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Y299/83

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E6-83-333

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NUCLEAR ORIENTATION OF ^{149}Pm IN GADOLINIUM HOST

Submitted to
"Czechoslovak Journal of Physics"

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1983

1. INTRODUCTION

The low-energy excited states in the $^{149}_{62}Sm_{87}$ nucleus are expected to arise from the odd-neutron configurations coupled to the collective excitations of the even-even core. At low excitations the $1h_{9/2}$ and $2f_{7/2}$ single particle odd-parity orbitals can be occupied by the 87th neutron. This provided the basis for interpretation of the ^{149}Sm ground state and the excited state at 285.9 keV which were experimentally established /1,2/ to have spins and parities $7/2^-$ and $9/2^-$, respectively, as the single-neutron states.

Following this interpretation, the ℓ-forbidden M1-transition proceeds between the 285.9 keV and the ground states in ^{149}Sm. The experimental transition probabilities, deduced /3/ from the life-time measurements and Coulomb excitation data revealed only a small (less than $\approx 1\%$) E2-component of the 285.9 keV transition and hindrance factors $F_W(M1) \approx 280$ and $F_W(E2) \approx 0.4$ which are consistent with the above simple interpretation. Recent in-beam spectroscopy study /4/ gave also the similar result. On the other hand the experimental internal conversion data /5/ have suggested the E2-admixture in the 285.9 keV transition to be from 9.6 to 64.6%.

Hence, a test of the multipolarity of the 285.9 keV transition is desirable. The experimental method suitable for such investigation is the nuclear orientation of the ^{149}Pm parent nuclei. The decay scheme of ^{149}Pm ($T_{1/2}$ = 53.08(5) h) was investigated by a number of authors /3,6,7,8/. The nuclear orientation of ^{149}Pm has already been studied by Chapman et al. /6/ using the hyperfine interaction acting on ^{149}Pm nuclei in $CeMg_3(NO_3)_{12}24H_2O$ and $Nd(C_2H_5SO_4)_3 9H_2O$ single crystals cooled down to 3 and 18 mK, respectively, by adiabatic demagnetization. The radioisotope ^{149}Pm was obtained by Chapman et al. in mixture with ^{151}Pm ($T_{1/2}$ = 28.4 h) from fission products. Although the ^{149}Pm gamma-ray spectrum is very simple, the 285.9 keV gamma-ray mixing ratio could not be precisely determined in ref. /6/ due to the presence of the ^{151}Pm admixture and NaI(Tl) detectors used.

Promethium and neodymium are known to be well dilutable in gadolinium. Thus gadolinium can be used as a proper host for nuclear orientation studies involving these admixtures. Up to present time nuclear orientation of ^{147}Nd and ^{151}Pm in gadolinium host have been studied /9,10/, but similar study involving ^{149}Pm isotope was not performed before.

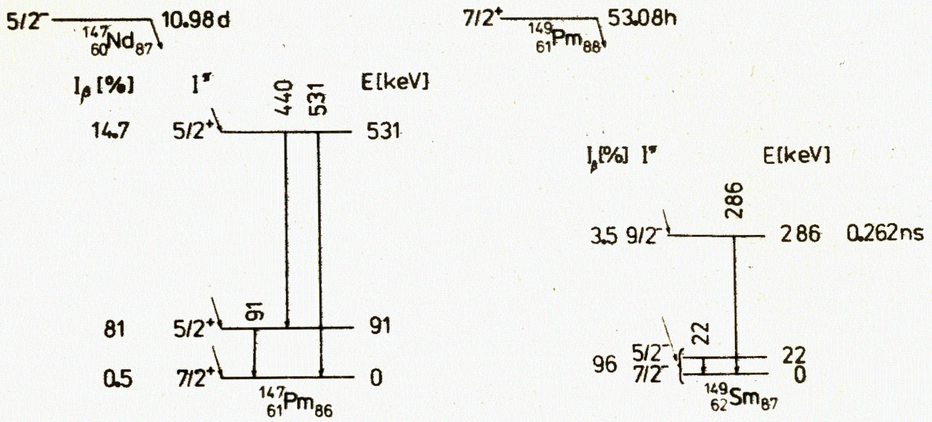

Fig.1. Parts of ^{147}Nd and ^{149}Pm decay schemes relevant to present work.

In the present work, the investigation of the decay of ^{149}Pm and ^{147}Nd oriented in a gadolinium host containing ≈ 1 At.% of stable neodymium was performed. The fragment of the ^{147}Nd decay scheme taken from ref. /6/ is shown in fig.1 together with a part of ^{149}Pm decay scheme of ref. /8/. Both radioisotopes were produced by irradiation of neodymium by thermal neutrons. We have measured the temperature dependences of the gamma-ray anisotropy of the 285.9 keV and 531.0 keV transitions of ^{149}Pm and ^{147}Nd, respectively. The gamma-rays were detected with the high-resolution Ge(Li) detectors. From the analysis of the experimental data, the magnetic saturation factor of the host, lower limit of $^{149}Pm\underline{Gd}$ hyperfine magnetic field and the multipole mixing ratio of the 285.9 keV transition were deduced.

The present paper is the first report on the investigations with the reactor-produced Pm and Nd radioisotopes oriented in NdGd alloys, which are now in progress on the SPIN-facility /11/ at JINR Dubna.

2. EXPERIMENT

2.1. Radioactive Sample

Metallic neodymium containing the natural mixture of neodymium isotopes was irradiated for 30 hours by thermal neutrons at a flux of $5 \times 10^{13} cm^{-2} s^{-1}$ in Tbilisi reactor. Five days after the end of irradiation only the gamma-rays of ^{147}Nd ($T_{1/2}$ = = 10.98(1) d) and the 285.9 keV gamma-ray of ^{149}Pm ($T_{1/2}$ = = 53.08(5) h, daughter of 1.73 h ^{149}Nd) were seen with remarkable intensity in the spectra, while other gamma-rays, in particular those of 28.4 h ^{151}Pm(daughter of 12.44 m ^{151}Nd) were not disturbing the measurements. A piece of the irradiated neodymium was then melted on tantalum foil with $\approx$50 mg of metallic gadolinium just above the melting point of gadolinium in the vacuum of $\approx 10^{-4}$Pa. The tantalum foil was soldered to a copper backing to provide a good termal contact with the cooling device /11/. The sample was finally abraded and cut to have form of a disk of 5 mm in diameter. The total sample activity was $\approx 10 \mu$Ci. The concentration of the inactive neodymium in gadolinium was $\approx$1 At.%.

2.2. Nuclear Orientation Facility and Counting Equipment

The ^{147}Nd and ^{149}Pm nuclei were oriented at low temperatures using hyperfine fields acting on these nuclei in the host. The ^{147}Nd^{149}Pm$\underline{Gd}$ sample was soldered to the termal support base of the ^{3}He–^{4}He dilution refrigerator /12/ of the SPIN-facility /11/ and cooled down to the temperature of 15 mK. A ^{54}Mn$\underline{Ni}$ nuclear orientation thermometer was used to determine the sample temperature. An external magnetic field of 1.2 T was applied to the samples to polarize the magnetic domains of the hosts.

The gamma-radiation was detected using two 30 cm^3 coaxial Ge(Li) detectors placed at angles $\theta = 0°$ and 90° relative to the direction of the external magnetic field. The source-to-detector distances were 9 cm. The Ge(Li) spectrometers gave the energy resolution of 2.7 keV FWHM at 0.5 MeV gamma-ray energy. The spectra were stored in the memories of 4096 channel analyzers and recorded on magnetic tape.

2.3. Measurements and Data Evaluation

The gamma-ray spectra measurements were performed for 16 temperatures T between 15 and 80 mK. Each spectrum was accumulated for 1 h. Several one-hour measurements were carried out at sample temperature $T_0 \approx 1$ K under which the nuclear spin directions have to be fully random. The normalized gamma-ray intensities, $W^{ex}(\theta,T)$, were calculated as ratios of peak areas obtained for temperatures T and T_0. Peak areas were corrected for decay of the radioisotope, the corrections being less than 15 and 10% for ^{149}Pm and ^{147}Nd, respectively. The errors of the decay corrections were less than 2%.

In figs.2 and 3 the measured temperature dependences of normalized intensities were plotted for the 285.9 keV and 531.0 keV gamma-rays of ^{149}Pm and ^{147}Nd, respectively.

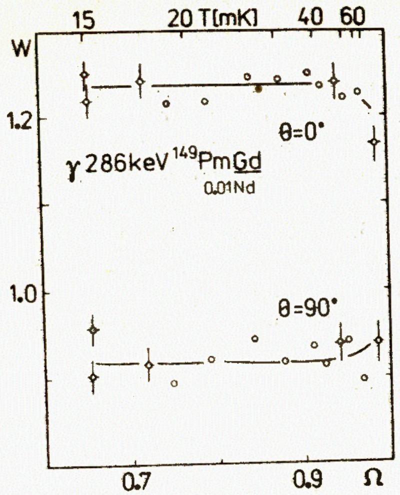

Fig.2. Normalized intensity $W(0°,T)$ of 285.9 keV gamma-ray of ^{149}Pm plotted versus normalized intensity $\Omega(0°,T)$ of 834.8 keV gamma-ray of ^{54}Mn$\underline{Ni}$ nuclear orientation thermometer.

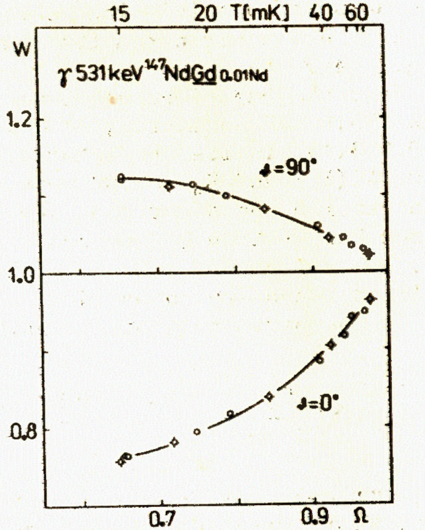

Fig.3. Normalized intensity $W(0°,T)$ of 531.0 keV gamma-ray of ^{147}Nd plotted versus normalized intensity $\Omega(0°,T)$ of 834.8 keV gamma-ray of ^{54}Mn$\underline{Ni}$ nuclear orientation thermometer.

3. DATA ANALYSIS AND RESULTS

3.1. Hyperfine Splitting for ^{149}PmGd (0.01 Nd)

As can be seen in fig.2, measured temperature dependence of the normalized intensity $W^{ex}(0°,T)$ for 285.9 keV gamma-ray exhibits saturation below 50 mK. The measurements above 80 mK were not reasonable due to poor temperature sensitivity of the ^{54}Mn$\underline{Ni}$ thermometer. For this reason, only lower limit of the magnitude of the hyperfine splitting parameter, $a_0 = gB_{eff}$, could be determined (g -factor in nuclear magnetons is considered here).

The theoretical angular distribution function $W(\theta,T)$ can be written as

$$W(\theta,T) = 1 + K_2 B_2(I_0, a_0, P, T) + K_4 B_4(I_0, a_0, P, T), \qquad (1)$$

where B_λ's are the orientation parameters dependent on sample temperature T and on the magnetic dipole and electric quadrupole hyperfine splitting parameters, a_0 and P, respectively; K_λ's stand for the products $G_\lambda \cdot A_\lambda \cdot U_\lambda \cdot Q_\lambda \cdot P_\lambda$ .The G_λ-factor accounts for possible incomplete magnetic saturation of the host[14]. All other parameters have their usual meaning (see, e.g., ref.[13]).

From the experimental normalized intensities obtained for the 285.9 keV gamma-ray, $W^{ex}(0°) = 1.232(14)$ and $W^{ex}(90°) = 0.900(15)$ inside the saturation region, the values of $K_2 = 0.146(12)$ and $|K_4| < 0.03$ were extracted. Taking into account that inside the saturation region parameter B_2 is about two times larger than B_4, we can see that the 4th order term in eq. (1) represents only a small contribution to the total normalized intensity compared to the 2nd order one.

In the parameter optimalization procedure the χ^2-functional

$$\chi^2 = \sum_i \left[\left(\frac{\Omega_i - \Omega_i^{ex}}{\sigma_{\Omega_i}} \right)^2 + \left(\frac{W(0°, T(\Omega_i)) - W_i^{ex}(0°)}{\sigma_{W_i}} \right)^2 \right]$$

was examined, where similarly to ref.[13] the normalized intensity Ω of the 834.8 keV gamma-ray of the ^{54}MnNi nuclear orientation thermometer rather than temperature T was involved as independent variable. The superscript 'ex' denotes corresponding experimental quantities.

It was assumed in the analysis that near the saturation region the nuclear orientation of ^{149}Pm nuclei is caused predominantly by the magnetic dipole hyperfine interaction and the electric quadrupole hyperfine splitting plays no important role in the analysis of the data. Hence, parameter P was fixed to be zero in the below analysis. The optimal values of K_2, K_4 and Ω_i's were searched for using the general minimization routine MINUIT[15] on CDC-6500 computer. Parameters K_2 and K_4 were allowed to vary within the above-mentioned limits. Parameter a_0 was kept fixed and the dependences of minimum χ^2-value, χ^2_{min}, and optimal values of K_2 and K_4 on a_0 were constructed and they were shown in fig.4. On the basis of the χ^2_{min}-curve of fig.4, the lower limit of $|a_0|$ could be estimated as $|a_0| = 0.6 \times 10^{-5}$ eV considering the 99% confidence level. The estimation of the confidence region was carried out according to ref.[16].

Using the value of the ^{149}Pm ground state magnetic dipole moment, $\mu = +3.3(5)\mu_N$, measured in ref.[17] we could set the lower limit on the effective magnetic field acting on trace ^{149}Pm admixtures in the gadolinium host containing ~1At.% of the inactive neodymium, $(B_{eff})_{low}$ = 120 T.

3.2. A_2-Coefficient and E2/M1 Mixing Ratio for the 285.9 keV Transition

As the measured normalized intensity $W^{ex}(0°)$ for the 285.9 keV gamma-ray appeared to be greater enough than one, its angular

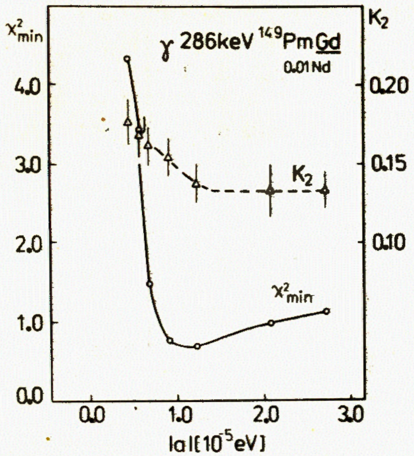

Fig.4. Results of the χ^2-analysis of measured temperature dependence of fig.2. Details of the analysis are described in text.

distribution coefficient, A_2, should be positive. To deduce more precise experimental data on this coefficient from the above experimental value of K_2 independent knowledge on G_2-factor in eq.(1) is necessary. This factor could be obtained from temperature dependence of normalized intensity of the 531.0 keV gamma-ray of ^{147}Nd measured in the present experiment, too (see fig.3).

It should be noted that the magnitude of the anisotropy measured in our work for the 531.0 and 439.9 keV gamma-rays of ^{147}Nd exceeded more than three times the results obtained recently[9] by the same method of nuclear orientation of ^{147}Nd in gadolinium host. This difference is probably due to higher external magnetic field of 1.2 T used in our work, while the external field of only 0.5 T was applied in ref.[9], which seems to be insufficient to saturate the gadolinium host[18]. Moreover, the gadolinium host is expected to become magnetically harder, when macroscopic amounts of neodymium carrier are present in the host, thus making the external magnetic field to be an important factor in such experiments.

The temperature dependent nuclear orientation parameter, B_2, and K_2-factors for 531.0 keV transition were deduced by the same least square fitting procedure as described above. Analogously to ref.[13] the dependences of the optimal values of $|g B_{eff}|$ and K_2 and the minimal value of χ^2-functional on the electric quadrupole splitting parameter P were constructed. The fitting procedure revealed the results summarized in fig.5. It can be seen from that figure, that the upper limit for K_2-parameter, $K_{2,max} = -0.21$ has followed from our experiment. The other parameters from the figure will be discussed separately as a part of our investigations of ^{147}Nd nuclear orientation in neodymium-gadolinium alloys at different concentrations of Nd, which are now in progress.

From the limit for K_2-parameter for 531.0 keV gamma-ray transition the estimate of the magnetic saturation factor, $G_2 > 0.66$ was obtained with 99% confidence level. In this estimate the deorientation factor U_2 (531 keV level) = 0.83(17) was considered which takes account of possible mixing of the $j\beta = 0$

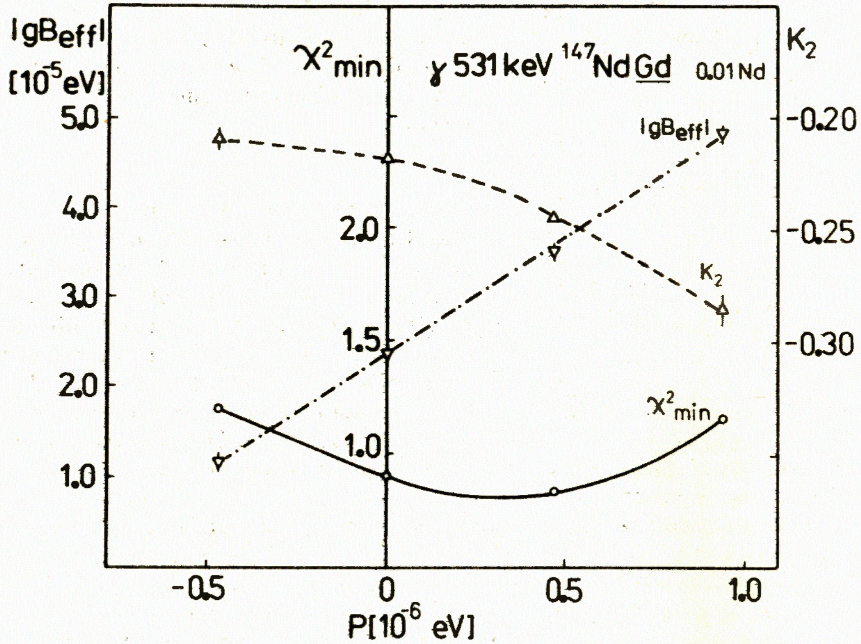

Fig.5. Results of the χ^2-analysis of measured temperature dependence of fig.3. For obtaining of G_2-factor we could consider only values of $|P| \leq 10^{-7}$ eV estimated on the basis of measured/23/ values of electric quadrupole hyperfine splitting constants for ^{143,145}NdGd and ground state electric quadrupole moments of ^{143,145,147}Nd quoted in/24/.

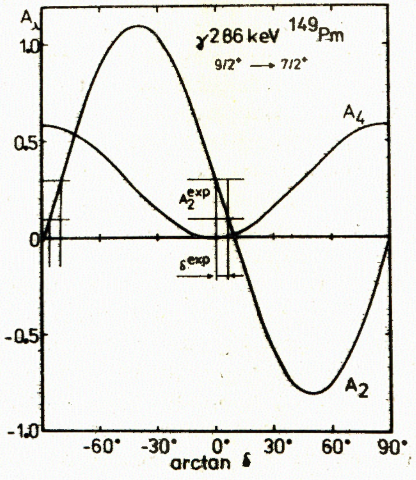

Fig.6. Mixing ratio analysis for 285.9 keV transition of ^{149}Pm.

and $j_\beta = 1$ components in the first-forbidden beta-transition feeding the 531 keV level in ^{147}Pm (see fig.1). The A_2-coefficient for 531.0 keV transition which is necessary for estimating the G_2-factor was deduced by the following way. At first for the transitions 439.9 and 531.0 keV depopulating the same level in ^{147}Pm (see fig.1), the ratio A_2 (γ 531 keV)/ A_2(γ 440 keV) =

= 0.450 (36) was derived independently of B_2-, U_2 -values from our normalized gamma-ray intensities using the relations shown, e.g., in ref./9/. Considering the value A_2 (γ 440 keV) =-0.688(25) measured by gamma-gamma angular correlation technique/9/, we finally obtained the value A_2 (γ 531 keV) = -0.310(42), which was used in the evaluation of the above limit of G_2-factor. Our A_2-value is consistent with the value of A_2 (γ 531 keV) = = -0.320 (75) obtained in ref./9/ (3 mean-square deviations were shown in the parenthesis in units of the last digit).

Taking the G_2-factor to be $0.66 < G_2 < 1$, we evaluated the limits on experimental values of A_2 (γ 285.9 keV) to be $0.097 < A_2$ (γ 285.9 keV) < 0.30 with 99% confidence level. In this evaluation the saturation value of orientation coefficient $B_2(I_0 = 7/2, T \to 0) = 1.53$ and the deorientation factor U_2 (285.9 keV level, $j_\beta = 0$) = 0.925 were used.

As can be seen from fig.6, our experimental result yields multipole mixing ratio, δ (E2/M1) lying in intervals $0.0 < \delta < +0.11$ or $-19 < \delta < -5.7$. The definition of δ and the sign convention used in our work are those introduced by Krane and Steffen/19/. Only the values $0.0 < \delta < +0.11$ are consistent with the small 4th order term in the angular distribution of the 285.9 keV gamma-ray intensity observed in our work.

Hence, the positive sign of the multipole mixing ratio δ (E2/M1) was definitely established in the present work for the 285.9 keV gamma-ray transition in ^{149}Sm. Our result has confirmed the predominant M1-character of the 285.9 keV transition proceeding between the $9/2^-$ and $7/2^-$ states in ^{149}Sm, allowing less than 1.2% E2 admixture. This appears to be in agreement with the result obtained in recent in-beam spectroscopy work/4/ and Coulomb excitation/20/ as well as with the experimental data on analogous $9/2_1^- \to 7/2_1^-$ transitions in neighbouring ^{147}Nd (ref./21/) and ^{151}Gd (ref./22/) isotones.

Authors are indebted to Dr. J.Koniček for taking part in the measurements and Eng. M.I.Fominykh for helping in data accumulation and analysis. One of us (MGB) is indebted to Prof.O.A.Tschilashvili for stimulating discussions and supporting during the course of the work.

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Баджелидзе М.Г. и др. E6-83-333
Ядерная ориентация ^{149}Pm в гадолиниевой матрице

Измерена температурная зависимость анизотропии для γ-перехода 285,9 кэВ, принадлежащего распаду ^{149}Pm. Материнские ядра ^{149}Pm ориентировались при низких температурах /14÷80 мК/ в гадолиниевой матрице, содержащей 1 ат.% неодима. Доменная структура матрицы поляризовалась внешним магнитным полем 1,2 Т. Из экспериментальных данных получены следующие величины:
/а/ $|g B_{эфф}| > 0{,}6\cdot10^{-5}$ эВ и $B_{эфф}(^{149}\mathrm{Pm}\,\underline{\mathrm{Gd}}) > 120$ Т.
/б/ $0{,}097 < A_2$ (γ 285,9 кэВ) $< 0{,}30$ и
$0{,}0 < \delta$ (E2/M1, γ285,9 кэВ) $< 0{,}11$.

Работа выполнена в Лаборатории ядерных проблем ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1983

Badzhelidze M.G. et al. E6-83-333
Nuclear Orientation of ^{149}Pm in Gadolinium Host

The temperature dependence of the anisotropy of the 285.9 keV gamma-ray following the decay of oriented ^{149}Pm was measured. The ^{149}Pm parent nuclei were oriented at low temperatures between 14 and 80 mK in a gadolinium host containing 1 At.% of neodymium admixture. The external magnetic field of 1.2 T was applied to polarize the domains of the host. The following quantities have been deduced from the present experimental data:
(i) $|g B_{eff}| > 0.6\cdot10^{-5}$ eV and $B_{eff}(^{149}\mathrm{Pm}\,\underline{\mathrm{Gd}}) > 120$ T.
(ii) $0.097 < A_2$ (γ285.9 keV) < 0.30 and
$0.0 < \delta$ (E2/M1 , γ285.9 keV) < 0.11.

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

Preprint of the Joint Institute for Nuclear Research. Dubna 1983