g factor of the 2_1^+ state of ^{164}Yb

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The g factor of the first excited 2^+ state of ^{164}Yb was measured by perturbed γ-γ angular correlation in an external static magnetic field of 5.55 T. The result, $g(2_1^+)=0.32(5)$, extends the systematics of $g(2_1^+)$ for Yb isotopes down to $N=94$. The behavior of the known experimental values of $g(2_1^+)$ vs neutron number N for all isotopic chains from Ba to Pt is discussed. Several trends are observed: for some chains, especially in transitional regions, a rather strong N dependence of the g factors is observed; in regions of stable structure this dependence is much weaker, and for the Yb and Pt chains it is almost flat. While the different behaviors can be separately explained by valence or collective models, a unified interpretation of these systematic trends remains a challenge to microscopic theories.

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I. INTRODUCTION

The magnetic moments of 2_1^+ states in even-even nuclei have been used for a long time in order to test the validity of nuclear models. The simplest model of g factors is that for a single j configuration in the shell model, that is, for states of the form $|j^n J\rangle$ for the outermost nucleons. Such a simple configuration is often amenable to a treatment in terms of the concept of seniority. For g factors, the relevant operator is of one-body odd tensor form. Such operators conserve seniority and their expectation values are independent of n [1]. Therefore, this scheme predicts constant g factors. Of course, medium and heavy mass nuclei such as those considered here exhibit collective properties associated with large and complex configuration mixing. Therefore collective models for g factors should be considered. One of the first and simplest of these collective models, proposed by Greiner [2], assumes a hydrodynamical behavior of the nucleus, and predicts the simple and well-known Z/A dependence of $g(2_1^+)$, with corrections which take into account the vibrational or rotational character of the specific nucleus involved. With the accumulation of experimental data, many deviations from this simple model have been observed and the need for the interpretation of the data within different models has become evident. In particular, for many isotopic chains the dependence of $g(2_1^+)$ on the total number of nucleons was found to be much stronger than the weak Z/A prediction, thus suggesting that not all the nucleons take part in the collective motion. Sambataro *et al.* [3] have shown that the proton-neutron version of the interacting boson approximation (IBA-2) provides a simple prediction for the $g(2_1^+)$ values of many even-even nuclei, which depends only on the number of valence nucleons. This prediction gives of course a much stronger dependence on A and N than Z/A, and was found to be in good agreement with experimental data for many isotopic chains. Important support in favor of this model was provided by the fact that the slope of the experimental values of $g(2_1^+)$ vs N for quite a large number of isotopic chains changes sign at midshell, as expected in the IBA when particles change to holes. This would be an indication for the presence of valence particle effects. These effects have been discussed in several papers, and in one of them [4] experimental g-factor data were used to estimate the effective number of valence protons in some rare-earth isotopes.

Although the relatively strong N dependence of $g(2_1^+)$ is a common feature of many isotopic chains, in some cases an almost constant dependence was observed. One of these chains, for which $g(2_1^+)$ was measured for a large number of isotopes, is that of the platinum isotopes. Stuchbery *et al.* [5] have measured $g(2_1^+)$ for ^{184}Pt, ^{186}Pt, and ^{188}Pt, thus extending the systematics of magnetic moments for the platinum isotopes from ^{184}Pt to ^{198}Pt, i.e., from $N=106$ to $N=120$. The results show a near constancy of $g(2_1^+)$ for the entire range, including the prolate to γ-soft shape transition around $A=190$. Although this is the same as the seniority scheme prediction, it would not be expected to apply for heavy collective nuclei whose structure emerges from a multi-j highly configuration-mixed environment. Whether the constancy of $g(2_1^+)$ somehow reflects a remnant of seniority (or generalized seniority), or whether it arises from purely collective effects is not clear. Also not clear is why the Pt isotopic chain differs from other nearby elements such as W and Os and how far in neutron number the constancy survives. To address the latter question in the Yb isotopes is a motivation for the present study.

The Yb isotopic chain is of particular interest because the

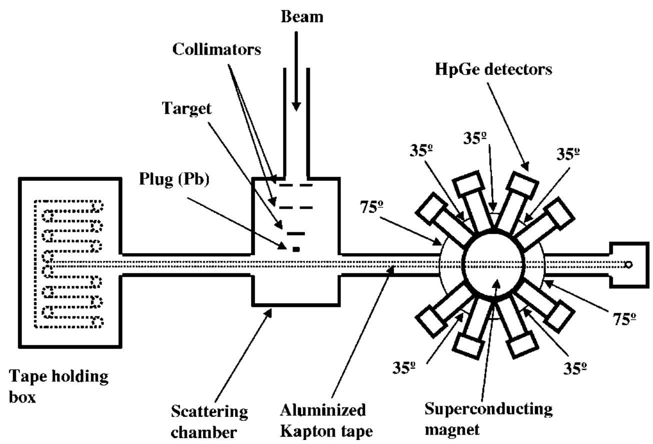

FIG. 1. Schematic description of the experimental system.

existing data, from ^{170}Yb to ^{176}Yb, includes the midshell (N=104) isotope ^{174}Yb, a point at which the IBA-2 predicts a change in slope for the g-factor dependence on N, an effect not seen experimentally.

The purpose of the present work was to measure the g factor of the 2_1^+ state in ^{164}Yb in order to extend the systematics for this isotopic chain from N=94 to N=106 and ascertain whether the g factors for the Yb isotopes, like those of Pt, exhibit no dependence on N.

II. EXPERIMENTAL TECHNIQUE

The experiment was carried out at the tandem accelerator of the Wright Nuclear Structure Laboratory (WNSL) at Yale University. A preliminary report of the present results was presented elsewhere [6].

An experimental setup for g factor measurements of excited states in proton-rich nuclei was recently implemented on one of the beam lines of the WNSL accelerator. The setup consists of a Kapton moving tape collector system connected on one side to a reaction scattering chamber and on the other side to a superconducting coil which can provide static magnetic fields of up to 6 T. Reaction products are deposited on the tape and transported to the center of the coil in a cyclic movement. A plug placed behind the target in the scattering chamber prevented the unscattered beam from directly hitting and burning the transport tape. The distances target-plug-tape were chosen according to the kinematics of the reaction, so that a large proportion of the heavy reaction products will hit the tape. This system was used to measure γ-γ angular correlations in nuclei produced following β-decay of the reaction products deposited on the tape. A detailed description of the moving tape collector technique was presented elsewhere [7].

In the present experiment, an 88 MeV ^{14}N beam with an intensity of about 15 pnA was used to produce the parent ^{164}Lu activity via the reaction ^{155}Gd(^{14}N,5n)^{164}Lu. A self-supporting, 5 mg/cm^2, 99.82% enriched ^{155}Gd target was used. A multidetector angular correlation system consisting of eight HpGe detectors with efficiencies of 20–25% was set around the center of the superconducting coil. A schematic description of the setup is given in Fig. 1.

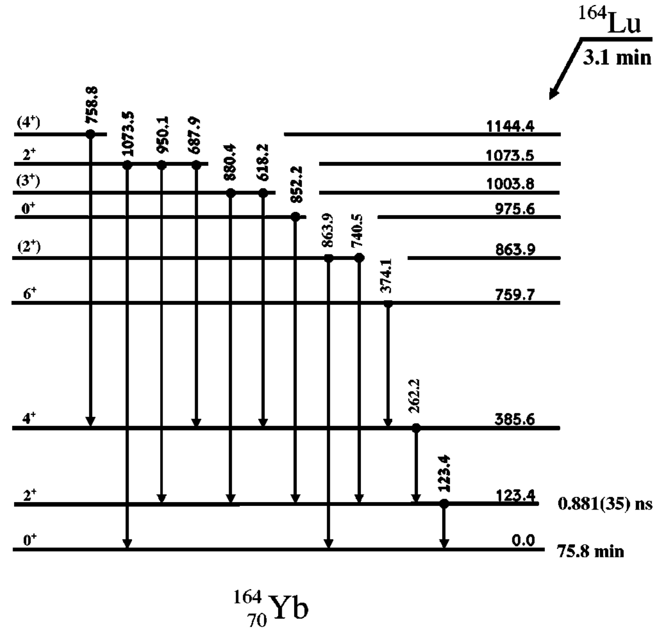

FIG. 2. Partial decay scheme of ^{164}Lu to ^{164}Yb, showing data relevant to the present work (from Ref. [8]).

A partial decay scheme of ^{164}Lu to ^{164}Yb is presented in Fig. 2 [8]. The half-life of the 2_1^+ state is 0.881(35) nsec [8]; since this value is of the order of magnitude of the electronic timing resolution, in the present work the integral perturbed angular correlation technique [9] was used in order to measure its g factor. When using this technique, one measures the γ-γ angular correlation of a given cascade in an external static magnetic field B, perpendicular to the correlation plane. The correlation function for a cascade with spin sequence $I_1 \rightarrow I \rightarrow I_2$ is given by the expression (see Ref. [9])

$$W(\theta,B) = 1 + \sum_{k=2}^{k_{max}} \frac{b_k}{\sqrt{1+(k\omega_B\tau)^2}} \cos k(\theta - \Delta\theta),$$

where b_k are the angular correlation coefficients for the given cascade, $\omega_B = g\mu_N B/\hbar$ is the Larmor precession frequency of the magnetic moment in the external magnetic field, g is the g factor of the intermediate level with spin I, τ is the mean lifetime of this level, and the angular shift $\Delta\theta$ is given by:

$$\tan k\Delta\theta = k\omega_B\tau.$$

For small angles, $\Delta\theta$ is approximately equal to the precession angle $\omega_B\tau$. From the above correlation function we see that the application of the external magnetic field has two effects on the angular correlation: it causes an angular shift $\Delta\theta$ and an attenuation of the anisotropy given by $\sqrt{1+(k\omega_B\tau)^2}$. Measurement of the correlation with and without the magnetic field determines the angular shift, and the reduction of the anisotropy. From these quantities the g factor of the intermediate state of the cascade can be deduced using the above relations. Another way to determine the g factor is to measure the coincidence intensity $I(\theta,B) = I_0 W(\theta,B)$ at a given angle θ with field up and field down, and then deduce the double ratio

TABLE I. The number of HpGe detector pairs at each angle for the setup in Fig. 1.

Angle (deg)	Number of pairs
35	6
70	4
75	2
105	2
110	4
145	6
180	4

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

The correlation intensities for field up and field down are obtained from the correlation matrix using the usual convention for positive and negative angles, as given in Ref. [9]. The use of the double ratio to determine the g factor has the advantage that normalization factors cancel out, and the only correction needed is for the effect of the finite solid angle of the detectors on the angular correlation.

For a given g factor g, external field B, and mean lifetime τ, the maximum double ratio $R(\theta,B)$ is obtained for $0\rightarrow 2\rightarrow 0$ correlations, at angles of about 35° and 145°. Therefore, the angles between the detectors were chosen so that 12 of the total 28 pairs of detectors were at 35° or 145°. The angles of the present setup are marked in Fig. 1, and the number of pairs at each angle are given in Table I. The g factor value was extracted from the coincidence data at angles 35° and 145°. The other angles were used as a consistency check for systematic errors. We used an external magnetic field of 5.55 T. The experiment was run for about 110 h with field up, and 105 h with field down.

III. RESULTS AND DISCUSSION

In Fig. 3 we present a typical coincidence spectrum obtained when a gate was set on the 123.4 keV, $2_1^+\rightarrow 0_1^+$ transition. The double ratio was calculated from the coincidence data for the 852-123, 740-123, and 262-123 keV cascades. The results are presented in Table II. The g factor was extracted from the value of $R(\theta,B)$ at 145° for the 852–123 keV, $0^+\rightarrow 2^+\rightarrow 0^+$ cascade, by comparing the calculated $R(\theta,B)$ for various values of $g(2_1^+)$ with the experimental result. This comparison is presented in Fig. 4. We obtain

$$g_{\mathrm{exp}}(2_1^+) = 0.32(5).$$

The experimental value of $R(145°,B)$ for the 852−123 keV cascade is quite large—1.505(60)—due to several factors: the relatively long lifetime of the 123.4 keV level, the strong anisotropy of the $0^+\rightarrow 2^+\rightarrow 0^+$ correlation, the value of the g factor, and the strong external magnetic field. The angular shift of the correlation $\Delta\theta\approx\omega_B\tau$ was 108(17) mrad. The other experimental values in Table II were used as a consistency check. In the last column of Table II we present the calculated values of $R(\theta,B)$ using $g(2_1^+)=0.32(5)$ for all the cases, except the one (at 145°) which was used to determine the g factor. Within experimental errors, all values in columns four and five are consistent. This may be considered as evidence that no significant systematic errors were present in the experiment. We also mention that $R(180°,B)$ should be 1.000 for all the cascades irrespective of the spin sequence or value of the g factor.

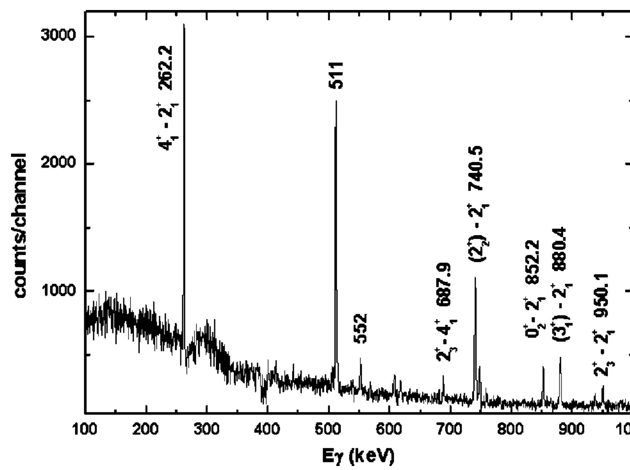

FIG. 3. Typical γ-γ coincidence spectrum obtained when the energy gate was set on the $2_1^+\rightarrow 0_1^+$, 123.4 keV transition. The energies marked on the peaks are in keV.

We now discuss the significance of the result in the framework of two different models: the hydrodynamical model [2] and the IBA-2 [3]. In Fig. 5 we present the systematics of the experimental data for $g(2_1^+)$ vs the number of neutrons N for the Yb isotopes, and the calculated values using these two models. The experimental data for $N=100-106$ were taken from the tables of Raghavan [10] and Stone [11]. The predictions of the hydrodynamical model were calculated for both vibrational and rotational states [2]. For the IBA-2 calculation we used the well-known relation [3]

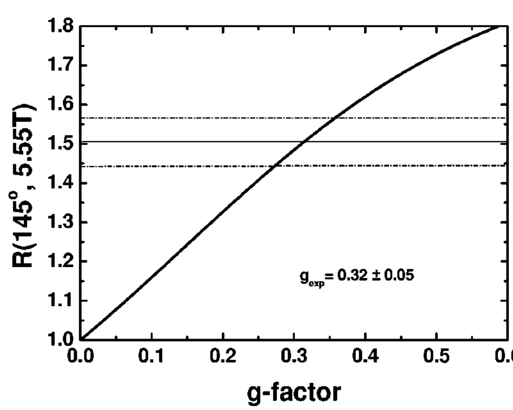

FIG. 4. The calculated double ratio $R(145°,5.55\ \mathrm{T})$ vs the g factor, and the experimental double ratio for the 852-123 keV, $0_2^+\rightarrow 2_1^+\rightarrow 0_1^+$ cascade.

TABLE II. The values of the double ratio $R(\theta,B)$ obtained from the coincidence data for several cascades of ^{164}Yb (see text).

Cascade (keV)	Spin sequence	Angle (deg)	$R_{\mathrm{expt.}}(\theta,B)$	$R_{\mathrm{calc}}(\theta,B)$[a]
852-123	0^+-2^+-0^+	145	1.505(60)	
740-123	2^+-2^+-0^+	145	1.100(30)	1.084(10)[b]
262-123	4^+-2^+-0^+	145	0.977(30)	1.024(4)
852-123	0^+-2^+-0^+	180	1.034(64)	1.000
740-123	2^+-2^+-0^+	180	1.031(43)	1.000
262-123	4^+-2^+-0^+	180	0.993(31)	1.000

[a]The values of R_{calc} and its error bars, where given, were obtained using the value $g_{\mathrm{exp}}=0.32(5)$ (see text).
[b]The double ratio was calculated assuming pure $E2$ character for the first transition of this $2^+\rightarrow 2^+\rightarrow 0^+$ cascade.

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

where N_π, N_ν are the number of proton, neutron bosons, and the parameters g_π and g_ν were taken as 1 and 0, respectively [3]. The result of the present experiment, at $N=94$, extends the systematics to the lower N values, and enables, despite its relatively large error bar, a test of the two models. Although our result has a larger error bar than the data for $N=100-106$, it is clear from Fig. 5 that the strong N dependence predicted by the IBA-2 is not found in the data. In fact, the data seem to exhibit an even weaker dependence than predicted by the hydrodynamical model.

We now compare the systematics of the Yb isotopes with those of all the isotopic chains from Ba to Pt. In Fig. 6 we present all the known [10, 11] experimental $g(2_1^+)$ values for these isotopes. Several interesting trends are clearly observed. In transitional regions, i.e., for Ba, Ce, Nd, Sm, Gd, W, and Os, the g factors vary quite strongly with N. As the structure becomes more stable, the N dependence is weaker, as seen for Dy and Er. Finally, for Yb, Hf, and Pt the g factors are almost constant.

The theoretical predictions of Fig. 5 can be used as generic predictions of a valence model (IBA-2) and a collective model (hydrodynamical) in order to discuss the various trends in Fig. 6. For Ba, Gd, W, and Os, the IBA-2 model describes the data quite well, especially the parabolical dependence around the midshell point $N=104$. For Dy and Er, the weaker N dependence is better described by the hydrodynamical model. The "flat" behavior of Yb and Pt is not consistent with either model. As mentioned already the seniority model [1] predicts constant g factors; however, this model is not expected to apply in this region. The peculiar N

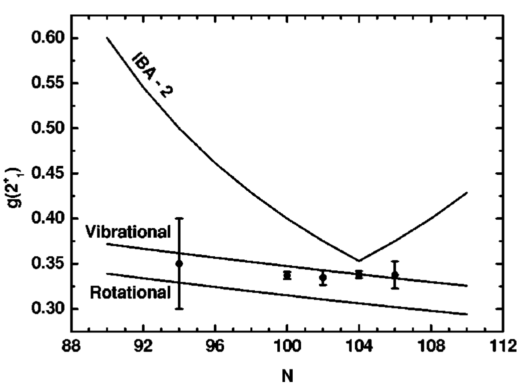

FIG. 5. Systematics of $g(2_1^+)$ data for the Yb isotopes. The results for $N=100-106$ are from the tables of Raghavan [10] and Stone [11]. The value at $N=94$ is from this work. The predictions of the IBA-2 [3] and of the hydrodynamical model [2] for vibrational and rotational nuclei are also presented.

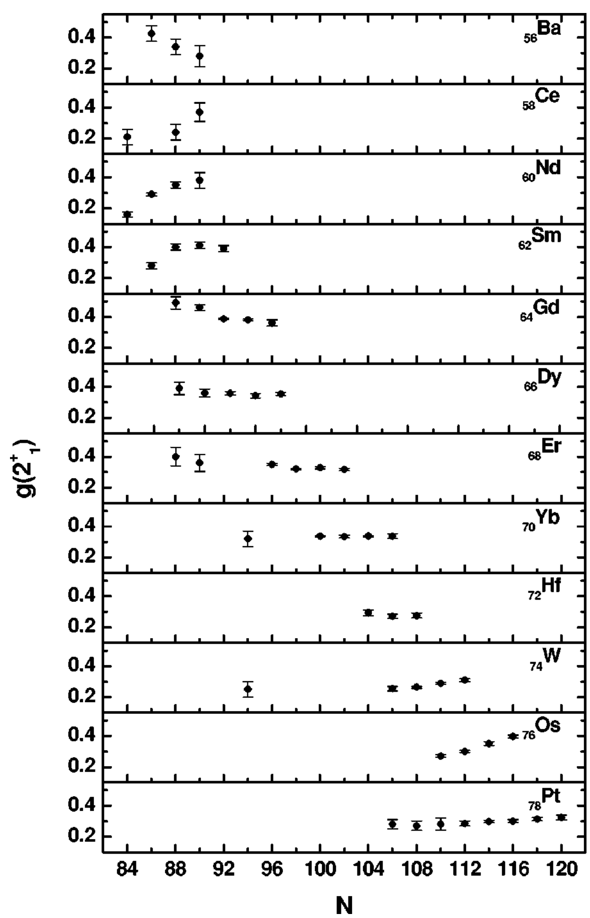

FIG. 6. Systematics of $g(2_1^+)$ data for the region Ba-Pt. Data from the tables of Raghavan [10] and Stone [11], and the new result presented in this work.

dependence for the Ce, Nd, and Sm isotopes was explained in Ref. [4] as being related to an increase in the effective number of valence protons due to the dissipation of the $Z=64$ subshell when N increases from 84 to 90. Finally, it is important to mention that single particle effects may also affect the behavior predicted by the collective or valence models. For example, the downsloping of $g(2_1^+)$ for the Nd isotopes as N approaches $N=82$ may be due to the increasing influence of $f_{7/2}$ neutrons which have negative g factors. Other single particle effects may also be present, which can, in principle at least, modify the expected trends that we mentioned above. In this context, a measurement of $g(2_1^+)$ for ^{140}Ba could be an interesting test of the evolution from nuclei where single particle effects are significant to those where collective motion comes into play.

In conclusion, the present experiment provides a result which extends the systematics of g factors of the Yb isotopes. When these systematics are analyzed in the context of all the known data for the Ba-Pt isotopic chains, various and quite different trends are observed. While the different classes of behavior (upsloping, downsloping, or constant) appear as characteristic features of various valence or collective models, a unified interpretation of these systematic trends remains a challenge to microscopic theories.

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