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Core polarization in the light of new experimental g factors of fp shell, $N=28$, isotones

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Precise experimental g factors of the first 2^+ states of ^{50}Ti, ^{52}Cr, and ^{54}Fe have been measured. They differ markedly from the g factors of the $(7/2)^-$ ground states of the odd-mass neighbors. The experimental results show that the g factors, $g(2_1^+)$ and $g((7/2)^-)$, lie approximately on straight lines as a function of Z albeit with different slopes. Shell model calculations were performed in which up to t nucleons were excited from the $f_{7/2}$ shell. The data are reproduced by calculations using the FPD6 interaction with $t=1$. However, the slope flattens out in the calculations with higher t. The sign of a key matrix element which allows for $f_{5/2}$ admixture is *positive* for the FPD6, *zero* for the KB3, and *negative* for the FPY interactions, respectively, indicating that a better understanding of the effective interaction in this region is needed.

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Core polarization is an effect which involves the excitation of an otherwise closed shell or inert core by valence nucleons. In general, such interactions result in a quenching of the magnetic moment of nuclear states, a pattern which has been observed in many g factor measurements [1,2]. This phenomenon was predicted by Arima and Horie [3–5] in their early work on core polarization, in particular with respect to the $N=28$ isotones of fp shell nuclei. These span a region (above doubly closed shell ^{40}Ca) from scandium ($^{49}_{21}$Sc) to cobalt ($^{55}_{27}$Co) where the ground state of the odd-proton members have spin and parity $(7/2)^-$ corresponding to a $f_{7/2}^n$ proton configuration. In the pure shell model, all configurations $[(7/2)^-]^n$ of the $N=28$ isotones should have the same g factor. If the bare values for the proton $g_l=1$ and $g_s=5.586$ are used, this g factor is $g(\pi f_{7/2})=1.655$, the Schmidt value. This result holds specifically for the $I^\pi=(7/2)^-$ ground states of the odd A nuclei and for the $I^\pi=2_1^+$ states of the even-even nuclei. Any deviations from this result would provide evidence for core polarization in terms of configuration mixing and/or the presence of meson exchange currents.

The very precise experimental g factors of the $(7/2)^-$ ground states of ^{51}V, ^{53}Mn, and ^{55}Co [6] in fact exhibit g factors significantly lower than the Schmidt value which, furthermore, differ from each other. As emphasized by Arima and Horie, core polarization accounts for both these features [3,4]. Their first order perturbation theory calculations yield a substantial quenching of these g factors whose magnitudes increase linearly with the number of proton holes in the $f_{7/2}$ shell. As a consequence, the g factor of ^{55}Co (with one proton hole) is predicted to be smaller than that of ^{51}V (with five proton holes), as has been experimentally confirmed.

Experimental data exist for the g factors of the first 2^+ states of the $N=28$ isotones ^{54}Fe [7] and ^{52}Cr [8]. In both cases, the g factors are substantially lower than those of their odd-mass neighbors. In order to understand this behavior the g factor of the remaining isotone, ^{50}Ti(2^+) with two protons or six proton holes in the $f_{7/2}$ shell, has been remeasured. In addition, the accuracy of the ^{54}Fe(2_1^+) g factor has been improved by a factor of 3–4 over the published values [6], via a new measurement. These new experimental data were critically needed to determine unambiguously the differences between the very precise g factors of the odd A nuclei and those of their even-even neighbors.

Beams of isotopically pure ^{50}Ti and ^{54}Fe, provided by the ion source of the Tandem accelerators at Cologne and Munich with an intensity of 1 pnA and an energy of 110 MeV and 130 MeV, respectively, were Coulomb excited by natural carbon to their first 2^+ states (^{50}Ti: $E_x=1.553$ MeV, ^{54}Fe: $E_x=1.408$ MeV). The same multilayered target (C-Gd-Ta-Cu) used in the former measurements for the other Ti and Cr isotopes [8,9] was also employed in the present experiments; in fact, all experimental conditions with respect to the transient field strength in the magnetized gadolinium layer were similar to those that pertain to the ^{46,48}Ti isotopes. In addition, the lifetimes of the 2_1^+ states were also determined by the Doppler-shift attenuation method with a Ge detector located at 0° with respect to the beam direction.

The g factors and lifetimes of the 2_1^+ states obtained for ^{50}Ti and ^{54}Fe using the transient field strength and procedures described in Refs. [8,9], are in good agreement with those of Refs. [6,7,10] but are more accurate by factors of 3–5 (see Table I). In addition, the transient field relevant to

TABLE I. Summary of measured logarithmic slopes of the particle-γ angular correlations S at $\theta_\gamma=\pm 65°$, and angular precessions Φ^{exp}, together with the deduced g factors and lifetimes τ.

Nucleus	$\lvert S(65°)\rvert$	Φ^{exp} [mrad]	g	τ [ps]
^{50}Ti	2.258(30)	33.8(8)	1.444(77)	1.62(7)
^{54}Fe	2.237(62)	29.6(10)	1.049(60)	1.09(3)

TABLE II. Comparison of the measured g factors of $N=28$ isotones and the results of calculations where *only one* particle is excited from $f_{7/2}$ to $p_{3/2}$, $f_{5/2}$, or $p_{1/2}$ orbits. Four different effective interactions were used. The calculated effective slopes $m_{I,eff}$ are compared with the experimental slopes obtained from a linear fit to the data. The last two lines represent the value of the key matrix element and of δg^{2^+}.

			g factor			
Nucleus		Exp.	FPD6	KB3	VHG	FPY
$I=(\frac{7}{2})^-$	^{49}Sc		1.469	1.562	1.562	1.674
	^{51}V	1.4710579(6)	1.437	1.487	1.482	1.571
	^{53}Mn	1.435(2)	1.400	1.432	1.423	1.475
	^{55}Co	1.378(1)	1.337	1.368	1.352	1.371
	$m_{\frac{7}{2}^-,eff}$	$-0.023(2)$	-0.025	-0.030	-0.032	-0.050
$I=2^+$	^{50}Ti	1.444(77)	1.484	1.543	1.534	1.439
	^{52}Cr	1.206(64)	1.335	1.456	1.425	1.473
	^{54}Fe	1.049(60)	1.162	1.345	1.297	1.490
	$m_{2^+,eff}$	$-0.096(20)$	-0.080	-0.050	-0.059	$+0.013$
	$\langle \frac{7}{2}\frac{7}{2}\vert V\vert \frac{7}{2}\frac{5}{2}\rangle_{I=2,T=1}$		0.280	0.000	0.000	-0.427
δg^{2^+}			0.116	0.000	0.000	-0.112

these ions was further calibrated through the remeasurement of the known g factor of ^{56}Fe(2_1^+) in conditions similar to those of the current measurements. Further experimental details are described in [9].

The present experimental g factors of all odd and even A, $N=28$ isotones are displayed in Table II and Fig. 1 (see also [6]). It must be stressed that *relative* values of the g factors and the corresponding slopes of g vs Z obtained in these experiments are less sensitive to the transient field parametrization than the absolute values. Table II also presents selected theoretical calculations of the g factors obtained with four different interactions.

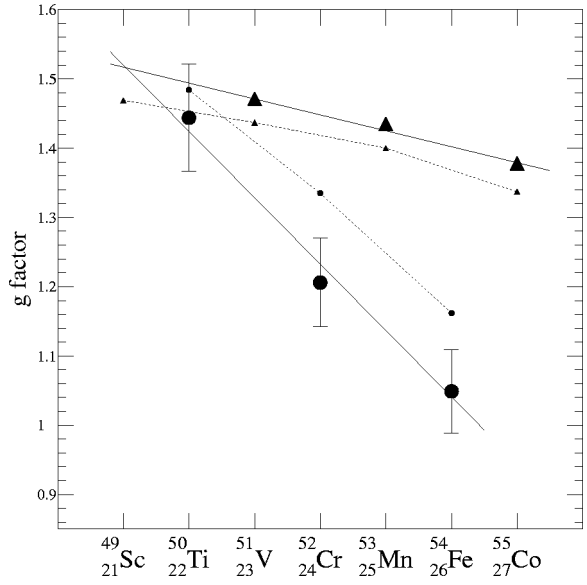

FIG. 1. Comparison of the experimental (large symbols) and theoretical (small symbols) g factors of the $N=28$ isotones. Only the results of the shell model diagonalization calculation with the FPD6 interaction (Table II) for the configuration $f_{7/2}^{n-1}\ j'$ $(p_{3/2}f_{5/2}p_{1/2})$ are displayed. The solid lines are linear fits to the data; the dashed lines are drawn to guide the eye.

The data show unambiguously that, for the $N=28$ isotones, the g factors of the $(7/2)^-$ ground states of the odd A and of the 2_1^+ states of even A nuclei are, to an excellent approximation, linear in Z, albeit with different, negative slopes. This strikingly different behavior of the odd and even mass nuclei can be understood in terms of core polarization effects which are discussed below in the framework of both *shell model diagonalization* and *perturbation theory calculations*.

Shell model calculations involving matrix diagonalization were carried out for several effective interactions: FPD6 [11], KB3 [12], VHG [13], and FPY [14]. The following configurations were included: $(f^{7/2})^n$ and $(f^{7/2})^{n-1}\ j'$ where j' can be $p_{3/2}$, $f_{5/2}$, or $p_{1/2}$.

The results of the shell model diagonalization are shown in Fig. 1 and Table II, but only the results obtained with the FPD6 interaction are shown in Fig. 1. To make comparisons as simple as possible, *effective* slopes can be defined as follows: $m_{2^+,eff}(\text{even}\,A)=[g(^{54}\text{Fe})^{I=2}-g(^{50}\text{Ti})^{I=2}]/4$ and $m_{\frac{7}{2}^-,eff}(\text{odd}\,A)=[g(^{55}\text{Co}^{I=7/2})-g(^{51}\text{V})^{I=7/2})]/4$.

The FPD6 theoretical values for g and for the effective slopes of g vs Z are in good agreement with experiment for both odd and even A isotopes. If the analysis were to be concluded at this point, it would appear that the experimental data are well understood. However, Table II shows that the g factors are very sensitive to the choice of interaction.

Thus, the FPY interaction (Calculation II in [14]) yields quite different results for $g(2_1^+)$, as well as an effective *slope* for $g(2_1^+)$ of opposite sign to that obtained for FPD6. The slopes for KB3 and VHG are almost the same and lie in between those for FPY and FPD6.

To obtain an insight into why such a variety of results ensued in the above shell model diagonalizations, the problem was examined more simply using first-order perturbation theory. This approach yields results that are somewhat different from those of the matrix diagonalization calculations shown in Fig. 1 and Table II. This difference arises in part because, in perturbation theory, only the excitation from $f_{7/2}$ to $f_{5/2}$ contributes to the change in g and only linear terms in the interaction were kept. The difference δg^I between the g factor of a nucleus with two protons coupled to I and that of a one-proton nucleus in the $I=\frac{7}{2}$ ground state, $\delta g^I = g(^{50}\mathrm{Ti})^{I=2} - g(^{49}\mathrm{Sc})^{I=7/2}$, is given by $\delta g^I = X^I\, M^I$, where

$$M^I = (g_l - g_s)\left\langle (jj)^I \left| \frac{V}{\Delta E} \right| (jj')^I \right\rangle_{I,T=1}$$

and

$$X^{2^+} = \frac{5}{7}\sqrt{\frac{2}{3}}, \quad X^{4^+} = \frac{3}{7\sqrt{5}},$$

and

$$X^{6^+} = \frac{2}{7\sqrt{6}}.$$

It can be shown that δg^I has the opposite sign for two holes or two particles. Thus, $g(^{54}\mathrm{Fe})^I = g(^{55}\mathrm{Co}) - \delta g^I$ [15]. A relation between the effective slopes of even-even and odd-even nuclei may be written in terms of δg^I, $m_{I=2} = \frac{3}{2} m_{\frac{7}{2}} - \frac{1}{2}\delta g^{I=2}$. Note that even when δg^I vanishes, even-even and odd-even nuclei have different slopes.

In the case of $I=2$, the key matrix element is $\langle (jj)^2 | V | (jj')^2 \rangle_{I=2,T=1}$ with $j = f_{7/2}$ and $j' = f_{5/2}$. Its value is listed in Table II, as well as that of δg^{2^+}. It is now obvious why such a variety of answers was obtained above. The value of the key matrix element for FPY is of opposite sign to that for FPD6. The values for KB3 and VHG are zero.

The g factors for the $N=28$ isotones obtained from perturbation theory (Fig. 2) are subject to several constraints. First, as previously mentioned, in the absence of configuration mixing, the g factors would all be the same and equal to the Schmidt value, $g=1.655$. In first order perturbation theory, the g factors of the 2_1^+ states of even A nuclei and of the $(7/2)^-$ ground states of odd nuclei lie on straight lines with different slopes. The second constraint, which has not been sufficiently pointed out in past theoretical papers, is that the two lines ($I=2$ and $I=\frac{7}{2}$) must intersect at midshell, namely at ^{52}Cr. Thus, in perturbation theory, if $g(2_1^+;{}^{50}\mathrm{Ti})$ is larger(smaller) than $g(\frac{7}{2};{}^{49}\mathrm{Sc})$, then $g(2_1^+;{}^{54}\mathrm{Fe})$ is smaller(larger) than $g(\frac{7}{2};{}^{55}\mathrm{Co})$.

The first order perturbation theory results for $\delta g^{2^+} > 0$ (FPD6) and for $\delta g^{2^+} < 0$ (FPY) are shown in Fig. 2. In the first case, $g(2_1^+;{}^{54}\mathrm{Fe}) < g(\frac{7}{2};{}^{55}\mathrm{Co})$ and $g(2_1^+;{}^{50}\mathrm{Ti}) > g(\frac{7}{2};{}^{49}\mathrm{Sc})$. In the second case, the opposite behavior prevails. The experimental data (Fig. 1), however, suggest both

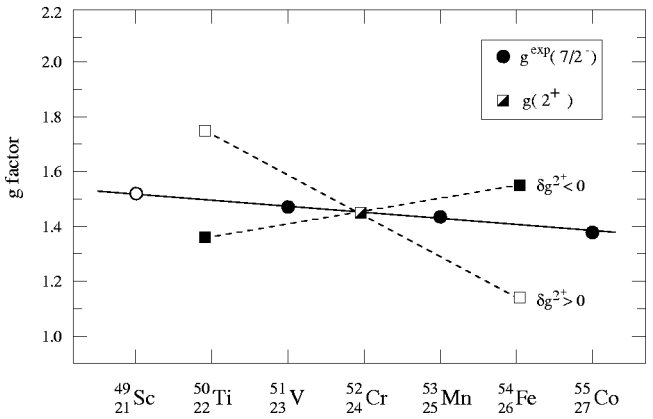

FIG. 2. Schematic of results of first-order perturbation theory calculations of g factors of 2_1^+ states of even A nuclei (square symbols) for the FPD6 and FPY interactions (see text). The open circle for ^{49}Sc is estimated from the extension of the straight line fit to the experimental values.

that $g(2_1^+;{}^{54}\mathrm{Fe})$ is smaller than $g(\frac{7}{2};{}^{55}\mathrm{Co})$ and $g(2_1^+;{}^{50}\mathrm{Ti})$ is smaller than $g(\frac{7}{2};{}^{49}\mathrm{Sc})$. This effect cannot be explained by either of the two scenarios presented in perturbation theory (Fig. 2).

Since the major focus of this work is to present new and more precise *experimental* data, it would not be appropriate here to make a detailed evaluation of one set of matrix elements against others. It is sufficient to say that the results presented here demand a better understanding of the effective interactions inside the nucleus. The most important matrix elements for calculations of binding energies of $N=28$ isotones are of the form $\langle f_{7/2} f_{7/2} | V | f_{7/2} f_{7/2} \rangle_{IT}$. Even if a phenomenological analysis obtained the right value for these matrix elements, there is no guarantee that the matrix elements relevant to g factors, such as the previously mentioned $\langle f_{7/2} f_{7/2} | V | f_{7/2} f_{5/2} \rangle_{I=2,T=1}$, will be calculated correctly.

A few clarifying remarks concerning the effective interactions are in order. Most realistic interactions would yield a negative value for the above matrix element, in agreement with FPY. However, Kuo and Brown [16] have shown that core polarization effects can be important. For example, with a ^{40}Ca core, the value of the effective matrix element $\langle f_{7/2} f_{7/2} | V | f_{7/2} f_{5/2} \rangle_{I=2,T=1}$ is given by $G = G_{bare} + G_{3p-1h} = -0.124 + 0.124 = 0$ (the fact that the matrix element vanishes is a coincidence). Indeed, KB3 and VHG also yield zero for this matrix element because these calculations use this same Kuo-Brown matrix element $\langle f_{7/2} f_{7/2} | V | f_{7/2} f_{5/2} \rangle$ while modifying others, such as $\langle f_{7/2} f_{7/2} | V | f_{7/2} f_{7/2} \rangle$. However, a careful reading of the Kuo-Brown paper [16] shows that a calculation using a ^{48}Ca core, which might be more relevant to the $N=28$ isotones, yields a negative matrix element, $G = G_{bare} + G_{3p-1h} = -0.124 + (-0.003) = -0.127$, similar to that obtained with the FPY interaction.

Thus far, only configuration mixing in which one particle ($t=1$) has been excited from the $f_{7/2}$ shell to $p_{3/2}$, $f_{5/2}$, or $p_{1/2}$ orbits has been discussed. Now consider the effect of exciting $t=2$, 3, or 5 nucleons [17]. The results for FPD6 are shown in Table III. The main consequence of including these

TABLE III. Shell model calculations using the bare FPD6 interaction of g factors and effective slopes as a function of the number of particles t excited from the $f_{7/2}$ shell to the remainder of the fp shell. (This work for $t=1,2$ and [17] for $t=3,5$.)

t	^{49}Sc	^{51}V	^{53}Mn	^{55}Co	$m_{7/2^-,eff}$	^{50}Ti	^{52}Cr	^{54}Fe	$m_{2^+,eff}$
1	1.47	1.44	1.40	1.34	−0.025	1.48	1.34	1.16	−0.080
2	1.49	1.46	1.46	1.46	−0.000	1.43	1.37	1.32	−0.028
3	1.45	1.40	1.39	1.37	−0.008	1.24	1.19	1.13	−0.020
5						1.15	1.04	1.05	−0.025

additional configurations is to decrease the g factors of the 2_1^+ states and their effective slope and, unfortunately, the good agreement with experiment obtained with $t=1$, particularly for ^{50}Ti, is destroyed. An almost identical flattening of the slope is obtained with the KB3 interaction, or with the full fp shell calculation [17]. Clearly, large scale calculations do not explain the observed experimental slopes. The calculated g factors for the ground states of the odd nuclei and the 2_1^+ states of ^{52}Cr and ^{54}Fe are in reasonable agreement with experiment, but the theory fails in the case of ^{50}Ti. In addition, the theory fails to correctly predict the $B(E2)$'s for the 2_1^+ states of ^{50}Ti as well as of the lighter isotopes, ^{46,48}Ti [8,9].

The question thus arises of why first order perturbation theory with $t=1$ gives better results than the large scale calculations. It appears that all the interactions in common use in this region allow too much configuration mixing, especially for ^{50}Ti.

The theoretical predictions can also be compared to the measurement of $g(6_1^+)=1.37(3)$ in ^{54}Fe [18]. The FPD6, $t=1$, calculation yields $g=1.362$, in excellent agreement with the measured value. The calculation also predicts that the slope $[m_{6^+,eff}=-0.015]$ should be smaller than $[m_{2^+,eff}]$, in agreement with the expectation of purer wave functions and smaller configuration mixing at higher spins.

A brief summary of the theoretical situation in the framework of core polarization indicates that configuration mixing calculations using matrix diagonalization with excitation of *one* particle display many of the qualitative features of the experimental results. In particular, the calculations reproduce the linear Z dependence and the corresponding slopes of the g factors of the 2_1^+ states of the even-even and of the ground states of the odd-even $N=28$ isotones (Fig. 1). Comparable results are obtained for various interactions, but the FPD6 interaction yields the closest agreement with the experimental slopes of the g factors. Most interesting, the fact that the experimental lines (solid lines in Fig. 1) for $I=2$ and $I=\frac{7}{2}$ do not intersect at ^{52}Cr as perturbation theory predicts, shows that calculations beyond perturbation theory are important. The theoretical situation is somewhat improved when matrix diagonalization is performed with one particle excited. There is still an intersection point (dashed lines in Fig. 1) but it is pushed to the lower half of the $N=28$ isotone series. In view of these facts, it is very surprising that full fp shell model calculations cannot explain the Z dependence of the g factors of the 2_1^+ states. Furthermore, the large scale calculations underestimate the experimental g factors of the even-even Ti isotopes [8,9].

Summarizing the experimental situation, the present technique of Coulomb excitation in inverse kinematics provides g factor data with higher statistical accuracy, hence higher precision and reliability. Thus, fine nuclear structure details hardly accessible otherwise may be revealed. The reduction of systematic errors through the use of the same target for several nuclei has contributed a very large improvement over measurements carried out on sequences of different targets.

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