g factor of the $\frac{59}{2}^-$ isomer in ^{147}Gd

M. Hass,* I. Ahmad, R. V. F. Janssens, T. L. Khoo, H. J. Körner,†
E. F. Moore, and F. H. L. Wolfs
Argonne National Laboratory, Argonne, Illinois 60439

N. Benczer-Koller
Rutgers University, New Brunswick, New Jersey 08903

E. Dafni*
Nuclear Science Research Laboratory, University of Rochester, Rochester, New York 14627

K. Beard and U. Garg
University of Notre Dame, Notre Dame, Indiana 46556

P. J. Daly and M. Piiparinen‡
Purdue University, West Lafayette, Indiana 47907
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The g factor of the 10 995 keV, $J^\pi = \frac{59}{2}^-$, and $T_{1/2} = 0.8$ ns level in ^{147}Gd has been determined by the transient field method for ions recoiling through a magnetized Gd foil at a temperature of 100 K. The ^{76}Ge(^{76}Ge,$5n$)^{147}Gd reaction at $E(^{76}\mathrm{Ge}) = 310$ MeV was used to provide high recoil velocity. A 100 ps flight time in vacuum between the target and the ferromagnet of 100 ps ensured that the γ-ray cascades fed the $\frac{59}{2}$ level before the recoil ions traversed the Gd foil. The g factor was extracted from standard double ratios with the known parametrization of the transient field, yielding $g = 0.38(7)$. This value is in agreement with the predicted wave function and experimental single-particle moments in this mass region. Results for levels in ^{146,148}Gd were also obtained.

I. INTRODUCTION

The experimental determination of magnetic moments has traditionally played an important role in the evolution of nuclear structure models since they probe primarily the single-particle degrees of freedom, in contrast to $E2$ properties which probe collective features. In particular, the determination of magnetic moments of high-spin levels can contribute significantly to our understanding of the single-particle motion at high angular momentum. For example, the measurements of g factors of high-spin levels in ^{158}Dy and in ^{238}U and ^{232}Th (Refs. 1 and 2) have demonstrated unambiguously the role of neutron or proton alignment in the structure of the yrast line in the backbending region.

The increased detection sensitivity of modern multidetector arrays, together with improved theoretical understanding of shell effects in a deformed potential, have renewed interest in g-factor measurements for nuclear states of very high spin. Since many particles are generally involved in nuclear motion at high angular momentum, the g factor observable is the only parameter which actually determines the relative contributions of neutrons and protons to the total spin.

In general, measurements of g factors of high-spin levels pose several experimental challenges. The Coulomb excitation reaction, used for populating the levels in the aforementioned Dy, U, and Th isotopes, suffers from relatively low counting rates and is limited to stable nuclei and moderate spins ($I \leq 25\hbar$). Fusion-evaporation reactions, on the other hand, are used to populate the highest spins, but the complex feeding and deexcitation patterns in the observed γ-ray cascades render the analysis of experimental results difficult. Moreover, for both types of reactions, the experimental signal (in the form of a precession of the angular correlation of decay γ rays) is very small. It can be made detectable only via the use of magnetic fields of many kT which can be obtained only via microscopic solid-state or atomic mechanisms. The transient magnetic field technique, which makes use of the rapidly fluctuating hyperfine fields acting on swift ions traversing a ferromagnetic material, is well suited[3] for such measurements. Extensive literature on the subject of g factor measurements using transient fields in Fe and Gd can be found, for example, in Refs. 4 and 5 and references therein.

The high-spin structure of ^{147}Gd has recently been investigated in great detail. Single-particle contributions to the total spin are found to be dominant on the yrast line and in its vicinity up to $I \approx 40\hbar$. The present measurement was undertaken to probe the neutron-proton contributions to the total spin, especially in view of theoretical predictions of concentrated proton strength just above the yrast line in this mass region.[7] The presence of the $\frac{59}{2}^-$ isomeric state with 0.8 ns half-life allows for a direct determination of its g factor. This measurement can in turn be used later as a reference and calibration point for measurements of *average g* factors at yet higher spins and excitation energies.[8]

II. EXPERIMENT

Previous experiments have used Si beams on Sn targets as a convenient way to populate high-spin states in ^{147}Gd. In particular, the ^{122}Sn(^{30}Si,5n)^{147}Gd reaction at $E(^{30}\mathrm{Si})=153$ MeV has been used[6] to populate the $\frac{59}{2}^-$ level. It was found, however, that with this reaction, the relatively low energy of the recoiling Gd nuclei and the associated problem of the straggling of low-energy heavy ions[9] required the use of a thin Gd foil of only 1–2 mg/cm^2 as the ferromagnetic medium. The choice of a thin Gd foil is necessary to ensure that the recoiling nuclei transverse the Gd at relatively high velocity before stopping in a perturbation-free material. However, this results in an unacceptably small angular precession angle. The ^{76}Ge(^{76}Ge,5n) reaction at $E(^{76}\mathrm{Ge})=310$ MeV was therefore selected. The beam from the ATLAS accelerator at Argonne impinged on a 1-mg/cm^2 ^{76}Ge foil deposited on a 1-mg/cm^2 Au backing. A 6.6-mg/cm^2 Gd foil, evaporated[10] onto a 1-mg/cm^2 Ta foil and backed by a 15-mg/cm^2 Au foil (to provide the perturbation-free environment for the stopped recoils) was placed downstream from the target at a distance of 1.2 mm, corresponding to a flight time of about 100 ps. Given the lifetimes[6] of levels above the $\frac{59}{2}^-$ isomer, this arrangement ensures that the γ cascade in the recoiling nuclei populates the $\frac{59}{2}^-$ level prior to entering the Gd (Fig. 1). The magnetization of the Gd foil was measured as a function of temperature and applied external field by using the Rutgers ac magnetometer[11] (Fig. 2) and a superconducting quantum interference device (SQUID) magnetometer at Argonne,[12] yielding a typical value of 98% of saturation magnetization at $T=100$ K and $H_{\mathrm{ext}}=0.1$ T. The foil was cooled to this temperature by a liquid-nitrogen flow device. An external magnetic field of 0.14 T at the target position was obtained with a pair of SmCo magnets whose orientation was periodically reversed by 180° in order to construct the standard "up-down" double ratios used to extract the Larmor precession angle (see the following paragraph).

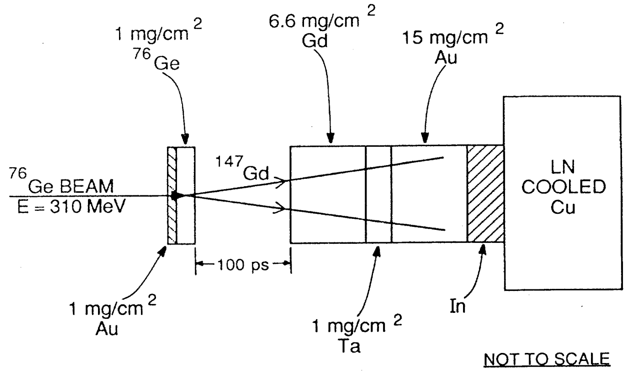

FIG. 1. Schematic view of the target assembly. The SmCo magnets (not shown) produce on target a reversible magnetic field of $H_{\mathrm{ext}}=0.14$ T in the perpendicular direction.

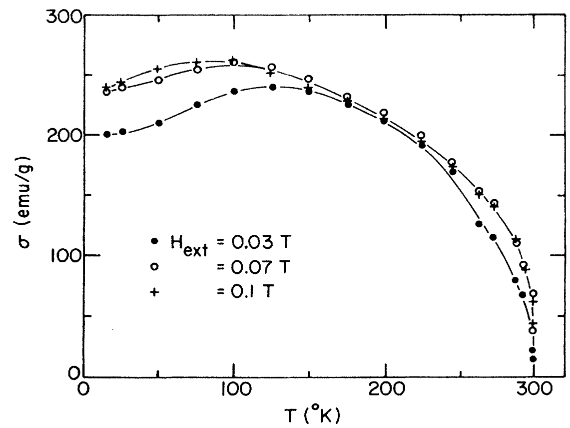

FIG. 2. Magnetization of the Gd foil as a function of temperature for three values of the external field. The magnetization at 100 K corresponds to 98% of the saturation magnetization of Gd and was used for extracting the g factor.

Prompt γ rays from the various reaction channels were detected in 12 Compton-suppressed Ge detectors of the Argonne–Notre Dame γ-ray facility. The 12 Ge detectors were located at ±35, ±90, and ±145 degrees with respect to the beam in two rings at a 17° angle above and below the horizontal plane. The forward and backward detectors are thus located at angles where the angular distribution of decay γ rays[6] exhibits a large slope: They were used to extract the precession information. The detectors at 90° are situated at a position of zero slope and were used to monitor the 35°/90° ratio which represents an on-line measure of the angular distribution. An additional requirement of high multiplicity of delayed radiation detected in a 50-element bismuth germanate (BGO) array surrounding the target was also imposed. This condition allows the selection of the ^{147}Gd channel with great sensitivity due to the presence of the well-known $\frac{49}{2}^+$, 510 ns isomer.[6] The data were collected in singles mode for each Ge detector, with each event containing the array information as well.

III. RESULTS

A. γ spectra and angular distributions

A typical spectrum of prompt γ rays in the backward detectors, gated by a delayed multiplicity >4, is shown in Fig. 3. The corresponding spectra for the forward and 90° detectors exhibit a somewhat lower peak/background ratio due to absorption in the target assembly for both positions, as well as to the angular distribution of the relevant lines (for the 90° detectors). Due to the long flight time between the target and the Gd foil, both the backward and forward spectra show the additional complication of multiple peaks (in-flight and stopped) for a given transition. This applies to all γ rays from decays above or bypassing the $\frac{59}{2}^-$ level. This fact is, however,

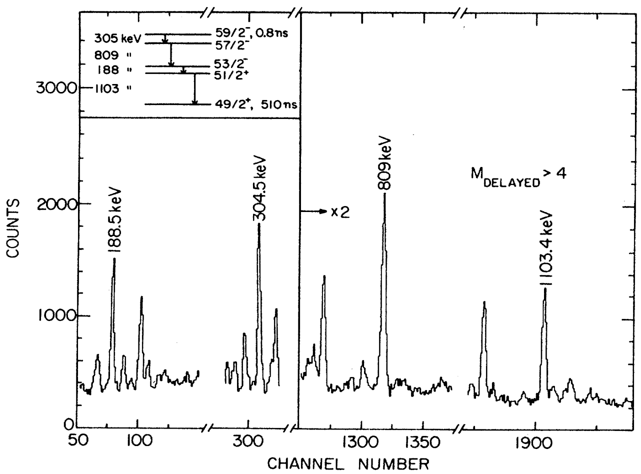

FIG. 3. Part of a typical γ spectrum in a backward detector with the delayed multiplicity condition of $M>4$. The four prominent lines at 188, 305, 809, and 1104 keV (see partial level scheme in the inset), used in the forming the double ratios of Table II, are indicated.

extremely useful in the interpretation of the experimental data. Any stopped peak from levels depopulating the $\frac{59}{2}^-$ level corresponds to transitions occurring after the recoiling ensemble has traversed the Gd foil and has come to a stop in the Au backing. Therefore the precession of the angular distribution of the stopped γ rays is a measure of the g factor of the $\frac{59}{2}^-$ level only and is not complicated by the cascading time history.

It is well known that the angular correlation of γ rays for highly-stripped ions recoiling into vacuum can be attenuated due to the random hyperfine fields acting on the nuclear spin.[13] This phenomenon has been utilized extensively to measure the absolute magnitude of g factors of levels with ps lifetimes. In the present context it has to be taken into account in the analysis of the angular correlation data when the relevant γ rays are emitted in vacuum. Table I presents the ratios of counts in the 35° to 90° detectors, after correction for efficiency and normalization for absorption. These ratios are a measure of the angular distribution of the relevant lines (again, only of the branch decaying out of the $\frac{59}{2}^-$ level). All ratios are consistent with an essentially unperturbed distribution, in agreement with the data of Ref. 6 which are then used for

TABLE I. The ratio of counts in the 35° to the 90° detectors for the three most intense γ lines depopulating the $\frac{59}{2}^-$ isomer in ^{147}Gd. The absorption at 90° for the 188 keV, $\frac{53}{2}^- \to \frac{53}{2}^+$ line was too severe to allow a significant determination of the ratio corresponding to this transition (see text for details).

Energy (keV)	$I_i - I_f$	$N(35°)/N(90°)$ (Present result)	$N(35°)/N(90°)$ (From Ref. 6)
304	$\frac{59}{2}^- - \frac{57}{2}^-$	1.42(4)	1.50(5)
809	$\frac{57}{2}^- - \frac{53}{2}^-$	1.33(3)	1.37(5)
1103	$\frac{53}{2}^+ - \frac{49}{2}^+$	1.43(4)	1.40(10)

the extraction of the precession angles from the experimental double ratios (see Sec. III B). The absence of a significant attenuation can be understood in the framework of a static hyperfine interaction, with a presumably broad distribution of hyperfine fields, and the fact that the nuclear spin of $I=\frac{59}{2}^-$ is much larger than the average atomic spin J.[14]

B. Double ratios

Standard double ratios were formed:

$$\rho_{ij}=\{[N^u(i)/N^d(i)]/[N^u(j)/N^d(j)]\}^{1/2}\ ,$$

where $N^u(i)$ and $N^u(j)$ represent, for example, the integrated counts under the stopped peak with magnetic field "up" for detectors at backward symmetric angles of $\pm 145°$. Table II summarizes the value of ρ for two cuts on the value of the delayed multiplicity (of $M=3,4$ and $M>4$) for the four prominent depopulating transitions of 188, 305, 809, and 1103 keV for the backward and forward detectors. The choice of these cuts is arbitrary; taken together they represent, however, the total of useful data.[15] As can be seen from Table II, all values of ρ are consistent with one another, and an average value of $\rho=0.956(6)$ can be deduced.

The Larmor precession angle, $\Delta\theta$, is obtained from ρ with the relations

$$\epsilon=(\rho-1)/(\rho+1) \text{ and } \Delta\theta=\epsilon/S,\ \ S=\frac{1}{W(\theta)}\cdot\frac{dW(\theta)}{d\theta}\ ,$$

where S is the logarithmic slope of the angular distribution. The value of $\Delta\theta$ is then combined with knowledge of the magnetic field to yield the measured g factor. Using the slope values of Ref. 6 for the 188, 304, and 309 keV transitions, we obtain a value for the precession angle of $\Delta\theta=74(9)$ (13) mrad., where the errors in parentheses reflect the statistical error on the ρ_{ij} values only and the combined error, including the error in S, respectively. The uncertainties in the value of S arise mostly from the fact that the 35°/90° ratio which is monitored in the experiment does not determine unambiguously the corresponding value of the slope. The presence of a significant a_4 term in the angular distribution can result in different values of S for the same value of the measured 35°/90° ratio; this is the reason for not including the 1103 keV line in the extraction of $\Delta\theta$ in the preceding equation. This uncertainty can be eliminated in future experiments by a direct measurement of the full angular distribution.

C. Transient field parametrization and g factors

The sense of the precession with respect to the external magnetic field corresponds to a positive g factor (the transient field which the nucleus experiences is in the direction of the applied field). In order to deduce its magnitude, the parametrization of the transient field as a function of velocity for Gd ions recoiling through Gd has to be known. The g factor is extracted from the measured precession angle via

TABLE II. Values of the double ratios ρ_{ij} for the various γ transitions depopulating the $\frac{59}{2}^-$ level in ^{147}Gd and for various transitions in ^{146,148}Gd (see text). Separate ρ_{ij} values are presented for the backward and forward detectors and for delayed-multiplicity conditions of $M=3$, 4, and $M>4$, respectively. Due to poorer peak/background conditions, not all double ratios could be reliably derived at all angles and/or under all multiplicity conditions. For a positive g factor, ρ is <1 for the backward detectors and ρ is >1 for the forward detectors. The cross ratios for detectors situated 180° apart (for the transitions and multiplicity cuts listed above for both the backward and forward detectors) are found to be consistent with $\rho=1$, as expected.

Energy (keV)	Nucleus	ρ_{ij} Backward $M=3,4$	Backward $M>4$	Forward $M=3,4$	Forward $M>4$
188	^{147}Gd	0.950(23)	0.938(19)		1.038(36)
304	^{147}Gd	0.947(20)	0.969(17)		1.029(26)
809	^{147}Gd	0.950(21)	0.970(18)	1.038(27)	1.036(23)
1103	^{147}Gd		0.937(25)		
1078 $5^- - 3^-$	^{146}Gd	0.975(20)	0.940(29)		
477 $18^+ - 16^+$	^{148}Gd		0.934(25)		
784 $2^+ - 0^+$	^{148}Gd	0.943(28)	0.953(29)		

$$\Delta\theta = -\mu_0/\hbar \cdot g \cdot \int e^{-t/\tau} B(t)\,dt\,(\mathrm{mrad}\cdot\mathrm{T}^{-1}\cdot\mathrm{ps}^{-1}) \ .$$

For τ much longer than the passage time through the ferromagnet, as in the present case, one can write

$$\Delta\theta = 1.487(gA/\rho c)\int_{v_{\mathrm{in}}}^{v_{\mathrm{out}}} B(v)(dE/dx)^{-1}dv \ ,$$

where $B(v)$ is the velocity-dependent transient field (in T), dE/dx is the stopping power (in $\mathrm{MeV\,mg^{-1}\,cm^2}$) of Gd in Gd, ρ (in $\mathrm{g\,cm^{-3}}$) is the density of Gd, and the numerical constant results from the choice of units. The present experimental conditions of beam, energy, and foil thicknesses correspond to a velocity range between $v_{\mathrm{in}}=6.0v_0$ and $v_{\mathrm{out}}=2.7v_0$, with v_0 being the Bohr velocity ($v_0=\alpha c$). This velocity region for Gd ions traversing a Gd ferromagnet has been investigated earlier by the Chalk River group,[5] and we use here their parametrization

$$B(v,Z)=29.0\cdot Z\cdot v/v_0\cdot\exp(-0.135v/v_0) \ ;$$

a typical uncertainty in this parametrization is of the order of 10%. We thus obtain

$$g(\tfrac{59}{2}^-)=+0.38(7) \ .$$

The γ spectra also contain lines from the ^{146}Gd and ^{148}Gd nuclei.[16,17] These nuclei are produced under the same recoil velocity conditions, albeit with much poorer peak/background ratios due to the fact that the beam energy was chosen to maximize the $5n$ channel. Furthermore, the lack of long-lived isomers like the $\frac{49}{2}^+$ level in ^{147}Gd does not allow for a clear channel selection with the delayed multiplicity condition. The corresponding double ratios (Table II) reflect, for ^{146}Gd, mostly the g factor of the 4-ns high-spin isomer at $E_{\mathrm{ex}}=8916$ keV, with some contribution from branches directly feeding the lower 7^-, 7-ns isomer. For ^{148}Gd, the results are sensitive primarily to the g factor of the $I=35$, 2-ns isomer, with some contribution from the $I=20^-$ and $I=9^-$ lower-lying isomers. A similar analysis, using S values taken from the 35°/90° ratios of Ref. 17 together with the assumption of small a_4 components, yields $g=+0.37(16)$ and $g=+0.60(16)$ for ^{146}Gd and ^{148}Gd, respectively. The accuracy of these results is not sufficient for any meaningful conclusions as to the structure of these levels. They are mentioned here only to indicate the possibility of obtaining more precise values in future experiments.

IV. DISCUSSION

The proposed[7] wave function for the $\frac{59}{2}^+$ level is composed of a $\nu(f_{7/2}h_{9/2}i_{13/2})$ neutron single-particle part and either a $\pi(g_{7/2}^{-1}h_{11/2}^{3})$ or a $\pi(d_{5/2}^{-1}h_{11/2}^{3})$ part. These two proton configurations differ in that an $(l+\frac{1}{2})$ proton is exchanged with an $(l-\frac{1}{2})$ proton. The experimental g factors of these single-particle configurations have been determined in this mass region for the odd-even Sm, Eu, and Gd isotopes.[18] In particular, for the proton orbitals under consideration, the g factors of the $d_{5/2}$ and the $g_{7/2}$ orbitals (in ^{151}Eu) have been precisely measured to be $g=+1.389$ and $+0.740$, respectively. The calculated g factor, based on these experimental single-particle values, are $g=+0.43$ and $+0.51$ for the two proposed wave functions, respectively. Even though only a small fraction of the total spin is carried by the $(l+\frac{1}{2})$ or $(l-\frac{1}{2})$ proton, the factor of 2 difference in the individual values results in the total, calculated g factor to differ by about 20%. As previously mentioned, when one includes uncertainties in S and in the field parametrization, the resulting error is rather large. Nevertheless, the present result would indicate a preference for the $g_{7/2}$ proton hole in the wave function and certainly indicates that the basic components of the suggested wave function are correct.

It should be stressed that the present result can be viewed as a first step towards future g-factor measurements in this nucleus. By varying the flight distance between the target and the ferromagnet, one can control the population of levels experiencing the transient field, without any change in the other experimental conditions. With flight times much shorter than the present 100 ps, the measured precession angle will reflect the average g factor of levels above the $\frac{59}{2}^-$ isomer. Since the feeding time history is known for ^{147}Gd in this energy region, the average values can be correlated with a specific energy and spin region. The uncertainties in the values of the logarithmic slope and in the parametrization of the transient field are then of minor importance only, and a readily available improvement in statistical accuracy can also be obtained. Although the resulting experimental sensitivity still allows a determination of only the gross features of the neutron versus proton contributions to the total spin, it is a unique experimental probe of this feature.

The present experiment and its subsequent extensions thus outlined can also provide the necessary information and expertise for a g-factor determination in the superdeformed region. Even though the lifetimes of individual levels are very short, the feeding and cascading pattern results in an accumulated time in the band of 150–200 fs. The advent of 4π, multidetector arrays (like the 110 Ge, GAMMASPHERE facility now under consideration[19] in the U.S.), together with the high recoil velocity obtained, as in the present case, by more symmetric reactions, will provide the necessary sensitivity for probing the (average) proton-neutron alignments in several nuclei.[20]

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*On leave from the Weizmann Institute, Rehovot, Israel.

†On leave from the Techniche University, Munich, W. Germany.

‡On leave from the University of Jyvaskyla, Finland.

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