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Tracking Intruder States

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TRACKING INTRUDER STATES

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Abstract

The deformation-driving effects of intruder states are studied by analysis of various types of data on rotational bands in rare-earth deformed nuclei. The sensitivity of four measurables (bandhead energy, $B(E2)$ value, neutron $i_{13/2}$ crossing frequency, and signature splitting) to increased deformation in an intruder band is shown. The analysis of signature splitting systematics is extended to known superdeformed bands.

1. Introduction

Single-particle states of large individual angular momenta, j, are surprisingly important in the properties of the nucleus as a whole. The promotion of single nucleons into such "intruder" states (the terminology that is appropriate when the high-j state lies significantly above the Fermi level) has a real effect on the nucleus in a number of observable ways. It is the purpose of this paper to summarize those examples of the influence of intruder states and to especially emphasize signature splitting, *i.e.* the energy shift between the two signatures of a high-j orbital. It is our thesis that this splitting or shift can be systematized and used as an indicator of the particular configuration in an odd-odd nucleus and furthermore as a measure of the shape influence of an intruder state present in the coupling. This analysis is done first for rotational bands of normal deformation and then applied to the more complex case of superdeformed bands. The natural paucity of specific information on observed superdeformed bands makes it very important to find ways to aid the classification of such structures.

In general there are four ways in which the shape-driving influence of a particular high-j intruder state can be observed when considering the "rare-earth" region of normal deformation: (1) lowered energy of bands built on intruder states due to the increased deformation, β_2; (2) increased $B(E2)$ values in such intruder bands; (3) shifts in the frequency of a "standard" band crossing (e.g. $i_{13/2}$ neutron alignment) due to the increased β_2 in the band; (4) changes in the $\nu i_{13/2}$ signature splitting in bands due to coupling with intruder proton orbitals. After demonstrating the signature-splitting systematics for this class of bands, we then use the observed shifts in the superdeformed $\pi i_{13/2}$ bands as a guide in understanding the physics of superdeformed bands in odd-odd Tl nuclei.

The discussion here is focused on the proton intruder states, $h_{9/2}$ and $i_{13/2}$, throughout the rare-earth region of normal deformation, and then on the $\pi i_{13/2}$ band as a "spectator" in superdeformed bands in Tl. The calculated single-proton level ordering is shown in Fig. 1. Note that the $K = 1/2$ $h_{9/2}$ level, 1/2[541], is clearly an intruder state (*i.e.* above the proton Fermi surface) for deformed (β_2 around 0.2) nuclei with $Z = 60$ (Nd) through 76 (Os), while the corresponding $i_{13/2}$ state retains its intruder status through Hg ($Z = 80$). However, at superdeformed shapes (β_2 around 0.5) there are four protons in the $i_{13/2}$ orbitals for Hg, which removes its status as an intruder orbital. For those cases, it is the $j_{15/2}$ neutron orbital that seems to have the largest shape-driving tendencies.

Some results discussed here are based on measurements led by our group: ^{179}Ir and ^{181}Ir [2,3], ^{175}Re

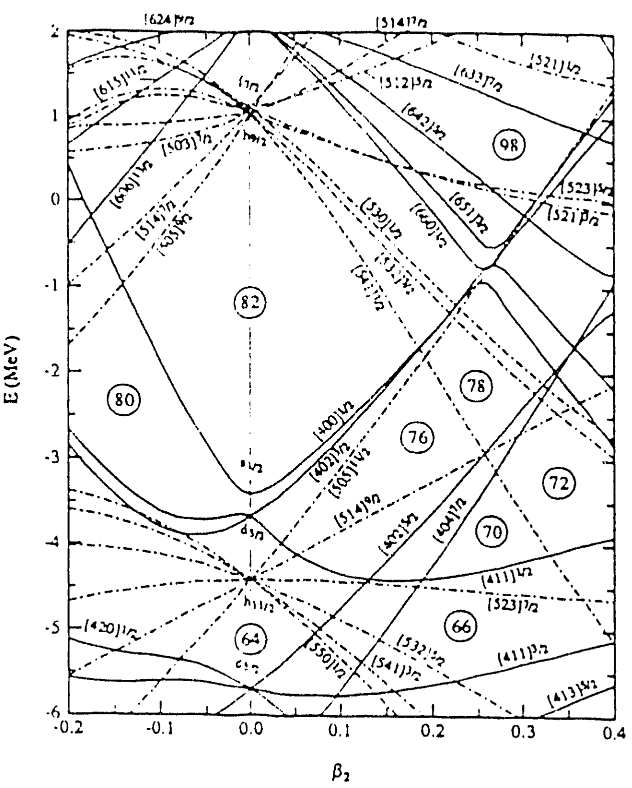

Fig. 1. Single-particle diagram for protons calculated by Wyss [1] using the Woods-Saxon potential. The calculation is done for β_4 and γ set equal to zero.

[4], ^{180}Ir [5], and ^{191}Tl [6].

2. Excitation Energies, Deformations, $B(E2)$ Values

The downsloping nature of the $\pi h_{9/2}$ and $\pi i_{13/2}$ orbitals in Fig. 1 should lead to a larger overall nuclear deformation if these are pure particle states (i.e. the Fermi surface is clearly below such orbitals). Indeed, Nazarewicz *et al.* [7] calculate that the deformation of the $\pi h_{9/2}$ bandhead in odd-A deformed nuclei throughout the rare-earth region is generally increased compared to the average of the ground-state values for the two adjacent even-even nuclei, e.g. a 20% increase for $^{165}_{71}$Lu$_{94}$. Such an increase in β_2 has the effect of lowering the expected energy of the single-particle excitation, to the point that it is easily observable in experiments on these nuclei, e.g. from around 1.2 MeV for the "normal" deformation in ^{165}Lu to half of that for the increased $\pi h_{9/2}$ deformation. The $\pi h_{9/2}$ band comes lower in energy as Z increases from 65 (Tb) to 73 (Ta), as the Fermi level of the nucleus increases closer to the $\pi h_{9/2}$ orbitals (see Fig. 1). An even more dramatic lowering in energy due to deformation occurs for the $\pi i_{13/2}$ excitation in this region, where the $\pi i_{13/2}$ band is observed regularly in isotopes of Re, Ir, and Au, even though it lies significantly above the $\pi h_{9/2}$ state in the single-particle scheme of Fig. 1.

While it is relatively easy to observe the bands built on proton intruder states throughout the rare-earth region, it is far more formidable to measure an increased deformation via a shorter state lifetime (increased $B(E2)$ value). Several measurements have been performed on $\pi h_{9/2}$ bands, e.g. that in ^{157}Ho by Gascon *et al.* [8]. Transition quadrupole moments, Q_t, were extracted in ^{157}Ho from lifetimes measured above $I = 37/2\ \hbar$ by the Doppler Shift Attenuation Method (DSAM) for states in both the $\pi h_{11/2}$ (7/2[523]) and $\pi h_{9/2}$ (1/2[541]) bands. Averaging over several states, Gascon *et al.* find that

Q_t is larger by $(28\,^{+17}_{-15})\%$ in the latter compared to the former. This can translate to a similar β_2 difference, which compares favorably to the calculated ratio of 1.18 [7]. Thus, there is direct evidence for an increased deformation for the $\pi h_{9/2}$ intruder state. There is also evidence for an increased deformation for the $\pi i_{13/2}$ intruder state in Ir nuclei, e.g. in ^{179}Ir as measured by Jin *et al.* [2,3]. Lifetime results are compatible with the calculated deformations extracted from self-consistent Total Routhian Surface (TRS) calculations [1], $\beta_2 = 0.30$ for the $\pi i_{13/2}$ band compared to 0.24 for normal states in ^{179}Ir.

3. Delayed $\nu i_{13/2}$ Band Crossings

A band crossing due to the rotational alignment of a pair of quasiparticles can be described and systematized by three extracted quantities: the crossing frequency, $\hbar\omega_c$, the gain in quasiparticle alignment, i, in the crossing, and the interaction strength between the crossing bands. It is possible to use the $\nu i_{13/2}$ crossing frequency (the common first backbend throughout the rare-earth region) as a broad indicator of the deformation of the nucleus in a particular band. Compared to the smooth trend of measured $\nu i_{13/2}$ crossing frequencies in even-even nuclei (Dy through Pt), there is generally a delay in the $\nu i_{13/2}$ crossing frequency in $\pi h_{9/2}$ bands, e.g. in ^{157}Ho as discussed by Gascon *et al.* [8]. This delay is qualitatively correct, as the increased deformation measured in DSAM work (see the previous section) results in an increase in the crossing frequency according to Cranked Shell Model calculations. However, in ^{157}Ho the measured 28% or calculated 18% increase in β_2 is insufficient to raise the $\hbar\omega_c$ from the "normal" value of 0.30 MeV to the measured value of 0.35.

The delay in the $\nu i_{13/2}$ crossing frequency for $\pi h_{9/2}$ bands disappears in Ir nuclei [2,3,9]. This sudden change in behavior is clearly related to a Fermi level effect. As seen in Fig. 1, the valence proton for $Z = 77$ Ir occupies the 1/2[541] level, which therefore removes the intruder status of this $\pi h_{9/2}$ orbital. In such a situation this excitation is considered to be half particle and half hole, and the shape-driving tendency of the orbital is canceled. So, what was certainly a "good" intruder state in $Z = 65$ to 73 nuclei ceases to be such for Ir and above because of the increased Fermi level.

4. $\nu i_{13/2}$ Signature Splitting

Another measurable quantity related to the deformation of the nucleus is the signature splitting of the $\nu i_{13/2}$ band. The amount of signature splitting is deduced for such bands by plotting the energies in the rotating frame of the nucleus and extracting the difference in Routhian energies at a certain rotational frequency, $\hbar\omega = 0.2$ MeV. We have extracted these quantities, $\Delta e'$, from all known $\nu i_{13/2}$ bands in odd-A odd-N nuclei. The trend of signature splittings is quite smooth, being large low in the $\nu i_{13/2}$ shell ($N = 89$) and decreasing steadily as the neutron Fermi level increases through the $i_{13/2}$ shell. This trend is shown for the upper part of this region ($N = 99 - 107$) in Fig. 2.

Even for a given neutron number, there is a strong variation in the $\Delta e'$ value for different values of Z in Fig. 2. This results from the varying deformation, β_2, for these isotones. For example, TRS calculations [1] yield β_2 values of 0.282, 0.277, and 0.258 for the $Z = 70$, 72, and 74 $N = 99$ isotones, the larger deformation giving rise to the smaller splitting. This is an important point for addressing the deformation driving properties of intruder states. That is, the coupling of the $\pi h_{9/2}$ intruder orbital to the $\nu i_{13/2}$ structure forms a band (usually yrast) in odd-odd nuclei. If the intruder state changes the deformation of the nucleus, then the $\nu i_{13/2}$ signature splitting in the odd-odd nucleus should change compared to the adjacent odd-A nuclei, as is the case in Fig. 2. Note that the $\Delta e'$ value for the $\nu i_{13/2}\pi h_{9/2}$ band in ^{172}Ta is reduced from an expected value of 74 keV (that value on the $N = 99$ curve for $Z = 73$) to an actual value of 29 keV, which could suggest a 5% increase

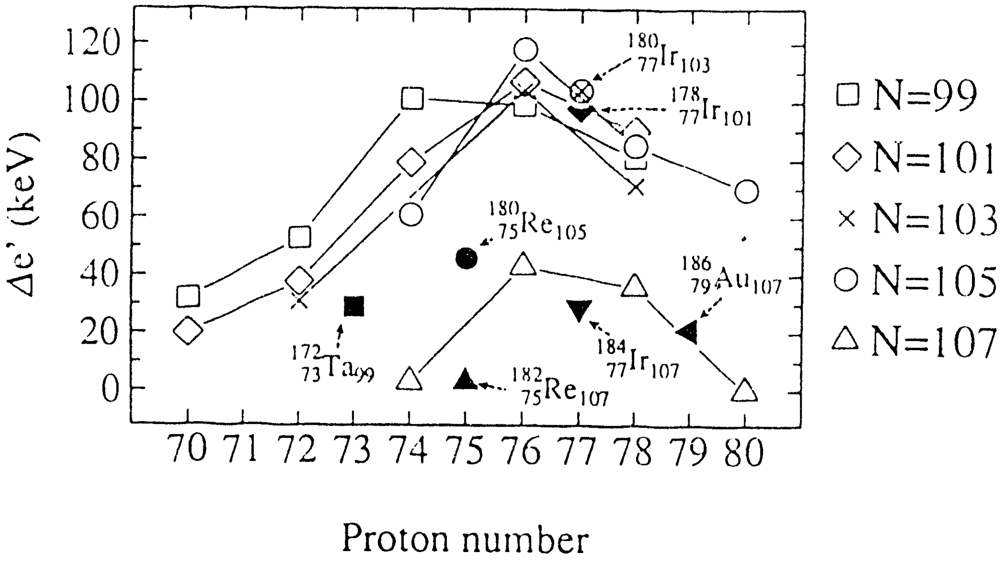

Fig. 2. Energy signature splittings, $\Delta e'$, for the $\nu i_{13/2}$ bands in odd-A odd-N nuclei and for the $\nu i_{13/2}\pi h_{9/2}$ bands in odd-odd nuclei. The values are extracted at $\hbar\omega = 0.20$ MeV from literature data on bands in these various odd-A nuclei, and from Kreiner *et al.* [10] for ^{172}Ta, Venkova *et al.* [11] for ^{180}Re, Slaughter *et al.* [12] for ^{182}Re, Yu *et al.* [5] for ^{178}Ir and ^{180}Ir, Kreiner *et al.* [13] for ^{182}Ir, and Kreiner *et al.* [14] for ^{184}Ir.

in β_2. Note also that the $\Delta e'$ decrease for odd-odd Re is still present (i.e. the $\pi h_{9/2}$ state is still a deformation-driving intruder orbital), but largely disappears for four known odd-odd Ir isotopes (two, ^{180}Ir and ^{178}Ir, from our measurements [5]). This correlates with the loss of intruder status by the $\pi h_{9/2}$ orbital, reflected also in the agreement in the $\nu i_{13/2}$ $\hbar\omega_c$ values in the $\pi h_{9/2}$ band of Ir nuclei, compared to the even-even cores. Thus, the measured $\Delta e'$ values in odd-odd nuclei do indeed reflect the change in shape induced by the coupling of the $\pi h_{9/2}$ intruder orbital to the $\nu i_{13/2}$ structure.

5. Energy Shifts in Superdeformed Bands

The superdeformed bands in the Hg region are generally thought to have a high-j composition of four protons in $i_{13/2}$ orbitals and two neutrons in $j_{15/2}$ levels (e.g. see [15]). It should be possible to do an analysis of signature splittings for the superdeformed bands now known in various isotopes of Hg and Tl in a manner similar to that described above. One difference is that the absolute energies of the levels are not known in the superdeformed cases. All one can measure at this time is the energies of the two sequences of $E2$ γ-ray energies, which are assumed to be related signatures of a strongly coupled superdeformed band. Until the next generation of 4π detectors is available, one can only make this association of γ-ray cascades into a strongly coupled band and hope that there are only a few confused cases. Since it is impossible to extract an actual signature splitting in these cases, we define instead an energy shift, ΔE, based on the average of two consecutive energies in one sequence to the comparable energy in the other signature:

$$\Delta E = E_\gamma(I \rightarrow I-2) - 1/2[E_\gamma(I+1 \rightarrow I-1) + E_\gamma(I-1 \rightarrow I-3)]$$

This quantity could be very different than the actual signature splitting, and thus one must be careful in the use of it. With this caution in mind, we attempt to systematize this quantity for the known superdeformed bands in Hg and Tl nuclei, as shown in Fig. 3.

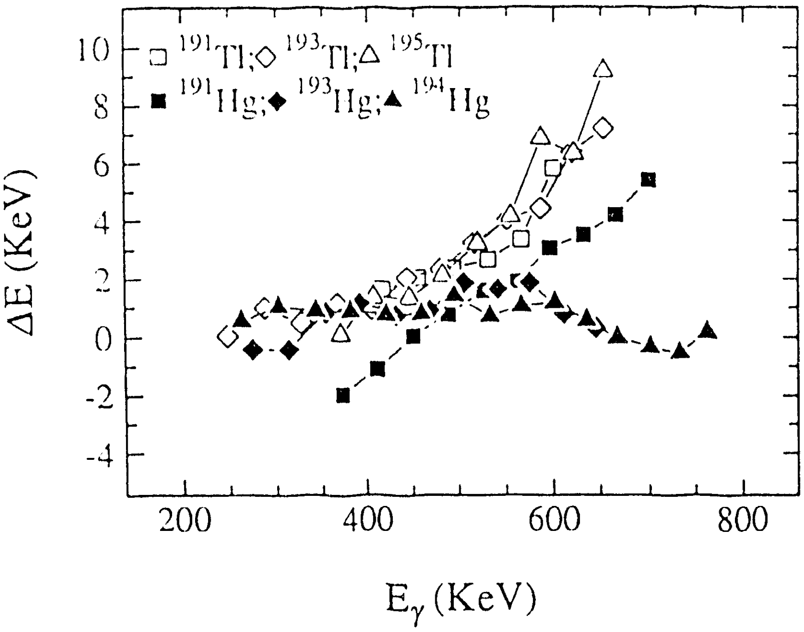

Fig. 3. Energy shifts, ΔE, for known superdeformed bands in Hg and Tl: ^{191}Tl [6], ^{193}Tl [16], ^{195}Tl [17], ^{191}Hg [18], ^{193}Hg [19], and ^{194}Hg [20].

Note first the essentially identical behavior for the superdeformed bands in the three odd-A Tl isotopes. In each case, these represent the two signatures of the $\pi i_{13/2}$ 5/2[642] band [6,16,17], and so the consistency is logical. For comparisons to the others, all three Tl isotopes show a ΔE of around 6 keV at a transition energy of 600 keV. By comparison, the three sets of bands in the Hg isotopes represent smaller energy shifts at 600 keV. The bands in ^{191}Hg are assigned [18] to the $\nu i_{11/2}$ 3/2[642] orbital, in ^{193}Hg to 9/2[642] $\nu i_{13/2}$ [19], and in ^{194}Hg likely to the coupling of this $\nu i_{13/2}$ orbital to neutron 5/2[512] ([20]). There is little signature splitting found in the calculations for any of these orbitals, and thus it is logical that the resulting ΔE values would be smaller than those in odd-A Tl.

The values of the energy shifts for ^{194}Tl are shown in Fig. 4, assuming the same association of energy cascades into bands as done by the original authors [21]. While none of the ΔE values is large, it is probably safe to conjecture that the pair with the largest values (called band 3 in Fig. 4) are associated with the odd-A structure with the largest shift, $\pi i_{13/2}$. The two signatures of this orbital are coupled to the only signature of the $\nu j_{15/2}$ orbital, 3/2[761], observed in ^{193}Hg [19]. The reduction of the ΔE for this ^{194}Tl band from 6 keV at 600 keV (the measured value for the $\pi i_{13/2}$ bands in odd-A Tl) to not more than half that could be due to a deformation increase caused by the intruder orbital, $\nu j_{15/2}$. As with the systematic shown for normal-deformed bands in Fig. 2, a deformation increase reduces the signature splitting of the "spectator" orbital. By comparison, the other two sets of bands in ^{194}Tl could be associated with one signature of $\pi i_{13/2}$ 5/2[642] coupled to the two signatures of the neutron 9/2[624] and 5/2[512] orbitals, since both of these have small ΔE in Hg nuclei (as discussed above).

This analysis of energy shifts between possible signature partners gives a suggestion of quasiparticle assignments that unfortunately cannot be checked currently by other means. The pattern of the moments of inertia is rather similar for the six observed cascades [21]. Eventually more measurements will give the details necessary to test the assignments suggested here.

The situation in ^{192}Tl is more complex. One association of the six newly observed bands produces three structures with energy shifts shown in Fig. 5. As discussed by Liang *et al.* [22], an analysis of

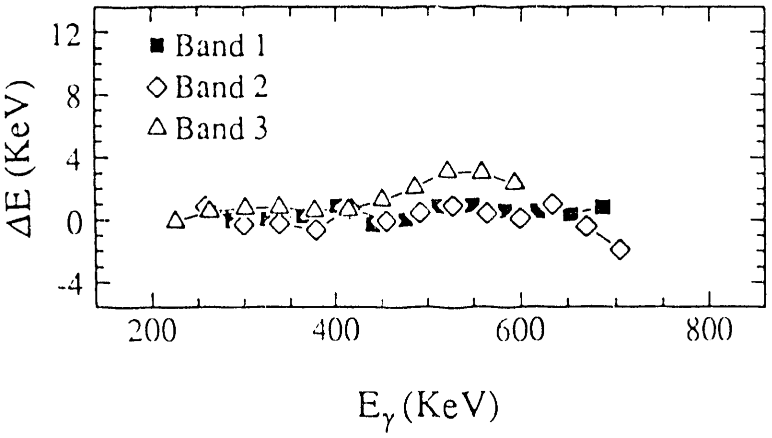

Fig. 4. Energy shifts, ΔE, for known superdeformed bands in ^{194}Tl [21].

the moments of inertia of the six cascades suggest the set labeled 2 in our Fig. 5 and called bands 3 and 4 there [22] should be assigned to $\nu j_{15/2}\pi i_{13/2}$ due to the unique flatness of the second moment as a function of frequency (double blocking of the expected crossing based on each of these orbitals). And this agrees with the trend discussed above, as the level of ΔE is reduced from the "expected" values for $\pi i_{13/2}$ (as in odd-A Tl) due to the deformation increase caused by the intruder orbital, $\nu j_{15/2}$.

The confusing aspects of ^{192}Tl correspond to the other structures labeled 1 and 3 in Fig. 5. Using 600 keV as the point of comparison, these two structures have ΔE values *larger* than any measured in adjacent odd-A nuclei. If one associates these two bands with the couplings of $\pi i_{13/2}$ 5/2[642] with $\nu i_{11/2}$ 3/2[642], then it is difficult to explain such significant changes from the smaller ΔE values observed for each in adjacent nuclei. This would suggest a ***decrease*** in the deformation of the nucleus to produce an ***increase*** in the energy shifts in odd-odd ^{192}Tl. That would be difficult to understand, but the association of the cascades into strongly coupled bands is probably too premature to allow one to make strong conclusions from this.

6. Conclusions

The role of intruder states in affecting the equilibrium deformation of nuclei is well known from a theoretical standpoint. The purpose of this work has been to demonstrate different ways in which the deformation changes might be observed, either by direct measurement (second effect discussed herein) or by deduction from measurements of three other quantities (bandhead energy, $\nu i_{13/2}$ crossing frequency, and $\nu i_{13/2}$ signature splitting). We have tried to show here that observing these effects and understanding their interpretation is important since these same fingerprints can be used to address the more complicated issues of superdeformed bands. Since it is even more difficult to measure the Q_t values for superdeformed bands than for bands of normal deformation, perhaps these indicators discussed here can be broadly used to give qualtitative measures of the configurationOdependent deformations, until more detailed spectroscopic information on families of superdeformed bands becomes available.

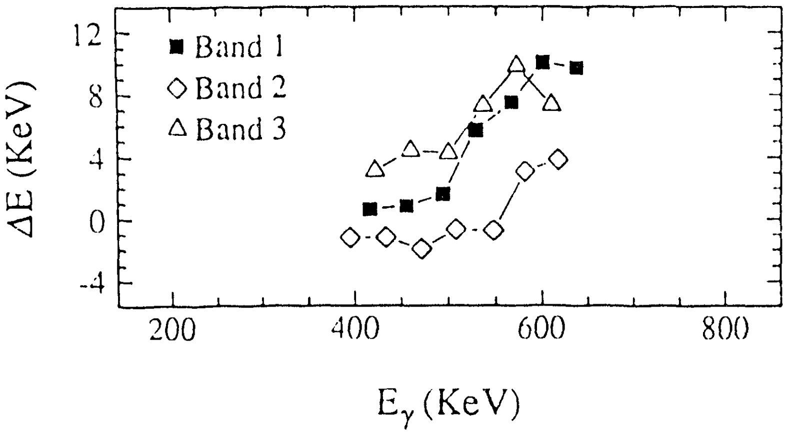

Fig. 5. Energy shifts, ΔE, for known superdeformed bands in ^{192}Tl [22].

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7 / 13 / 93