g Factor Measurements of High-Spin ($I^\pi \le 10^+$) Rotational States

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The ion implantation perturbed angular correlation (IMPAC) technique was used to measure the precession angles of the 4^+, 6^+, 8^+, and 10^+ rotational states of ^{158,160,162}Dy nuclei recoil implanted into magnetized Gd ($T = 77\,^\circ$K). The Gd(α, $2n$)Dy reaction ($E_\alpha = 27$ MeV) on natural Gd was used to populate the levels studied. By comparing the precession results obtained from the (α, $2n$) experiments for the 4^+ and 6^+ states to those obtained from Coulomb excitation IMPAC measurements one can conclude the following: (i) $g(^{158}\mathrm{Dy}) = 0.36 \pm 0.06$ for $I^\pi = 4^+$, 6^+, and 8^+; (ii) no effect due to final feeding times into the g.s. rotational band can be observed; and (iii) the deduced g factors are constant for members of the g.s. bands of ^{158,160,162}Dy up to $I^\pi \le 8^+$ but a possible drop in g for the 10^+ states may be indicated by the data. A reduction in the g factors is theoretically expected to accompany the "back bending" in the energy levels which was recently observed for high-spin rotational states in some deformed nuclei.

INTRODUCTION

Experimental studies of the energy spectra of even deformed nuclei have recently revealed striking deviations from the $I(I+1)$ rule for rotational states of spins $\gtrsim 12^+$. The theoretical explanation for these "back bending" phenomena lies, in one way or the other, in the breakup of the pairing correlation, which causes drastic changes in the moment of inertia of the fast rotating nucleus.[1]

One would expect this breakup of the pairing correlation responsible for the "back bending" to be reflected also in other properties of the high-spin rotational states, i.e., in their electromagnetic properties.

The collective gyromagnetic ratios may, in particular, prove to be a sensitive probe to any change in the pairing correlation, since it is a direct measure of the relative superfluidity of the proton system compared to that of the neutron system.

In this work we report the results of integral precession measurements on members of the g.s. rotational band in the even Dy isotopes. The relative magnetic moments of the 4^+, 6^+, 8^+, and 10^+ states in ^{158,160,162}Dy extracted from the precession data may indicate the existence of a decrease in g_R for the 10^+ states relative to those of the lower-spin states. Such a drop in the g factors is indeed expected theoretically to accompany the changes in the moments of inertia.[2]

EXPERIMENTAL

The members of the ground-state rotational band in ^{158,160,162}Dy were populated simultaneously via the (α, $2n$) reaction by bombarding metallic Gd foils (0.025 mm thick) with 27-MeV α particles. The decay γ rays were detected by Ge(Li) detectors in which the rotational transitions up to the $10^+ \to 8^+$ could clearly be seen (see Fig. 1).

Four kinds of experiments were carried out:

(i) The magnetically unperturbed angular distribution $W(\theta)$ of the γ rays was measured with the target at room temperature, using two movable Ge(Li) detectors. A third Ge(Li) detector at a fixed angle served as a normalization counter. The measured angular correlations were least-squares fitted by the expression

$$W(\theta) = A_0 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta) \qquad (1)$$

after having been corrected for absorption in the target and for dead time in the analysis system. The deduced A_2 and A_4 coefficients for all the 6^+, 8^+, and 10^+ states studied were of the order of $A_2 = 0.35 \pm 0.02$, $A_4 = -0.02 \pm 0.02$, in agreement with the results of previous experiments[3] and with the theoretical predictions of Halpern, Shepherd, and Williamson.[4] The coefficients for the $4^+ \to 2^+$ correlation were more attenuated: $A_2 \simeq 0.30 \pm 0.02$, $A_4 \sim 0$.

(ii) The precession angles of the short-lived states (in particular the 8^+ and 10^+ states) were measured with the γ counters at fixed angles ($\pm 55^\circ$) at which the relative slope of the angular correlation is maximum.

The Gd target was cooled to liquid nitrogen temperature so that the Gd became ferromagnetic, and an external magnetic field of about 4 kOe was applied "up" and "down" perpendicular to the count-

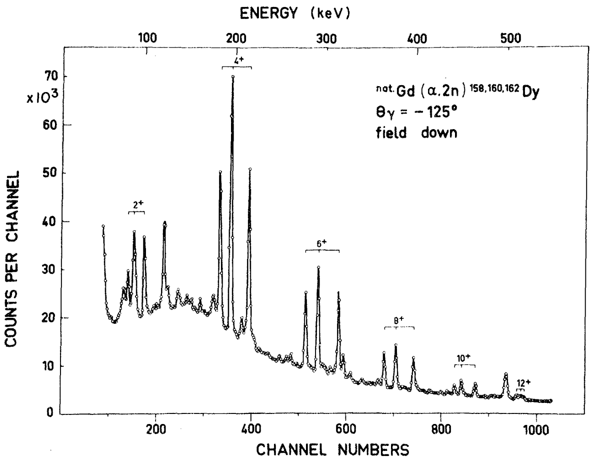

FIG. 1. Typical γ-ray spectrum following the bombardment of a natural Gd foil with 27-MeV α particles.

er plane to polarize the Gd foil. The experimental shift of the angular correlation $(\Delta\theta)_{\rm exp}$ was deduced from the ratio $[N(\uparrow) - N(\downarrow)]/[N(\uparrow) + N(\downarrow)]$.

(iii) The experiments described above (ii) were repeated with the target at room temperature. The observed shift in the angular correlation in this case is entirely due to the bending of the α beam in the stray magnetic field, which results in a shift of the beam spot and a rotation of the beam axis according to the field direction.

The experimentally determined beam shift and beam bending correction (0.020 ± 0.002) was found to be in agreement with the results of numerical integrations over the magnetic field profile.

(iv) The large precession angles of the longer-lived states (the 6^+ and in particular the 4^+ group) could not easily be deduced from the slope angle measurements (ii). The full angular correlation was therefore measured, for the polarizing field $\uparrow$ or $\downarrow$, and the data were fitted to the formula for the integral angular correlation in the presence of static and time-dependent magnetic interaction.[5] The results are in agreement with the A_K coefficients deduced from the $W(\theta)$ experiments (i), with the $\omega\tau$ values deduced from the shift angle experiments (ii), and with attenuation coefficients obtained elsewhere[6] (see Fig. 2).

In order to find out what the effective hyperfine field of Dy in Gd for "in beam" experiments is, an additional experiment was done in which the 4^+ and 6^+ states of the even Dy isotopes were Coulomb excited and implanted into a polarized Gd backing using the standard Coulomb excitation IMPAC method. An internal field of 1.4 MOe was deduced from this work. The complete agreement in the field and in the relaxation parameters between the Coulomb excitation (CE) and the present results justifies our confidence in the analysis of the 4^+ data and also resolves other problems which will be discussed below. A detailed analysis of the hyperfine and relaxation phenomena involved will be given elsewhere.[7]

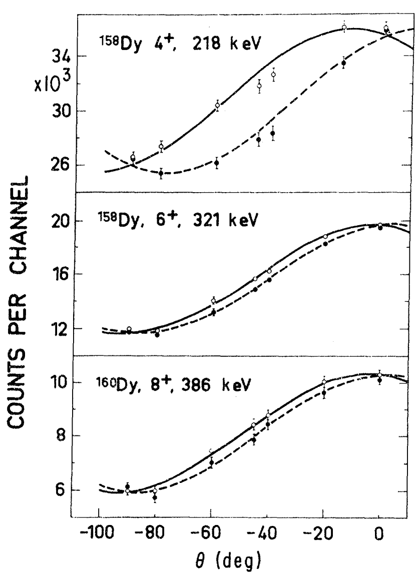

FIG. 2. Precessed angular correlations for field $\uparrow$ (open circles) and field $\downarrow$ (full circles) for typical 4^+, 6^+, and 8^+ states. The solid and dashed lines represent computer fits to the $\uparrow$ and $\downarrow$ data, respectively.

RESULTS AND DISCUSSION

In order to extract the precession angle $(\omega\tau)$ of a particular state from the measured angular shifts several corrections had to be applied to the data. First, the apparent shift of the angular correlation due to beam bending and beam shift in the polarizing field had to be subtracted. Second, the fact that a state under study was partly fed from the compound system, and partly from cascades of higher rotational states (which themselves undergo precession before decaying) had to be taken into account.

The branching ratios of direct to cascade feeding of the various states were estimated from the present data and were found to be in agreement with previous results. The total "feeding correction" for a state with spin I amounted to about 50% of the net precession measured for the $I+2$ spin.

A convenient way of displaying the precession results, which illustrates possible deviations of the g factors from a constant value, is to plot the measured $\omega\tau$ values versus τ (mean life) for each one of the 12 states which were studied in this work (see Fig. 3). As can be seen from the fig-

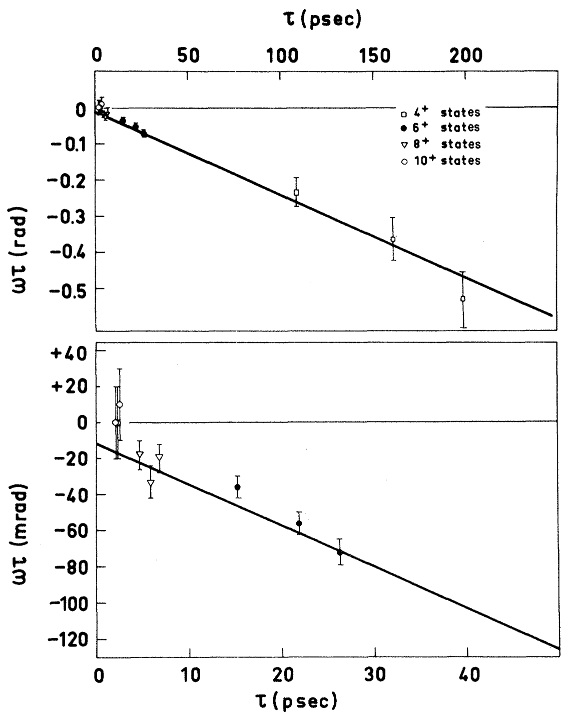

FIG. 3. Summary of the precession results. The lower figure is an enlargement of the short lifetime range (6^+, 8^+, and 10^+ states) of the upper figure. The slope of the lines in both figures are identical and were deduced from the 4^+ and 6^+ points only.

ure, all the experimental data points lie on a straight line with the probable exception of the three points of the 10^+ group, which are all consistently, though by only 1 standard deviation, higher than the line.

The following points have to be considered in constructing the figure:

(i) The g factor of the low I states of ^{158}Dy is about the same as that for ^{160,162}Dy. In order to see that, one should concentrate on only the data for the 4^+ and 6^+ states for which it is very likely that no breakdown of the simple rotational model occurs. This means that τ can be calculated from the rotational model[8,9] and that g is the same for the 2^+, 4^+, and 6^+ states.[10] Numerous previous measurements show that $g(2^+, {}^{162}\mathrm{Dy}) \simeq g(2^+, {}^{160}\mathrm{Dy}) = 0.36 \pm 0.01$. Since $\tau(6^+, {}^{162}\mathrm{Dy}) < \tau(4^+, {}^{158}\mathrm{Dy}) < \tau(4^+, {}^{160}\mathrm{Dy})$ and the ^{158}Dy 4^+ point falls on the straight line drawn through the ^{160}Dy and the ^{162}Dy 4^+ data, we conclude that $g(4^+, {}^{158}\mathrm{Dy}) = 0.36 \pm 0.06$. The same conclusion was reached in previous $(\alpha, 2n)$ work[3] as well as in CE IMPAC experiments.[7]

(ii) The slope of the line drawn through the 4^+ and 6^+ points of the present work, determines a static hf field for Dy implanted into cooled Gd of 1.3×10^6 Oe, in agreement with the above mentioned CE IMPAC result.[11] A transient effect $(\omega_t \tau_t)$ of ~ -0.050 rad was measured for ~20-MeV Dy or Gd ions recoiling through Gd.[12] Using the known dependence of the transient effect on recoil velocity,[13] one can estimate $\omega_t \tau_t$ to be $\sim -0.010 \pm 0.003$ for the recoil velocities relevant to this work.

(iii) The results of recoil-distance Doppler-shift lifetime measurements on high-spin rotational states ($I \leq 10^+$), Refs. 8 and 9, show that the experimental lifetimes do not deviate by more than ~10% from those calculated from the rotational model. The lifetimes used in Fig. 3 were calculated in that way. Recent (^{40}Ar, xn) experimental results[8] on lifetimes of rotational nuclei show that there is a mean time interval (feeding time) of the order of 10^{-11} sec between the formation of the compound nucleus and the population of the g.s. band. Not much is known about feeding times following (α, xn) reactions, but it seems that for 40-MeV α particles most of the feeding is prompt.[14] The present data put a rather sensitive test to the existence and nature of the feeding state: If such a state exists for times $>10^{-12}$ sec, and if it has a nonvanishing magnetic moment, its precession in the magnetic fields should be observable. If, for instance, the feeding state lives for 10^{-11} sec, and has a collective g factor of ~0.4 all the data points should be plotted at times $t = \tau + 10^{-11}$ sec, and the line through these points should pass through the transient field value at $t = 0$. The present data clearly show that this is not the case. Furthermore, the 6^+ precession results from the CE experiments (no feeding time) agree remarkably well with the present reaction data (after properly taking into account the different transient effect due to the large difference in recoil velocities), indicating that the latter are not subject to any precession due to a delayed feeding process.

The following conclusions regarding the nuclear physics may thus be drawn from Fig. 3 and from the above discussion:

(a) The g factor of the g.s. rotational band of ^{158}Dy up at least to spin 8^+ is $g = 0.36 \pm 0.06$.

(b) No precession of "feeding states" prior to entry into the g.s. rotational band can be observed, i.e., $g\tau H \sim 0$ for these states.

(c) The relative g factors of rotational states in the g.s. band of ^{158,160,162}Dy is constant for $I \leq 8^+$. A decrease in g for the 10^+ states from this constant value cannot be excluded from the present data. One could argue that the vanishingly small precession angles measured for the 10^+ states are due to the "extinction" of the hf fields for short times following the nuclear reaction. Although this argument cannot completely be ruled out, it seems rather unlikely since the full precession was measured for 8^+ states which differ in lifetime by only a factor of 2 from the 10^+ lifetimes.

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