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TESTS OF SUPERSYMMETRIES WITH THE (n,γ) REACTION

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ABSTRACT

The characteristics of the SU(3) and O(6) boson-fermion symmetries stemming from a U(6/12) group structure are discussed and compared with recent results of (n,γ) studies in the W-Pt region. The nuclei ^{185}W and ^{195}Pt are shown to represent the best empirical examples of the SU(3) and O(6) limits, respectively, and it is also shown that the Consistent Q Formalism can be extended to the odd A Hamiltonian to describe the transition between these two limits. Preliminary comparisons with the low lying structure of the odd Os nuclei are presented. The question of the empirical evidence for supersymmetry in this region is also discussed.

1. INTRODUCTION

The development of the Interacting Boson-Fermion Model[1], and the recognition of its associated symmetries[2], offers the chance to test our understanding of the collective structure of odd A nuclei over far broader ranges of mass and excitation energy than has hitherto been possible. This extension in scope stems principally from the inclusion of a core description which can run the full gamut of vibrational, rotational or asymmetric structure, and which incorporates essentially all collective excitations. Thus, in the region of well deformed nuclei, for instance, one can expect the model to generate an equally detailed description of both the low lying rotational structure which emerges from a Nilsson model treatment, and the subsequent vibrational modes which to date have, in general, been treated only qualitatively. Moreover, in regions outside those of axially symmetric deformation or near sphericity, the IBFM's capabilities should prove even more crucial, since here deficiencies in the core description can manifest themselves even at low excitation energies.

The validity of the IBFM can obviously first be examined in terms of its ability to reproduce odd-even structure in regimes which are already well understood. However its advantages, and the new insights which it may offer, must be searched for in regions which are as yet only poorly understood and, as a result, often neglected in experimental studies. The hallmark of the model, as explained above, is its implicit ability to generate the complete spectrum of collective modes in the odd A nucleus, and thus one of the most suitable probes to test it is the (n,γ) reaction. The statistical nature of the decay of the compound state formed after neutron capture ensures population of a broad range of final states, irrespective of their specific structural characteristics. The use of the Average Resonance Capture (ARC) technique is particularly important in this regard since it results in a reduction in the fluctuations inherent in the statistical origins of the final state population, to the point where typically all final states which can be attained by E1 primary radiation must be populated, up to an excitation energy dependent on the sensitivity of the measurement. Thus the completeness of the theoretical predictions is tested in absolute terms.

2. SYMMETRY IN ODD-EVEN NUCLEI

The development of the IBFM is following a similar course to that of its even-even counterpart and predecessor, the IBM. Thus the "basic" Hamiltonian appears relatively complex and holds little hope for physical intuition. For instance, the number of terms, and hence number of parameters, in the boson-fermion interaction alone is approximately n^3, where n is the number of single particle orbits considered. Nevertheless, as in the case of the IBM, it is possible to simplify the situation, and at the same time produce a Hamiltonian whose terms have a more physical interpretation, and which can be applied to broad ranges of nuclei in a comprehensible way. This simplification involves two steps. In the first, the various terms in the Hamiltonian are grouped according to their tensorial properties, so that, in the IBFM, only two significant composite contributions to the boson-fermion interaction remain, a quadrupole-quadrupole term and an "exchange" term. Note that essentially all descriptions of collective odd A structure incorporate a Q·Q interaction between core and particle, and hence it is the exchange term which is particular to the IBFM, in that it implicitly recognizes the underlying fermionic origins of the bosonic core.

The second step centers on the recognition of dynamical symmetries. These provide analytic solutions in certain specific limits of the general Hamiltonian and can be associated with a well defined geometrical structure appropriate to particular regions of nuclei. They thus define starting points, at least, in determining the parameterization of a specific nucleus, and they also provide insights into how to change that parameterization in a smooth and physically reasonable way to describe the transition regions between symmetries.

The group structure of a boson-fermion system is described by $U^B(6) \times U^F(m)$ where m specifies the number of states available to the odd fermion, and thus depends on the single particle space assumed. The ability to construct group chains corresponding to the symmetries SU(5), SU(3) or O(6) depends on the value of m, and this problem has already been discussed in detail in a separate contribution[3]. Of the structures studied in detail to date, the case of m=12 is the one with the broadest potential. The fermion is allowed to occupy orbits with j = 1/2, 3/2 and 5/2, so that the assumed single particle space corresponds to the negative parity states available to an odd neutron at the end of the N = 82-126 shell, namely, $p_{1/2}$, $p_{3/2}$ and $f_{5/2}$. The region of interest thus spans the W-Pt nuclei, and since one prerequisite for an odd-A symmetry is the existence of that same symmetry in the neighboring even-even core nucleus, the odd Pt nuclei around A = 196 offer the obvious testing ground for the O(6) limit[4] of U(6/12). The heavier even-even W nuclei, on the other hand, have the characteristics of an axial rotor, and hence the negative parity structure of the neighboring odd W isotopes offers the possibility to study the validity of the SU(3) limit. Finally, given a definition and understanding of these two limits, the construction of a simple description of the transitional odd A Os nuclei can be considered.

The above discussion centers on symmetries in the boson-fermion system. However, if a particular symmetry exists in neighboring even-even and odd-even nuclei, it is possible to ask whether the two schemes stem from a common parent supersymmetric group structure of the type U(6/m). The only way to examine such a question in the nuclear regime is to test whether the members of a given supermultiplet, characterized by a constant total number of bosons and fermions, can all be described by a single Hamiltonian. In practice, this reduces to asking whether the odd-even and appropriate even-even nuclei can be described with the same parameters.

3. (n,γ) STUDIES IN THE W-Pt REGION

As pointed out earlier, the (n,γ) reaction in general, and the ARC technique in particular represent ideal probes to test the completeness of the predicted IBFM symmetry schemes. Such data must, of course, be complemented by studies that probe the structure of the states via single particle transfer cross sections or electromagnetic matrix elements. Nevertheless, the (n,γ) studies represent the crucial first step in locating essentially all low-lying, low spin states in the nuclei of interest.

A detailed discussion of the physical principles underlying the ARC technique is presented in a separate contribution[5] to these proceedings. However, it is worth summarizing the basic characteristics of the method here, and considering how they pertain to the specific case of odd mass nuclei in the W-Pt region.

In single resonance, or thermal, neutron capture, the γ decay of the compound state to low-lying final states is characterized by intensities which, after correction for an energy dependence, follow a Porter-Thomas distribution with one degree of freedom. The form of such a distribution is illustrated by the $\nu=1$ curve in Fig. 1a. Clearly, the probability for zero decay width is high; so that not all final states need be populated and those that are will be fed with widely ranging intensities. The ARC technique overcomes these problems by using neutron beams with a finite spread in energy, such that a number of resonances are encompassed. This results in a corresponding reduction in the intensity fluctuations, as shown in Fig. 1a. As the number of resonances (or ν) becomes large, the intensity distribution tends to a Gaussian with variance $4/\nu$.

Given sufficient averaging, therefore, a complete set of levels populated by E1 primaries can be established. In the case of interest here, this corresponds to $J^{\pi} = 1/2^-, 3/2^-$ states in the odd A nuclei in the W-Pt region. However, the resonance level

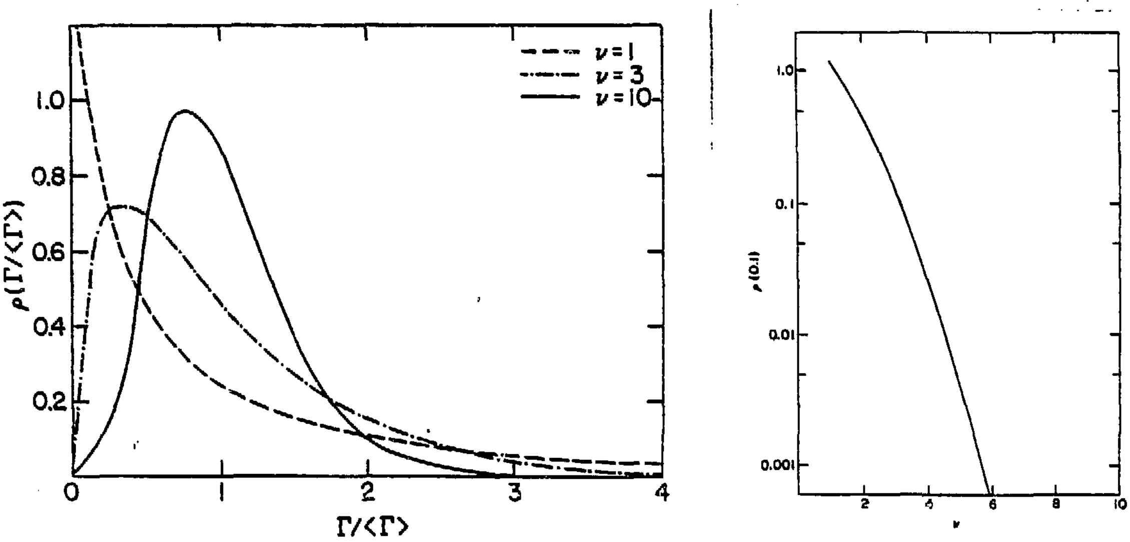

Fig. 1. a) Porter Thomas distributions for different numbers of degrees of freedom ν.
b) The probability function for $\Gamma/\langle\Gamma\rangle$=0.1.

density for these nuclei is low, so that on average only 5-10 resonances are involved in the averaging process. The question then arises as to whether the population of even $J^\pi = 1/2^-, 3/2^-$ states can be guaranteed under such conditions. The answer can be seen in Fig. 1b, which shows the probability function for $\Gamma/\langle\Gamma\rangle$ = 0.1, i.e., for primary intensities one tenth of the mean. It is clear that for ν=5, the probability is already negligible. Since a reduced intensity of 10% of the mean is easily observable in these measurements, at least up to excitation energies ≈ 1200 keV, one can conclude that the ARC technique can still guarantee population of all $J^\pi = 1/2^-, 3/2^-$ states in this region.

4. ODD Pt NUCLEI: THE O(6) LIMIT OF U(6/12)

As pointed out in Section 2, the well established O(6) symmetry in ^{196}Pt and its neighbors[4], coupled with the isolated $p_{1/2}$, $p_{3/2}$ and $f_{5/2}$ orbits available to an odd neutron in this region, implies that the odd Pt nuclei should offer the best opportunity to test the predictions of the O(6) group chain of U(6/12). The results of recent (n,γ) studies[6] of ^{195}Pt are summarized in the level scheme of Fig. 2. The scheme was constructed following ARC studies at Brookhaven National Laboratory, and also measurement of the secondary γ-ray spectrum with the GAMS curved crystal spectrometers at the Institut Laue-Langevin, Grenoble. It is worth noting that the completeness of the observed set of $J^\pi = 1/2^-, 3/2^-$ states led to the establishment of a level at 222 keV which had hitherto escaped detection in other studies[7]. As will become apparent, this level plays a crucial role in the structural interpretation of this nucleus.

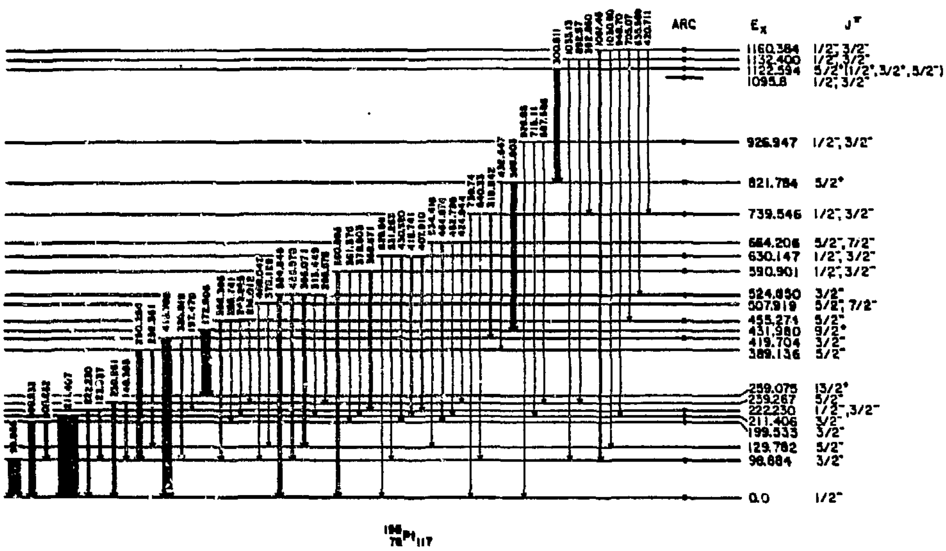

Fig. 2. The level scheme of ^{195}Pt (ref. 6).

It is evident that ^{195}Pt displays no obvious rotational structure. Indeed, simply the number of low-lying $J^{\pi} = 1/2^-$, $3/2^-$ states precludes a simple Nilsson description, since a maximum of 8 such states can arise from the Nilsson orbits in this region. These features stem, of course, from the nature of the core nucleus which exhibits γ-unstable, rather than axially-symmetric structure. Moreover, earlier attempts[8] to allow for this difference by including the effects of coupling to the low-lying 2^+_γ core state also encountered severe problems, and appear unable to account for the newly discovered 222 keV state. Thus it appears that a more complete and realistic core description is necessary.

The comparison with the U(6/12) O(6) symmetry scheme is given in Fig. 3. The origins of this scheme, and its associated quantum numbers, have been discussed in detail elsewhere[9]. It is therefore sufficient to remark here that it offers an adequate description of the observed structure, at least below 600 keV. It is particularly encouraging that a one-to-one correspondence can be made between experimental and theoretical levels up to this energy. Moreover, subsequent (n,n',γ) studies[10] have removed a number of the ambiguities in the spin assignments of Fig. 2, and in all cases, the results confirm the association of states shown in Fig. 3. Data from Coulomb excitation studies[7,11] and single particle transfer studies[12] are also largely in agreement with the symmetry predictions, although some important discrepancies have been found[13] in the latter case for the reaction ^{195}Pt+^{196}Pt. However, it is possible, and indeed likely, that these stem from uncertainties in the form of the IBFM transfer operator itself.

A distinctive feature of the symmetry scheme is the existence of couplets of levels with J, J+1 separated by a constant J(J+1) spacing. This feature shows up clearly in the data and results

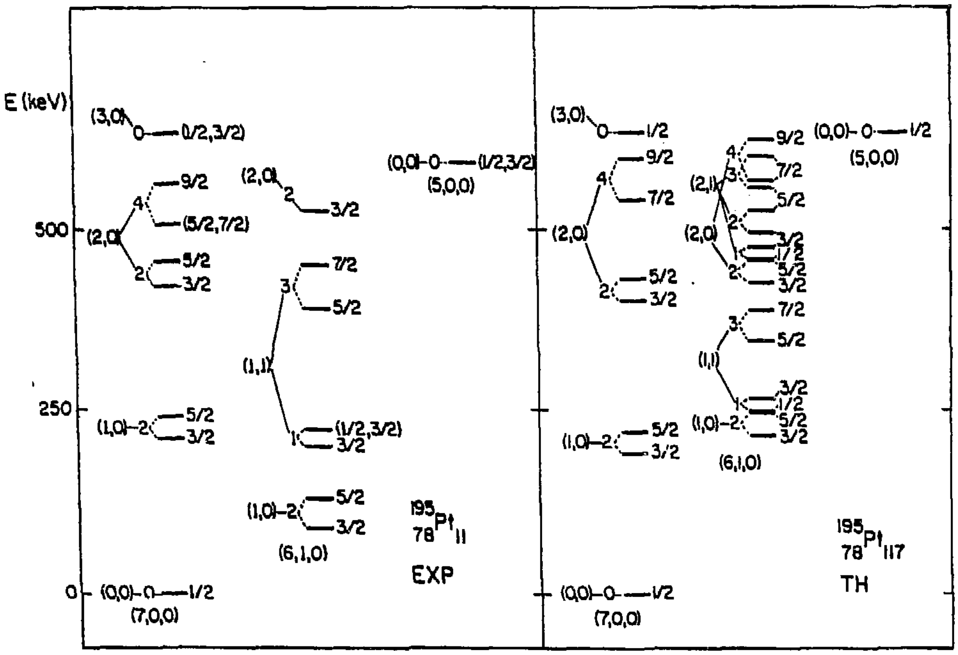

Fig. 3. A comparison of the O(6) symmetry scheme of U(6/12) with the levels of ^{195}Pt.

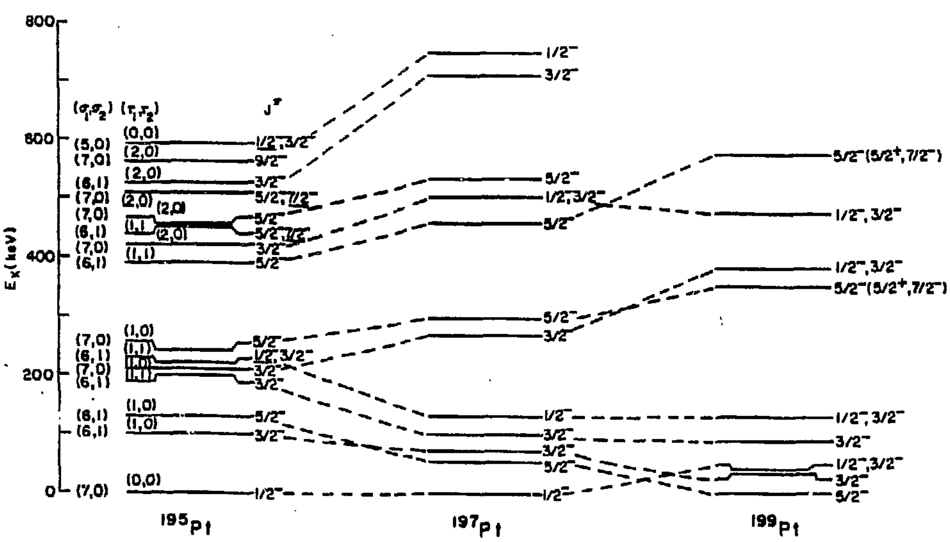

Fig. 4. Association of low lying levels in ^{195,197,199}Pt.

from the pseudo-spin symmetry inherent in all the group chains of U(6/12). There is, however, a clear discrepancy between theory and experiment at higher excitation energies in that the predicted states in the representation labelled [N,1] are two compressed, relative to the data. A modification to the original scheme which removes this problem, while maintaining the symmetry, is discussed in ref. 14.

It is clearly of interest to study if, and for how long, the symmetry structure persists in neighboring odd Pt nuclei, and to this end further ARC studies were made of ^{197,199}Pt. The results of these are discussed in detail in ref. 15, but can be summarized by reference to Fig. 4, which shows the evolution of the low lying states in this region. The number of low lying $J^{\pi} = 1/2^{-}, 3/2^{-}$ states found in ^{197}Pt was essentially identical to that in ^{195}Pt, and the couplet structure is also evident, although with less constancy in spacing. The situation for ^{199}Pt is, however, far less convincing. These basic conclusions are confirmed by a study[12] of single particle transfer cross sections, which indicate substantially increased symmetry breaking in ^{197}Pt.

5. ODD W NUCLEI: THE SU(3) LIMIT OF U(6/12)

The SU(3) limit of U(6/12) requires a rotational core structure, coupled to j = 1/2, 3/2 and 5/2 orbits. The odd W nuclei represent the best chance of observing characteristics of this symmetry since, in nuclei of lower mass in the well deformed rare earth region, the Fermi surface is progressively farther from the single particle orbits of interest. The predicted representations and their associated quantum number are illustrated in Fig. 5 for the case of coupling the boson and fermion degrees of freedom at the level of U(6), and again the reader is directed elsewhere[16] for a more detailed discussion of the origins of the scheme.

The SU(3) limit has the attractive advantage that its predictions can be compared with those of the Nilsson model for the same shell model states, so that a more physical interpretation of its structure can be formulated. To facilitate this type of comparison, the rotational band structure has been indicated in Fig. 5, in terms of the K quantum numbers of the bands contained within each SU(3) representation. Moreover, the results of a detailed study[16] have shown that in the lowest two representations, the only core states involved are those of the ground state rotational band, so that, in these cases, the bases of the two descriptions are identical. A more quantitatively-based link can then be established by means of the single particle structure of the wave functions. This is illustrated in Fig. 6, where the quantity $C_{j\ell}^{eff}$ is compared for the lowest three bands in the SU(3) scheme, and the lowest of the Nilsson orbits emanating from the $p_{1/2}$, $p_{3/2}$ and $f_{5/2}$ states, namely, the 1/2[521], 1/2[510] and 3/2[512] bands. The $C_{j\ell}^{eff}$ values in the Nilsson scheme correspond to the sum of $C_{j\ell}$ coefficients for a state I=j over the Coriolis mixed orbits. Coriolis coupling should be incorporated automatically in the equivalent IBFM scheme, and it is easy to show that the equivalent

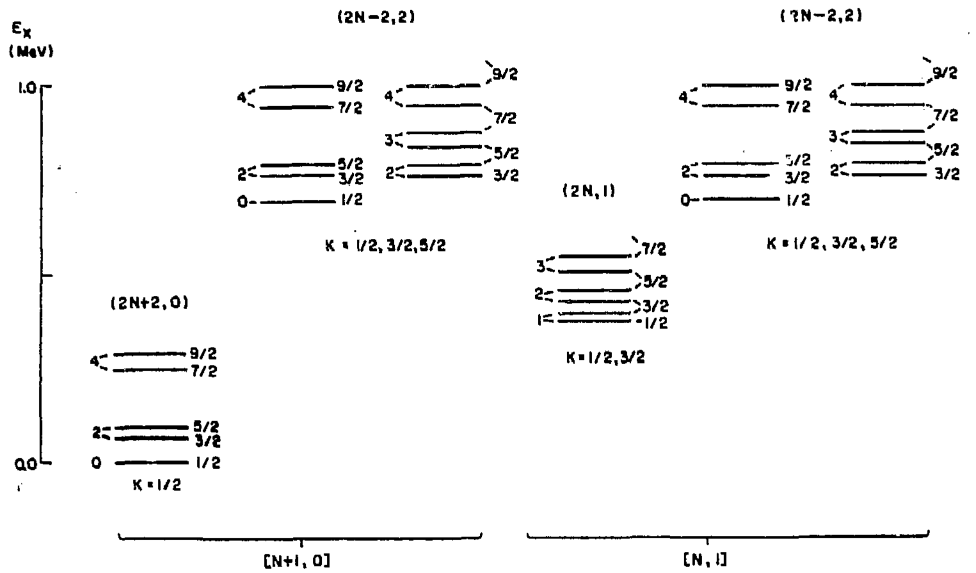

Fig. 5. The SU(3) scheme of U(6/12). Representations are labelled by the (λ,μ) quantum number of $SU^{BF}(3)$ and by the $[N_1N_2]$ labels of $U^{BF}(6)$.

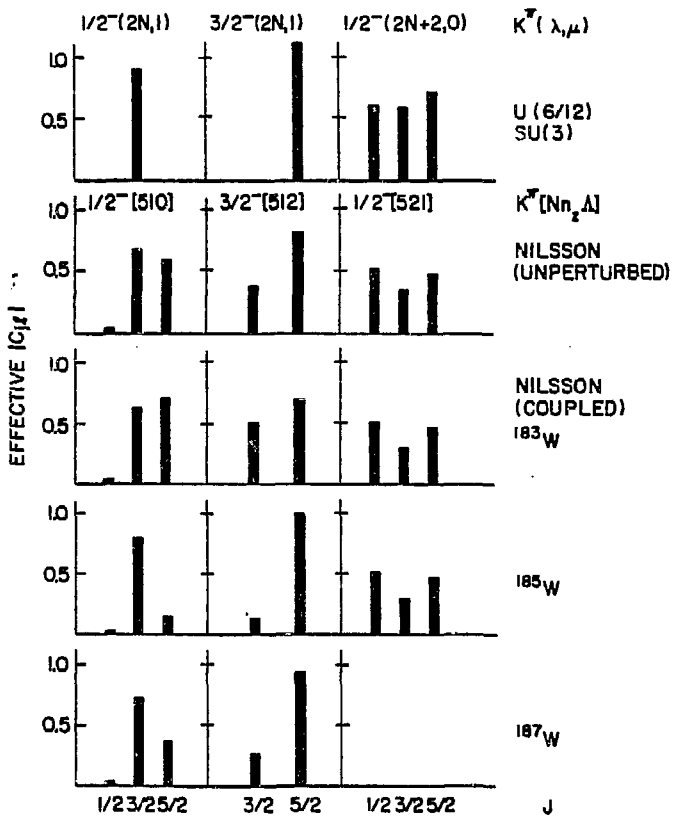

Fig. 6. Values of $C_{j\ell}^{eff}$ in the U(6/12) and Nilsson schemes. Those for the latter are calculated using the wave functions and Coriolis mixing amplitudes of ref. 17.

quantities correspond, with suitable normalization, to the amplitudes a_{j0}, for a single particle orbit of spin j coupled to the 0^+ ground state of the core.

Nilsson coefficients for both the unperturbed and Coriolis mixed orbits are shown in Fig. 6, the latter having been obtained from the results of ref. 17. The connection between the two frameworks is evident. The 1/2[521] and $(\lambda,\mu) = (2N+2,0)$ bands show an almost identical single particle structure throughout the W isotopes, although the absolute values in the latter case are larger because of the missing strength from the $f_{7/2}$ and $h_{9/2}$ orbits, which are not included in the U(6/12) basis. In the case of the K = 1/2 and 3/2 bands from the (2N,1) representation, the figure shows that the required structure corresponds to that of the 1/2[510] and 3/2[512] bands, after inclusion of a specific Coriolis interaction which is found empirically in ^{185}W.

Consideration of the predicted energy spectrum reinforces the above conclusions and the U(6/12) scheme is compared with the levels in ^{185}W in Fig. 7. Note that the $(\lambda,\mu) = (2N,1)$ representation of Fig. 5 can be made the ground state representation by a suitable choice of the strength of the Casimir operator of the group $U^{BF}(6)$. The Coriolis interaction between the 1/2[510] and 3/2[512] bands and the single particle structure of the 1/2[521] manifest themselves as a near degeneracy between states in the former pair, and a decoupling parameter near unity in the latter. Both features appear naturally in the symmetry scheme. However the figure also shows that recent ARC measurements[18] have identified five additional $J^\pi = 1/2^-$, $3/2^-$ states in the region of 600-800 keV.

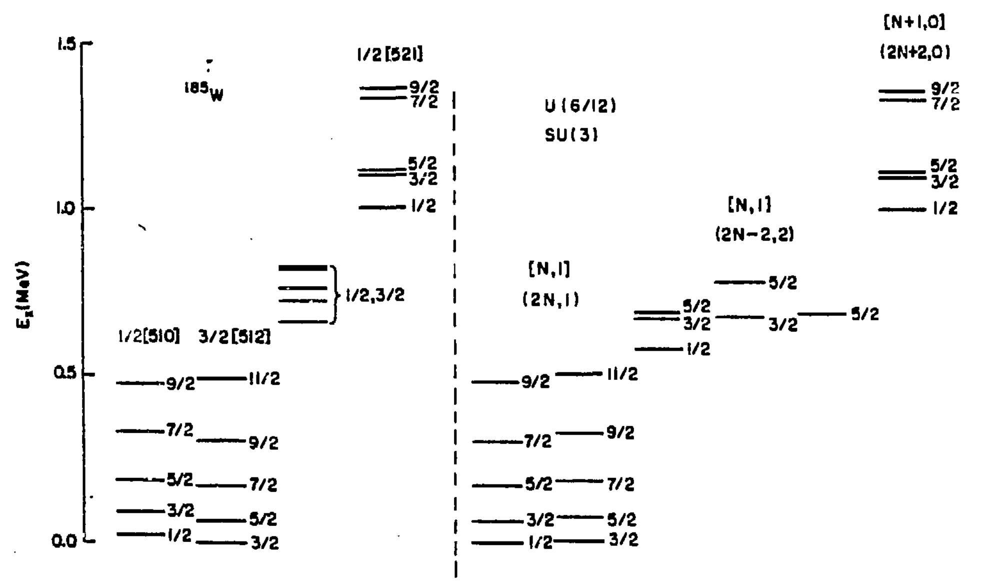

Fig. 7. Comparison of assigned Nilsson bands in ^{185}W with the SU(3) scheme of U(6/12). The location of five as yet unassigned $J^\pi = 1/2^-$, $3/2^-$ states is also shown. Assigned bands stemming from the $f_{7/2}$ and $h_{9/2}$ orbits are not included.

Three of these were known from earlier work[17], but could not be associated with simple Nilsson configurations. The symmetry scheme, on the other hand, provides an interpretation for three of the five, but still leaves two unaccounted for. This draws attention to a fundamental inadequacy of the U(6/12) scheme in the deformed region, in that the single particle space is not sufficient. It has already been pointed out that significant components of the $f_{7/2}$ and $h_{9/2}$ orbits appear in the wave functions of the bands of interest, and in addition, the 9/2[505], 7/2[503] and 5/2[512] bands themselves have been identified below 1 MeV in ^{185}W. Thus a similar origin can be sought for the two "extra" $1/2^-$, $3/2^-$ states, in terms of the $1/2^-[770]$ and/or $3/2^-[761]$ bands from the $j_{15/2}$ state.

6. THE SU(3)→O(6) TRANSITION AND THE CQF IN ODD A NUCLEI

Despite its limited applicability, it is clear that the U(6/12) SU(3) scheme yields a basically valid description of the structure of ^{185}W. Thus there are now two benchmarks in the U(6/12) basis, ^{195}Pt and ^{185}W, which define the SU(3) and O(6) limits, respectively, and it is possible to consider a description of the transitional odd A nuclei in between. For the even-even nuclei in this region, a simple approach involves the Consistent Q Formalism[19], in which the variation of the single parameter χ in the boson quadrupole operator

$$Q_B = (s^+\tilde{d} + d^+s)^{(2)} + \chi/\sqrt{5}\ (d^+\tilde{d})^{(2)} \quad (1)$$

between its SU(3) and O(6) values ($-\sqrt{35}/2$ and 0) reproduces the gross structural changes across the region.

In the IBFM, the quadrupole operators, both boson and fermion, enter the symmetric Hamiltonian via the Casimir operator $C_{2SU^{BF}(3)}$, which generates a quadrupole-quadrupole interaction of the form

$$Q\cdot Q = (Q_B+Q_F)\cdot(Q_B+Q_F) \quad (2)$$

In fact, recent work[20] has shown that the fermion operator Q_F can also be parameterized by χ, such that when $\chi=0$

$$C_{2SU^{BF}(3)} = C_{2O^{BF}(6)} - C_{2O^{BF}(5)} \quad (3)$$

and the SU(3) Hamiltonian reduces to that of O(6), with the restriction that the O(6) and O(5) Casimirs are governed by the same constant. In fact, the first success of this approach can be taken as the fact that, in the best fit to ^{195}Pt of Fig. 3, the relevant two constants were indeed found to be almost equal (33.5 and 35.0 keV).

The transitional region in question spans the odd Os nuclei and unfortunately, our experimental knowledge of these nuclei is still, in most cases, inadequate to attempt a detailed fit. However, the low lying structure has been a subject of considerable interest for some time[21,22]. The situation can be summarized by noting that the four lowest low spin states have $J^{\pi} = 3/2^-$, $1/2^-$, $5/2^-$ and $3/2^-$ in these nuclei, similar to ^{185}W. In fact, the accepted interpretation to date, based on the Nilsson model, is that these studies indeed stem largely from the Coriolis coupled 1/2[510] and 3/2[512] orbits, these being kept near the Fermi surface by the decreasing deformation in this region. However, the large single particle structure factors deduced for the second $3/2^-$ and first $5/2^-$ states in each case cannot be accounted for by these orbits alone, so that it has been assumed that fragments of the higher lying 3/2[501] and 5/2[503] also enter in the wave functions. The term fragment is used here to imply that mixing with

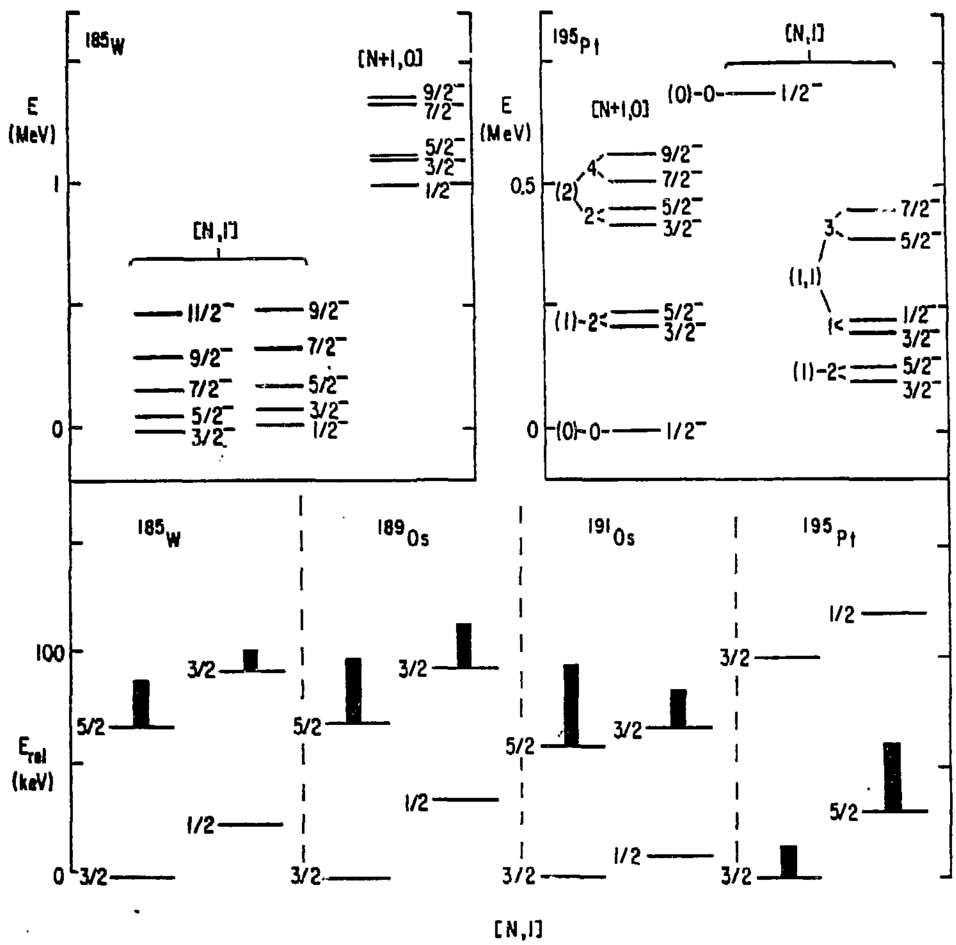

Fig. 8. (Top) The characteristic SU(3) and O(6) structure in ^{185}W, ^{195}Pt and (bottom) the single particle structure factors across the region in the low lying group of states shown (see text for details).

vibrational core excitations has to be assumed in order to bring the additional single particle strength sufficiently low in energy, and to account in general for the known spread of that strength across a large number of states in this region[23]. Such a conclusion is not, of course, surprising given the non-rotational structure of the even-even Os nuclei and, in particular, the low lying second 2^+ state in each.

The empirical situation is summarized in Fig. 8. At the top, the spectra of ^{185}W and ^{195}Pt are shown, displaying the characteristic features of the SU(3) and O(6) symmetries, respectively. Below, the four low lying states mentioned above are shown on a relative energy scale, and also their (d,t) structure factors. Note that in ^{195}Pt, the group of states no longer form the ground state, but appear at 99, 129, 199 and 222 keV instead. Figure 9 shows the simplest possible calculation within the CQF framework; in which all parameters, including the boson number, have been kept constant, except for χ. Figure 9a shows the SU(3) scheme and, for convenience, the various bands have been labelled with pseudo-K quantum numbers appropriate to the values of pseudo orbital angular momenta contained within each. The evolution of these bands as $\chi \rightarrow 0$ is then displayed in Fig. 9b. This part of the figure is necessarily schematic, since the exact details of the changing structure of states are extremely complex, and the rotational band structure disappears at some stage. Nevertheless, the most important feature is unambiguous. The K_p = 2 band descends rapidly in energy and eventually joins the K_p = 1 band to form the $(\sigma_1,\sigma_2,\sigma_3)$ = (N,1,0) structure of the O(6) limit. It is remarkable that it is precisely this band which has been shown[16] to contain the 3/2[501] and 5/2[503] Nilsson orbits, albeit mixed with β and γ vibrational core excitations. Thus the CQF predicts in this region, in a quantitative fashion, the same qualitative behavior deduced earlier.

The structure factors as a function of χ are shown in Fig. 9c. Two crucial points emerge. The predicted ratio S(5/2):S(3/2) is constant, and equal to 3:2. Empirically it ranges from 1.4 to 2.1. In addition, the effect of changing χ results in an increase in the absolute values and, again, this increase is seen in the data. Note that neither effect depends significantly on boson number.

Thus it must be concluded that the extension of the CQF to odd A nuclei can reproduce at least the low lying structure of the odd Os nuclei and therefore represents an attractively simple starting point for a general IBFM calculation in this region.

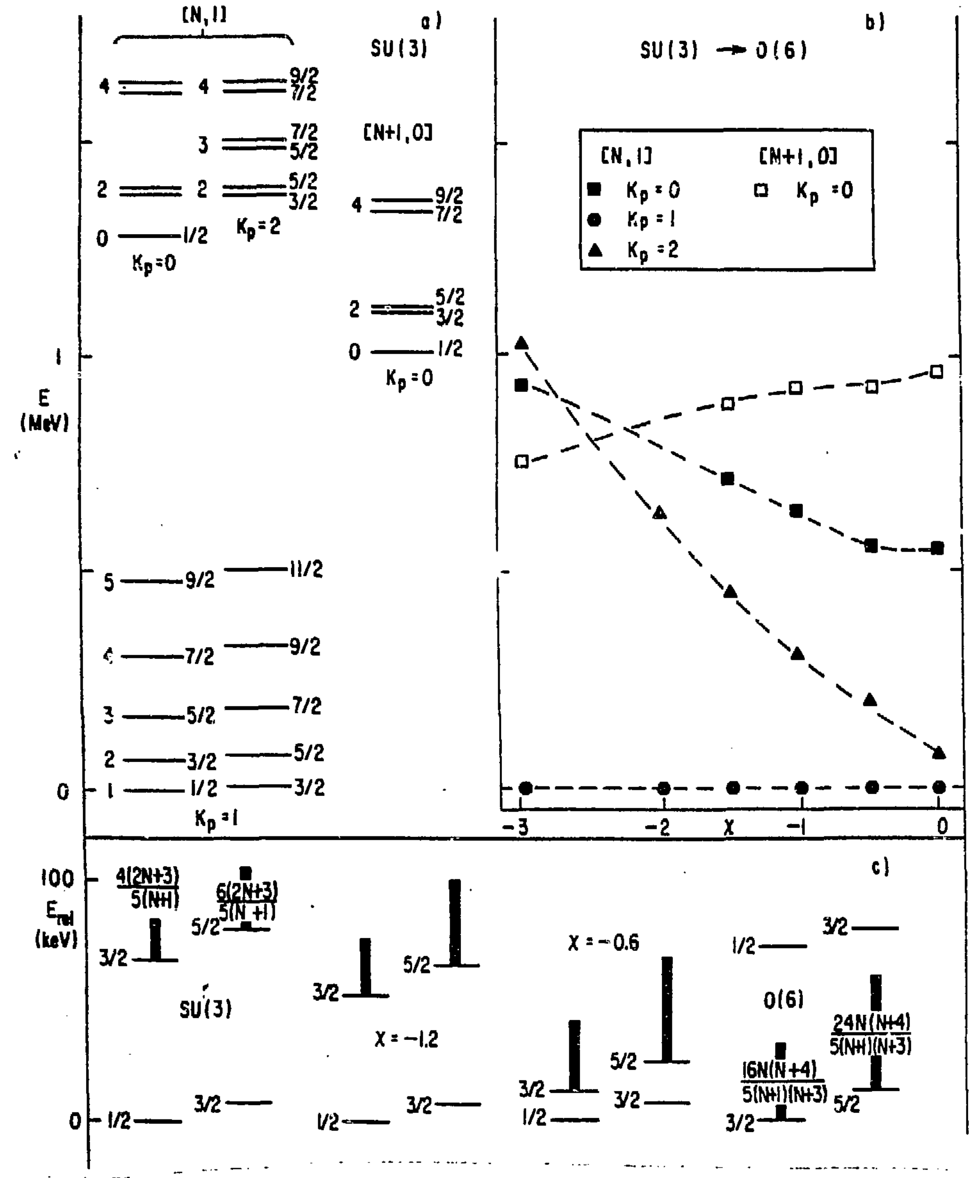

Fig. 9. a) The SU(3) limit; bands have been labelled by the pseudo projection quantum number K_p.
b) Schematic indication of the evolution of the bands as χ changes from its SU(3) value (−2.958) to O(6) (0).
c) The corresponding changes in the single particle structure factors of the low lying group of states shown in Fig. 8 (bottom).

7. EVIDENCE FOR SUPERSYMMETRY

Up to this point, the validity of the U(6/12) schemes has been considered in the context of odd A nuclei only. However, as pointed out in Section 2, supersymmetry can be thought of as implying the simultaneous description of both even-even and odd-even partners in a multiplet characterized by a given total number of bosons plus fermions.

The eigenvalue expression for the O(6) limit can be written

$$AC_{2U^{BF}(6)} + BC_{2O^{BF}(6)} + CC_{2O^{BF}(5)} + DC_{2O^{BF}(3)} + EC_{2\ Spin(3)} \qquad (4)$$

where the various terms represent the relevant Casimir operators of the subgroups. The SU(3) expression is then obtained by replacing the second and third terms by $B'C_{2SU^{BF}(3)}$.

The supersymmetric partners of interest are $^{194,195}Pt$ and $^{184,185}W$, and the parameters deduced for the even-even and odd-even nucleus in each case are compared in Table 1. The contribution from the $U^{BF}(6)$ Casimir is constant for all states in the even-even core, and hence does not affect the present discussion. Also, the last two groups of expression (1) combine in the even-even nucleus, so that it is the sum of the constants D and E which is relevant.

Table 1

	O(6)		SU(3)	
Constant[a)] in Exp (4)	^{194}Pt [b)]	^{195}Pt [c)]	^{184}W	^{185}W
B	46.5	33.5		
C	42.0	35.0		
D+E	17.5	11.0	18.5	17.5
B'			>10	5.75

a) All parameter values are in keV.
b) From ref. 4.
c) From ref. 14.

The agreement for the O(6) case is reasonably good and, in fact, intermediate values of the two sets of parameters in Table 1 would produce a reasonable description of both ^{194}Pt and ^{195}Pt. In the SU(3) case, however, there is a clear problem. The strength of the Q·Q interaction, represented by the Casimir operator of SU(3), is required to be at least a factor of two stronger in ^{185}W than in its even-even partner and, in this case, there is no compromise which can be found to give acceptable fits in both cases. This result is perhaps not surprising in that it is known that the SU(3) symmetry in the even-even case does not extend to the E2 matrix elements, so that in the CQF, a χ different from the SU(3) value has to be adopted to obtain the best overall description. Since, of course, the same core quadrupole matrix elements enter into the IBFM problem, via the core-particle interaction of eq. (2), it is likely that this approach may represent a necessary symmetry breaking in ^{185}W also.

ACKNOWLEDGEMENT

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