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The magnetic properties of collective states in $A \sim 100$ fission fragments

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Abstract
The magnetic moments of $I^\pi = 2_1^+$ states in even–even $A \sim 100$ fission fragments have been measured using the Gammasphere array, using the technique of time-integral perturbed angular correlations. The collective (core) g factors of several odd nuclei have also been determined. The data are interpreted within the context of the interacting boson model (IBA2).

The $A \sim 100$ region of neutron-rich nuclei is an ideal subset of the nuclear chart in which to investigate the origins of nuclear collectivity. One sees near $N = 50$, nuclei characteristic of the shell model. If neutron number is increased, a transition to deformed rotational behaviour is observed at $N \approx 60$. This transition is particularly sharp in the case of $_{38}$Sr and $_{40}$Zr but becomes steadily weaker as Z is increased. A useful indicator of this transition is the ratio of the excitation energies of the lowest $I^\pi = 4^+$ and 2^+ states. In the case of Zr, $E_{4_1^+}/E_{2_1^+}$ is 1.6 for $N = 58$, 2.6 for $N = 60$, and approaches the rotational limit $\left(3\frac{1}{3}\right)$ with a value of 3.1 for ^{102}Zr. In contrast, $E_{4_1^+}/E_{2_1^+}$ varies slowly in the isotopes of $_{46}$Pd, from a value of 2.2 in ^{102}Pd to 2.58 in ^{116}Pd. The onset of rotational collectivity is also observed in the large reduced transition probabilities ($B(E2; 2 \rightarrow 0)$ values) shown in table 1.

Talmi [1], Federman and Pittel [2, 3] and Casten [4] have all stressed the importance of neutron–proton interactions in producing deformed states in this region of the nuclear

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Table 1. g factors of 2^+ States in the $A \sim 100$ region. The γ-ray pairs which define the angular correlation are given in the form $E_i \otimes E_j$, where E_i and E_j are the γ-ray energies (in keV) of the populating and depopulating transitions, respectively. For each pair, several isotropic gates are used to ensure clean selection of the nucleus of interest. $B(E2)$ values for the $2_1^+ \to 0_1^+$ transitions have been calculated from the lifetimes with corrections made for internal conversion.

Nucleus	E_{4^+}/E_{2^+}	ϕ_p (mrad)	τ (ns)	$B(E2)$ (e^2 b^2)	B (Tesla)	g	Correlations used
^{98}Zr	1.51	+1(38)	<0.29 [31]		−27.4(4)		621 ⊗ 1223, 648 ⊗ 1223
^{100}Zr	2.65	+301(24)	0.78(3) [32, 33]	0.22(1)	From	+0.30(3)	352 ⊗ 213, 497 ⊗ 213
^{102}Zr	3.14	+810(150)	2.76(36) [34, 35]	0.32(4)	[40]	+0.22(5)	326 ⊗ 152, 487 ⊗ 152
^{102}Mo	2.51	+92(44)	0.180(6) [36]	0.20(1)	−25.6(1)	+0.4(2)	584 ⊗ 297
^{104}Mo	2.92	+340(20)	1.040(59) [36]	0.28(2)	From	+0.27(2)	368 ⊗ 192, 519 ⊗ 192
^{106}Mo	3.03	+460(40)	1.803(43) [34]	0.28(1)	[41]	+0.21(2)	351 ⊗ 172, 511 ⊗ 172
^{108}Mo	2.91	+420(130)	0.72(43) [37]	0.4(2)		+0.5(3)	371 ⊗ 193
^{106}Ru	2.64	+170(80)	0.29(3)[a]		−47.8(1)	+0.3(1)	445 ⊗ 270, 581 ⊗ 270
			0.264(6) [44]			+0.28(13)	
^{108}Ru	2.74	+265(34)	0.498(43) [34]	0.19(2)	From	+0.23(4)	423 ⊗ 242, 575 ⊗ 423
			0.417(9) [44]			+0.28(4)	
^{110}Ru	2.75	+430(60)	0.433(29) [35]	0.23(2)	[42]	+0.44(7)	423 ⊗ 241, 576 ⊗ 241
			0.47(3) [44]			+0.41(6)	
^{112}Ru	2.73	+470(90)	0.462(43) [34, 38]	0.23(2)		+0.44(9)	408 ⊗ 237, 545 ⊗ 237
^{110}Pd	2.46	+47(31)	0.067(2) [39]	0.16(1)	−42(2)	+0.3(2)	547 ⊗ 374, 653 ⊗ 374
^{114}Pd	2.56	+55(26)	0.289(87) [38]	0.07(2)	From	+0.09(5)	520 ⊗ 332, 648 ⊗ 332
			0.505(36) [44]			+0.24(11)	
^{116}Pd	2.58	+67(27)	0.159(43) [25]	0.11(3)	[43]	+0.2(1)	538 ⊗ 341, 682 ⊗ 341

[a] Lifetime estimated assuming same transition quadrupole moment as ^{108}Ru.

chart. Specifically, the proton $g_{9/2}$, and the neutron $g_{7/2}$ and $h_{11/2}$ orbitals are thought to be most important in establishing collectivity [2, 3]. Casten [4] has shown that $E_{4_1^+}/E_{2_1^+}$ varies reasonably smoothly with the product of the number of active neutrons (neutron holes) N_n, with the number of active protons (proton holes) N_p. In obtaining a smooth curve, it is necessary to count protons from the $Z = 38$ shell gap if $N < 60$ but from $Z = 28$ if $N \geqslant 60$. The closure of the gap at $Z = 38$ is possibly a result of the interaction between the $\pi g_{9/2}$ and the $\nu g_{7/2}$ spin-orbit partners. The importance of the occupation of $\nu h_{11/2}$ intruder orbitals is stressed in the shell-corrected rotating liquid-drop calculations of Skalski *et al* [5]. At intermediate spin, the low-Ω components of the $\nu h_{11/2}$ orbital are often identified with the S bands in the even–even nuclei of this region, and there is experimental evidence for rotational bands built on this orbital in odd-neutron Sr, Zr, Mo, Ru and Pd nuclei [6–14]. It should be pointed out, however, that the experimental evidence for the influence of the $\nu h_{11/2}$ on deformation is based mainly on level structures and branching ratios at spins greater than $I = 2$, interpreted within the context of rotational models.

To better determine the influence of the $h_{11/2}$ orbital on structural change in this region, it is crucial to have other experimental observables that allow direct access to the details of the wavefunction of the 2_1^+ state. In particular, given that the neutron–proton interaction is suspected as the driving force behind the establishment of collectivity, the g factor has particular relevance. While determination of the electric quadrupole moment can give important information on the deformation of the nucleus, it is the g factor with its very different sensitivity to the neutron and proton degrees of freedom that allows neutron and proton contributions to the collectivity to be disentangled. From a theoretical point of view,

g factors of deformed nuclei should be investigated at a fundamental level through a shell-model representation of the collective state using a suitable basis and residual interactions, but the basis space required to contain the physics of the whole region turns out to be extremely large, allowing only restricted shell-model calculations. On the other hand, it is possible to include the effect of shell gaps through the use of the interacting boson model (IBA2) [15]. In the limit of good F-spin, this model gives the collective g factor as

$$g_R = g_\pi \frac{N_\pi}{N_\pi + N_\nu} + g_\nu \frac{N_\nu}{N_\pi + N_\nu},$$

where N_π and N_ν are the number of proton and neutron bosons (or boson holes), respectively, and g_π and g_ν are the proton and neutron boson g factors, respectively. This expression is useful because it can be used in transitional regions of the nuclear chart, as long as one knows the particle numbers associated with the dominant shell closures. Naturally, if all shell gaps are ignored, and the boson g factors are taken to be $g_\pi = 1$ and $g_\nu = 0$, the IBA2 expression yields $g_R = Z/A$, the value expected for collective motion of a uniformly charged droplet. The underlying microscopic basis of the IBA2 approach is expressed in the variation of g_π with Z and g_ν with N.

The $A \sim 100$ region of deformed rotors is most readily accessed using spontaneous fission. The development of high efficiency, high granularity Ge-detector arrays such as Euroball [16] and Gammasphere [17] has allowed many neutron-rich nuclei to be investigated through the use of ^{252}Cf and ^{248}Cm fission sources. Recently, a technique has been developed that allows access to the g factors of states with lifetimes of the order of a nanosecond [18]. This technique uses the 4π geometry of Gammasphere and Euroball to measure the time-integral perturbed angular correlations (IPAC) of secondary-fragment γ-rays emitted following implantation into a ferromagnetic host.

Table 1 gives the results of the precession measurements. In all cases, triple γ-ray coincidences have been used to cleanly select the nucleus of interest and in most cases the angular correlation has been measured between the $4_1^+ \rightarrow 2_1^+$ and $2_1^+ \rightarrow 0^+$ transitions as well as between the $6_1^+ \rightarrow 4_1^+$ and $2_1^+ \rightarrow 0^+$ transitions.

The results of this work are presented in figure 1 together with data from previous g factor measurements in $^{102-110}$Pd [19], ^{100}Zr [20, 21] ^{98,100}Mo [22], ^{102,104}Mo [23], ^{98,104}Ru [24], ^{102}Ru [25] and ^{100,102}Ru [26]. Where there is an overlap between this and other work, i.e. in the cases of ^{100}Zr and ^{102,104}Mo, there is excellent agreement which provides supporting evidence for the validity of the technique and the saturation of the impurity hyperfine fields. In general, the g factors obtained in this work lie below Z/A indicating that uniform rotation/vibration of a uniformly charged drop is not a valid picture for the collective states of this region. The sudden change in the structure of the 2_1^+ states in the Zr isotopes that occurs at $N = 58$ results in a change from the negative g factors of ^{92,94}Zr [27] to near zero for ^{96}Zr [28] and then to positive values for ^{100,102}Zr. In the Mo and Ru isotopes, where the onset of deformation is more gradual, the g factors show a pronounced decrease from values close to Z/A for $N \leqslant 60$ to a minimum of around 0.2 at $N = 64$. The data suggest that the decrease in the 2_1^+ state g factor also occurs in the Pd isotopes, though, as with the onset of deformation, the effect occurs at higher neutron numbers than in the case of Mo and Ru.

The large variation in the g factors with neutron number suggests that it may be possible to gain some insight into the neutron orbitals that are involved in driving deformation in this region. In an attempt to separate neutron and proton degrees of freedom, we have carried out calculations within the IBA2 scheme with different values of g_π and g_ν. In these calculations we have taken the number of proton and neutron bosons according to the prescription of Casten [4], i.e. by counting proton bosons from the $Z = 28, 50$ shell closures for $N > 60$ and for $N = 60$ by using effective proton boson numbers to reproduce the energy systematics.

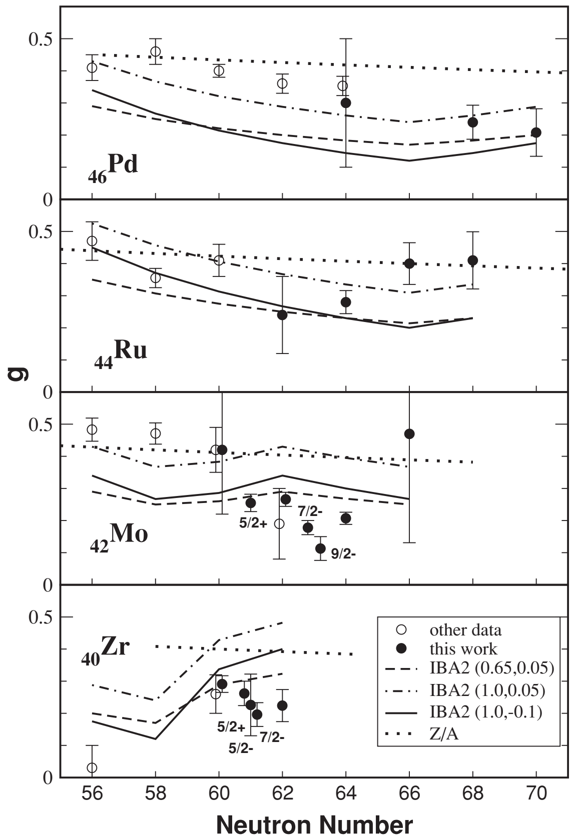

Figure 1. Summary of the g factor measurements of 2_1^+ states in the $A \sim 100$ region from this, and other work. The experimental results are compared with the predictions of the IBA2 model using values of (g_π, g_ν) given in the legend. Also included are g_R values for states in ^{101}Zr, ^{103,105}Mo deduced from the g factors and M_1/E_2 mixing ratios within the context of a rotational model.

This allows us to work within a framework in which the E_{4^+}/E_{2^+} ratio depends smoothly on the product $N_\pi N_\nu$. We count neutron bosons between the $N = 50$ and $N = 82$ shell closures. Figure 1 shows the results of three such calculations with the following parameters: $g_\pi = 1.0$, $g_\nu = 0.05$; $g_\pi = 0.65$, $g_\nu = 0.05$; $g_\pi = 1.0$, $g_\nu = -0.1$. Sambataro and Dieperink [29] have shown that with $g_\pi > 1.0$ and $g_\nu \approx 0$ it is possible to reproduce the g factors of the Ru and Pd nuclei with $N \leqslant 60$ and the Pd nuclei with $N \leqslant 64$. It is clear from our calculations that this choice of parameters yields results that are too large to explain the most deformed nuclei in this data set, ^{100,102}Zr and ^{104,106}Mo, while giving rough agreement with ^{110,112}Ru. Far better agreement with most of the nuclei measured in this work is obtained if either g_π is reduced to around 0.65, or if g_ν is made slightly negative. Since to a first approximation, g_π should be a function of proton number only, it is preferable to suppose that the marked variation of the g factors with neutron number is a result of a small change in g_ν rather than to a larger variation in g_π. Furthermore, a choice of $g_\pi \approx 1$ and $g_\nu \approx 0$ gives consistency with IBA2 fits to data in other regions of the nuclear chart, notably the rare-earth nuclei discussed in [30]. In the simple picture of collective orbital motion $g_\nu = 0$; a shift to negative values may be taken as an indication of the filling of single particle orbitals that couple to give a 2^+ state with a negative g factor.

According to the deformed shell-model calculations of Skalski *et al* [5], the neutron Fermi level for the nuclei presented here should lie in the region of the $g_{7/2}$, $d_{3/2}$ and $h_{11/2}$ orbitals. Of these, only $h_{11/2}$ couples to give a 2^+ state with a negative g factor; for a pure $\nu g_{7/2}^2$, $L = 2$ configuration $g = +0.42$, while $g\left(\nu h_{11/2}^2, L = 2\right) = -0.35$. These considerations lead to the suggestion that the large deformations in this region are associated with the filling of low-$\Omega h_{11/2}$ neutron orbitals, rather than $\nu g_{7/2}$ orbitals. In the Pd nuclei, the decrease may be delayed because there is a lower proton contribution to the collectivity, leading to the nucleus having lower deformation and a smaller $h_{11/2}$ component for a given neutron number. To determine more precisely the contribution of $h_{11/2}$ orbitals to the g factors of the 2_1^+ states would require a large-basis shell-model calculation using appropriate residual interactions and is beyond the scope of this work.

In addition to the measurements in the even–even nuclei, we have recently been able to measure angular correlations and g factors in the odd nuclei ^{101}Zr and ^{103,105}Mo. By combining the mixing ratios for $M1/E2$ transitions in a coupled band with the results of g factor measurements, it is possible to deduce g_k and g_R values, thereby separately probing the magnetic properties of the odd neutron and the rotational core. The g_R values extracted in this way are compared with the measurements for the 2^+ states in figure 1. It can be seen that collective magnetic properties of the odd nuclei are very close to those of the even–even neighbours with perhaps slightly lower values in the odd nuclei. These data are preliminary and will be the subject of a forthcoming paper.

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