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# $g$ Factors of High-Spin States in $^{160}$Dy and $^{170,174}$Yb Measured by the Transient Magnetic Field Interaction

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Ground-band states up to $16\hbar$ in $^{160}$Dy and $^{170,174}$Yb have been Coulomb excited by 350-MeV $^{86}$Kr ions. The excited nuclei recoiled through magnetized iron where they experienced transient magnetic fields as high as ~3800 T. The nuclear precessions, determined from $\gamma$-ray time-integral perturbed angular correlations, suggest a small decrease of the $g$ factors with increasing spin for all three nuclei.

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It is generally accepted that the breakdown of the pairing field and the alignment of nucleon pairs in high-$j$ orbitals play a major role in phenomena observed in deformed nuclei at high angular momentum.[1-4] Mosel,[1] and others, have pointed out that $g$ factors provide a unique measure of the relative contribution of protons and neutrons to the total angular momentum and are therefore very sensitive to pairing breakdown and alignment. Recent Hartree-Fock-Bogoliubov (HFB) cranking-model calculations[3-4] have shown that $g \sim 0$ for neutron alignment and $g \sim 1$ for proton alignment, and predict significant variations in different nuclei. In this Letter, we present the first results for $g$ factors of high-spin discrete collective states.

The paucity of previous nuclear-moment information at high spin in deformed nuclei is a consequence of the very short ($\tau \lesssim 1$ ps) lifetimes of rotational states which makes it practically impossible to obtain measurable precession for even the largest static hyperfine fields. We have overcome this difficulty by taking advantage of the very large (several thousand teslas) transient magnetic fields (TMF) which occur when recoiling ions slow down in a polarized ferromagnetic material.[5,6] The availability of energetic heavy ion beams from the Berkeley SuperHILAC made it possible to Coulomb excite states up to spin $16\hbar$, and obtain high recoil velocities thus increasing the precession, since the TMF increases with velocity.[5] The present results were made possible only by extensive measurements undertaken to calibrate the TMF, which will be described elsewhere.[7] Previous experiments to measure $g$ factors for discrete states by the TMF technique were limited to spins below $J \lesssim 8$ because of the lighter projectiles employed.[6,8]

We have investigated the nuclei $^{160}$Dy and $^{170,174}$Yb since the lifetimes of the high-spin states, necessary for the interpretation of the data, have been measured,[9] and HFB predictions of the variation of their $g$ factors with spin exist.[3] The nuclei were excited by multiple Coulomb excitation with ~350-MeV $^{86}$Kr ions. In measurements involving the TMF, the targets play a critical role. In our work they consisted of a ~1-mg/cm$^2$-thick rare-earth ($^{170,174}$Yb or $^{160}$Dy) material evaporated onto a rolled and annealed 5.5-mg/cm$^2$-thick iron foil backed by 15 mg/cm$^2$ of copper. The excited nuclei recoiled through the magnetized iron, with an initial velocity $v/c \sim 6\%$, during which time they were subjected to an intense TMF, initially, ~3800 T. The nuclei then stopped in copper, thereby avoiding exposure to both the static field of iron and the TMF at low velocities which is not known precisely. A polarizing field of 0.15 T was applied, which has been found sufficient to saturate the iron foils.[6]

$\gamma$-rays in coincidence with the backscattered $^{86}$Kr ions were detected in two Ge(Li) counters placed 8 cm from the target and positioned at ±63° with respect to the beam direction. At these angles the slope of the $\gamma$-ray angular correlation pattern was a maximum for the high-spin stretched $E2$ transitions. The $^{86}$Kr ions were detected in an annular parallel-plate avalanche counter,[10] subtending an angular range of 125°–160°. The detector housing and its axial 5-mm-diam beam tunnel, which extended to within 5 mm of the target, were made of magnetically soft iron to minimize beam-bending effects.[5] Extensive field mapping and calculations showed them to be negligible in our experiments. A typical $\gamma$-ray spectrum is shown in Fig. 1.

During the runs the direction of the polarizing field was automatically reversed every two minutes to minimize the possible systematic errors

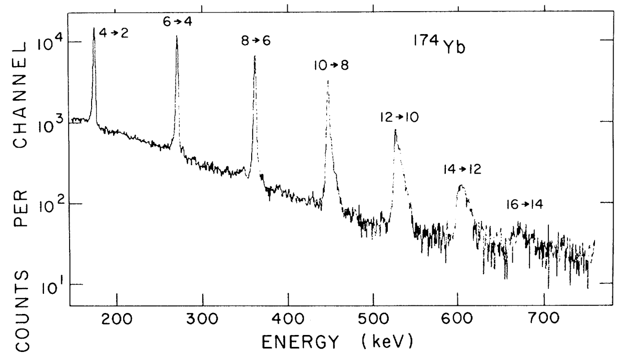


FIG. 1. Typical spectrum of $\gamma$ rays in coincidence with backscattered 350-MeV $^{86}$Kr ions impinging on a multiple-layer target.

due to gain shifts and changes in beam intensity and position. After a small correction for random coincidences, the $\gamma$-ray peaks in the coincidence spectra were integrated and corrected for dead-time effects measured with rate-dependent triggered pulsers. The precession angle $\varphi$ was obtained experimentally via the usual relation[5,6] $\varphi = \epsilon/S$, where $S = -(dW/d\theta)/W$, and $W$ is the calculated angular correlation function, $\epsilon = (\sqrt{R} - 1)/(\sqrt{R} + 1)$, and $R = N_1^{\uparrow} N_2^{\downarrow}/N_1^{\downarrow} N_2^{\uparrow}$ is the double ratio of counting rates; $N_1^{\uparrow}$, e.g., represents the intensity of a $\gamma$-ray photopeak observed in the detector at +63°, for the polarizing field in the "up" direction. Typical values of $\epsilon$ were around 2–3%.

The precession angles could also be calculated by taking into account the initial populations and alignments, the level lifetimes and $g$ factors, the stopping powers, and the TMF calibration. This is a complicated process described in detail in Refs. 5 and 6. For the TMF, we have taken[5,6] $B(v) = B_{\rm LW} + B_v$, where $B_{\rm LW}$, the Lindhard-Winther field,[11] was a small contribution (~3.5%) at these high recoil velocities and[7] $B_v = aZ(v/v_0)\exp(-\beta v/v_0)$, where $Z$ is the atomic number of the recoiling nucleus, and $v_0 = c/137$ is the Bohr velocity. The two parameters $a = 15.8$ and $\beta = 0.1$ were extracted[7] from extensive data obtained with the Chalk River tandem accelerator for reactions involving states of known $g$ factors in $^{169}$Tm, $^{160}$Dy, and $^{174}$Yb at various recoil velocities. In our velocity range, the integrated effect of the TMF was calibrated with a precision of 7%. The results were found to be insensitive to the exact form of $B(v)$ because the calibration runs essentially covered the velocity range encountered in the experiment. However, caution should be exercised in applying this calibration to situations outside the present velocity range.

At 350 MeV, the incoming $^{86}$Kr ions had sufficient energy to populate significantly states of the ground band up to $16^+$ in $^{160}$Dy and $^{170,174}$Yb. The instantaneous population of these states and their alignment tensors (entering into the quantities $S$) were calculated with the Winther–de Boer program.[12] Because of the low statistical accuracy of the observed precessions, the $g$ factors of individual levels were not determined. We have rather endeavoured to establish a trend for the $g$ factors with spin, most conveniently expressed by the value of $\alpha$ in the relation $g(I) = g_0(1+\alpha I^2)$. In this way all the precession data in a given nucleus could be combined in an overall fit.[6] This quadratic dependence was suggested by theoretical calculations[3,4] in the spin range ($I < 16\hbar$). The quantities $g_0$ were taken from the known $g$ factors of the $2^+$ states.

The results are presented in Fig. 2. The $g$ factors in the top panel were calculated from the $\alpha$ values that gave the best overall fit to the precession data shown in the center panel. The dashed lines are the rotational-model prediction ($\alpha = 0$). In the middle panel, the systematic reduction of the calculated precessions at higher spins, even for $\alpha = 0$, is due to the shorter half-lives of those states which decayed significantly before the recoiling ions had left the iron layer. The effect of a trend in the $g$ factors with spin shows up mainly as an overall scaling of all the precessions. In the bottom panel of Fig. 2, the results are seen to be most sensitive to precessions occurring in the $8^+$, $10^+$, and $12^+$ states. The TMF did not perturb the low-spin states directly because they were only weakly populated during the passage

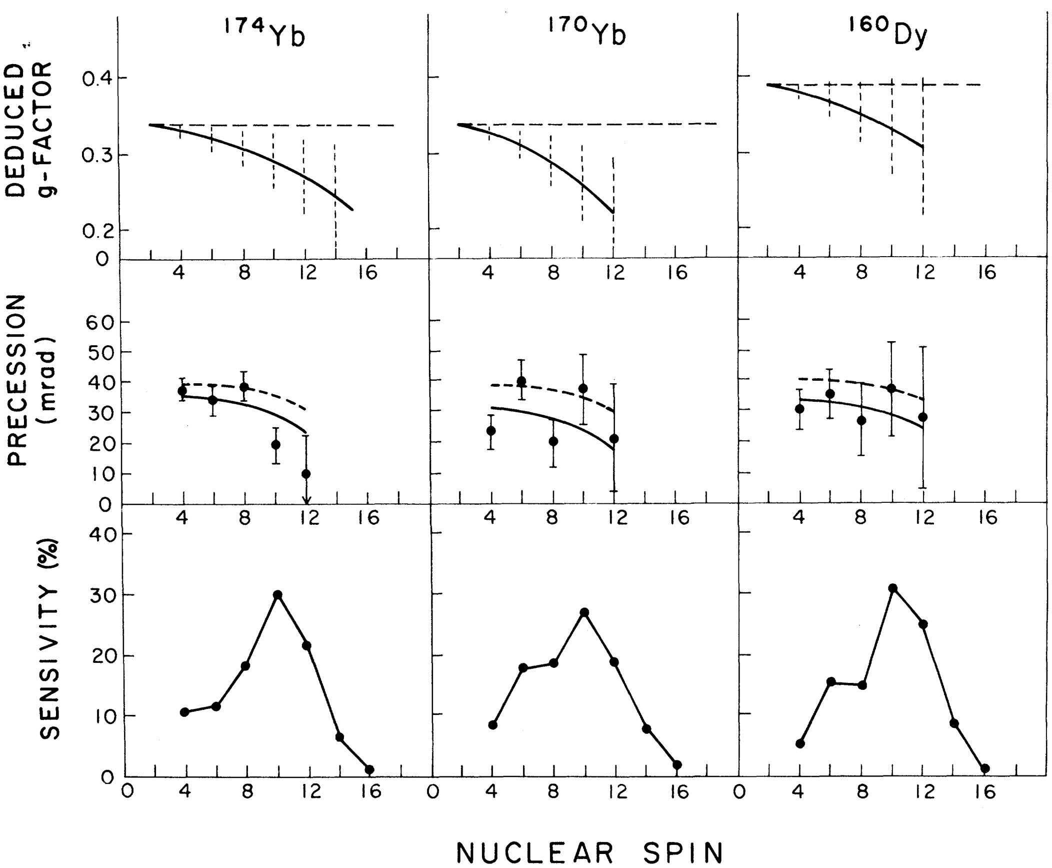


FIG. 2. Results obtained from multiple Coulomb excitation of deformed $^{160}$Dy and $^{170,174}$Yb by 350-MeV $^{86}$Kr ions. $g$ factors are displayed in the top panel deduced from a fit to the precession data shown in the center panel, with $g(I) = g_0(1+\alpha I^2)$. The dashed lines are the rotational-model predictions, $\alpha = 0$. In the bottom panel the calculated sensitivities of $\alpha$ to the individual precessions are shown. These values take into account all the experimental observables including the initial populations and alignments, experimental geometry, level lifetimes, and relative statistical errors in the measured precessions.

through iron (0.06–0.67 ps). Nevertheless, the angular correlation pattern for those levels did display a rotation from the accumulation of precessions occurring in various higher-lying levels, and hence the overall fit provided data on the high-spin $g$ factors.

The values of the parameter $10^{-3}\alpha$ obtained for $^{160}$Dy and $^{170,174}$Yb were $-1.5 \pm 1.3$ (1.6), $-2.4 \pm 1.3$ (1.5), and $-1.3 \pm 0.8$ (1.0), respectively, generally consistent with the predictions[4] of Sano, Takemasa, and Wakai (−1.7, −0.6, and −0.6) except possibly for $^{170}$Yb. Two sets of errors are quoted. The first are standard deviations from fits to the experimental $\varphi$'s. The total errors, given in parentheses, include in addition the uncertainties in the $g$ factors for the $2^+$ states measured previously, in the field calibration, and in the Fe thickness, all combined in quadrature. The dashed "error bars," shown in the top panel of Fig. 2, were calculated by taking into account these total errors. The actual $g$ factors shown depend on the assumption of the $\alpha$ parametrization, but the conclusion of decreased $g$ factors in the $(8-12)\hbar$ spin region is model independent.

The results for the three nuclei imply a reduction (possibly as much as ~35% at the $12^+$ level) of the $g$ factors with increasing spin. Thus, for the first time, direct experimental evidence has been established for the weakening of the neutron pairing relative to proton pairing. Moreover, the effect does not appear to be strongly dependent on the neutron number, at least not for the three nuclei and the angular momentum range studied. It is clear that the measurement of $g$ factors could be a sensitive probe of the aligned component of the nuclear wave function. It would be desirable to extend the measurements to still higher spins where the effects should be even more pronounced.

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