g Factors of High-Spin Yrast States in ^{232}Th and ^{238}U

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(Received 18 August 1981)

Extremely large precession angles (0.24 rad) have been observed when Coulomb-excited, 2-MeV/A actinide recoils decelerate in ferromagnetic Gd. In both ^{232}Th and ^{238}U the g factors increase above spin $I = 18\hbar$. This is the first direct evidence for rotation alignment of $i_{13/2}$ protons in the actinides. In ^{232}Th there is also evidence for alignment of $j_{15/2}$ neutrons below $I = 16\hbar$.

PACS numbers: 21.10.Ky, 21.10.Pc, 25.70.Kk, 27.90.+b

When the angular velocity of well-deformed rotational nuclei increases, the angular momenta of single-particle configurations tend to align along the axis of rotation.[1] This interplay between collective and single-particle degrees of freedom has been extensively studied in deformed rare-earth nuclei where it is now believed[2,3] that the onset of strong spin alignment derives from $i_{13/2}$ neutron configurations.

In contrast to the rare-earth nuclei, the high-spin excitations in the actinides provide a much less explored, and probably more complex testing ground of rotational alignment. Multiple-Coulomb-excitation experiments with ^{208}Pb beams[4-7] have recently shown a very gradual increase of the aligned spin i which is indicative of strong interactions between the ground-state band and the superband. In the actinides both $i_{13/2}$ proton and $j_{15/2}$ neutron quasiparticles are near the Fermi surface and cranked shell-model calculations[2,8-10] predict that the critical frequencies for alignment of these high-j particles are nearly the same. Consequently the aligned spin i may contain both proton and neutron quasiparticle components. Specific information about the alignment has come from the odd nuclei $^{237}_{93}$Np and $^{235}_{92}$U where the unpaired particle blocks one of the two band crossings.[7] A more direct test is the measurement of nuclear g factors since the aligned proton and neutron contributions are of opposite sign.

Because of the short mean lifetimes of the collective rotational states which become shorter than 1 ps at $I \gtrsim 22\hbar$, polarized magnetic fields much larger than 10 MG (=1 kT) are required to generate substantial precession angles. Such intense magnetic fields are experienced by nuclei decelerating in polarized ferromagnetic materials.[11] These "transient magnetic fields" (TMF) have been studied extensively in several laboratories[12] with recent emphasis on high recoil velocities. They have already been exploited to obtain g factors of collective states below[13] and at[14] the critical frequency in some rare-earth nuclei. In this Letter we report the first measurements of the spin dependence of g factors in the actinides. The precession angles and the associated TMF's are by far the largest that have been observed.

Empirical systematics of the TMF have established its approximate dependence on the velocity and Z of the recoiling nuclei in various ferromagnetic hosts, but no model is available for reliable calculations, or even for reliable extrapolations into the actinide region from the nearest calibration points at $Z = 64$ and 69.[15] The present experiment was designed so that firm conclusions could be drawn independent of the detailed behavior of the TMF. The basic method is a comparison of the spin precessions of the lower spin states with that of the higher spin states of the same nucleus, providing the same time history of the TMF in both experiments. To reach two different spin regimes, 1-mg/cm^2-thick targets of ^{232}Th or ^{238}U on thick (150 mg/cm^2) single crystals of ferromagnetic Gd (kept at 80 K) were multiply Coulomb excited, first with use of a 4.1-MeV/A ^{127}I beam from the Max-Planck-Institut für Kernphysik (Heidelberg) postaccelerator, and then with the 5.1-MeV/A ^{142}Nd beam from the Darmstadt UNILAC. The maximum spins populated in the two bombardments were $(16-18)\hbar$ and $(22-26)\hbar$, respectively. Scattered projectiles were detected at backward angles between 125° and 160° in an annular parallel-plate avalanche detector,[16] and corresponding actinide recoils emerged at 0° in a narrow cone from the targets. To match the initial recoil velocities into the Gd, a nonmagnetic buffer layer of 4.6 mg/cm^2 Pb was sandwiched between the targets and the Gd for the ^{142}Nd experiments, reducing the recoil energies from 3 MeV/A to the 2 MeV/A in the ^{127}I runs. Corrections for γ decays in the buffer layer (transit time 0.2 ps) have been made by using the computer code TRAFIC (see Ref. 16); because of large feeding intensities from higher states they are negligible for $I \leq 16\hbar$.

γ rays in coincidence with backscattered beam particles were observed in two large-volume Ge(Li) detectors positioned at $\theta_\gamma = \pm 63°$ where the logarithmic slope of the angular correlation, $S = -(dY/d\theta_\gamma)/Y$, is near a maximum for $E2$ transitions between high-spin states. The γ ray spectrum for ^{238}U in coincidence with backscattered ^{142}Nd is shown in Fig. 1. The experimental cross sections for the strongly excited yrast bands are given in the top panels of Fig. 2; they are in good agreement with multiple-Coulomb-excitation calculations.[17] Doppler-broadened lines from excitation of the noncollective projectiles ^{127}I and ^{142}Nd were only seen weakly, and did not interfer significantly with the lines of interest.

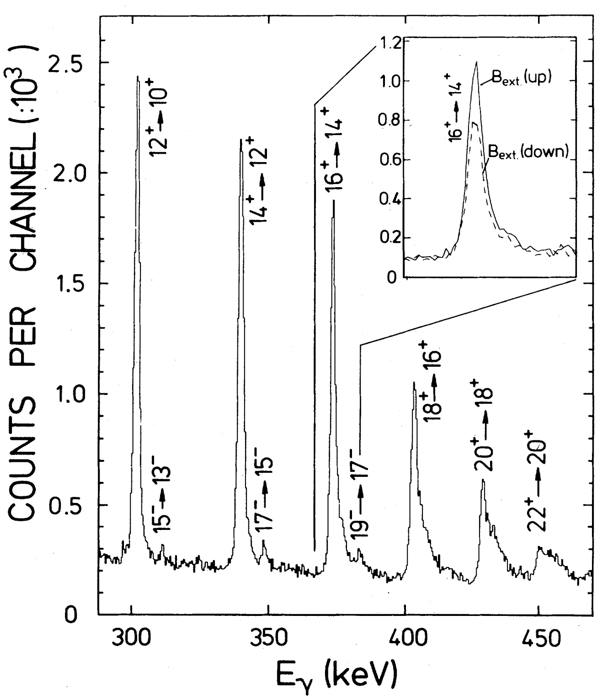

FIG. 1. Typical spectrum of γ rays observed in coincidence with ^{142}Nd backscattered from a ^{238}U multilayer target. The inset shows the yield change for one of the transitions when reversing the external polarizing field.

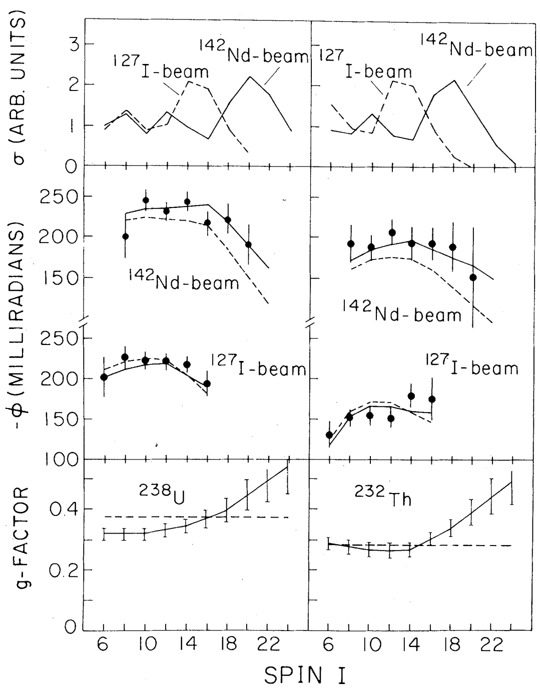

FIG. 2. Results obtained from multiple Coulomb excitation of ^{232}Th and ^{238}U with beams of ^{127}I and ^{142}Nd. Upper panel: cross sections observed in coincidence with backscattered ^{127}I (dashed line) and ^{142}Nd (solid line). Middle panel: precession angles φ for the $E2$ transitions from various probe states, observed experimentally and calculated with the assumed g factors shown in the lower panel. Lower panel: the g factors assumed in the analysis of the precession angles to be either constant (dashed lines) or to include rotational alignment effects (solid lines). Total errors (vertical lines) refer to relative g factors and do not include uncertainties from the extrapolation of the transient field.

The effect of reversing the polarizing field ($B_{ext}=0.26$ T) is shown in the inset of Fig. 1 for one of the 63° detectors. With use of the total line intensities the yield effect, $\epsilon=(Y\uparrow - Y\downarrow)/(Y\uparrow + Y\downarrow)$, was obtained in the usual way[16] from the double ratio of counting rates in the two detectors. The ϵ values varied between 10% and 16%. The computed logarithmic slopes S vary slowly from 0.71 for the $8\rightarrow 6$ transition to 0.66 for the $24\rightarrow 22$ transition. The precession angles, $\varphi=\epsilon/S$, are shown in the middle panel of Fig. 2 (the rather inaccurate values for the highest transitions are omitted).

Several conclusions follow from the precession values as a function of spin:

(1) The static magnetic fields on Th and U nuclei are small (-20 ± 20 T). This follows from the fact that the precession angles for the lower states are independent of the mean lives which range from 87 ps (at $I=6\hbar$ in ^{232}Th) to 4.7 ps (at $I=14\hbar$); the stopping time is 3 ps.

(2) For both ^{232}Th and ^{238}U the g factors for the high-spin states $(18-24)\hbar$ are higher than those for the lower states $(10-16)\hbar$. This follows from the observed increase of the mean precession angle $|\bar{\varphi}|$ for the transitions $14\rightarrow 12\rightarrow 10\rightarrow 8$ when these states are probing the higher-spin states in the ^{142}Nd runs. For the probe states precessions in the static field and γ decays in flight (see line shapes in Fig. 1) are negligible. In going from ^{127}I to ^{142}Nd beams $|\bar{\varphi}|$ increases from 159 ± 8 to 197 ± 11 mrad in ^{232}Th and from 219 ± 6 to 240 ± 8 mrad in ^{238}U, whereas the probed average spin of precession increases by $\sim 2.8\hbar$. From a statistical t test we find probabilities of only ~5% that the probe-state precessions are caused by constant g factors.

(3) Further evidence for proton alignment can be seen in the ^{142}Nd data only. With constant g factors one would expect a marked decrease of $|\bar{\varphi}|$ above $I=16\hbar$ because of γ decays in flight (see discussion in Ref. 16). The near constancy of the data indicates that the g factors are increasing with spin and compensate for the effect of finite lifetimes.

(4) The g factors for the lower $[(10-16)\hbar]$ states in ^{238}U are significantly higher than those in ^{232}Th since it appears unlikely that the large change in $|\bar{\varphi}|$ from 159 to 219 mrad can be ascribed to an increase in the TMF on increasing Z by ~2%.

The qualitative features of the g factors are in agreement with recent cranked shell-model calculations.[8-10] The calculations indicate that the interaction V between the ground band and the lowest $j_{15/2}$ quasineutron band is at a maximum at $N=142$, and near a minimum at $N=146$, while V between the ground band and the lowest $i_{13/2}$ quasiproton band is near a maximum for both $Z=90$ and 92. Thus early neutron alignment is expected in $^{232}_{90}\mathrm{Th}_{142}$ but not in $^{238}_{92}\mathrm{U}_{146}$, while proton alignment is expected in both.

For a quantitative analysis we have followed Ref. 16 in calculating the precession angles for various trial values of the g factors, taking into account the initial populations and angular-correlation tensors, and the level lifetimes[6] up to the 26^+ level. For the TMF we have assumed the expression $B(v,Z)=aZv/v_0\exp(-\beta v/v_0)$, where v/v_0 is the recoil velocity in units of the Bohr velocity $v_0=c/137$. The parameters $a=27\pm 1.5$ T and $\beta=0.105\pm 0.020$ were determined for $Z=64$ and 69 recoils.[15] The heavy-ion stopping powers were derived as described in Ref. 16 and are in excellent agreement with recent experiments[18] using 0.6–1.4 MeV/A ^{238}U beams. The dashed lines in the middle panels of Fig. 2 are fits to the ^{127}I data sets assuming constant g factors. The values are $g(^{232}\mathrm{Th})=0.28\pm 0.02$ and $g(^{238}\mathrm{U})=0.37\pm 0.02$, where only statistical errors are quoted. The differences in g are larger than would be expected in these well-deformed nuclei. Furthermore, the precession angles observed with ^{142}Nd beams are significantly above the dashed lines.

More reasonable fits to the data are obtained when rotation alignment effects are included on the basis of the conclusions given above, i.e., under the assumptions of proton alignment in ^{238}U (see also Ref. 7) and a combination of both proton and neutron alignment in ^{232}Th. Each unit of aligned proton spin adds an amount $(g_i^p-g_R)/I\sim 0.9/I$ (Ref. 19) to the constant rotational g factor g_R, whereas each unit of aligned neutron spin subtracts $(g_i^n-g_R)/I\sim -0.5/I$ (Ref. 19) from it. The aligned spins i can be estimated from the difference between the experimental spins and those of a smooth reference band.[2,7]

The set of g factors $g(I)$ represented by solid lines in the lower panels of Fig. 2 is one of several similar ones that are in good agreement with the precession data. It implies rotational g factors, $g_R(^{232}\mathrm{Th})=0.30\pm 0.02$ and $g_R(^{238}\mathrm{U})=0.32\pm 0.02$, that are reasonably similar. Our analysis suggests that, to an estimated total uncertainty of 40%, the aligned proton spin increases with I in both nuclei, under the assumption of a value of $i_p\sim 2.8\hbar$ at $I=20\hbar$, whereas the aligned neutron spin reaches a value $i_n\sim 1.6\hbar$ at $I=16\hbar$ in ^{232}Th.

These aligned spins are possibly larger than those derived from the experimental spins by using adopted reference bands. In ^{238}U we find a factor of 2.5 ± 1.0 over the proton alignment $i_p(20^+) = (1.1 \pm 0.5)\hbar$ obtained in Ref. 7.

In summary, we have observed extremely large transient field effects for actinide recoils in single crystals of ferromagnetic Gd. From a comparison of accurate precession angles for probe-state transitions which sample g factors in two different spin regions, we find evidence for the onset of proton alignment at spins $I = (18-24)\hbar$ in both ^{232}Th and ^{238}U, and for partial neutron alignment below $I = 16\hbar$ in ^{232}Th. These qualitative findings are independent of details of the TMF, of the static field, and of the level lifetimes. They demonstrate the importance of high-j intruder orbitals for yrast states in the actinides.

The authors are indebted to H. Folger, H. Klemm, and H. Krieger for the preparation of multilayer targets. Two of us (O.H. and L.G.) wish to thank the Max-Planck-Institut für Kernphysik, Heidelberg, for generous hospitality and support. One of us (L.G.) is an A. v. Humboldt Fellow.

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[1]F. S. Stephens, Rev. Mod. Phys. 47, 45 (1975).

[2]R. Bengtsson and S. Frauendorf, Nucl. Phys. A314, 27 (1979), and 327, 139 (1979); R. Bengtsson, J. Phys. C 10, 84 (1980).

[3]A. Faessler, M. Ploszajczak, and K. R. Sandhya Devi, Nucl. Phys. A301, 529 (1978); A. Faessler, J. Phys. C 10, 143 (1980).

[4]R. B. Piercey *et al.*, Phys. Rev. Lett. 46, 415 (1981).

[5]H. Ower *et al.*, J. Phys. C 10, 102 (1980).

[6]E. Grosse *et al.*, Phys. Scr. 24, 337 (1981); R. P. de Vito *et al.*, to be published.

[7]R. S. Simon *et al.*, Z. Phys. A 298, 121 (1980).

[8]J. L. Egido and P. Ring, to be published.

[9]M. Diebel and U. Mosel, to be published.

[10]S. Frauendorf and R. S. Simon, Gesellschaft für Schwerionenforschung Report No. 80-25, 1980 (to be published.

[11]R. R. Borchers *et al.*, Phys. Rev. Lett. 20, 424 (1968).

[12]N. Benczer-Koller, M. Hass, and J. Sak, Ann. Rev. Nucl. Part. Sci. 30, 53 (1980).

[13]H. R. Andrews *et al.*, Phys. Rev. Lett. 45, 1835 (1980).

[14]G. Seiler-Clark, D. Pelte, A. Balanda, H. Emling, E. Grosse, R. Kulessa, D. Schwalm, M. Hass, G. J. Kumbartzki, and K. H. Speidel, Gesellschaft für Schwerionenforschung Annual Report No. GSI 81-2, 1980 (unpublished), p. 45.

[15]O. Häusser, Hyperfine Interact. 9, 19 (1981).

[16]O. Häusser *et al.*, Nucl. Instrum. Methods 196, 539 (1980).

[17]A. Winther and J. de Boer, *Coulomb Excitation* (Academic, New York, 1966), p. 303.

[18]H. Geissel, Y. Laichter, W. F. W. Schneider, and P. Armbruster, Gesellschaft für Schwerionenforschung Annual Report No. GSI 81-2, 1980 (unpublished), p. 139; H. Geissel, private communication.

[19]S. Frauendorf, Phys. Lett. 100B, 219 (1981).