Isomers in Exotic Nuclei

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Future of Low Energy Nuclear Physics in Poland
and
Development of National Research Infrastructure

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Underlying Recent Evolution and Results

A part of this presentation employs the results of the recent article:

Spectroscopic criteria for identification of nuclear tetrahedral and octahedral symmetries: Illustration on a rare earth nucleus

PHYSICAL REVIEW C 97, 021302(R) (2018)

J. Dudek, D. Curien, I. Dedes, K. Mazurek, S. Tagami, Y. R. Shimizu and T. Bhattacharjee

announcing for the first time
the discovery of the tetrahedral and octahedral symmetries in atomic nuclei

Symmetries Are the Factors Determining Stability*) of Atomic Nuclei

*) *... by imposing hindrance mechanisms*

Symmetries Are the Factors Determining Stability*) of Atomic Nuclei

Nuclear mean field theory and group representation theory which are used in this research belong to the most powerful tools of nuclear structure theory arsenal

*) *... by imposing hindrance mechanisms*

Why Are We Interested in High-Rank Symmetries

• Theory predicts whole families of nuclear states in many regions of the Periodic Table compatible with exotic, new symmetries

• These symmetries may lead to well pronounced potential energy minima and unprecedented, attractive new nuclear mechanisms

• For instance: unprecedented degeneracies of nucleonic levels that are neither equal to $(2j + 1)$ nor to 2 (time-up, time-down)

• For instance: exotic (16-fold) degeneracies of 2p-2h excitations

• For instance: unprecedented degeneracies of rotational states

• For instance: unprecedented forms of the nuclear rotational behaviour - rotational bands without 'rotational (E2) transitions'

In relation to rotational bands with B(E2)=0
→ see the following comments →

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First Contact with Nuclear Tetrahedral Symmetry

Quadrupole Moments Generated by Octupole Shapes

- Nuclear surface Σ is defined in terms of multipole deformations:

$$\Sigma : \quad R(\vartheta, \varphi) = R_0 \left[1 + \sum_\lambda \sum_\mu \alpha_{\lambda\mu} Y_{\lambda\mu}(\vartheta, \varphi)\right]$$

- Given uniform density $\rho_\Sigma(\vec{r}\,)$ defined using the surface Σ

$$\rho_\Sigma(\vec{r}\,) = \begin{cases} \rho_0 : & \vec{r} \in \Sigma \\ 0 : & \vec{r} \notin \Sigma \end{cases}$$

- Express the multipole moments as usual by

$$Q_{\lambda\mu} = \int \rho_\Sigma(\vec{r}\,)\, r^\lambda\, Y_{\lambda\mu}\, d^3\vec{r}$$

- We can calculate the quadrupole moments as functions of $\alpha_{3\mu}$

One can demonstrate that among $\lambda = 3$ (octupole) deformations only α_{32} leads to $Q_2 \equiv 0$!

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The Notion of Isomeric Bands

Once tetrahedral nuclei are populated one may expect the presence of numerous isomers since B(E2) and B(E1) at the exact tetrahedral and/or octahedral symmetry limits – vanish!

In particular, one expects series of long living (isomeric) states with unprecedented parabolic energy-spin relation

Isomers at: $E_I \propto I(I+1) \leftarrow$ **Isomeric Bands**

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Introduction to Tetrahedral and Octahedral Symmetries

and

How to Establish Their Presence in Subatomic Physics

Tetrahedral Symmetry: Spherical-Harmonic Basis

Only special combinations of spherical harmonics may form a basis for surfaces with tetrahedral symmetry and only odd-order except 5

Three Lowest Order Solutions: Rank ↔ Multipolarity λ

$$\lambda = 3: \quad t_3 \equiv \alpha_{3,\pm 2}$$

$\lambda = 5:$ no solution possible

$$\lambda = 7: \quad t_7 \equiv \alpha_{7,\pm 2} \quad \text{and} \quad \alpha_{7,\pm 6} = -\sqrt{\tfrac{11}{13}} \cdot \alpha_{7,\pm 2}$$

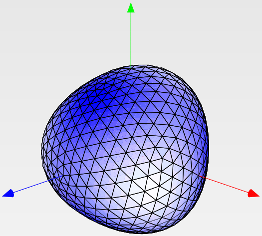
$$\lambda = 9: \quad t_9 \equiv \alpha_{9,\pm 2} \quad \text{and} \quad \alpha_{9,\pm 6} = +\sqrt{\tfrac{28}{198}} \cdot \alpha_{9,\pm 2}$$

- Problem presented in detail in:

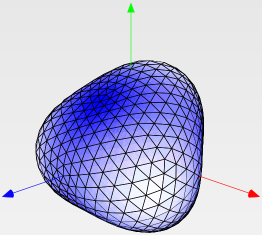
J. Dudek, J. Dobaczewski, N. Dubray, A. Góźdź, V. Pangon and N. Schunck, Int. J. Mod. Phys. E16, 516 (2007) [516-532].

Nuclear Tetrahedral Shapes – 3D Examples

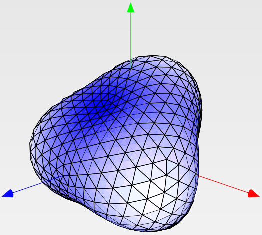
Illustrations below show the tetrahedral-symmetric surfaces at three increasing values of rank $\lambda = 3$ deformations α_{32}: 0.1, 0.2 and 0.3



$\alpha_{32} \equiv t_3 = 0.1$



$\alpha_{32} \equiv t_3 = 0.2$



$\alpha_{32} \equiv t_3 = 0.3$

Observations:

- There are infinitely many tetrahedral-symmetric surfaces
- Nuclear 'pyramids' do not resemble pyramids very much!

Octahedral Symmetry: Spherical-Harmonic Basis

Only special combinations of spherical harmonics may form a basis for surfaces with octahedral symmetry and only in even-orders $\lambda \geq 4$

Three Lowest Order Solutions: Rank $\leftrightarrow$ Multipolarity λ

$$\lambda = 4: \quad o_4 \equiv \quad \alpha_{40} \quad \text{and} \quad \alpha_{4,\pm4} = -\sqrt{\tfrac{5}{14}} \cdot \alpha_{40}$$

$$\lambda = 6: \quad o_6 \equiv \quad \alpha_{60} \quad \text{and} \quad \alpha_{6,\pm4} = -\sqrt{\tfrac{7}{2}} \cdot \alpha_{60}$$

$$\lambda = 8: \quad o_8 \equiv \quad \alpha_{80} \quad \text{and} \quad \alpha_{8,\pm4} = \sqrt{\tfrac{28}{198}} \cdot \alpha_{80}$$

$$\text{and} \quad \alpha_{8,\pm8} = \sqrt{\tfrac{65}{198}} \cdot \alpha_{80}$$

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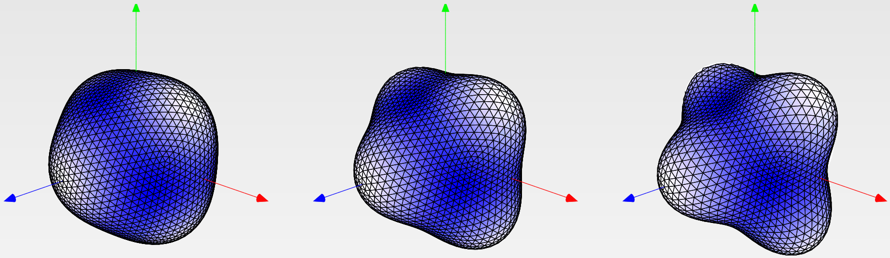


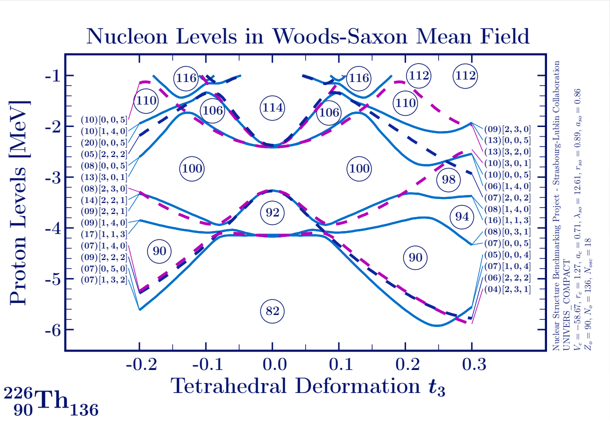
$o_4 = 0.1$ $o_4 = 0.2$ $o_4 = 0.3$

Observations:

- There are infinitely many octahedral-symmetric surfaces
- Nuclear ‘diamonds’ do not resemble diamonds very much!

Nuclear Tetrahedral Symmetry - Proton Spectra

Double group T_d^D has two 2-dimensional - and one 4-dimensional irreducible representations → Three distinct families of nucleon levels



Full lines ↔ 4-dimensional irreducible representations [four-fold degenerate] - marked with double Nilsson labels.

Observe large gaps at Z = 90 and 100.

Nuclear Tetrahedral Symmetry - Neutron Spectra

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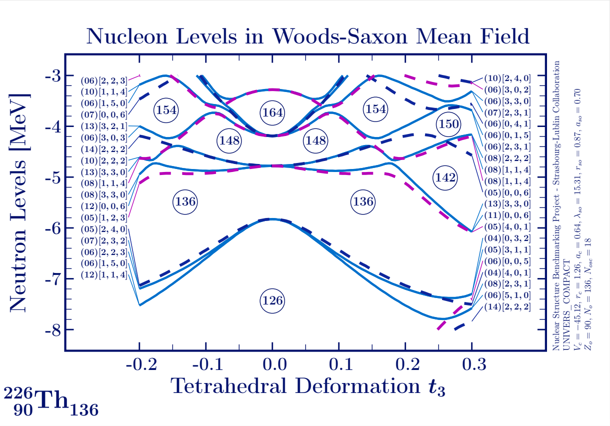
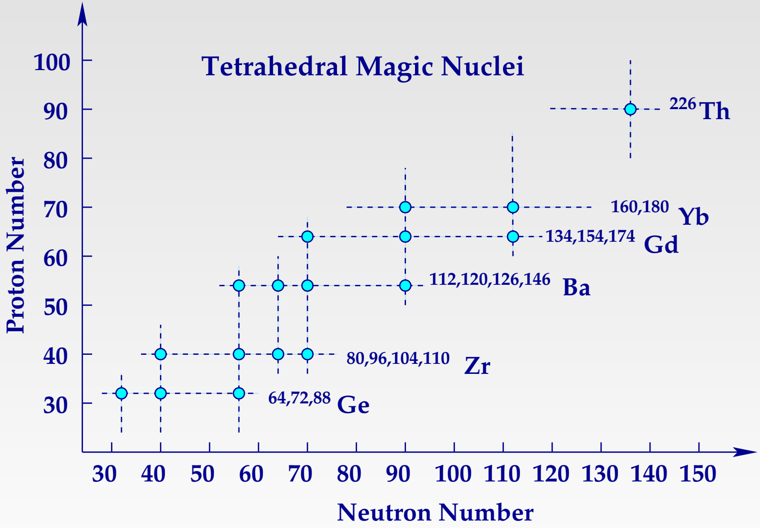


Full lines ↔ 4-dimensional irreducible representations [four-fold degenerate] - marked with double Nilsson labels.

Observe large gaps at N = 136 and ~142

Numerous Tetrahedral Doubly-Magic Nuclei



It may be instructive to recall that in the exact symmetry limit tetrahedral nuclei emit neither E2 nor E1 transitions → ISOMERS

Quantum Rotors: Tetrahedral vs. Octahedral

- The tetrahedral symmetry group has 5 irreducible representations
- The ground-state $I^\pi = 0^+$ belongs to A_1 representation given by:

$$\mathrm{A}_1: \quad \underbrace{0^+, 3^-, 4^+, \underbrace{(6^+, 6^-)}_{\text{doublet}}, 7^-, 8^+, \underbrace{(9^+, 9^-)}_{\text{doublet}}, \underbrace{(10^+, 10^-)}_{\text{doublet}}, 11^-, \underbrace{2\times 12^+, 12^-}_{\text{triplet}}, \cdots}_{\textbf{Forming a common parabola}}$$

- There are no states with spins $I = 1, 2$ and 5. We have parity doublets: $I = 6, 9, 10 \; \ldots$, at energies: $E_{6^-} = E_{6^+}$, $E_{9^-} = E_{9^+}$, etc.
- One shows that the analogue structure in the octahedral symmetry

$$\underbrace{A_{1g}: \; 0^+, 4^+, 6^+, 8^+, 9^+, 10^+, \; \ldots, \;\; I^\pi = I^+}_{\textbf{Forming a common parabola}}$$

$$\underbrace{A_{2u}: \; 3^-, 6^-, 7^-, 9^-, 10^-, 11^-, \ldots, \;\; I^\pi = I^-}_{\textbf{Forming another (common) parabola}}$$

Consequently we should expect two independent parabolic structures

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Since No Electromagnetic Transitions Expected:

**How do we look for rotational bands
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What To Start With?

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What To Start With?

About criteria for the experimental data search

- Central condition followed here: Nuclear states with exact high-rank symmetries produce neither dipole-, nor quadrupole moments

- Such states neither emit any collective/strong E1/E2 transitions nor can be fed by such transitions → focus on the nuclear processes

- Therefore we decided to focus first of all on the nuclei which can be populated with a big number of nuclear reactions since we may expect that - in such nuclei - the states sought exist in the literature

- We have verified that the nucleus ^{152}Sm can be produced by about 25 nuclear reactions, whereas surrounding nuclei can be produced typically with about a dozen but usually much fewer reactions only

- Energy-wise – tetrahedral bands form regular sequences

$$E_I \propto \alpha_2 I^2 + \alpha_1 I + \alpha$$

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Tetrahedral Bands Are Not Like the Others!

One may show using the methods of point-group representation theory that, for instance,
bands based on 0^+ state have the structure:

$$\mathrm{A}_1: \quad 0^+,\ 3^-,\ 4^+,\ 6^+,\ 6^-,\ 7^-,\ 8^+,\ 9^+,\ 9^-,\ 10^+,\ 10^-,\ 11^-,\ 2\times 12^+,\ 12^-,\ \cdots$$

and NOT

$$\boldsymbol{I^\pi}: \quad \mathbf{0^+,\ 2^+,\ 4^+,\ 6^+,\ 8^+,\ 10^+,\ 12^+,\ \cdots}$$

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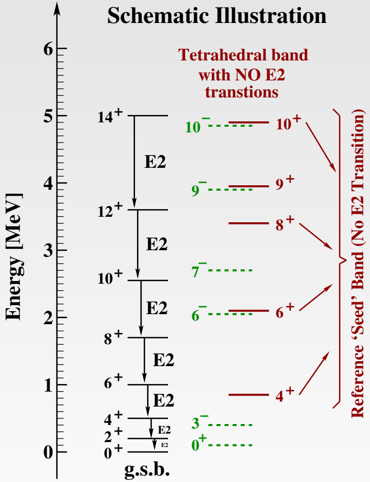
Similarly there exist **no analogues** of the “octupole bands”

$$\boldsymbol{I^\pi : \quad 3^-,\ 5^-,\ 7^-,\ 9^-,\ 11^-,\ 13^-,\ 15^-,\ \cdots}$$

Starting Point in Collecting the Experimental Evidence



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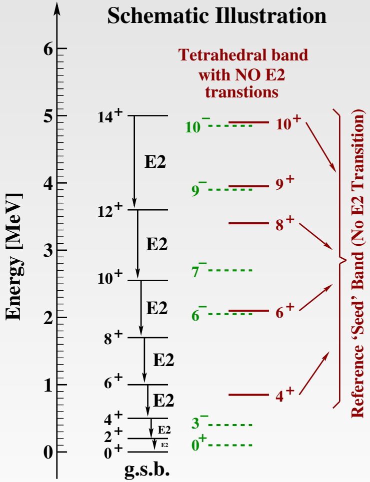

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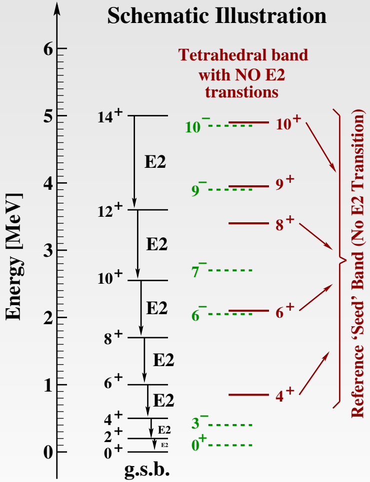

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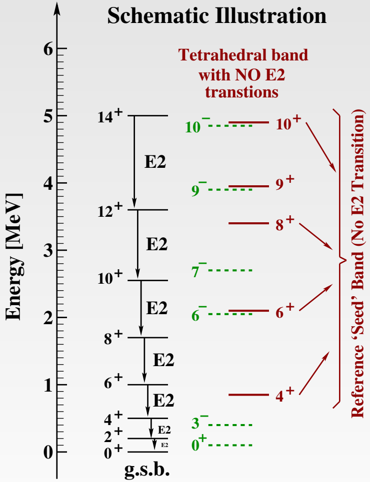


We begin by looking for experimental candidates for the 'reference seed band'

Starting Point in Collecting the Experimental Evidence

We proceed like this:

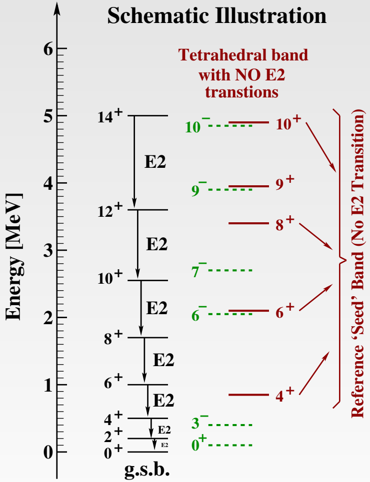
• We must try to find the sequence

$$4^+,\ 6^+,\ 8^+,\ 10^+\ \ldots$$

which is parabolic, no E2 transitions

• If successful, we will fit coefficients of the reference seed-band parabola

• Once this parabola is known – we select other experimental candidate states - close to reference seed-band



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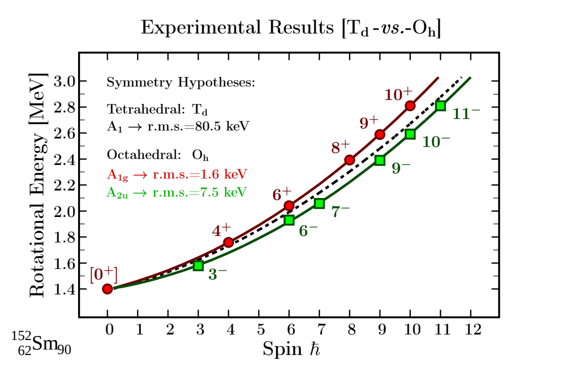
This has been done in the first identification article of both tetrahedral and octahedral symmetries in: Phys. Rev. C97, 021302(R) (2018)



Should We Enter This Physics in Poland in the Future?

WHY?

WHAT SHALL WE NEED?

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Why? Because of Novelty and Extreme Exoticity

- High-rank symmetries: With a number of unprecedented quantum-mechanical features they open a new era in nuclear spectroscopy. Why?
- Four-fold degenerate levels – never seen so far in atomic nuclei; it follows the issue of the totally new structure of particle-hole excitations
- Properties called in jargon "nuclear black holes": tetrahedral nuclei once populated[1] by nuclear reaction emit nearly no electromagnetic radiation and "live forever"
- The tetrahedral doubly magic structures are numerous, much more numerous than the spherical doubly magic structures
- They are expected to play a role of the new class of waiting-point nuclei → Nucleosynthesis processes in astrophysics
- Rotational bands [$E_I \propto I(I+1)$] containing degenerate doublets, triplets, ... composed of isomers with no E2-transitions

[1]Octupole radiation is several orders of magnitude slower, so is the β-decay

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What Shall We Need? – Roughly speaking...

Accelerator capable of producing 'reasonably heavy' ion beams

Mass spectrometers with a 'reasonable' mass resolution
[since electromagnetic transitions are expected to be very weak]

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Powerful Germanium multi detector systems [AGATA?]
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