Oblate Deformation of High-Spin Levels in Gd Isotopes

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(Received 14 September 1984)

Oblate shapes of four high-spin isomers in Gd isotopes (10^+ in ^{144}Gd, $\frac{13}{2}^+$, $\frac{27}{2}^-$, and $\frac{49}{2}^+$ in ^{147}Gd) were established in measurements of the *signs* of the respective quadrupole moments. A combined tilted-multifoil and time-differential perturbed-angular-distribution technique was employed. The present results are direct evidence for the presumed oblate nature of high-spin states in the $A \approx 150$ region.

PACS numbers: 21.10.Ft, 21.10.Ky, 23.20.En, 27.60.+j

An intriguing problem in nuclear physics is the possible shape transition from nearly spherical or prolate at low spins to oblate at high spins.[1,2] The prevailing view is that such transitions occur in the rare-earth region as a result of the alignment of several valence nucleons, occupying orbitals of high angular momenta, and a subsequent polarization of the core into an oblate shape. The model further predicts[1,2] the existence of high-spin yrast traps, discovered experimentally[3] and explained theoretically.[4-6] Indirect verification of the oblate nature of the isomers has been presented but to date there has been no direct measurement of the sign of the deformation (negative for oblate shape, positive for prolate).

The magnitudes of the quadrupole moments for several Gd high-spin isomers are known[7,8]: in ^{147}Gd, 73(7), 126(8), and 314(17) $e\cdot\mathrm{fm}^2$ at spins $\frac{13}{2}$, $\frac{27}{2}$, and $\frac{49}{2}$, respectively; and in ^{144}Gd, 145(5) at $I=10$. The values of the Gd quadrupole moments are not consistent with the spherical shell model,[8-10] and the authors of Ref. 8 conclude that a significant core deformation, up to $|\beta| \approx 0.18$ at $I=\frac{49}{2}$, is present. A negative sign of the deformation was inferred[8] from calculations with the deformed independent-particle model.[9,10] The oblate nature at high spins in ^{147}Gd has also been deduced from discontinuities in the slope of the yrast line: A reduced slope at high spins has been interpreted as evidence of increased oblate deformation.[11]

The present work addresses itself directly to the question of the nuclear shape of high-spin Gd levels. The signs of the quadrupole moments of the four Gd isomers were measured by a technique which has been developed in our laboratory and tested on the ^{54}Fe(10^+) isomer, where it yielded a positive quadrupole moment.[12,13] In conventional time-differential perturbed-angular-distribution (TDPAD) experiments the nuclei are aligned by the reaction and only the magnitude of Q can be determined. The present technique employs the tilted-multifoil interaction to polarize the reaction products prior to the TDPAD observation, and allows the determination of the sign of Q as well as the magnitude.

The polarization process and the apparatus are discussed elsewhere[14]; here we describe the experimental arrangement only briefly. The Gd isomers were populated by fusion evaporation reactions of pulsed ^{28}Si beams from the 14UD Koffler Pelletron accelerator at Rehovot and the BNL tandem Van de Graaff accelerator with 600-μg/cm^2 isotopically en-

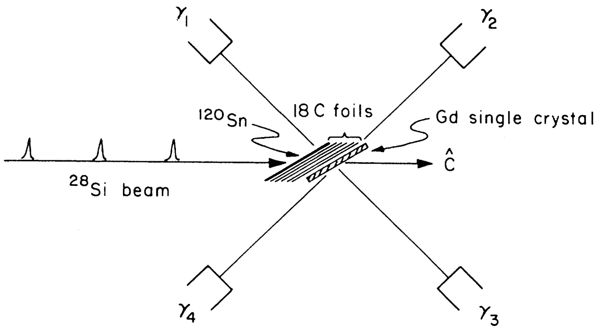

FIG. 1. A scheme of the experimental arrangement [shown for the ^{144}Gd(10^+) isomer].

TABLE I. Experimental conditions.

Reaction	E (^{28}Si) (MeV)	Number of C foils	Interfoil flight distance (μm)	Observed γ rays (keV)	Isomer studied I^{π}
^{122}Sn(^{28}Si, 4n)^{144}Gd	136	18	150	328,545	10^{+}
	120	22	400	272,278,997,1491	$\frac{27}{2}^{-}, \frac{13}{2}^{+}$
^{124}Sn(^{22}Si, 5n)^{147}Gd	144	24	450	254,339	$\frac{49}{2}^{+}$

riched Sn targets tilted with the normal at 60° to the beam (Fig. 1). The recoiling reaction products passed through arrays of equally spaced 4-8-μg/cm^2-thick C foils and stopped in a single crystal of Gd, oriented with the $\hat{c}$ axis along the beam direction. The interaction of the recoiling ions with the exit surfaces of the C foils induced an electronic polarization along an axis perpendicular to the normal to the foils and the beam direction (tilt axis), which in turn was transferred to the nuclei via the hyperfine interaction in vacuum.[12-14] After stopping in the hexagonal Gd host, the polarized nuclear spins underwent a spin precession due to the hyperfine quadrupole interaction with the internal electric field gradient (EFG); the sense of the rotation depends on the sign of Q and the sign of the EFG.

The number of C foils and the interfoil distances (Table I) were chosen to maximize the induced nuclear polarization, given the g factors and recoil velocities,[14] and to minimize the stopping in the C foils and frames. The tilt direction (left or right relative to the beam) was alternated periodically, corresponding to measurements with polarization up and down.[14]

Four coaxial Ge(Li) detectors were used to accumulate time spectra of decay γ rays of interest. For each measurement two summed time spectra were formed:

$$Y_a(t) = Y_{1,U}(t) + Y_{2,D}(t) + Y_{3,U}(t) + Y_{4,D}(t)$$

and

$$Y_b(t) = Y_{1,D}(t) + Y_{2,U}(t) + Y_{3,D}(t) + Y_{4,U}(t)$$

for detectors 1-4, in the polarization directions up and down, after normalization and subtraction of background time spectra.

From the summed yields, the ratio function was generated,

$$R(t) = [Y_a(t) - Y_b(t)]/[Y_a(t) + Y_b(t)],$$

and least-squares fitted by the expression[12, 13]

$$R(t) = -\tfrac{3}{2} P_I F_2 \textstyle\sum_n S_{n1}^{12} \sin(n\omega_0 t),$$

where $P_I = \langle Iz \rangle / [I(I+1)]^{1/2}$ is the nuclear polarization induced by the multifoil array, and F_2 is the γ-ray angular distribution coefficient.[15] The coefficients S_{n1}^{12} are defined, for example, by Dafni *et al.*[16] and $\omega_0 = 3e^2qQ/4I(2I-1)\hbar$ $[6e^2qQ/4I \times (2I-1)\hbar]$ for integer (half-integer) spins.

The sign of the EFG, eq, for Gd in a Gd matrix is known to be positive[17] and the sign of F_2 is known for each of the measured γ rays. Thus, the sign of Q is deduced directly from the fits. (Note that the S_{n1}^{12} coefficients are negative.) In all fits, the magnitude of ω_0 was in agreement with the published

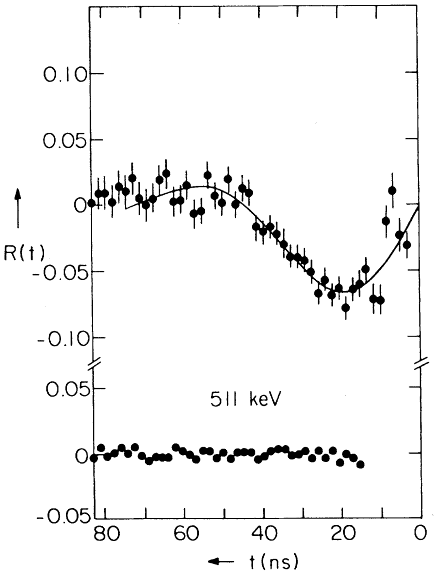

FIG. 2. Upper part: experimental ratio function and a fitted curve for the ^{144}Gd(10^+) isomer. Data for the 328- and 545-keV transitions are summed together. Lower part: ratio function for the 511-keV radioactivity, serving as a control measurement.

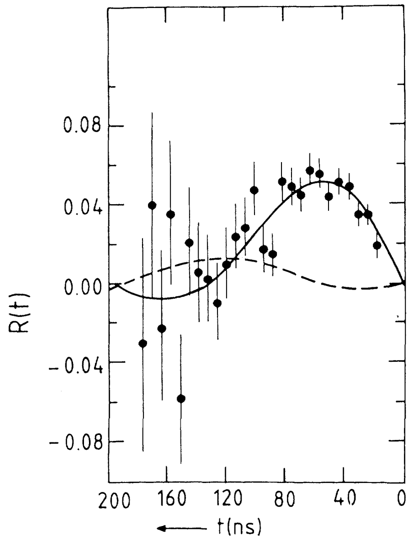

FIG. 3. Experimental ratio function and fit for the 997-keV transition, depopulating both the $\frac{27}{2}^-$ and $\frac{13}{2}^+$ isomers in ^{147}Gd. The two-level fit (solid line) yields a negative sign of Q for both isomers; the dashed line is calculated with the assumption of positive Q for the $\frac{27}{2}^-$ state and negative Q for the $\frac{13}{2}^+$ state.

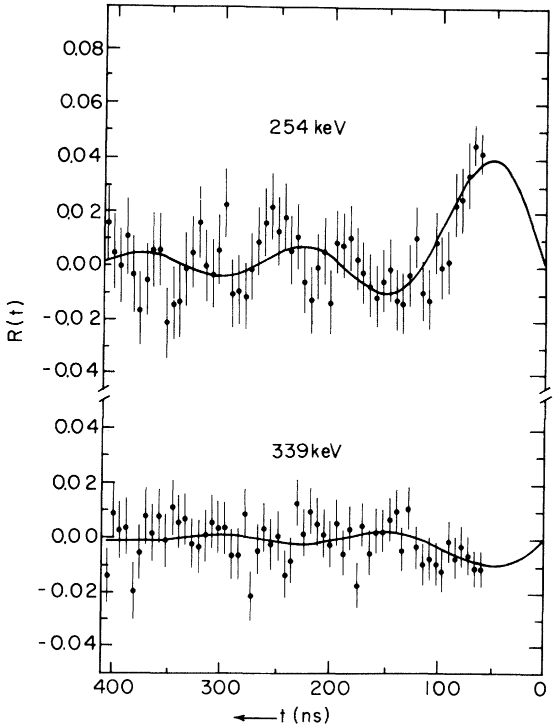

FIG. 4. Experimental ratio functions and fitted curves for the 254- and 339-keV transitions from the decay of the ^{147}Gd($\frac{49}{2}^+$) isomer. The opposite sign and different magnitudes of the effects for the two γ rays are due to different F_2 coefficients; both measurements are consistent with the same value of ω_0 and P_l and a negative sign of Q.

values[7,8]; the parameters determined were P_l and the sign of Q. The levels studied are as follows:

(i) *^{144}Gd(10^+) (Fig. 2).*—Runs with different interfoil spacings gave essentially identical results. Control measurements using beam-induced radioactivity lines or with the polarizing C foils removed from the assembly yielded a null effect. The negative effect in Fig. 2 corresponds to a negative sign of Q since F_2 is positive for the observed $9^- \rightarrow 8^+$ and $8^- \rightarrow 7^-$ transitions.[18]

(ii) *^{147}Gd($\frac{13}{2}^+, \frac{27}{2}^-$) (Fig. 3).*—Under the present experimental conditions the 997-keV $\frac{13}{2}^+ \rightarrow \frac{7}{2}^-$ transition contains information about both the $\frac{13}{2}^+$ and $\frac{27}{2}^-$ isomers depopulated by it.[8] This is actually a fortunate situation since the lifetime of each isomer by itself is too short to allow a sensitive measurement. The solid line in Fig. 3 represents a fit by a two-level formalism,[19] which yields a negative sign of Q for both isomers (with negative F_2, Ref. 8). The dashed line in Fig. 3, with the assumption that the quadrupole moments of the two isomers have opposite signs, demonstrates the sensitivity of the present experiment to the relative signs of the two quadrupole moments. A control experiment without C foils yielded null results. For transitions depopulating the $\frac{27}{2}^-$ state directly we have applied a different analysis procedure consisting of integration of the yields in a time window after the prompt γ and normalization by absolute efficiencies obtained by measurements without C foils. This procedure also yielded a negative sign of Q for the $\frac{27}{2}^-$ state.

(iii) *^{147}Gd($\frac{49}{2}^+$) (Fig. 4).*—This is the most interesting case in the present study, being the highest-spin isomer with a measured quadrupole moment. The two main transitions depopulating this isomer, the $\frac{49}{2}^+ \rightarrow \frac{45}{2}^+$ 254-keV and the $\frac{45}{2}^+ \rightarrow \frac{43}{2}^-$ 339-keV lines, have F_2 values of opposite signs and different magnitude (negative and large for 254 keV, positive and small for 339 keV[8]). The data for the two transitions yield consistent values of ω_0 and P_l with amplitudes of the effect corresponding to the known F_2 values (Fig. 4). The sign deduced for the ^{147}Gd($\frac{49}{2}^+$) quadrupole moment is negative.

In conclusion, the signs of the electric quadrupole moments of four Gd levels, including the ^{147}Gd($\frac{49}{2}^+$) isomer, have been determined to be negative. This is the first direct evidence for the presumed oblate shape of high-spin states in the $A \approx 150$ mass region. A deformation parameter value of $\beta = -0.18$, previously suggested for the $^{147}\mathrm{Gd}(\frac{49}{2}^{+})$ isomer,[8-10] is now confirmed.

This work is supported in part by the Minerva Foundation, Munich, Germany and the U.S. Department of Energy under Contract No. DE-AC02-76CH00016. Three of us (E.D., G.G., and M.H.R.) would like to thank the BNL tandem accelerator group for their kind hospitality. The devoted support of the accelerator and target laboratory staff at BNL and Rehovot is appreciated.

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[1] A. Bohr and B. R. Mottelson, Phys. Scr. **10A**, 13 (1974).

[2] G. Anderson, S. E. Larsson, G. Leander, P. Möller, S. G. Nilsson, I. Ragnarsson, S. Aberg, R. Rengtsson, S. Dudek, B. Nerlo-Pomorska, K. Pomorksi, and Z. Szymanski, Nucl. Phys. **A268**, 205 (1976).

[3] J. Pedersen, B. B. Back, F. N. 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).

[4] M. Cerkaski, J. Dudek, Z. Szymanski, G. G. Andersson, G. Leander, S. Aberg, S. G. Nilsson, and I. Ragnarsson, Phys. Lett. **70B**, 9 (1977).

[5] T. Døssing, K. Neërgard, K. Matskyanagi, and Hsi-Chen Chang, Phys. Rev. Lett. **39**, 1395 (1977).

[6] C. G. Andersson, G. Hellström, G. Leander, and I. Ragnarsson, Nucl. Phys. **A309**, 141 (1978).

[7] O. Häusser, H.-E. Mahnke, J. F. Sharpy-Schafer, M. L. Swanson, P. Taras, D. Ward, H. R. Andrews, and T. K. Alexander, Phys. Rev. Lett. **44**, 132 (1980).

[8] O. Häusser, H.-E. Mahnke, T. K. Alexander, H. R. Andrews, J. F. Sharpey-Schafer, M. L. Swanson, D. Ward, P. Taras, and J. Keinonen, Nucl. Phys. **A379**, 287 (1982).

[9] K. Neërgard, T. Døssing, and H. Sagawa, Phys. Lett. **99B**, 191 (1981).

[10] T. Døssing, K. Neërgard, and H. Sagawa, J. Phys. (Paris) Colloq. **41**, C10-79 (1980).

[11] O. Bakander, C. Baktash, J. Borggreen, J. B. Jensen, K. Kowanacki, J. Pedersen, G. Sletten, D. Andrews, O. Häusser, P. Skensved, and P. Taras, Nucl. Phys. **A389**, 93 (1982).

[12] E. Dafni, M. Hass, H. H. Bertschat, C. Broude, F. D. Davidovsky, G. Goldring, and P. M. S. Lesser, Phys. Rev. Lett. **50**, 1652 (1983).

[13] M. Hass, E. Dafni, H. H. Bertschat, C. Broude, F. D. Davidovsky, G. Goldring, and P. M. S. Lesser, Nucl. Phys. **A414**, 316 (1984).

[14] C. Broude, E. Dafni, G. Goldring, M. Hass, O. C. Kistner, B. Rosenwasser, and L. Sapir, Nucl. Instrum. Methods (to be published).

[15] T. Yamazaki, Nucl. Data Sect. A **3**, 1 (1967).

[16] E. Dafni, R. Bienstock, M. H. Rafailovich, and G. D. Sprouse, At. Data Nucl. Data Tables **23**, 315 (1979).

[17] E. Bauminger, A. Diamant, I. Felner, I. Novick, and S. Ofer, Phys. Rev. Lett. **34**, 962 (1975).

[18] M. A. J. Mariscotti, H. Beuscher, W. F. Davidson, Y. Geno, H. M. Jäger, R. M. Lieder, M. Müller-Veggian, A. Neskakis, D. R. Haenni, and D. R. Zolnowski, Nucl. Phys. **A311**, 395 (1978).

[19] E. Dafni, M. H. Rafailovich, T. Marshall, G. Schatz, and G. D. Sprouse, Nucl. Phys. **A394**, 245 (1983). In the present case averaging over the orientation of the EFG is not required and the exact single-crystal perturbation factors are used.