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NUCLEAR ORIENTATION OF ^{147}Tb ($T_{1/2}$ = 1.7 h), ^{149}Tb ($T_{1/2}$ = 4.15 h) AND ^{151}Tb ($T_{1/2}$ = 17.7 h) IN A GADOLINIUM HOST

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1. INTRODUCTION

Recently there has been growing interest in studies of nuclei with mass-numbers A ≈ 150 as a result of the observed/1/ double closed-shell features of ^{146}Gd (Z =64, N =82). In this regard it is important to investigate the ground state spins of odd-proton terbium isotopes (Z =65).

The ground state spins of ^{159,157,155}Tb nuclei were measured /2,3/ as I_0 =3/2. All three nuclei apparently belong to the region of deformed rare-earth nuclei and their ground state configurations are associated with the $3/2^+$[411] Nilsson orbital which should be occupied by the 65th proton at a prolate deformation with deformation parameter value $\delta \approx 0.3$ /4/. The spin of the ^{153}Tb ground state was measured/2/ to be I_0 =5/2 and the shape transition features were indicated in this nucleus by several investigators (see, e.g., refs. /5,6/). The value I_0 =1/2 was experimentally determined/2/ for the ^{151}Tb ground state and the $1/2^+$[420] configuration at a small oblate deformation was suggested/5/ on the basis of calculations performed in the framework of a nonadiabatic treatment of rotational motion and Coriolis coupling.

The spins of the beta decaying states of ^{147}Tb and ^{149}Tb nuclei have not yet been measured and different tentative proposals for their spins were made /7-9/ on the basis of indirect experimental information and their analogy with neighbouring nuclei. In ^{147}Tb(N =82) the $3s_{1/2}$, $2d_{3/2}$ and $1h_{11/2}$ shell-model orbitals are the most probable ones available for the 65th proton at low energies/1/. The low-lying $11/2^-$ states with considerable electron capture or β-decay branches have been indentified /10,11/ in ^{147,149,151}Tb nuclei. In the two heavier isotopes they appear as excited states, while in the ^{147}Tb the order of the two known beta-decaying states cannot be definitely established on the basis of available experimental information /1/.

The measurements of directional distribution of gamma-rays emitted by an oriented ensemble of radioactive nuclei provide in principle a possibility to test the spin value of the initial state. When an anisotropic directional distribution is observed for at least one gamma-ray transition accompanying the decay of the parent state, the spin I_0 of this state cannot be less than unity[12]. On the other hand, when the observed directional distribution appears to be isotropic within certain limits of experimental errors, the conclusion that I_0 is less than unity is usually not easy to make for several reasons: (i) It may be that B_λ is zero or close to zero even if $I_0 \geq 1$ when either the magnetic momentum of the state to be oriented is close to zero or when field which this magnetic moment experiences is too small to lead to a significant orientation. (ii) The initial orientation can be largely destroyed by the emission of unobserved radiation preceding the observed gamma-ray transitions. (iii) The directional distribution coefficient $A_\lambda(\gamma)$ may be small depending on the multipole mixing ratio and the spins of the initial and final states connected by the observed transition.

In the present work the ^{147}Tb ($T_{1/2} = 1.7(1)$ h), ^{149}Tb ($T_{1/2} = 4.15(5)$ h) and ^{151}Tb ($T_{1/2} = 17.7(1)$ h) nuclei were oriented in a gadolinium host at low temperatures $T \lesssim 20$ mK using a dilution refrigerator of the SPIN-facility[13]. The directional distributions of gamma-rays accompanying the decays of these nuclei were measured. On the basis of these results the spin values of the parent terbium states are discussed and in the analysis of the experimental data we take account of the results of numerous studies of the decays of ^{147}Tb, ^{149}Tb and ^{151}Tb isotopes[7-8, 14-18]. The present investigation is a continuation of our preceding studies of terbium and gadolinium isotopes by means of the nuclear orientation technique[19].

2. EXPERIMENTAL TECHNIQUE

2.1. Sample Preparation

The ^{147}Tb, ^{149}Tb and ^{151}Tb nuclei were produced using the spallation reaction induced by 660 MeV protons on a tantalum target on the JINR synchrocyclotron. Chemical separation of the terbium fraction from the irradiated target was carried out and the desired terbium isotope was mass-separated and implanted into a gadolinium host. The TbGd samples were prepared according to the procedure used in other experiments[13,19] and we have found the method to be reliable and reproducible. Sample activities were typically $\approx 10^6$ Bq and the atomic concentration of Tb in Gd was less than 1 part in 10^5.

2.2. Apparatus and Data Handling

The terbium atoms were oriented by the hyperfine interaction at low temperatures. The hyperfine magnetic field acting on terbium nuclei in gadolinium is known[20] to be 303 T. The TbGd samples were cooled to $T \lesssim 20$ mK. An external magnetic field of 0.85T was applied to polarize the magnetic domains of the hosts.

The gamma-ray spectra were measured using coaxial Ge(Li) detectors of 30, 55 and 50 cm^3 sensitive volumes. The spectrometers gave resolution of 3.1, 3.1 and 2.0 keV FWHM, respectively, at 1.3 MeV gamma-ray energy. The spectra were taken simultaneously at emission angle $\theta = 0$ (or π) and $\theta = \pi/2$ relative to the external magnetic field direction.

The intensities of dominant gamma-ray transitions were determined using the peak fitting routine SIMP[21] and these were normalized to sets of measurements carried out at 800 mK when the source ensemble was considered to be fully random. From these two measurements the gamma-ray anisotropies were determined and an important correction in this calculation was to account for the source decay.

3. MEASUREMENTS AND RESULTS

3.1 Decay of ^{147}Tb

The data taking procedure was carried out in the following sequence. Two gamma-ray spectra measurements were carried out at a sample temperature of $T \approx 15$ mK. They were followed by two runs performed at $T_0 \approx 800$ mK. Each run was taken for 1 h and the first one started 2 h after the sample was loaded into the refrigerator and 3 h after the end of mass-separation. The averaged normalized intensities, W, of the nine prominent gamma-rays of ^{147}Tb observed at $\theta = 0$ are given in table 1. The mean-square deviations quoted in the table include the errors of the peak area determination and a decay correction factor of less than 2%. As the data of table 1 demonstrate, no deviations from isotropic directional distributions of gamma-

Table 1

Normalized intensities of gamma-rays accompanying the decay of oriented ^{147}Tb isotope

E_γ [keV]	W(0)	E_γ [keV]	W(0)	E_γ [keV]	W(0)
139.8	0.97(4)	554.2	1.01(4)	1947.1	0.98(5)
406.9	1.06(6)	694.1	1.01(3)	2562.1	1.05(6)
547.1	0.96(6)	1152.0	1.01(3)	2680.2	1.06(6)

Table 2

Peak area ratios and normalized gamma-ray intensities for prominent transitions in the decay of the 38.1 h ^{147}Gd (daughter of the 1.7 h ^{147}Tb)

E_γ [keV]	$A(E_\gamma)$: A(229.3 keV)		W(0) - 1 Present work	$B_2A_2U_2$ ref.[28]
	T = 15 mK	T = 800 mK		
229.3			a)	0.008(6)
369.9	0.2772(30)	0.2592(20)	0.078(16)	0.037(5)
395.9	0.4885(45)	0.5063(40)	-0.027(13)	-0.033(7)
928.9	0.1595(35)	0.1462(15)	0.100(28)	0.085(6)

a) Reference value for normalisation of our data of ref./28/.

ray intensities have been found at temperature T≈15 mK, i.e. normalized intensities W (0) are equal to unity within the experimental errors. Very similar results were obtained also for the emission angle $\theta = \pi/2$. We also followed several prominent gamma-rays accompanying the decay of daughter isotope ^{147}Gd ($T_{1/2}$ =38.1 h). Although the decay corrections in this case were more complicated, anisotropic directional distributions were still observed for these gamma-rays (see table 2), proving that the source preparation method was good.

In the analysis of our data the decay scheme of a recent work/15/ was used. Our experimental results support the spin value I_0 =1/2 suggested for the 1.7 h ^{147}Tb isotope/22/. However, it may be noted that the I_0 =3/2 possibility cannot be ruled out mainly due to ambiguities of the ^{147}Tb decay data. For instance, assumming the spin I_0 =3/2 of the parent state, the statistical tensor component B_2 (I_0=3/2) $\lesssim$ 1 is implied and the deorientation factor $U_2 \lesssim 0.2$ can be estimated for the first excited $3/2^-$ level at 1153 keV in ^{147}Gd. The directional distribution coefficient is A_2 =−0.14 for the $3/2^- \rightarrow 7/2^-$ ground state E2 transition. Consequently, the anisotropy for the 1153 keV transition at θ =0 is expected to be less than 0.03 which is in accordance with the experimental value in table 1.

3.2. Decay of ^{149}Tb

The measurements were carried out in a similar way to the ^{147}Tb experiment and the directional distributions of 36 gamma-rays were found to be isotropic within the experimental errors (see table 3). A ^{57}CoFe nuclear orientation thermometer was used to check the ^{149}TbGd sample temperature.

Table 3

Normalized intensities of gamma-rays accompanying the decay of oriented ^{149}Tb isotope

E_γ [keV]	W(0)	E_γ [keV]	W(0)	E_γ [keV]	W(0)
165.0	1.00(1)	955.7	1.00(5)	1341.2	1.02(2)
187.2	1.00(1)	965.6	0.96(4)	1379.1	0.96(5)
352.2	1.00(1)	979.1	0.99(4)	1402.9	0.96(5)
388.6	1.00(1)	1002.1	0.97(7)	1449.1	1.00(3)
464.9	1.00(1)	1040.7	0.98(2)	1640.3	1.00(2)
652.1	0.99(1)	1131.7	0.95(4)	1806.0	0.96(5)
674.6	0.99(5)	1135.3	0.99(2)	1827.4	0.98(3)
740.2	1.00(6)	1167.1	0.98(5)	1940.1	1.00(6)
772.7	0.98(2)	1175.4	1.00(1)	1948.5	1.05(5)
817.1	1.00(1)	1191.9	1.02(6)	2007.9	1.00(4)
853.4	1.00(1)	1205.2	0.97(4)	2182.6	1.01(5)
861.9	0.99(2)	1302.9	1.00(3)	2282.6	1.01(5)

Our results are consistent with the tentative suggestion/7/ that the ground state spin of ^{149}Tb is I_0 =1/2. In a similar manner to the ^{147}Tb decay, it can be shown that the spin I_0 = =3/2 cannot be ruled out using our experimental data and the present ^{149}Tb decay scheme/7/.

The ^{149}Tb ground state spin values I_0 =5/2 or 3/2 were proposed in ref./9/. On the basis of our experimental data, we may exclude the I_0 =5/2 possibility. The statistical tensor component $B_2(I_0=5/2) < 0.98$ was estimated from our data on the 1302.9 and 1341.2 keV transitions at a 3σ confidence level. These gamma-rays are known/7/ to be the E1 transitions de-exciting the 1655.2 and 2158.3 keV positive parity levels in ^{149}Gd to the 352.2 and 817.1 keV $3/2^-$ levels, respectively. Both the initial levels are populated through strong direct beta-transitions from the ^{149}Tb ground state and their population through beta-gamma cascades is negligible/7/. We have assumed the spins of the initial levels 1655.2 and 2158.3 keV to be 3/2 or 5/2 on the basis of the decay branching and logft

Table 4

Normalized intensities of gamma-rays accompaying the decay of oriented ^{151}Tb isotope

E_γ[keV]	W(0)	E_γ[keV]	W(0)	E_γ[keV]	W(0)
180.4	0.99(1)	604.8	1.00(1)	1182.2	1.01(1)
192.1	1.00(2)	616.6	1.00(1)	1191.4	1.00(2)
251.7	1.00(1)	656.7	1.00(2)	1195.4	0.97(3)
287.0	0.99(1)	661.0	1.00(2)	1222.3	0.99(1)
380.4	0.99(1)	692.3	1.00(1)	1312.4	1.00(1)
385.4	0.96(5)	703.8	1.00(1)	1384.0	1.04(3)
395.3	1.00(1)	731.1	1.00(1)	1483.6	1.02(2)
416.4	0.99(1)	762.8	1.02(2)	1495.4	1.01(2)
426.5	1.00(1)	805.6	1.01(1)	1599.7	1.00(2)
443.7	0.99(1)	905.7	1.00(1)	1670.7	1.00(1)
467.4	0.98(3)	1110.2	1.00(1)	1779.0	1.03(3)
536.7	1.02(5)	1157.9	1.03(2)	1815.8	0.99(2)
587.3	1.00(1)	1171.2	1.00(1)	1870.1	0.98(2)

values of ref./7/. Neglecting the electric quadrupole hyperfine interaction, the value of the ^{149}Tb ground state magnetic dipole moment $|\mu| < 0.9$ n.m. (i.e., 4.6×10^{-27} J/T) can be deduced from the above limit of the B_2-value. This limit of μ appears to be too low in comparison with the measured μ-values of the lowest $5/2^+$ states in the neighbouring odd-proton nuclei ^{151}Eu, ^{147,149}Pm and ^{141,143}Pr, for which the values 2.5 n.m. have been reported/23/ thus making the spin $I_0 = 5/2$ of ^{149}Tb ground state very improbable.

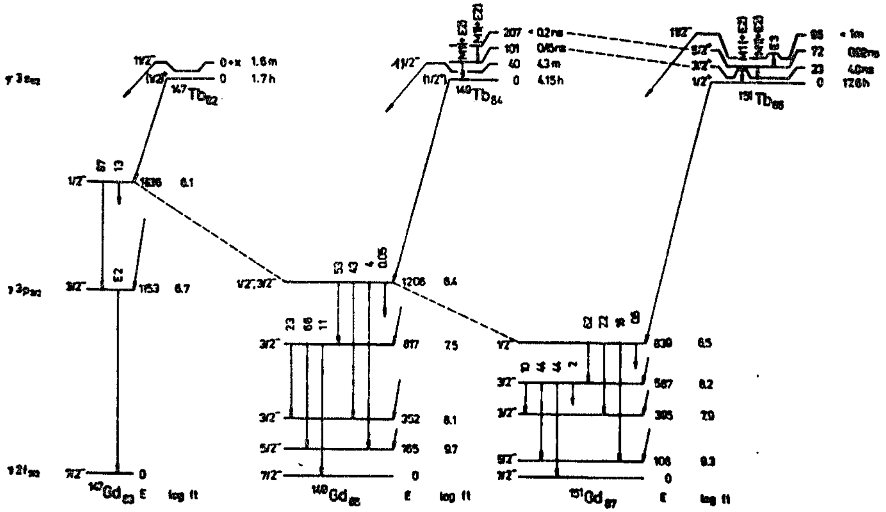
3.3. Decay of ^{151}Tb

Normalized intensities of 39-gamma-rays occurring in the decay of 17.7 h ^{151}Tb at $\theta = 0$ are summarized in table 4 as weighted averages of several measurements performed with several samples. A ^{54}Mn<u>Ni</u> nuclear orientation thermometer was used to control the temperature of the ^{151}Tb<u>Gd</u> sample. From the data of the table and from quite similar results obtained for the emission angle $\theta = \pi/2$, one may conclude, that gamma-ray directional distributions of the observed transitions are isotropic within experimental errors at a sample temperature of $T \approx 15$ mK. This is consistent with the measured/2/ value $I_0 = 1/2$ of ^{151}Tb ground state spin.

4. DISCUSSION

Recently high-spin states in light-mass terbium and gadolinium nuclei were investigated by several groups /1,24,25/ and regularities in properties of these states in ^{147,149,151}Tb and ^{147,149}Gd nuclei were observed and shown/25/ to be understandable in terms of excitations of few-valence particles added to the (N = 82, Z = 64) - core. Similar picture for the low-spin levels in these nuclei cannot be drawn, due to lack of experimental data, however, some regularities may exist, too.

Some experimental data on the low-spin states in terbium and gadolinium nuclei with mass-numbers A = 147, 149, 151 are summarized in the figure (gamma-ray branching was normalized



<u>Figure.</u> Parts of the decay schemes of odd-mass terbium isotopes. Log ft values for A = 147 were recalculated by us assuming no beta-feeding of the ^{147}Gd ground state. The other data shown on the figure are discussed in text or taken from references cited in text.

to 100% for each initial level in the figure separately). The spin of the $T_{1/2}$ =1.7 h state in ^{147}Tb is obviously 1/2 (ref.[22]) and the spins of the ^{151}Tb levels shown in figure are well established[2,11]. The ^{149}Tb ground state spin is obviously less than 5/2. The spins of the 101 and 207 keV states in ^{149}Tb are not definitely determined, however their certain resemblance to the ^{151}Tb levels seems to hold. Measured M1 - transition probabilities[8,18] of corresponding transitions (see the figure) in both nuclei do not contradict to this resemblance. Thus spin and parity $1/2^+$ is the most probable one for the ^{149}Tb ground state, too. The nuclear orientation data presented here are consistent with the 1/2 assignments to the low-spin beta-decaying states in all three odd-mass terbium isotopes.

The beta-transitions from the low-spin states in ^{147,149,151}Tb to the odd-parity levels at 1847, 1206 and 839 keV in ^{147}Gd, ^{149}Gd and ^{151}Gd, respectively, differ from the other first forbidden beta-transitions occurring in the decays by having rather low values of log ft =6.1, 6.4 and 6.5, respectively, compared to log ft$\gtrsim$7 for the other beta-transitions. The level at 1847 keV in ^{147}Gd was recently shown to be a $1/2^-$-level[26] and the beta-transition to this level may proceed mainly by the $\pi 3s_{1/2} \rightarrow \nu 3p_{1/2}$ transition. Analogous low log ft values of ≈5.2 and ≈6.3 were observed[27] for the $\pi 3s^{-1}_{1/2} \rightarrow \nu 3p^{-1}_{1/2}$ first forbidden beta-transitions in the vicinity of the ^{208}Pb nucleus.

The similarity between ^{149}Gd and ^{151}Gd nuclei has recently been outlined[7], however, the spin 3/2 was considered in ref.[7] for the 839 keV level in ^{151}Gd, which is different from the 1/2-value accepted in the figure on the basis of the angular correlation results[11]. Moreover, considering the angular correlation coefficients of ref.[16] and ^{149}Tb decay scheme of ref.[7], the unambiguous $3/2^-$-assignment to the 1206 keV level in ^{149}Gd seems not to be clear and $1/2^-$-possibility should be also considered. Thus further investigations of low-spin states in odd-mass terbium and gadolinium nuclei will be necessary in order to provide the complementary data to those on high-spin states.

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Фингер М. и др. Ядерная ориентация ^{147}Tb / $T_{1/2}$ =1,7 ч/, ^{149}Tb / $T_{1/2}$ =4,15 ч/ и ^{151}Tb / $T_{1/2}$ =17,7 ч/ в гадолиниевой матрице E6-82-150

Радиоизотопы ^{147}Tb / $T_{1/2}$ =1,7 ч/, ^{149}Tb / $T_{1/2}$ =4,15 ч/ и ^{151}Tb / $T_{1/2}$ =17,7 ч/ ориентировались в гадолиниевой матрице при низких температурах. Угловое распределение интенсивных γ -переходов оказалось изотропным в рамках экспериментальных ошибок. Этот факт находится в согласии с присвоением спина 1/2 для всех трех материнских состояний.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

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Finger M. et al. Nuclear Orientation of ^{147}Tb($T_{1/2}$=1.7 h), ^{149}Tb ($T_{1/2}$=4.15 h) and ^{151}Tb ($T_{1/2}$ =17.7 h) in a Gadolinium Host E6-82-150

Radioactive ^{147}Tb ($T_{1/2}$ =1.7 h), ^{149}Tb ($T_{1/2}$ =4.15 h) and ^{151}Tb ($T_{1/2}$ =17.7 h) nuclei were oriented in a gadolinium host at low temperatures. Angular distributions of prominent gamma-rays were found to be isotropic within the experimental errors. This is consistent with the 1/2 - spin assignments to all three parent states.

The investigation has been performed at the Laboratory of the Nuclear Problems, JINR.

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