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Onset of collectivity in the ground-state band of ^{50}Cr

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Transient field precessions of the first excited states in ^{50}Cr have been measured. The states were excited by the inverse ^{12}C(^{40}Ca, $2p$)^{50}Cr reaction and the recoil nuclei traversed a thick gadolinium foil, where they experienced the rotation. The observed precessions, for the $2^+, 4^+, 6^+, 8^+$ states of the ground-state band, were equal within experimental error indicating these states have g factors similar to that of the 2^+ state value of 0.55 ± 0.10 measured previously. This feature is contrary to the predictions of the shell model and suggests a higher collectivity for the ground-state band. Limited results were also obtained for the cross conjugate nucleus ^{46}Ti supporting this conclusion.

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The spectroscopy of fp-shell nuclei from ^{40}Ca to ^{56}Ni has provided clear tests for shell model calculations and effective interactions. While most of these nuclei are described rather well by the model, the accumulated experimental evidence [1–5] supports a more collective trend in the middle of the shell from ^{46}Ti to ^{50}Cr. The most recent work by Cameron *et al.* [1] suggests that the region of collectivity is much more limited and is confined to within one nucleon middle of shell at ^{48}Cr, while g factors of the first excited states of ^{50}Cr and ^{46}Ti measured previously [6–9] cannot differentiate between collective and shell model structures. To elucidate the situation we have attempted to measure the magnetic moment properties of ^{50}Cr and ^{46}Ti as a function of spin, by the transient field technique. The variation of g factor with spin given by the $(f_{7/2})^n$ or the $(f_{7/2})^{n-1}$ $(p_{3/2}, f_{5/2}, p_{1/2})$ shell model is clearly different (Fig. 1) from the behavior associated with collective motion [9].

The measurements were performed by adopting the conventional transient field method [10] and by utilizing, as an excitation process, the inverse reaction ^{40}Ca + ^{12}C, which populates states in the residual nuclei via simple decay patterns (Fig. 2). The population of individual states forms a critical element in the application of transient fields to magnetic moment measurements and is discussed in some detail in our recent papers on ^{39}K [11] and ^{49}Cr [12]. Specifically for ^{50}Cr it was known [13] that for heavy ion (HI, $np\gamma$) reactions, high spin states up to spin $J^+ = 12^+$ are selectively populated. Moreover, from neighboring nuclei, it was known [11,12,14] that this population to medium spin states is fast.

The details of this experiment have been described in a recent publication [12] in which g-factor results for ^{49}Cr were discussed. Our setup has also been outlined before [15] but we will present here the features particular to this work. The experiment was designed to observe the integral rotation of the gamma-ray angular correlation pattern due to the precessions of excited nuclei in the transient magnetic field, as the nuclei recoil in a polarized gadolinium foil where they also come to rest.

A gadolinium foil, thick enough for recoiling ions to stop in it, was prepared by rolling and subsequently annealing in vacuum at 600 °C. Its magnetization was measured as a function of field and temperature in a low temperature magnetometer and found to be 80% of the maximum, in the field of 0.12 T used in this experiment. A carbon layer of 500 μg/cm^2 was deposited on the surface of the gadolinium from the graphite-suspension spray.

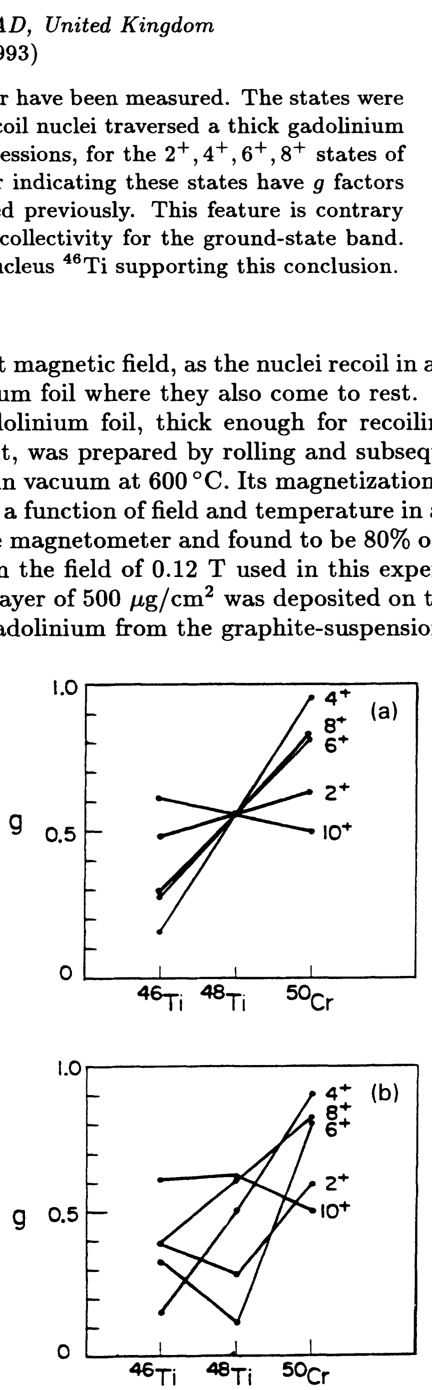

FIG. 1. Shell model calculations from Ref. [9], (a) $(f_{7/2})^n$; (b) $(f_{7/2})^{n-1}$, $(p_{3/2}, f_{5/2}, p_{1/2})$.

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The states of interest were populated at a beam energy of 140 MeV supplied by the 20 MV tandem accelerator at the Daresbury Laboratory. The choice of beam energy was a compromise between obtaining reasonable rates for the Ti and Cr nuclei but avoiding the production of ^{50}Mn which beta decays to the low-lying states of the ^{50}Cr nuclei. The beam current was limited to 5 nA to avoid any magnetization reduction due to the target heating.

Prompt γ rays (Fig. 3) from the various reaction channels were detected in four Compton-suppressed, 25% efficiency, Ge detectors. The detectors were positioned at ±60° and ±120° with respect to the beam, at a distance of 15 cm from the front of the Ge crystal.

Measurements to determine the slope of the γ-ray angular distribution $(1/W)dW/d\theta$ were carried out during the course of the experiment. For this purpose the detectors were moved from their original position by ±4° about the magnetic field axis, to mimic the rotation of the γ-ray distribution. An angular distribution measurement was performed to corroborate the slope measurements. The measurement was carried out with the four detectors placed at $75°, 135°, 195°$, and $255°$, the only technically accessible positions. An efficiency measurement with a Eu source performed at the end of the experiment allowed the yields from the detectors to be combined for the angular correlation fitting procedure. Results on the slopes, determined both through the effect and the angular correlation measurements, are compared in Table I. Results of the direct feeding determined via the angular correlation measurement are included in Fig. 2.

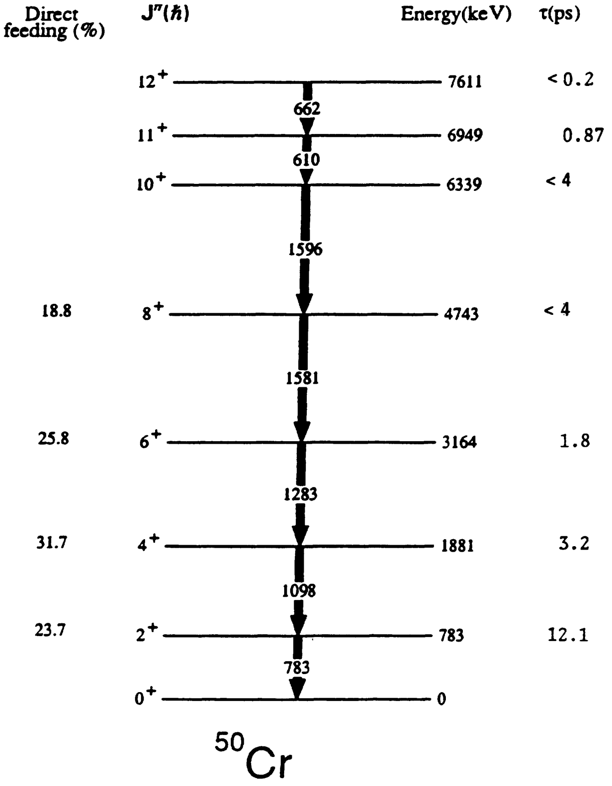

FIG. 2. Level scheme for ^{50}Cr. Only levels observed in the experiment are included. The lifetimes are from Ref. [5]. The values under the label "direct feeding" were obtained through the angular correlation measurement. In particular the measurement adopted for the 8^+ level represents not only the direct feeding of the level itself but also the cascades from higher levels.

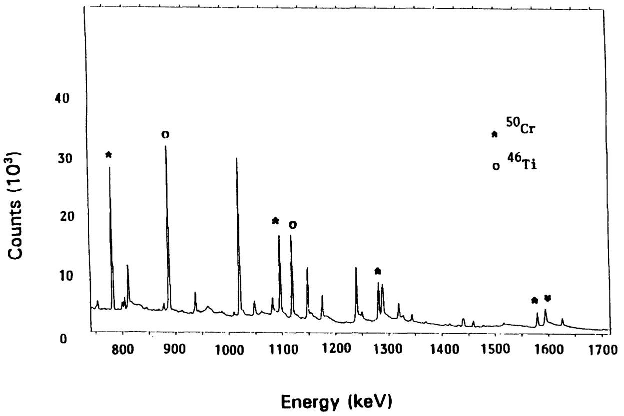

FIG. 3. A partial γ-ray spectrum from the detector at 60°.

Nuclear precession angles $\Delta\theta$ were deduced from the double ratios of adjacent pairs of detectors, defined by

$$\rho = \frac{N_i(\uparrow)}{N_i(\downarrow)}\frac{N_j(\downarrow)}{N_j(\uparrow)}\ , \tag{1}$$

where $N(\uparrow)$ refers to the counts in a γ-ray peak in the spectrum of the detector 1 with field "up." The rotation is then given by

$$\Delta\theta = \frac{1}{S(\theta)}\frac{\sqrt{\rho}-1}{\sqrt{\rho}+1}\ , \tag{2}$$

where $S(\theta) = (1/W)dW/d\theta$ is the logarithmic slope of the γ-ray distribution. The above analysis assumes that the feeding from the continuum states has been completed before the recoil enters the gadolinium. This is a reasonable assumption in light of the fast side-feeding times $[T_{\text{meas}}(^{49}\text{Cr}, 19/2) < 100$ fs$, T_{\text{meas}}(^{39}\text{K}, 11/2) < 130$ fs$, T_{\text{calc}}(^{41}\text{Ca}, 17/2) = 30\text{–}100$ fs$]$ measured previously [11,12,14] in neighboring nuclei. It should be noted, however, that side-feeding times are not known for ^{50}Cr itself.

Our experimental results are shown in Table II, together with other details of the measurement. Corrections due to the very small static field [16] experienced in gadolinium were negligible (the highest experienced rotation would be 0.7 mrad) and thus were not applied here. The only corrections up to 10%, which were applied, are due to Mn feeding. This means that the rotations shown

TABLE I. Slopes at 60°, obtained via an effect run and via an angular correlation run.

$J_i^\pi \to J_f$	S_{effect}	$S_{\text{ang. corr}}$
$2^+ \to 0^+$	0.68(3)	0.65(1)
$4^+ \to 2^+$	0.69(4)	0.64(2)
$6^+ \to 6^+$	0.67(6)	0.61(4)
$8^+ \to 6^+$	0.67(7)	0.68(3)

TABLE II. g factors, precessions, and slopes for some of the states obtained in the present experiment.

						Experiment		Theory	
Nucleus	$J_i^+ \to J_f^+$	τ (psec)	$(v/v_0)_{\text{in}}$	Slope (60°)	$\Delta\theta$ (mrad)	g_{previous} [a]	g_{present} [b]	g [c]	g [d]
^{50}Cr	$2^+ \to 0^+$	12.1(12)	7.8	0.68(3)	57.6(31)	0.55(10)	0.64(11)	+0.545	+0.48
	$4^+ \to 2^+$	3.2(4)		0.69(4)	51.4(40)		0.43(9)	+0.891	+0.48
	$6^+ \to 4^+$	1.8(4)		0.67(6)	57.4(61)		0.54(16)	+0.692	+0.48
	$8^+ \to 6^+$	< 4		0.67(7)	57.5(98)		0.54(9)	+0.760	+0.48
^{46}Ti	$2^+ \to 0^+$	6.5(7)	8.4	0.46(3)	46.0(40)	0.48(8)		+0.485	+0.48
	$4^+ \to 2^+$	2.6(3)		0.47(5)	53.0(70)			+0.155	+0.48

[a] Mean values from Refs. [6,9] for Cr and [7,8] for Ti.

[b] Obtained by modeling the time evolution of nuclei, see text.

[c] Shell model calculations, Ref. [9].

[d] $g = Z/A$.

in Table II represent average rotations of the precision of the level itself plus the precession accumulated from the higher levels. Levels contributing to these precessions are mainly the $2^+, 4^+, 6^+$, and 8^+ states as resulting from our feeding pattern measurement (see Fig. 2).

Observing the rotations shown in Table II, we can notice a striking similarity which should stem from the g-factor resemblance. Taking into account that the transient field rotation was experienced by all levels during the whole recoiling time of the ion (only the stopped part of the peaks was integrated so the rotation is independent of the lifetime of each level), we can form a mean rotation which equals $\Delta\theta_{\text{mean}} = 56 \pm 4$. If this value subsequently will be compared with a calculated one (see details of calculation in the next paragraph) of $\Delta\theta/g = 103 \pm 16$ mrad, it gives a g factor equal to 0.54 ± 0.10. The last value is in very good agreement with previous measurements concerning the 2^+ level magnetic moment (Table II).

An attempt was made to obtain individual g factors modeling [17] the time evolution of nuclei as they slowed down in the gadolinium foil. By using the Chalk River [18] strength of the field modified as before [12], the program starts by putting all the initial population in the continuum states, and calculates the precession accumulated by each state being passed to the next state by the γ decay. The g factors obtained by this procedure are shown in Table II. The general trend, although the quoted errors are large, is consistent with a constant g factor not far from the collective value, ~ 0.5. It should be mentioned, however, that the above calculation was performed under the following conditions concerning feeding times and field calibration.

Feeding times: It is assumed that the feeding from the continuum states has been completed before the recoil enters the gadolinium. That way side-feeding times were set equal to zero and the continuum g factor does not enter the analysis. The above assumption is supported by experimental evidence met in neighboring nuclei as explained in a previous paragraph.

Field calibration: The Chalk River parametrization applies to heavy nuclei and has not been extensively verified for the light mass region met in the present experiment. However, it was found previously [11,12] that this parametrization applies well in the $A \approx 40$–50 region if its strength is multiplied by a factor of 1.3 ± 0.2. The modification was adopted here and the parametrization was applied for Ti and Cr nuclei recoiling in a thick gadolinium foil with velocities in the range $v_0 \leq v \leq v_{\text{initial}}$. For lower velocities in the range $0 \leq v \leq v_0$, the field was set equal to zero. The above treatment of the experienced transient field by an ion recoiling in a thick ferromagnetic foil was approximated previously by comparing thin and thick foil experiments and is explained in detail in Refs. [17,19]. A cutoff velocity is also supported by x-ray measurements [20].

The $10^+, 11^+$, and 12^+ states were also excited in the present measurement; however, the analysis of the γ ray deexciting the 10^+ state (1596 keV) was obscured by other overlapping lines with the same energy, while the 11^+ and 12^+ states are very short lived and thus their rotation is not observable.

In ^{46}Ti, due to unresolved γ rays (1289 and 1598 keV), only the first two excited states were studied and their precessions were included in Table I. The conclusions are the same as for ^{50}Cr. However, it should be pointed out here that a strong side feeding leading to the 4^+ state from the decay of the $3^-, 4^-$, and 5^- states with unknown lifetime might alter the results for this state. If the lifetime of the feeder states is of the order of a

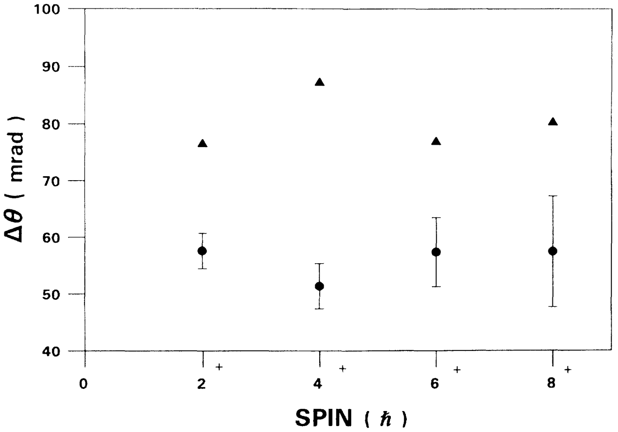

FIG. 4. Experimental and predicted rotations using shell model g factors (Table II).

few picoseconds and if a g factor of 0.5 is assumed for the continuum, the correction can be estimated. It was found not to exceed 1.5 mrad. Into the same context as before, if we form a mean of the rotations shown in Table II, $\Delta\theta_{\text{mean}} = 48 \pm 6$, we deduce a g factor of 0.51 ± 0.10, which compares well with previously measured values for the 2^+ state (see Table II).

The results are presented in an alternative way in Fig. 4, where our measured rotations are compared with predicted rotations assuming the shell model g factors of ^{50}Cr given in Table II. The most obvious difference here is that the mean of the predicted rotations is about 1.4 times larger than the experimental values. This is largely due to the high predicted g factors of the $4^+, 6^+$, and 8^+ states which of course contribute to the 2^+ rotation as well. The significance of the difference between the mean experimental and predicted rotations entirely depends on the calibration of the transient field in this experiment. However, if a similar analysis was performed for the ^{46}Ti yrast states, we would predict rotations of all states which would be less than half of the ^{50}Cr predictions. The similarity of, for example, the experimental 2^+ rotations in ^{46}Ti and ^{50}Cr then indicates that, independent of the field calibration, the g factors of the states contributing to the rotation (in this case this includes $4^+, 6^+$, and 8^+ states) are similar in the two nuclei and therefore in contradiction to the shell model predictions.

Summarizing, transient field rotations were measured for several excited states of the ground-state band in ^{50}Cr. An attempt was made to determine the precessions of the ^{46}Ti ground-state band. Due mainly to unresolved gamma rays, only the rotations of the first two excited states were determined. As it is seen from Table II, all the obtained values for both nuclei are consistent with a constant rotation of $\approx 54 \pm 5$ mrad. This result is contrary to the shell model predictions [9] where g factors varying with spin are predicted for both ^{50}Cr and ^{46}Ti. Therefore the present results suggest an onset of collectivity near the middle of the $f_{7/2}$ shell, consistent with previous findings [2–5] on other nuclear properties.

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