Magnetic moments of pre-yrast high spin and first-excited levels in neutron-deficient ^{162,163,164}Hf isotopes

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Average magnetic moments of high spin, pre-yrast levels in neutron-deficient ^{162,163,164}Hf isotopes were measured by utilizing the transient field technique using a 3.4 mg/cm^2 Gd ferromagnetic layer. The reactions ^{128,126}Te(^{40}Ca,xn)^{164,163,162}Hf at a Ca beam energy of 175 MeV were used to populate high spin regions. Most of the reaction-product Hf nuclei have sufficient energy to traverse the Gd layer. A considerable fraction of recoils of each isotope stops in the Gd and experiences the static hyperfine field in addition to the transient magnetic field, experienced by the whole ensemble. Comparison of the measured precessions of transitions from the first excited, longer-lived levels with precessions from much shorter-lived, high-spin transitions yields g-factor ratios of the first excited states in the three isotopes. The previously unknown lifetimes of the relevant transitions were measured in a recoil-distance experiment. The possibility of measuring g-factor ratios in neutron-deficient nuclei by utilizing a combination of transient and static magnetic fields is discussed. [S0556-2813(98)05402-8]

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I. INTRODUCTION

The measurements of g factors play an important role in nuclear structure physics since these moments probe mostly the single-particle degrees of freedom. In particular, measurements of magnetic moments of high spin levels are sensitive to the changes in nuclear structure which take place due to single-particle alignment. As an example, the measurements of g factors of high-spin states in ^{158}Dy, ^{238}U, and ^{238}Th using the transient field (TF) technique have unambiguously determined the role of neutron and proton alignment in the structure of the backbending region [1,2]. The purpose of this publication is to probe for similar phenomena of neutron (proton) alignment for pre-yrast levels at medium excitation via the determination of their average magnetic moments. Hf belongs to the rare earth elements for which high spin states have been the subject of intensive research in recent years [3–5]. The g factors of pre-yrast levels in ^{166,165}Hf isotopes with 94 and 93 neutrons were measured recently [6]. We report here on a similar measurement in lighter ^{162,163,164}Hf isotopes for which the nuclear deformation decreases and the backbending curve, associated with the interaction of the yrast ground band and the aligned band, becomes more pronounced due to smaller interband interaction strength.

The transient field is the only method available for magnetic moment determination of such short lived, high spin and high excitation nuclear states. This technique makes use of the large hyperfine interaction experienced by fast nuclei traversing a ferromagnetic material [7]. A typical TF experiment incorporates complicated multilayer targets, with a thin ferromagnetic layer and a nonmagnetic stopper. However, by having a fraction of recoils stop in the ferromagnet, information about nuclear structure at low excitation and low angular momentum can be simultaneously obtained. In particular, the ^{164,163,162}Hf isotopes are situated in the transitional region between rotational and single particle regimes, with neutron numbers below the midshell values between the closed $N=82$ and $N=126$. Measurements of magnetic moments in these nuclei should probe theoretical estimates in a hitherto unexplored region.

II. EXPERIMENT

The reactions ^{128,126}Te(^{40}Ca,xn), using beams of ^{40}Ca from the Koffler accelerator of the Weizmann Institute at an energy of 175 MeV, were used to populate high spin states in ^{164,163,162}Hf. The main features of the experimental chamber and the target structure are shown in Fig. 1 of Ref. [6]. We present here only a few salient points. The target, consisting of an 800 μg/cm^2 equal mixture of ^{126}Te and ^{128}Te isotopes, was evaporated on a 3.4 mg/cm^2 Gd layer and backed with a thick (40 mg/cm^2) gold layer. The Gd foil was prepared by rolling, followed by annealing in high vacuum at 600 °C. An off-line magnetization measurement of the Gd foil used in the present experiment yielded 85% of the saturation value for Gd at 100 K in an external field of 0.04 T, exhibiting a very similar behavior to that of earlier Gd samples (Fig. 2 of Ref. [6]). A thin gold layer (500 μg/cm^2) was evaporated on one side of the Gd foil and this side was adhered to the clean, thick (40 mg/cm^2) gold foil to provide a perturbation-free stopping medium for the Hf ions not stopping in the Gd itself. The tellurium layer of 800 μg/cm^2 was evaporated on the second surface of the Gd foil. The utilization of the mixture of two Te isotopes as target nuclei allows us to measure the magnetic moments in several reaction channels under the same experimental conditions. The thickness of the Gd layer was chosen so as to have a fraction of recoiling nuclei stop in the ferromagnet; this stopped fraction was determined experimentally and can also be estimated for each of the three isotopes by using the TRIM95 [8] code (see Sec. III A below). The stopped nuclei experience both the TF and the static field (SF) while those traversing the Gd and stopping in the Au layer experience *only* the TF. The effect of the SF is manifested almost exclusively in the transitions de-exciting

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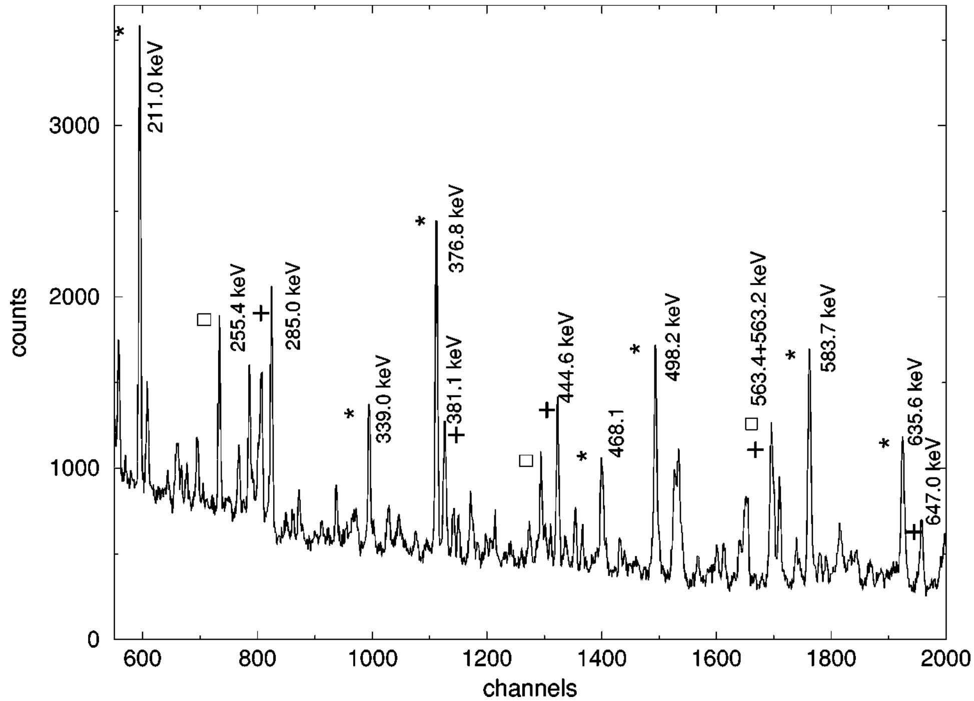

FIG. 1. The γ spectrum from the ^{128,126}Te(^{40}Ca,4n)^{164,163,162}Hf reactions at $E_{\rm beam}=175$ MeV with a multiplicity condition of $M\geqslant 2$. The transitions in ^{164,163,162}Hf are denoted by stars, squares, and crosses, respectively.

the first excited states of each nuclei. The life-times of the higher transitions are mostly too short to be affected by the SF. Since the first excited states inherit the precession in the TF of the preceding states, a comparison of ''up/down'' ratios of the first excited states to those of the higher transitions for each of the isotopes carries information about the g-factors of the first excited states. The thickness of the Gd foil, resulting in a relatively small stopped fraction was chosen as a compromise between a large SF effect and the desire to ensure that most of the recoiling nuclei experience *only* the TF and emerge from the Gd foil, thus minimizing the uncertainties of TF parametrization at very low velocities [6,7].

The target was mounted on a cryogenic copper finger; a 0.5 cm thick layer of boron nitride between the target and the copper cryofinger provided good thermal contact and electrical isolation for monitoring the beam current on the target. The external part of the cryofinger was immersed in a Dewar of liquid nitrogen. The temperature of the cooled target was measured by a thermocouple to be 85 K. The large cold surface of the cryofinger served to improve the vacuum in the chamber (6×10^{-6} mbar) and to reduce the accumulation of cracked-carbon contaminations on the target surface. The average beam current on the target was about 1 particle nA.

The ferromagnetic Gd was polarized by an external field (600 G) in the 7 mm gap of an electromagnet. The direction of the external field (and hence the transient field) was changed every 3 min by reversing the current in the electromagnet coil.

Decay γ rays were detected in four 25%-efficient Ge detectors surrounded by NaI(Tl) anti-Compton shields. The detectors were placed in the horizontal plane at angles of large logarithmic slope of the angular distribution (58° and 122° with respect to the beam axis). Ten NaI detectors served as a multiplicity filter in order to reduce background in the Ge spectra due to contamination reactions (Coulomb excitation, reactions with surface impurities). Two spectra, corresponding to up and down polarization directions and gated by the multiplicity condition, were generated for each detector. These spectra were used to form the up/down ratios.

III. RESULTS

A. Measurement of the stopped fraction *a*

We have determined experimentally the stopped fraction of the ^{164}Hf reaction products. The decay of ^{164}Hf proceeds by the following chain: ^{164}Hf$\rightarrow^{164}$Lu$\rightarrow^{164}$Yb(τ=110 m) $\rightarrow^{164}$Tm$\rightarrow^{164}$Er($E_\gamma=91.5$ keV). We have measured the yield of the 91.5 keV line *separately* from an identical Gd foil to the one used in the precession experiment and from the Au backing. We thus determine the fraction of ^{164}Hf stopping in Gd to be $a=0.33(2)$. This experimental value is in good agreement with results of simulations of the passage of ions through the multilayer target using the TRIM code [8]. For estimating the small change in a for the other Hf isotopes as compared to ^{164}Hf, one can rely on the agreement between the experiment and simulations and estimate these small corrections by using TRIM (see Table II below).

B. The precession measurement

A typical γ-ray spectrum from the reaction with the condition of multiplicity in the NaI(Tl) filter of $M\geqslant 2$ is shown in Fig. 1. The spectrum is rather rich due to the existence of three strong channels; the strongest transitions of each isotope [9] are indicated in Fig. 2. The strong 279 and 548 keV transitions are due to Coulomb excitation lines of the gold stopper which were only partially suppressed by the $M\geqslant 2$ multiplicity condition.

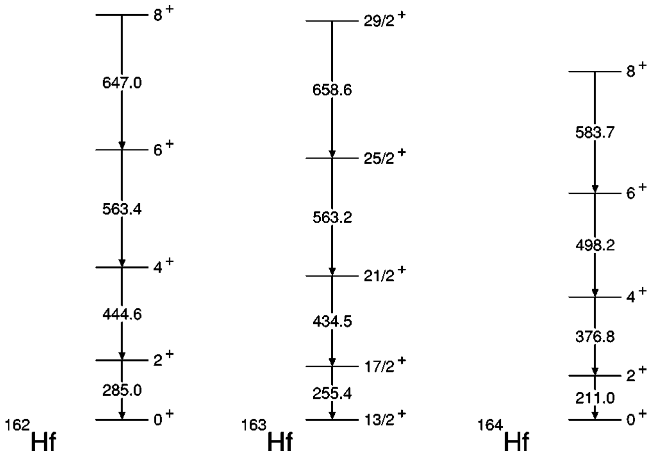

FIG. 2. The analyzed transitions in the ^{162,163,164}Hf nuclei.

The angular distribution was measured at six angles: 360°, 330°, 300°, 295°, 265°, 235°, by using a target which did not contain the Gd layer. The intensities of the four ground-band lines of ^{164}Hf: 211.0, 376.8, 498.2, and 583.7 keV were measured and normalized to the detector efficiencies obtained from source measurements under the identical geometry. The normalized intensities were fitted to the expression for the angular distribution function W(θ):

$$W(\theta)=A_0[1+A_2P_2(\cos\theta)+A_4P_4(\cos\theta)].$$

The angular distribution coefficients averaged over all the lines are $A_2=0.29\pm0.05$ and $A_4=-0.03\pm0.04$. These coefficients yield a value of

$$S=\frac{1}{W(\theta)}\frac{dW(\theta)}{d\theta}=-0.43\pm0.03$$

for the logarithmic slope at 58° (at which angle the precession measurements were carried out). These coefficients are very similar to those obtained in our previous measurement of high-spin states in ^{166}Hf [6]. A detailed analysis of angular distributions of numerous high-spin transitions in ^{193,194}Hg from a Gammasphere experiment [10] using a ^{48}Ca beam also yielded very similar coefficients for $E2$ transitions, all agreeing with the picture of almost complete alignment of high-spin levels in such fusion-evaporation reactions. The above logarithmic slopes have therefore been adopted for all the cases studied here.

The standard double ratios are defined as

$$\rho_{ij}=\left(\frac{N(\theta_i)\uparrow\cdot N(\theta_j)\downarrow}{N(\theta_i)\downarrow\cdot N(\theta_j)\uparrow}\right)^{1/2}$$

where $N(\theta_i)\uparrow$, $N(\theta_i)\downarrow$ are the γ counts in detector i with the external field in the up and down directions, respectively. The double ratios were formed for backward ρ_{23} and forward ρ_{14} detectors for the following transitions: the $2^+\rightarrow0^+$, $4^+\rightarrow2^+$, $6^+\rightarrow4^+$, and $8^+\rightarrow6^+$ in ^{162}Hf (^{164}Hf) at 285.0 (211.0) keV, 444.6 (376.8) keV, 563.4 (498.2) keV, and 647.0 (583.7) keV, respectively, and the $17/2^+\rightarrow13/2^+$, $21/2^+\rightarrow17/2^+$, and $29/2^+\rightarrow25/2^+$ transitions in ^{163}Hf at 255.4, 434.5, and 658.6 keV. The $25/2^+\rightarrow21/2^+$ at 563.2 keV was not used in the analysis as it coincides in energy with the 6^+ transition in ^{162}Hf of a much larger intensity. For the transient field analysis we use only the precessions of γ lines above the ground-state transition; these individual precessions do not have sufficient statistical accuracy and, in any case, all reflect the same magnetic-moment information of preceding, unobserved higher-spin transitions in the same nucleus (see below). Hence, we quote and use the average values of the double ratios $\rho=(\rho_{23}/\rho_{14})^{1/2}$ and precessions $\Delta\theta=(1/S)[(1-\rho)/(1+\rho)]$, which are presented in Table I.

The double ratios of the lowest transition in each isotope result from the interaction with both the TF (for the whole ensemble) and the SF (for the fraction a); the values for the higher transitions reflect to a very good approximation only the influence of the TF. Still, a small correction to the transient field precession due to the SF precession of the second excited state in each isotope has to be applied; all other transitions are too swift to be influenced by the SF. The transitions from the second excited states are 4^+-2^+ for the even Hf isotopes and $21/2^+$-$17/2^+$ for the odd isotope. The lifetime of the 4^+ level in ^{164}Hf is known to be 18.8 ± 3.8 ps [9]; for the other two second transitions we assumed an E^5 dependence of the lifetime on transition energy. As the correction is small, any other estimate of the lifetime of these transitions can not change the average precessions in Table I in any significant manner. We also note that, based on the known efficiency of the Ge detectors and on the intensity ratios of the first and second transitions, the branch of the γ flux into the first excited states which bypasses the second excited states is negligible for all three isotopes.

The standard Chalk-River TF parametrization

$$B(v,Z)=29Zv/v_0\ \exp(-0.135v/v_0)[T],$$

where v_0 is Bohr velocity ($v_0=\alpha c$) and Z is the atomic number of the recoiling nucleus, was applied in a manner similar to the analysis for ^{166,165}Hf [6]. The present ensemble also includes a fraction of stopped nuclei; since the TF is proportional to velocity for low velocities, the precession depends only on the thickness of the ferromagnetic foil. Under these conditions, the use of the standard TF parametriza-

TABLE I. The results of precession measurements.

	First transition			Higher transitions	
Nucleus	$I_i\rightarrow I_f$	E(keV)	$\epsilon\,[10^{-3}]$	$\epsilon\,[10^{-3}]$	g factor
^{164}Hf	$2^+\rightarrow0^+$	211	-26.7 ± 1.3	13.4 ± 0.7	0.23(1)(2)
^{163}Hf	$\frac{17}{2}^+\rightarrow\frac{13}{2}^+$	255.4	8.3 ± 2.1	10.8 ± 1.7	0.18(4)(2)
^{162}Hf	$2^+\rightarrow0^+$	285	-0.4 ± 1.5	12.3 ± 0.9	0.21(2)(2)

TABLE II. Results of life time measurements and g factors ratios of first excited transition.

Nucleus	a(exp.+TRIM)	τ (ps)	g factor (estimated)
^{164}Hf	0.33	497±29	0.33±0.06
^{163}Hf	0.33	149±12	0.05±0.08
^{162}Hf	0.32	148±11	0.29±0.07

tion for the present ensemble can be justified. The extracted g factors of the higher, unobserved transitions which experience the transient field precession are also listed in Table I. The quoted errors of the g-factors are statistical and systematic errors, respectively. We would like to emphasize that the uncertainties in the TF parametrization mentioned above could affect only the *magnitudes* of the average g factors of the higher transitions, but not their ratios.

For the first excited states, especially in ^{164}Hf, the analysis is more complicated due to the SF precession. For the case of appreciable precessions in the SF ($\omega_{SF}\tau\approx 1$), the angular distribution function changes considerably and the small precession approximation, which we used above for the analysis of the TF precession, is no longer applicable. One can write, however, an explicit expression for $N(\theta)\uparrow/N(\theta)\downarrow$ ratios, taking into account the stopped fraction a, the preceding TF precession and the modified form of the angular distribution. The modified perturbed angular distribution is given by [11]

$$W(\theta)=\sum_k \frac{b_k}{[1+(k\omega\tau)^2]^{1/2}}\cos[k(\theta\pm\Delta\theta_k)],$$

where the precession angle $\Delta\theta_k$ is defined by

$$\tan(k\Delta\theta_k)=k\omega\tau,$$

and

$$b_0=1+\frac{1}{4}A_2+\frac{9}{64}A_4,\quad b_2=\frac{3}{4}A_2+\frac{5}{16}A_4,$$

$$b_4=\frac{35}{64}A_4.$$

One can extract numerically the g factors of the first excited states in the three isotopes by taking the static hyperfine field of Hf in Gd to be about 500±70 kGs [12] for 85% of the Gd magnetization, the ϵ values from Table I and the measured lifetimes (see below). As discussed above, the stopped fraction a has been measured in the present experiment for ^{164}Hf and a small correction for the other isotopes has been estimated by TRIM. The resulting lifetimes, a values, and g factors are listed in Table II. The *absolute* errors on the g factors include the statistical error of the precession and the errors on the lifetime, hyperfine field, and the a parameters.

We would like to emphasize that for small $\omega_{SF}\tau$, the derivation of *relative* g factors is straightforward even in the presence of the SF and, to a very good approximation, independent of the values of a. For large $\omega_{SF}\tau$, the derivation has to proceed in the manner described above and the extracted values depend in an explicit manner on various parameters, such as the stopping fraction a.

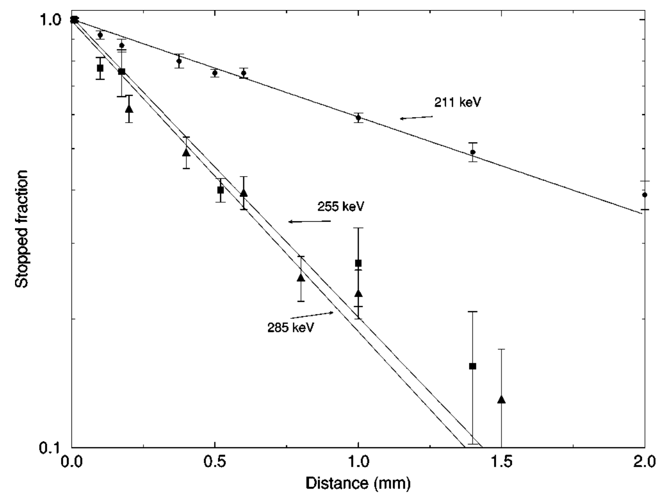

FIG. 3. Recoil-distance curves for transitions de-exciting the first excited states in ^{162,163,164}Hf. The solid lines are the results of a fit to a pure exponential decay (see text), justified for long distances (times).

C. Lifetime measurements

In order to extract g factors (or g-factor ratios) from the quantity $\omega_{SF}\tau$ as derived in the procedure above, the lifetimes of the first excited states are required. For that purpose, measurements were carried out using a recoil-distance apparatus [13]. Two separate targets of 500 μg/cm^2 ^{128}Te and ^{126}Te were made by evaporating the isotope on 1.5 mg/cm^2 thin, stretched gold foils. The target and stopper foils were mounted in a plunger device and were made parallel using standard techniques. Because of the relatively long lifetimes involved, the distances could be easily read out by a standard micrometer. The stopper foil of 9 mg/cm^2 stretched gold was sufficiently thick to stop the Hf reaction products but allowed the beam ions to traverse the foils into a Faraday cup upstream. The stopped/total fractions of the low lying transitions were measured as a function of the plunger distance. The results of the measurement are shown in Fig. 3 and in the third column of Table II. We have modeled the feeding of higher transitions in the band into the first excited states by a simple E^5 lifetime scaling. These corrections are small for the first excited states and hence, for large plunger distances, a simple exponential function fits the data well. However, side feeding and feeding from above can have a significant influence on the extracted lifetimes of the second excited states with much shorter lifetimes. A separate experiment, beyond the scope of the present measurement, has to be carried out in order to obtain accurate information on lifetimes of the second excited states.

The results of the lifetime measurements are shown in Table II. The lifetime of the 4^+ level in ^{164}Hf has been determined previously [9] to be 18.8(3.8) ps. The present value for the 2^+ level in ^{164}Hf is in good agreement with an earlier measurement [9] and we use the average of these two measurements, $\tau=503(23)$ ps for the g-factor estimate.

The measured lifetimes of the 2^+ level in ^{162,164}Hf correspond to a $BE2$ value of 0.26 and 0.38 e^2b^2, respectively.

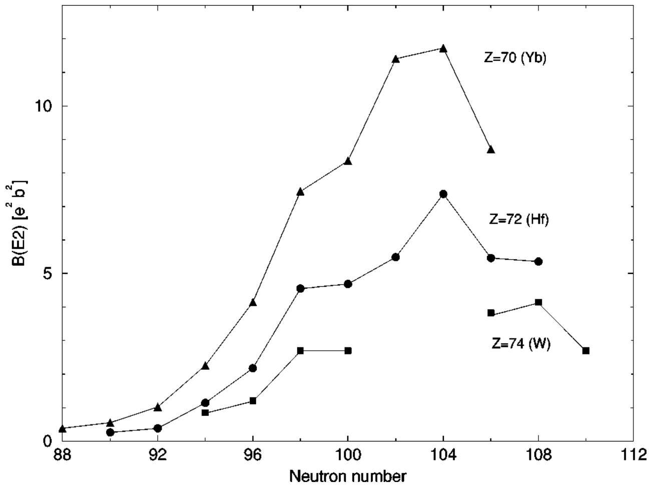

FIG. 4. Systematic of $BE2$ values for the $2^+ \rightarrow 0^+$ transitions in Hf isotopes and the neighboring W and Yb isotopes (Ref. [14], and references therein). The result for ^{162}Hf is from the present measurement; the result for ^{164}Hf is the weighted average of the present measurement and that reported in [14].

These $BE2$'s should be compared to the $BE2$'s from the 2^+ levels in other Hf isotopes [14]. In a similar manner to that found also in the isotopes of W, Yb, and other neighboring nuclei [14], the $BE2$'s decrease with decreasing neutron number away from midshell, indicating the transition from collective to single-particle nature. We present these $BE2$ values in Fig. 4.

IV. DISCUSSION

A. Average *g* factors of high-spin levels

The TF precession carries information regarding average magnetic moments of the ensemble of states which are populated within the narrow time window defined by the passage of the recoiling nuclei through the gadolinium layer. Monte Carlo simulations were carried out to map the decay cascade [15,16]. The details of the Monte Carlo procedure, as applied for ^{166}Hf, can be found in Ref. [6]. One has to use, however, different quadrupole moments $Q \approx 3.0$ and 3.6 eb, for ^{162}Hf and ^{164}Hf, respectively, as estimated from the measured lifetimes. According to the results of the simulations, the nuclear spins populated inside the gadolinium layer are in the range of $I = 29$-$22\,\hbar$, $I = 28$-$22\,\hbar$, and $I = 26$-$20\,\hbar$ for ^{162}Hf, ^{163}Hf, and ^{164}Hf, respectively. It is important to note that the Monte Carlo calculations depend necessarily on the assumptions of the model and on the values of the input parameters [6] and are therefore meant only to guide the examination and discussion of the experimental results.

The results of the measurements of magnetic moments of high spin states can be combined with similar data in ^{166,165}Hf [6]. In general, one can summarize that the magnetic moments of a ''warm'' nucleus (about 1–1.5 MeV above the yrast line) at a broad range of spin values is not much different in all the isotopes $^{162-166}$Hf, in spite of the fact that the $BE2$ values of the ground state transition (and hence deformation at lower spins) change considerably from ^{166}Hf to ^{162}Hf (see Fig. 4). The reduction of the average g factors of the high-excited levels compared with the collective rotation g factors of 2^+ levels (Table II) indicates an appreciable contribution of aligned neutrons, for example from the $i_{13/2}$ orbital for which $g_{i_{13/2}} = -0.16$ [14] or from other $j = l + 1/2$ orbital with similar g factors. The smaller g factor of ^{165}Hf [6] and ^{163}Hf [0.15(2)—average over the odd isotopes] could be simply explained by the existence of an additional unpaired neutron as compared to the even isotopes [0.22(1)—average over the even isotopes]. Similar differences in the magnetic moments of high, pre-yrast transitions in even and odd isotopes were observed in ^{193,194}Hg [10].

There are several previous measurements of average magnetic moments of high-spin levels in even-even isotopes in this mass region [1,6,16–22]; these measurements are summarized in Fig. 5. In general, one can observe a strong reduction of magnetic moments in the backbending region $I = 10$–$12\,\hbar$. At higher spins, the values of the g factors increase, but remain well below the value of g factors of rotational levels, e.g., 2^+ levels in the deformed rare-earth region. This fact indicates an enhanced neutron contribution to

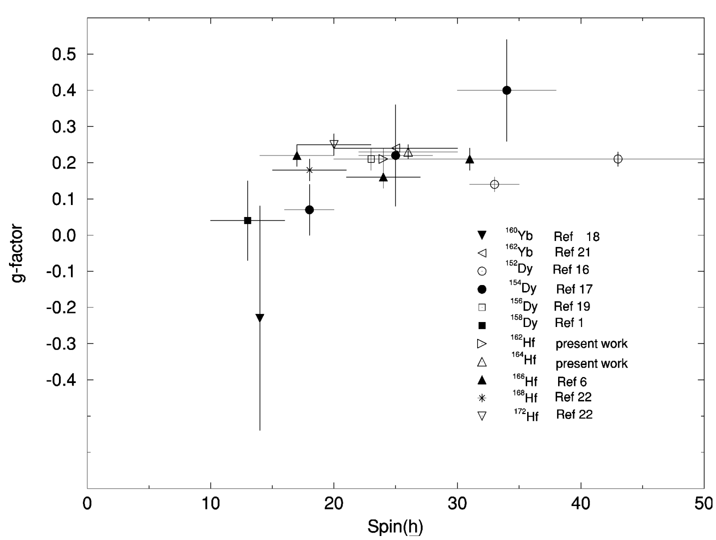

FIG. 5. Summary of previous determinations of (average) g factors at high spin in even rare-earth nuclei (Refs. [1,6,16–22], and the present work).

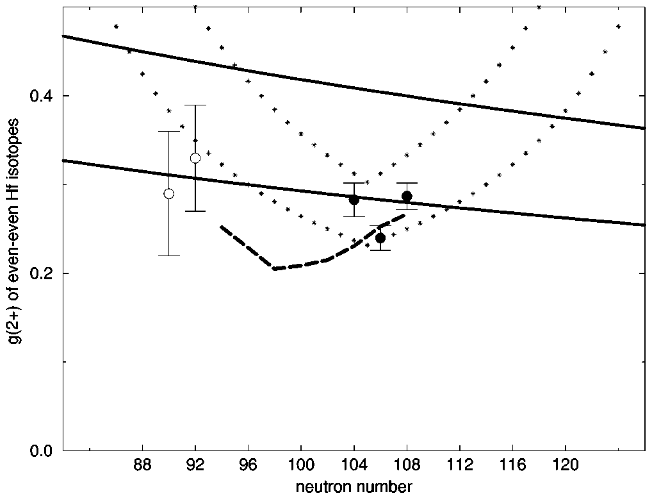

FIG. 6. Systematics of g factors of 2^+ levels in Hf isotopes. Following Ref. [24], the solid lines correspond to a Z/A and 0.7 Z/A, respectively. The dotted lines are IBM-2 estimates $[g=g_\pi N_\pi/N_t+g_\nu N_\nu/N_t$, where $N_{\pi(\nu)}$ is number of proton (neutron) bosons and $N_t=N_\pi+N_\nu]$, with $g_{\pi(\nu)}=1(0)$ (upper dotted line) and $g_{\pi(\nu)}=0.65(0.05)$ (lower dotted line), respectively. The dashed line is from Kumar and Baranger [26].

the total spin for medium and high spin states seems to form a rather general trend. As such, it calls for a better theoretical understanding of this phenomenon.

More elaborate experiments are needed to examine in detail possible structural changes at high spin via magnetic-moment determination. Such measurements include gating on particular yrast bands in order to probe subsets of the pre-yrast quasicontinuum. Another possibility is using a target with a gap between the target and Gd to control the time window (and hence level population) for which the transient field precession occurs. Such investigations have been recently carried out on ^{193,194}Hg using the Gammasphere array [10].

B. g factors of first excited states

The deduced g factors from the present work are presented in Table II. The large errors on the magnitude of the g factors are mainly due to the large uncertainties in the static hyperfine field, in the fraction a and due to the errors of lifetime measurements. Better knowledge of the SF under conditions similar to the present ones are highly desirable.

The very small g factor of the $17/2^+$ level in ^{163}Hf can be directly correlated to the simple wave function of this level of an unpaired $i_{13/2}$ neutron with $g_{i_{13/2}}=-0.16$ [14] coupled to a collective rotation. A better experimental value is required for a quantitative comparison to a specific model. The results for the even isotopes are presented in Fig. 6, together with measured g factors in stable Hf isotopes [14,23] and with predictions of several theoretical models (Ref. [24], and references therein). The errors in the g factors include the statistical error, the error in the lifetimes, the uncertainty in the static hyperfine value and the common error in the stopped fraction a as detrimined experimentally (see Sec. III A above). As is obvious from Fig. 6, better g-factor measurements in neutron deficient isotopes are needed to discriminate between the theoretical models.

In general, g factors in other series of isotopes could be measured by a similar technique, using a mixture of several target nuclei which precess in both the TF and SF under the same conditions. The analysis is simplified considerably for $\omega_{\mathrm{SF}}\tau \ll 1$. In this case, the differences of precessions of the first excited states and the precessions of the higher transitions are proportional to $\omega_{\mathrm{SF}}\tau$; therefore ratios of g factors of the first excited states could be extracted, avoiding the uncertainties of the SF. One can choose many combinations of neutron deficient isotope sequences in various ferromagnetic materials to satisfy the condition above. As is evident from Ref. [24] and Fig. 6, even the ratios of even-even g factors in various neutron-deficient isotopes can provide a very valuable test of theoretical models. Moreover, the use of large Ge arrays will enable much more accurate results, also for the much shorter lived 4^+ states. Similar measurements in odd isotopes can also be very instructive since they provide unique information about nuclear Nilsson configurations. These experiments are presently being discussed [25]. We would like to point out that the advantage of using a ferromagnetic foil which stops a fraction of the recoiling ions lies in the possibility of a *simultaneous* determination of both high, and low-spin nuclear levels.

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