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ON THE MAGNETIC DIPOLE MOMENT OF THE ^{153}Tb GROUND STATE

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1. INTRODUCTION

The ^{153}Tb nucleus is situated at the onset of deformation in the transition region from the well deformed nuclei with mass numbers $A \geq 155$ to nuclei near $A = 146$ which are considered to be essentially of spherical shape at low-energy excitations. Recently it has been suggested /1-4/ that among the odd-mass terbium nuclei the shape transition occurs just for the ^{153}Tb nucleus. Therefore, the ^{153}Tb nucleus provides a good possibility to test the validity of nuclear models proposed to describe transitional nuclei. In this connection the studies of various aspects of the structure of ^{153}Tb nucleus are of great importance. One of these studies is the experimental investigation of electromagnetic multipole matrix elements. Some experimental data concerning the multipole mixing of electromagnetic transitions in ^{153}Tb have been obtained from previous gamma-ray and internal conversion electron studies of ^{153}Dy decay (see Refs. /1-3/ and the references cited herein). Several multipole mixing ratios for the transitions in ^{153}Tb have been determined /3/ also using the gamma-gamma angular correlation technique. Up to now, however, no experimental information was available about the ^{153}Tb ground state magnetic dipole moment. Theoretical investigations /5/ of the odd-mass terbium isotopes, made in the framework of non-adiabatic model with Coriolis coupling, have recently appeared, which predict the ^{153}Tb ground state magnetic moment to be $\mu = 3.34\,\mu_N$.

The aim of the present study was to measure the magnetic dipole hyperfine splitting in ^{153}Tb(Gd) using low-temperature nuclear orientation technique and to provide experimental data on the magnetic dipole moment of the ^{153}Tb ground state. The temperature dependence of angular distribution of the 212.0 keV gamma-ray following the electron capture decay of 2.4 d ^{153}Tb has been measured at temperatures between 16 and 70 mK. This study is a continuation of our investigation of the decay of oriented ^{155}Tb(Gd) reported recently /6/, in which some aspects of the method of present experiment and analysis of data have already been described in more detail.

2. EXPERIMENTAL PROCEDURE

2.1. Sample Preparation

The ^{153}Tb isotope was produced using the spallation reaction on tantalum induced by 660 MeV protons at JINR synchrocyclotron. The ^{153}Tb was separated by mass-separator and implanted into a gadolinium foil. Afterwards, the thermal and mechanical treatment of the ^{153}Tb(Gd) sample described in Ref. /6/ has been performed. Concentration of ^{153}Tb atoms in the gadolinium host was estimated not to exceed 10^{-5} At %.

2.2. Experimental Apparatus

The orientation of ^{153}Tb nuclei was achieved by means of the SPIN-facility /7/ which can use the hyperfine field in ferromagnetic hosts and the ultra-low temperatures to polarize ensembles of radioactive nuclei. A ^{57}Co(Fe)nuclear orientation thermometer was used to determine the temperature of the ^{153}Tb(Gd) sample. Magnetic domains of gadolinium and iron hosts were polarized by applying an external magnetic field of 0.85 T.

The low-energy gamma-rays below 300 keV were detected. For this purpose a planar X-ray Ge(Li) detector of 5 mm thickness and 50 mm^2 area which gave 0.55 keV resolution (FWHM) at 122 keV energy was used. The detector was positioned at angle $\theta = \pi$ related to external magnetic field direction. The sample-to-detector distance was 8 cm.

2.3. Measurements and Results

The measurement of gamma-ray angular distribution function $W(\theta, T)$ was carried out for the set of 15 temperatures T selected in the interval from 16 to 70 mK. Because of poor temperature sensitivity of the ^{57}Co(Fe) nuclear orientation thermometer measurements at temperatures T above 70 mK were not reasonable. To normalize the gamma-ray intensities, several spectra were collected at temperature $T_0 \approx 1K$ for which the gamma-ray angular distribution became isotropic. Typical running time at an adjusted temperature was 8000 s. The photopeak areas $A_T(\theta)$ and their mean square deviations were evaluated by computer code SIMP (Ref. /8/). In Fig.1, the experimental normalized intensities

$$W^{exp}(\theta, T) = \frac{A_T(\theta)}{A_{T_0}(\theta)}$$

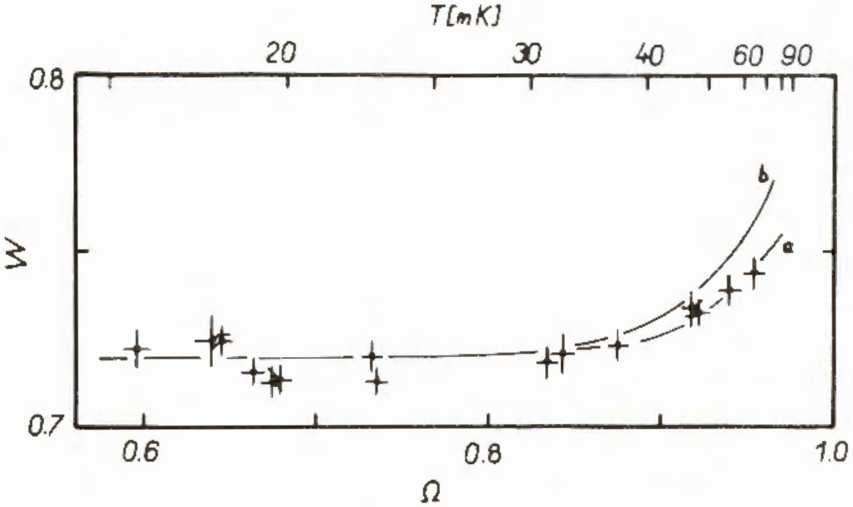

Fig. 1. The plot of normalized intensity W of the 212.0 keV gamma-ray transition in ^{153}Gd versus the normalized intensity Ω of the 136.5 keV gamma-ray transition of ^{57}Co(Fe) nuclear orientation thermometer. Temperature scale is also shown. Circles with crosses stand for measured quantities and their mean-square deviations. Full lines mean the calculated curves for zero limit value of P-parameter for ^{153}Tb(Gd) and for the optimal value of $K_2 = -0.212$ provided by our experiment. Curves a and b were obtained for the optimal value of the magnetic dipole hyperfine splitting parameter for ^{153}Tb(Gd) $a_0 = 1.4 \times 10^{-5}$ eV and the lower limit $a_0 = 1.2 \times 10^{-5}$ eV provided by present experimental data, respectively.

of the 212.0 keV gamma-ray transition in ^{153}Gd are plotted versus corresponding normalized intensities Ω^{exp} of the 136.5 keV gamma-ray of the ^{57}Co(Fe) nuclear orientation thermometer.

3. ANALYSIS AND RESULTS

As can be seen from Fig.1, the anisotropies for the 212.0 keV gamma-ray measured at the low-temperature part of the curve are close to the value $(1-W(0)) \approx 0.27$ observed in recent decay study /9/ of ^{153}Tb(Gd) oriented at temperature

T=15 mK. Note that the sample preparation procedure used in Ref.[9] was essentially the same as that used in the present work. Our experimental anisotropies appeared to be nearly constant below 40 mK and changed only slightly when temperature approached 70 mK. This considerably restricts the amount of information about the magnetic dipole hyperfine splitting parameter for ^{153}Tb(Gd) which could be obtained from analysis of measured temperature dependence and indicates that the hyperfine splitting energy for ^{153}Tb(Gd) should be rather large.

The gamma-ray transition at 212.0 keV is known [9,10] to be pure E1-transition which proceeds from a $3/2^+$-level to the ground state of ^{153}Gd. The ^{153}Tb ground state spin was measured [11] as $I_0 = 5/2$. Hence the theoretical angular distribution function $W(\theta, T)$ for this transition involves the zeroth and second order terms only and can be written [6] as

$$W(\theta = \pi,\ T(\Omega)) = 1 + K_2 \cdot B_2(I_0 = 5/2,\ a_0,\ P,\ T(\Omega)). \qquad (1)$$

Normalized gamma-ray intensity Ω of the nuclear orientation thermometer line at 136.5 keV was introduced as an independent variable in eq. (1). The dependence of $W(\theta, T(\Omega))$ on the sample temperature T and the magnetic dipole and electric quadrupole hyperfine splitting parameters [6] of ^{153}Tb(Gd), $a_0 \equiv \mu H_{eff}/I_0$ and $P \equiv 3eV_{zz}Q_{I_0}/(4I_0(2I_0 - 1))$, respectively, come through nuclear orientation coefficient B_2 only.

The χ^2-functional defined as

$$\chi^2 = \sum_{i=1}^{15} \frac{(W(\theta = \pi, T(\Omega_i)) - W_i^{exp})^2}{\sigma_i^2} \qquad (2)$$

was examined, in which W_i^{exp} and σ_i^2 were the above-specified experimental normalized gamma-ray intensities and their mean square deviations, respectively. The parameters K_2, a_0 and P were varied. The minimum value of χ^2 and the optimal value of $K_2 = -0.212(5)$ found in our analysis appeared to be independent of P in the wide range of P-values considered, while the optimal value of a_0-parameter increased linearly from 1.4×10^{-5} to 2.2×10^{-5} eV when P was risen from zero to 2.0×10^{-6} eV.

Independent knowledge on the electric quadrupole hyperfine splitting for ^{153}Tb(Gd) is necessary if one wants to deduce information on the magnetic dipole hyperfine splitting parameter from our experimental data. The systematics of data about the hyperfine interactions in the rare earth metals [12] have suggested the electric field gradient V_{zz} for Tb(Gd) to be positive. The ^{153}Tb nucleus has been indicated by experimental results [1-3] to have a small prolate ground state deformation, which did not exceed that of ^{159}Tb nucleus. Then the P-parameter for ^{153}Tb(Gd) should be expected to lie between $P = 0$ and 5×10^{-7} eV. The last value was calculated from the P-value for ^{159}Tb(Gd) measured [13] as $P = 1.45(1)\times10^{-6}$ eV and from known [14] quadrupole moment of the ^{159}Tb ground state $Q_{I_0} = 1.34(11)\times10^{-28}$ m^2.

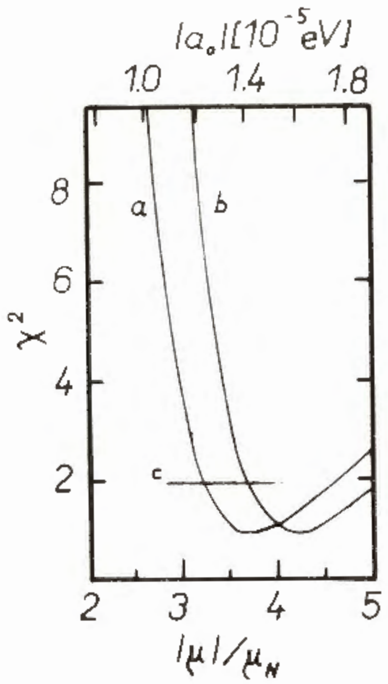

Fig.2. The plot of χ^2-value (divided by the number of degrees of freedom) versus parameter a_0 of magnetic dipole hyperfine splitting for ^{153}Tb(Gd). Both the curves were obtained for the optimal value of $K_2 = -0.212$. The curves a and b correspond to limit P-values for ^{153}Tb(Gd) zero and 5×10^{-7} eV, respectively, as discussed in text. The estimated 95% confidence level c is also inserted.

Under these conditions the lower limit of $|a_0| = 1.2\times10^{-5}$ eV has been estimated for ^{153}Tb(Gd) from our experimental data considering the confidence level higher than 95%. This is illustrated by Fig.2. The confidence region was found following the procedure recommended in Ref.[15]. The magnetic hyperfine field for Tb(Gd) is known from NMR-measurements [13] to be $H_{hf} = 303(3)$ T. Hence, the limit on the value of magnetic dipole moment μ of ^{153}Tb ground state can be set as $|\mu| \geq 1.6\times10^{-26}$ J/T (i.e., 3.1 μ_N). As can be seen from Fig.2, no reasonable upper limit of parameters $|a_0|$ and μ could be deduced from our experimental data.

The value of $\mu = 3.34\mu_N$ predicted for ^{153}Tb ground state by the calculations [5] mentioned above is in accordance with the experimental limit provided by the present work.

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