Pramāṇa - J. Phys., Vol. 36, No. 1, January 1991, pp. L125–L131. © Printed in India.

Signature effects in odd mass ytterbium nuclei in an angular momentum projected Hartree-Fock analysis

C R PRAHARAJ*† and A K RATH†

*SERC Daresbury Laboratory, Warrington WA4 4AD, UK
†Institute of Physics, Bhubaneswer 751 005, India

MS received 4 October 1990

Abstract. We explain the signature effects in the spectrum of odd mass Yb nuclei in a projected Hartree-Fock calculation without assuming gamma asymmetry. Rotation-alignment of nucleons in large j orbits is responsible for the signature dependence in energy and transition rates.

Keywords. Nuclear structure; high spin states; rotational bands; electromagnetic transitions.

PACS Nos 21·65; 21·10; 23·20

Study of the signature effects in odd-A rare-earth nuclei has been a topic of interest for the last several years (Hagemann *et al* 1982, 1984; Frandsen *et al* 1986, 1988; Hamamoto 1984). In these nuclei the bands, built on the nucleon orbit with either a unique parity high-j (Frandsen *et al* 1986, 1988) or a natural parity high-j-like orbit (Jonsson *et al* 1984; Holzman *et al* 1985), split into two branches with two signatures:

$$\alpha = +1/2 \text{ for } I = 1/2, 5/2, 9/2, \ldots..$$

$$\alpha = -1/2 \text{ for } I = 3/2, 7/2, 11/2, \ldots..$$

The branch with the angular momentum sequence $I = j \pmod 2$ is energetically lowered (F, favoured) than the branch (U, unfavoured) with $I = J + 1 \pmod 2$. In addition the electromagnetic transitions connecting these two branches are enhanced or reduced depending on whether the transition is from an unfavoured signature state to the favoured or from the favoured state to the unfavoured (or vice versa).

The experimental data on $B(M1; I \to I-1)$ and $B(E2; I \to I-1)$ transition rates are numerous (Kownacki and Garrett 1983; Bacelar 1985; Oshima *et al* 1988, 1989; Fewell *et al* 1988) and these have often been discussed in particle-rotor (Onishi *et al* 1986; Hamamoto and Sagawa 1988), and interacting boson fermion (IBFM) models (Yoshida *et al* 1989). A wide variation in gamma deformation (triaxial deformation (Hamamoto 1984) or gamma vibrations (Ikeda *et al* 1989; Matsuzaki 1989)) has been invoked in attempts to explain these signature effects. In this work we have studied the signature effects in odd Yb nuclei by projecting out states of good angular momenta from axially symmetric deformed Hartree-Fock intrinsic states and find that the signature effects are related to the rotation-alignment of $i_{13/2}$ neutrons in these nuclei (Rath and Praharaj 1990). We present the results here for the $K = 3/2^+$ band in ^{165}Yb and briefly discuss about $E2$ transitions and rotation-alignments in ^{163}Yb.

The deformed Hartree-Fock calculation was done assuming a spherical $^{132}_{50}\mathrm{Sn}_{82}$ core. The active protons and neutrons occupy one major shell each. The proton single-particle states are $3s_{1/2}$, $2d_{3/2}$, $2d_{5/2}$, $1g_{7/2}$ and $1h_{11/2}$ with energies 3·654, 3·288, 0·731, 0·0, 1·705 MeV respectively. The neutron single-particle states $3p_{1/2}$, $3p_{3/2}$, $2f_{5/2}$, $2f_{7/2}$, $1h_{9/2}$, $1i_{13/2}$ have energies 4·462, 2·974, 3·432, 0·0, 0·686, 1·487 MeV. We use a surface delta interaction with force strengths $F_{pp} = F_{pn} = F_{nn} = 0{\cdot}3$ MeV as the residual force among the active nucleons. The axially symmetric prolate Hartree-Fock solutions are lower in energy than the oblate ones and we restrict ourselves to the prolate solutions. The prolate HF orbits for ^{165}Yb are shown in figure 1. The orbits for the protons show $\pm m$ time-reversal symmetry, while, for the neutrons, there is a small departure from time-reversal symmetry due to the presence of the odd neutron. The ground configuration of ^{165}Yb is $K = 3/2^+$, while the ground configuration for ^{163}Yb has $\Omega = 1/2^+$.

A deformed configuration $|\varphi_K\rangle$ is a superposition of several states of good angular momenta:

$$|\varphi_K\rangle = \sum_I C^I_K |\psi^I_K\rangle. \tag{1}$$

We project out the states of good angular momenta using the projection operator

$$P^{IM}_K = \frac{2I+1}{8\pi^2} \int D^{I*}_{MK}(\Omega) R(\Omega)\, \mathrm{d}\Omega \tag{2}$$

where $R(\Omega)$ is the rotation operator and Ω represents the Euler angles α, β, γ. Details of the angular momentum projection formalism can be seen in (Praharaj 1988). Using this formalism we calculate not only the energy spectrum, but also the rotation-alignment (angular momentum carried by neutrons in $i_{13/2}$ orbits $I_{i_{13/2}}$) and $E2$ and $M1$ matrix elements for electromagnetic transitions.

The projected energy spectrum for $K = 3/2^+$ band of ^{165}Yb is compared with the experimental spectrum (Roy 1982) in figure 2. In the experimental spectrum the $\alpha = -1/2$ branch is systematically raised in energy compared to the $\alpha = +1/2$ branch. Our calculation reproduces the overall trend of the experimental spectrum to high spins, in particular the sign of the signature-splitting in the spectrum. Angular momentum projection from a single K configuration is adequate to explain signature effects. In the particle-rotor model sometimes a gamma deformation is needed (Bhatt 1989).

In figure 3 we have plotted the amounts of angular momentum carried by $i_{13/2}$ neutrons ($I_{i_{13/2}}$) and by all the other active protons and neutrons combined (I_{core}). The favoured branch shows characteristically more rotation-alignment and a correspondingly lower collective rotational energy than the unfavoured branch; and thus it is possible to understand the signature-splitting (relative lowering of the $\alpha = +1/2$ branch of the spectrum) of figure 2. We note that the absence of the low spin $3/2^+$, $5/2^+$ and $7/2^+$ states in the experimental spectrum in figure 2 does not pose a contradiction, because the very low energy transitions are hard to detect and often missed in the experiments (Riley 1990).

We briefly discuss about the rotation-alignment property of $K = 1/2^+$ band of ^{163}Yb (figure 3a) obtained by angular momentum projection calculation. The favoured branch has a large and almost constant $i_{13/2}$ neutron alignment ($I_{i_{13/2}}$) and the

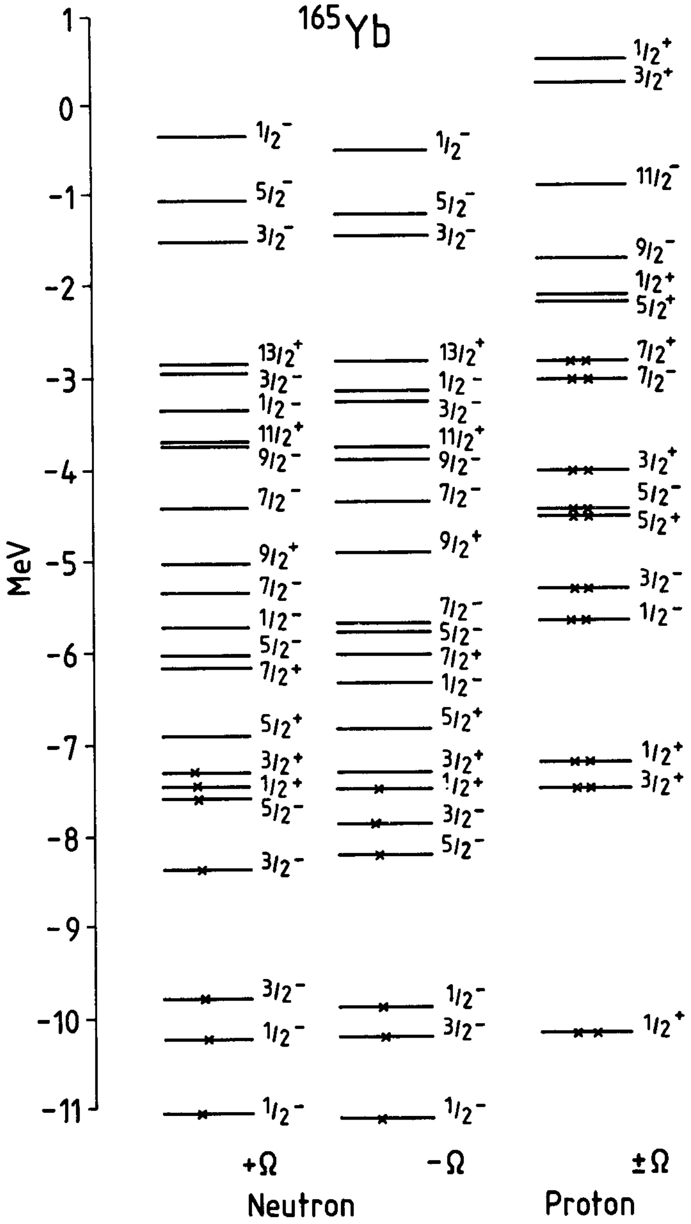


Figure 1. Prolate deformed Hartree-Fock orbits for ^{165}Yb. The occupied orbits are shown by crosses. The proton orbits are two-fold degenerate. The ground band in ^{165}Yb has $K = 3/2^+$. ^{163}Yb has two neutrons less and its ground band is $K = 1/2^+$.

unfavoured branch has a much smaller rotation-alignment. The angular momentum of the rest of the protons and neutrons (I_{core}) increases sharply with angular momentum (I) within each branch, with a huge staggering between $\alpha = -1/2$ and $\alpha = +1/2$ branches. In figure 4 we plot the $B(E2)$ values calculated for $I \rightarrow I-1$ transitions in the angular momentum projection formalism (Praharaj 1988). Effective charges 1·5 e

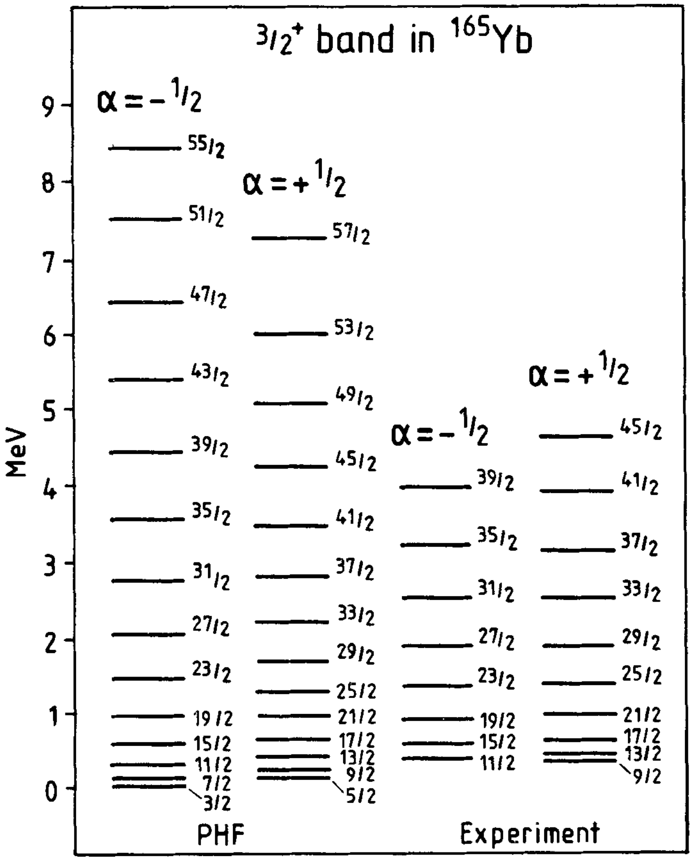
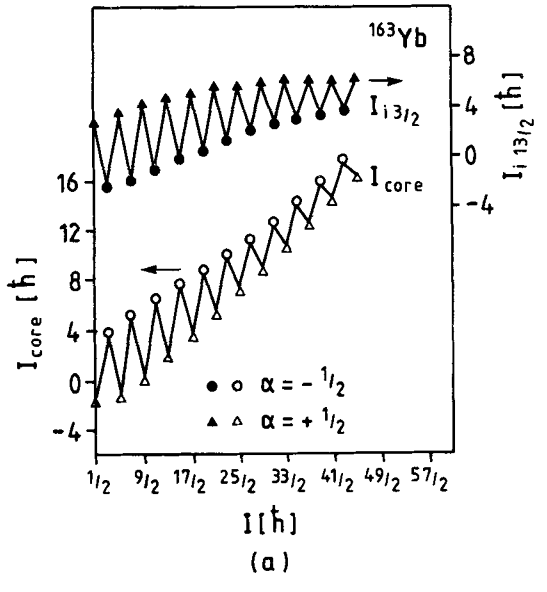


Figure 2. The projected energy spectrum of ^{165}Yb is compared with the experimental spectrum (Bacelar *et al* 1985). One sees considerable signature splitting at higher spins.



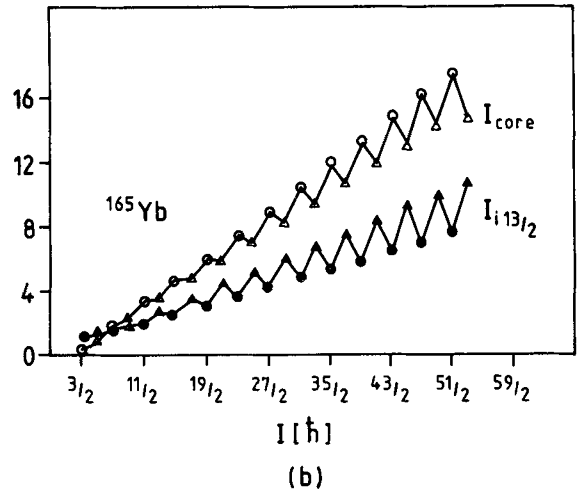


Figure 3. Angular momentum carried by $i_{13/2}$ neutrons ($I_{i_{13/2}}$) and by the rest of the active protons and neutrons (I_{core}) obtained in the angular momentum projection calculation for (**a**) the $1/2^+$ band in ^{163}Yb and (**b**) the $3/2^+$ band in ^{165}Yb.

for protons and 0·5 e for neutrons have been used in the calculation. Since $E2$ transition is dominated by the collective motion of the particles, $I \rightarrow I-1$ $E2$ transitions in ^{163}Yb show a characteristic signature dependence (upper curve in figure 4), which is in phase with the signature dependence of I_{core} in figure 3a (i.e. $I(\alpha = -1/2) \rightarrow I-1(\alpha = +1/2)$ transitions dominate).

The rotation-alignment in $K = 3/2^+$ band of ^{165}Yb (figure 3b) is much less prominent than $K = 1/2^+$ band of ^{163}Yb discussed above, with I_{core} being larger than $I_{i_{13/2}}$ in the entire spin range in ^{165}Yb. In the angular momentum projection calculation the signature effect is almost absent at low spins in ^{165}Yb and gradually becomes important at higher spins. The $I \rightarrow I-1$ $E2$ transitions in ^{165}Yb are very collective at low spins (till $21/2\hbar$) (figure 4) and show no signature dependence, a trend that is also apparent in I_{core} and $I_{i_{13/2}}$ in figure 3(b). Beyond $21/2\hbar$, where the signature dependences in I_{core} and $I_{i_{13/2}}$ become pronounced, the $I \rightarrow I-1$ $B(E2)$ value has dropped by an order of magnitude and shows considerable signature effect. It is thus rotation-alignment which leads to signature effects in these bands.

To conclude, angular momentum projection from deformed configurations is able to account for the spectrum and the signature effect in ^{165}Yb and other odd Yb nuclei. Although signature effects in rare-earth nuclei have often been parametrized in terms of gamma asymmetry by many authors, we find that it is rotation-alignment which is responsible for the signature dependence.

One of the authors (CRP) thanks the SERC, UK, for a visit to Daresbury Laboratory and acknowledges discussions with M A Nagarajan, M A Riley, N Rowley and J A Sheikh.

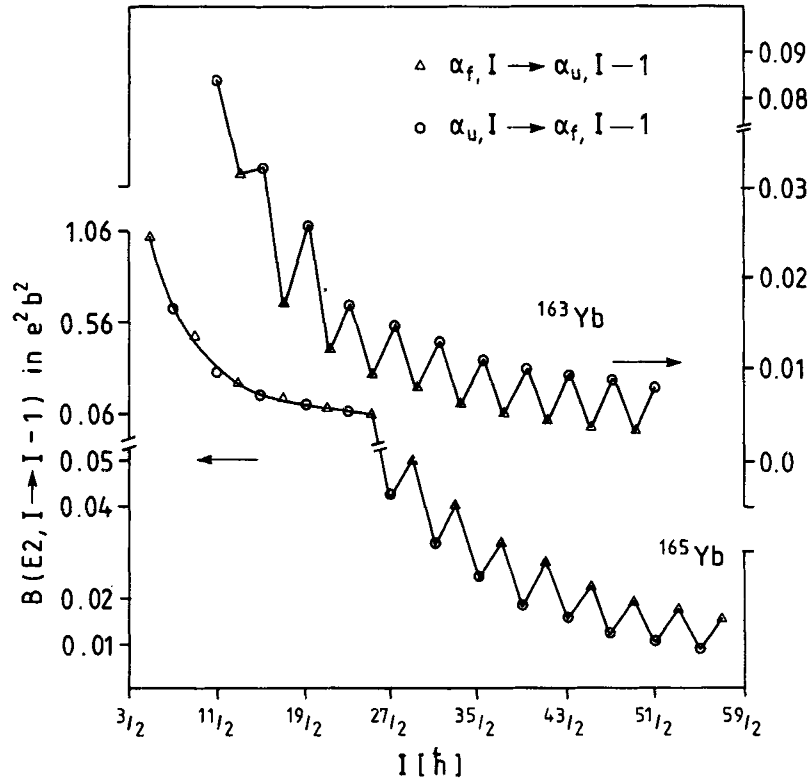


Figure 4. $B(E2)$ values calculated for $I \rightarrow I-1$ $E2$ transitions in ^{163}Yb and ^{165}Yb. Effective charges $e_p = 1{\cdot}5e$ and $e_n = 0{\cdot}5e$ have been used in the calculation. The arrows to the right and the left indicate the scales.

References

Bacelar J *et al* 1985 *Nucl. Phys.* **A442** 509

Bhatt K H 1989 Workshop on microscopic models in nuclear structure physics, (eds) M W Guidry *et al* (Singapore: World Scientific) p. 194

Fewell M P *et al* 1988 *Phys. Rev.* **C37** 101

Frandsen P *et al* 1986 *Phys. Lett.* **B177** 287

Frandsen P *et al* 1988 *Nucl. Phys.* **A489** 508

Hagemann G B, Garrett J D, Herskind B, Sletten G, Tjom P O, Henriquez A, Ingebretsen F, Rekstad J, Lovhoiden G and Thorsteinsen T F 1982 *Phys. Rev.* **C25** 3224

Hagemann G B, Garrett J D, Herskind B, Kownacki J, Nyako B M, Nolan P L, Sharpey-Schafer J F and Tjom P O 1984 *Nucl. Phys.* **A424** 365

Hamamoto I 1984 *Nucl. Phys.* **A421** 109C

Hamamoto I and Sagawa H 1988 *Phys. Lett.* **B201** 415

Holzman R, Loiselet M, Vanttove M A and Vervier J 1985 *Phys. Rev.* **C31** 421

Ikeda A and Shimano T 1989 *Phys. Rev. Lett.* **63** 139

Jonsson S *et al* 1984 *Nucl. Phys.* **A422** 397

Kownacki J, Garret J D, Gaardhoje J J, Hageman G B, Herskind B, Jonsson S, Roy N, Ryde H and Walus W 1983 *Nucl. Phys.* **A394** 269

Matsuzaki M 1989 *Nucl. Phys.* **A491** 433

Onishi N, Hamamoto I, Aberg S and Ikeda A 1986 *Nucl. Phys.* **A452** 71

Oshima M, Minehara E, Ichikawa S, Iimura H, Inamura T, Hashizume A, Kusakari H and Iwasaki S 1988 *Phys. Rev.* **C37** 257

Oshima M, Minehara E, Kikuchi S, Inamura T, Hashizume A, Kusakari H and Matsuzaki M 1989 *Phys. Rev.* **C39** 645

Praharaj C R 1988 *J. Phys.* **G14** 843

Rath A K and Praharaj C R Contributed paper to Int. Conf. on high spin physics and gamma soft nuclei, Pittsburgh, USA

Riley M A 1990 private communication

Roy N, Jonsson S, Ryde H, Walus W, Gaardhoje J J, Garrett J D, Hagemann G B and Herskind B 1982 *Nucl. Phys.* **A382** 125

Yoshida N, Sagawa H, Otsuka T and Arima A 1989 *Nucl. Phys.* **A503** 90