (Wiley, New York, 1996).
[3] G. Friedlander, M. Goldhaber, and G. Scharff-Goldhaber, Phys. Rev. **74**, 981 (1948).
[4] R. S. Narcisi, A.E.C.U. Report 4336 (1958).
[5] G. Chandra and V. R. Pandharipande, Nucl. Phys. **46**, 119 (1963).
[6] K. C. Mann, F. A. Payne, and R. P. Chaturvedi, Can. J. Phys. **42**, 1700 (1964).
[7] E. P. Mazets and Y. V. Sergeenkov, Izv. Akad. Nauk SSSR, Ser. Fiz. **30**, 1185 (1966); Bull. Acad. Sci. USSR, Phys. Ser. **30**, 1237 (1967).
[8] W. B. Walters and R. A. Meyer, Phys. Rev. C **14**, 1925 (1976).
[9] R. Prasad, Czech. J. Phys., Sect. B **29**, 737 (1979).
[10] L. Longoria-Gandara, M. U. Rajput, and T. D. MacMahon, Nucl. Instrum. Methods Phys. Res. A **286**, 529 (1990), and references therein.
[11] N. I. Fawwaz and N. M. Stewart, J. Phys. G **19**, 113 (1993).
[12] J. Goswamy, B. Chand, D. Mehta, N. Singh, and P. N. Trehan, Appl. Radiat. Isot. **42**, 1025 (1991).
[13] T. Rodland, J. R. Lien, J. S. Vaagen, G. Lovhoiden, and C. Ellegaard, Phys. Scr. **29**, 529 (1984).
[14] J. Katakura, M. Oshima, K. Kitao, and H. Iimura, Nucl. Data Sheets **70**, 217 (1993).
[15] M. Sainath, K. Venkataramaniah, and P. C. Sood, Phys. Rev. C **56**, 2468 (1997).
[16] R. S. Hager and E. C. Seltzer, Nucl. Data Sheets **4**, 1 (1968).
[17] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. **35**, 74 (1963).
[18] H. Dias and L. Losano, Phys. Rev. C **50**, 1377 (1994).
[19] C. A. P. Ceneviva, L. Losano, and H. Dias, Int. J. Mod. Phys. E **4**, 419 (1995).
[20] V. Bondarenko, J. Honzatko, and I. Tomandl, Z. Phys. A **354**, 235 (1996).