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Isotope shift studies in UV lines of Sm I on FTS: level isotope shifts and configuration assignments of the energy levels of neutral samarium atom

B.K. Ankush[1,a], M.N. Deo[2,b], A. Venugopalan[1,c], and S.A. Ahmad[1,d]

[1] Spectroscopy Division, Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India
[2] Synchrotron Radiation Section, BARC, Trombay, Mumbai-85, India

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Abstract. Isotope shifts $\Delta\sigma^{148,154}$ in 200 spectral lines of neutral samarium atom (Sm I) in the region of 355−455 nm (28160−21970 cm^{-1}) have been measured using a Fourier Transform Spectrometer. Isotope shift data in 187 spectral lines of Sm I are being reported for the first time. Level isotope shifts, $\Delta T^{148,154}$ of 119 high odd- and 7 low even-parity energy levels have been evaluated using present isotope shift data combined with the earlier available data. These $\Delta T^{148,154}$ values have enabled us to check the assignments to $4f^6 6s6p$ and $4f^5 5d6s^2$ configurations of the odd-parity levels made earlier on the basis of parametric calculations. For several levels, the reported compositions of the mixed configuration of type [$4f^5(^6\mathrm{H}^0, {}^6\mathrm{F}^0)$ $5d6s^2 + 4f^6(^7\mathrm{F})$ $6s6p(^3\mathrm{P}^0)$] have been interpreted with the help of our $\Delta T^{148,154}$ values. 20 unassigned energy levels have been uniquely assigned to $4f^5 5d6s^2$ configuration. The present study provides $\Delta T^{148,154}$ values of the levels, which were tentatively assigned to $4f^5 5d^2 6s$ and $4f^6 5d6p$ configurations. We could also identify $4f^6 5d6p$ configuration for 12 unassigned levels.

PACS. 31.30.Gs Hyperfine interactions and isotope effects, Jahn-Teller effect

1 Introduction

The studies of spectrum of neutral samarium atom (Sm I) by Albertson [1], Carlier et al. [2], Blaise et al. [3] and Henny-Schweighofer [4] have resulted in the identification of 65 even-parity and 404 odd-parity energy levels; these have been compiled by Martin et al. [5]. The identified even-parity configurations are $4f^6 6s^2$, $4f^6 5d6s$ and $4f^6 6s7s$ and the odd configurations identified are $4f^5 5d6s^2$ and $4f^6 6s6p$; a few levels have been tentatively assigned to $4f^5 5d^2 6s$ and $4f^6 5d6p$ configurations [5]. The leading percentage of the ^{7}F levels of the ground $4f^6 6s^2$ configuration is listed by Martin et al. [5]. The compositions for the odd-parity configurations [$4f^5(^6\mathrm{H}^0, {}^6\mathrm{F}^0)$ $5d6s^2 + 4f^6(^7\mathrm{F})$ $6s6p(^3\mathrm{P}^0)$] were calculated by Carlier et al. [2] and are given in [5]. Carlier [6] also gave the compositions for the energy levels assigned to $4f^6(^7\mathrm{F})$ $5d6s$ and $4f^6(^7\mathrm{F})$ $6s7s$ configurations and their leading percentages are given in [5]. For some of the known odd-parity energy levels, there are tentative designations to $4f^5 5d^2 6s$ and $4f^6 5d6p$ configurations as no complete calculation exists for these configurations. The status of the configuration assignment to the known even- and odd-parity energy levels of Sm I is summarized in Table 1 which shows that about 60 percent of the known odd-parity levels are without configuration assignment [5].

Table 1. Status of configuration assignment to the known energy levels of Sm I [5].

Parity	No. of levels	Configuration assignment
	7	$4f^6 6s^2$
	3	$4f^6 6s^2$(?)
Even	40	$4f^6 5d6s$
(65 known levels)	15	$4f^6 6s7s$
	75	$4f^6 6s6p$
	53	$4f^5 5d6s^2$
Odd	9	$4f^5 5d^2 6s$(?)
(404 known levels)	9	$4f^6 5d6p$(?)
	258	Unassigned

The classified lines of Sm I are listed in Schweighofer's thesis [4] and in NBS Table [7]. Schweighofer [4] has listed more than 5000 lines of Sm I and Sm II between 262.8 and 978.9 nm with about seventy five percent of the lines provided with the energy level classification. Blaise et al. [3] list 1812 lines between 818.6 and 2455.8 nm with 859 lines

[a] e-mail: bkankush@magnum.barc.ernet.in
[b] e-mail: mndeo@vsnl.com
[c] e-mail: avenu@apsara.barc.ernet.in
[d] e-mail: saahmad@vsnl.com

classified. Morillon [8] has reported 370 lines of samarium between 2382.0 and 4106.1 nm.

Worden et al. [9] observed high members of a series in Sm I using laser photoionisation technique. Recently Jayasekharan et al. [10] have discovered hundreds of even-parity energy levels in the region 34850−45300 cm^{-1} using two-step photoexcitation and photoionization method. These energy levels are not classified and are not relevant to the present study and hence are not included in Table 1.

Isotope shift (IS) studies in the spectrum of samarium have been very fascinating and has led to some new concepts in atomic interactions (see King [11]). The J-dependence of IS in the ground term of Sm I was studied by Bauche et al. [12]. Brandt et al. [13] measured IS between all the stable isotopes of Sm in a few transitions and evaluated relative changes in nuclear mean square charge radii $\delta\langle r^2\rangle$. Griffith et al. [14,15] studied optical IS using tunable dye laser heterodyne spectroscopy in 8 spectral lines of Sm I and anomalies in the optical IS for two spectral lines were reported which were explained as due to the upper level at 19174 cm^{-1} mixed with the level at 19192 cm^{-1}. Kronfeldt et al. [16] tested the applicability of parametric description of the IS to the lanthanides and concluded that the $4f^n6s^2$ (Nd, Sm, Dy and Er) configurations were suitable candidates for investigations. England et al. studied [17] IS and hyperfine structure (hfs) in Sm isotopes in the mass range of 144−154 and evaluated the magnetic dipole (μ) and electric quadrupole (Q) moment of the odd-isotopes and $\delta\langle r^2\rangle$ of the even ones which were found to be consistent with the information obtained from nuclear spectroscopy. Wakasugi et al. [18] evaluated values of $\delta\langle r^2\rangle$ for natural even-even isotopes of Sm and analysed the data using the Fermi distribution of the nuclear charge density. Jin et al. [19] measured IS and hfs of 12 transitions from the high lying metastable $^9\mathrm{H}_J$ states of the $4f^65d6s$ configuration in Sm I and studied the J-dependence of the IS and z_{5d}/λ was calculated. IS studies in spectral lines of Sm I using diode-laser based Doppler-free spectroscopy was carried out by Park et al. [20]. Wilson [21] carried out Hartree-Fock calculations of the s-electron density at the nucleus, $|\psi(0)|^2_{6s}$ for a few selected electronic configurations of Sm I which were chosen for their interest in interpreting the observed isotope and isomer shifts. Theoretical screening ratios and core relaxation effects were also discussed by him and compared with those derived by experimental means.

As can be seen from Table 1, so far only two odd-parity configurations, $4f^66s6p$ and $4f^55d6s^2$ are confirmed by theoretical calculations [2,6] whereas 9 odd-parity energy levels of $^9\mathrm{I}^0$? multiplet each, are tentatively assigned to $4f^55d^26s$(?) and $4f^65d6p$(?) configurations [5]. Out of 404 odd-parity levels known 258 levels have no configuration assignment. Actually between 28000 cm^{-1} and 35200 cm^{-1} there are 220 odd-parity levels known and only 4 of them have been assigned to $4f^55d6s^2$ configuration [5].

The present studies of IS in the spectral lines of Sm I in UV region have been taken up with the objectives of evaluating term IS, $\Delta T^{148,154}$ of the high odd-parity energy levels of Sm I, and to use these $\Delta T^{148,154}$ values for confirming the assignment of these levels, to check the theoretical configuration composition of a level wherever it is available, and to suggest possible electronic configurations to unassigned levels. $\Delta T^{148,154}$ values of certain odd-parity levels also could be used to interpret their assignments to $4f^55d^26s$ and $4f^65d6p$ configurations.

2 Experimental

In the present investigations, IS, $\Delta\sigma^{148,154}$ have been recorded on a Bomem DA8 Fourier Transform Spectrometer (FTS), using Quartz beam splitter and photomultiplier detector. The spectra were recorded by co-addition of 44 scans (~1 hour integration time) to get good signal-to-noise ratio. Measurements were performed in 200 spectral lines in the ultraviolet (UV) region of 355−455 nm (21970−28160 cm^{-1}). Light source was a liquid nitrogen cooled all-metal hollow cathode discharge lamp with the cathode coated with a mixture of the oxides of highly enriched isotopes ^{148}Sm (95.4%) and ^{154}Sm (99.2%) in 7:10 ratio. The discharge was run at 35 mA current with Ne at 2.5 torr as the carrier gas.

Measurement of the isotope shifts has been carried out using the Origin 6.0 computer program. For lines with low intensity, we have applied the Savitzky-Golay smoothing technique by selecting data points on both sides of the peak. Following points have been taken into account while analyzing the data, (a) centre of gravity of the IS pattern, (b) full width at half maximum of the profile and (c) intensities of the individual components.

The largest positive IS in Sm I ($\Delta\sigma^{148,154} = 245.5$ mK) has been observed in the line at 435.583 nm (Fig. 1), which is classified as transition from $4f^55d6s^2$ to $4f^66s^2$ configuration. The IS of $\Delta\sigma^{148,154} = -78.9$ mK in the line at 388.399 nm a transition from $4f^65d6p$ to $4f^66s^2$ configuration is shown in Figure 2.

3 Results and discussions

3.1 Isotope shift in UV lines of Sm I in 355−455 nm region

The UV lines of Sm I in which IS, $\Delta\sigma^{148,154}$ have been measured in the present study are listed in Table 2. The wavelengths of the spectral lines in units of nm, are given in column 1, energy level classifications in column 2, and the measured values of IS, $\Delta\sigma^{148,154}$ are listed in column 3, in units of mK. The wavelengths and the energy level classifications are taken from Schweighofer's thesis [4] where enriched ^{152}Sm (99.18%) was used for recording the spectrum. The accuracy of measurement in strong lines with $\Delta\sigma \geq 80$ mK is about ±3 mK whereas for weak lines with $\Delta\sigma \leq 80$ mK, it is about ±5 mK and $\Delta\sigma \leq 30$ mK are estimated values.

Out of the 200 spectral lines presently investigated, IS in one line at 444.181 nm has been reported by Striganov

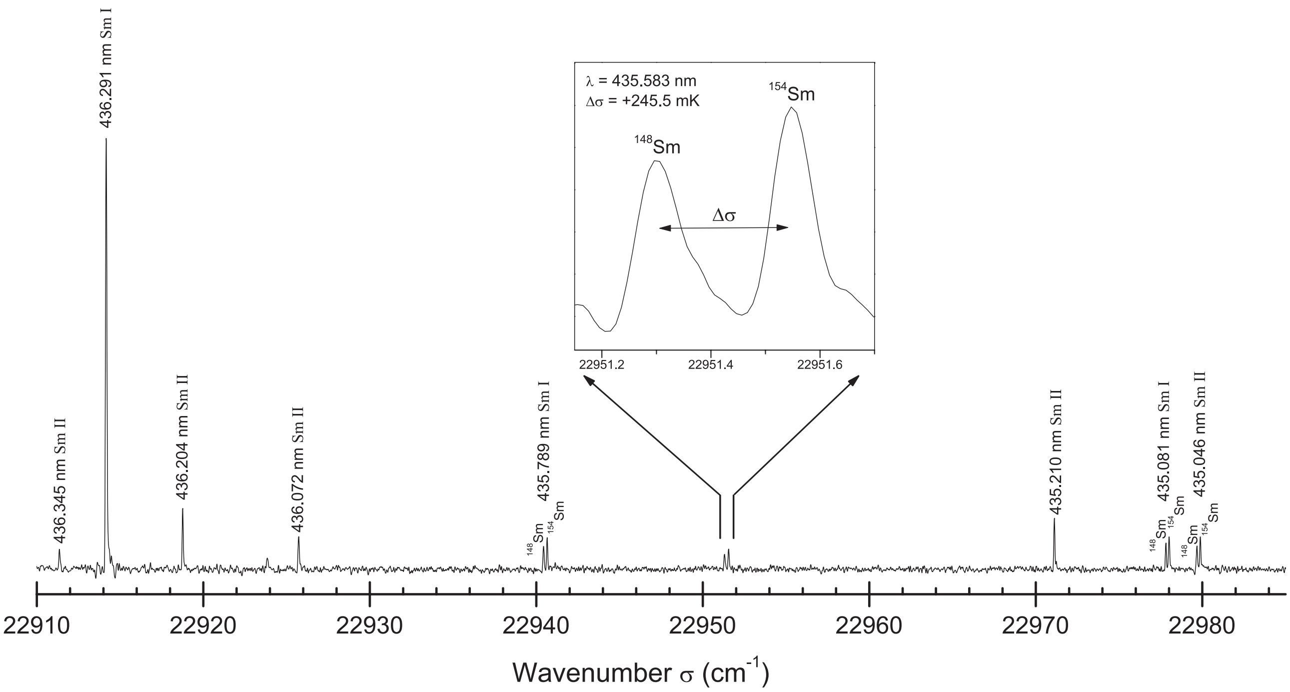

Fig. 1. The largest measured isotope shift, $\Delta\sigma^{148,154} = +245.5$ mK in the Sm I line at 435.583 nm on FTS with enriched isotopes ^{148}Sm (95.4%) and ^{154}Sm (99.2%) taken as a mixture in the ratio 7:10 excited in liquid nitrogen-cooled all metal hollow cathode lamp operating at 35 mA.

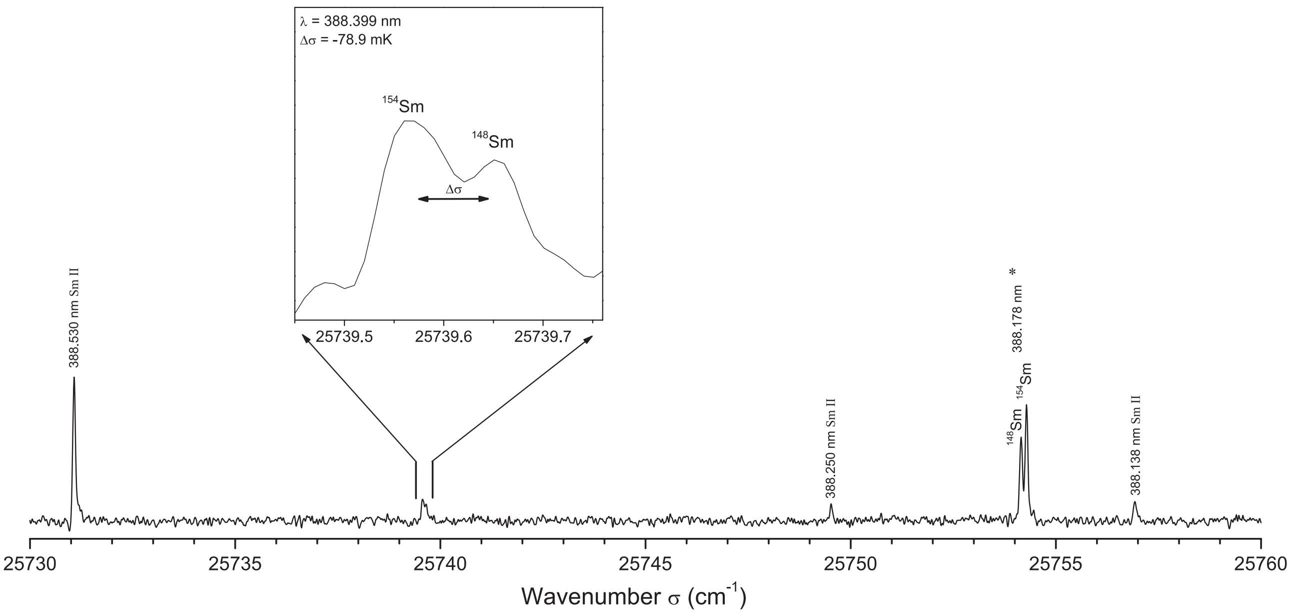

Fig. 2. IS $\Delta\sigma^{148,154} = -78.9$ mK in the Sm I line at 388.399 nm under same experimental conditions as for Figure 1. * Unclassified line.

et al. [22] with $\Delta\sigma^{148,154} = +130.3$ mK which perfectly agrees with our measurement. Bauche et al. [12] have measured IS, $\Delta\sigma^{144,152}$ in 6 lines in the region of our study and these IS values have been compared with our $\Delta\sigma^{148,154}$ values using the relation $\Delta\sigma^{144,152}/\Delta\sigma^{148,154} = 1.300 \pm 0.004$ based on studies reported in [17,20] and all their values in general agree with our measurements within the accuracy.

Within the accuracy of measurement we have assumed that the observed IS is mainly due to field shift (FS). The observed IS between two isotopes in an atomic spectral line consists of mass shift (Normal mass shift and Specific mass shift) which is proportional to $1/A^2$ and the FS, which is due to change in mean square nuclear charge radius, $\delta\langle r^2\rangle$ between the two isotopes. For high Z elements like the lanthanides, the observed IS is mostly due

Table 2. Isotope Shift $\Delta\sigma^{148,154}$ measured presently in the lines of Sm I in the wavelength region 355−455 nm. The wavelengths of the lines and their classifications are taken from [4]. The accuracy of measurement in lines with $\Delta\sigma \geq 80$ mK is ±3 mK and for lines with $\Delta\sigma \leq 80$ mK is ±5 mK. For lines with $\Delta\sigma \leq 30$ mK, the accuracy is about ±10 mK.

Wavelength (nm)	Classification Even level	Odd level	$\Delta\sigma^{148,154}$ (mK) (1 mK = 10^{-3} cm^{-1})
358.636	811	29365	+187
360.764	1489	29200	−85
362.441	2273	29855	−100
362.912	811	28359	−65
362.948	811	28356	+146
364.400	3125	30560	−39.4
364.578	811	28233	−175
365.142	292	27671	+170
365.732	292	27627	+25
366.627	0	27267	+20
366.791	292	27548	−195
368.788	3125	30233	+95
368.813	292	27398	∼0
368.961	1489	28585	−175
369.008	1489	29365	+192
370.763	3125	30089	+168.0
370.785	0	26962	+168.0
370.903	2273	29226	−200.0
371.678	811	27709	−60
372.065	1489	28359	−80
372.103	1489	28356	+140
372.203	811	27671	+170
372.816	811	27627	+30
373.074	2273	29069	−35
373.714	2273	29023	∼0
374.075	2273	28998	−125
374.546	1489	28180	+130.6
374.736	3125	29803	∼0
374.775	1489	28164	+ 40
374.852	292	26962	+164.0
375.643	811	27425	+130.6
376.017	811	27398	−25
376.693	4020	30560	−143
376.831	292	26822	∼0
376.880	811	27338	∼0
377.333	292	26786	+98.5
377.546	2273	28752	+110
377.584	3125	29602	−130
378.215	3125	29557	∼0
378.268	292	26721	∼0
378.733	4020	30416	−170
378.737	3125	29521	−170
379.316	3125	29481	+35
379.333	811	27166	−70

Table 2. *Continued.*

Wavelength (nm)	Classification Even level	Odd level	$\Delta\sigma^{148,154}$ (mK) (1 mK = 10^{-3} cm^{-1})
380.394	0	26281	+127.8
380.647	4020	30284	−60
380.995	3125	29365	+189.1
381.284	1489	27709	−70
381.383	4020	30233	+95.1
381.685	2273	28465	−165
381.836	1489	27671	+170
382.297	811	26962	+170.7
382.481	1489	27627	−35
383.281	2273	28356	+143.2
383.447	4020	30092	+77.3
384.629	811	26803	∼0
384.676	292	26281	+147.5
385.233	2273	28224	+77
385.329	3125	29069	−50
385.459	1489	27425	+128.0
385.581	4020	29948	−90
385.736	1489	27406	−90
385.853	1489	27398	−20
385.864	4020	29929	−180
385.875	2273	28180	+130.6
386.015	3125	29023	∼0
386.763	1489	27338	−30
387.379	811	26619	+64
387.748	4020	29803	∼0
388.064	292	26054	−207.1
388.399	3125	28864	−78.9
388.604	4020	29746	+138
389.195	292	25979	−40
390.826	2273	27852	−40
390.995	3125	28694	∼0
392.468	1489	26962	−40
392.522	811	26281	+130.6
392.633	2273	27734	+200
393.546	811	26214	−60
394.525	3125	28465	−165
394.985	2273	27583	∼0
395.189	1489	26786	+98.0
396.047	(811	26054)[a]	−60
396.213	1489	26721	∼0
396.488	1489	26702	+160.7
396.614	3125	28331	∼0
397.227	811	25979	∼0
397.466	2273	27425	+129.7
397.812	4020	29151	−160.0
397.824	1489	26619	+67.4
399.002	3125	28180	+120.5
399.102	4020	29069	−45

Table 2. *Continued.*

Wavelength (nm)	Classification Even level	Odd level	$\Delta\sigma^{148,154}$ (mK) (1 mK = 10^{-3} cm^{-1})
399.835	4020	29023	∼0
400.161	2273	27255	∼0
405.451	3125	27782	+202.8
406.232	3125	27234	+221.7
406.975	1489	26054	−201.5
407.983	2273	26776	+211.5
408.750	3125	27583	∼0
409.996	3125	27509	+55
410.132	0	24375	∼0
410.628	2273	26619	−40
412.523	2273	26507	+59
412.606	4020	28250	∼0
412.999	292	24498	∼0
413.380	0	24184	−90
413.550	1489	25663	+99.0
413.873	811	24967	∼0
414.297	3125	27255	∼0
414.524	4020	28138	+236.5
414.664	2273	26382	+20
414.797	811	24913	+20
415.113	292	24375	∼0
415.122	1489	25572	∼0
415.885	2273	26311	−83.5
416.479	3125	27129	+130.6
418.333	1489	25387	+152.6
420.578	4020	27790	+209.0
420.725	4020	27782	+220.1
421.863	4020	27718	+239.1
421.931	292	23986	+208.0
422.618	811	24467	+198.4
422.686	3125	26776	+198.5
423.072	0	23639	∼0
424.045	1489	25065	+231.4
424.425	292	23847	∼0
425.621	4020	27509	+55
425.817	1489	24967	∼0
426.631	811	24244	+65.7
427.186	2273	25675	+188.9
427.401	2273	25663	+100
428.221†	3125	26471	+136.4
428.283†	2273	25615	+72.8
428.350	811	24150	+60
428.377	292	23629	∼0
429.083	2273	25572	∼0
429.374	1489	24772	∼0
429.914	292	23546	+192
430.099	0	23243	+251.8
430.127	4020	27263	∼0

Table 2. *Continued.*

Wavelength (nm)	Classification Even level	Odd level	$\Delta\sigma^{148,154}$ (mK) (1 mK = 10^{-3} cm^{-1})
431.285	1489	25453	∼0
431.387	811	23986	+210.2
431.953	1489	24633	∼0
432.446	2273	25390	+179.0
432.516	2273	25387	+151.4
432.614	4020	27129	+126.6
433.002	292	23380	+ 30
433.072	0	23629	0
433.145	1489	24570	+208.2
433.614†	3125	26180	+126.3
433.896	811	23852	+247.1
433.992	811	23847	∼0
434.484	1489	24498	∼0
435.081	1489	24467	+192.6
435.583	292	23243	+245.5
435.789	3125	26065	+215.8
436.291	0	22914	−30
436.595	811	23709	+98.8
438.042	1489	24312	+186.2
438.126	811	23629	0
438.622	2273	25065	+231.3
439.136	-	-	∼0
439.313	4020	26776	+217.3
439.335	1489	24244	+70.4
439.734	811	23546	+195.4
440.117	3125	25840	+85.4
440.523	2273	24967	∼0
440.313	2273	24977	+160.7
441.158	1489	24150	+65
441.933	292	22914	−35
442.338	292	22893	+30
442.966	811	23380	+30
443.306	292	22844	∼0
443.333	3125	25675	+186
444.181$	1489	23996	+132.6
444.227	811	23316	−30
444.327	2273	24772	∼0
444.515†	3125	25615	+70.0
445.295†	4020	26471	+134.1
445.671	811	23243	+236.5
445.929	811	23230	∼0
446.390	2273	24668	+55
447.089	2273	24633	−30
447.150	1489	23847	+60
447.750	2273	25453	∼0
448.032	0	22313	−30
448.491	4020	26311	−70
449.002	3125	25390	+180.0

Table 2. *Continued.*

Wavelength (nm)	Classification Even level	Odd level	$\Delta\sigma^{148,154}$ (mK) (1 mK = 10^{-3} cm^{-1})
449.911	1489	23709	+105.9
450.338	292	22491	+170.1
451.133†	4020	26180	+127.0
452.255	1489	23594	−78.7
452.318	811	22914	−40
452.742	811	22893	+30
453.244	1489	23546	+192.7
453.380	2273	24323	−25
453.487	4020	26065	+226.7
453.610	2273	24312	+187.6
453.757	811	22844	0
453.984	292	22313	−40

a: Classification of this line in [4] is not correct.
†: $\Delta\sigma^{144,152}$ reported by Bauche et al. [12].
$: Lines studied by Striganov et al. [22].

to FS [11]. FS has two factors, the nuclear part related to $\delta\langle r^2\rangle$ and the electronic part related to configuration; when different transitions are investigated for the same isotope pair as in our case, the $\delta\langle r^2\rangle$ is kept constant and we are essentially studying the electronic part. Most of the energy level classifications of the spectral lines listed in Table 2 have been confirmed by the fact that lines with same common upper level to different lower levels (of same configuration) show similar isotope shifts.

There are three lines at 387.379 nm, 397.824 nm and 410.628 nm which respectively have IS $\Delta\sigma^{148,154}$ of +65, +67.4 and −40 mK; all these lines involve a common upper level at 26619.16 cm^{-1} ($J = 3$). We suggest revision of the classification of the line at 410.628 nm given in [4]. The classification of line at 396.047 nm is not correctly given in [4] as is evident from the $\Delta T^{148,154}$ evaluated by us for the level at 26054.05 cm^{-1} on the basis of two more transitions at 388.064 nm and 406.975 nm which exhibit $\Delta\sigma^{148,154}$ of −207.1 and −201.5 mK respectively. There is only one unclassified line at 439.136 nm in Table 2 and the isotope shift value obtained presently may be useful in its future classification.

3.2 Evaluation of level isotope shift $\Delta T^{148,154}$ in the energy levels of Sm I

The transitions studied presently (Tab. 2) are mostly from high odd- to low even-parity levels of $4f^66s^2$ configuration. We have assumed the value of IS in the ground state of Sm I, $\Delta T^{148,154}$ ($4f^66s^2$, ^{7}F$_0$) = X mK; the approximate value of X is estimated to be ∼470 mK on the basis of our earlier work on Sm II [23]. The low even-parity levels of $4f^66s^2$ involved in the present study are listed in Table 3. A difference of about 1 mK in $\Delta T^{148,154}$ values for the successive ^{7}F$_J$ levels (J = 0–6) of $4f^66s^2$ configuration has been reported by Bauche et al. [12] because of J-dependence. With the available accuracy and the present resolution of FTS, it was not possible for us to differentiate between $\Delta T^{148,154}$ values of ^{7}F terms with different J values, so we have assumed the same value of $\Delta T^{148,154} = X$ mK for all these low even-parity levels except for the last two levels ^{7}F$_5$ and ^{7}F$_6$ for which $\Delta T = (X + 5)$ mK has been taken [12].

Table 3. $\Delta T^{148,154}$ values for the even-parity energy levels (^{7}F$_J$) of Sm I encountered in the present study. The energy levels, their J values and configurations are from [5]. The estimated value of $X \approx 470$ mK.

Energy level (cm^{-1})	J	Configuration	$\Delta T^{148,154}$ mK)
0.00	0	$4f^66s^2$	X
292.58	1	$4f^66s^2$	X
811.92	2	$4f^66s^2$	X
1489.55	3	$4f^66s^2$	X
2273.09	4	$4f^66s^2$	X
3125.46	5	$4f^66s^2$	$X + 5$
4020.66	6	$4f^66s^2$	$X + 5$

The term IS, $\Delta T^{148,154}$ of 117 high lying odd-parity levels of Sm I, evaluated relative to the assumed value of X mK mentioned above, are listed in Table 4. The energy levels, their J values and configurations (column 1 to 3) are from [5]. Earlier studies [4,12,19,22] involve only 9 of these levels and they are indicated in the footnotes of Table 4. Table 4 is arranged in to different sub-sections A, B, C, D, E, F, G and H.

As mentioned earlier, $\Delta T^{148,154}$ values are useful for checking the assigned configurations, for verifying the theoretical composition of these assigned levels wherever available, and for checking the tentative configuration assignment of the energy levels. Before taking up these issues, we will briefly discuss the evaluation of $\Delta T^{148,154}$ of the energy level with a pure configuration, as could be derived from the present isotope shift studies.

3.2.1 $\Delta T^{148,154}$ values of pure known configurations of Sm I

As indicated in Table 1, for the known energy levels of Sm I, there are three even-parity configurations ($4f^66s^2$, $4f^65d6s$ and $4f^66s7s$) and two odd-parity configurations ($4f^66s6p$ and $4f^55d6s^2$) identified so far; two odd-configurations $4f^55d^26s$ and $4f^65d6p$ also have been tentatively assigned [5].

Large negative shifts have been reported for some strong lines of Sm I which are classified as transitions of $4f^66s6p \to 4f^66s^2$ type. Based on the earlier studies and our present studies we have taken $\Delta T^{148,154}$ ($4f^66s6p$) = (X − 175) mK. Large positive shifts have been reported for the transitions classified as $4f^55d6s^2 \to 4f^66s^2$. Earlier studies have reported for a level of $4f^55d6s^2$, a maximum value of $\Delta T^{148,154}$ = (X + 221) mK. The present study has provided $\Delta T^{148,154}$ = (X + 245) mK for the level at 23852 cm^{-1} ($J = 3$) and we have taken this value of $\Delta T^{148,154}$ for a pure configuration of $4f^55d6s^2$. For a level

Table 4. $\Delta T^{148,154}$ values for the odd-parity energy levels of Sm I encountered in the present study. The energy levels, their J values and configurations are from [5]. The estimated value of $X \approx 470$ mK.

Energy level (cm^{-1})	J	Configuration	$\Delta T^{148,154}$ (mK)	Configuration suggested
A				
22313.63	1	$4f^6 6s6p$	$X - 30$	c_1
22632.30[a,b]	3	$4f^6 6s6p$	$X - 95$	
22893.37	2	$4f^6 6s6p$	$X + 30$	c_1
22914.07	1	$4f^6 6s6p$	$X - 30$	
23594.84	4	$4f^6 6s6p$	$X - 77$	c_1
24184.05	1	$(4f^6 6s6p)^d$	$X - 90$	$4f^6 6s6p$
24323.51	5	$4f^6 6s6p$	$X - 25$	
24498.96	2	$(4f^6 6s6p)^d$	X	c_3
24668.79	5	$4f^6 6s6p$	$X - 50$	
25572.10	4	$(4f^6 6s6p)^d$	X	c_3
26311.45	5	$(4f^6 6s6p)^d$	$X - 78$	$4f^6 6s6p$
27287.58	7	$4f^6 6s6p$	$X - 25$	
23709.98	3	$4f^6 6s6p$	$X + 102$	$4f^5 5d6s^2$
23996.55[e]	4	$4f^6 6s6p$	$X + 133$	$4f^5 5d6s^2$
25840.31	6	$4f^6 6s6p$	$X + 85$	$4f^5 5d6s^2$
B				
22491.94	2	$4f^5 5d6s^2$	$X + 170$	
22893.05	4	$4f^5 5d6s^2$	$X + 130$	
23243.84	1	$4f^5 5d6s^2$	$X + 236$	
23546.54	2	$4f^5 5d6s^2$	$X + 195$	
23852.43	3	$4f^5 5d6s^2$	$X + 247$	
23986.48	2	$4f^5 5d6s^2$	$X + 210$	
24150.80	3	$4f^5 5d6s^2$	$X + 60$	
24467.27	3	$4f^5 5d6s^2$	$X + 200$	
25065.37	4	$4f^5 5d6s^2$	$X + 231$	
25387.17	4	$4f^5 5d6s^2$	$X + 150$	
25390.91	5	$4f^5 5d6s^2$	$X + 180$	
25615.55[a]	5	$4f^5 5d6s^2$	$X + 70$	
25675.50	5	$4f^5 5d6s^2$	$X + 188$	
26065.85	5	$4f^5 5d6s^2$	$X + 225$	
26281.09	1	$4f^5 5d6s^2$	$X + 135$	
26471.33	6	$4f^5 5d6s^2$	$X + 135$	
26786.80	2	$4f^5 5d6s^2$	$X + 98$	
26962.12	1	$4f^5 5d6s^2$	$X + 170$	
27129.49	6	$4f^5 5d6s^2$	$X + 130$	
27425.50	3	$4f^5 5d6s^2$	$X + 130$	
27671.35	2	$4f^5 5d6s^2$	$X + 175$	
27718.35	7	$4f^5 5d6s^2$	$X + 240$	
28138.00	7	$4f^5 5d6s^2$	$X + 237$	
28180.95	4	$4f^5 5d6s^2$	$X + 130$	
28356.22	3	$4f^5 5d6s^2$	$X + 145$	
29365.03	4	$4f^5 5d6s^2$	$X + 190$	
30092.53	6	$4f^5 5d6s^2$	$X + 77$	
30233.64	5	$4f^5 5d6s^2$	$X + 95$	

Table 4. *Continued.*

Energy level (cm^{-1})	J	Configuration	$\Delta T^{148,154}$ (mK)	Configuration suggested
23316.63	3	$4f^5 5d6s^2$	$X-30$	c_1
23380.75	2	$4f^5 5d6s^2$	$X+30$	c_1
24633.75	4	$4f^5 5d6s^2$	X	c_3
24772.74	4	$4f^5 5d6s^2$	X	c_3
25979.30	2	$4f^5 5d6s^2$	$X-35$	c_3
29023.96	5	$4f^5 5d6s^2$	X	c_3
C				
22844.00	2	$4f^5 5d^2 6s$?	X	$4f^5 5d^2 6s$
23230.75	3	$4f^5 5d^2 6s$?	X	$4f^5 5d^2 6s$
26214.75	3	$4f^6 5d6p$?	$X-60$	$4f^6 5d6p$
27852.78	5	$4f^6 5d6p$(?)	$X-40$	
28864.89	6	$4f^6 5d6p$?	$X-80$	$4f^6 5d6p$
29948.33	7	$4f^6 5d6p$?	$X-90$	$4f^6 5d6p$
23629.98	1	$(4f^6 5d6p + 4f^5 5d^2 6s)$[d]	X	$4f^5 5d^2 6s$
23847.25	2	$(4f^6 5d6p + 4f^5 5d^2 6s)$[d]	X	$4f^5 5d^2 6s$
24244.80	3	$(4f^6 5d6p + 4f^5 5d^2 6s)$[d]	$X+70$	$4f^5 5d6s^2$
26721.35	2	$(4f^6 5d6p + 4f^5 5d^2 6s)$[d]	X	$4f^5 5d^2 6s$
27166.50	6	$(4f^6 5d6p + 4f^5 5d^2 6s)$[d]	$X-70$	$4f^6 5d6p$
27338.00	2	$(4f^6 5d6p + 4f^5 5d^2 6s)$[d]	$X-30$	
27406.90	2	$(4f^6 5d6p + 4f^5 5d^2 6s)$[d]	$X-90$	$4f^6 5d6p$
27548.28	1	$(4f^6 5d6p + 4f^5 5d^2 6s)$[d]	$X-195$	$4f^6 5d6p$
27709.40	2	$(4f^6 5d6p + 4f^5 5d^2 6s)$[d]	$X-85$	$4f^6 5d6p$
29151.15	5	$(4f^6 5d6p + 4f^5 5d^2 6s)$[d]	$X-167$	$4f^6 5d6p$
D				
24312.02	4	-	$X+187$	$4f^5 5d6s^2$
24570.03	4	-	$X+210$	$4f^5 5d6s^2$
24977.83	5	-	$X+160$	$4f^5 5d6s^2$
25663.60	4	-	$X+100$	$4f^5 5d6s^2$
26180.92[a]	6	-	$X+127$	$4f^5 5d6s^2$
26507.31	5	-	$X+60$	$4f^5 5d6s^2$
26619.16	3	-	$X+70$	$4f^5 5d6s^2$
26703.85	3	-	$X+160$	$4f^5 5d6s^2$
26776.98	5	-	$X+220$	$4f^5 5d6s^2$
27509.09	6	-	$X+55$	$4f^5 5d6s^2$
27734.99	4	-	$X+220$	$4f^5 5d6s^2$
27782.41	6	-	$X+220$	$4f^5 5d6s^2$
27790.77	7	-	$X+210$	$4f^5 5d6s^2$
28164.78	3	-	$X+40$	$4f^5 5d6s^2$
28224.05	3	-	$X+77$	$4f^5 5d6s^2$
28752.34	4	-	$X+110$	$4f^5 5d6s^2$
29481.25	4	-	$X+35$	$4f^5 5d6s^2$
29746.53	6	-	$X+140$	$4f^5 5d6s^2$
30089.27	5	-	$X+170$	$4f^5 5d6s^2$
30560.08	5	-	$X+100$	$4f^5 5d6s^2$

Table 4. *Continued.*

Energy level (cm^{-1})	J	Configuration	$\Delta T^{148,154}$ (mK)	Configuration suggested
E				
24375.60	1	-	X	c_3
24913.28	2	-	X	c_3
24967.14	3	-	X	c_3
25453.11	5	-	X	c_3
26382.25	4	-	$X+20$	c_3
27255.97	5	-	X	c_3
27263.07	7	-	X	c_3
27583.38	4	-	X	c_3
27627.25	2	-	X	c_3
28250.02	7	-	X	c_3
28331.84	5	-	X	c_3
28694.06	5	-	X	c_3
29803.32	6	-	X	c_3
F				
27398.92	2	-	$X-25$	$4f^66s6p$
28998.13	3	-	$X-125$	$4f^66s6p$
29069.90	5	-	$X-45$	$4f^66s6p$
29855.91	4	-	$X-100$	$4f^66s6p$
30284.40	5	-	$X-60$	$4f^66s6p$
G				
26054.05	2	-	$X-210$	$4f^65d6p$(?)
28233.08[f]	1	-	$X-175$	$4f^65d6p$
28359.00	2	-	$X-75$	$4f^65d6p$(?)
28465.30	4	-	$X-165$	$4f^65d6p$
28585.07	3	-	$X-175$	$4f^65d6p$
29200.62	2	-	$X-85$	$4f^65d6p$(?)
29226.71	3	-	$X-200$	$4f^65d6p$
29521.75	4	-	$X-170$	$4f^65d6p$
29602.09	5	-	$X-130$	$4f^65d6p$
29929.38	6	-	$X-180$	$4f^65d6p$
30416.80	5	-	$X-170$	$4f^65d6p$
30560.04	6	-	$X-145$	$4f^65d6p$
H				
26803.70	1	-	X	$4f^55d^26s$(?)
26822.13	0	-	X	$4f^55d^26s$
27267.94	1	-	$X+20$	$4f^55d^26s$
29557.87	4	-	X	$4f^55d^26s$

[a] Bauche et al. [12]. [b] Schweighofer [4]. c_1 Configuration mixing with $4f^55d6s^2$ indicated in [5] reflects in our $\Delta T^{148,154}$ value. c_2 Configuration mixing with $4f^66s6p$ indicated in [5] reflects in our $\Delta T^{148,154}$ value. c_3 Predominantly (60−70%) $4f^66s6p$ configuration mixed with $4f^55d6s^2$ configuration. [d] Assignment by Blaise et al. [3]. [e] Striganov et al. [22]. [f] Jin et al. [19]. Their classification of the lines at 571.68 nm and 570.87 nm involving the level at 29365.03 cm^{-1} ($J=4$) is not correct. These two lines are unclassified in [4].

of $4f^55d^26s$ configuration we expect $\Delta T^{148,154} \sim X$ mK, same as for $4f^66s^2$ configuration, on the basis of term IS reported by Ahmad [24] for $4f^n6s^2$ and $4f^{n-1}5d^26s$ configuration of several rare earths (Nd I, Dy I, Er I and Yb I). Similarly on the basis of the general trend observed in the studies carried out by Rao et al. [23], we expect $\Delta T^{148,154} = (X - 300)$ mK for $4f^65d6p$ configuration.

In the region covered presently, we have not encountered any transition involving high even-parity level of $4f^65d6s$ configuration. But on the basis of ΔT values reported by Schweighofer [4] and our recent studies of IS in Sm I lines in the region 456−600 nm [25], we conclude $\Delta T^{148,154} = (X-220)$ mK for a level of pure $4f^65d6s$ configuration. Based on the above discussions, the $\Delta T^{148,154}$ values for the levels of known pure configurations of Sm I are summarized below.

	$\Delta T^{148,154}$
even configuration	
$4f^66s^2$	X mK $\approx$ 470 mK
$4f^65d6s$	$(X-220)$ mK $\approx$ 250 mK
$4f^66s7s$	$(X-160)$ mK = 310 mK
odd configuration	
$4f^66s6p$	$(X-175)$ mK $\approx$ 295 mK
$4f^55d6s^2$	$(X+245)$ mK $\approx$ 715 mK
$4f^55d^26s$	X mK $\approx$ 470 mK
$4f^65d6p$	$(X-300)$ mK $\approx$ 170 mK

Figure 3 shows partial energy level diagram of Sm I where the configurations are represented by the lowest energy level known for that configuration. Expected IS for a pure level of that configuration is shown below the line representing the configuration and expected IS in transitions are shown along the line representing the transitions.

Wilson [21] has carried out Non Relativistic Hartree-Fock (NRHF) calculations of the s-electron density of $6s$ electron, that is $4\Pi|\Psi(0)|^2_{6s}$, for a number of configurations of Sm I, chosen for their interest in interpreting the observed isotope shifts. The $\Delta T^{148,154}$ values of the pure configurations derived by us and the values of $4\Pi|\Psi(0)|^2_{6s}$ of various configurations from [21] are given in Table 5. As can be seen from the plot of $\Delta T^{148,154}$ vs. $4\Pi|\Psi(0)|^2_{6s}$, in Figure 4 there is good agreement between the present experimental data obtained by us and the theoretical results obtained by Wilson [21].

3.2.2 ΔT values of the energy levels with mixed configuration ($4f^66s6p + 4f^55d6s^2$)

For the energy levels of Sm I, the only calculations reported by Carlier et al. [2] are for $4f^66s6p$ and $4f^55d6s^2$ configurations. They calculated the energy eigen-values and the Landé g-factors of the energy levels of the sub-configurations $[4f^6(^7\mathrm{F})\ 6s6p + 4f^5(^6\mathrm{H}{-}^6\mathrm{F})\ 5d6s^2]$ taken together and they interpreted 127 observed energy levels of Sm I. The eigen vectors, in the LS coupling show the mixture of $4f^66s6p$ and $4f^55d6s^2$ configurations beginning at 18000 cm^{-1} [5].

According to the well-known "sharing rule", for a state whose wave function 'Ψ' results from mixing of 'n' configurations, the term IS, ΔT equals the sum of isotope shift ΔT_i of individual configurations multiplied by the square of the weight C_i of the configuration.

$$\Delta T = \sum_{i=1}^{n} C_i^2 \cdot \Delta T_i \quad \text{with} \quad \sum C_i^2 = 1.$$

We have evaluated $\Delta T^{148,154}$ values for hypothetical odd-parity levels with varying percentage compositions of configurations, taking the $\Delta T^{148,154}$ values of pure configurations $4f^66s6p$ and $4f^55d6s^2$ (see Sect. 3.2.1) and they are presented below.

$\Delta T^{148,154}$ (mK)	$(X-175)$	$(X-87)$	$(X-4)$
$4f^66s6p$ (%)	100	80	60
$4f^55d6s^2$ (%)	0	20	40
$\Delta T^{148,154}$ (mK)	$(X+79)$	$(X+162)$	$(X+245)$
$4f^66s6p$ (%)	40	20	0
$4f^55d6s^2$ (%)	60	80	100

3.3 Comments on theoretically assigned configurations to some odd-parity energy levels of Sm I

We are reporting new $\Delta T^{148,154}$ values for 13 energy levels of $4f^66s6p$ configuration [3,5] and assignment of these levels have been confirmed; only two levels of this configuration have been studied earlier [12,22,26]. All these 15 levels are listed in Table 4A.

The levels at 24184 cm^{-1} ($J=1$), 24498 cm^{-1} ($J=2$) and 25572 cm^{-1} ($J=4$) are assigned to $4f^66s6p$ by Blaise et al. [3] but these are left unassigned in [5]. As discussed under Section 3.2.1, for a level of pure $4f^66s6p$ configuration, the expected $\Delta T^{148,154}$ value is $\sim(X-175)$ mK.

The level at 24184 cm^{-1} ($J=1$) has $\Delta T^{148,154}(X-90)$ mK; we conclude that the assignment of $4f^66s6p$ configuration to this level is correct and has some mixing with $4f^55d6s^2$ configuration. The levels at 22632.30 cm^{-1} ($J=2$), 23594.84 cm^{-1} ($J=4$), and 24668.79 cm^{-1} ($J=5$) have $\Delta T^{148,154}$ values ranging between $(X-50)$ to $(X-95)$ mK. These ΔT values indicate configuration mixing of about $\sim$60% of $4f^55d6s^2$ configuration with $4f^66s6p$ configuration for these levels. The levels at 24498.96 cm^{-1} ($J=2$) and 25572.10 cm^{-1} ($J=4$) have both $\Delta T^{148,154} = X$ mK, we have assigned these to the mixed configuration ($4f^66s6p + 4f^55d6s^2$) with $\sim$60% of $4f^55d6s^2$ configuration.

The levels at 22313.63 cm^{-1} ($J=1$), 22914.07 cm^{-1} ($J=1$), 24323.51 cm^{-1} ($J=5$) and 27287.8 cm^{-1} ($J=7$) (Tab. 4A) have $\Delta T^{148,154}$ values of $\sim(X-25)$ mK, these $\Delta T^{148,154}$ values indicate 35 to 40% of $4f^55d6s^2$ configuration mixing with $4f^66s6p$ configuration.

In order to highlight the sensitiveness of ΔT on the configuration purity of a level, we present in Table 6,

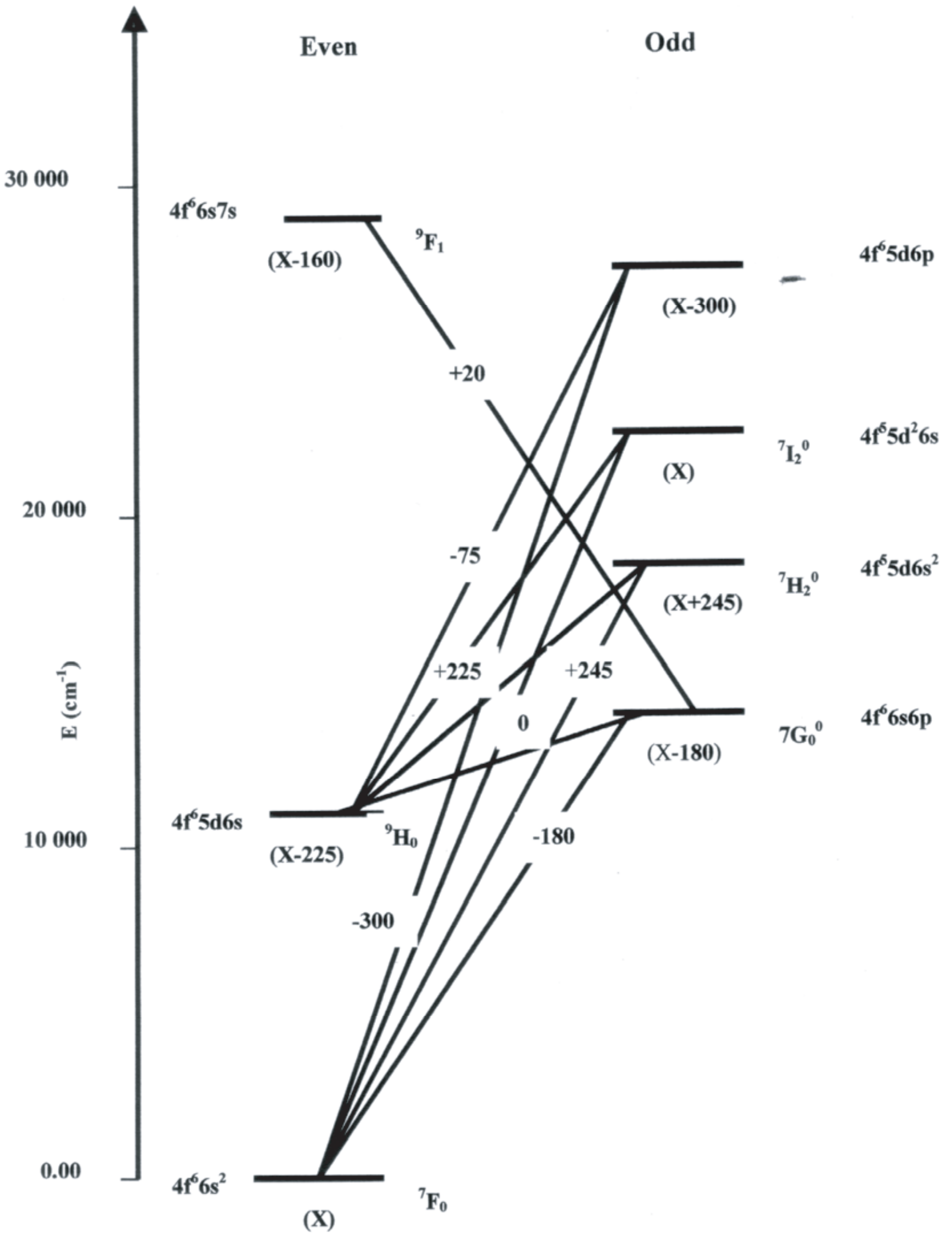

Fig. 3. Energy Level diagram of Sm I, showing the position of the lowest level identified for a particular configuration. The level isotope shift, $\Delta T^{148,154}$ of a particular configuration is shown in parentheses and the $\Delta\sigma^{148,154}$ value in a particular transition is shown along the lines. The estimated value of $X \approx 470$ mK.

Table 5. The NRHF values of the total electron densities at the nucleus, i.e. $4\pi|\psi(0)|^2$ (in units of a_0^{-3}) for odd- and even-configurations of Sm I. $\Delta T^{148,154}$ values of pure configurations of Sm I as discussed under Section 3.2.1.

Configurations	$4\pi\lvert\psi(0)\rvert^2_{\text{Total}} - 2128000$ (a_0^{-3})	FS in terms of X ($X = 470$ mK)	FS in mK
$4f^6 6s^2$	803.498	X	470
$4f^6 6s6p$	757.812	$X - 200$	270
$4f^6 5d6s$	727.182	$X - 235$	235
$4f^6 5d6p$	683.430	$X - 335$	135
$4f^5 5d6s^2$	940.573	$X + 245$	715
$4f^5 5d^2 6s$	848.687	$X + 25$	495
$4f^5 6s^2 6p$	1001.895	$X + 400$	870

Table 6. $\Delta T^{148,154}$ values evaluated presently by us for the levels of term ^{7}D of $4f^6(^7\mathrm{F})\ 6s6p(^3\mathrm{P}^0)$ configuration of Sm I

E (cm^{-1})$^{\#}$	Designation$^{\#}$	Leading percentage$^{\#}$				$\Delta T^{148,154}$ (mK)
21193.68	$^7\mathrm{D}_1$	87	$4f^66s6p$	8	$4f^55d6s^2\ ^7\mathrm{D}$	$(X-130)^{\mathrm{a}}$
21813.22	$^7\mathrm{D}_2$	85	$4f^66s6p$	8	$4f^55d6s^2\ ^7\mathrm{D}$	$(X-115)^{\mathrm{a}}$
22632.30	$^7\mathrm{D}_3$	81	$4f^66s6p$	8	$4f^55d6s^2\ ^7\mathrm{D}$	$(X-95)^{\mathrm{b}}$
23594.84	$^7\mathrm{D}_4$	67	$4f^66s6p$	10	$4f^55d6s^2\ ^7\mathrm{G}$	$(X-77)^{\mathrm{b}}$
24323.51	$^7\mathrm{D}_5$	35	$4f^66s6p$	20	$(^7\mathrm{F})\ (^3\mathrm{P}^0)^7\mathrm{F}$	$(X-25)^{\mathrm{b}}$

$^{\#}$ From [5], $^{\mathrm{a}}$ from our recent work [25]; $^{\mathrm{b}}$ present work.

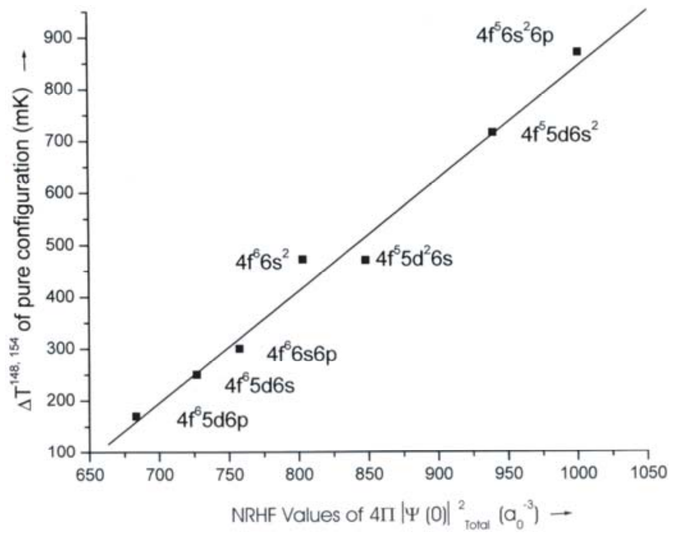

Fig. 4. Plot of level isotope shifts, $\Delta T^{148,154}$ in mK units for various configurations of Sm I versus NRHF values of $4\pi|\psi(0)|^2_{Total}-2128000$ (in units of a_0^{-3}) calculated by Wilson [21], (see Tab. 5). The $4f^56s^26p$ configuration was not encountered in our present studies, however $\Delta T^{148,154}$ for this configuration has been derived from data reported in [24].

$\Delta T^{148,154}$ values of the levels of the multiplet ^{7}D of $4f^6(^7\mathrm{F})\ 6s6p(^3\mathrm{P}^0)$ configuration along with the leading percentages for these levels as reported in [5]. As can be seen, the $\Delta T^{148,154}$ values go up with decreasing leading percentages of $4f^66s6p$ and increasing contribution of $4f^55d6s^2$ configuration, confirming the theoretical calculations of Carlier et al. [2].

There are three levels (Tab. 4A) at 23709.98 cm^{-1} ($J=3$), 23996.55 cm^{-1} ($J=4$) and 25840.31 cm^{-1} ($J=6$) which have $\Delta T^{148,154}$ values $(X+102)$, $(X+133)$ and $(X+85)$ mK respectively. These $\Delta T^{148,154}$ values have been derived from IS measured in two or more transitions involving each of these levels. These levels, assigned to $4f^66s6p$ have been shown to have some mixing with $4f^55d6s^2$ configuration [2,5]. But the $\Delta T^{148,154}$ values for these 3 levels suggest revision of the earlier assignment and we assign these levels to have predominantly $4f^55d6s^2$ configuration.

$\Delta T^{148,154}$ values for 34 odd-parity levels (Tab. 4B) assigned to $4f^55d6s^2$ configuration [2,5] are being reported now, among this only the level at 25615 cm^{-1} ($J=5$) has been studied earlier [12]. $\Delta T^{148,154}$ values show that the levels at 24150 cm^{-1} ($^7\mathrm{H}_3$) and 27129 cm^{-1} ($^7\mathrm{H}_6$) are having configuration mixing; for $^7\mathrm{H}_3$, the reported leading percentage is supported by our $\Delta T^{148,154}$ value. For $^7\mathrm{H}_6$, with the reported leading percentage, we should have obtained $\Delta T^{148,154} \approx (X+220)$ mK whereas we get $\Delta T^{148,154} = (X+130)$ mK. The level at 29023.96 cm^{-1}, $^7\mathrm{F}_5$ has $\Delta T^{148,154} = X$ mK indicating that this level has considerable mixing of $4f^66s6p$ configuration (see Sect. 3.2.2), most probably with the level at 29069.90 cm^{-1} ($J=5$) which has $\Delta T^{148,154} = (X-45)$ mK and assigned by us to have predominantly $4f^66s6p$ configuration. For the level at 30233.64 cm^{-1} ($^7\mathrm{D}_5$), we get $\Delta T^{148,154} = (X+95)$ mK which is rather low value compared to $\Delta T^{148,154}$ of other levels of ^{7}D multiplet. We suggest configuration mixing for this level with the level at 30284.40 cm^{-1} ($J=5$) which has been assigned by us to $4f^66s6p$ configuration (Tab. 4F).

3.3.1 Comments on the tentative assignments of $4f^55d^26s$ and $4f^65d6p$ configurations

As mentioned earlier, a few odd-parity levels have been tentatively assigned to configurations $4f^55d^26s$ and $4f^65d6p$ [5]. There are nine levels belonging to $^9\mathrm{I}_J$ multiplet ($J=2$ to 10) between 22844.00 cm^{-1} and 29467.69 cm^{-1} and eight other levels between 25808.90 cm^{-1} and 33808.29 cm^{-1} which were assigned to $(4f^65d6p+4f^55d^26s)$ configuration [3]. Blaise et al. [27] have later revised these assignments, stating that in view of the regular variation of the distances between configurations in the lanthanides, the lower energy levels beginning at 22844.0 cm^{-1} could belong to $4f^55d^26s$ and the upper one beginning at 25808.9 cm^{-1} could be the lowest multiplet of $4f^65d6p$ configuration. Martin et al. [5] have tentatively assigned the nine levels of $^9\mathrm{I}^0_J$ multiplet ($J=2$ to 10) between 22844.00 cm^{-1} and 29467.69 cm^{-1}, to $4f^55d^26s(?)$ configuration and the nine levels between 25808.90 cm^{-1} and 33808.29 cm^{-1} have been assigned to $^9\mathrm{I}^0_J$ of $4f^65d6p(?)$ configuration. No isotope shift data were available for these tentatively assigned multiplets prior to the present study. We have evaluated $\Delta T^{148,154}$ for the levels of $4f^55d^26s(?)$ configurations at 22844.00 cm^{-1} ($^9\mathrm{I}_2$) and 23230.75 cm^{-1} ($^9\mathrm{I}_3$) and we get $\Delta T^{148,154} \approx X$ mK (Tab. 4C) for both these levels which is the expected $\Delta T^{148,154}$ value for a level of $4f^55d^26s$ configuration (see Sect. 3.2.1). This is the first confirmation of the tentative assignment of $4f^55d^26s$ configuration to Sm I levels on the basis of IS data.

We have encountered four levels, which are tentatively assigned to $4f^65d6p$(?) configuration in [5] (Tab. 4C). For a pure $4f^65d6p$ level we expect $\Delta T^{148,154} \approx (X-300)$ mK. The $\Delta T^{148,154}$ values evaluated for these levels suggest that the predominant configuration of these levels could be $4f^65d6p$ with considerable mixing.

There are 10 levels (Tab. 4C) which have been assigned by Blaise et al. [3] to $(4f^65d6p+4f^55d^26s)$ configuration; all these are left unassigned in [5]. The configurations suggested by us, given in column 5 are self-explanatory. For the levels assigned to $4f^65d6p$, we have taken into consideration the intensities of the transitions from these levels. Transition of type $4f^66s6p \rightarrow 4f^66s^2$ is expected to be strong as it is $s \rightarrow p$ transition, whereas for $4f^65d6p \rightarrow 4f^66s^2$ type transition the intensity is expected to be rather weak. The intensities of the transitions involving the levels, which are assigned by us to $4f^65d6p$ configuration, are weak, except for the level at 27548.28 cm^{-1}.

3.3.2 New assignment of configurations to unassigned odd-parity energy levels of Sm I

We have evaluated $\Delta T^{148,154}$ values for 54 unassigned odd-parity levels in the region 24310−30560 cm^{-1} (Tabs. 4D, 4E, 4F, 4G, and 4H). On the basis of our $\Delta T^{148,154}$ values and also taking into account the intensities of the observed transitions from these levels, we have suggested possible electronic configurations to these unassigned levels.

There are 14 unassigned odd-parity levels for which $\Delta T^{148,154}$ values evaluated presently lie mostly in the range $(X+100)$ mK and $(X+220)$ mK. For 6 levels, the $\Delta T^{148,154}$ values lie between $(X+35)$ and $(X+80)$ mK and all these 20 levels should belong to predominantly $4f^55d6s^2$ configuration (Tab. 4D).

13 unassigned levels (Tab. 4E) which show $\Delta T^{148,154} \approx X$ mK, except the one level at 26382.25 ($J=4$) which has $\Delta T^{148,154}$ $(X+20)$ mK could belong to $4f^55d^26s$ or to (60% $4f^66s6p$ + 40% $4f^55d6s^2$) mixed configuration. The transitions we have studied are all emerging from the lower even levels of $4f^66s^2$ configuration, i.e. transition of type $4f^66s6p \rightarrow 4f^66s^2$, $4f^55d6s^2 \rightarrow 4f^66s^2$ and $4f^55d^26s \rightarrow 4f^66s^2$. The $s \rightarrow p$ and $d \rightarrow f$ transitions will be strong whereas $d^2 \rightarrow fs$ will be weak in intensity. Using the reported intensities of the Sm I lines [4,28] along with ΔT values we could suggest mixed configuration $(4f^66s6p+4f^55d6s^2)$ to a number of unassigned levels in Table 4E and these are marked with 'c_3' in the last column.

There are five unassigned levels (Tab. 4F), at 27398.92 cm^{-1} ($J=2$), 28998.13 cm^{-1} ($J=3$), 29069.90 cm^{-1} ($J=5$), 29855.91 cm^{-1} ($J=4$) and 30284.40 cm^{-1} ($J=5$) which have $\Delta T^{148,154}$ values, $(X-25)$ mK, $(X-125)$ mK, $(X-45)$ mK, $(X-100)$ mK and $(X-60)$ mK respectively. On the basis of $\Delta T^{148,154}$ values and observed intensities of the spectral lines involving these levels we have assigned all these levels to $4f^66s6p$ configuration.

The lowest level of $4f^65d6p$ configuration is reported at 25808.90 cm^{-1}, (^{9}I$_2$). Above 26000 cm^{-1} there are 12 unassigned levels for which we have obtained $\Delta T^{148,154}$ values in the range $(X-75)$ and $(X-210)$ mK (Tab. 4G). On the basis of these $\Delta T^{148,154}$ values and also the observed intensities of the transitions, we have suggested $4f^65d6p$ configuration for 10 of these unassigned odd-parity levels, and 2 levels are tentatively assigned to $4f^65d6p$(?) configuration.

The levels at 26803.70 cm^{-1} ($J=1$), 26822.13 cm^{-1} ($J=0$), 27267.94 cm^{-1} ($J=1$) and 29557.87 cm^{-1} ($J=4$) have been assigned by us to $4f^55d^26s$ configuration (Tab. 4H), considering the intensity of the lines as discussed above in addition to their $\Delta T^{148,154}$ value X mK.

4 Conclusion

The high-resolution studies of Sm I carried out on FTS have provided new IS data, $\Delta\sigma^{148,154}$ in 187 spectral lines in 355−455 nm region. The data has enabled us to evaluate level IS, $\Delta T^{148,154}$ for 117 odd-parity energy levels of Sm I; $\Delta T^{148,154}$ values for 109 energy levels are being reported for the first time.

The $\Delta T^{148,154}$ values have enabled us to check the theoretically reported composition of $[4f^5(^6\mathrm{H}^0, {}^6\mathrm{F}^0)\ 5d6s^2 + 4f^6(^7\mathrm{F})\ 6s6p(^3p^0)]$ for several levels made on the basis of parametric calculations. The present study has provided new $\Delta T^{148,154}$ values for 34 odd-parity levels assigned to $4f^55d6s^2$ configuration.

The odd-parity configurations $4f^55d^26s$ and $4f^65d6p$ of Sm I are yet to be theoretically studied. Our $\Delta T^{148,154}$ values support the tentative assignments of two levels to $4f^55d^26s$ and four levels to $4f^65d6p$ configuration and to the best of our knowledge this is the first experimental support to the tentative assignments. Energy levels assigned to $(4f^65d6p+4f^55d6s^2)$ configurations have been also studied and $\Delta T^{148,154}$ of 10 such levels have been evaluated and predominant configuration for these levels suggested. We have suggested configurations to 54 unassigned odd-levels encountered in the present investigation.

It is hoped that new term IS values provided for 117 odd-parity energy levels of Sm I would provide impetus for new theoretical calculations as the present $\Delta T^{148,154}$ values will be valuable in checking the theoretically calculated composition of these levels.

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