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V.P.Afanasiev, M.Budzynski, I.Demeter,[1] H.Fuia,
K.Ya.Gromov, I.I.Gromova, I.Holbaev,[2]
R.Ion-Mihai, D.Maczka,[3] V.A.Morozov,
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THE g-FACTORS OF THE FIRST AND SECOND EXCITED STATES IN ^{151}Gd

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[1] Central Research Institute for Physics, Budapest.
[2] State University, Samarkand, USSR.
[3] State University, Lublin, Poland.

1. Introduction

The $^{151}_{64}Gd_{87}$ nucleus belongs to the region of transition nuclei. Therefore, it is very interesting to study the nature of its excited states.

The purpose of this investigation was to determine the unknown g-factors of the 108 keV and 395 keV levels in ^{151}Gd, the life-times τ_N, and the spins I^{π} of which are shown in Table 1. The reversed field method with the hyperfine magnetic field of Gd implanted in iron was used for the $\gamma-\gamma$ integral perturbed angular correlation (IPAC) determination of these g-factors.

The problems regarding PAC measurements using the hyperfine interactions experienced by radioactive nuclei embedded in iron foil by means of isotope separator have been discussed in several articles, proceedings and reviews (refs./5-8/).

The magnetic precession $\Delta N/N$ is defined to be

$$\frac{\Delta N}{N} = 2\,\frac{W(\uparrow) - W(\downarrow)}{W(\uparrow) + W(\downarrow)}, \qquad (1)$$

where the arrow denotes the direction of the magnetic field, which is perpendicular to the plane of the detectors.

For an integral angular correlation, with just a P_2 term one finds for an angle $\theta = 135°$ between the detectors

$$\frac{\Delta N}{N} = -\,\frac{3A_2}{4 + A_2}\,\sin 4\Delta\theta, \qquad (2)$$

where the rotation $\Delta\theta$ of the angular correlation is

$$\Delta\theta = 1/2\ \mathrm{arctg}\,(2\omega\tau_N). \qquad (3)$$

Table 1

Levels and cascades in ^{155}Gd and ^{151}Gd used in IPAC measurements

Nucleus	Level /keV/	I	Lifetimes /ns/	Cascade /keV/	A_2	A_4
^{155}Gd	86	$5/2^+$	9.64 ± 0.17 [1,2]	180 - 86	-0.214±0.006 [1]	+0.009±0.015 [1]
	108	$5/2^-$	4.33 ± 0.15 [3]	287 - 108	-0.240±0.015 [4]	-0.008±0.016 [4]
^{151}Gd	395	$3/2^-$	0.45 ± 0.05 [3]	444 - 287	-0.161±0.017 [4]	+0.013±0.025 [4]

The presence of the time dependent magnetic interactions caused by paramagnetic spin relaxation results in the attenuation of the maximal possible value of $\Delta N/N$ and of, the rotation $\Delta\theta$:

$$\frac{\Delta N}{N} = - \frac{3A_2}{4a + A_2} \sin 4\Delta\theta' \qquad (2')$$

and

$$\Delta\theta' = 1/2 \operatorname{arctg}\left(\frac{2\omega\tau_N}{a}\right). \qquad (3')$$

Here

$$a = 1 + \lambda\tau_N \qquad (4)$$

is the relaxation coefficient and λ is the relaxation rate.

In the case of the large hyperfine fields and large τ_N, the ambiguity appears on the rotation $\Delta\theta$ and therefore, on the experimental g-value. It is also possible that a large attenuation on the angular correlation, i.e., a very small effect $\Delta N/N$, takes place. To avoid this ambiguity and to be able to know the attenuation of angular correlation (AC) we have made some preliminary studies on ^{155}Gd.

2. The Lifetime Dependence on the $\Delta N/N$ Magnetic Precession

Using the non-relaxation model (i.e., $a = 1$) the magnetic precession is given by (2) and (3).

The magnetic field dependence of $\Delta N/N$ for different τ_N is shown in fig. 1. The g-factor and lifetime τ_N of the 86 keV level of ^{155}Gd and the A_2-coefficient of the 180-86 keV cascade of the same nucleus have been used.

For each value of τ_N, there is one single value of H for which $\Delta N/N$ is unattenuated and corresponds to the same value of the rotation $\Delta\theta = 22°30'$. This H-value increases, when τ_N decreases.

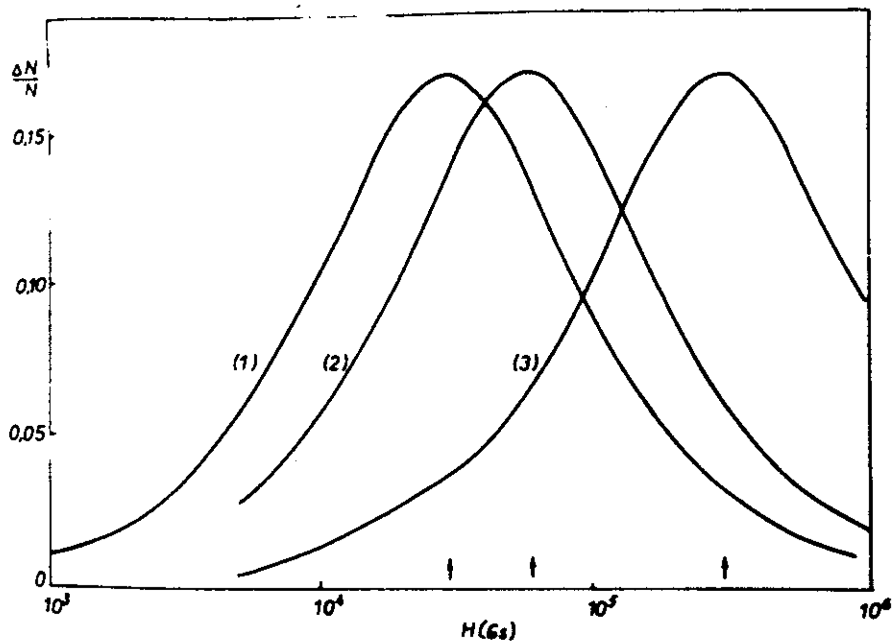

Fig. 1.The theoretical magnetic field dependence of $\Delta N/N$ for different lefitimes and non-relaxation model (A_2 = = -0.214, g = -0.376; (1) τ_{N1} = 9.6 nsec; (2) τ_{N2} = = 4.8 nsec; (3) τ_{N3} = 0.96 nsec).

If the experimental value of $\Delta N/N$ is smaller than the attenuated one (and this is usually the case) there is an ambiguity on $\Delta\theta$. Experimentally one can decide between the two possible values by measuring $\Delta N/N$ for two or more different values of the magnetic field H. Usually, large magnetic fields are produced by the magnetization procedure, which gives saturation for large magnetizing coil current I.

The coil current dependence of $\Delta N/N$ for different lifetimes τ_N is shown in fig. 2. The curve(a) corresponds to the case when $\tau_N(a)$ and the saturation field gives just a rotation of $22°30'$, i.e., the maximum value for $\Delta N/N$.For larger coil currents $\Delta N/N$ has a plateau at this maximum value.

The curve (b) shows the case when $\tau_N(b)$ is smaller than $\tau_N(a)$. The plateau appears for a rotation smaller than $22°30'$, i.e., for an attenuated $\Delta N/N$ value. Such an experimental curve has been obtained by Deutch et al /6/. The curve (c) corresponds to the case when $\tau_N(c)$ is longer than $\tau_N(a)$, i.e., the $\Delta N/N$ plateau appears for a rotation $\Delta\theta$ longer than $22°30'$. In all these cases, the presence of the relaxation processes will further attenuate the $\Delta N/N$ effect, thus, even the maximum value of $\Delta N/N$ may be very small. Fig. 3 shows the strong effect of the relaxation processes in the case of 86 keV level in ^{155}Gd (τ_N = 9.64 ns).

Here, (a) and (b) denote the theoretical curves for the magnetic field dependence of $\Delta N/N$ calculated with the non-relaxation model and with the relaxation model (α = 2.14), respectively.

3. Experimental Procedure and Results

3.1. Sources

The ^{155}Tb and ^{151}Tb sources were obtained in spallation reaction by bombarding a tantalum target with 660 MeV protons from the Dubna synchrocyclotron. The ^{155}Tb and ^{151}Tb sources have been implanted

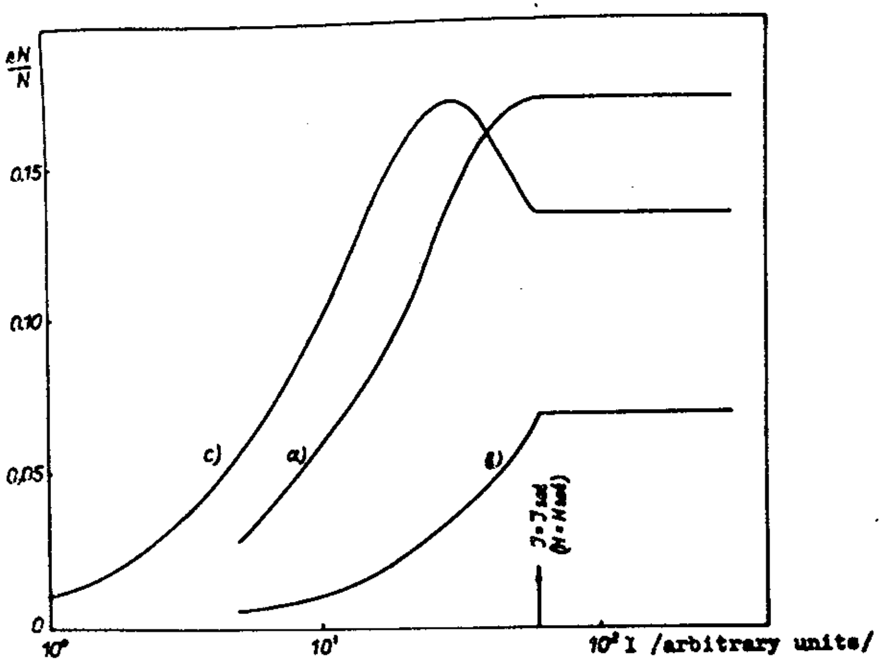

Fig. 2. The theoretical coil current dependence of ΔN/N for different lifetimes ($\tau_N(c) > \tau_N(a) > \tau_N(b)$) .

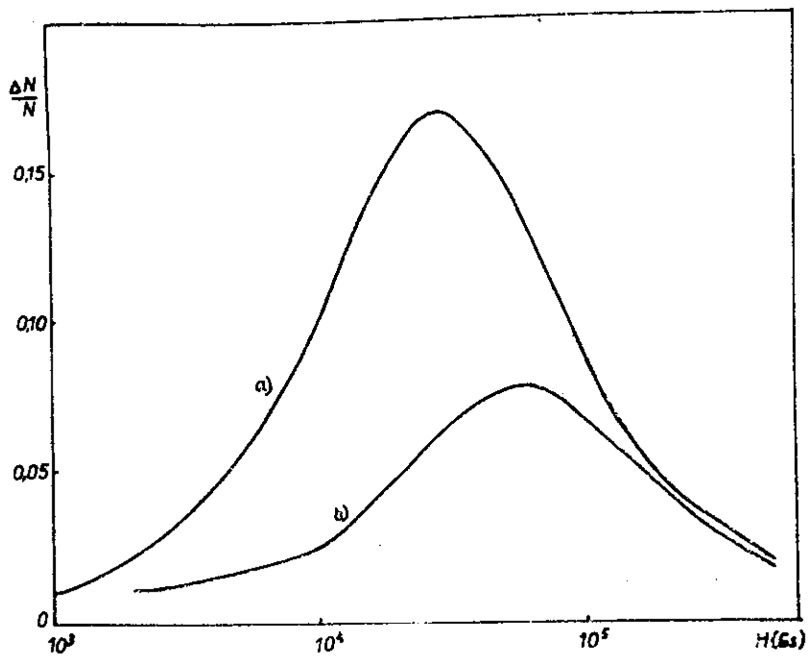

Fig. 3. The theoretical ΔN/N curves calculated with the non-relaxation model (a) and with relaxation model (b) (a = 2.14).

simultaneously into the iron X-ray filter foil 0.0012 cm (obtained from Johnson Mottley Chemical Ltd) by means of on isotope separator. The energies of implantation were of 25 keV and 75 keV. The measurements were made with non-annealed sources, at room temperature.

3.2. Apparatus

The angular correlation apparatus used in these experiments is a conventional automatically operated coincidence system using the fast-slow electronics with 40 x x 40 mm NaI(Tl) and a 45-cc Ge(Li) detectors /12,13/. The alignment of the iron domains in the direction of the applied fields was obtained using a small magnet with a great number of amper-turns. The sense of the magnetic field was automatically changed every 5 minutes. The information obtained for the two directions of the magnetic field was analysed by using the computer MINSK-2. Simultaneously the background coincidences were analysed.

3.3. IPAC Measurements in ^{155}Gd and ^{151}Gd

The γ-γ cascades used for g-factor determination and their angular correlation coefficients are given in Table 1.

Firstly, we have performed the coil current dependence of $\Delta N/N$ using the 180-86 keV cascade for ^{155}Gd implanted in iron foil with an imlantation energy of 25 keV. The result is shown in fig. 4. The experimental points lie on a curve similar to curve (c) from fig. 2. It is seen from fig. 4 that for coil current $I = 60$ mA one obtains the saturated hyperfine field, the value of which was previously determined in ref. /8,9/ $H = (200\pm50)$ KG. In view of the discussion from sect. 2 we can conclude that $\Delta\theta > 22°30'$ for the 180-86 keV cascade at $I = 100$ mA.

All the other measurements of PAC in ^{155}Gd and ^{151}Gd were performed for $I = 100$ mA, i.e., with the saturated magnetic field. The results are summarized in Table 2.

To obtain the g-factors from Table 2 we have used the nonrelaxation model. It is seen that the g-factor of 86 keV

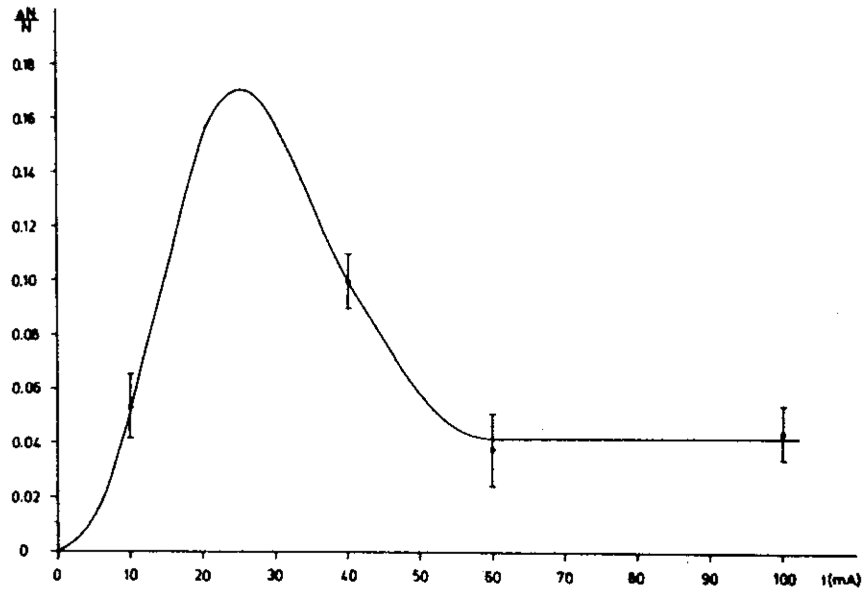

Fig. 4. The experimental coil current dependence of $\Delta N/N$ for 180-86 keV cascade in ^{155}Gd implanted in Fe.

level in ^{155}Gd, obtained from measurements performed with an implantation energy of 25 keV, is in good agreement with the g-value obtained from IPAC measurements in the external magnetic field /10/.

We can conclude that a) the static quadrupole interactions from radiation damage are not present, b) the effect of relaxation processes on $\Delta N/N$ is negligible and c) the range of Tb ions for 25 keV implantation energy is long enough in our iron foil to attain the maximal value for the effective magnetic field at the Gd nucleus.

The PAC measurements for the 287-108 keV cascade of ^{151}Gd were performed for 25 keV and 75 keV implantation energies. It is seen also from Table 2, that the magnetic precession is the same, in the limit of the errors, for the two ion energies. This fact supports the conclusion (c).

The measurements for the 444-287 keV cascade were made for 75 keV implantation energy. The value obtained for the magnetic precession is almost equal to the maximal possible value $\Delta N/N$ for this cascade. We can conclude that the effect of relaxation processes is also negligible at room temperature for cascades measured in ^{151}Gd. So the g-factors were deduced by using the non-relaxation model ($a = 1$). The ambiguity on g-value for the 108 keV level has been solved by using the analogy to the 180-86 keV cascade of ^{155}Gd; the same spins, almost equal the A_2-coefficients and large lifetimes made more probable the rotation $\Delta\theta > 22°30'$ and its corresponding g-value. This is also supported by the results obtained for the 395 keV level, the lifetime of which is ten times smaller: both the two possible values $\Delta\theta$ are large (in the vicinity of $\Delta\theta = 22°30'$). So, for the 395 keV level we cannot resolve the ambiguity on its g-value, but the two possible values indicate the order of its true value. In the view of the fact that ^{151}Gd nucleus is spherical its quadrupole moment will be smaller than that of the deformed ^{155}Gd nucleus. Thus, we have also neglected the static quadrupole interactions in determining the g-factors for ^{151}Gd levels.

In Table 3 the results of angular correlation measurements are given obtained without the external magnetic

Table 2

The results of IPAC measurements with $H_{ext} = 0$.

Nucleus	Implantation energy /keV/	Level /keV/	$(\Delta N/N)_{exp} = -\frac{3A_2}{4+A_2}\sin 4\Delta\theta$	$(\Delta N/N)_{max} = \frac{3A_2}{4+A_2}$	$\Delta\theta$	$g_{exp.}$	$g_{exp.}$ Other works
^{155}Gd	25	86	+0.044 ± 0.008	0.169	3°45′ or 41°15′	−0.006±0.001 or −0.410±0.080	−0.376±0.026 10
^{151}Gd	25	108	+0.070 ± 0.015	0.192	5°20′ or 39°40′	−0.02 ± 0.01 or −0.63 ± 0.13	-
	75	108	+0.065 ± 0.010	0.192	4°57′ or 40°03′	−0.02 ± 0.01 or −0.69 ± 0.17	-
		395	+0.122 ± 0.022	0.126	18°35′ or 26°25′	−0.90 ± 0.27 or −1.49 ± 0.41	-

Table 3

The results of AC measurements with $H_{ext} = 0$.

Source	Temperature	Cascade /keV/	A_2	G_2
aqueous solution of ^{151}Gd in HCl [4]	room	287-108	-0.240 ± 0.017	1
	room	444-287	-0.161 ± 0.015	1
^{151}Gd implanted in Fe	room	287-108	-0.255 ± 0.046	unattenuated
	liquid-nitrogen	287-108	-0.155 ± 0.022	0.64
	room	444-287	-0.229 ± 0.079	unattenuated
	liquid-nitrogen	444-287	-0.121 ± 0.050	0.75

Table 4

The g-factors of the first and second excited states in ^{151}Gd

Level /keV/	$g_{exp.}$	$g_{theor.}$ core + /Schmidt/$_{g.s.}$	$g_{theor.}$ core + /A-H/$_{g.s.}$
108	-0.69 ± 0.17	-0.69	-0.35
395	-0.90 ± 0.27 or -1.49 ± 0.41	-1.55	-0.96

field at room and liquid nitrogen temperatures for the two cascade of ^{151}Gd. It is seen that at room temperature the A_2 coefficients for ^{151}Gd implanted in iron are unattenuated. This confirms our previous conclusion on the absence of the static quadrupole interactions and of the effect of relaxation processes. At liquid-nitrogen temperature the A_2-coefficients are strongly attenuated.

4. Discussion

The quantum characteristics of ^{151}Gd ground state agree with the prediction of the shell model ($f_{7/2}$). The 108 keV state cannot be interpreted as a single particle state. The Schmidt model predicts for a single neutron $f_{5/2}$ state a g-factor, the sign of which is in disagreement with the experimental one: $g = +0.55$. Within the de Shalit model /11/ the 108 keV state can be interpreted as a coupling of the $f_{7/2}$ single neutron state to the collective excitation of the even-even core. This core excitation model predicts for the g-factor of a member of the core multiplet

$$g(I_i) = 1/2(g_c + g_p) + 1/2(g_c - g_p)\frac{I_c(I_c+1) - j(j+1)}{I_i(I_i+1)}, \quad (5)$$

where I_i, I_c, j are the spins of the excited state, of the excited core and of the single particle state, respectively; g_c and g_p are the g-factors of the excited core and of the single-particle state. In the absence of measurements for the g-factor of the 2^+state of ^{150}Gd we have used the value $g_c = Z/A = 0.41$. For the g-factor of the ground state of ^{151}Gd we have used in eq. (5) both the Schmidt theoretical value and the Arima and Horie value, which takes into account the configuration mixing /14/. The results are summarized in Table 4.

From the comparison with the experimental result one can conclude that this level is of collective nature. The same conclusion was obtained from lifetime measurements /3/.

It is seen from Table 4 that the 395 keV level in ^{151}Gd can be interpreted as another member of this core multiplet, i.e., of collective nature; also in agreement with the conclusion from the lifetime measurements /3/.

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