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Consistent description of magnetic dipole properties in transitional nuclei

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Abstract

It is shown that a consistent description of magnetic dipole properties in transitional nuclei can be obtained in the interacting boson model-2 by the F-spin breaking mechanism, which is associated with differences between the proton and neutron deformations. In particular, the long standing anomalies observed in the g-factors of the Os-Pt isotopes are resolved by a proper inclusion of F-spin breaking without appeal to shape-coexistence or single-particle degrees of freedom.

The description of magnetic dipole ($M1$) properties in the interacting boson model (IBM) [1] has had a checkered career (see [2] for a recent review). In the original model (IBM-1 with s and d bosons), the one-body $M1$ operator, being proportional to the angular momentum, results in vanishing $M1$ transitions. Thus to explain observed $M1$ transitions one needs at least a two-body $M1$ operator [3] whose microscopic origin is not very clear. The discovery of the "scissors" mode [4] has shifted attention to the proton-neutron version of the model (IBM-2) which provides a more natural basis for description of $M1$ properties via the F-spin breaking mechanism. F-spin measures the degree of symmetry between the valence protons and neutrons and its breaking is linked to the difference between the proton and neutron deformations [5]. In this sense, $M1$ properties provide complementary information to $E2$ observables which depend on the average deformation and are, therefore, insensitive to F-spin breaking.

In IBM-2, the one-body $M1$ and magnetic moment operators are given by

$$T(M1) = \sqrt{3/4\pi}\hat{\boldsymbol{\mu}}, \quad \hat{\boldsymbol{\mu}} = g_\pi \boldsymbol{L}_\pi + g_\nu \boldsymbol{L}_\nu, \qquad (1)$$

where $\boldsymbol{L}_\rho$, $\rho = \pi, \nu$ are the angular momentum operators for proton and neutron bosons and g_ρ are the respective boson g-factors. In the limit of exact F-spin symmetry, the $M1$ operator in (1) leads to vanishing $M1$ transitions within an F-spin multiplet, and g-factors in a given nucleus are constant, having the value

$$g(L) = (g_\pi N_\pi + g_\nu N_\nu)/N. \qquad (2)$$

Here N_π, N_ν denote the proton and neutron boson numbers, and $N = N_\pi + N_\nu$. As N_ν are hole-like in the transitional isotopes of Os and Pt, Eq. (2) predicts an increase in g-factors with neutron number. Initial

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IBM-2 calculations employing Eq. (2) were thought to explain the g-factor variations in rare-earth nuclei reasonably well with the bare boson g-factors, $g_\pi = 1$, $g_\nu = 0$ [6]. However, subsequent accurate measurements of g-factors at the Australian National University and elsewhere uncovered rather large deviations, the most conspicuous being in transitional nuclei (see Refs. [7,8] for reviews and further references). For example, the measured $g(2_1^+)$ values for the Os isotopes increase as predicted by Eq. (2) but the $g(2_2^+)$ values decrease, in total conflict with it [9]. As Eq. (2) predicts the same g-factor for all states, this problem *cannot* be resolved by allowing arbitrary variations of g_ρ from their bare values. In the Pt isotopes, the measured g-factors of the $2_1^+, 2_2^+$ and 4_1^+ states all have similar values and remain constant with changing neutron number. This behaviour can be explained by Eq. (2) at the expense, however, of using $g_\pi \simeq g_\nu \simeq 0.3$. Such large deviations of g_ρ from their bare values are not accommodated by microscopic theory, and alternative explanations are needed. In view of these shortcomings, attempts have been made to include F-spin mixing effects via numerical diagonalization of IBM-2 Hamiltonians [9,10]. However, all of these calculations used the parameters of Bijker et al. [11] which were obtained by fitting the energy levels and $E2$ transitions in Os and Pt isotopes. Naturally, these fits are insensitive to the F-spin mixing needed to describe $M1$ properties, and it is not surprising that the above attempts did not resolve the g-factor discrepancies.

Recent analytic calculations using the intrinsic state formalism [12] and the $1/N$ expansion method [13,14] have provided new insight toward the solution of this problem. The analytic expressions obtained for g-factors of various bands include F-spin mixing effects explicitly and have been instrumental in mapping out the parameter dependence of $M1$ properties for various F-spin breaking terms in the Hamiltonian. These systematic studies have shown, in particular, that g-factors of ground and excited bands respond very differently to F-spin breaking in the quadrupole interaction, but show a similar behaviour toward a breaking in the one body energies, thus suggesting that a judicious use of F-spin breaking could lead to a consistent description of $M1$ properties. The analytic formalism, though useful in pointing toward the solution, is limited in accuracy when applied to Os-Pt nuclei because the number of bosons is small ($N < 10$) and they have soft energy surfaces. Thus, for accurate results, higher order terms (in $1/N$) and band mixing contributions must be included in the calculations. These are technically involved and have not been performed so far. Alternatively, one can resort to numerical diagonalization of the IBM-2 Hamiltonian with guidance from the analytic results. In this Letter we present the results of our numerical studies of $M1$ properties in $^{186-192}$Os and $^{190-198}$Pt using the computer code NPBOS [15].

The calculations employed the simplest IBM-2 Hamiltonian suggested by microscopics [1]

$$H = \epsilon_\pi \hat{n}_{d\pi} + \epsilon_\nu \hat{n}_{d\nu} + \kappa Q_\pi \cdot Q_\nu + \xi M, \quad (3)$$

where $\hat{n}_{d\rho}$ are the d_ρ-boson number operators, M is the Majorana operator in Casimir form and Q_ρ are the quadrupole operators given by

$$Q_\rho = [d_\rho^\dagger s_\rho + s_\rho^\dagger \tilde{d}_\rho] + \chi_\rho [d_\rho^\dagger \tilde{d}_\rho]^{(2)}. \quad (4)$$

Although other terms are often included in detailed IBM-2 studies, Eq. (3) adequately covers the F-spin breaking needed to describe $M1$ properties. In discussing F-spin breaking effects, it is convenient to introduce F-spin scalar and vector parameters

$$\epsilon_s = (\epsilon_\pi + \epsilon_\nu)/2, \quad \epsilon_v = (\epsilon_\pi - \epsilon_\nu)/2,$$
$$\chi_s = (\chi_\pi + \chi_\nu)/2, \quad \chi_v = (\chi_\pi - \chi_\nu)/2. \quad (5)$$

The $E2$ matrix elements were calculated using the the same quadrupole operator (4) as in the Hamiltonian, with effective charges $e_\pi = e_\nu = 0.15$ eb. Bare values for the boson g-factors ($g_\pi = 1$, $g_\nu = 0$) were employed in the $M1$ operator (1) throughout.

We first present a schematic study of F-spin breaking effects generated by the two vector parameters ϵ_v and χ_v. Since the energies and $E2$ transitions show little sensitivity to variations in the vector parameters [13], only the $M1$ properties are shown in Fig. 1. The effect of F-spin breaking on $M1$ transitions has been amply discussed in the literature [2] but its effect on g-factors has been largely ignored until recently [12,14,16]. It is clear from Fig. 1 that g-factors are also very sensitive to changes in the vector parameters and, for consistency, it is important to describe both quantities simultaneously. Clues toward the resolution of the g-factor anomalies in the Os-Pt isotopes

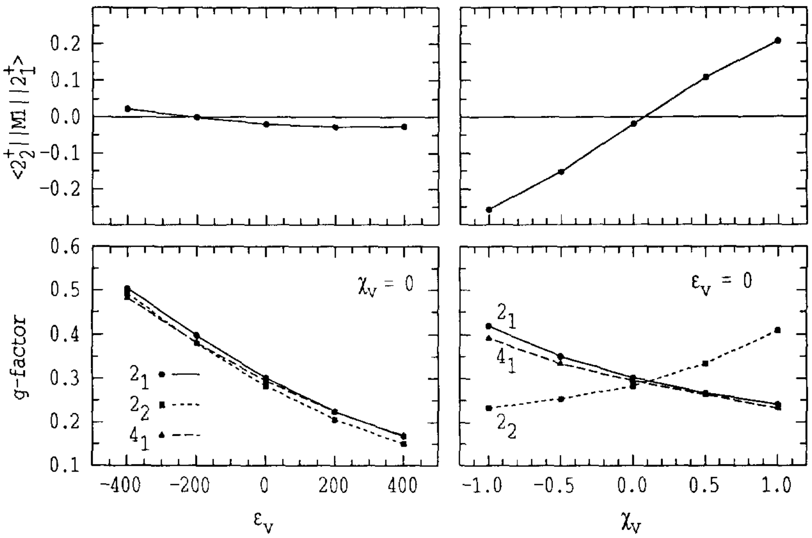

Fig. 1. Study of F-spin breaking effects on $M1$ properties in ^{190}Os. The fixed parameters are $\epsilon_s = 0.45$ MeV, $\chi_s = -0.25$, $\kappa = -0.15$ MeV, $\xi = 0.17$ MeV.

can be surmised from this systematic study. Specifically, the ϵ_v breaking leads to a monotonic decrease in all g-factors as is required in the Pt isotopes to offset the increase in theoretical values predicted by Eq. (2). The χ_v breaking, on the other hand, leads to a crossing of g-factors of ground and γ bands, which is precisely the behaviour exhibited by the experimental data in $^{188-192}$Os.

The systematics of the $M1$ transitions have been included in Fig. 1 to emphasize a robust prediction of IBM-2, namely, that the sign of χ_v determines both the sign of $M1$ matrix element and $g(2_2^+) - g(2_1^+)$. This prediction is consistent with the measured g-factors [7] and mixing ratio data [17] in ^{190}Os and ^{192}Os but is in conflict with the published data in the case of ^{188}Os. As a by-product of the measurement of g-factors in the Os isotopes [9], the angular correlations for the mixed $2_2^+ \rightarrow 2_1^+$ transitions were also measured (but not published). In Fig. 2, are shown the angular correlations for the $2_2^+ \rightarrow 2_1^+$ transitions obtained in that experiment and the resulting mixing ratios, $\delta(E2/M1)$. The new δ values agree well with the values in the literature, except for ^{188}Os where the present result ($\delta = +7.2 \pm 1.1$) has the opposite sign to that reported previously. The angular correlation data in Fig. 2 clearly support a change of sign in δ in ^{188}Os,

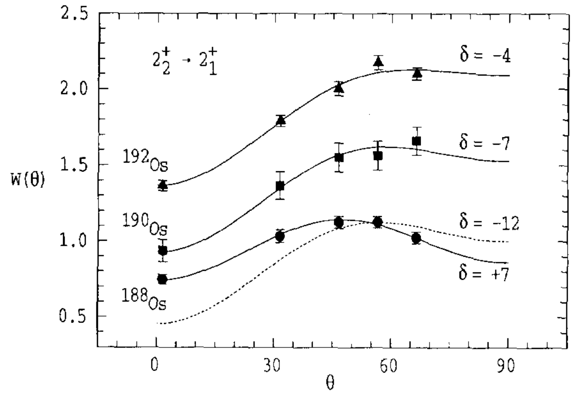

Fig. 2. Measured and fitted (solid lines) angular correlations for the $2_2^+ \rightarrow 2_1^+$ transitions in $^{188-192}$Os. The dashed line shows the angular correlation implied by the previously published mixing ratio for ^{188}Os [17].

consistent with the IBM-2 prediction for this nucleus.

In the light of the systematics discussed above, we carried out a new global fit for $^{186-192}$Os and $^{190-198}$Pt. The parameters κ, ξ, ϵ_s and χ_s were determined from a fit to the energy levels and $E2$ transitions. The first two were kept fixed in a given isotope chain while ϵ_s and χ_s were slightly varied to simulate the onset of deformation with increasing N_ν. The vector parameters, ϵ_v and χ_v, were then determined from the $M1$

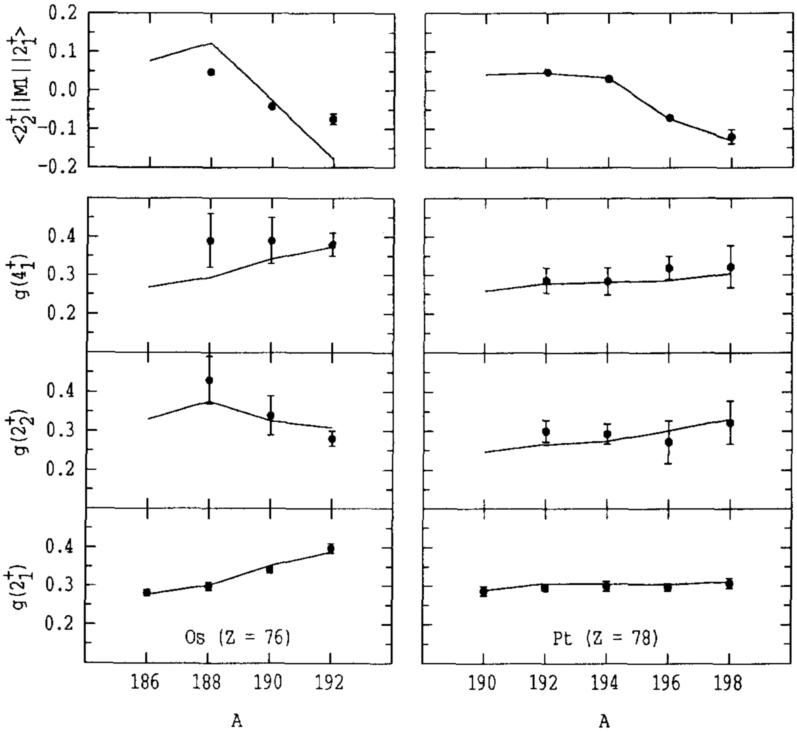

Fig. 3. Experimental g-factors and $M1(2_2^+ \rightarrow 2_1^+)$ transition rates compared with the present calculations. The data are from Refs. [7,9,17,18].

Table 1
Scalar and vector composition of ϵ and χ parameters in the Os-Pt isotopes. Other parameters (in MeV): $\kappa = -0.15$ (Os), -0.18 (Pt), and $\xi = 0.17$

Nucleus	N_π	N_ν	ϵ_s	ϵ_v	χ_s	χ_v
^{186}Os	3	8	0.32	−0.28	−0.32	0.40
^{188}Os	3	7	0.35	−0.22	−0.28	0.50
^{190}Os	3	6	0.40	−0.12	−0.25	−0.05
^{192}Os	3	5	0.40	0.	−0.18	−0.50
^{190}Pt	2	7	0.45	−0.25	0.18	0.10
^{192}Pt	2	6	0.50	−0.17	0.18	0.10
^{194}Pt	2	5	0.55	−0.07	0.18	0.05
^{196}Pt	2	4	0.58	0.02	0.18	−0.20
^{198}Pt	2	3	0.58	0.10	0.18	−0.30

properties. The parameter set thus obtained (Table 1), gives a reasonable description of the energy spectra and electromagnetic properties (i.e. comparable to previous work). The details of the calculation will be published in a forthcoming article [18]. The resulting g-factors and $M1$ transition matrix elements are shown in Fig. 3. The trends in the data are correctly reproduced and the level of agreement, especially in the Pt isotopes, is good. The range of vector parameters used in the fits (Table 1) are typical of those used in the study of $M1$ transitions in IBM-2, and the amount of F-spin admixture in the low-lying levels varies between 2-4%, consistent with the literature values [2]. The rapid change in the vector parameters is necessary in order to explain the anomalous behaviour of the g-factors. It seems to be specific to the transitional nuclei, and is presumably due to the softness of their energy surface and the prolate-oblate shape transition in Os-Pt nuclei.

It is of interest to note the qualitative implications of F-spin mixing for the proton and neutron deformation [5]. To investigate the impact of the rapid change in the vector parameters on the proton-neutron deformations, we performed a mean field analysis of the IBM-2 Hamiltonian (3) [13]. The deformation parameters, β_π, β_ν, which correspond to the mean field amplitudes for d_π, d_ν bosons, were calculated. Since

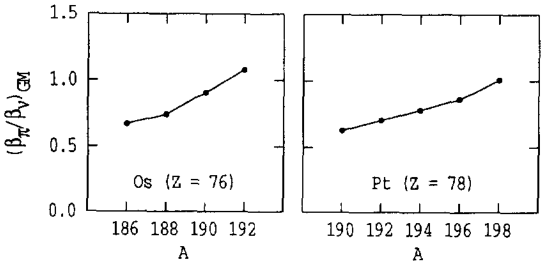

Fig. 4. Proton to neutron deformation ratios in Os (solid line) and Pt (dashed line) isotopes extracted from mean field calculations. These calculations are intended to show the qualitative mass-dependent trends and should not be taken as accurate predictions.

deformation in the IBM refers to the valence nucleons only, we translate these to the more conventional geometric model (GM) deformation ratios using the simple scaling [19]

$$\left(\frac{\beta_\pi}{\beta_\nu}\right)_{\mathrm{GM}} \approx \frac{N_n}{N_p}\frac{N_\pi}{N_\nu}\left(\frac{\beta_\pi}{\beta_\nu}\right)_{\mathrm{IBM}}, \tag{6}$$

where N_p and N_n denote the number of protons and neutrons respectively. The results of the GM deformation ratios are shown in Fig. 4. As stressed in the introduction, the mean field results are not very reliable for transitional nuclei. Further, as Eq. (6) is only a qualitative relationship between the IBM and GM, the rapid increase in the deformation ratio (Fig. 4) is certainly exaggerated. This trend is not specific to the IBM analysis, but appears to be a concomitant of two-fluid models. A similar analysis [20] of the g-factors using the Migdal formalism [21] shows a trend in ratio of proton to neutron deformation that is remarkably like that in Fig. 4. The concurrence between these two entirely different approaches is suggestive. The issue of differences in proton versus neutron deformation requires further attention both theoretically and experimentally. Recently, the proton-neutron deformation ratio was measured in ^{165}Ho from pion single-charge-exchange reactions [22]. It would be interesting to carry out such experiments in the Os-Pt region and determine whether the changes in deformation ratio are consistent with those implied by the description of $M1$ properties in the IBM-2.

In summary, we have shown that the anomalies displayed by the g-factors of the Os-Pt isotopes can be resolved in the IBM-2 by using the F-spin breaking mechanism which is related to differences between the proton and neutron deformations. A satisfactory description of the $M1$ properties has been obtained without resorting to anomalous boson g-factors, effective boson numbers, shape coexistence effects, or single particle behaviour.

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