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g factor of the 2_1^+ state of ^{170}Hf

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The g factor of the 2_1^+ state of ^{170}Hf was measured by perturbed γ-γ angular correlation in a static external magnetic field. The result, $g(2_1^+) = 0.28(5)$, extends the systematics of g factors of even-even Hf isotopes to $N = 98$ and enables a better test of theoretical models. The $g(2_1^+)$ experimental values of these isotopes exhibit a remarkable constancy as a function of neutron number. This phenomenon, which was also observed for other isotopic chains in the Gd–W range, is explained in terms of a recently proposed empirical model.

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Measurements of the g factors of the first 2^+ states of even-even nuclei in isotopic chains in the $A = 150$–200 region have shown, in some cases, a dependence on the neutron number N, which is remarkably weak [1–3]. The data for the Yb and Pt isotopes seem to be even more constant as a function of N than expected from the simple Z/A prediction [4]. In a recent work [5], these experimental observations were attributed to a modification of the effective neutron number, caused by a saturation of the proton-neutron interaction around midshell. This simple explanation was used to obtain a consistent interpretation of $B(E2)$ and $g(2_1^+)$ experimental data in heavy nuclei and theoretical predictions for g factors and $B(E2)$s in these nuclei. According to these predictions, almost constant values of $g(2_1^+)$ are characteristic for nuclei in isotopic chains from Gd ($Z = 64$) to W ($Z = 74$), for the range of neutron numbers from $N = 96$ to $N = 108$. Measurements of g factors in this region of the periodic table can provide further data to test the proposed interpretation [5] and therefore further our understanding of the proton-neutron interaction.

In this Brief Report we describe the measurement of the g factor of the 2_1^+ state in ^{170}Hf at an excitation energy of 100.8(2) keV. This experiment is part of a series of g-factor measurements undertaken at the Wright Nuclear Structure Laboratory (WNSL) at Yale University. In this study we use ion beams produced by the Tandem accelerator of the WNSL to induce heavy ion reactions in a relatively thick target. The projectile, its energy, and the target are chosen in such a way that the heavy reaction fragment produced with maximum cross section is the parent of the nucleus to be studied. In the present experiment we used a 100 MeV, ^{16}O beam with a current of about 14 pnA on a 4 mg/cm^2 thick Terbium target to produce ^{170}Ta via the reaction ^{159}Tb(^{16}O,5n)^{170}Ta. A statistical model fusion-evaporation calculation using the program PACE [6] predicts that ^{170}Ta is produced in this reaction with a cross section of about 550 mb; all other fragments of the reaction are produced with much smaller cross sections, so that by using this particular combination of projectile, target, and projectile energy we obtain an almost pure ^{170}Ta source. The reaction products are emitted in a forward solid angle cone, deposited on an aluminized tape collector, and transported to the center of a superconducting coil capable of producing magnetic fields of up to 6 T. The tape was moved cyclically every 15 min. A 3 mm diameter, 2 mm thick gold plug was placed between the target and the tape collector to stop the beam and avoid burning the tape. Levels in ^{170}Hf are populated following β^+/ε decay of the parent ^{170}Ta ($T_{1/2} = 6.8$ min).

A set of eight coaxial hyperpure germanium detectors positioned around the center of the coil was used to measure the perturbed angular correlation of γ rays emitted following β^+/ε decay of the reaction products. In Fig. 1 we present a total projection γ spectrum. All significant lines are from the decay of ^{170}Ta. A detailed description of the experimental setup is given in Ref. [2]. The half-life of the 2_1^+ state of ^{170}Hf was recently measured [7] and reported to be 1.21(4) nsec. We therefore used the integral perturbed γ-γ angular correlation method [8]. To determine the g factor we used the 779–101 keV, $0_2^+ \to 2_1^+ \to 0_1^+$ cascade. From the coincidence data we calculated the double ratio:

$$R(\theta, B) = \left[\frac{I(\theta, B)}{I(\theta, -B)}\Big/\frac{I(-\theta, B)}{I(-\theta, -B)}\right]^{1/2}. \qquad (1)$$

$I(\theta, B)$ is the coincidence intensity at angle θ and external field B. The functions $I(\theta, B)$ and $R(\theta, B)$ can be calculated for any spin sequence and field B using the formulas in Refs. [2,8]. The use of the double ratio as defined in Eq. (1) has the obvious advantage that normalization for the integral charge on target at each field direction is not necessary. For a $0_2^+ \to 2_1^+ \to 0_1^+$ cascade, the maximum double ratio is obtained at

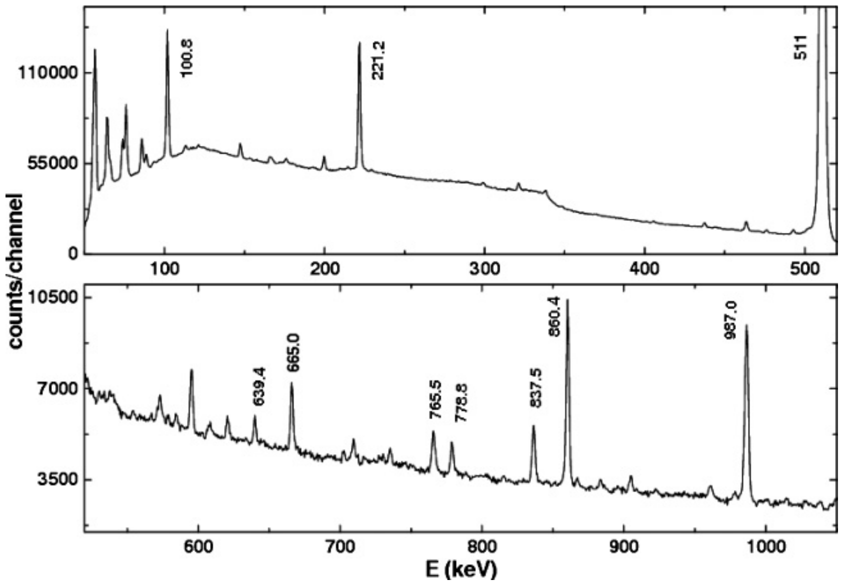

FIG. 1. Total projection γ spectrum obtained in this experiment. All γ lines labeled by their energy in keV belong to the decay of ^{170}Ta to ^{170}Hf.

35° and 145°. Therefore, the eight detectors were arranged so that 12 of the 28 possible pairs were at these angles. Of the remaining pairs, eight were at 70°, 110°; four were at 75°, 105°; and the remaining four were at 180°. The data acquisition system was set so that coincidence matrices of all possible pairs of detectors were recorded. In the data sorting, the events from detector pairs at the same angle were sorted in the same two-dimensional γ-γ coincidence matrix. The signs of the angles (positive or negative) with respect to the external field were determined using the convention as given by Dorum and Selsmark [9]. In addition to the 779–101 keV cascade, we also calculated the double ratio $R(\theta, B)$ for three other cascades: 221–101, 860–101, and 987–101 keV. These results were used as a consistency check. Two separate runs were carried out: one with an external field of 5.85 T and the second one with a field of 4.40 T. Running time was approximately 100 h for each field direction for each run.

The results of the double ratio $R(\theta, B)$ for all four cascades mentioned above for the two experimental runs are given in Table I. To obtain the experimental value of the g factor, we calculated the function $R(145°, B)$ as a function of the g factor for the $0_2^+ \to 2_1^+ \to 0_1^+$ cascade. This was done for the two values of the magnetic field 4.40 and 5.85 T. The g factor is deduced by comparing the experimental values in Table I with the calculated functions. The results are presented in Fig. 2. Two values of $g(2_1^+)$ were obtained for the two values of the magnetic field : 0.28(7) and 0.28(6) for 4.40 and 5.85 T, respectively. The average of the two values gives the final result of this experiment:

$$g(2_1^+)_{\rm exp} = 0.28(5). \tag{2}$$

Note that the experimental double ratio $R(145^0, B)$ for the $0_2^+ \to 2_1^+ \to 0_1^+$ cascade is higher for the higher value of the magnetic field, as expected. All the other experimental values in columns four and five of Table I were extracted from the data as a consistency check. In columns six and seven we present the calculated values of the double ratios, obtained using the value of the g factor given by Eq. (2). At 180°, the expected value of the double ratio for all the cascades is 1.00. Comparison of columns four, five, six, and seven of Table I clearly shows that all the experimental values of the double ratio are, within the experimental error, in good agreement with

TABLE I. The values of the double ratio $R(\theta, B)$ obtained from the coincidence data for several cascades of ^{170}Hf (see text).

Cascade (keV)	Spin sequence	Angle	$R_{\rm exp}(\theta, 4.40\ {\rm T})$	$R_{\rm exp}(\theta, 5.85\ {\rm T})$	$R_{\rm calc}(\theta, 4.40\ {\rm T})$[a]	$R_{\rm calc}(\theta, 5.85\ {\rm T})$[a]
779–101	$0_2^+ - 2_1^+ - 0_1^+$	145°	1.51(12)	1.62(11)	1.48(8)	1.61(8)
860–101	$2_2^+ - 2_1^+ - 0_1^+$	145°	1.08(5)	1.10(4)	1.080(10)[b]	1.095(10)[b]
987–101	$3_1^+ - 2_1^+ - 0_1^+$	145°	0.80(6)	0.88(5)	0.920(10)[b]	0.900(10)[b]
221–101	$4_1^+ - 2_1^+ - 0_1^+$	145°	1.01(3)	1.02(2)	1.025(5)	1.033(5)
779–101	$0_2^+ - 2_1^+ - 0_1^+$	180°	1.01(7)	1.06(11)	1.00	1.00
860–101	$2_2^+ - 2_1^+ - 0_1^+$	180°	1.00(6)	1.09(8)	1.00	1.00
987–101	$3_1^+ - 2_1^+ - 0_1^+$	180°	0.97(9)	0.99(11)	1.00	1.00
221–101	$4_1^+ - 2_1^+ - 0_1^+$	180°	0.99(3)	0.99(3)	1.00	1.00

[a]The values of $R_{\rm calc}$ and its error bars, where given, were obtained using the value $g_{\rm exp} = 0.28(5)$ (see text).
[b]The double ratio was calculated assuming pure $E2$ character for the first transition of the cascade.

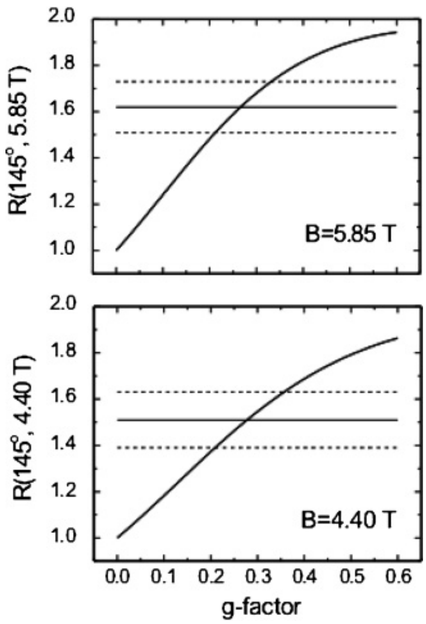

FIG. 2. The calculated double ratio $R(145^0, B)$ vs the g factor, and the experimental double ratio for the 779–101 keV, $0_2^+ \rightarrow 2_1^+ \rightarrow 0_1^+$ cascade, for the two values of the magnetic field used in this experiment.

the calculated ones. This can be considered as experimental evidence that systematic errors are smaller than the statistical errors.

We now discuss this new experimental value within the systematics of g factors of 2_1^+ states in the even-even Hf isotopes. In Fig. 3 we present the existing data and the result of the present work as a function of the neutron number N. The value reported in this work extends the systematics to $N = 98$ and thus enables a better test of theoretical models. We first attempt to interpret the data in terms of two models: the hydrodynamical model [4] and the proton-neutron version of the Interacting Boson Model (IBA-2) (see, for example, Ref. [10] for treatment of g factors in IBA-2). In the F-spin

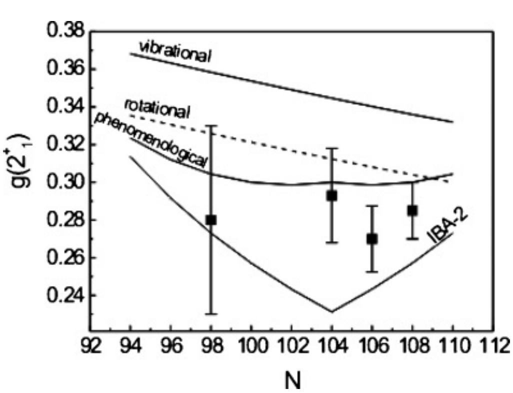

FIG. 3. Systematics of $g(2_1^+)$ data for the Hf isotopes. The results for $N = 104$, 106, and 108 are from the tables of Raghavan [12] and Stone [13]. The value at $N = 98$ is from this work. The predictions of the rotational and vibrational limits of the hydrodynamical model [4], the IBA-2 model [10], and the phenomenological model of Zhang *et al*. [5] are also presented.

symmetry limit of the IBA-2, the values of $g(2_1^+)$ are given by the simple relation

$$g(2_1^+) = \frac{g_\pi N_\pi + g_\nu N_\nu}{N_\pi + N_\nu}, \tag{3}$$

where N_π, N_ν are the numbers of proton, neutron bosons and g_π, g_ν are the boson g factors. For the latter parameters we use the values $g_\pi = 0.63$ and $g_\nu = 0.05$ [11]. Because IBA-2 is a valence model, only the valence particles contribute to the magnetic moment, and therefore the N-dependence prediction for the g factors is quite strong, as shown in Fig. 3. We also note the change of slope of the IBA-2 calculated values at midshell ($N = 104$). The vibrational and rotational predictions of the hydrodynamical model, presented in Fig. 3, show a weak N dependence that is due to the fact that in this model all nucleons are assumed to contribute to the magnetic moment. Although the error bars are relatively large, the data in Fig. 3 indicate an N dependence even weaker than that predicted by the hydrodynamical model. This behavior of the $g(2_1^+)$ data vs N has also been observed for the even-even Yb isotopes [2]. However, while for the Yb isotopes the experimental values were between the rotational and vibrational values, in the present case both these calculations overestimate the data. We conclude that both the hydrodynamical and the IBA-2 models do not provide a good description of the data. In a recent work, Zhang *et al*. [5] have proposed a simple phenomenological model to explain the constancy of g factors in deformed nuclei. This model assumes that a reduction in the effective proton-neutron interaction across the midshell region can be simulated by introducing effective proton and neutron boson numbers. This is the same effect that causes the saturation of $B(E2)$ values in the same region. The reduction of the boson numbers is phenomenologically described in Ref. [5] by the equation

$$N_\tau^{\text{eff}} = N_\tau(1 - N_\tau f) \qquad (\tau = \pi, \nu). \tag{4}$$

The parameter f was found to be $f = 0.05$ from a fit to all existing experimental g-factor data for even-even isotopes from Gd to W and for the range of neutron numbers from $N = 88$ to $N = 112$. The predictions of the simple phenomenological model for the Hf isotopes can be calculated by inserting the effective boson numbers given above Eq. (4) into Eq. (3). The results of this calculation are also presented in Fig. 3. We see that the data are in good agreement with the phenomenological model. The new result reported in this Brief Report provides further experimental support for this model and for the concept of effective boson numbers. This phenomenological concept was used in the past [11] to explain anomalies of g-factor and $B(E2)$ data in the region of nuclei around $A = 150$. More theoretical work is needed to provide a microscopical basis for the phenomenological scheme mentioned above, which was found [5] to provide a consistent interpretation for both g-factor and $B(E2)$ data. Further experimental data will also contribute to a better understanding of the nuclear structure in this region. In particular, from Fig. 3 we see that g-factor values at $N = 94$, 96, 100, and 102 are of special interest to substantiate the conclusions of the present work. These experiments are now being planned.

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[1] A. E. Stuchbery, S. S. Anderssen, A. P. Byrne, P. M. Davidson, G. D. Dracoulis, and G. J. Lane, Phys. Rev. Lett. **76**, 2246 (1996).
[2] Z. Berant *et al.*, Phys. Rev. C **69**, 034320 (2004).
[3] A. Wolf *et al.*, Phys. Rev. C **72**, 027301 (2005).
[4] W. Greiner, Nucl. Phys. **80**, 417 (1966).
[5] Jing-ye Zhang, R. F. Casten, A. Wolf, Z. Berant, R. B. Cakirli, N. V. Zamfir, and E. A. McCutchan, Phys. Rev. C **73**, 037301 (2006).
[6] A. Gavron, Phys. Rev. C **21**, 230 (1980).
[7] A. Costin, T. Ahn, B. Bochev, K. Dusling, T. C. Li, N. Pietralla, G. Rainovski, and W. Rother, Phys. Rev. C **74**, 067301 (2006).
[8] H. Frauenfelder and R. M. Steffen, in *Alpha-*, *Beta-*, and *Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland, Amsterdam, 1965), p. 1151.
[9] O. Dorum and B. Selsmark, Nucl. Instrum. Methods **97**, 243 (1971).
[10] M. Sambataro, O. Scholten, A. E. L. Dieperink, and G. Piccito, Nucl. Phys. **A423**, 333 (1984).
[11] A. Wolf and R. F. Casten, Phys. Rev. C **36**, 851 (1987).
[12] P. Raghavan, At. Data Nucl. Data Tables **42**, 189 (1989).
[13] N. J. Stone, Table of Nuclear Magnetic Dipole and Electric Quadrupole Moments, NNDC, http://www.nndc.bnl.gov, 2001.