ed for in the thermal and cascade models.

We would like to thank Y. Yariv and Z. Fraenkel for making the computer code ISABEL available to us, and L. Oliveira for computer assistance. We thank J. O. Rasmussen, M. Gyulassy, J. I. Kapusta, and P. J. Siemens for helpful discussions.

This work was supported by the Nuclear Physics Division of the U. S. Department of Energy under Contract No. W-7405-ENG-48 and by the Bundesministerium für Forschung und Technologie, West Germany.

[a] Present address: Argonne National Laboratory, Argonne, Ill. 60439.

[b] Present address: Department de Physique Nucléaire à Moyen Energie, Centre d'Etudes Nucléaires de Saclay, 91190 Gif-sur-Yvette, France.

[c] Present address: Institute for Nuclear Studies, 38044 Grenoble, France.

[1] R. Stock, Gesellschaft für Schwerionenforschung, Darmstadt, Report No. GSI-P-5-78, 1978 (unpublished), p. 66; H. Gutbrod, *ibid.*, p. 124.

[2] R. K. Smith and M. Danos, in *Proceedings of the Topical Conference on Heavy Ion Collisions, Fall Creek Falls State Park, Tennessee, 1977* (National Technical Information Service, Springfield, Va., 1977), Conf-770602, p. 363.

[3] Z. Fraenkel and Y. Yariv, to be published. The results using this calculation shown in Fig. 1 were grouped into 20-MeV bins with ≈50 counts per bin, on the average.

[4] J. Gosset, J. I. Kapusta, and G. D. Westfall, Phys. Rev. C 18, 844 (1978), and references quoted therein.

[5] A. A. Amsden, A. S. Goldhaber, F. H. Harlow, and J. R. Nix, Phys. Rev. C 17, 2080 (1978).

[6] M. Gyulassy, Lawrence Berkeley Laboratory Report No. LBL-6594, 1977 (unpublished), and Fizika (Zagreb), Suppl. 9, 623 (1977).

[7] J. Chiba, K. Nakai, I. Tanihata, S. Naganiya, H. Bowman, J. Ingersoll, and J. O. Rasmussen, to be published.

[8] K. L. Wolf, A. Sandoval, Nguyen Van Sen, J. Gosset, H. H. Gutbrod, J. C. Jourdain, C. H. King, Ch. Lukner, W. G. Meyer, A. M. Poskanzer, R. Stock, and G. D. Westfall, Bull. Am. Phys. Soc. 23, 959 (1978), and to be published.

[9] D. R. F. Cochran, P. N. Dean, P. A. M. Gram, E. A. Knapp, E. R. Martin, D. E. Nagle, P. B. Perkins, W. J. Shlaer, H. A. Thiessen, and E. O. Theriot, Phys. Rev. D 6, 3085 (1972).

[10] D. A. Sparrow, M. M. Sternheim, and R. R. Silbar, Phys. Rev. C 10, 2215 (1974).

[11] Y. Kitazoe and M. Sano, Lett. Nuovo Cimento 22, 153 (1978).

[12] P. J. Siemens and J. O. Rasmussen, Phys. Rev. Lett. 42, 880 (1979).

[13] W. Scheid, H. Müller, and W. Greiner, Phys. Rev. Lett. 32, 741 (1974).

g Factors of High-Spin Yrast Traps in ^{146,147}Gd

O. Häusser, P. Taras,[a] W. Trautmann,[b] D. Ward, T. K. Alexander, H. R. Andrews, B. Haas,[c] and D. Horn[d]

Atomic Energy of Canada Limited, Chalk River Nuclear Laboratories, Chalk River, Ontario K0J 1J0, Canada

(Received 21 December 1978)

Pulsed beams of ^{28}Si and ^{4}He were used to determine *g* factors of eight isomeric states in ^{144,146,147,148}Gd by the time-differential spin-rotation method. The results show that proton and neutron configurations contribute about equally to the generation of angular momenta of two high-spin yrast isomers in ^{146,147}Gd ($I \sim 19$ and 49/2) whose detailed quasiparticle structure is suggested.

After the initial discovery[1] of an "island" of high-spin isomers in nuclei near the neutron shell closure at $N = 82$, considerable progress has been made in identifying individual yrast states up to very high spin. The excitation energies of these states with spins $14 \lesssim J \lesssim 36$ in ^{152}Dy (Ref. 2) and ^{154}Er,[3] when plotted versus $I(I+1)$, follow very closely a straight line characterized by an effective moment of inertia close to,[3] or larger than,[2] that for a rotation of a rigid sphere. Very recent lifetime measurements[4] in ^{152}Dy have demonstrated that the reduced $E2$ probabilities for transitions between yrast states are strongly inhibited relative to typical rotational values, indicating that these transitions involve rearrangements of single-particle orbitals.[5]

The more detailed structure of the high-spin yrast states can best be investigated by measurements of *g* factors since these depend on the coupling scheme for the individual particles, particu-

larly the relative contributions of protons and neutrons to the total angular momentum. Such measurements are of great current interest for the highest possible spin values since the excitation energies in ^{152}Dy (Ref. 2) and ^{154}Er (Ref. 3) suggest that deformation effects may become important *above* $I \sim 14$. This Letter reports measurements of g factors for two isomers in Gd isotopes having spins well above the $I = 14$ level. These are the 4.1-ns isomer in ^{146}Gd and the 530-ns isomer in ^{147}Gd, whose spins ($J \sim 18$–20 and $\lesssim 49/2$, respectively) and γ-decay schemes have been determined previously by Borda *et al.*[6]

Measurements of g factors in rare-earth nuclei are difficult because paramagnetic relaxation effects are encountered that tend to destroy the orientation of spins aligned by the nuclear reaction. The Gd isotopes occupy a special role related to the fact that Gd^{3+} has an $^8S_{7/2}$ electronic ground state[7] and hyperfine fields are correspondingly small because of the absence of large orbital contributions. We report here the magnetic hyperfine fields deduced for Gd in three metallic environments and comment on the spin relaxation mechanism.

The high-spin levels in Gd isotopes were populated and aligned via (HI,xn) reactions with pulsed beams of ^{4}He and ^{28}Si at energies of 30 and 108–144 MeV, respectively. The beam bursts were $\lesssim 2$ ns wide and pulse repetition times between 0.4 and 3.2 μs were selected to exceed the half-life of the relevant isomer by at least a factor of 5. The recoil nuclei either were stopped in thick targets of isotopically enriched ^{144}Sm, ^{120}Sn, ^{122}Sn, and ^{124}Sn, or—in the case of ^{28}Si-induced reactions—were implanted into backings of Sm or Pb. Typical applied magnetic fields were ~ 3.0 T at room temperature and ~ 1.6 T at elevated target temperatures between 293 and 968 K. The time distributions of delayed γ rays, detected in two Ge(Li) spectrometers placed at $\theta_\gamma = \pm 135°$, were recorded event by event on magnetic tape. A more detailed account of the experimental and analysis procedures is given elsewhere.[8]

Paramagnetic correction factors, $\beta(T)$, for Gd in hosts of metallic Sn, Sm, and Pb were determined by using the 130-ns, 10^+ isomer in ^{144}Gd (Ref. 9) and the 530-ns isomer in ^{147}Gd (Ref. 6) as probes. Since the Zeeman splitting is small compared to the thermal energy kT, one can approximate $\beta(T)$ by[10]

$$\beta(T) = 1 + g_J \mu_B (J+1) B_0 / 3kT,$$

where the Landé factor is $g_J = 1.9913$,[7] $J = \frac{7}{2}$ for the Gd^{3+} ground state, and B_0 is the value of the internal magnetic field at $T = 0$ K. The ratios of γ-ray yields, $R(t) = [Y(135°) - Y(-135°)]/[Y(135°) + Y(-135°)]$, for some transitions deexciting the isomers are shown in Fig. 1. The data are well reproduced with the assumption of an exponential decay of the γ-ray angular distribution coefficient $a_2(t) = a_2(t=0)\exp(-t/\tau_2)$, where τ_2 is the relaxation time. A total of eight different products of $g\beta(T)$ were determined and fitted by five parameters: $g(^{144}\text{Gd}, 130\text{ ns}) = 1.276 \pm 0.014$; $g(^{147}\text{Gd}, 530\text{ ns}) = 0.446 \pm 0.008$; $B_0(\text{Gd}Sn) = -16.5 \pm 4.7$ T; $B_0(\text{Gd}Sm) = -16.7 \pm 1.5$ T; and $B_0(\text{Gd}Pb) = -16.2 \pm 1.9$ T. The measured paramagnetic correction factors are shown in Fig. 2. Our absolute value for $B_0(\text{Gd}Sn)$ is smaller and more accurate than the one measured very recently by Faestermann *et al.*[11] ($B_0 = -31 \pm 15$ T). The measured hyperfine fields B_0 differ from those for free Gd^{3+} ions[12] ($B_0 = -34 \pm 2$ T), indicating for every host substantial and similar conduction-electron contributions.

The relaxation times τ_2, measured for two nuclear g factors differing by nearly a factor of 3, are useful indicators of the origin of the spin relaxation process. Above the melting point of Sn (505 K) the relaxation times are nearly constant, with the values for ^{144}Gd ($\tau_2 = 80 \pm 10$ ns) and ^{147}Gd ($\tau_2 = 750 \pm 200$ ns) inversely proportional to g^2.

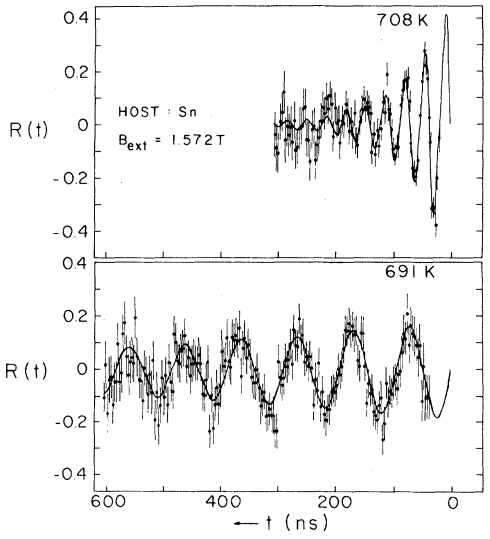

FIG. 1. Larmor precession patterns $R(t)$ for $M1E2$ transitions ($E_\gamma = 231$, 328 and 545 keV) deexciting the 130 ns, $J^\pi = 10^+$ isomer in ^{144}Gd (upper panel). The lower panel shows $R(t)$ for the 254-keV γ ray, one of about fifteen deexcitation γ rays exhibiting the effect of the half-life and g factor of the 530-ns yrast trap in ^{147}Gd. The theoretical curves are explained in the text.

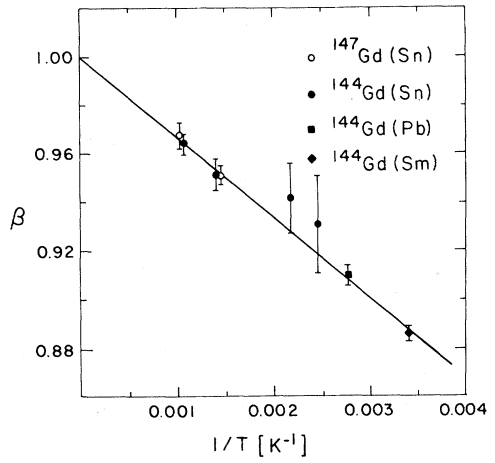

FIG. 2. Paramagnetic correction factor $\beta(T)$ for Gd recoils in three metallic environments as a function of the inverse of the host temperature T, expressed in K^{-1}. The solid line, corresponding to $\beta(T) = 1 - 33/T$, is consistent with all data points.

This dependence suggests the dominance of magnetic relaxation effects. Below the melting point of Sn, τ_2 becomes much shorter, probably as a result of additional effects from quadrupole interactions.

The isomer half-lives and g factors, as well as energies and angular distribution coefficients of representative, strongly anisotropic γ rays, are given in Table I. The g-factor values were obtained by dividing the measured products $g\beta(T)$ by the appropriate paramagnetic correction factors $\beta(T)$. In ^{146,147}Gd, where several isomers exist, the fitting procedure[8] took account of up to four isomers although the bombarding energies were chosen to reduce feeding from higher isomers to less than 50%. For the short-lived isomers ($T_{1/2} < 10$ ns) it was of crucial importance to determine accurately the beam arrival time and to include in the analysis the bending angle of the incoming beam resulting from the external magnetic field. In two cases, which show small g factors ($|g| < 0.05$), only a fraction of a full Larmor precession was observable, and the quoted values assume standard a_2 coefficients for the pure $E\lambda$ transitions deexciting the isomers. Two of the eight g factors quoted in Table I have also been measured very recently by Faestermann *et al.*[11] With our more accurate value for B_0(GdSn), their results imply $g(^{147}\mathrm{Gd}, \frac{27}{2}^-) = 0.849 \pm 0.017$ in excellent agreement with our measurement (0.840 ± 0.017). Substantial disagreement exists, however, for the 7^- states in ^{146}Gd where our value (1.283 ± 0.027) is appreciably higher than theirs

TABLE I. g factors of isomeric states in Gd isotopes.

Nucleus	$T_{1/2}$ (ns)	J^π	E_γ (keV)	$a_2(t=0)$	suggested[a] main configuration	g_{main}[b]	g_{exp}[c]
^{144}Gd	130 ± 10	10^+	328	-0.60	$(\pi d_{5/2}^{-2} h_{11/2}^{2})10(\nu h_{11/2}^{-2})0$	see text	1.276 ± 0.014
^{146}Gd	6.7 ± 0.1	7^-	324	+0.24	$(\pi d_{5/2}^{-1} h_{11/2})7$	1.39	1.283 ± 0.027
		7^-			$(\pi g_{7/2}^{-1} h_{11/2})7$	1.14	
	4.1 ± 0.2	(19^+)	865	-0.19	$(\pi d_{5/2}^{-2} h_{11/2}^{2})10(\nu h_{11/2}^{-1} f_{7/2})9$	0.58	0.63 ± 0.09
^{147}Gd	22.2 ± 1.5	$13/2^+$	997	0.45	$(\nu i_{13/2}) + (3^- \otimes \nu f_{7/2})$	see text	-0.037 ± 0.011
	5 ± 1	$21/2^+$	1491	0.24	$(\pi d_{5/2}^{-1} h_{11/2})7(\nu f_{7/2})$	0.75	0.72 ± 0.11
	26.8 ± 0.7	$27/2^-$	183	-0.10	$(\pi d_{5/2}^{-2} h_{11/2}^{2})10(\nu f_{7/2})$	0.88	0.840 ± 0.017
	530 ± 30	$(49/2^+)$	254	0.30	$(\pi d_{5/2}^{-2} h_{11/2}^{2})10(\nu h_{11/2}^{-1} i_{13/2} f_{7/2})29/2$	0.45	0.446 ± 0.008
^{148}Gd	16.5 ± 0.3	9^-	785	0.26	$(\nu i_{13/2} f_{7/2})9$	-0.12	-0.028 ± 0.009

[a] Relative to a closed ^{146}Gd core ($N = 82$, $Z = 64$).

[b] The following basic g factors were used: for protons $d_{5/2}^{-1}$, 1.66; $h_{11/2}$, 1.30; for neutrons $h_{11/2}^{-1}$, −0.18; $f_{7/2}$, −0.30; $i_{13/2}$, −0.04.

[c] Paramagnetic correction factors have been applied as explained in the text.

(1.08 ± 0.08). This discrepancy arises probably from the different reactions utilized to populate the isomer. Using the reaction ^{144}Sm(^{4}He, $2n$)^{146}Gd we observe essentially no feeding from higher-lying isomers in striking contrast to the ^{28}Si-induced reaction employed by Faestermann *et al.*[11]

Guided by the measured g factors we have arrived at the most likely quasiparticle structure of the isomers. The configurations relative to doubly closed ^{146}Gd ($N=82, Z=64$) are shown in Table I. Some of the low-spin isomers ($J \lesssim 10$) deserve a brief discussion. The 10^+ isomer in ^{144}Gd has a g factor similar to that for the $\pi(h_{11/2})$ state in ^{141}Pr ($g=1.30\pm0.08$),[13] in disagreement with the previously suggested[9] two-neutron-hole configuration, $\nu(h_{11/2}^{-2})$. Our result is compatible with a very pure proton structure for this state and deemphasizes the importance of the proton shell closure at $Z=64$.[14]

Another important g factor, that for the $\frac{13}{2}^+$ first excited state in ^{147}Gd, is considerably higher than that for the $i_{13/2}^{-1}$ neutron orbital in the Pb region ($g=-0.154$).[15] The difference can probably be explained by a large $(3^- \otimes \nu f_{7/2})$ octupole component in ^{147}Gd, which is also consistent with the reduced spectroscopic factors for $l=6$ single-nucleon transfer reactions.[16]

With the basic magnetic moments of single-particle states from the present work and from a recent compilation,[17] we have calculated g factors for several high-spin quasiparticle states in ^{146,147}Gd. In both cases comparison with experiment leads to a preferred quasiparticle configuration, although several would have spins in the required[6] range. The quoted spins are the most likely; however, an uncertainty of one unit of $\hbar$ must be conceded to allow for different vectorial couplings of the quasiparticle spins. The proposed spin and parity assignments should be of considerable value for future theoretical and experimental studies of the yrast properties in these nuclei. It should be noted that the high-spin yrast traps have approximately equal numbers of protons (n_p) and neutrons (n_n) contributing to the total spin, and that their g factor can be estimated by $g \approx n_p/(n_p+n_n)$ to an accuracy of 25%. Near doubly closed shells, the high-spin yrast states, whose configurations arise from excitations of both protons and neutrons, can apparently be described by the concept of an effective rigid-body moment of inertia.

A most important open question with regard to high-spin yrast states concerns the magnitude of their (oblate) deformation. Perhaps the most direct answer may be provided again by the long-lived yrast traps whose static deformation can, in principle, be determined by difficult perturbed angular-correlation experiments. The relatively long relaxation times observed in the present study should encourage such future attempts.

---

[a] Permanent address: Laboratoire de Physique Nucléaire, Université de Montréal, Montréal, Québec, Canada.

[b] Summer visitor, from University of Munich, München, West Germany.

[c] Permanent address: Centre National de la Recherche Scientifique, Strasbourg, France.

[d] Present address: Brookhaven National Laboratory, Upton, N. Y. 11973.

[1] J. Pedersen, B. B. Back, F. M. Bernthal, S. Bjornholm, J. Borggreen, O. Christensen, F. Folkmann, B. Herskind, T. L. Khoo, M. Neiman, F. Pühlhofer, and G. Sletten, Phys. Rev. Lett. 39, 990 (1977).

[2] T. L. Khoo, R. K. Smither, B. Haas, O. Häusser, H. R. Andrews, D. Horn, and D. Ward, Phys. Rev. Lett. 41, 1027 (1978).

[3] C. Baktash, E. der Mateosian, O. C. Kistner, and A. W. Sunyar, private communication.

[4] B. Haas, H. R. Andrews, O. Häusser, D. Horn, J. F. Sharpey-Schafer, P. Taras, W. Trautmann, D. Ward, T. L. Khoo, and R. K. Smither, to be published.

[5] A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, New York, 1975), Vol. 2.

[6] R. Broda, M. Ogawa, S. Lunardi, M. R. Maier, P. J. Daly, and P. Kleinheinz, Z. Phys. A285, 423 (1978).

[7] D. J. Bellafiore and M. E. Caspari, Hyperfine Interact. 3, 173 (1977).

[8] O. Häusser, T. K. Alexander, J. R. Beene, E. D. Earle, A. B. McDonald, F. C. Khanna, and I. S. Towner, Nucl. Phys. A273, 253 (1976).

[9] M. A. J. Mariscotti, H. Beuscher, W. F. Davidson, Y. Gono, H. M. Jager, R. M. Lieder, M. Muller-Veggian, A. Neskalis, and D. R. Zolnowski, Kernforschungsanlage, Jülich, Annual Report, 1977 (unpublished).

[10] R. Kalish, U. Shreter, and J. Grunzweig-Genossar, Hyperfine Interact. 1, 65 (1975).

[11] T. Faestermann, H. Bohn, F. B. Feilitzsch, A. W. Sunyar, R. Broda, P. Kleinheinz, and M. Ogawa, to be published.

[12] S. Hüfner and J. H. Wernick, Phys. Rev. 173, 448 (1968).

[13] H. Ejiri, T. Shibata, and M. Takeda, Nucl. Phys. A221, 211 (1974).

[14] M. Ogawa, R. Broda, K. Zell, P. J. Daly, and P. Kleinheinz, Phys. Rev. Lett. 41, 289 (1978).

[15] K. Nakai, B. Herskind, J. Blomqvist, A. Filevich, K. G. Rensfelt, J. Sztarkier, and S. Nagamiya, Nucl. Phys. A183, 526 (1972).

[16] W. Booth, S. Wilson, and S. S. Ipson, Nucl. Phys. A229, 61 (1974).

[17] G. H. Fuller, Phys. Chem. Ref. Data 5, 835 (1976).