Introduction to Nuclear physics; The nucleus a complex system

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• What is the heaviest nucleus?

• How many nuclei do exist?

• What are the shapes of the nuclei?
A huge discovery potential

Exotic Nuclei

- Nuclear chart
- 291 stable nuclei
- 2000 « artificial » nuclei synthesized since Joliot&Curie
- 5000 to 7000 bound exotic nuclei to be discovered up to drip lines
Ground-state nuclear deformation predicted with the Hartree-Fock-Bogoliubov approach with the Gogny force

Nuclei are predicted to be either:

- spherical
- prolate
- or
- oblate

Héloïse Goutte CERN Summer student program 2009

http://www-phynu.cea.fr
I) Some features of the nucleus
The discovery of the nucleus

The structure of the atom was first probed by the Rutherford experiment in 1909. A beam of $\alpha$ particles generated by the radioactive decay of radium was directed onto a sheet of a very thin gold foil.

The unexpected results demonstrated the existence of the atomic nuclei.
I) Some features about the nucleus
   discovery
   radius
   binding energy
   nucleon-nucleon interaction
   life time
   applications

II) Modeling of the nucleus
   liquid drop
   shell model
   mean field

III) Examples of recent studies
   exotic nuclei
   isomers
   shape coexistence
   super heavy

IV) Toward a microscopic description of the fission process
Before this exp. people thought that α particles should all be deflected by at most a few degrees.  
But some α’s were deflected through angles much larger than 90 degrees!!

→ The results suggest that the greater part of the mass of the atom was concentrated into a very small region.  
→ Atoms are almost empty except a hard scattering center: the atomic nuclei
Some questions about the Rutherford experiment

- Why a thin target?
- What about electrons?
- Why in the vacuum?
- How can we determine the size of the atomic nucleus from this experiment?
Some tracks about the Rutherford experiment

- **Why a thin target?**
  To be sure that the projectile do interact with only one nucleus

- **What about electrons?**
  Electrons do not affect the trajectory of the projectile which is much heavier

- **Why in the vacuum?**
  In the air, the slowing down of the beam and of the scattered α make the analysis more complicated and can even stop the particles before detection.

- **How can we determine the size of the atomic nucleus from this experiment?**
  At the distance « a_0 » from the center of the nucleus, when the α particle go back:
  Coulomb repulsion = kinetic energy of the α particle
  \[
  \frac{1}{2}mv^2 = \frac{1}{4\pi\varepsilon_0} \cdot \frac{q_1q_2}{a_0}
  \]
  The size of the gold nucleus is 2.8 \(10^{-14}\) m
A nucleus is made of Z protons and N neutrons (the nucleons).

A nucleus is characterized by its mass number \( A = N + Z \) and its atomic number \( Z \).

It is written \(^A\!X\).

Do all the nuclei have the same radius?
The radius increases with $A^{1/3}$

$R = 1.25 \times A^{1/3} \text{ (fm)}$

Radii are extracted from elastic scattering of $\alpha$ particles on different targets.

The volume increases with the number of particles.
From infinitely small to infinitely large

A multi-scale Universe

Nucleons and nuclei the first steps in the hierarchy of complex systems

Olivier LOPEZ (LPC Cern)
Proton and neutrons are:

hadron particles (particles governed by the strong interaction)

They are baryons (made of 3 quarks)

- Proton: \( uud \) (charge +e)
- Neutron: \( udd \) (charge 0)

Proton and neutron have almost the same mass

\[
\begin{align*}
M_p c^2 &= 938.272 \text{ MeV} \\
M_n c^2 &= 939.565 \text{ MeV} \\
M_e c^2 &= 0.511 \text{ MeV}
\end{align*}
\]

2000 times the mass of the \( e^- \):

\[
M_p = 1.7 \times 10^{-27} \text{ kg}
\]
Proton and neutron interact through the strong interaction.

The strong interaction is very intense of short range.

The nuclear interaction is stabilizing the nucleus.

Proton - neutron interaction: \( V_{pn} > V_{nn} \)
\[ V_{pp} \approx V_{nn} \]

PLUS

Coulomb interaction between protons (repulsive)

What about gravitation in a nucleus?
### The four elementary interactions

<table>
<thead>
<tr>
<th>Name</th>
<th>Intensity</th>
<th>bosons</th>
<th>range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>strong</strong></td>
<td>1</td>
<td>Gluons</td>
<td>1 fm =10^{-15}m</td>
</tr>
<tr>
<td><strong>Electromagnetic</strong></td>
<td>10^{-2}</td>
<td>Photons</td>
<td>infinity</td>
</tr>
<tr>
<td><strong>faible</strong></td>
<td>10^{-5}, 10^{-6}</td>
<td>Leptons</td>
<td>contact</td>
</tr>
<tr>
<td><strong>gravitation</strong></td>
<td>10^{-34}</td>
<td>Gravitons ?</td>
<td>long</td>
</tr>
</tbody>
</table>
There is no derivation of the nucleon-nucleon interaction from the first principles of the Quanta Chromo Dynamics theory. Phenomenological parameterization of the interaction;

**THIS IS ONE OF THE MOST IMPORTANT PROBLEM NOWADAYS**
A stable nucleus is a bound system
i.e. its mass is lower than the mass of its components.

(if not the nucleus would release its excess of energy by
spontaneously evolving to a state of lower energy composed of
free particles)

\[
M(A,Z) = N M_n + Z M_p - B(A,Z)
\]

\( B(A,Z) \): binding energy

**Stable bound system for** \( B > 0 \)

**Binding energy per nucleon:** \( B(A,Z)/A \approx 8 \text{ MeV} \)
Which nuclei could fission spontaneously?
FISSION

$$A \rightarrow B + C + \Delta E$$

Energy balance:  $$A M_N - B_A = B M_N - B_B + C M_N - B_C + \Delta E$$  

Energy difference:  $$\Delta E = B_B + B_C - B_A$$

FUSION

$$A + B \rightarrow C + \Delta E$$

Energy balance:  $$A M_N - B_A + B M_N - B_B = C M_N - B_C + \Delta E$$

Energy difference:  $$\Delta E = B_C - B_B - B_A$$

Energetic features: fission possible only for elements heavier than Fe; fusion possible for elements lower than Fe;
Some results on stellar nucleosynthesis

Correlation between B/A and abundance

- The abundance of the elements in the Universe depends on their stability.
- The abundance of the elements in the Universe reflects the nuclear interaction.
- The most abundant element (hydrogen) is also the lighter one.
- Fe (the most stable and abundant) is the nucleus at the limit between:
  * the burning by fusion for the elements lighter than Fe
  * the radiative capture of neutrons by elements heavier than Fe.

From E. Gallichet
The most stable nuclei

ITER project

Nuclear powerplant
A few nuclei are stable: their lifetimes are infinite (comparable to the lifetime of the proton $10^{33}$ years.)

The others are unstable: they transform into more stable nuclei.

**Exponential decay**

$$\frac{dN}{dt} = -\lambda N(t)$$

Half-life $T$ defined as the time for which the number of remaining nuclei is half of its initial value.
Different types of radioactivity

Neutrons

Protons

\[ \begin{align*}
\text{Neutrons} & : A^{Z}_{N-1} \\
\text{Protons} & : A^{Z+1}_{N-1} \\
\beta^{-} & : A^{-1}^{Z}_{N-1} \\
\beta^{+}, \varepsilon & : A^{Z+1}_{N+1} \\
\alpha & : A^{-4}^{Z-2}_{N-2} \\
\end{align*} \]
Total versus partial life times

\[ \frac{1}{29\,\text{h}} = \frac{1}{35\,\text{h}} + \frac{1}{170\,\text{h}} + \frac{1}{55\,\text{y}} \]
Examples: half lives

Life times span many orders of magnitude:

Nitrogen 16 \[ T_{1/2} = 7.13 \text{ s} \]
Oxygen 15 \[ = 2.037 \text{ mn} \]
Radium 224 \[ = 3.62 \text{ d} \]
Carbon 14 \[ = 5730 \text{ y} \]
Molybdenum 100 \[ = 10^{19} \text{ y} \]
Tellurium 124 \[ = 2.2 \times 10^{28} \text{ y} \]
Why do the stable nuclei do not follow the N= Z line?

Why do we search for new nuclei?
Nucleosynthesis paths

- rp process
- s process
- r process
- Big Bang
- Stellar evolution
- X-ray Burster
- Stable
- Unstable
- Super-nova
A very competitive field

World Wide Radioactive Beam Facilities

- under construction
- projects

1997

2007

+ other RIB projects
How do we experimentally study a nucleus?

I) Elastic and inelastic scattering

*e-, e+, p, n*

Heavy ions

II) Transfer  

ex: (p, n), (d, p) ...  

Knock out ...

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2009
III) Gamma spectroscopy

1) To excite the nucleus

2) To observe its decay
Example of a level scheme

The barcode of a nucleus
Some applications of Nuclear Science

Nuclear physics makes indeed many essential contributions to

- **Energy production**
  - *Electricity generation*
  - *fission*: research on
    - *new generations of power plants, new fuel cycles*
    - *reduction by transmutation of the long-term impact of the nuclear wastes produced (ADS or GEN IV reactors)*
    - *fusion for the far future: (ITER project)*

- **Medicine**
  - *diagnostic*
    - *detection of the decay of radioactive isotopes*
    - SPECT Single Photon Emission Computer Tomography
    - PET Positron Emission Tomography
  - *IRM Imaging by Magnetic Resonance*
  - *therapy* (proton-, hadron-therapy …)
Some applications of Nuclear Science (2)

- **Art and archaeology**
  * datation
  * identification of constituent materials
    (ex: AGLAE Accélérateur Grand Louvre pour l’Analyse Elémentaire)

- **Environmental studies**
  * ex: observation of modification of ocean circulation patterns
    (measurement of $^{129}$I/$^{127}$I in seawater as a function of depth and distance to the coast)

- ...

From NuPECC long Range Plan 2004
Some features of the nuclei: Summary

• The existence of the atomic nuclei: the Rutherford experiment in 1909

• The nucleon-nucleon interaction is not precisely known.

• Many nuclei are predicted but not observed up to now.

• Most of them are neutron rich, and are supposed to have played a role during the nucleosynthesis.

• Nuclei are characterized by their level scheme: their barecode.

• Many applications of the nuclear physics