value of 0.9 mb at about 14 MeV, then falls smoothly to about 0.4 mb at 26 MeV. The hyperspherical-harmonics calculations yield cross sections which appear either to peak at too high an energy or else to attain too high a peak value at the maximum, although it should be noted that the dash-dot-dash curve[7] is for a Volkov force with no spin dependence and never was intended to be compared with experiment.

The measured integrated cross sections and their first and second moments for the reactions ^{3}H(γ, n) and ^{3}H(γ, $2n$) are given in Table I. Up to a photon energy of 19.2 MeV, the values for the reaction ^{3}H(γ, n) are the larger.

We hope that these data stimulate the additional theoretical work necessary to understand these fundamental cross sections, particularly the three-body photodisintegration cross section, for which no presently available calculation is adequate.

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Quadrupole Moment of a High-Spin Yrast Trap in ^{147}Gd

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Static quadrupole interactions of three ^{147}Gd isomers in single crystals of hexagonal gadolinium have been observed. The quadrupole moments increase with increasing spin and imply a substantial (oblate) deformation ($\beta \sim -0.2$) for the 500-ns high-spin yrast trap.

The discrete yrast states with spins between $14\hbar$ and $36\hbar$ that have recently been observed in the neutron-deficient rare-earth nuclei ^{152}Dy (Ref. 1) and ^{154}Er (Ref. 2) exhibit a new kind of collective motion. Many individual particles align their angular momenta along the symmetry axis producing an oblate deformation. It had been predicted by Bohr and Mottelson[3] that the yrast energies of such nuclei, when plotted versus $I(I+1)$, should follow closely a straight line corresponding to an effective moment of inertia, $\mathscr{G}$, of about the rigid-body value. In ^{152}Dy, $\mathscr{G}$ exceeds $\mathscr{G}_{\rm rigid}$ by about 10%,[1] which may be taken as an indication that the valence particles induce a sizable oblate deformation of the core. Experimental attempts to verify this speculation have so far met with difficulties. The $E2$ transitions between yrast states are inhibited (cf. Ref. 4) because they involve rearrangements in the filling of single-particle orbitals. Collective bands based on individual yrast states might arise from collective rotations around an axis perpendicular to the symmetry axis. Observations of the corresponding in-band transitions are hampered by the weak sidefeeding intensities and the competition of statistical γ rays.

In the present Letter we report the first direct observation of a quadrupole moment in the very high-spin region ($I \sim 25\hbar$). Of the rare-earth metals, gadolinium occupies a unique role since Gd^{3+} has an almost pure, spherical $^8S_{7/2}$ electronic ground state. The magnetic hyperfine fields for Gd are correspondingly weak and spin relaxation times as long as ~ 1 μs have been observed.[5] The 500-ns isomer of ^{147}Gd (Ref. 6) appeared to be one of a few long-lived high-spin states (yrast traps) for which static quadrupole interactions (QI) might be observable. The ^{147}Gd isomer decays by more than 50 γ rays which have not yet been ordered into a consistent decay scheme. Its excitation energy, 7.55 ± 0.35 MeV, was recently determined by Borggreen *et al.*[7] with a large-volume NaI(Tl) γ-ray sum spectrometer. The g factor of the isomer, $g = 0.45$,[5] indicates a five-quasiparticle structure with a tentative spin-parity assignment of $I^\pi = \frac{49}{2}^+$.

In this experiment high-spin states in ^{147}Gd were populated and aligned in the ^{124}Sn(^{28}Si, $5n$) reaction by use of pulsed beams of ^{28}Si at a bombarding energy of 144 MeV. The beam bursts were ≤ 2 ns wide and had a repetition time of 3.2 μs. The excited Gd recoils traversed the 2-mg/cm^2-thick targets of enriched ^{124}Sn and were implanted into 1-mm-thick single crystals of Gd. The single crystals were obtained commercially[8] or by annealing arc-melted Gd buttons at 1230 °C for about one day. The orientation of the crystals was determined to an accuracy of $\sim 3°$ from x-ray measurements. During the experiment the target assembly was heated to elevated temperatures between 324 and 469 K, well above the Curie point for Gd (293 K).

The quadrupole modulation was measured by use of the standard perturbed-angular-distribution (PAD) method.[9] Background-corrected time spectra were derived for several γ rays observed with two Ge(Li) spectrometers placed at 0° and 90° to the beam direction. The ratios of γ-ray yields, $R(t) = [Y(0°,t) - Y(90°,t)]/[Y(0°,t) + Y(90°,t)]$ are shown in Fig. 1 for the 254-keV γ ray (an-

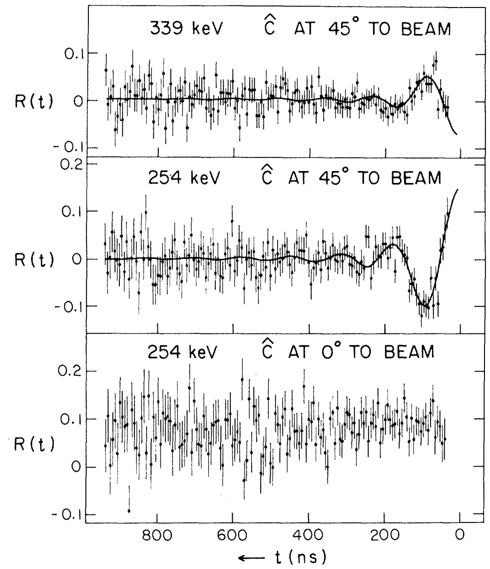

FIG. 1. Modulation patterns resulting from quadrupole interaction of the 500-ns isomer in ^{147}Gd in a single crystal of Gd at 413 K. The reduced $R(t=0)$ in the lower panel arises from the fact that one of the γ detectors was placed at 68° rather than at 90° to the beam direction to avoid absorption of low-energy γ rays.

gular distribution coefficient $a_2 > 0$) and the 339-keV doublet ($a_2 < 0$). For the top two panels the symmetry ($\hat{c}$) axis of the crystal was at 45° to the beam in the γ-detector plane. This $\hat{c}$ orientation of a single crystal produces a much more pronounced interference feature near time $t = 0$ (see Ref. 10) compared to a polycrystalline host. Since the basic QI frequency decreases quadratically with spin, the full modulation pattern for high-spin states is rarely observable. In this case the use of a single crystal presents a distinct advantage, although the theoretical fit (solid line) determines merely the *ratio*[10] $|eqQ|/I$, where eq is the axially symmetric electric field gradient produced by the hexagonal crystal lattice, and Q is the nuclear quadrupole moment. Assuming $I = \frac{49}{2}$ for the 500-ns isomer,[5] we obtain a quadrupole coupling constant, $\nu_Q = e^2qQ/h = 250 \pm 7$ MHz at 413 K.

The use of a single crystal in QI experiments allows one to effectively switch off the QI by turning the $\hat{c}$ axis to coincide with the beam axis. In the lower panel of Fig. 1 the characteristic modulation pattern has disappeared and most of the initial alignment is preserved over times longer than 1 μs. This demonstrates that most ^{147}Gd recoils substitute in the Gd lattice, and that the fitted modulation results from static QI with a unique eq.

We have observed QI for the 27-ns $\frac{27}{2}^-$ isomer at 2.582 MeV[6] and the 22-ns $\frac{13}{2}^+$ isomer at 0.997 MeV in addition to that for the 500-ns isomer. For these measurements the bombarding energy was lowered to 120 and 108 MeV, respectively, to minimize interference from the population of higher-lying isomers. The quadrupole modulation pattern for the $\frac{27}{2}^-$ isomer observed via the 272-keV γ ray is shown in Fig. 2. The fitted QI frequency $\nu_Q = 100.4 \pm 6.6$ MHz (solid line) gives equally good fits to the QI patterns for the 183- and 1491-keV deexcitation γ rays (not shown).

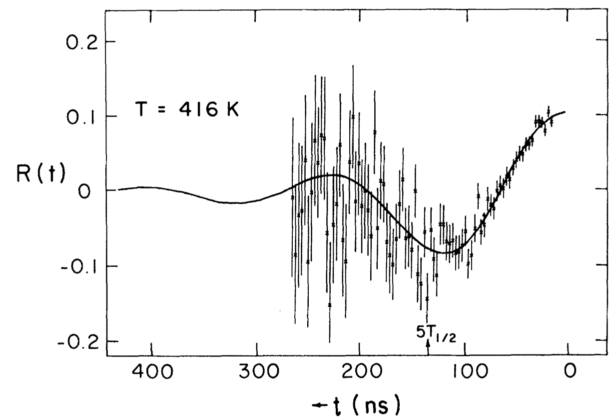

FIG. 2. Quadrupole modulation of the 27-ns, $J^\pi = 27/2^-$ isomer in ^{147}Gd observed via the $21/2^+ \to 17/2^+$, 272-keV $E2$ transition.

The measured quadrupole-coupling constants ν_Q can be interpreted in terms of nuclear quadrupole moments provided the magnitude and temperature dependence of eq for Gd are known. In a Mössbauer experiment Bauminger *et al.*[11] have determined $\nu_Q = e^2q\,^{155}Q(0)/h = 105.6 \pm 2.8$ MHz for the ^{155}Gd ground state in a Gd single crystal at 4 K. The same group of authors[12] has also measured the moment ratio $^{156}Q(2^+)/^{155}Q(0) = -1.51 \pm 0.02$. Since ^{156}Gd is a good rotational nucleus,[13] $^{156}Q(2^+)$ can be calculated from the 2^+ lifetime[13] and combined with the moment ratio to yield $^{155}Q(0) = 1.29 \pm 0.02$ b (1 b $= 10^{-28}$ m^2). A recent independent measurement of the optical hyperfine splitting in ^{155,157}Gd (Ref. 14) has yielded a Sternheimer corrected value $^{155}Q(0) = 1.258 \pm 0.065$ b. Both determinations of $^{155}Q(0)$ are in excellent agreement and imply $eq = (3.41 \pm 0.14)10^{17}$ V/cm^2 for a Gd single crystal at 4 K. Subsidiary experiments were necessary to determine eq at temperatures above the Curie point for Gd where the present experiment was performed. We have Coulomb excited a Gd single crystal at $T = 332$ K using a 6-MeV ^{4}He beam. From the observed PAD spectra for the $2^+ \to 0^+ \gamma$ rays in the rotational nuclei ^{156,158,160}Gd we deduce[14] $eq(332\ \mathrm{K}) = (3.43 \pm 0.14)10^{17}$ V/cm^2. Apparently, eq remains nearly constant in the ferromagnetic regime. For paramagnetic Gd we have measured the temperature dependence of eq at four temperatures between 324 and 469 K. Using the 130-ns, $I^\pi = 10^+$ isomer in ^{144}Gd (Ref. 5) as a convenient probe nucleus, we find[14] a weak temperature dependence which is well fitted by $q(T)/q(332\ \mathrm{K}) = [1 - (1.5 \pm 0.4)10^{-5}T^{3/2}]/0.9093$.

The spins, half-lives, quadrupole-coupling constants and quadrupole moments of isomers in ^{147}Gd are summarized in Table I together with the energies and a_2 coefficients of γ rays used in their determination. The quasiparticle configurations are suggested on the basis of the known g factors.[5] The $I^\pi = \frac{59}{2}^-$ configuration for the 500-ns isomer has been included to demonstrate the dependence

TABLE I. Quadrupole moments in ^{147}Gd.

$T_{1/2}$ (ns)	I^π (assumed)	Quasiparticle configuration	E_γ (keV)	$a_2(t=0)$	$\nu_Q = e^2qQ/h$ [a] (MHz)	$\lvert Q_{\mathrm{exp}} \rvert$ [b] (b)	Q_{SM} [c] (b)	β
510(20)	(49/2$^+$)	$\pi h_{11/2}{}^2 \nu h_{11/2}{}^{-1} f_{7/2} i_{13/2}$			260(9)	3.14(17)	−0.84	−0.18 [0.20]
			254	0.23				
	(49/2$^+$)	$\pi h_{11/2}{}^2 \nu f_{7/2} i_{13/2} h_{9/2}$			260(9)	3.14(17)	−1.36	−0.18 [0.20]
			339	−0.10				
	(59/2$^-$)	$\pi d_{5/2}{}^{-1} h_{11/2}{}^3 \nu f_{7/2} i_{13/2} h_{9/2}$			315(16)	3.80(20)	−1.40	−0.22 [0.23]
26.8(0.7)	27/2$^-$	$\pi h_{11/2}{}^2 \nu f_{7/2}$	272	0.17	105(7)	1.26(8)	−0.78	−0.06 [0.10]
22.2(0.5)	13/2$^+$	$\nu i_{13/2}, 3^- \otimes \nu f_{7/2}$	997	0.31	61(6)	0.73(7)	−0.36	−0.05 [0.05]

[a] For a common temperature of 332 K, with $q(T)/q(332\ \mathrm{K}) = [1 - 1.5(4)10^{-5}T^{3/2}]/0.9093$.

[b] Experimental moment deduced from ν_Q, with $eq(332\ \mathrm{K}) = (3.43 \pm 0.14)10^{17}$ V/cm^2.

[c] Theoretical shell-model moment calculated with e(proton) = 1.53, e(neutron) = 1.0.

of the results on the assumed spin I, although the calculated g factor (0.61) differs from the observed one [0.45 (Ref. 5)]. The shell-model moments, Q_{SM}, were calculated with standard expressions assuming charges of 1.53 and 1.0 for protons and neutrons, respectively. These "effective" charges are typical for the Pb region, and the proton charge reproduces the measured[15] $B(E2, \pi h_{11/2}{}^2, 10^+ \rightarrow 8^+)$ in ^{148}Dy. The observed quadrupole moments increase with excitation energy and exceed $|Q_{SM}|$. Even for the $\frac{13}{2}^+$ and $\frac{27}{2}^-$ states large effective neutron charges of 2.0 and 2.9 are required to fit $|Q_{exp}|$. The quadrupole moment for the 500-ns yrast trap implies exceedingly large neutron effective charges of 8.5, 3.1, and 4.0, respectively, for the three configurations quoted in Table I.

Alternatively, the quadrupole moments can be explained with bare nucleon charges if the aligned quasiparticles producing the high-spin move outside a deformed core. In a deformed representation the quadrupole moment of an yrast trap is[10] $Q = f(I)(Q_i + Q_{core})$, where Q_i are the intrinsic quadrupole moments of the valence protons, and $f(I) = I(2I-1)/[(I+1)(2I+3)]$ transforms the intrinsic into static moments. The last column of Table I contains the deformation parameters β inferred from $|Q_{exp}|$. The prolate solutions ($\beta > 0$) shown in square brackets are considered unlikely, because the oblate deformation is energetically favored, especially for the 500-ns isomer, which contains several valence particles with large Ω. The quadrupole moment for the 500-ns isomer implies a substantial (oblate) deformation whose magnitude ($\beta \sim -0.2$) is determined to an accuracy of $\pm 15\%$ considering the constraints on configuration and spin imposed by other experiments.[5,7] Future measurements to establish the spins, parities, energies, and γ-decay modes of high-spin yrast states in ^{147}Gd would clearly be most valuable. It is also hoped that the present results will encourage further theoretical studies of the yrast structure in the $N = 82$ region of high-spin isomerism. The strong increase in deformation with increasing spin on the yrast line shown by this experiment is most likely a feature common to all nuclei in the region, and must be included in theoretical treatments.

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