Complementary Mechanisms in Nuclear Structure: Isomers, Highly Excited States and Giant Resonances

Jerzy DUDEK

UdS/IN_2P_3/CNRS, France and UMCS, Poland

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

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- **Case 1: Isomers can exist at high energies, so are giant resonances (after Brink hypothesis) – so what the heck! Measure, & that's it!**
  Triviality!

- **Case 2: All above elements manifest the presence of symmetries, symmetry breaking, phase transitions, critical points & phenomena.**
  Fascinating!

Motto:

Symmetries Are the Tool of Choice

In Our Studies

of Stability of Atomic Nuclei

K-Isomers and Yrast - Traps

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What are they?

K-Isomers and Yrast-Traps

What are they?

... and what are the good reasons to study them in Poland in the years to come?

Nuclear Spins Aligned With the Symmetry Axis

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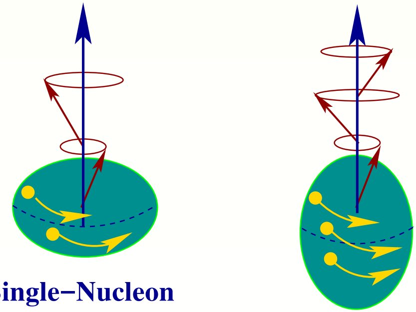
Projections of Angular Momenta Are Conserved in the Presence of Axial Symmetry



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- Consequently

$$\boxed{\hat{H}\,\varphi_{\nu,m_\nu} = e_{\nu,m_\nu}\,\varphi_{\nu,m_\nu}}$$

$$\boxed{\hat{\jmath}_z\,\varphi_{\nu,m_\nu} = m_\nu\,\varphi_{\nu,m_\nu}}$$

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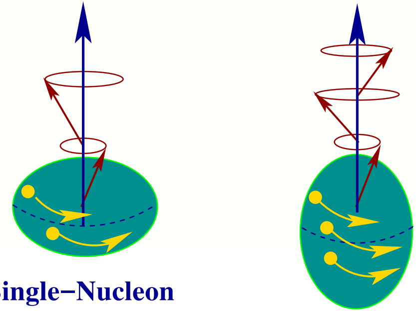
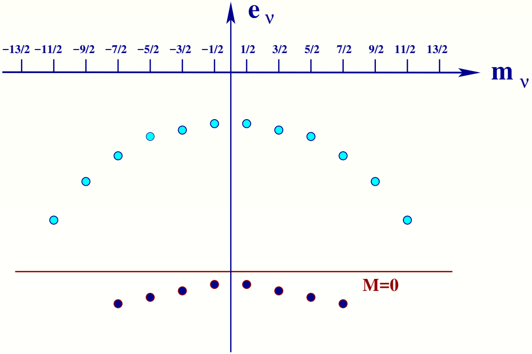


Single−Nucleon Alignment

Tilted Fermi Surface: Energy Minimisation at Given Spin



For the particle-hole excited-states we obtain at the same time the theoretical energy and theoretical spin:

$$\boxed{E^* = \sum_p e_{p,m_p} - \sum_h e_{h,m_h}} \quad \text{and} \quad \boxed{I \approx M^* = \sum_p m_p - \sum_h m_h}$$

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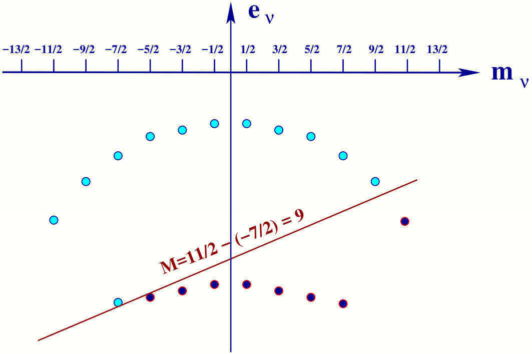

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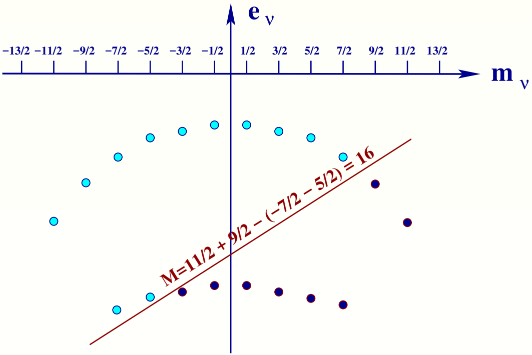

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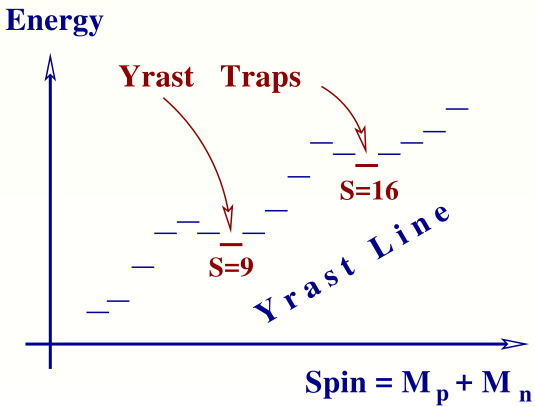
Irregular Nature of p-h Excitations Generates Yrast Traps



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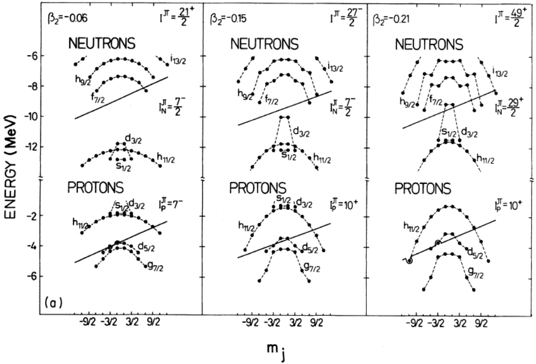
How Powerful the Idea Is – See Illustration 1

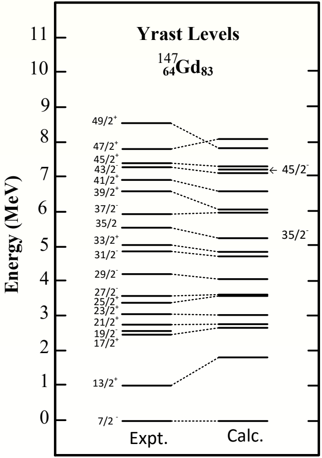


Spins & parities of all experimentally known isomers can be deduced from the diagrams: **4.50 ns** at $I^\pi = 21/2^+$, **26.8 ns** at $I^\pi = 27/2^-$, **530 ns** at $I^\pi = 49/2^+$. Ground state: $I^\pi = 7/2^-$ has **38 h** half-life. Maximum alignment neutron configurations lead to $I^\pi = 9/2^-$ and $I^\pi = 13/2^+$ states have lifetimes of **0.35 ps** and **21.4 ns**, respectively. $I^\pi = 19/2^-$ isomer, of **0.37 ns** is given by $[\pi d^{-2}_{5/2}]_0 \times [h^2_{11/2}]^{\max}_6 \times \nu[f^1_{7/2}]_{7/2}$.

All these structures can be directly deduced from the presented diagrams.

How Powerful the Idea Is – See Illustration 2

- Yrast ^{147}Gd sequence calculated using the realistic phenomenological **WS-universal** mean field approach.



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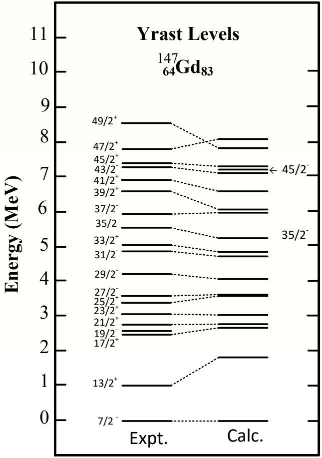

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- Somebody may ask:

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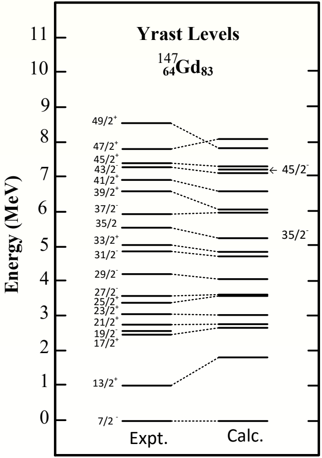

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NONE – no parameter adjusted to the presented data;
This is what is meant as Woods-Saxon Universal mean-field

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• **The axial-symmetry nuclei may choose to rotate collectively**

$$\boxed{(\vec{I} \perp \mathcal{O}_{\text{symmetry}}) \; - \; \text{bands}}$$

as alternative to

$$\boxed{(\vec{I} \parallel \mathcal{O}_{\text{symmetry}}) \; - \; \text{isomers}}$$

or both at the same shape at the same time (in competition).

Why? Which mechanisms cause this or that behaviour?

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• **By the way: No serious tests of the mean-field theory are possible without the cross-checking of the above information!**

New Kind of Isomers

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or

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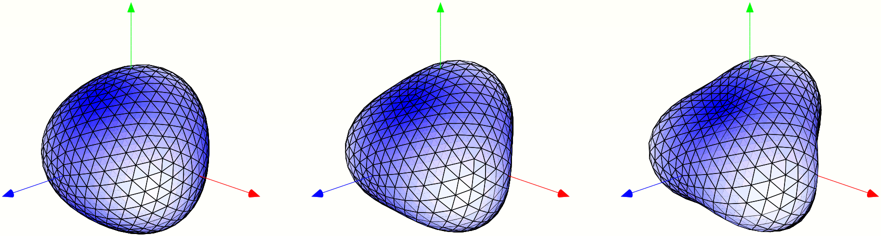
Nickname: High-Rank Symmetries:

Tetrahedral and Octahedral Point-Group Symmetries

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

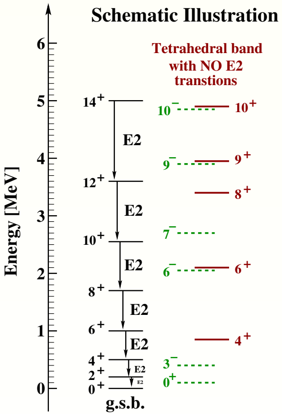


$\alpha_{32} \equiv t_3 = 0.1$ $\qquad$ $\alpha_{32} \equiv t_3 = 0.2$ $\qquad$ $\alpha_{32} \equiv t_3 = 0.3$

Observations:

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

Tetrahedral Bands Are Not Like the Others!



- The A_1-representation sequence of spin-parity states forms a single parabola

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

- There belong states of both parities and, in addition, they form doublets, triplets, etc.

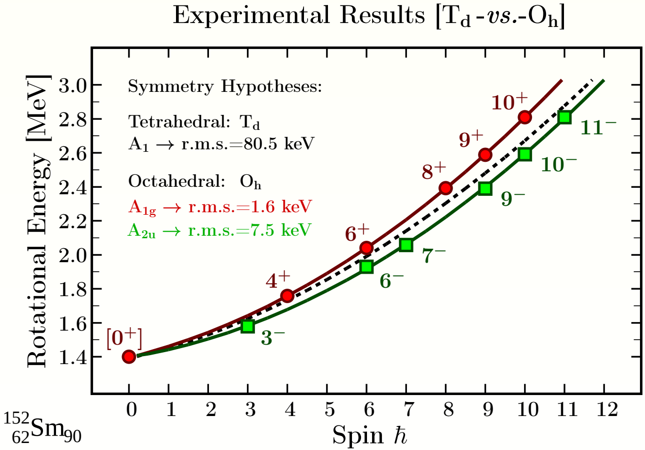


Illustration of experimental results, cf. PHYS. REV. C 97, 021302(R) (2018). Curves represent the fit and are *not* meant 'to guide the eye'. Markedly, point [$I^\pi = 0^+$], is a prediction by extrapolation - not an experimental datum.

Suppose We Give Ourselves the Means For Studying Tetrahedral Bands

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- **Life-times of those states, not known today, may be primarily given by the E3-decay and/or β-decay $\rightarrow$ therefore very long**

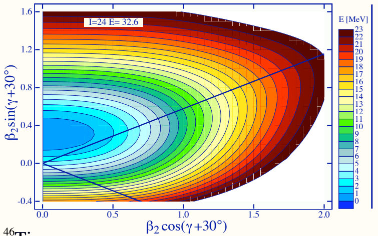
For more details about this type of isomers cf. presentation by Irene Dedes

High Energy Excitations,

Giant Resonances

Jacobi and Poincaré Shape Transitions

- Consider an example of Jacobi shape transitions: ^{46}Ti and ^{142}Ba;



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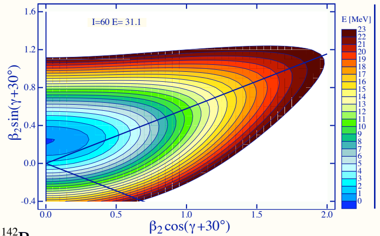

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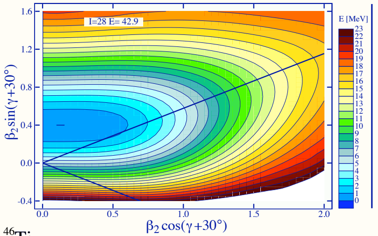

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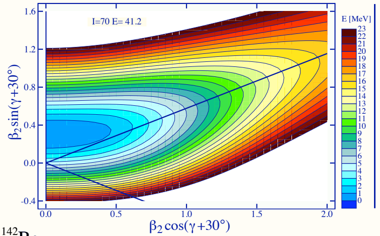

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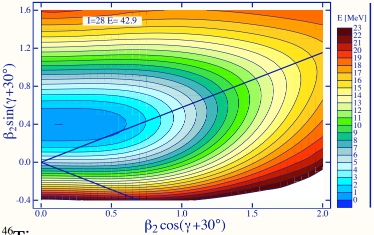

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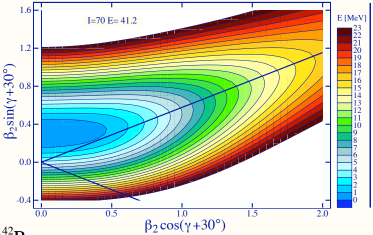

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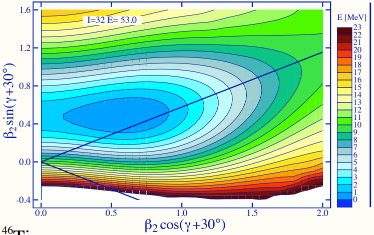

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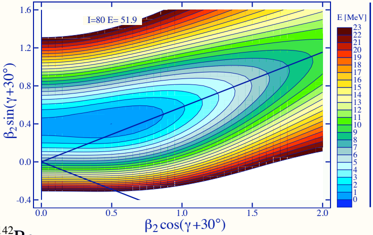

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Jacobi Transitions - Mechanism of Criticality

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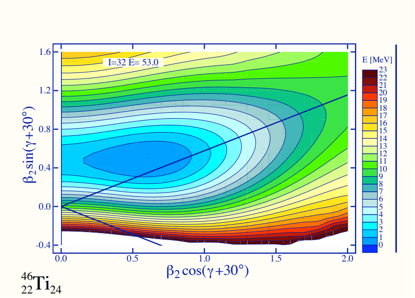
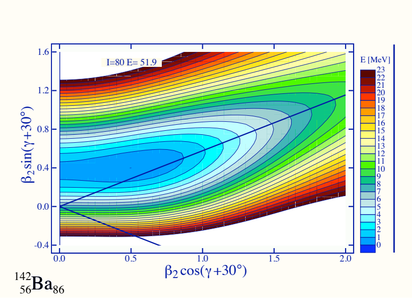
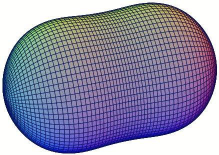
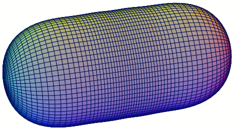




Shape at β_2 =0.6



Shape at β_2 =0.9



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• Consequently, one has to solve quantum mechanical problem of the nuclear collective motion, find the wave functions and the most probable deformations, root-mean-square deviations (σ-values), etc.

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Posing the Problem of Large Amplitude Motion

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- The corresponding Schrödinger equation has a usual general from

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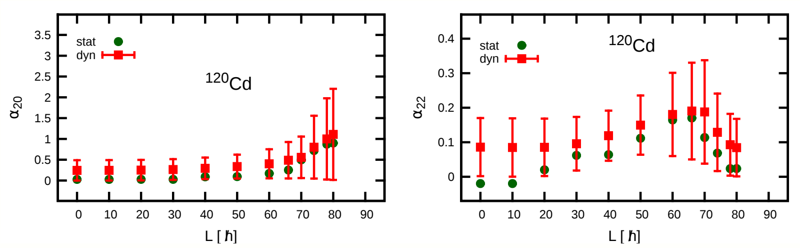
• Knowing the solutions we can calculate the expected values $\bar{\alpha}_{\lambda\mu}$ taken as a measure of the most probable deformation and given by:

$$\langle \alpha^2_{\lambda\mu} \rangle \equiv \int d\alpha\,\Psi^*_n(\alpha)\,\alpha^2_{\lambda\mu}\Psi_n(\alpha) \;\rightarrow\; \bar{\alpha}_{\lambda\mu} = \sqrt{\langle \alpha^2_{\lambda\mu} \rangle}$$

• In this way we obtain two, different and non-equivalent realisations of the description of physical deformations: static and dynamical:

$$(\alpha_{20}, \alpha_{22})_{stat.} \quad \rightarrow\rightarrow \quad \boxed{(\bar{\alpha}_{20}, \bar{\alpha}_{22})_{dyn.}}$$

- Results of calculations*) obtained by solving Schrödinger equation



*) **Collaboration with K. Mazurek and D. Rouvel**

Shape Uncertainties During Jacobi Transitions

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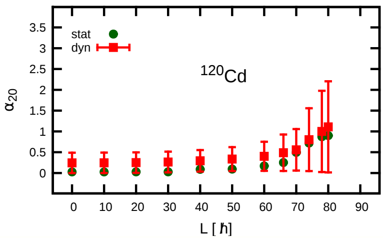

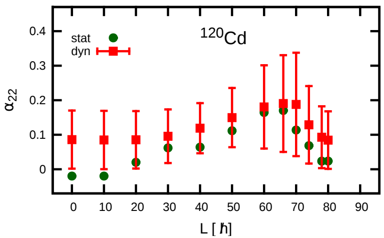

- To obtain the results above we have introduced dispersion coeffs.

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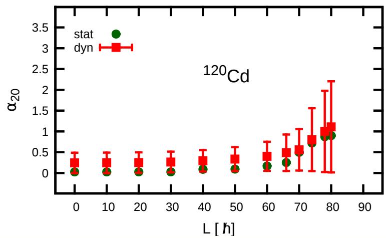
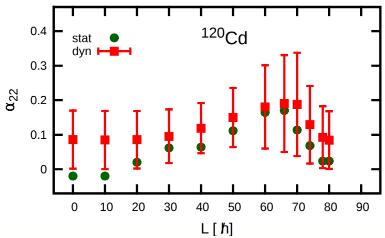




- To obtain the results above we have introduced dispersion coeffs.

$$\sigma_{20} \equiv \sqrt{\langle \alpha_{20}^2 \rangle - \langle \alpha_{20} \rangle^2} \quad \text{and} \quad \sigma_{22} \equiv \sqrt{\langle \alpha_{22}^2 \rangle - \langle \alpha_{22} \rangle^2}$$

- Positions of the squares are given by $\sqrt{\langle \alpha_{20}^2 \rangle}$ and $\sqrt{\langle \alpha_{22}^2 \rangle}$. The bars represent the intervals of the size $(\pm\sigma)$ as the quantitative estimates

*) **Collaboration with K. Mazurek and D. Rouvel**

- Experiment vs. modelling with high-temperature thermal shape-fluctuations; Splitting of the GDR allows to deduce deformation

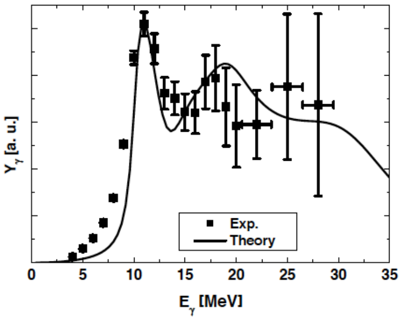
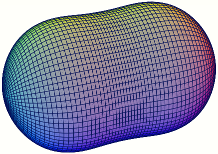


Figure 4. The full drawn line shows the theoretical prediction (at $< T > \approx 2$ MeV and in the spin region 28–34 $\hbar$) of the GDR lineshape in ^{46}Ti obtained from the thermal shape fluctuation model based on free energies from the LSD model calculations [2]. The filled squares are the experimental data shown also in the right panel of Figure 2.

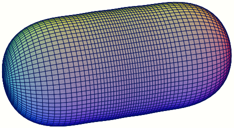
- Experimental results from A. Maj et al., Nucl. Phys. A731, 319 (2004)

Dramatic Shape Changes Cost Nearly No Energy

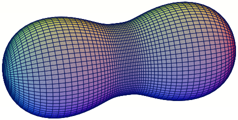
Shape at $\beta_2 = 0.6$



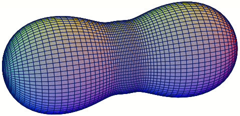
Shape at $\beta_2 = 0.9$



Shape at $\beta_2 = 1.2$



Shape at $\beta_2 = 1.5$



Suppose We Give Ourselves the Means For Studying Giant Resonances

What Do We Learn
From the GDR Shape-Probability Profiles?

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- From competition between Jacobi and Poincare shape transitions we control the fission fragment mass distributions with increasing spin – important nuclear structure information

Final Remarks about a Special Edition of Potential Interest When discussing future of nuclear physics

Physica Scripta

Focus issue to celebrate the 40 year anniversary of the 1975 Nobel Prize to Aage Niels Bohr, Ben Roy Mottelson and Leo James Rainwater

Guest Editor: Jerzy Dudek

The 1975 Nobel Prize awarded to Aage, Ben and Leo was awarded after an extensive and successful research programme in nuclear structure physics was held by the Niels Bohr Institute of the University of Copenhagen, Denmark. This enterprise was followed by a comparably successful period during which many researchers from all over the world met and worked in Copenhagen. In this focus issue published by *Physica Scripta*, all of the authors wish to express their gratitude for the long-lasting impact this Nobel Prize has had, leading to many scientific successes, stimulating the shared fascination so many of us have for our field of research. Traces of this event and of ideas related to the physics for which it was awarded can be seen in thousands of articles in our research domain and will be present in many more to come.

Preface

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J Dudek 2016 *Phys. Scr.* **91** 030301

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