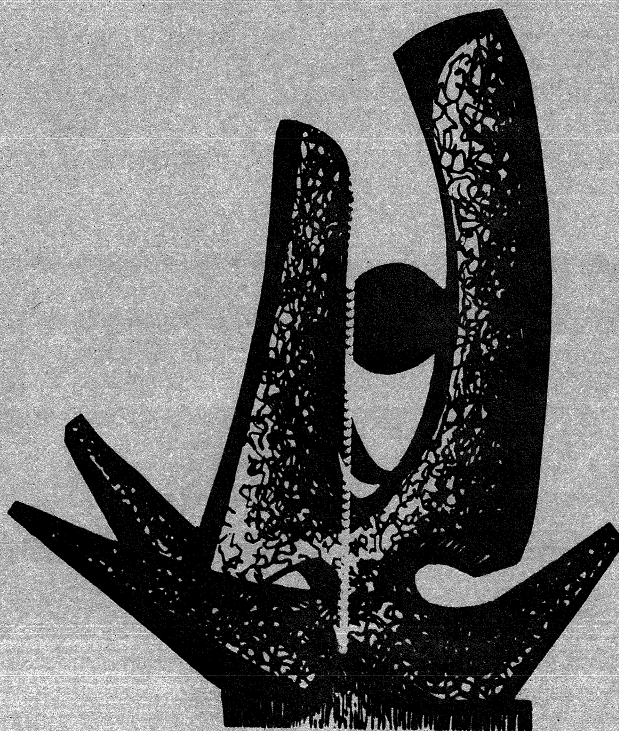


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DECOUPLED  $i_{13/2}$  NEUTRONS AND BACKBENDING  
IN RARE-EARTH NUCLEI

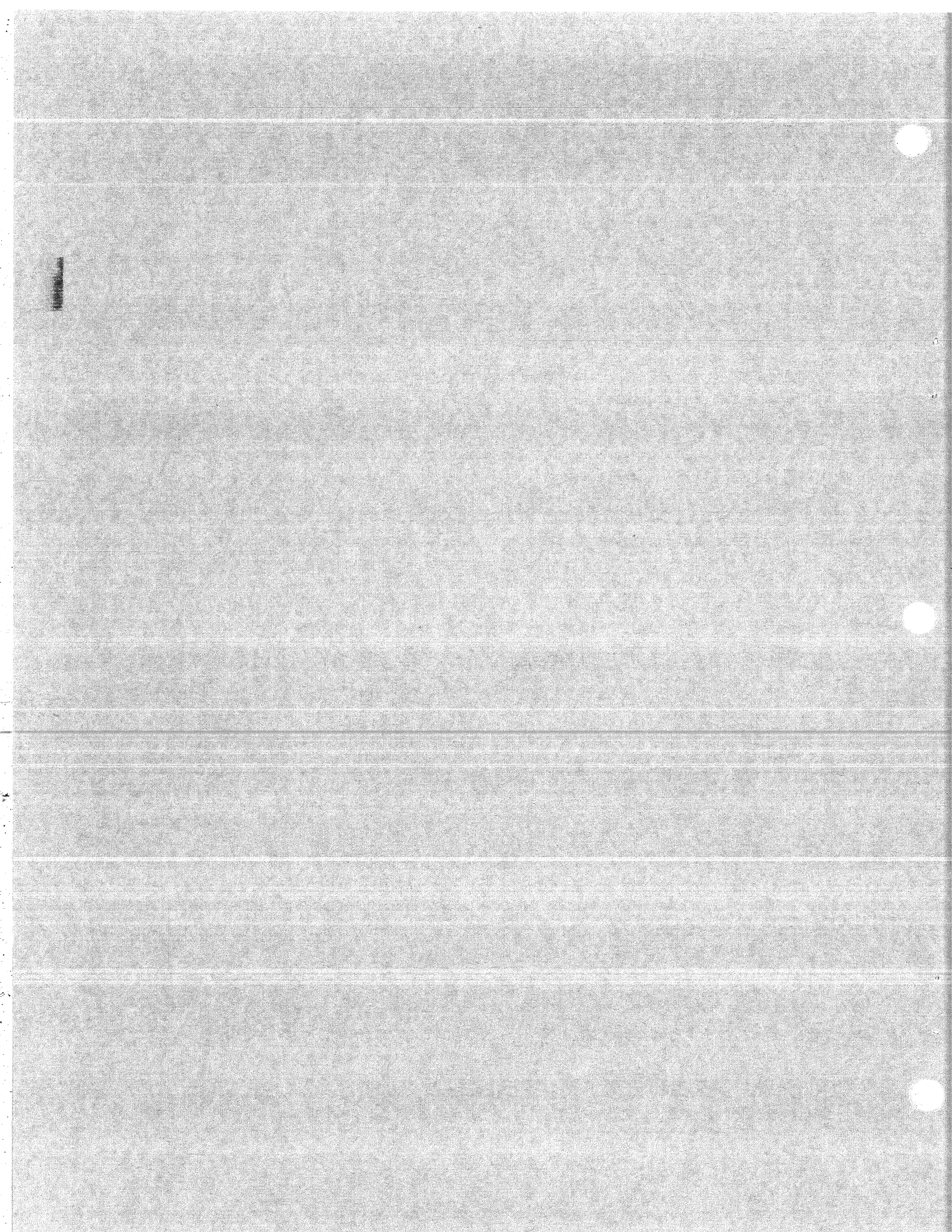
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## DECOUPLED $i_{13/2}$ NEUTRONS AND BACKBENDING IN RARE-EARTH NUCLEI

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### ABSTRACT

Analysis of rotational band structure in odd-N deformed rare-earth nuclei shows that if rotation-particle decoupling is the correct explanation for backbending in the region  $N = 92-96$ , then it can also explain the phenomenon in  $^{180}\text{W}$  and  $^{182,184,186}\text{Os}$ .

### A. INTRODUCTION

The discovery in 1972 of the so-called "backbending" effect<sup>1</sup> in the *yrast* band structure of even-even rare earth nuclei prompted an initial interpretation that the data confirmed the breakdown of nuclear superfluidity at high spins, an effect proposed ten years earlier by Mottelson and Valatin.<sup>2</sup> More recently however, Stephens and Simons<sup>3</sup> (SS) proposed that the observed effect could be explained in a much simpler, albeit related way, as arising from the recoupling of a single pair of  $i_{13/2}$  neutrons in a "rotation-aligned" coupling scheme.

Subsequent experimental data, especially those obtained in the odd-A neighbors of the "backbending" nuclei have for the most part tended to support the SS model. If indeed the  $i_{13/2}$  neutrons nearest the Fermi surface were

primarily responsible for the backbending effect, it seemed clear that the high-spin behavior of these neutrons in odd-N nuclei should provide a qualitative picture of what to expect in the neighboring even-even nuclei.

Stephens *et al.*<sup>4</sup> recently proposed a very simple criterion for gauging the adiabaticity of the single particle motion in the presence of a rotating core: the spin  $17/2 \rightarrow 13/2$  energy level spacing of the lowest  $i_{13/2}$  band is compared with the average  $2 \rightarrow 0$  spacing in neighboring even-even nuclei, the assumption being that the spacing should be identical in the decoupled limit. The results of such an analysis are less than conclusive, however, for the W and Os nuclei in precisely that region of the nuclear chart where the recent observation of striking "backbending" phenomena<sup>5</sup> seemed most difficult to understand in terms of the original SS model.

In this paper we show that a quantitative analysis of the particle-core decoupling in odd-neutron  $i_{13/2}$  rotational bands places the backbending phenomena in the even-even Os nuclei squarely within the domain of the SS model, and in fact can account for all such effects so far observed in the "rare-earth" deformed region with the notable exception of the  $^{170}\text{Yb}$  case.<sup>6</sup>

## B. CALCULATIONS

The experimental data pertinent to the calculations described consist of even-parity rotational and intrinsic states known to be associated with the  $i_{13/2}$  neutron orbitals. We have not made an exhaustive study of the data in this regard, but instead have made use of the available published wave functions obtained from Coriolis-coupling calculations on even-parity band structure in several odd-N rare-earth nuclei. All of the published calculations involve a similar procedure, more or less that described by Lindblad *et al.*,<sup>7</sup> for example. Briefly, the expansion coefficients in  $\Omega$  for the single-particle motion are



obtained by diagonalizing the Coriolis secular determinant, where the single particle energies are determined in a Nilsson-model calculation and corrected for the effects of pairing.

The Hamiltonian appropriate to the description of the various rotational and intrinsic states is taken as the sum of the quasi-particle energy and the rotational contribution, and is diagonalized with a consistent parameter set for each spin state. This yields the eigenvectors consisting of linear combinations in  $\Omega$  of the conventional wave functions which describe a nuclear rotation superimposed on an intrinsic state with projection  $\Omega$ .

$$|IM\rangle = \sqrt{\frac{2I+1}{16\pi^2}} \sum_{\Omega>0} f_{\Omega}^I \left[ \mathfrak{D}_{M\Omega}^I \chi_{\Omega} + (-1)^{I-\Omega} \mathfrak{D}_{M-\Omega}^I \chi_{-\Omega} \right]$$

Here, the  $f_{\Omega}^I$  are the expansion coefficients in  $\Omega$  obtained from the diagonalization for each spin.

With the availability of the  $f_{\Omega}^I$  coefficients for numerous even parity rotational bands in the rare earth region, it becomes a particularly simple matter to solve for the rotational energy,  $\langle \vec{R}^2 \rangle \hbar^2 / 2J$ , if one first transforms the conventional wave functions to the  $|IRj\rangle$  representation suggested by Vogel,<sup>8</sup>

$$|IRj\rangle = \sqrt{\frac{2I+1}{8\pi^2}} \sum_{\Omega=-j}^{+j} (-1)^{j-\Omega} \langle Ij\Omega-\Omega | RO \rangle \mathfrak{D}_{M\Omega}^I |j\Omega\rangle$$

The expectation value for the operator  $\vec{R}^2$  is then easily evaluated,

$$\langle \vec{R}^2 \rangle = \sum_{R,j} \langle IRj | IM \rangle^2 R(R+1)$$

where R is restricted to even values, and

$$\langle IRj | IM \rangle = \sqrt{2} \sum_{\Omega=\frac{1}{2}}^j (Ij\Omega-\Omega | RO) f_{\Omega}^I C_{j\ell}^{\Omega}$$

The  $C_{j\ell}^{\Omega}$  are the usual coefficients of the Nilsson wavefunctions; in this case only the  $i_{13/2}$  and  $g_{9/2}$  ( $\sim 10\%$ ) components are significant.

One is thus provided with a simple criterion for estimating the degree of particle-core decoupling in rotational bands. We have obtained values of  $\langle \vec{R}^2 \rangle$  for the even-parity bands in 18 deformed odd-N nuclei from  $^{155}_{64}\text{Gd}_{91}$  to  $^{187}_{76}\text{Os}_{111}$ . Fortunately, most of the available data span the region of greatest interest, i.e. those nuclei where a transition between backbending and normal behavior seems to occur. In Fig. 1 we show  $[\langle \vec{R}^2 \rangle - \langle \vec{R}_{\text{dec}}^2 \rangle]$  plotted as a function of spin for selected cases of interest. Here,  $\vec{R}_{\text{dec}}^2$  is just the decoupled limit; in that limit, the quantity plotted should approach zero. In the strong-coupling limit it is an increasing function of spin (cf.  $^{179}\text{Hf}$ ). On the left of Fig. 1 we show schematically just the  $I = 13/2$  values for other nuclei for which reliable wave-functions were available, and we indicate (boxes) those odd-A nuclides where one or more of the even-A neighbors display backbending<sup>4</sup> in the strictest sense (decreasing rotational frequency with increasing spin).

The picture emerges rather clearly from Fig. 1 that the regions of backbending nuclei are in general characterized by rotation-particle decoupling in the neighboring odd-A  $i_{13/2}$  band structure. The principal difference between the conclusions from our calculations and the data presented in Ref. 4 is the clear



inclusion in Fig. 1 of  $^{187}\text{Os}$  and  $^{179}\text{W}$  in the region of essential particle-core decoupling. Though the case for  $^{183}\text{Os}$  (bounded by backbending  $^{182}\text{Os}$  and  $^{184}\text{Os}$ ) is not so clear, it too becomes quite decoupled at relatively low spin. One also notes that  $^{179}\text{W}$  and  $^{159}\text{Dy}$  adjoin  $^{180}\text{W}$  and  $^{158,160}\text{Dy}$ , all three of which fail to meet the strict "backbending" requirement by only a few keV for at least one high spin state; the g.r.b. behavior of these three even-even nuclei is certainly anomalous.<sup>4</sup>

The single difficulty in drawing a broad conclusion from Fig. 1 is the  $^{170}\text{Yb}$  case. The appearance of "backbending" in the ground band of this nucleus is not so easily understood in the SS model. Neither  $^{169}\text{Yb}$  nor  $^{171}\text{Yb}$  approaches the degree of decoupling displayed by all the other odd-A nuclei in the vicinity of "backbenders". Some authors<sup>6,9</sup> have attempted to explain the  $^{170}\text{Yb}$  data in the pairing-collapse theory as a partial consequence of the variation in level density near the Fermi surface for the series  $^{166,168,170}\text{Yb}$ , and in view of the modest decoupling exhibited by the  $i_{13/2}$  particles in  $^{169}\text{Yb}$  and  $^{171}\text{Yb}$ , it may well be that the  $^{170}\text{Yb}$  g.r.b. singularity arises from a more concerted breakdown of pairing at high spins.

An obvious question to be asked with regard to the results for  $^{179}\text{W}$  and  $^{183,187}\text{Os}$  in Fig. 1 is why the comparison of rotational energy spacings in the  $9/2^+[624]$  and  $11/2^+[615]$  bands in these nuclei fails to indicate the highly decoupled character of those bands. Although the band-fitting which we have carried out for those nuclei makes use of much more experimental information than does the analysis in Ref. 4, it is also true that the even-even moment of inertia is implicit in the band-fitting calculations. One might suspect that the  $17/2 \rightarrow 13/2$  spacing of the  $i_{13/2}$  bands in  $^{179}\text{W}$  and  $^{187}\text{Os}$  is somewhat misleading, and there is some evidence that this is indeed the case, as the data in Fig. 2 show. The  $17/2 \rightarrow 13/2$  energy spacing in the

higher- $\Omega$  bands appears to be anomalously large when compared with  $^{161}\text{Er}$  and  $^{163}\text{Er}$ , both relatively well-decoupled cases. For higher-spin states however, the spacings of the  $^{183,187}\text{Os}$  and  $^{179}\text{W}$  "favored" spin states ( $I = j+2, 4, 6 \dots$ ) fall rather quickly into much closer agreement with the  $^{161,163}\text{Er}$  spacings. It thus seems likely that the higher-spin states in the high- $\Omega$   $i_{13/2}$  bands provide an important constraint on the wave functions obtained in the band-fitting procedure.

Finally, an important question to be answered is just how sensitive the wavefunctions obtained from the Coriolis matrix diagonalizations of various groups are to the details of the fitting parameters. This is very important for the reliability of the curves in Fig. 1, since only the wavefunctions are used in our calculations. Fortunately, it is our experience and apparently that of other groups as well,<sup>10</sup> that the wave-functions are not in fact very sensitive to the quality of the fit to the energy data. In the case of  $^{187}\text{Os}$  for example, we performed numerous fits at various times as the analysis of our data progressed. Though the eigenvectors for the higher-lying (unseen) bands showed considerable variation in these fits, those of the two bands for which experimental data were available ( $11/2^+[615]$  and  $9/2^+[624]$ ) varied but little with relatively large changes in the input parameters and the quality of the energy fits.

In summary, a simple, quantitative criterion for the tendency of high- $j$  particles to decouple from the nuclear core rotation has been presented. If decoupling of  $i_{13/2}$  neutrons from the core is indeed the explanation for "backbending" in the ground rotational band of neutron-deficient even-even deformed rare-earth nuclei where the effect was first reported, then that explanation can apply equally well to the W and Os isotopes which have also been found to exhibit strong backbending behavior.<sup>5</sup> While the possible role of



$h_{9/2}$  protons in this region should not be ignored,<sup>4</sup> it appears that an understanding of the ground-band behavior in  $^{180}\text{W}$  and  $^{182-186}\text{Os}$  does not require the involvement of protons. The  $^{170}\text{Yb}$  case is difficult to explain in this picture however, and may offer the first instance of a departure from the straightforward Stephens-Simon model.

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FIGURE CAPTIONS

Fig. 1 The approach to rotation-particle decoupling for even-parity (predominant  $i_{13/2}$ ) rotational bands in several odd-A rare-earth nuclei. Not all spins are plotted for all nuclei, but data for spin  $13/2$  are indicated on the left portion in each case. The  $^{179,181}\text{W}$  and  $^{183,187}\text{Os}$  data are from our laboratory; wavefunctions for all other nuclei are taken from references cited in Ref. 4.

Fig. 2 Qualitative estimate of particle-core decoupling deduced from ratio of transition energies in odd-A and neighboring even-even nuclei (cf. Ref. 4). The coupled limit for spin  $17/2$  is 5.33.





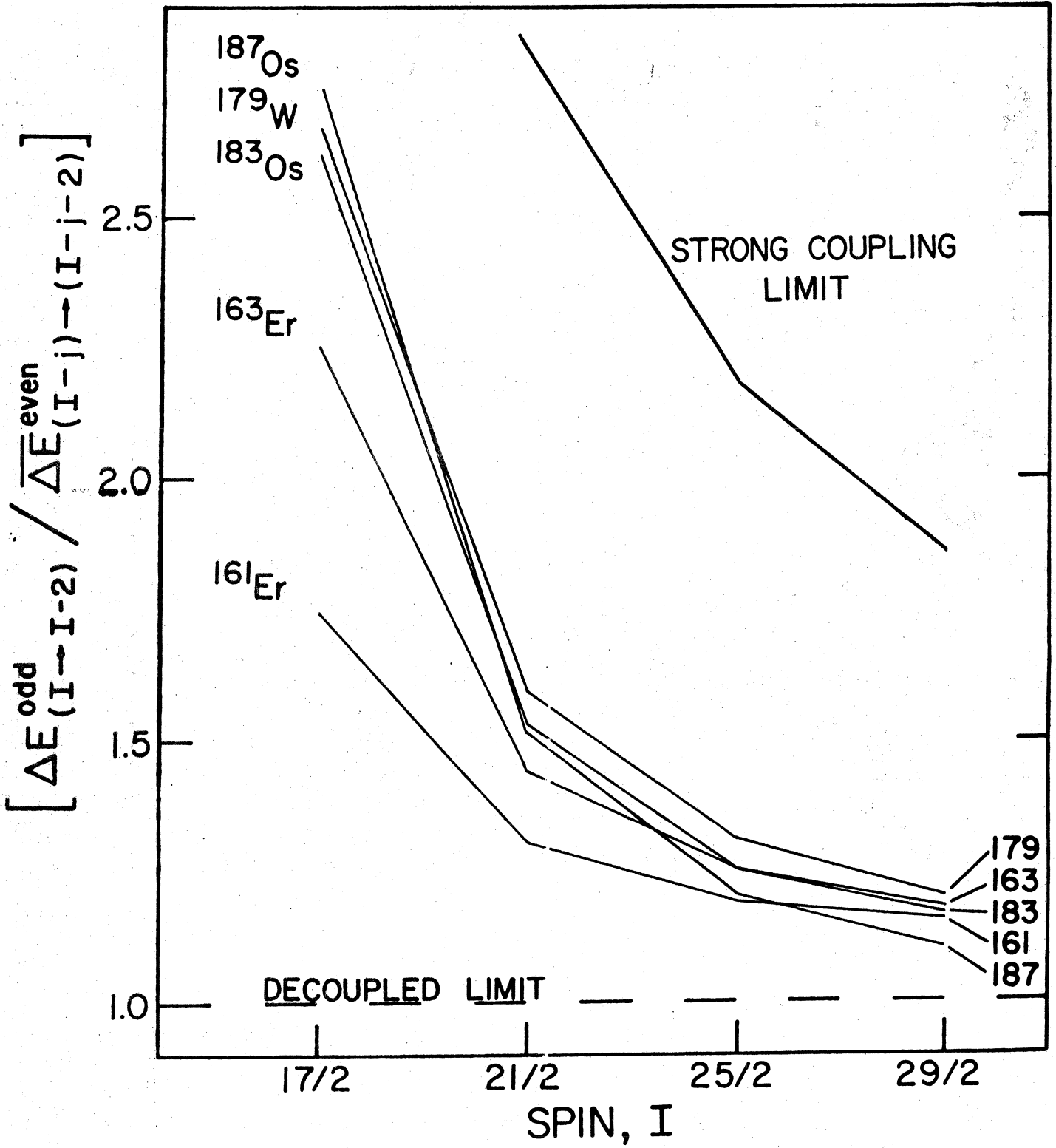


Fig. 2



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