Exotic Shapes and Symmetries of Atomic Nuclei

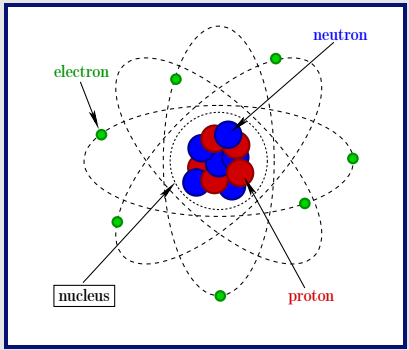
Irene DEDES

The Henryk Niewodniczański
Institute of Nuclear Physics
Polish Academy of Sciences
Kraków, Poland

Open Meeting of the Nuclear Physics Section
of the Polish Physical Society

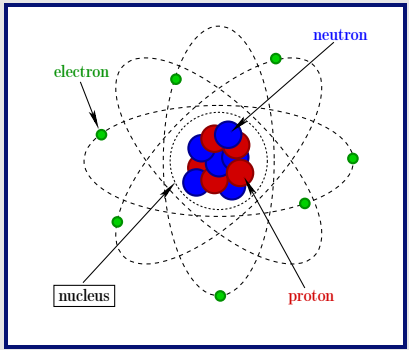
27 October 2023

The Atomic Nucleus



Introduction – Keywords

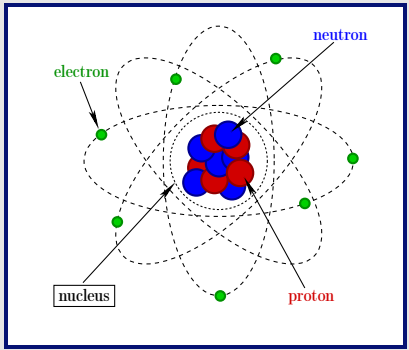
The Atomic Nucleus



- The **atomic nucleus** is the small and dense part at the center of an atom.

Introduction – Keywords

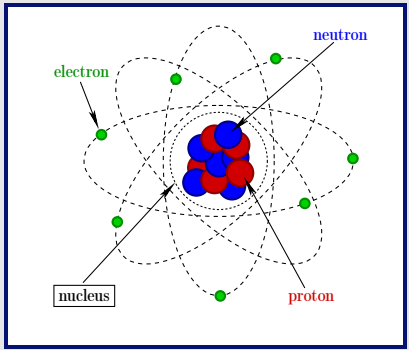
The Atomic Nucleus



- The **atomic nucleus** is the small and dense part at the center of an atom.
- It is composed of Z **protons** and N **neutrons**, and it contains 99.9% of the mass of the atom.

Introduction – Keywords

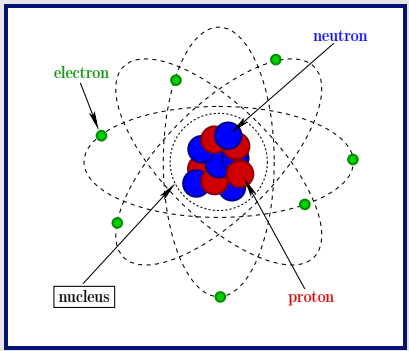
The Atomic Nucleus



- The **atomic nucleus** is the small and dense part at the center of an atom.
- It is composed of Z **protons** and N **neutrons**, and it contains 99.9% of the mass of the atom.
- Thanks to the scientific experiments which allow us to detect and analyze the atomic nuclei microscopically, we observe that **they can take different shapes**, far from spherical ones.

Introduction – Keywords

The Atomic Nucleus

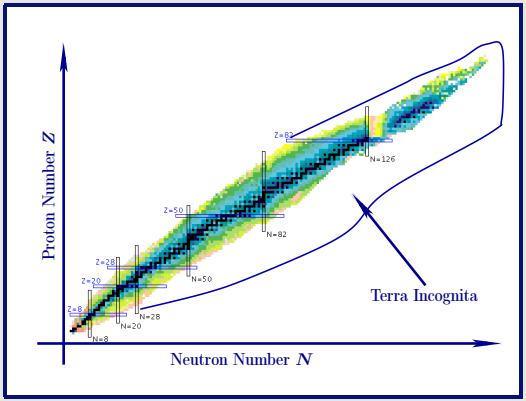


- The **atomic nucleus** is the small and dense part at the center of an atom.
- It is composed of Z **protons** and N **neutrons**, and it contains 99.9% of the mass of the atom.
- Thanks to the scientific experiments which allow us to detect and analyze the atomic nuclei microscopically, we observe that **they can take different shapes**, far from spherical ones.

The Atomic Nucleus Can Be Deformed!

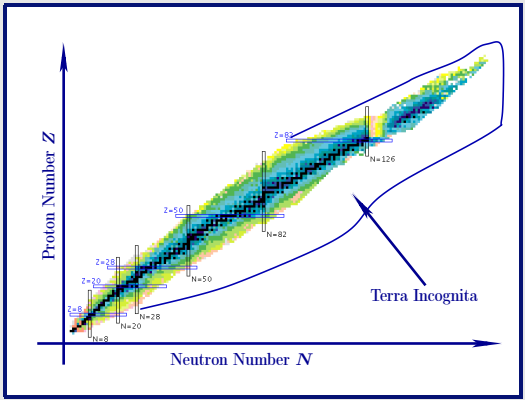
There Are Nearly 3000 Nuclei Observed So Far

The Chart of Nuclides



There Are Nearly 3000 Nuclei Observed So Far

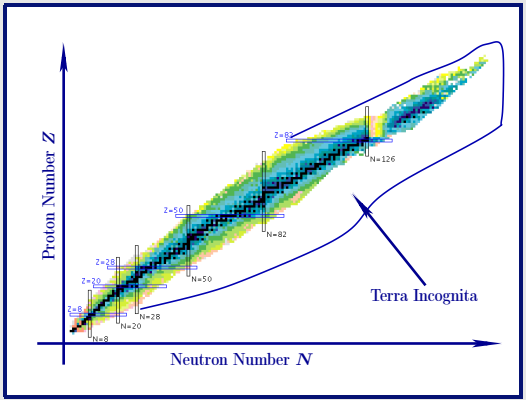
The Chart of Nuclides



- Among nearly 3000 systems known experimentally:

There Are Nearly 3000 Nuclei Observed So Far

The Chart of Nuclides

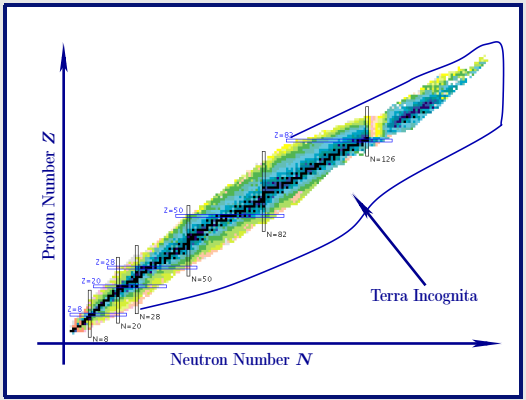


• Among nearly 3000 systems known experimentally:

→ about 200 nuclei are stable; they are marked in black.

There Are Nearly 3000 Nuclei Observed So Far

The Chart of Nuclides



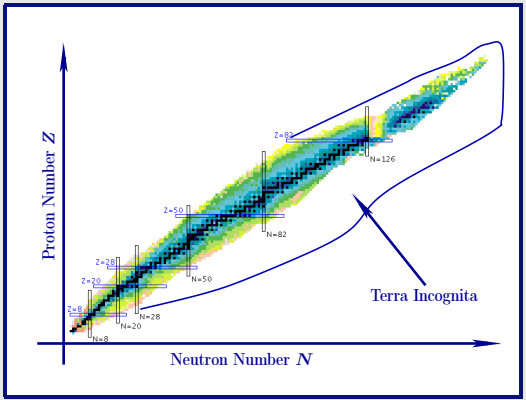
• Among nearly 3000 systems known experimentally:

→ about 200 nuclei are stable; they are marked in black.

→ more than 80% are strongly deformed, only about 8 ‘really spherical’

There Are Nearly 3000 Nuclei Observed So Far

The Chart of Nuclides



- Among nearly 3000 systems known experimentally:

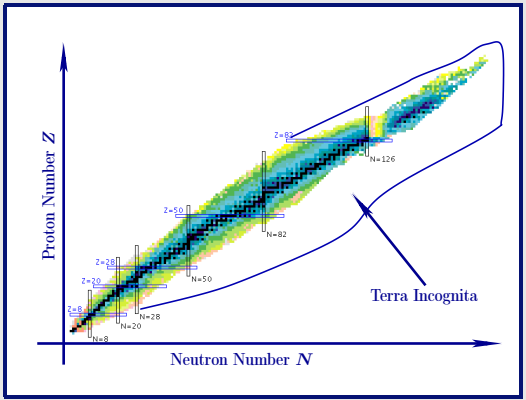
→ about 200 nuclei are stable; they are marked in black.

→ more than 80% are strongly deformed, only about 8 ‘really spherical’

- **Terra Incognita**: Still >6000 nuclei are expected to exist...

There Are Nearly 3000 Nuclei Observed So Far

The Chart of Nuclides



- Among nearly 3000 systems known experimentally:

→ about 200 nuclei are stable; they are marked in black.

→ more than 80% are strongly deformed, only about 8 ‘really spherical’

- **Terra Incognita**: Still >6000 nuclei are expected to exist...

High chances that they are deformed!

Main Scope of Our Research

• Give the theoretical explanations to the experimental nuclear structure phenomena observed, as well as predicting the still unknown

How do we perform our studies?

• We describe the nuclear interior, i.e. *nuclear structure*, with a simple but very reliable and powerful theory called: **The Nuclear Mean-Field Theory**

• We combine contemporary **mathematical tools** of group theory, inverse problem theory and graph-theory with phenomenological nuclear mean-field theory

• One of the most important strategies: Making sure the theory we use is reliable, offering realistic, experiment comparable results for many nuclei.

Main Scope of Our Research

• Give the theoretical explanations to the experimental nuclear structure phenomena observed, as well as predicting the still unknown

How do we perform our studies?

• We describe the nuclear interior, i.e. *nuclear structure*, with a simple but very reliable and powerful theory called: **The Nuclear Mean-Field Theory**

• We combine contemporary **mathematical tools** of group theory, inverse problem theory and graph-theory with phenomenological nuclear mean-field theory

• One of the most important strategies: Making sure the theory we use is reliable, offering realistic, experiment comparable results for many nuclei.

Main Scope of Our Research

• Give the theoretical explanations to the experimental nuclear structure phenomena observed, as well as predicting the still unknown

How do we perform our studies?

• We describe the nuclear interior, i.e. *nuclear structure*, with a simple but very reliable and powerful theory called: **The Nuclear Mean-Field Theory**

• We combine contemporary **mathematical tools** of group theory, inverse problem theory and graph-theory with phenomenological nuclear mean-field theory

• One of the most important strategies: Making sure the theory we use is reliable, offering realistic, experiment comparable results for many nuclei.

Main Scope of Our Research

• Give the theoretical explanations to the experimental nuclear structure phenomena observed, as well as predicting the still unknown

How do we perform our studies?

• We describe the nuclear interior, i.e. *nuclear structure*, with a simple but very reliable and powerful theory called: **The Nuclear Mean-Field Theory**

• We combine contemporary **mathematical tools** of group theory, inverse problem theory and graph-theory with phenomenological nuclear mean-field theory

• One of the most important strategies: Making sure the theory we use is reliable, offering realistic, experiment comparable results for many nuclei.

Research Projects of Our Group
"Nuclear Structure Microscopic Studies"

- **Nuclear Exotic Symmetries:** Symmetries from the world of *molecules* but detected in *subatomic* physics, such as Tetrahedral and Octahedral Symmetries (High Rank Symmetries)

- **Shape Coexistence and Evolution**

- **Special Shape Isomers** in axially symmetric nuclei

- **Shape Phase Transitions**: Known from astronomy Jacobi and Poincaré shape transitions taking place in stars → here: detected and studied in detail in nuclei

- **Stability of Nuclear Theory Predictions**: As a remark "for experts" – Parameter correlation removal as professional means of stabilising the theory prediction capacities

- **Improving the Phenomenological Description of Nuclear Mean-Field Hamiltonian**: Density dependent spin-orbit together with tensor-force components

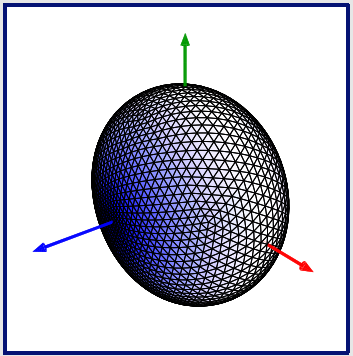
Standard (Non-Exotic) Nuclear Shapes

- Typically, the nuclei have axially symmetric shapes, called

Standard (Non-Exotic) Nuclear Shapes

- Typically, the nuclei have axially symmetric shapes, called

Oblate

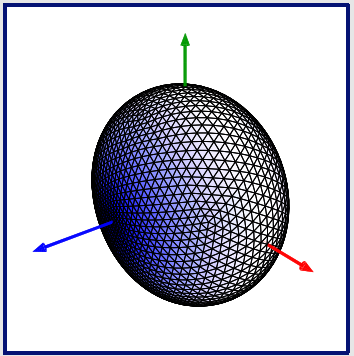


Pancake

Standard (Non-Exotic) Nuclear Shapes

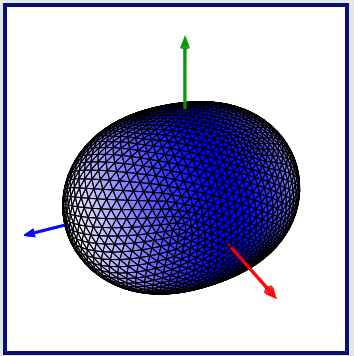
- Typically, the nuclei have axially symmetric shapes, called

Oblate



Pancake

Prolate

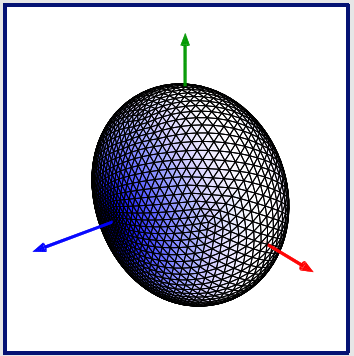


American football

Standard (Non-Exotic) Nuclear Shapes

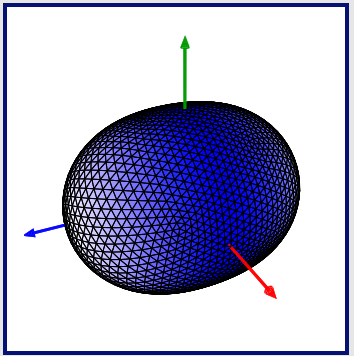
- Typically, the nuclei have axially symmetric shapes, called

Oblate



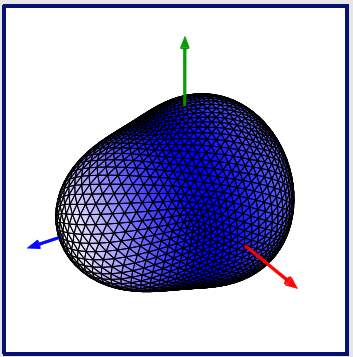
Pancake

Prolate



American football

Pear-shape



Pear fruit

Non-Trivial Exotic Nuclear Shapes: Historical Perspective

- Already in Ancient Greece, they were interested in the *beauty in symmetry*

Non-Trivial Exotic Nuclear Shapes: Historical Perspective

- Already in Ancient Greece, they were interested in the *beauty in symmetry*
- **Platonic Solids** (Plato, 428-347 bC): Polyhedra whose faces are identical regular convex polygons

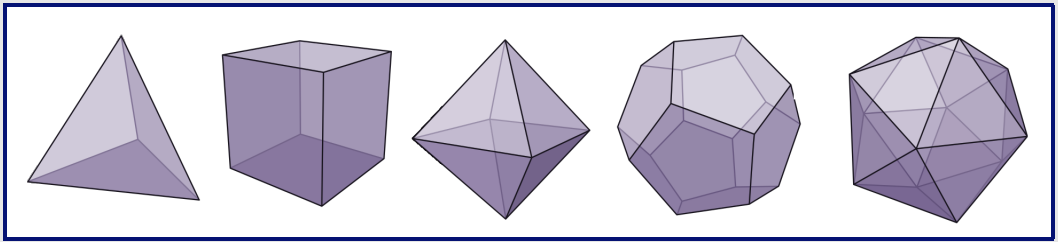
Non-Trivial Exotic Nuclear Shapes: Historical Perspective

- Already in Ancient Greece, they were interested in the *beauty in symmetry*
- **Platonic Solids** (Plato, 428-347 bC): Polyhedra whose faces are identical regular convex polygons
- The allowed polygons are: triangles, squares and regular pentagons

Non-Trivial Exotic Nuclear Shapes: Historical Perspective

- Already in Ancient Greece, they were interested in the *beauty in symmetry*
- **Platonic Solids** (Plato, 428-347 bC): Polyhedra whose faces are identical regular convex polygons
- The allowed polygons are: triangles, squares and regular pentagons
- Thus, there are only five Platonic Solids:

Tetrahedron	Cube	Octahedron	Dodecahedron	Icosahedron

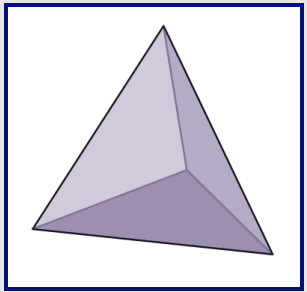


Non-Trivial Exotic Nuclear Shapes: Tetrahedral Symmetry

Tetrahedron

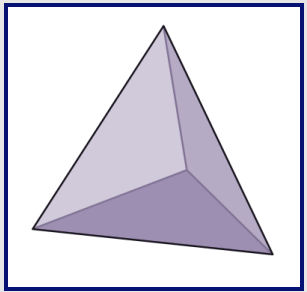
Non-Trivial Exotic Nuclear Shapes: Tetrahedral Symmetry

Tetrahedron



Non-Trivial Exotic Nuclear Shapes: Tetrahedral Symmetry

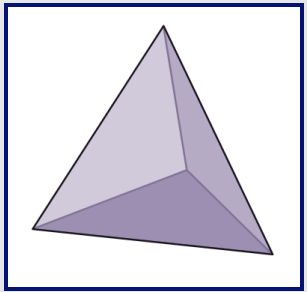
Tetrahedron



- It has 4 equal walls

Non-Trivial Exotic Nuclear Shapes: Tetrahedral Symmetry

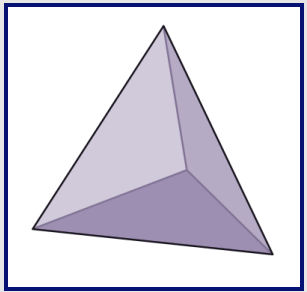
Tetrahedron



- It has 4 equal walls
- Invariant with respect to 24 symmetry elements,

Non-Trivial Exotic Nuclear Shapes: Tetrahedral Symmetry

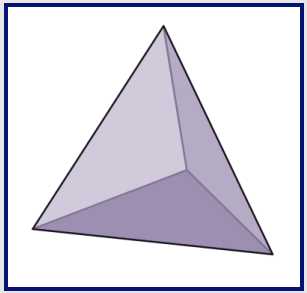
Tetrahedron



- It has 4 equal walls
- Invariant with respect to 24 symmetry elements,
- But it is not invariant with respect to inversion

Non-Trivial Exotic Nuclear Shapes: Tetrahedral Symmetry

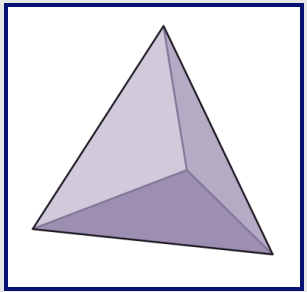
Tetrahedron



- It has 4 equal walls
- Invariant with respect to 24 symmetry elements,
- But it is not invariant with respect to inversion
- Nuclei cannot be represented by a sharp-edge pyramid

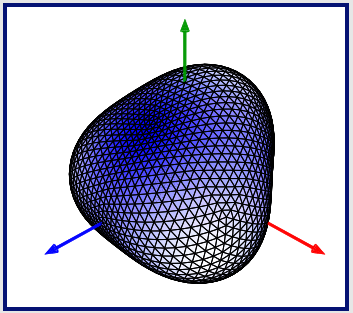
Non-Trivial Exotic Nuclear Shapes: Tetrahedral Symmetry

Tetrahedron



- It has 4 equal walls
- Invariant with respect to 24 symmetry elements,
- But it is not invariant with respect to inversion
- Nuclei cannot be represented by a sharp-edge pyramid

Nuclear Tetrahedron

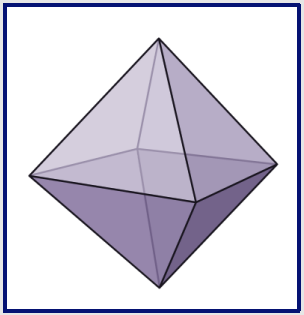


Non-Trivial Exotic Nuclear Shapes: Octahedral Symmetry

Octahedron

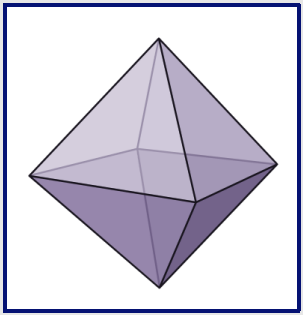
Non-Trivial Exotic Nuclear Shapes: Octahedral Symmetry

Octahedron



Non-Trivial Exotic Nuclear Shapes: Octahedral Symmetry

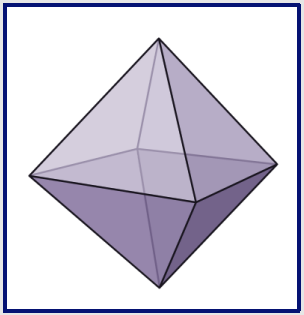
Octahedron



- It has 8 equal walls

Non-Trivial Exotic Nuclear Shapes: Octahedral Symmetry

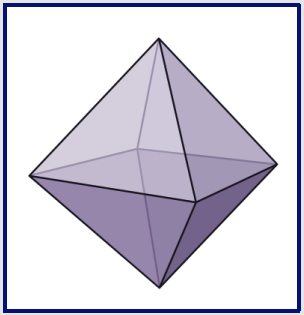
Octahedron



- It has 8 equal walls
- Invariant with respect to 48 symmetry elements,

Non-Trivial Exotic Nuclear Shapes: Octahedral Symmetry

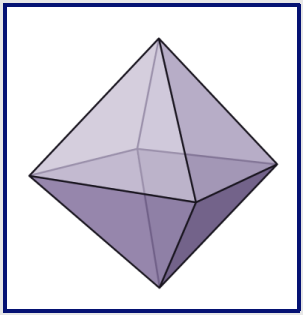
Octahedron



- It has 8 equal walls
- Invariant with respect to 48 symmetry elements,
- Including inversion

Non-Trivial Exotic Nuclear Shapes: Octahedral Symmetry

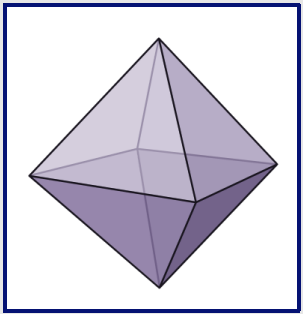
Octahedron



- It has 8 equal walls
- Invariant with respect to 48 symmetry elements,
- Including inversion
- Nuclei cannot be represented by a sharp-edge diamond

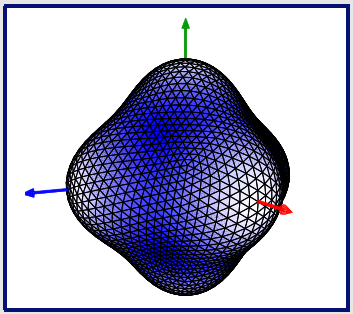
Non-Trivial Exotic Nuclear Shapes: Octahedral Symmetry

Octahedron



- It has 8 equal walls
- Invariant with respect to 48 symmetry elements,
- Including inversion
- Nuclei cannot be represented by a sharp-edge diamond

Nuclear Octahedron



Why Studying Molecular Symmetries in Nuclear Physics ?

- Atomic nuclei can adopt several different shapes (depending on their number of protons and neutrons, among others)
- Such symmetries might range from a 'simple' sphere, or trivial modifications of it (e.g. oblate, prolate), to more exotic shape such as *tetrahedral (nuclear pyramid)* and *octahedral (nuclear diamond)*
- Such exotic symmetries present new properties never seen before in nuclear physics
- Thus, they may lead to new explanations and interpretations of the nuclear interior, thus helping in completing the Nuclear Chart

Interestingly Enough:

- Exotic Symmetries are widely studied in Molecular Chemistry (from where *molecular* symmetries), not so much in Nuclear Physics
- We have already proven that such symmetries exist in the sub-atomic (nuclear) world

Why Studying Molecular Symmetries in Nuclear Physics ?

- Atomic nuclei can adopt several different shapes (depending on their number of protons and neutrons, among others)
- Such symmetries might range from a 'simple' sphere, or trivial modifications of it (e.g. oblate, prolate), to more exotic shape such as *tetrahedral (nuclear pyramid)* and *octahedral (nuclear diamond)*
- Such exotic symmetries present new properties never seen before in nuclear physics
- Thus, they may lead to new explanations and interpretations of the nuclear interior, thus helping in completing the Nuclear Chart

Interestingly Enough:

- Exotic Symmetries are widely studied in Molecular Chemistry (from where *molecular* symmetries), not so much in Nuclear Physics
- We have already proven that such symmetries exist in the sub-atomic (nuclear) world

Why Studying Molecular Symmetries in Nuclear Physics ?

- Atomic nuclei can adopt several different shapes (depending on their number of protons and neutrons, among others)
- Such symmetries might range from a 'simple' sphere, or trivial modifications of it (e.g. oblate, prolate), to more exotic shape such as *tetrahedral (nuclear pyramid)* and *octahedral (nuclear diamond)*
- Such exotic symmetries present new properties never seen before in nuclear physics
- Thus, they may lead to new explanations and interpretations of the nuclear interior, thus helping in completing the Nuclear Chart

Interestingly Enough:

- Exotic Symmetries are widely studied in Molecular Chemistry (from where *molecular* symmetries), not so much in Nuclear Physics
- We have already proven that such symmetries exist in the sub-atomic (nuclear) world

Why Studying Molecular Symmetries in Nuclear Physics ?

- Atomic nuclei can adopt several different shapes (depending on their number of protons and neutrons, among others)
- Such symmetries might range from a 'simple' sphere, or trivial modifications of it (e.g. oblate, prolate), to more exotic shape such as *tetrahedral (nuclear pyramid)* and *octahedral (nuclear diamond)*
- Such exotic symmetries present new properties never seen before in nuclear physics
- Thus, they may lead to new explanations and interpretations of the nuclear interior, thus helping in completing the Nuclear Chart

Interestingly Enough:

- Exotic Symmetries are widely studied in Molecular Chemistry (from where *molecular* symmetries), not so much in Nuclear Physics
- We have already proven that such symmetries exist in the sub-atomic (nuclear) world

Why Studying Molecular Symmetries in Nuclear Physics ?

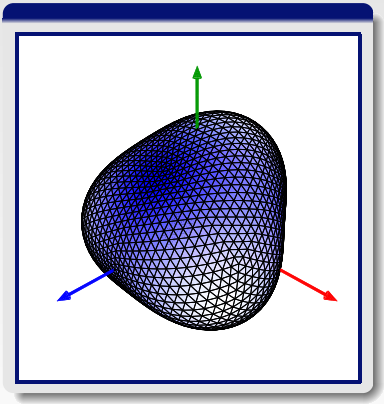
- Atomic nuclei can adopt several different shapes (depending on their number of protons and neutrons, among others)
- Such symmetries might range from a 'simple' sphere, or trivial modifications of it (e.g. oblate, prolate), to more exotic shape such as *tetrahedral (nuclear pyramid)* and *octahedral (nuclear diamond)*
- Such exotic symmetries present new properties never seen before in nuclear physics
- Thus, they may lead to new explanations and interpretations of the nuclear interior, thus helping in completing the Nuclear Chart

Interestingly Enough:

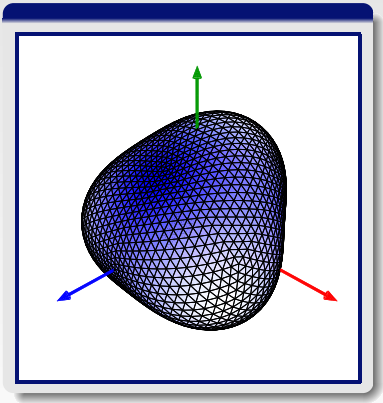
- Exotic Symmetries are widely studied in Molecular Chemistry (from where *molecular* symmetries), not so much in Nuclear Physics
- We have already proven that such symmetries exist in the sub-atomic (nuclear) world

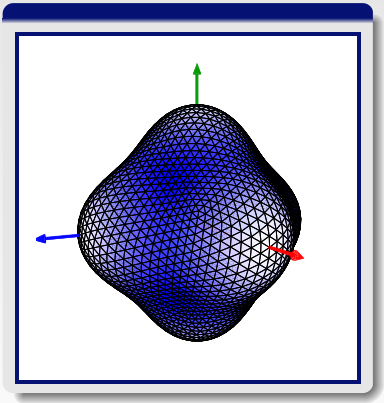
Research in Nuclear Physics: Exotic Beautiful Shapes

Research in Nuclear Physics: Exotic Beautiful Shapes

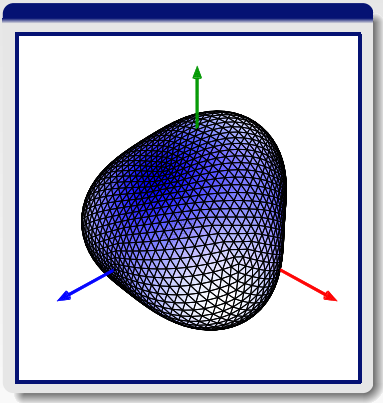


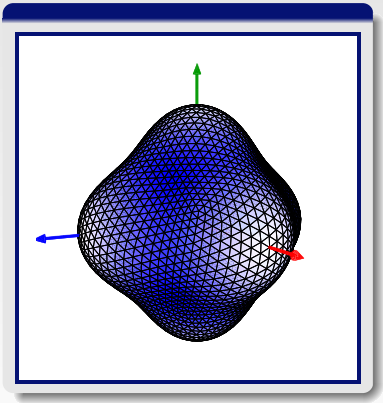
Research in Nuclear Physics: Exotic Beautiful Shapes

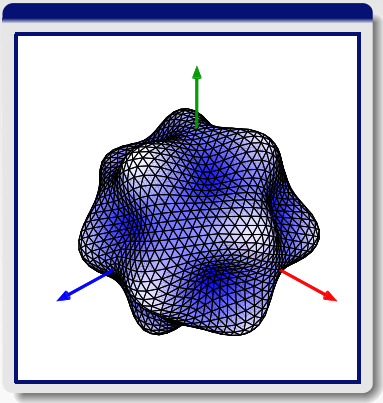




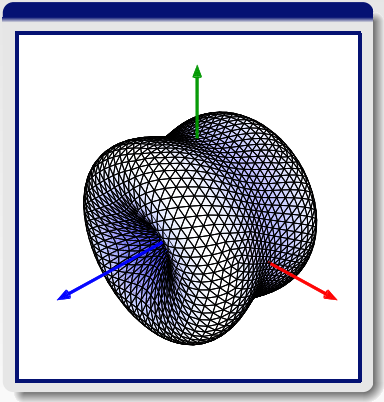
Research in Nuclear Physics: Exotic Beautiful Shapes



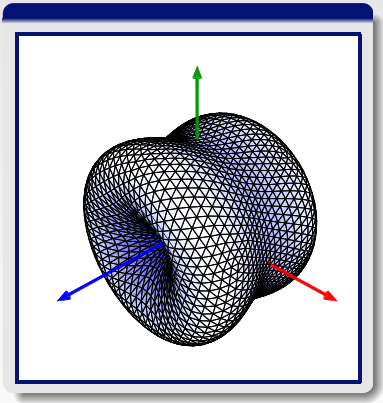


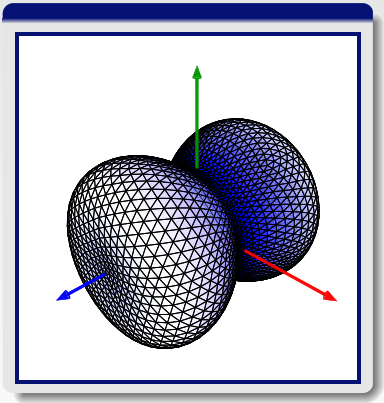


Research in Nuclear Physics: Exotic Beautiful Shapes

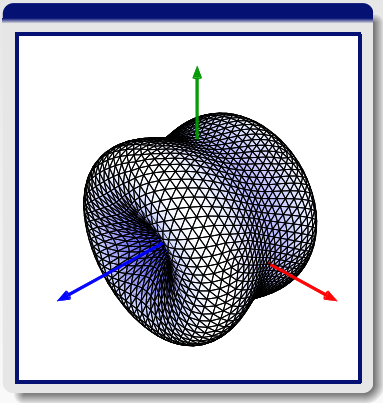


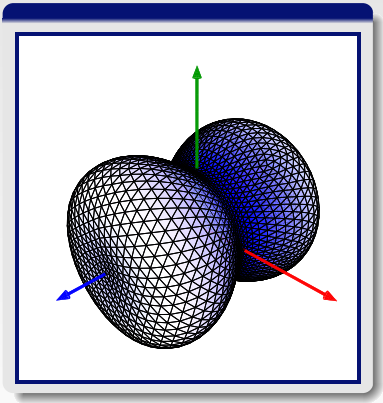
Research in Nuclear Physics: Exotic Beautiful Shapes

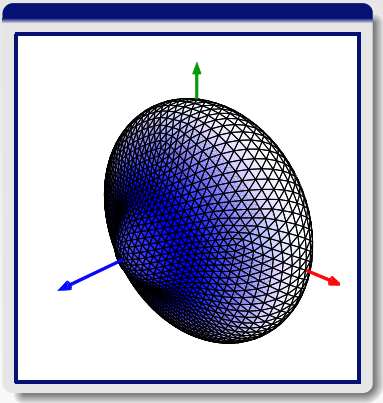




Research in Nuclear Physics: Exotic Beautiful Shapes



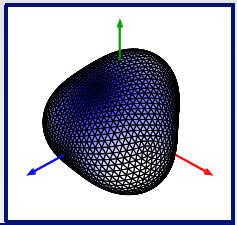


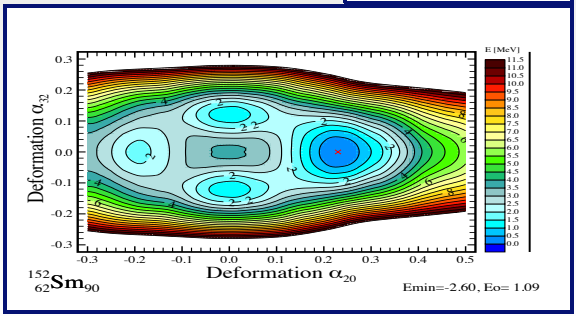


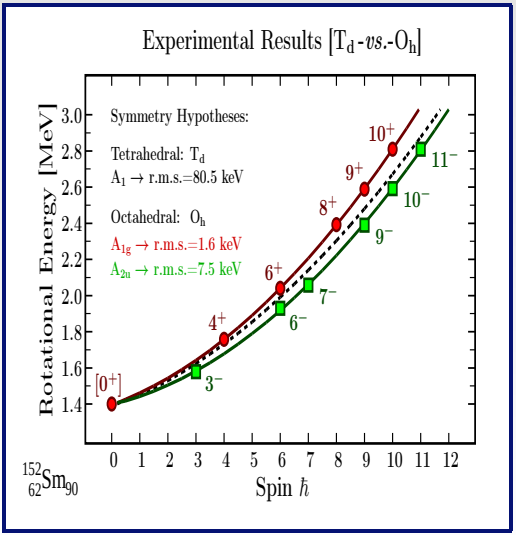
Research in Nuclear Physics: Exotic Beautiful Shapes

Investigations on ^{152}Sm

Phys.Rev.C**97**, 021302(R) (2018)

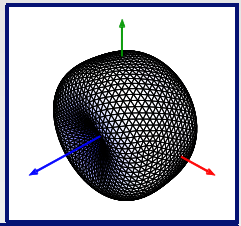


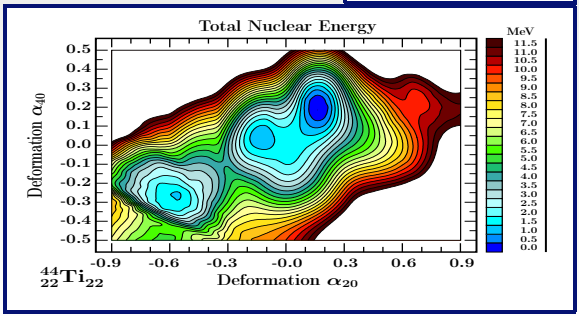


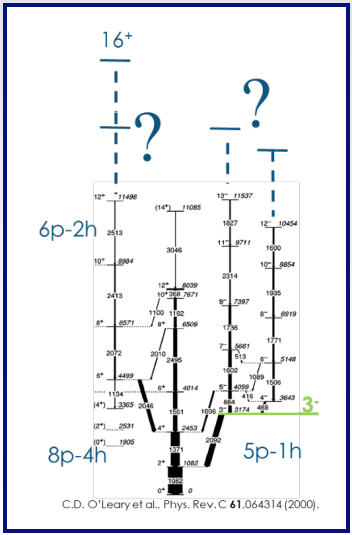


Research in Nuclear Physics: Exotic Beautiful Shapes

Investigations on ^{44}Ti







C.D. O'Leary et al., Phys. Rev. C **61**,064314 (2000).

Why am I interested in Research in Nuclear Physics

I have a great interest in understanding the quantum world surrounding us

1. I would like to imagine **what the atomic nuclei are like** – knowing that we will never be able to observe them the way we observe insects under the microscopes

2. For that I collect the already known information and **formulate the questions**: What do we think we understand? What don't we understand? Why?

3. I learn **quantum mechanics** and **computing** to be able to answer such questions *myself* and then explain other people... *but newer, more interesting and exciting questions appear!!*

5. Then I invent my methods in quantum mechanics and write my computer programs and **have even bigger satisfaction in providing next steps of understanding**

6. I find it fascinating that atomic nuclei can take such **exotic beautiful shapes**, which bring new perspectives and challenges to the whole understanding of Nuclear Physics

Why am I interested in Research in Nuclear Physics

I have a great interest in understanding the quantum world surrounding us

1. I would like to imagine **what the atomic nuclei are like** – knowing that we will never be able to observe them the way we observe insects under the microscopes

2. For that I collect the already known information and **formulate the questions**: What do we think we understand? What don't we understand? Why?

3. I learn **quantum mechanics** and **computing** to be able to answer such questions *myself* and then explain other people... *but newer, more interesting and exciting questions appear!!*

5. Then I invent my methods in quantum mechanics and write my computer programs and **have even bigger satisfaction in providing next steps of understanding**

6. I find it fascinating that atomic nuclei can take such **exotic beautiful shapes**, which bring new perspectives and challenges to the whole understanding of Nuclear Physics

Why am I interested in Research in Nuclear Physics

I have a great interest in understanding the quantum world surrounding us

1. I would like to imagine **what the atomic nuclei are like** – knowing that we will never be able to observe them the way we observe insects under the microscopes

2. For that I collect the already known information and **formulate the questions**: What do we think we understand? What don't we understand? Why?

3. I learn **quantum mechanics** and **computing** to be able to answer such questions *myself* and then explain other people... *but newer, more interesting and exciting questions appear!!*

5. Then I invent my methods in quantum mechanics and write my computer programs and **have even bigger satisfaction in providing next steps of understanding**

6. I find it fascinating that atomic nuclei can take such **exotic beautiful shapes**, which bring new perspectives and challenges to the whole understanding of Nuclear Physics

Why am I interested in Research in Nuclear Physics

I have a great interest in understanding the quantum world surrounding us

1. I would like to imagine **what the atomic nuclei are like** – knowing that we will never be able to observe them the way we observe insects under the microscopes

2. For that I collect the already known information and **formulate the questions**: What do we think we understand? What don't we understand? Why?

3. I learn **quantum mechanics** and **computing** to be able to answer such questions *myself* and then explain other people... *but newer, more interesting and exciting questions appear!!*

5. Then I invent my methods in quantum mechanics and write my computer programs and **have even bigger satisfaction in providing next steps of understanding**

6. I find it fascinating that atomic nuclei can take such **exotic beautiful shapes**, which bring new perspectives and challenges to the whole understanding of Nuclear Physics

Why am I interested in Research in Nuclear Physics

I have a great interest in understanding the quantum world surrounding us

1. I would like to imagine **what the atomic nuclei are like** – knowing that we will never be able to observe them the way we observe insects under the microscopes

2. For that I collect the already known information and **formulate the questions**: What do we think we understand? What don't we understand? Why?

3. I learn **quantum mechanics** and **computing** to be able to answer such questions *myself* and then explain other people... *but newer, more interesting and exciting questions appear!!*

5. Then I invent my methods in quantum mechanics and write my computer programs and **have even bigger satisfaction in providing next steps of understanding**

6. I find it fascinating that atomic nuclei can take such **exotic beautiful shapes**, which bring new perspectives and challenges to the whole understanding of Nuclear Physics

Why am I interested in Research in Nuclear Physics

I have a great interest in understanding the quantum world surrounding us

1. I would like to imagine **what the atomic nuclei are like** – knowing that we will never be able to observe them the way we observe insects under the microscopes

2. For that I collect the already known information and **formulate the questions**: What do we think we understand? What don't we understand? Why?

3. I learn **quantum mechanics** and **computing** to be able to answer such questions *myself* and then explain other people... *but newer, more interesting and exciting questions appear!!*

5. Then I invent my methods in quantum mechanics and write my computer programs and **have even bigger satisfaction in providing next steps of understanding**

6. I find it fascinating that atomic nuclei can take such **exotic beautiful shapes**, which bring new perspectives and challenges to the whole understanding of Nuclear Physics

Why am I interested in Research in Nuclear Physics

I have a great interest in understanding the quantum world surrounding us

1. I would like to imagine **what the atomic nuclei are like** – knowing that we will never be able to observe them the way we observe insects under the microscopes

2. For that I collect the already known information and **formulate the questions**: What do we think we understand? What don't we understand? Why?

3. I learn **quantum mechanics** and **computing** to be able to answer such questions *myself* and then explain other people... *but newer, more interesting and exciting questions appear!!*

5. Then I invent my methods in quantum mechanics and write my computer programs and **have even bigger satisfaction in providing next steps of understanding**

6. I find it fascinating that atomic nuclei can take such **exotic beautiful shapes**, which bring new perspectives and challenges to the whole understanding of Nuclear Physics

PUBLICITY: EURO-LABS Project – MeanField4Exp

- Our Team is developing a website to improve the cooperation between nuclear physicists