Dynamic Chirality in the Interacting Boson Fermion-Fermion Model

S. Brant1, D. Tonev1,2, G. de Angelis2, A. Ventura4

1 Department of Physics, University of Zagreb, Croatia, 2 INFN Laboratori Nazionali di Legnaro, Italy, 3 INRNE, BAS, Sofia, Bulgaria, 4 ENEA and INFN Sezione di Bologna, Italy

In the last decade considerable experimental and theoretical effort was invested in the research of chirality in nuclei. In the pioneering work [1] it was proposed that the rotation of triaxial nuclei may give rise to pairs of identical $\Delta I = 1$ bands with the same parity in odd-odd nuclei - the chiral doublet bands. The possible chiral interpretation of twin bands provides a rare opportunity to observe specific physical properties in deformed odd-odd nuclei. The structure in which a pair of twin bands is close in excitation energy, but the electromagnetic decay properties do not show the chiral pattern, will be denoted as case A. The structure where the pair of twin bands is close in excitation energy and the electromagnetic decay properties display the chiral pattern, will be denoted as case B. Odd-odd nuclei in the A–130 mass region can be classified as case A or case B nuclei. In all these nuclei the cores are $\gamma$-soft, their odd-proton odd-mass neighbours have also a similar structure and their odd-neutron odd-mass neighbours have also a similar structure, too. Therefore, there is a priori no evident reason why should they be different in structure, some of them being chiral (case B) and some being not chiral (case A).

The structure of twin bands will be described in the Interacting Boson Fermion-Fermion Model (IBFFM) [2,3], in the version where there is no distinction between proton bosons and neutron bosons. The structure of $^{134}$Pr in the IBFFM framework has been described in Refs. [4,5] with the detailed analysis of wave functions in Ref. [6]. In the IBFFM besides the orientation in space, the deformation of the core is the additional degree of freedom. Valence quasiparticles are coupled to all structures of the boson core that are present in the basis, limited by the total boson number. For $^{134}$Pr the parameters for the core nucleus $^{134}$Ce were taken close to $\gamma$-soft values. The triaxial equilibrium deformation was generated by the cubic (three-body) term added to the standard IBM-1 core Hamiltonian. The electromagnetic decay properties were found in excellent agreement with the experimental data [5,6].

As a typical representative for the A–130 mass, both for the case A and case B, the boson core will be taken using a slightly smaller value of the cubic (three-body) term $\Theta_\gamma = 0.022$ MeV with respect to the one ($\Theta_\gamma = 0.030$ MeV) used for $^{134}$Pr [5,6]. In the present work the residual proton-neutron interaction is taken as a tensor interaction $V = V_{r} V(r) [3 (\vec{\sigma}_p \cdot \vec{r}_n) (\vec{\sigma}_n \cdot \vec{r}_p) / r_{pn}^3 (\vec{\sigma}_p \cdot \vec{\sigma}_n)]$ with the Gaussian radial dependence $V(r) = \exp(-r^2/r_0^2)$ with range $r_0 = 2.7$ fm. Since the boson-fermion interactions are derived from the quadrupole-quadrupole proton-neutron interaction, the residual proton-neutron interaction in IBFFM is an effective residual interaction, whose parameters depend on the fermion model space. In the present calculation this reflects in the range of the tensor interaction, that is larger than the bare range 1.4–2.0 fm.

With the residual proton-neutron interaction the staggering of the signature $S(I)$ for yrast states with medium and high spin is in agreement with the experimental data in the A–130 mass region. It exhibits a weak staggering, being bigger for states with odd than for those with even spins. The wave functions are not sizeably changed in respect to Refs. [5,6]. Consequently, the $B(E2)$ and $B(M1)$ values, calculated with the same effective charges and gyromagnetic ratios as in Refs. [5,6], are very close to the values obtained in those calculations. The only difference is that the $B(E2)$ value in the side band has now the minimum at spin 12 instead at spin 13 [5,6].

![FIG. 1. IBFFM $\beta$ and $\gamma$ distributions, defined as in Ref. [6], for the case A and the case B. In the upper panels the distributions for the yrast $^{17_1}$ states and in the panels on bottom for the side band $^{17_2}$ states are presented. The axis in the $\beta - \gamma$–plane have $\gamma = 0^\circ$ and $\gamma = 60^\circ$, while the middle line in the $\beta - \gamma$–plane marks $\gamma = 30^\circ$.](Image)

The result of the IBFFM calculation predicts the structure typical for the case A: twin bands, correct signature, different $B(E2)$ values in the two bands, absence of $B(M1)$ staggering in both bands and a very weak $B(M1)$ staggering for $\Delta I = 1$ transitions from the side to the yrast band. This structure was attributed to a weak dynamic (fluctuation dominated) chirality in Ref. [6].
The same boson core allows to describe nuclei classified as case B provided one modifies the boson-fermion coupling parameters. The spin of the band head of the yrast band depends on the proton and neutron number of the nucleus through the occupation probabilities of fermion configurations. The structure of intermediate and high spins in the yrast and side band is, on the other hand, mainly determined by the interaction strengths. In the present work, therefore, no fit was attempted to obtain the spin value of the band head that should be connected to a certain nucleus.

The common feature of odd-odd nuclei with twin bands is that their odd-even neighbours with the odd fermion being a hole, have as the lowest state of the high-spin unique parity structure the \( j = 1 \) state \((\{\nu h_{11/2}\}9/2^- \) in the A-130 region and \([\pi g_{9/2}]7/2^+ \) in the A-105 region). In the IBFM for odd-mass nuclei this is a consequence of a strong exchange interaction. As the exchange interaction takes into account the antisymmetrization of the odd fermion with the fermion structure of the boson, it is in fact the consequence of the Pauli principle. For the case B in our calculation we have taken the odd-neutron boson exchange interaction strength \( \Lambda_0^\nu \pi \) still strong, but significantly weaker than in the case A, \( \Lambda_0^\pi \nu = 1.0 \) MeV instead of 1.6 MeV for the case A. In addition, the strengths of the other two odd-neutron boson and the residual proton-neutron interaction have been reduced: \( \Gamma_0^\nu \gamma = 0.65 \) MeV, \( A_0^\gamma \nu = 0.02 \) MeV, \( V_\psi = -16.0 \) MeV. All other parameters were the same as in the case A. This calculation we refer as case B. In both the yrast and the side band the \( B(\text{M}1) \) values above spin \( I = 12 \) exhibit the same odd-even staggering, the \( B(\text{M}1) \) values being much bigger for odd spins than for the even ones. The \( B(\text{M}1) \) values for \( \Delta I = 1 \) transitions from the side to the yrast band exhibit the odd-even staggering out of phase with the \( B(\text{M}1) \) staggering in the yrast and side bands, i.e. \( B(\text{M}1) \) values for even spins are much bigger than for the odd ones. The \( B(\text{M}1) \) staggering in the side band is in phase with the \( B(\text{M}1) \) staggering in the yrast band. The effects are less pronounced than chirality requires, but are in the range of values observed in \(^{130}\text{Cs}\) [7]. The \( B(\text{E}2) \) values are not equal in the yrast and the side bands, but are closer than in the case A.

The distributions \( \xi (j_x, j_y), \psi (j_x, R) \) and \( \xi (j_x, R) \) of the angles between \( j_x, j_y \) and \( R \), and the \( \sigma \) distribution (details of the procedure can be found in Ref. [6]), for the case B show no significant differences in respect to the case A [6]. In both cases the presence of configurations with the angular momenta of the proton, neutron and core in the favorable, almost orthogonal geometry, is substantial but far from being dominant. The presence of all chiral signatures in the case B is not the consequence of (for chirality) more favorable geometry.

The main, decisive, difference is revealed in the analysis of distributions in the \( \beta = \gamma \)-plane. The \( \beta \) and \( \gamma \) distributions for cases A and B are sizeably different. The yrast bands in both cases are similar, with fluctuations on higher spins being somewhat smaller in the case B. In addition, in the case B components with \( \gamma \) closer to \( \gamma = 30^\circ \) are more pronounced.

The side band on medium and higher spins has far less shape fluctuations and a significant decrease of components with small \( \beta \) in the case B. The similarities, in the case B, between states of the two bands are more pronounced for odd spin members than for the even ones. Different deformations and larger fluctuations in the case A reflect in \( B(\text{E}2) \) values, that are much smaller in the side band than in the yrast band. In the case B, due to more similar deformations, the \( B(\text{E}2) \) values for transitions between states in the side band are closer to the \( B(\text{E}2) \) values in the yrast band. Smaller shape fluctuations and more similar deformations in the case B increase the probability that the two bands could be even and odd superpositions of separated left-handed and right-handed configurations, that reflects in the chiral-like behavior of \( B(\text{M}1) \) values.

The distribution of the core structure in the wave function reveals the dynamical mechanism. In the case B the weaker, but still strong, boson-fermion interactions (particularly the exchange interaction) for the neutron (hole-like) quasiparticle are not strong enough to admix big components from higher lying core bands. The ground and the \( y \)-band components are dominant in the states of the side band. All chiral signatures are present, but large shape fluctuations sizably reduce their magnitude in respect to the full chiral predictions. The \( \gamma \)-softness and shape fluctuations prevent the angular momenta of the proton, neutron and core to create chiral favorable geometry on the scale they would do if the core is triaxial. For nuclei where the boson-fermion interaction is stronger, other higher lying core structures admix into the states of the side (and partially into the yrast, too) band, increasing the shape fluctuations. This allows the admixture of more contributions from near axial shapes and consequently washes out the \( B(\text{M}1) \) staggering. The only visible signature of dynamical chirality remains the vicinity of the excitation energies of the two bands. The chirality materializes only in a dynamical way, as a slow anharmonic vibration. This finding can be extended equally well to the A-105 and A-190 mass regions.

The present IBFMM calculation shows that the dominant role in the formation of different types of chiral patterns has the exchange interaction, i.e. the antisymmetrization of odd fermions with the fermion structure of the bosons. The physical foundation of chirality could therefore be beyond geometry and shape fluctuations, in the microscopic structure of twin bands. More details can be found in Ref. [8].

This research has been supported by the European Commission through contract number RII3-CT-2004-506065.