BNL-26770

CONF-790976--6

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MASTER

Invited Talk Presented At

International Symposium on Future Directions in Studies of Nuclei Far from Stability

Nashville, Tennessee - September 10-13, 1979

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Pseudomagic Nuclei*

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It was shown previously that, below a critical angular momentum, yrast bands of non-magic nuclei are well described by the two-parameter Variable Moment of Inertia model. Some striking exceptions to this rule are found in nuclei which have the same mass number as doubly magic nuclei but possess either one (or two) proton pairs beyond a magic number and one (or two) neutron hole pairs, or vice versa. Yrast bands in these "pseudomagic" nuclei resemble those in magic nuclei.

The recognition of the existence of "pseudomagic nuclei" [1] evolved from a new, more stringent test of the validity of the Variable Moment of Inertia (VMI) equations near the lower limit, i.e. for near-magic nuclei. Whereas previously only states with $J \leq 8$ had been known in this region, the present test includes states with $J \leq 14$.

The VMI equations

$$(1) \quad E_J = C(\mathcal{J} - \mathcal{J}_0)^2 + \frac{J(J+1)}{2\mathcal{J}}$$

$$(2) \quad \frac{\partial E}{\partial \mathcal{J}}\Big|_J = 0$$

where $\mathcal{J}(J)$ denotes the effective moment of inertia and C and $\mathcal{J}_0$ are parameters characteristic for a given nucleus, were shown to describe [2,3] with surprising accuracy the energies of "yrast bands" in non-magic even-even nuclei ($J\pi$ = 0+, 2+, 4+, 6+, 8+ .... up to J_c, the critical angular momentum at which a sudden increase of $\mathcal{J}$ occurs). The energies of yrast bands are most efficiently presented in a "Mallman plot" which relates the ratios $R_J (\equiv E_J/E_2)$ to R_4. The limit of validity [2] of the VMI equations is reached for $\mathcal{J}_0 = -\infty$, giving $E_J \propto (J(J+1))^{1/2}$ and thus $R_4 = 1.82$. Between $\mathcal{J}_0 = 0$ and $\mathcal{J}_0 = -\infty$, the ground state moment of inertia is $\mathcal{J}(0) = 0$. Nuclei in this region are one or two pairs of particles or holes away from singly magic [4]. Below $R_4 = 1.82$ are found yrast bands of singly and doubly magic nuclei, which are characterized by appreciably higher excitation energies of the first 2+ state than their non-magic neighbors. The increase in excitation energy is due to the fact that in magic nuclei excitation can only take place by promotion of one or two nucleon pairs to a higher orbit. A drastic reduction in energy spacings occurs above the 2+ state, which leads to a near degeneracy of the 4+, 6+, and 8+ states in the Mallmann plot. Theoretical efforts to find a microscopic basis for the VMI model have yet to succeed [5].

A second expression which yields curves of the Mallmann type is the heuristic Ejiri formula [6]

$$(3) \quad E_J = aJ + kJ(J+1), \text{ which leads to}$$

$$(4) \quad R_J = \frac{J(J-2)}{8} R_4 - \frac{J(J-4)}{4} .$$

The Ejiri formula was later shown to be identical with a formula resulting from the anharmonic oscillator model [7]. The recently proposed interpretation of collective bands in even-even nuclei in terms of three subgroups of SU(6), namely SU(5) (applied to vibrators), SU(3) (applied to rotors), and O(6) (applied in detail to the transitional nucleus ${}^{196}Pt$), deduced from the "Interacting Boson Approximation" (IBA) [8], also represents the yrast band energies and energy ratios by (3) and (4). However, a comparison [7] of the predictions from the two sets of equations showed that for $J = 6$ and even more for $J = 8$ equations (1) and (2) give a considerably better fit.

At the time the extended VMI model [2] was proposed, the only striking exception noted was for ${}^{208}Po$ which, with $R_4 = 1.96$, lies in the "spherical region" ($1.82 \leq R_4 \leq 2.23$). We stated then that one is tempted to include ${}^{208}Po$ in the "magic branch," which extends to the right from $R_4 > 1$.

The results of a study [9,3] of the yrast bands of Te and Cd nuclei suggest an explanation for the exceptional structure of the ${}^{208}Po$ spectrum: it was found that for ${}^{132}Te$ which possesses 2 valence protons and 2 neutron holes away from the closed shells 50 and 82 respectively, R_4 lies even below the VMI limit, namely at 1.716, i.e. in the magic region, and R_6 lies "on the magic branch"! Since ${}^{208}_{84}Po_{124}$ is also characterized by 2 valence protons and 2 neutron holes (away from the magic numbers 82 and 126 respectively), it seems tempting to propose the hypothesis that two particles of one kind (neutrons or protons) may couple to two holes of the other kind to form a "pseudomagic" nucleus.

A previously started experimental investigation of nuclei pertaining to the "spherical" region, $1.82 \leq R_4 \leq 2.23$, namely of the neutron deficient Pd ($Z = 46$) nuclei, appears to support this hypothesis. Whereas in Ref. [2] only states with $J \leq 8$ were included, we populated yrast bands in ${}^{104}Pd$ [10], ${}^{102}Pd$ and ${}^{100}Pd$ [11, 12], and ${}^{98}Pd$ [13], up to $J = 14$. While the results for ${}^{98}Pd$ and ${}^{102,104,106}Pd$ [14] turn out more or less as expected (Fig. 1a) (i.e. the R_6 and R_8 values agreed with VMI predictions (and for ${}^{98}Pd$ and ${}^{102}Pd$ the agreement continues to $J = 12$ and 14, respectively)), the spectrum of ${}^{100}Pd$ displays an increasing downward deviation from the VMI predictions, indicating "backbending" already above the 4+ state. As ${}^{100}Pd$ possesses four proton holes and four neutrons away from the magic number 50, this result suggests that also two nucleon pairs can couple to two hole pairs to form a pseudomagic nucleus, but that in this case the reduction in energy spacing is not as abrupt as in the case of one nucleon pair being coupled to one hole pair: here the 6+ and 8+ states are far from degenerate, implying that the moment of inertia does not increase as radically as in nuclei with one particle pair - one hole pair.

Fig. 1b compares the experimental data also to the predictions from Eq. 4. In order to carry out the comparison, we have extended the "Ejiri curves" to $R_4 = 1.82$, the limit of validity of the VMI model. (One notices that below $R_4 = 2$, the sequence of states according to the Ejiri formula becomes inverted, so that the 18+ state eventually coincides with the 4+ state. Behavior of this type has never been observed.) It is seen that in contrast to the good fit of the VMI model (with the exception of ${}^{100}Pd$), the agreement of the Pd spectra with the Ejiri curves is far from satisfactory.

The hypothesis of the occurrence of pseudomagic structure can be further tested using all known spectra of nuclei possessing one (two) particle pairs - one (two) hole pairs, as shown in Fig. 2. It is obvious that the expected features indeed occur in all cases known, namely in ${}^{40}_{18}Ar_{22}$, ${}^{88}_{40}Zr_{48}$, (${}^{88}Sr$ is considered to be doubly magic), ${}^{48}_{22}Ti_{26}$, ${}^{48}_{24}Cr_{24}$, ${}^{132}_{54}Xe_{78}$ and ${}^{208}_{86}Rn_{122}$ [15]. The only exception is ${}^{56}Fe$, an isobar of ${}^{56}Ni$, whose 6+ and 8+ states are quite close to the VMI curves. It may be noted here that for the one particle pair - one hole pair excitation in ${}^{48}Ti$, level energies based on a generator coordinate method and on two different shell model calculations deviate appreciably from the experimental spectrum, although the two shell model calculations agree well with each other [16]. One

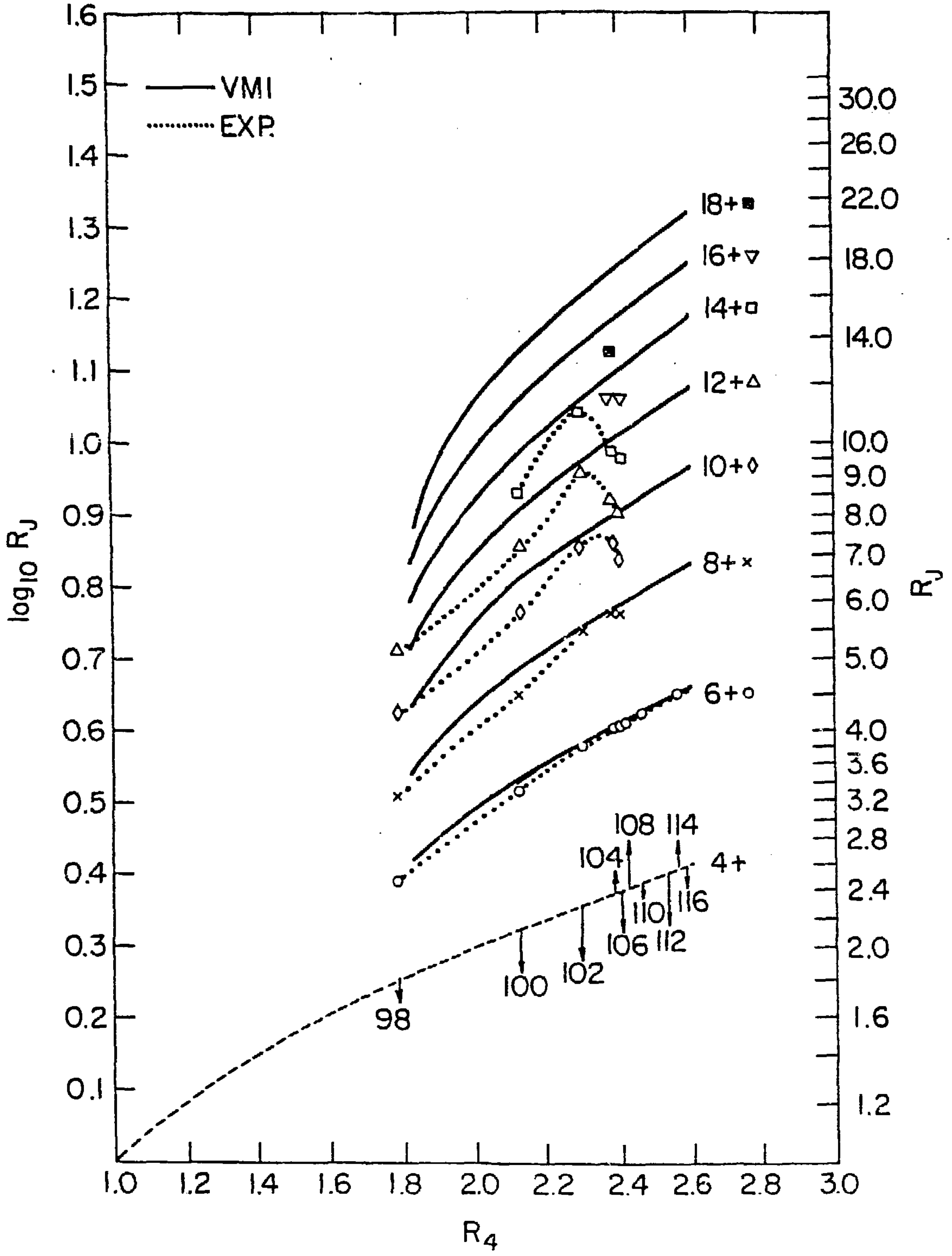

Figure 1a: Comparison of ground state band energies in even-even Pd nuclei with predictions of the VMI model (solid lines). The figure presents log R_J vs R_4 (the lowest curve (short dashes) indicates R_4 on the logarithmic scale, with arrows pointing to the mass numbers of even-even Pd nuclei). (See text.)

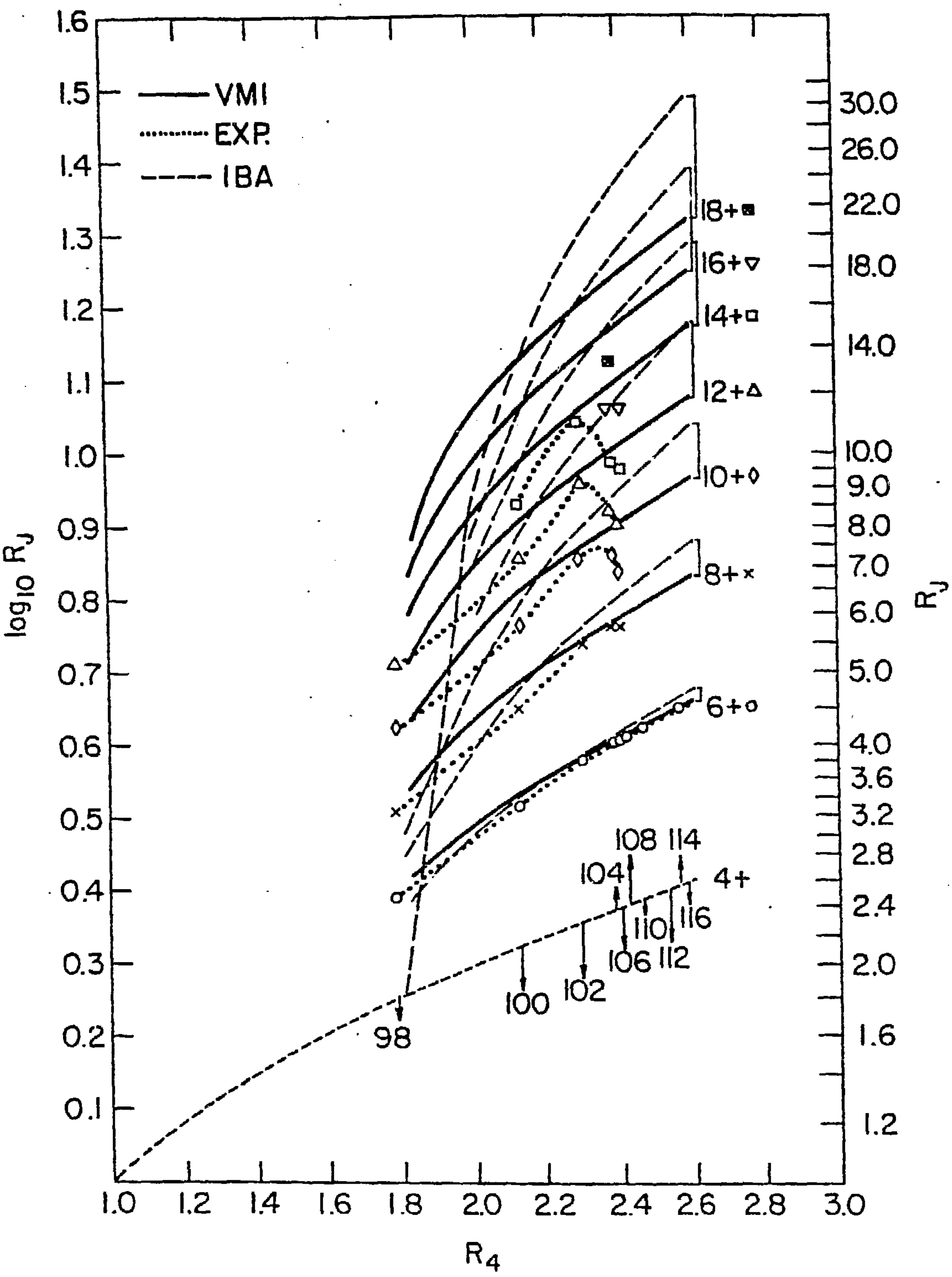

Figure 1b: This figure is identical with Fig. 1a, apart from the fact that experimental points are here also compared with the Interacting Boson Approximation (IBA) or Ejiri predictions (Eq. 4). It is noteworthy that the IBA curves tend to cross each other below $R_4 = 2$, i.e. the order of the predicted states in the band is reversed--a phenomenon which contradicts observation.

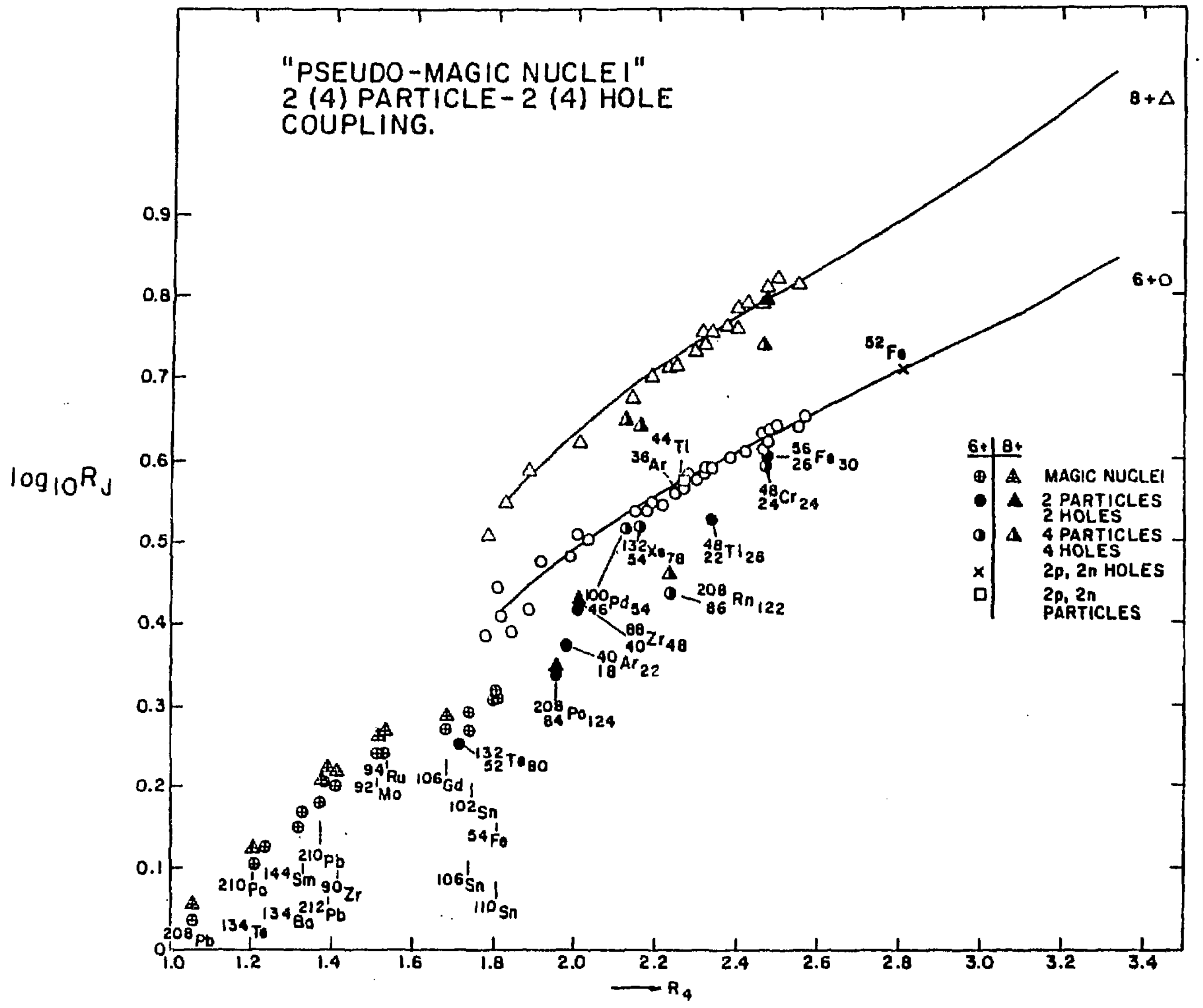

Figure 2: The values log R_J for pseudomagic nuclei as well as for doubly and singly magic (see Ref. 2) and "ordinary" non-magic nuclei are plotted vs R_4. In one of the pseudomagic nuclei, namely ^{132}Te, "backbending" occurs already above the 2+ state, while in the remaining nuclei it occurs above the 4+ state.

may raise the question whether the presence of one valence proton pair and one valence neutron pair or of one proton hole pair and one neutron hole pair might also produce a pseudomagic spectrum. However, this is not the case. As is seen from Fig. 2, the R_6 values for $^{36}_{18}Ar_{18}$ (h-h), $^{44}_{22}Ti_{22}$ (p-p) and $^{52}_{26}Fe_{26}$ (h-h) agree excellently with the VMI curve.

It seems plausible that the exceptional behavior of yrast bands in pseudomagic nuclei is related to the fact that the nuclear quadrupole moment changes sign at the magic number. Hence the presence of a particle pair and a hole pair may be expected to bring about a partial cancellation of the prolate versus the oblate shape [17]. The backbending observed at low J in these nuclei ($J \leq 4$ instead of $J \geq 8$) may be attributed to a change in shape brought about by the effect of cranking which counteracts the cancellation of opposing shapes and thus leads to an abrupt shape change. The lack of pseudomagic behavior in ^{56}Fe is probably ascribable to the poor overlap of the orbits of the proton hole pair ($f_{7/2}$) with those of the neutron pair ($p_{3/2}$ or $p_{1/2}$), which suppresses cancellation. It would be interesting to compare the yrast band energies of two pseudomagic nuclei which might yield to experimental investigation, namely ^{16}C, an isobar of ^{16}O, for which only E_2 and E_4 have so far been determined, and ^{100}Cd, an isobar of ^{100}Sn, for which no excited state appears to be known.

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*Research supported by US Department of Energy, under Contract No. EY-76-C-02-0016.

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[17] I am indebted to L. Zamick for this suggestion.