Stringent Tests of Shell Model Calculations in fp Shell Nuclei ^{46,48}Ti and ^{50,52}Cr from Measurements of g Factors and $B(E2)$ Values

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Measurements of magnetic moments and lifetimes of 2_1^+ and 4_1^+ states of ^{46,48}Ti and ^{50,52}Cr were performed with high accuracy via projectile Coulomb excitation and the technique of transient magnetic fields. The high quality of the data allows for the first time to establish stringent constraints on large scale shell model calculations. Whereas the global behavior of the data is well explained by full fp shell model calculations, distinct deviations in the g factors and $B(E2)$ values of ^{46,48}Ti from theoretical predictions can be attributed to excitations of the ^{40}Ca core. This suggestion is supported by recent Monte Carlo calculations which provide evidence that ^{48}Ca is a better inert core.

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Magnetic moments are most sensitive to single particle components in the wave function of nuclei as well as to their interplay with collective degrees of freedom. Because of the different sign of the spin g factors of protons and neutrons ($g_s^p = 5.586$ and $g_s^n = -3.826$) measurements of g factors of excited states enable the determination of their microscopic structure. The combination of these measurements with those of $M1$ and $E2$ transition probabilities provides stringent tests of theoretical models. The most comprehensive shell model calculations available are those of sd shell [1] and fp shell [2–4] nuclei.

In order to distinguish between results of different nuclear models, g factors must be determined with high accuracy as was demonstrated by recent measurements on Se isotopes [5]. The main purpose of the present experiments was to determine g factors of excited states of four fp shell nuclei, ^{46,48}Ti and ^{50,52}Cr close to shell closures at $Z = 20$ and $N = 28$ in order to constrain unequivocally the nucleon-nucleon interaction used in the microscopic calculations. The measurements of $g(2_1^+)$ were carried out with much higher precision than obtained previously [6,7], and in addition, g factors of 4_1^+ states were determined for the first time.

This goal was achieved by the use of projectile Coulomb excitation in inverse kinematics in combination with the transient magnetic field (TF) technique [5,8]. This novel approach has been developed over the last five years and provides, for the first time, highly accurate and reliable data. The main merit of this version of Coulomb excitation of an energetic beam of nuclei by lighter target nuclei consists in the high efficiency of detection of deexcitation γ rays in coincidence with forward recoiling target nuclei. In addition to the kinematic focusing in the beam direction, the projectile ions have high velocities which are favorable since the transient field strength generally increases with ion velocity. Furthermore, the same target can be used for several different beams obviating the systematic errors associated with the difficult preparation of different targets in the traditional technique of target excitation. These characteristics have also the advantage of being appropriate for experiments with low intensity beams of radioactive nuclei.

In the present experiments, beams of isotopically pure ^{46}Ti, ^{48}Ti, ^{50}Cr, and ^{52}Cr, provided in their natural abundance by the ion source of the Tandem accelerators at Cologne and Munich, with intensities of $\sim$1 pnA and energies between 110 and 120 MeV, were Coulomb excited by natural carbon. In all nuclei, the first 2^+ and 4^+ states (Fig. 1) were mainly excited; the γ rays from the deexcitation of the ^{12}C($2_1^+ \rightarrow 0_1^+$; 4.43 MeV) target nuclei were weak and therefore contributed only a nondisturbing Compton background to the spectra, an essential feature for measuring the ($4_1^+ \rightarrow 2_1^+$) transitions.

The multilayered target consisted of a 0.75 mg/cm^2 $^{\text{nat}}$C layer over 3.6 mg/cm^2 of gadolinium vacuum deposited on a 1 mg/cm^2 tantalum foil backed by a 3.6 mg/cm^2 Cu layer. The beam ions, excited in the C layer, traversed the ferromagnetic gadolinium layer where they experienced the transient field and were finally stopped in the hyperfine interaction free Cu layer. For the nuclear spin precessions the target was cooled to liquid nitrogen temperature and magnetized to saturation by an external field of 0.06 T. The γ rays emitted from the excited states were measured in coincidence with the carbon ions using 12.7 cm $\times$ 12.7 cm NaI(Tl) and 9 cm $\times$ 9 cm BaF_2 scintillators.

A Ge detector at 0° to the beam direction served as monitor for contaminant lines and for measuring the nuclear lifetimes by the Doppler-shift–attenuation method (DSAM). Ions were registered in a 100 μm thick Si counter placed at 0° and subtending an angle of $\pm 20°$.

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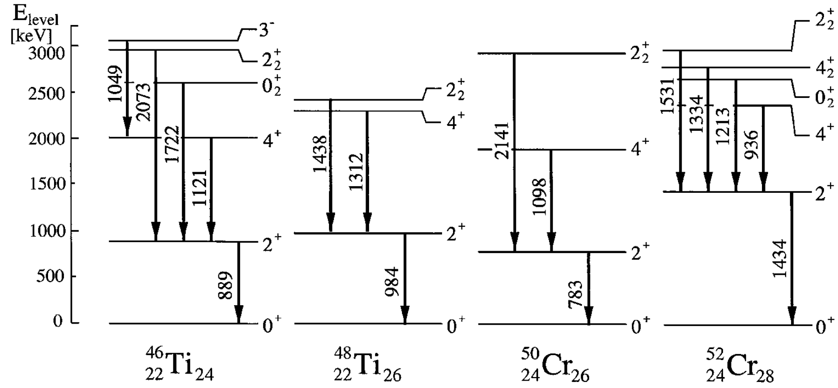

FIG. 1. Low-lying states of ^{46,48}Ti and ^{50,52}Cr with relevant γ transitions.

The beam was stopped in a tantalum foil placed behind the target.

Particle-γ angular correlations W(θ_γ) were measured for the ($2_1^+ \rightarrow 0_1^+$) and ($4_1^+ \rightarrow 2_1^+$) transitions in each nucleus in order to determine the logarithmic slopes, $S = \frac{1}{W(\theta_\gamma)} \frac{dW(\theta_\gamma)}{d\theta_\gamma}$ in the rest frame of the γ emitting nuclei at the angle θ_γ where the spin precession measurements were carried out. Precession angles Φ, derived from double ratios R of coincident counting rates with an external field applied perpendicular to the γ-detection plane, alternately in the "up" and "down" directions, are given by [9]

$$\Phi^{\exp} = \frac{1}{S} \frac{\sqrt{R} - 1}{\sqrt{R} + 1} = g \frac{\mu_N}{\hbar} \int_{t_{\rm in}}^{t_{\rm out}} B_{\rm TF}(v_{\rm ion}(t)) e^{-t/\tau} \, dt \,, \tag{1}$$

where g is the nuclear g factor of the state of interest and $B_{\rm TF}$ is the transient field acting for the time ($t_{\rm out} - t_{\rm in}$) during which the ions traverse the gadolinium layer; the exponential accounts for the nuclear decay of the excited state with lifetime τ. The data, relevant to all four nuclei, are summarized in Table I.

The g factors (Table II) were derived from the experimental precessions, $\Phi^{\exp}$, by determining the effective transient field strength on the basis of the linear parametrization [10]:

$$B_{\rm TF}(v_{\rm ion}) = G(\text{beam}) B_{\rm lin} \tag{2}$$

with

$$B_{\rm lin} = a(\text{Gd}) Z_{\rm ion} v_{\rm ion}/v_0 \,, \tag{3}$$

where the strength parameter a(Gd) = 17(1) T [11,12], $v_0 = e^2/\hbar$, and $G = 0.83(4)$ is the attenuation factor accounting for dynamic demagnetization of gadolinium induced by the ion beam. The magnitude and the dependence of the attenuation factor G on relevant parameters such as velocity, stopping power, and intensity of the beam ions, as well as on the electron orbitals of the excited beam ions, were determined in several experiments carried out in conditions very similar to those of the present work [11]. The parametrization was reconfirmed through a precession measurement on the 2_1^+ state of ^{56}Fe ($g = 0.61(8)$ [6]) performed with the same target and under the same kinematic conditions as those that pertain to the current experiment. An attenuation factor $G = 0.77(10)$ was obtained, in agreement with the adopted value.

As seen in Table II, the uncertainty in the transient field strength contributes mainly to the error in $g(2_1^+)$, whereas the statistical error in the measured precession angle dominates the uncertainty in the g factors of the 4_1^+ states. In addition, a small correction due to feeding from the 4_1^+ state was included in the analysis of $g(2_1^+)$. Beam bending effects were negligible due to effective shielding of the stray magnetic field. Further experimental details will be presented in a forthcoming more extensive paper [12].

In addition, the lifetimes of all states discussed above have been measured simultaneously using the DSAM technique with the 0° Ge detector. Maximum ion velocities between $0.035c$ and $0.044c$ implied high sensitivity for lifetimes of the order of picoseconds. The Doppler-broadened line shapes of the emitted γ-ray lines were fitted for the known reaction kinematics applying stopping powers to Monte Carlo simulations including the second order

TABLE I. Measured logarithmic slopes of the angular correlation at $|\theta_\gamma| = 65°$, angular precessions, calculated precession based on the linear parametrization of the transient field for the 2_1^+ and 4_1^+ states in ^{46,48}Ti and ^{50,52}Cr. The $\Phi^{\rm lin}/g$ values were calculated using Eqs. (1)–(3) with the appropriate parameters.

	I^π	E_x (MeV)	$\lvert S(\theta_\gamma = 65°)\rvert$	$\Phi^{\exp}$ (mrad)	$\Phi^{\rm lin}/g$ (mrad)
^{46}Ti	2^+	0.889	2.158 (26)	14.56 (35)	29.34 (141)
	4^+	2.010	0.769 (84)	14.56 (426)	25.07 (121)
^{48}Ti	2^+	0.984	2.230 (5)	11.42 (14)	29.16 (141)
	4^+	2.296	0.951 (63)	12.29 (281)	22.61 (109)
^{50}Cr	2^+	0.783	2.275 (29)	21.04 (33)	33.97 (164)
	4^+	1.881	0.765 (43)	24.00 (391)	30.93 (149)
^{52}Cr	2^+	1.434	2.387 (39)	28.60 (66)	23.72 (114)
	4^+	2.370			

TABLE II. Measured g factors and lifetimes with deduced $B(E2)$ values in Weisskopf units, and full fp shell model (FSM) calculations for the 2_1^+ and 4_1^+ states in ^{46,48}Ti and ^{50,52}Cr.

	I^π	τ (ps) [17–20]	τ (ps) Present	$B(E2)$ (W.u.) Expt.	$B(E2)$ (W.u.) FSM	g Expt.	g FSM
^{46}Ti	2^+	7.4 (6)	8.1 (4)	18.5 (9)	11.7	0.496(27)	0.285
	4^+	2.4 (2)	2.3 (2)	20.5 (18)	15.7	0.58 (17)	0.244
^{48}Ti	2^+	6.2 (4)	5.7 (2)	15.0 (5)	9.1	0.392(19)	0.211
	4^+	1.8 (4)	1.1 (1)	18.4 (17)	13.7	0.54 (13)	0.472
^{50}Cr	2^+	12.8 (7)	13.2 (4)	19.2 (6)	18.3	0.619(31)	0.568
	4^+	3.2 (4)	3.2 (7)	14.6 (32)	26.0	0.78 (13)	0.742
^{52}Cr	2^+	1.02(4)	1.13(3)	10.3 (3)	12.4	1.206(64)	1.172
	4^+	1.5 (5)	9.6^{+50}_{-24}	10.3 (34)	11.7		1.230

Doppler effect as well as the finite size and energy resolution of the Ge detector. The feeding from higher states was also taken into account. The computer code LINESHAPE [13] was used in the analysis. The measured lifetimes and deduced $B(E2)$ values are summarized in Table II. Significant differences between the present measurements and values quoted in the literature are found, in particular, for ^{48}Ti(4_1^+) and ^{52}Cr(4_1^+).

The g factor and $B(E2)$ results were compared with full fp shell model (FSM) calculations (Table II) carried out with the computer code ANTOINE [14] and using a modified version of the Kuo-Brown interaction KB3 [2]. It is noteworthy that the present results differ considerably from the earlier calculations [15] which used a drastically truncated model space due to the computer limitations of the time.

The general trend of the precise measurements of $g(2_1^+)$ shows a small but significant decrease from ^{46}Ti to ^{48}Ti and a subsequent rise towards ^{52}Cr where the $N = 28$ shell is closed. This trend is well reproduced by the calculations (Fig. 2). The pattern observed is clearly associated with excitations of nucleons from the $0f_{7/2}$ orbit to the $1p_{3/2}$, $0f_{5/2}$, and $1p_{1/2}$ orbits which break the particle-hole symmetry of the cross-conjugate nuclei ^{46}Ti and ^{50}Cr [15].

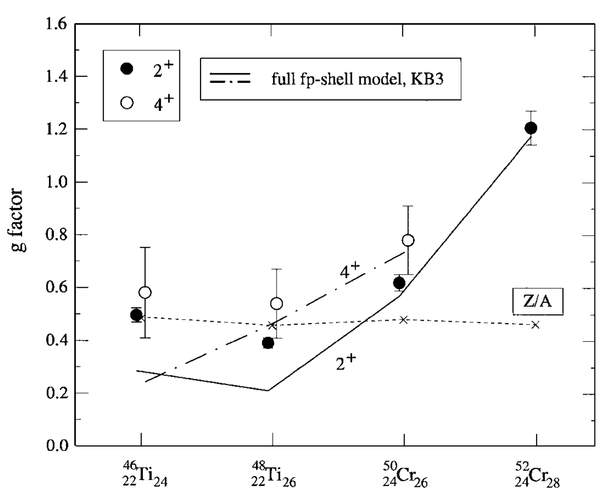

FIG. 2. Experimental g factors of the first 2^+ and 4^+ states of Ti and Cr nuclei are compared to the full fp shell model calculations, represented by solid and dot-dashed lines, respectively, and the collective value Z/A (dashed curve).

The most interesting, and indeed surprising, results emerge when the full fp shell calculations are compared with the new experimental data (Table II and Fig. 2). In the upper half of the $f_{7/2}$ shell, the g factors and the $B(E2)$ values of ^{50,52}Cr agree very well with theory. The prediction that the g factors should be large is confirmed. The unexpected results show up when the theory is applied to ^{46,48}Ti. One would expect *a priori* that the full fp shell calculations would better represent the collectivity of these nuclei. Hence, the KB3 interaction is most likely deficient in this regard, and excitations of the ^{40}Ca core must be included. It has long been recognized that ^{40}Ca is not as good a closed shell nucleus as ^{48}Ca. This suggestion is also supported by recent Monte Carlo shell model calculations which favor ^{48}Ca as a better inert core [16]. There are low-lying, highly deformed states in ^{40}Ca, ^{41}Ca, ^{42}Ca, and other neighboring nuclei which could admix with sufficient probability into the 2_1^+ and 4_1^+ states of ^{46,48}Ti.

The importance of including the whole fp shell in the description of the structure of these nuclei is further put in evidence by the calculations of $g(I)$ for ^{50}Cr [21] in which an increasing number t of valence particles is excited from the $0f_{7/2}$ orbit to the other fp shell orbits (Fig. 3). The best agreement between theory and the present data is achieved for $t \geq 2$. The same conclusion has been drawn by Nakada *et al.* [22] for describing the structure of heavier fp shell nuclei.

Figure 3 also displays the former g factor measurements in ^{50}Cr [7], which disagreed strongly with microscopic calculations. The striking discrepancy no longer exists for the new data. The previous measurements were carried out on nuclei excited by a fusion evaporation reaction. The analysis of the complex feeding pattern typical for this type of reaction often prevents a precise determination of the precession of the particular nuclear state in which the nucleus finds itself as it traverses the gadolinium foil. This uncertainty is, however, absent in Coulomb excitation measurements.

In summary, although the data for low-lying states of the four fp shell nuclei studied show an overall agreement

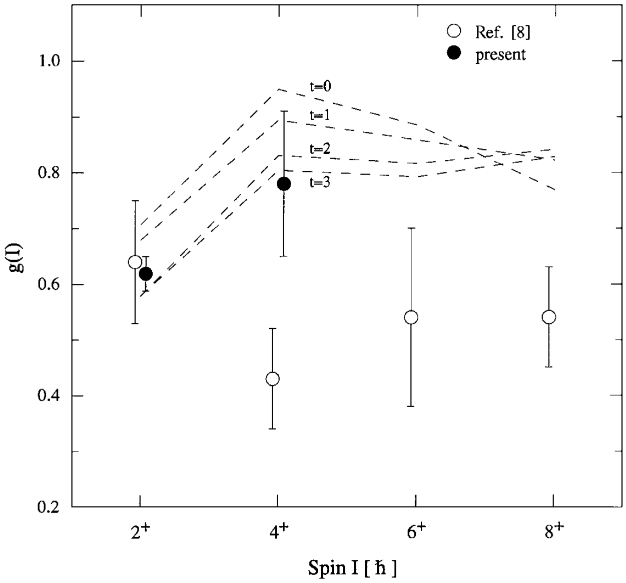

FIG. 3. Comparison of experimental g factors for ^{50}Cr and shell model calculations which allow t valence nucleons to lie outside the $0f_{7/2}$ shell [21].

with full fp shell model calculations, there are surprisingly large discrepancies in the g factors of these states and the $B(E2)$ values of the respective transitions. Whereas the data for the ^{50,52}Cr nuclei are in good agreement with theory, the experimental g factors for ^{46,48}Ti are closer to the collective value of Z/A. The remaining deviations are attributed to shortcomings in the theory which ignores contributions from possible excitations of the sd shell core. This paper shows that high precision g factors reveal fine details of the structure of short-lived nuclear states which otherwise are hardly perceptible. Moreover, the successful measurement of the g factor of the very weakly excited 4_1^+ states in the present experiments emphasizes the potential of the experimental technique. This experience gives confidence that the technique will be applicable to future experiments with radioactive beams.

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[1] B. A. Brown and B. H. Wildenthal, Annu. Rev. Nucl. Part. Sci. **38**, 29 (1988).
[2] A. Poves and A. Zuker, Phys. Rep. **70**, 235 (1981).
[3] E. Caurier, J. L. Egido, G. Martinez-Pinedo, A. Poves, J. Retamosa, L. M. Robledo, and A. P. Zuker, Phys. Rev. Lett. **75**, 2466 (1995).
[4] G. Martinez-Pinedo, A. Poves, L. M. Robledo, E. Caurier, F. Nowacki, J. Retamosa, and A. Zuker, Phys. Rev. C **54**, R2150 (1996).
[5] K.-H. Speidel, N. Benczer-Koller, G. Kumbartzki, C. Barton, A. Gelberg, J. Holden, G. Jakob, N. Matt, R. H. Mayer, M. Satteson, R. Tanczyn, and L. Weissman, Phys. Rev. C **57**, 2181 (1998).
[6] P. Raghavan, At. Data Nucl. Data Tables **42**, 189 (1989).
[7] A. A. Pakou, J. Billowes, A. W. Mountford, and D. D. Warner, Phys. Rev. C **50**, 2608 (1994).
[8] N. Benczer-Koller, M. Hass, and J. Sak, Annu. Rev. Nucl. Part. Sci. **30**, 53 (1980).
[9] K.-H. Speidel, G. Jakob, H. Busch, U. Grabowy, A. Gohla, J. Gerber, and H. Trinkaus, Nucl. Instrum. Methods Phys. Res., Sect. B **122**, 84 (1997).
[10] J. L. Eberhardt and K. Dybdal, Hyperfine Interact. **7**, 387 (1979).
[11] G. Jakob, J. Cub, K.-H. Speidel, S. Kremeyer, H. Busch, U. Grabowy, A. Gohla, O. Jessensky, and J. Gerber, Z. Phys. D **32**, 7 (1994), and references therein.
[12] R. Ernst, K.-H. Speidel, O. Kenn, U. Nachum, J. Gerber, P. Maier-Komor, N. Benczer-Koller, G. Jakob, G. Kumbartzki, and L. Zamick (to be published).
[13] J. C. Wells and N. R. Johnson, computer code LINESHAPE, ORNL, 1994.
[14] E. Caurier, computer code ANTOINE, Strasbourg, 1989.
[15] A. Pakou, R. Tanczyn, D. Turner, W. Jan, G. Kumbartzki, N. Benczer-Koller, Xiao-Li Li, Huan Liu, and L. Zamick, Phys. Rev. C **36**, 2088 (1987).
[16] T. Otsuka, M. Honma, and T. Mizusaki, Phys. Rev. Lett. **81**, 1588 (1998).
[17] T. W. Burrows, Nucl. Data Sheets **68**, 1 (1993).
[18] T. W. Burrows, Nucl. Data Sheets **75**, 1 (1995).
[19] L. K. Peker, Nucl. Data Sheets **68**, 271 (1993).
[20] H. Junde, Nucl. Data Sheets **71**, 659 (1994).
[21] L. Zamick and D. C. Zheng, Phys. Rev. C **54**, 956 (1996).
[22] H. Nakada, T. Sebe, and T. Otsuka, Nucl. Phys. **A571**, 467 (1994).