Simple structures in complex nuclei versus complex structures in simple nuclei: a nuclear moments perspective

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Abstract. Patterns in \( g \)-factor systematics across the nuclear landscape and the pathway to collectivity are explored for heavy nuclei (\( A > 90 \)). The emergence of simple collective structures in complex nuclei with many valence nucleons is viewed from the perspective of the magnetic moments. Examples of the collective complexities in 'simple' nuclei with few valence nucleons, that are revealed by magnetic moment measurements and may be pre-cursors for the development of collectivity in more complex nuclei, are also discussed.

1. Introduction
The quest to understand the microscopic origins of 'simple' collective structures in 'complex' nuclei is ongoing. Insights into the evolution of nuclear structure as the number of valence nucleons changes can be gained from trends in observables such as \( R_{42} = E_x(4^+_1)/E_x(2^+_1) \) (see for example [1] and references therein). In this paper trends in the \( g \) factors for \( 2^+_1 \) states in heavy even-even nuclei will be reviewed and the path from spherical to deformed nuclei considered from the point of view of the magnetic moments. Nuclear collectivity will then be considered in relation to the complexities of the low-excitation levels in nominally 'simple' spherical nuclei wherein the lowest states may contain collective components, which are absent in a shell-model description.

2. Simple patterns in complex nuclei: magnetic moments perspective
The trends in \( g(2^+_1) \) values for medium to heavy nuclei have been discussed previously, however it is timely to reconsider these systematics in the light of theoretical advances (see below) and the availability of new data, which either increase the span of the data set (e.g. [2]) or significantly improve the precision (e.g. [3]). Discussion here will be limited to two regions. Data for the rare-earth region \( (50 \leq Z < 82 \) and \( 82 \leq N < 126 \)) are displayed in figure 1 as a function of the valence proton fraction, \( N_p/N_t \), where \( N_p \) is the number of valence protons or proton holes relative to the nearest magic number, and \( N_t \) is the total number of valence nucleons (protons plus neutrons) counted in the same way. Color has been used to indicate the \( R_{42} \) value associated with each measured \( g \) factor. The data for \( N_p/N_t < 0.7 \) cluster around a straight line, which can be interpreted in terms of the proton-neutron Interaction Boson Model expression \( g = g_\nu + (g_\pi - g_\nu)(N_p/N_t) \). Although the boson \( g \) factors from the fit, \( g_\nu = 0.23 \) (neutrons)
Figure 1. $g(2^+)$ as a function of the valence proton fraction for nuclei with $50 \leq Z < 82$ and $82 \leq N < 126$. The broken line indicates the trend for $N_p/N_t < 0.7$. Data points (from [5]) are colored to indicate $R_{42}$.

and $g_x = 0.45$ (protons), depart significantly from the nominal $g_\nu = 0$ and $g_x = 1$, the trend for an increase in $g(2^+)$ as the shell closures at $N = 82$ and $N = 126$ are approached is correct; in contrast, this experimental feature of the rare-earth region is contrary to the $Z/A$ estimate, even when corrections for pairing are included [4].

It is known from observables such as $R_{42}$ that heavy nuclei make a rapid transition from spherical to deformed behavior. The rapidity of this transition is evident in the $g$ factors as well. Aside from the semimagic $N = 82$ isotones, the nuclei that show strong departures from the collective trend line all have $R_{42} < 2.4$, and 4 or fewer valence neutrons. Turning to figure 2 and the $A \sim 100$ region ($40 \leq Z < 50$ and $50 \leq N < 82$), the $g$ factors departing strongly from the trend for collective nuclides again have $R_{42} < 2.4$. In both regions, $g(2^+) \sim 1$ for the semimagic nuclei, the specific value being determined by the particular proton configuration. Then, with the addition of two neutrons, $g(2^+)$ falls well below the collective trend.

This phenomenon was noted and discussed about a decade ago [6]. An important observation is that the coupling between protons and neutrons in these nuclei with few valence nucleons is rather weak. For example, the level spectrum of $^{144}_{60}$Nd can be obtained by superimposing the level schemes of $^{142}_{60}$Nd (the 4-proton excitation) and $^{148}_{64}$Gd (the 2-neutron excitation; $^{142}_{64}$Gd is approximately a closed-shell nucleus). It was suggested that (i) coupling between the valence protons and neutrons is relatively weak because the protons and neutrons are in different shells, and (ii) neutron excitations are then favored in the lowest $2^+$ state because their residual interactions are more attractive than those between protons. Considerable progress has been made since then. The shell model calculations of Holt et al. [7] for the $N=52$ isotones, shown in the insert of figure 2, give a good description of the data and illuminate the underlying nuclear structure phenomena. The weak coupling of the proton and neutron excitations leads to a ‘configurational isospin polarization’, which means that the $2^+_1$ and $2^+_2$ states in $^{92}$Zr, for example, do not form the fully-symmetric and mixed-symmetry states of the proton-neutron interacting boson model. The consequent difference in their $g$ factors has been observed [8].

Research into the $g$ factors of nuclei near closed shells, the formation of mixed symmetry
Figure 2. $g(2^+_1)$ as a function of neutron number for nuclei with $40 \leq Z < 50$ and $50 \leq N < 82$. Data are summarized in [3]. The broken line indicates the trend for $56 \leq N \leq 70$. See figure 1 for color key. The inset shows $g(2^+_1)$ for the $N = 52$ isotones. The dashed line is $Z/A$; the solid line is the shell model calculation of Holt et al. [7].

states, and the on-set of collectivity, is on-going. In the $A \sim 80$ region the $N = 48$ isotones $^{84}$Kr and $^{86}$Sr follow the pattern of $g(2^+_1) \ll Z/A$. On the other hand $^{132}$Te$_{80}$, which has two valence protons and two neutron holes, has $g \sim Z/A$ [9, 10]. This case will be discussed elsewhere [11].

Whereas the behavior of $g(2^+_1)$ follows a similar path to collectivity in the $A \sim 100$ and rare earth regions, the trends differ once collectivity sets in. In the $A \sim 100$ nuclei the $g$ factors are not well correlated with $N_p/N_t$. Instead they decrease steadily as $N$ increases beyond mid-shell at $N = 66$. Why the difference between these two regions? It must stem from the sensitivity of the $g$ factors to the underlying single-particle composition of the quadrupole collectivity.

The question has been illuminated by microscopic calculations using the tidal-wave model of Frauendorf and collaborators [3]. This model, which describes the yrast states of transitional and deformed nuclei by means of the self-consistent cranking model, allows the calculation of the magnetic moment directly from the nucleonic currents. It was found that the decrease in $g(2^+_1)$ along the isotope chains in the $A \sim 100$ region is primarily due to an increasing angular momentum contribution from the $h_{11/2}$ neutrons, which can begin even below $N = 64$, as illustrated for the Mo isotopes in figure 3. The mechanism is akin to the strong increase of angular momentum carried by neutrons in deformed nuclei, caused by the rotational alignment of the $i_{13/2}$ and $j_{15/2}$ neutrons, which reduces the $g$ factors of high-spin states below $Z/A$.

It is therefore proposed that the difference in the $g$-factor systematics observed for the $N = 50 – 82$ shell compared to the $N = 82 – 126$ shell stems from the difference in the location of the high-spin intruder orbital. As seen in figure 3, the neutron $h_{11/2}$ orbit is near the top ($N = 82$ end) of the $N = 50 – 82$ shell. In contrast, the $i_{13/2}$ orbit is much nearer to the middle of the $N = 82 – 126$ shell. A study of the data in figure 1 in the tidal-wave model is needed. The aim would be to provide a microscopic basis for the trends observed, including the trend of rising $g$ factors towards the $N = 126$ end of the shell.
3. Moments and quadrupole collectivity in neutron-rich S and Ar isotopes

New regions of quadrupole collectivity are being explored in neutron-rich nuclei. The sulfur and argon isotopes between $N = 20$ and $N = 28$ show collective features that can be explored through shell model calculations [12–15]. For example, shell model calculations with the SDPF-NR interaction [13, 14] are very successful in describing the $E2$ transition rate and $g(2^+)$ in $^{40}$S. The experimental $B(E2)$ suggests prolate deformation, and the shell model calculations give $Q(2^+_1)$ and $B(E2)$ values consistent with the same deformation in the rotor model. The $g$ factor, however, is not near $Z/A$, but near zero in both theory and experiment [16, 17]. The microscopic reason is that intrinsic-spin contributions from the $f_{7/2}$ neutrons cancel out the positive contribution from the orbital proton current. According to the shell-model calculations, the collectivity stems from the motion of relatively few nucleons. Rather than picture the quadrupole collectivity here in terms of the rotation of a deformed fluid, it is therefore better to understand it in terms of the symmetries of the underlying shell structure: quasi-$SU(3)$ for the $\nu f_{7/2} - p_{3/2}$ orbits and pseudo-$SU(3)$ for the $\pi d_{3/2} - s_{1/2}$ orbits [13].

Despite these successes of the SDPF-NR shell model in the case of $^{40}$S, the theoretical $g$ factors for the neighboring $N = 22$ isotones $^{38}$S and $^{40}$Ar underestimate the experimental values significantly, as shown in figure 4. There is a more dramatic disagreement between theory and experiment for $^{42}$Ca and $^{44}$Ar. In addition to the experimental data shown in figure 4, the trends have been confirmed in our new $g(2^+_1)$ measurements on the neutron-rich isotopes $^{42,44,46}$Ar performed at NSCL. These experimental $g$ factors suggest that, along with the symmetries in the shell-model space that cause quadrupole collectivity, there are also contributions from collective core-excitations that are not explicitly included in the shell-model space. Indeed, it has been known since the 1960s that the $2^+_1$ states in the Ca isotopes are not pure $\nu f_{7/2}$ configurations, but in $^{42,44}$Ca they are a strong mixture of shell model and deformed.
multiparticle-multi-hole configurations [20]. This mixing makes the \( g(2^+_1) \) values positive in \(^{42,44}\)Ca. In contrast, the negative \( g \) factor in \(^{46}\)Ca is closer to the shell model value [19], which reflects the fact that the deformed contribution decreases towards \( N = 28 \).

There is a puzzling discrepancy between theory and experiment [12, 15] for \( B(E2; 0^+_1 \rightarrow 2^+_1) \) in the \( N = 28 \) nucleus \(^{46}\)Ar, where shell model calculations with several alternative interactions in the SDPF model space all overestimate the \( E2 \) strength. One possibility is that the experimental \( B(E2) \) values based on intermediate energy Coulomb excitation are not correct (see [21]). However another possibility, should the Coulomb-excitation data prove correct, is that the discrepancy may stem from the fact that the shell-model interactions have been tuned to fit the energy spectra in a limited basis space, without explicitly including the coupling of the shell-model configurations to the deformed core excitations. The shell model interactions might implicitly include the effect of the core excitations that occur near \( N = 20 \), but not account for the fact that they diminish toward \( N = 28 \).

4. Conclusion

Patterns in \( g(2^+_1) \) systematics for heavy nuclei have been examined and found to be sensitive to the underlying single-particle structure. Near closed shells the magnetic moments show pronounced changes that depend on the strength of the coupling between protons and neutrons, which is known to be important in the development of ‘simple’ collective excitations in ‘complex’ nuclei. Studies of magnetic moments can therefore provide a sensitive probe of the pathway to collectivity in atomic nuclei.

From another perspective, magnetic moment measurements on ‘simple’ nuclei near closed shells can sometimes show that collective components are already present in the nuclear wavefunctions. It is a matter for further research to investigate the ways in which these collective ‘complexities’ may be precursors of the ‘simple’ collective structures that emerge in more ‘complex’ nuclei.

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References

[1] Cejnar P, Jolie J and Casten R F 2010 Rev. Mod. Phys. 82 2155
[2] Berant Z et al 2009 Phys. Rev. C 80 057303
[3] Chamoli S K et al 2011 Phys. Rev. C 83 054318
[4] Stuchbery A E 1995 Nucl. Phys. A 589 222
[5] Stone N J 2011 INDC(NDS)-0594 http://www-nds.iaea.org/publications/indc/ndc-nds-0594/
[6] Stuchbery A E 2001 Nuclear Physics A 682 470
[7] Holt J D, Pietralla N, Holt J W, Kuo T T S and Rainovski G 2007 Phys. Rev. C 76 034325
[8] Werner V et al 2008 Phys. Rev. C 78 031301
[9] Stone N J et al 2005 Phys. Rev. Lett. 94 192501
[10] Stuchbery A E and Stone N J 2007 Phys. Rev. C 76 034307
[11] Danchev M et al 2011 these proceedings and to be published
[12] Scheit H et al 1996 Phys. Rev. Lett. 77 3967
[13] Retamosa J, Caurier E, Nowacki F and Poves A 1997 Phys. Rev. C 55 1266
[14] Caurier E, Martínez-Pinedo G, Nowacki F, Poves A and Zuker A P 2005 Rev. Mod. Phys. 77 427
[15] Robinson S J Q, Sharon Y Y and Zamick I 2009 Phys. Rev. C 79 054322
[16] Davies A D et al 2006 Phys. Rev. Lett. 96 112503
[17] Stuchbery A E et al 2006 Phys. Rev. C 74 054307
[18] Stefanova E A et al 2005 Phys. Rev. C 72 014309
[19] Taylor M et al 2005 Physics Letters B 605 265
[20] Gerace W and Green A 1967 Nuclear Physics A 93 110
[21] Mengoni D et al 2010 Phys. Rev. C 82 024308