ODD-ODD NUCLEI AS THE CORE-PARTICLE-HOLE SYSTEMS AND CHIRALITY

Chirality seen from the laboratory frame

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Outline

1. Introduction: Chirality in nuclei

2. A description of odd-odd nuclei
   - The Core-Particle-Hole Coupling (CPHC) Model
   - Description of the even-even core
   - The single-particle proton and neutron bases

3. Results and conclusions
   - The calculations
   - Symmetries of the core and the valence particles
   - The α-symmetric cores
   - The α-asymmetric cores
   - The broken proton-neutron symmetry

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CHIRALITY

- Chirality in nuclei — the topic of the present session — is since a few years a hot topic in the nuclear structure physics of odd and odd-odd nuclei. It allows us to interpret the odd nuclei spectra in a simple way.
- Is it really the chirality?
  The chirality or the handedness phenomenon is usually connected with the inversion of the three-dimensional physical space.
  In nuclear physics we discuss the chirality which is connected with time reversal rather than the space inversion.
  (Perhaps, the term spin-chirality would be plausible to distinguish the phenomena.)
- A model nuclear chiral system considered originally is:
  the odd proton, the odd neutron hole, and the rigid triaxial even-even core.
  (in the quasi-classical picture: the three mutually perpendicular angular momenta $\vec{j}_\pi$, $\vec{j}_\nu$, $\vec{R}$ along the three intrinsic principal axes of the core)

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THE CHIRALITY SIGNATURES

Commonly considered main signatures of the chirality in nuclei:

- Appearance of a pair of the almost degenerate $\Delta I = 1$ bands of the same parity and similar electromagnetic properties (called chiral partner bands).
- Staggering of the intraband and interband M1 and $\Delta I = 1$ E2 transitions.

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Core-Particle-Hole Coupling

- The odd-odd nucleus is treated as the three-body system: the even-even core, the proton and the neutron-hole.
- States of the odd-odd nucleus with the proton and neutron numbers Z and N, respectively, are assumed in the following form:

$$|Z, N; iIM\rangle = \sum_{\rho,\sigma} \sum_{L,R,r} U_{Ii}(\rho, \sigma, L, R, r) \left[\left[a^{\dagger}_{\pi\rho} \times \tilde{a}_{\nu\sigma} \right]_L \times |Z-1, N+1; rR\rangle \right]_{IM}$$

- The quadrupole-quadrupole two-body interaction between the proton, the neutron and the core is assumed.
  (The coupling constant $\chi_2 = 40\text{MeV/b}^2$, relatively strong, is taken in the calculations)
- Details in: K. Starosta et al, Phys. Rev. C **65**, 044328 (2002); Ch. Droste et al, Eur. Phys. J., **42**, 79 (2009).

The Bohr Hamiltonian

The core states $|Z-1, N+1; rRM_R\rangle$ are described by a version of the Bohr Hamiltonian in the following form:

$$H(\beta,\gamma,\Omega) = -\frac{1}{2B_{\beta\beta}}\frac{1}{\beta^4}\frac{\partial}{\partial\beta}\left(\beta^4\frac{\partial}{\partial\beta}\right) - \frac{1}{2B(\gamma)}\frac{\Lambda^2(\gamma,\Omega)}{\beta^2} + V(\beta,\gamma)$$

with the potential of the form

$$V(\beta,\gamma) = \frac{1}{2}V_C\beta^2 \quad + \quad \left(G + h_1\cos 3\gamma + h_2(\cos^2 3\gamma - 1)^\kappa\right) \times \left(\exp\left(-\beta^2/d^2\right) - 1\right)$$

The Bohr Hamiltonian

- The seniority operator is

$$\Lambda^2(\gamma,\Omega) = \frac{1}{\sin 3\gamma}\frac{\partial}{\partial\gamma}\left(\sin 3\gamma\frac{\partial}{\partial\gamma}\right) - \sum_{k=1}^{3}\frac{R_k^2(\Omega)}{\sin^2\left(\gamma - 2\pi k/3\right)}$$

- Variables β and γ are the Bohr deformation parameters, Ω stands for the three Euler angles of orientation of the body-fixed system and $R_k(\Omega)$ for $k = 1,\ 2,\ 3$ are the three (dimensionless) intrinsic components of angular momentum.

The Bohr Hamiltonian

- The rotational inertial function is

$$B(\gamma) = b_0 + b_1 \cos 3\gamma$$

- The parameters of the potential V_C, G, h_1, h_2, κ and d, and the kinetic energy b_0 and b_1 and $B_{\beta\beta}$ are selected in a way to obtain the values of energy of the lowest excited state $E(2_1^+)$ and reduced transition probability $B(\mathrm{E2}; 2_1^+ \to 0_1^+)$ always close to the experimental values $E(2_1^+) = 354$ keV and $B(\mathrm{E2}; 2_1^+ \to 0_1^+) = 0.282\ e^2\mathrm{b}^2$ for $^{128}_{56}$Ba ($A = 128$, $Z - 1 = 56$).
- Parameters h_2 and κ are responsible for the γ-softness of the potential.
- Parameters h_1 and b_1 are responsible for the γ-asymmetry of the Bohr Hamiltonian.

Proton and neutron states

- The proton and the neutron hole can occupy the single-particle states in the spherically symmetric potential well:
  $\pi\rho = \pi nl_j$ and $\nu\sigma = \nu nl_j$, respectively.
- The calculations are performed assuming that the proton and neutron bases contain only one orbital ρ and σ, respectively.
- For the proton $\rho = h_{11/2}$.
- For the neutron $\sigma = h_{11/2}$, or $g_{9/2}$.

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Principles of the calculations

- A fictitious nucleus with $Z = 57,\ N = 71$ (^{128}La ?).
- Variants of the calculation:
  - The α-symmetric cores: $h_1 = b_1 = 0$, and $h_2 = 20$ MeV [potential well (PW)], $h_2 = -8$ MeV [potential barrier (PB)], compared to $h_2 = 0$ [the Wilets-Jean (WJ) soft potential],
    The single-particle states: $\rho = \sigma = h_{11/2}$ ($\pi h \otimes \nu h$).
  - The α-asymmetric cores: $h_2 = 0$, $b_1 = 0$, and $h_1 = 2$ MeV [$\langle\gamma\rangle \approx 21°$], $h_1 = 8$ MeV [$\langle\gamma\rangle \approx 15°$],
    The single-particle states: $\rho = \sigma = h_{11/2}$.
  - The Wilets-Jean potential : $h_1 = h_2 = b_1 = 0$,
    The different single-particle states: proton $\rho = h^{-}_{11/2}$, neutron $\sigma = g^{+}_{9/2}$ ($\pi h \otimes \nu g$).

The α-parity of the core

- The laboratory quadrupole variables are related to $\beta,\ \gamma,\ \Omega$ as follows:

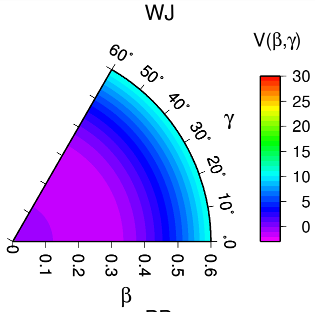
$$\alpha_\mu(\beta,\gamma,\Omega) = D^2_{\mu 0}(\Omega)\beta\cos\gamma + \frac{1}{\sqrt{2}}\left(D^2_{\mu 2}(\Omega) + D^2_{\mu -2}(\Omega)\right)\beta\sin\gamma$$

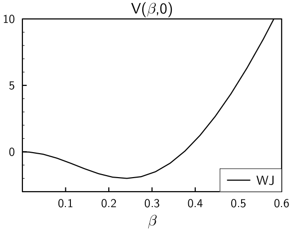
- The inversion in the five-dimensional space (the O(5) inversion) is: $\alpha_{2\mu} \to -\alpha_{2\mu}$
- A possible realisation of the inversion in the intrinsic variables: $\gamma \to \gamma \pm \pi$.
- If the Bohr Hamiltonian is invariant under the O(5) inversion (the α-symmetric) the core states possess the definite α-parity (the γ-parity introduced by Bés, 1959).
- In the present calculations
  - when $h_1 = b_1 = 0$ the core is the α-symmetric,
  - when $h_1 \neq 0$ (the α-asymmetric potential) and/or $b_1 \neq 0$ (the α-asymmetric kinetic energy) the α-symmetry is broken.

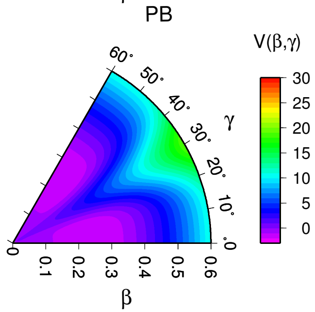
The proton-neutron symmetry

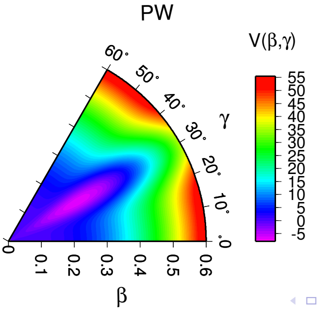
- The symmetry with respect to the exchange of the proton and the neutron states:
  $\pi\rho \to \pi\sigma, \nu\sigma \to \nu\rho$
  is (a bit misleading) called the proton-neutron symmetry.
- It is not the particle-hole exchange (time reversal).
- In the present calculations
  - when $\rho = \sigma = h_{11/2}$ (the proton and the neutron hole on the same orbital) the proton-neutron symmetry is conserved,
  - when $\rho = h_{11/2}$ and $\sigma = g_{9/2}$ (the proton and the neutron hole on different orbitals) the proton-neutron symmetry is broken.

Collective α-symmetric potentials


WJ


V(β,0)


PB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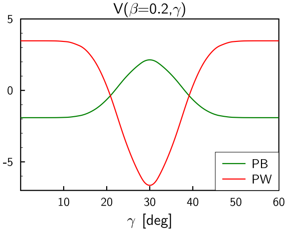
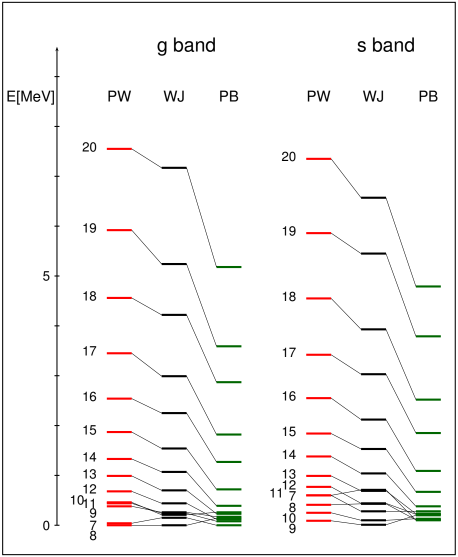

V(β=0.2,γ)

Partner bands



Ground (g) and side (s) partner bands at α-symmetric cores and $\pi h_{11/2} \otimes \nu h^{-1}_{11/2}$

Partner bands

- The partner bands appear for an arbitrary rigidity.
- The bands become more and more stretched when the core is more and more rigid.
- The bands are the most split and squeezed for the potential barrier in γ.

Magnetic dipole moments

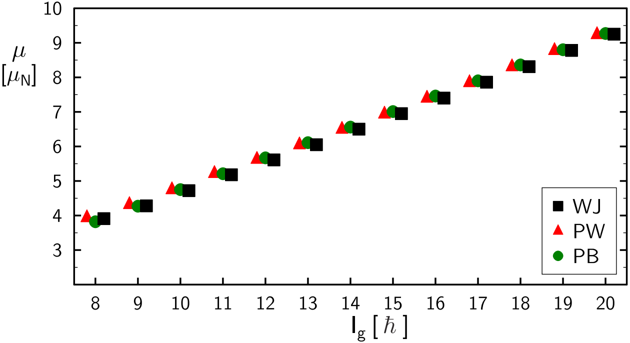


Figure: Magnetic dipole moments $\mu(I_g)$.

Electromagnetic moments

- The magnetic dipole moments in the s-band states are close to those in the g-band states.
- The magnetic dipole moments are independent practically on the rigidity of the core.
- The quadrupole electric moments are smaller than the single-particle estimates for a given spin ($|Q| < 0.1eb$) for the states of both bands at each rigidity of the core.

Stretched E2 transitions

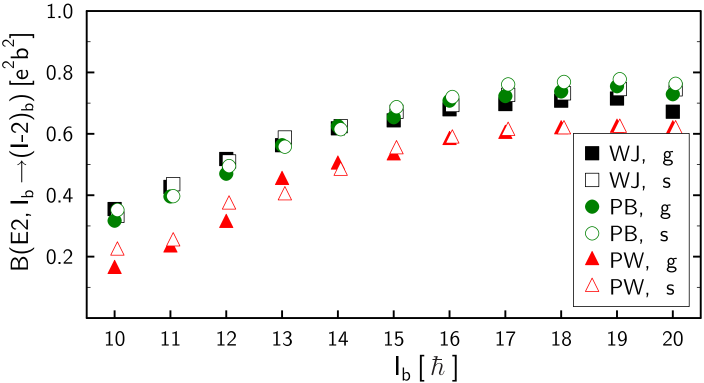


Figure: Reduced transition probabilities $B(\mathrm{E2}; I_\mathrm{b} \rightarrow (I-2)_\mathrm{b})$ of the stretched intra-band E2 transitions for the b=g ground band and the b=s side band.

$\Delta I = 1$ intra-band transitions

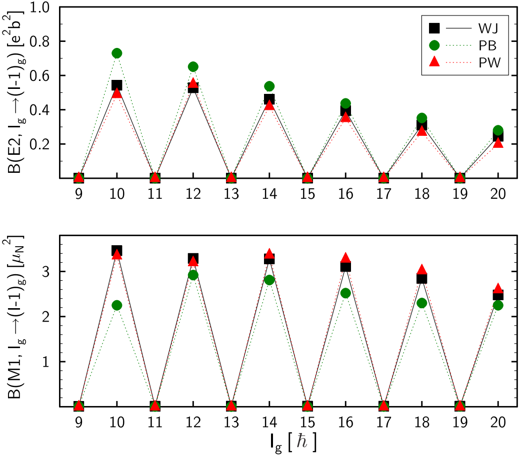


Figure: Reduced transition probabilities of the $\Delta I = 1$ intra-band electromagnetic transitions for the ground band.

$\Delta I = 1$ inter-band transitions

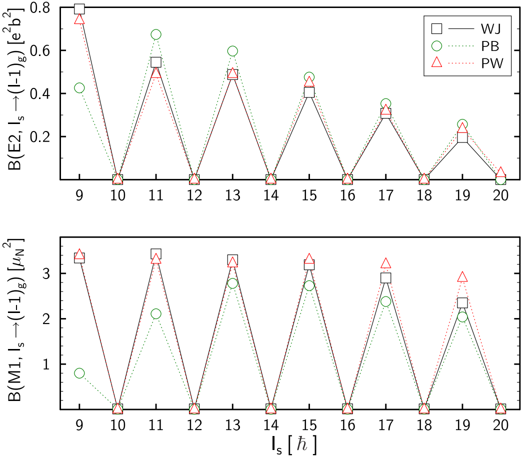


Figure: Reduced transition probabilities of the $\Delta I = 1$ inter-band electromagnetic transitions.

The α-symmetry — conclusion

- Properties of the partner bands:
  - A small splitting of the bands.
  - The similar electromagnetic properties (moments and transitions).
  - The strong staggering of the intra- and the inter-band E2 and M1 transitions.
- The chirality signatures are manifested in all cases of the α-symmetric cores and the particle and the hole on the same orbital.

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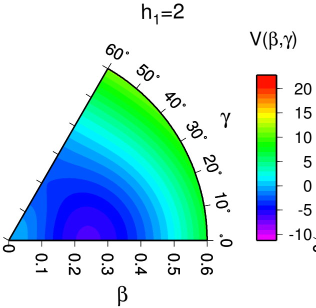
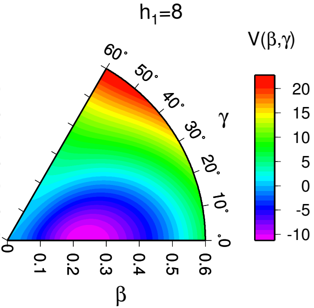
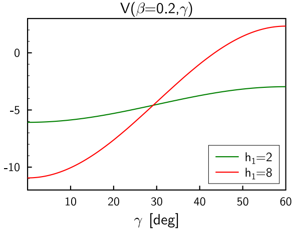
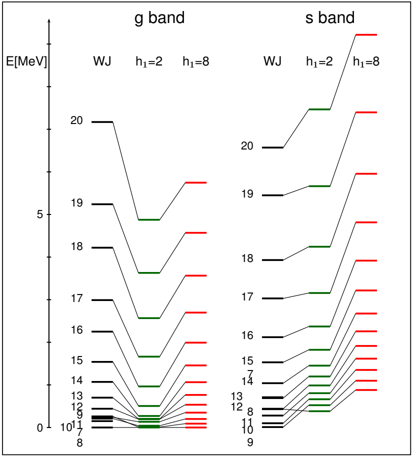
Collective α-asymmetric potentials







Partner bands



Ground (g) and side (s) (partner?) bands at α-asymmetric cores and $\pi h_{11/2} \otimes \nu h_{11/2}^{-1}$

Magnetic dipole moments

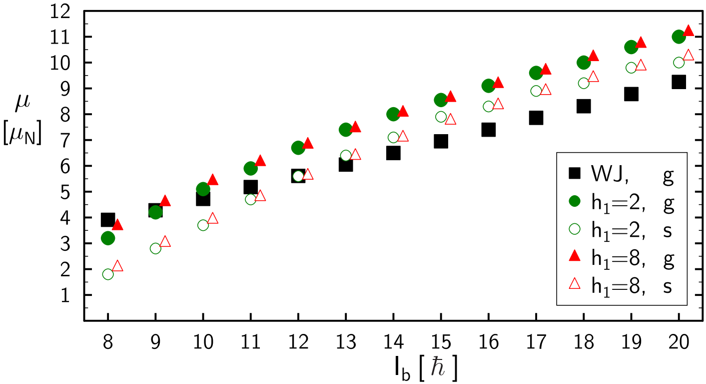


Figure: Magnetic dipole moments $\mu(I_b)$ for the ground (b=g) and the side (b=s) bands.

Electric quadrupole moments

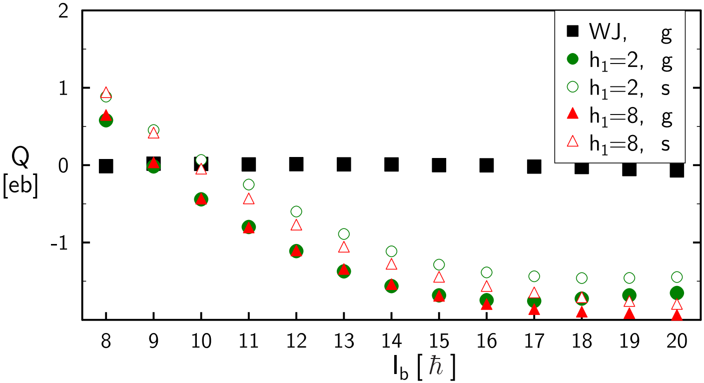
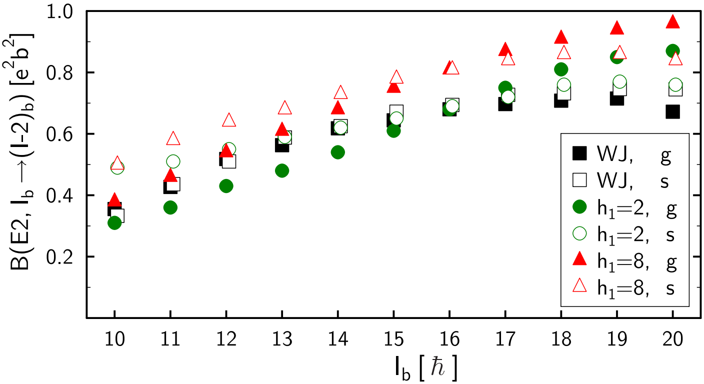


Figure: Electric quadrupole moments $Q(I_b)$ for the ground (b=g) and the side (b=s) bands.

Electromagnetic moments

- Small differences between the magnetic dipole moments of states in the ground and side bands.
- Considerable values of the electric quadrupole moments.
- Visible differences between the values of Q in the states of the ground and side bands.

Stretched E2 transitions



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$\Delta I = 1$ electromagnetic intra-band transitions

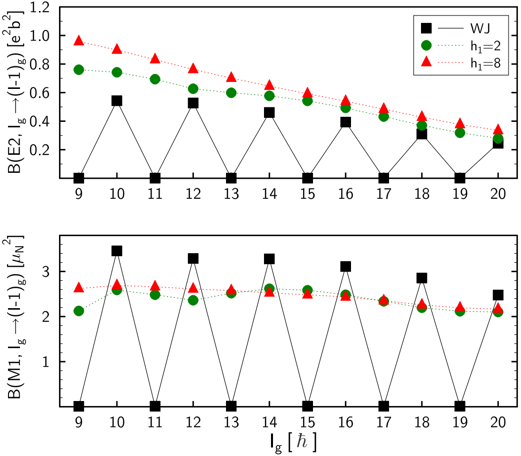

Figure: Reduced transition probabilities of the $\Delta I = 1$ intra-band electromagnetic transitions for the ground band.

$\Delta I = 1$ electromagnetic inter-band transitions

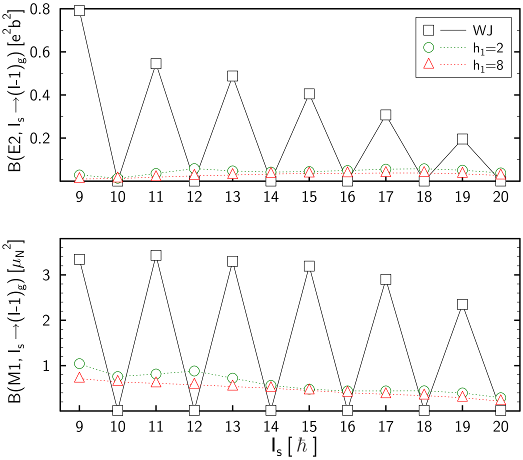

Figure: Reduced transition probabilities of the $\Delta I = 1$ inter-band electromagnetic transitions.

The α-asymmetry — conclusion

- Properties of the partner bands:
  - A strong splitting of the partner bands.
  - Not quite big differences between the electromagnetic properties of the partner bands.
  - The immediate disappearance of staggering in the intra- and the inter-band $\Delta I = 1$ electromagnetic transitions with the appearance of the asymmetry.
- The signatures of chirality vanish in the cases of the α-asymmetry of the core.
- A similar conclusion could be drawn in the case of the α-asymmetry in the collective kinetic energy ($b_1 \neq 0$).

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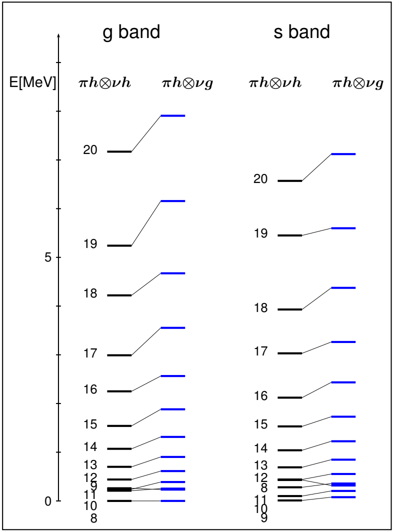
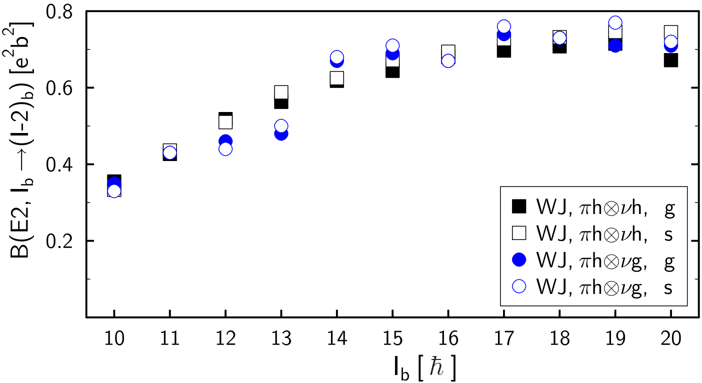


Ground (g) and side (s) partner bands at the WJ soft core and $\pi h_{11/2} \otimes \nu g_{9/2}^{-1}$

Stretched E2 transitions



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$\Delta I = 1$ electromagnetic transitions

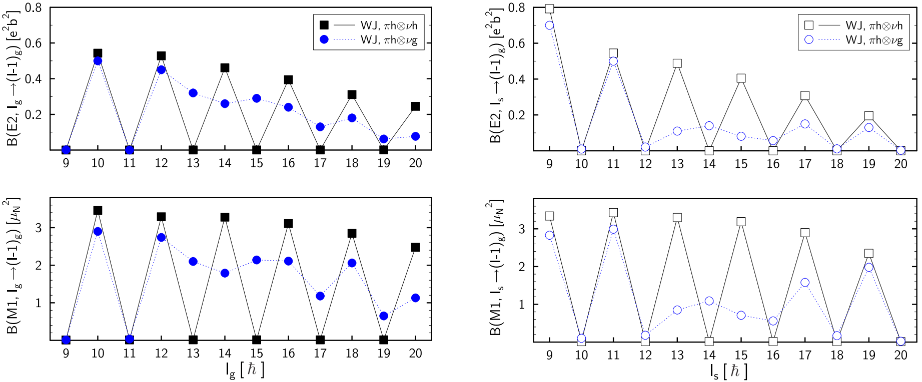

Figure: Reduced transition probabilities of the $\Delta I = 1$ intra-band (left) and inter-band (right) electromagnetic transitions.

The broken proton-neutron symmetry — conclusion

- Properties of the partner bands:
  - A little stronger splitting the partner bands than that in the case of the same orbitals.
  - Weak differences between the electromagnetic properties of the ground and side bands.
  - A weaker and irregular staggering of the intra- and the inter-band electromagnetic transitions.
- The signatures of chirality are obscure.

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Summary

- The use of the laboratory frame of reference:
  - The body-fixed frame of reference is eventually introduced in the description of the core structure
  - The properties of the core enter the description of the odd-odd nucleus only through the energies of the collective levels and the E2 matrix elements within the collective states.
  - No need and will to introduce an intrinsic frame of reference in the calculations for the odd-odd nucleus.
  - No assumptions of the chiral symmetry were made.
- Sufficient conditions for the odd-odd nucleus to manifest the chirality signatures are:
  - The odd-odd nucleus can be described as the three-body system: the even-even core, the proton and the neutron hole.
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  - No assumptions of the chiral symmetry were made.
- Sufficient conditions for the odd-odd nucleus to manifest the chirality signatures are:
  - The odd-odd nucleus can be described as the three-body system: the even-even core, the proton and the neutron hole.
  - The core is the α-symmetric regardless of its rigidity.
  - The proton-neutron symmetry is conserved.