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NUCLEAR ORIENTATION STUDY OF ^{155}Tb DECAY

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Изучение распада ^{155}Tb методом ядерной ориентации

В работе изучалось угловое распределение гамма-лучей, сопровождающих распад ядер ^{155}Tb, ориентированных в гадолиниевой матрице при сверхнизких температурах. Получено значение параметра сверхтонкого магнитного дипольного расщепления для ^{155}Tb(Gd) и найдено значение магнитного момента основного состояния ^{155}Tb μ=2,0(2) я.м. Определены соотношения смеси мультиполей для 9 гамма-переходов в ^{155}Gd .

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Nuclear Orientation Study of ^{155}Tb Decay

The angular distribution of gamma-rays following the electron capture decay of ^{155}Tb nuclei oriented in a gadolinium host has been studied at temperatures between 16 and 80 mK. The magnetic dipole hyperfine splitting parameter for ^{155}Tb(Gd) has been deduced and the value of the magnetic dipole moment of ^{155}Tb ground state has been found to be $\mu = 2.0(2)\mu_N$. The multipole mixing ratios have been determined for 9 gamma-transitions in ^{155}Gd .

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

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1. INTRODUCTION

The odd-mass terbium nuclei (Z=65) are important for nuclear structure studies because they provide good possibility of investigating systematically the effects connected with changes of nuclear shape in the transitional region of mass numbers near A =150. Therefore, precise experimental data about the energy levels of odd-mass Tb isotopes, their decay properties and nuclear moments are required.

The well developed rotational bands were recently observed in ^{155,157,159}Tb nuclei/1/ and, therefore, all three isotopes were considered/1,2/ to have well pronounced stable equilibrium deformation. On the other hand, experimental features of ^{151,153}Tb nuclei indicated changes of nuclear shape and decrease of deformation/2/. The ground state spins of ^{155,157,159}Tb nuclei are known to be I_0 =3/2. For the ^{157,159}Tb isotopes, the ground state magnetic dipole moments μ =2.0(1) and + 1.994(4)μ_N , respectively, were determined/3/. The only experimental information on the magnetic dipole moment of the ^{155}Tb ground state was obtained from the analysis of observed interband transition probabilities in the ground state rotational band. In such a way the value of $\mu = 1.20(5)\,\mu_N$ was obtained[4] which appeared to be considerably smaller in comparison with the experimental μ-values for ^{157,159}Tb isotopes.

The electron capture decay of ^{155}Tb ($T_{1/2}$ =5.6d) to the levels of ^{155}Gd has alredy been investigated in many studies in which the precise gamma-ray energies and intensities and the internal conversion data were obtained as well as the gamma-gamma coincidences and angular correlations were measured[5,6]. Recently the nuclear orientation and angular correlation methods were applied[7] to investigate the level spins and multipole mixing of the gamma-transitions in ^{155}Gd. Continuing this work we have used the technique of nuclear orientation in hyperfine field at ultra-low temperatures to investigate the magnetic dipole hyperfine splitting parameter a_o for ^{155}Tb atoms soluted in the gadolinium host matrix. For this purpose the temperature dependences of angular distribution of gamma-rays following the decay of oriented ^{155}Tb nuclei were maesured using the nuclear orientation facility SPIN (Ref. [8]). The experimental value of the magnetic dipole moment μ of the ^{155}Tb ground state was deduced. In addition, the multipole mixing ratios of several gamma-transitions in ^{155}Gd were obtained.

2. BASIC THEORETICAL EXPRESSIONS

The angular distribution $W(\Theta, T)$ of gamma-rays emitted by an ensemble of oriented radioactive nuclei can be expanded[9] in terms of the Legendre polynomials P_k. In our case, the oriented nuclear state has the spin $I_o = 3/2$. Therefore, only zero and second order terms are involed and we can write for a particular gamma-ray transition

$$W(\Theta; T) = 1 + A_2 U_2 Q_2 B_2 G_2 P_2(\cos\Theta) . \qquad (1)$$

The gamma-ray emission angle Θ is related to the orientation axis.

The multipole mixing ratio δ of an observed gamma-ray transition comes into eq. (1) through the angular distribution coefficient A_2 which can be written in terms of tabulated F_2-coefficients[10] as

$$A_2(\delta) = [F_2(I_i, I_f, L, L) + 2\delta F_2(I_i, I_f, L, L+1) +$$

$$+ \delta^2 F_2(I_i, I_f, L+1, L+1)](1+\delta^2)^{-1} .$$

The deorientation due to the transitions preceding the gamma-ray transition observed is included in eq. (1) by the U_2-coefficient. The correction for the finite solid-angle of the detection and for the absorbers between a radioactive source and a detector is taken into account by the Q-coefficient.

When hyperfine splitting of nuclear levels is combined with an ultra-low temperature technique to achieve nuclear orientation, the orientation coefficient B_2 is written as[9]

$$B_2(I_o, a_o, P, T) = \sqrt{5(2I_o+1)} \sum_{m=-I_o}^{+I_o} (-1)^{I_o+m} \begin{pmatrix} I_o & I_o & 2 \\ -m & +m & 0 \end{pmatrix} p_m ,$$

Boltzman factors p_m involve the temperature T of the ensemble and the energy E_m of m-th substate which is expressed/11/ through the magnetic dipole and electric quadrupole hyperfine splitting parameters $a_o = \mu H_{hf}/I_o$ and P, respectively,

$$E_m = -a_o \cdot m + P[m^2 - \frac{1}{3} I_o(I_o + 1)].$$

Here μ is the magnetic dipole moment of the oriented state and H_{hf} means the magnetic hyperfine field. The parameter P is proportional to the spectroscopic quadrupole moment Q_{I_o} of the oriented state and the gradient q of the hyperfine electric field/11/

$$P = \frac{3eqQ_{I_o}}{4I_o(2I_o - 1)} . \qquad (2)$$

The G_2 -factor in eq. (1) accounts for possible incomplete saturation of the ferromagnetic matrix/12/.

3. EXPERIMENTAL PROCEDURE

3.1. Sample Preparation

The ^{155}Tb isotope was produced by bombarding the tantalum target by 660 MeV protons at JINR synchrocyclotron. The terbium fraction was chemically separated from the irradiated target and the ^{155}Tb isotope was then selected by mass-separation onto an aluminium foil. After chemical purification from the Al backing the ^{155}Tb activity was obtained in the form of terbium chloride. The ~10μC activity was deposited together with ~0.05 g of gadolinium onto the tantalum foil of 0.1 mm thickness. The foil was then dryed and after that a 10 second heating just above the melting point of gadolinium was carried out in a furnace in a vacuum of ~10^{-4} Pa. A 10 min controlled cooling of the sample down to the 950°C followed. Then the cooling continued at the cut off heater. Afterwards the Ta backing was soldered in vacuum to a copper foil of ~0.5 mm thickness with AgCuTi solder. Finally the sample was cutted and abraded. After these procedures the sample having the shape of 0.5 cm diameter disk could be soldered to the thermal support base of the low temperature apparatus.

3.2. Experimental Equipment

Nuclear orientation was produced by means of the SPIN-facility/8/ using the hyperfine field in ferromagnetic host to polarize an ensemble of radioactive nuclei at ultra-low temperatures. The top-loading ^{3}He-^{4}He dilution refrigerator/13/ was utilized to obtain ultra-low temperatures. A ^{54}Mn(Ni) nuclear thermometer was used for determining temperature of the ^{155}Tb(Gd) sample. An external magnetic field of 0.85 T was applied to align the magnetic domains in the Gd and Ni hosts .

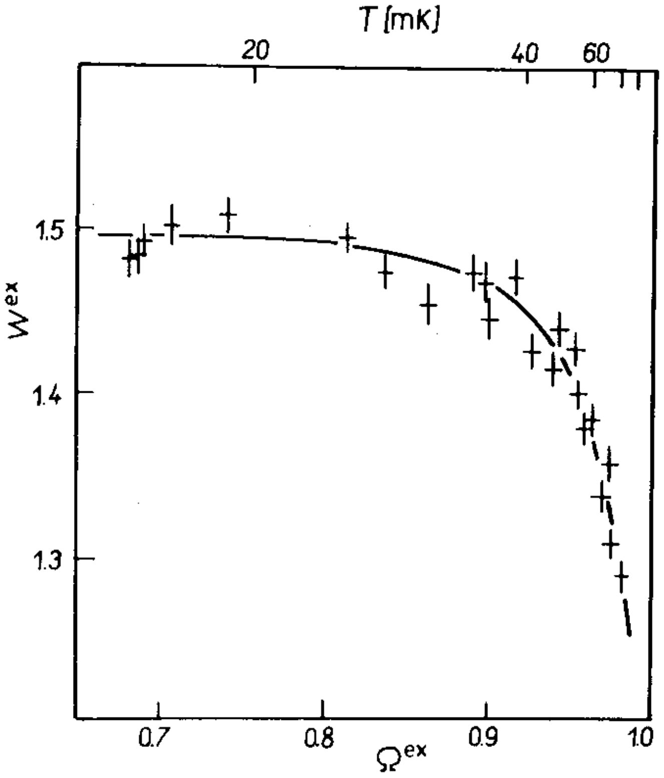
The gamma-rays emitted in the directions $\Theta = 0$ and π related to the external magnetic field were measured simultaneously using two

Ge(Li) detectors. The low-energy gamma-rays below 200 keV were detected at $\Theta=0$ by a planar X-ray detector having 100 mm^2 area, 7 mm thickness and 0.63 keV resolution at 160 keV gamma-ray energy. A 35 cm^3 coaxial detector shielded by a 0,5 mm lead absorber was used at $\Theta=\pi$ to detect the gamma-rays having energy between 200 and 1000 keV. The source-to-detector distances were 7.5 cm for the planar detector and 9.0 cm for the coaxial one. The data collection system has been described elsewhere/8/ .

4. MEASUREMENTS AND RESULTS

The angular distributions $W(\Theta,T)$ of ^{155}Tb gamma-rays were measured in the region from 16 to 80 mK. The three 3000 seconds runs were usually taken for the temperature T adjusted and the summing of appropriate spectra was then performed. Several runs were also carried out at a temperature $T_o \approx 1$K for which the gamma-ray angular distribution is isotropic. The normalized gamma-ray intensities $W^{ex}(\Theta,T)$ were determined as the ratios of areas of peaks observed at the temperatures T and T_o. Peak areas and their mean square deviations were evaluated by means of the BESM-6 computer using the system of programs SIMP(Ref./14/).

In the Figure the observed normalized intensities W^{ex} of the 161.3 keV gamma-ray of ^{155}Tb are plotted versus the normalized intensities Ω^{ex} of the 835 keV gamma-line of the ^{54}Mn(Ni) nuclear thermometer.



The observed normalized intensities W^{ex} of the 161.3 keV gamma-transition in ^{155}Gd plotted versus the normalized intensities Ω^{ex} shown by the 835.4 keV gamma-transition of the ^{54}Mn(Ni) nuclear thermometer. The theoretical curve (full line) was obtained by least-square fit for $P=0.9\times10^{-6}$ eV. The temperature scale is also shown.

4.1. The Mixing Ratios of Gamma-Ray Transitions in ^{155}Gd

The normalized intensities were determined for 13 gamma-transitions in ^{155}Gd. In the temperature region from 16 to 23 mK they were found to be independent of temperature within the experimental errors (see the Figure). Therefore, the weighed average values of normalized intensities were obtained from six runs made in this temperature region. These average values are presented in Table 1. Moreover, one can take for this region of temperatures the maximum value of the orientation coefficient B_2 which is $B_2 = 1$ for the spin $I_o = 3/2$.

The multipole mixing ratios δ were determined from our normalized intensities using the ^{155}Tb decay scheme published earlier/6,7/ . The 161.3 keV gamma-transition between the $5/2^+$-level at 266.6 keV and $3/2^+$-level at 105.3 keV was considered as the reference one and its A_2-coefficient 1.00(12) was taken from Ref./7/ . The deorientation coefficient for the 266.6 keV level can be easily calculated as direct beta-feeding of this level from ^{155}Tb ground state strongly prevails the other modes of feeding. Using the above results the experimental A_2-coefficients and the δ-mixing ratios for 9 gamma-transitions in ^{155}Gd were obtained. They are listed in Table 2. Single-valued mixing ratios were deduced by comparing our results with those of gamma-gamma angular correlation study/7/ or using the experimental conversion coefficients/6/ . The general agreement of the present δ-values with those of Refs./6,7/ can be seen from Table 2.

Table 1

The normalized intensities of observed gamma-transitions in ^{155}Gd

E_γ [keV]	W^{ex}	E_γ [keV]	W^{ex}
86.6	1.057(7)	200.4	1.08(7)
105.3	0.957(7)	262.3	0.99(1)$^{a)}$
148.6	0.973(7)	268.6	0.95(2)
161.3	1.489(9)	281.1	1.03(3)$^{a)}$
163.3	0.931(6)	287.0	0.90(3)
180.1	0.914(5)		
181.7	0.89(12)	367.4	1.011(7)$^{b)}$

a) The transition depopulates the $1/2^+$-level/6/ .

b) The line is an unresolved doublet/6/ .

4.2. The Hyperfine Splitting Parameter a_o for ^{155}Tb(Gd)

The temperature dependence of normalized intensity of the 161.3 keV gamma-transition in ^{155}Gd was used to obtain the value of a_o for the ^{155}Tb(Gd). The temperature T of the ^{155}Tb(Gd) sample and, consequently, the angular distribution function W of 161.3 keV gamma-ray were understood as functions of the normalized intensity Ω of the nuclear thermometer gamma-ray. Eq. (1) is then rewritten as

Table 2

The multipole mixing ratios of observed gamma-transition in ^{155}Gd.

Initial level					Present results		Ref. /7/		$\lvert\delta\rvert$
E level [keV]	$I_i\ \pi_i$	U_2 a)	E_γ [keV]	$I_f\ \pi_f$	A_2	δ	δ		Ref./6/ d)
							b)	c)	
86.6	$5/2^+$	0.27(5)	86.6	$3/2^-$	0.30(6)	0.039(34)		0.039(8)	e)
105.3	$3/2^+$	0.19(3)	105.3	$3/2^-$	-0.32(8)	-0.05(5)		-0.06(7)	e)
266.6	$5/2^+$	0.704(6)	148.6	$7/2^+$	-0.06(2)	-0.14(1)	-0.12(2)	-0.23(8)	0.14(4)
			161.3	$3/2^+$	1.00(12) f)				
			180.1	$5/2^+$	-0.18(3)	-0.23(2)	-0.215(14)		0.18
268.6	$3/2^+$	0.20 g)	163.3	$3/2^+$	0.49(7)	0.06(5)	$0.12(^{+13}_{-11})$	0.13(9)	0.1
			268.6	$3/2^-$	-0.38(15)	-0.01(10)	$0.12(^{+11}_{-12})$		e)
287.0	$3/2^-$	0.2÷1.0 h)	181.7	$3/2^+$	-0.6÷0.1	-0.32÷0.14			e)
			200.4	$5/2^+$	-0.0÷0.4	-0.11÷0.27		-0.16(12)	e)
			287.0	$3/2^-$	-0.45÷(-0.07)	-0.21÷0.03	-0.24÷0.21		0.5

Table 2

Continued

a) The U_2 -coefficients calculated from the ^{155}Tb decay scheme of Ref./6/; with the one exception (see comment h) pure $L_\beta = 1$ beta-transitions were assumed.

b) The nuclear orientation results.

c) The gamma-gamma angular correlation results.

d) The internal conversion results.

e) The E1 multipolarity suggested by the experimental internal conversion coefficients.

f) The reference value/7/.

g) The tabulated value/10/ for direct beta-transition from ^{155}Tb ground state; the influence of beta-gamma cascade feeding was neglibible.

h) The limits corresponding to assumption of pure L_β=0 and L_β= 1 direct beta transition from the ^{155}Tb ground state.

$$W(0, T(\Omega)) = 1 + K_2 B_2(I_o, a_o, P, T(\Omega)), \qquad (3)$$

where $K_2 = G_2 A_2 U_2 Q_2$. Following the general least-square method/16/, the functional

$$\chi^2 = \sum_i \left[\frac{(\Omega_i - \Omega_i^{ex})^2}{\sigma^2_{\Omega_i}} + \frac{(W_i - W_i^{ex})^2}{\sigma^2_{W_i}} \right] \qquad (4)$$

was considered involving the sets of the experimental values Ω_i^{ex}, W_i^{ex} and the respective mean square deviations $\sigma^2_{\Omega_i}$ and $\sigma^2_{W_i}$.

Taking the constraint conditions $W_i = 1 + K_2 \times B_2(I_o, a_o, T(\Omega_i))$ and considering the P-parameter to be fixed the optimal values of parameters a_o and K_2 and set of the Ω_i were searched for. The minimalization of the χ^2-functional was performed using the known Gauss-Newton method. It turned out that the minimal value of χ^2 and the optimal value of the K_2-parameter appeared to be practically independent of P in the broad region of P-values while the optimal values of a_o increased linearly with P.

An alternative approach to the analysis of $W^{ex}(0, T(\Omega))$ was also performed. An appropriate experimental point was considered as a reference one (the quantities related to this point are indexed by "r"). The quantities

$$R_i = [W(0, T(\Omega_i)) - 1]/[W(0, T(\Omega_r)) - 1]$$

are introduced together with the experimental values $R_i^{ex} = (W_i^{ex} - 1)/(W_r^{ex} - 1)$ and their mean square deviations $\sigma^2_{R_i}$. Using equation (3) we have then

$$R_i = B_2(I_o, a_o, P, T(\Omega_i))/B_2(I_o, a_o, P, T(\Omega_r)). \qquad (5)$$

Inserting the quantities R_i, R_i^{ex} and $\sigma^2_{R_i}$ instead of W_i, W_i^{ex} and $\sigma^2_{W_i}$, respectively, into eq. (4), the minimalization of χ^2 was carried out under the constraint conditions (5) which did not involve the K_2-parameter. As in the former case the P-parameter was considered to be fixed. The results of minimalization agreed closely with those obtained by the former procedure.

So we can see that if we want to obtain the magnetic dipole hyperfine splitting parameter a_o for ^{155}Tb independent knowledge on the electric quadrupole hyperfine splitting for ^{155}Tb(Gd) is required. From the data on the rare-earth metals summarized in Ref./11/ we can take the P-parameter for ^{155}Tb(Gd) to be positive. The value of $P = 1.46(1) \times 10^{-6}$ eV was obtained from NMR-measurements/17/ for the ^{159}Tb(Gd). Experimental data indicate the ^{155}Tb nucleus to be deformed and its deformation does not exceed that of the ^{159}Tb isotope/1/. Expression (2) then implies that the P-parameter for ^{155}Tb(Gd) is not greater than 1.5×10^{-6} eV.

The optimal value of a_o obtained from our fit increased linearly from $1.64(6) \times 10^{-5}$ to $2.06(6) \times 10^{-5}$ eV when P was risen from zero to 1.5×10^{-6} eV. Considering the 3σ confidence level we then find that the magnetic dipole hyperfine splitting parameter a_o for the ^{155}Tb(Gd) must lie between 0.9×10^{-5} and 1.5×10^{-5} eV.

4.3. The Magnetic Dipole Moment of the ^{155}Tb Ground State

Using the above limits of the a_o-parameter and the value of the magnetic hyperfine filed of the Tb(Gd) $H_{hf} = 303(3)$ T which was obtained from the NMR-measurements/17/ we can see that the magnetic dipole moment μ of the ^{155}Tb ground state must fall inside the interval from 0.77×10^{-26} to 1.2×10^{-26} J/T(from 1.5 to 2.3 μ_N). This means that the magnetic dipole moment of the ^{155}Tb ground state is greater than the value of $\mu = 1.20(5)\,\mu_N$ estimated/3/ from experimental interband transition probabilities of the ^{155}Tb ground state rotational band.

In Ref./3/ the value of the electric quadrupole moment of the ^{155}Tb ground state $Q_o = 4.2(5)\times10^{-28}\,\mathrm{m}^2$ was derived. Taking this result and using experimental value of the spectroscopic quadrupole moment of the ^{159}Tb ground state $Q_{I_o} = 1.32(10)\times10^{-28}\,\mathrm{m}^2$/16/ the electric quadrupole splitting parameter for the ^{155}Tb(Gd) $P = 0.9(1)\times10^{-6}$ eV can be found. In this case we obtained from our experimental result the value of $\mu = 1.0(1)\times10^{-26}$ J/T (i.e. $2.0(2)\mu_N$). Similar experimental values of magnetic dipole moments $\mu = 2.0(1)$ and $+1.994(4)\,\mu_N$ were obtained/4/ for ^{157}Tb and ^{159}Tb isotopes, respectively. In the framework of the nonadiabatic model with the Coriolis coupling the values of $\mu = 2.0\,\mu_N$ and $Q = 4.2\times10^{-28}\,\mathrm{m}^2$ for the ^{155}Tb ground state were obtained/2/ .

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