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Thursday        10:50 – 11:40
Friday          11:45 – 12:35
Friday(T)       8:00 – 8:50

Tutor: Kanhaiya Jha (kanhaiya.jha@iitrpr.ac.in)
Facility for Antiproton and Ion Research
Budget: 85 Mio. € (90% Bund, 10% Hessen)

Employees: 1100

External Scientific Users: 1200

Large Scale Facilities: Accelerators and Experiments
Accelerator Facility

Ion Sources
all elements

Linear-Accelerator
20% speed of light

UNILAC

Experimental Areas

Ring-Accelerator
90% speed of light

SIS

FRS

ESR

Indian Institute of Technology Ropar
Hans-Jürgen Wollersheim - 2018
Accelerator Facility
Rare ISotope INvestigation at GSI
Tentative outline of Nuclear Physics

- **Gross properties of nuclei**
  - Rutherford scattering
  - nuclear radii, masses, and binding energies
  - Bethe-Weizäcker mass formula
  - angular momentum, magnetic moment

- **Radioactivity**
  - $\alpha$ - decay
  - $\beta$ - decay
  - $\gamma$ – decay

- **Fundamental forces**
  - nuclear force between nucleons
  - nuclear shell model
  - spherical and deformed nuclei

- **Nuclear reactions**
  - direct reactions
  - fusion reaction
Literature

- Recommended Textbook
- Supplemental Textbook

www.bookzz.org
neutron star

supernovae

sun

unstable nuclei

heavy ion nuclear reactions
Brief historical overview
in search of the building blocks of the universe ...

**Greek philosophers**
4 building blocks

- **earth**
- **air**
- **water**
- **fire**

5th BC - Democritus
atomic hypothesis

18th - 19th century Lavoisier, Dalton, ...
put atomic hypothesis on firm basis
distinction between compounds and pure elements

1896 Dmitri Mendeleev
92 building blocks
(chemical elements)

$^1\text{H}$, $^2\text{He}$, ..., $^{92}\text{U}$
Brief historical overview
in search of the building blocks of the universe ...

1896 Henri Becquerel

discovers radioactivity

emission of radiation from atoms
3 types observed: $\alpha$, $\beta$ and $\gamma$

$\alpha$ and $\beta$ deflected in opposite direction $\Rightarrow$ opposite charges
$\alpha$ deflected less than $\beta$ $\Rightarrow$ $\alpha$ must have larger mass
$\gamma$ not deflected $\Rightarrow$ uncharged

~1900 Ernest Rutherford

investigates new radiation

$\alpha$ and $\beta$ emissions change nature of element
$\alpha$‘s charge = $+2e$ $\quad \alpha$‘s mass $\sim 4H$
$\beta$ radiation = electrons
$\gamma$ = electromagnetic radiation (photons)

1911 Ernest Rutherford tests Thomson’s model of the atom

N electrons (-e·N) embedded in (+e·N) charge
uniformly distributed over atomic volume

“plum pudding model”

“... it was as incredible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you”

expected
$\alpha$‘s ($^2\text{He}$) pushed a little to the side by charges of atom ($^{79}\text{Au}$)

observed
some $\alpha$’s deflected backwards to 180°!!
Brief historical overview
in search of the building blocks of the universe

1913 Niels Bohr
planetary model of atom
all positive charges (and ~ all mass)
concentrated in tiny region at the center

1920 Francis William Aston mass spectrograph
measures masses of atoms

<table>
<thead>
<tr>
<th></th>
<th>mass</th>
<th>charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>~ 4 H</td>
<td>He = 2 H</td>
</tr>
<tr>
<td>C</td>
<td>~ 12 H</td>
<td>C = 6 H</td>
</tr>
<tr>
<td>O</td>
<td>~ 16 H</td>
<td>O = 8 H</td>
</tr>
</tbody>
</table>

1925 Werner Heisenberg
quantum mechanic
simplest atom = H
its nucleus = proton

1932 James Chadwick
discovers the neutron
3 building blocks
electron + proton + neutron

NUCLEAR PHYSICS
Brief historical overview
in search of the building blocks of the universe

1932 Enrico Fermi

developed the theory of $\beta$-decay

1934 Irene Joliot-Curie & Frederic Joliot

artificial radioactivity $^{27}_{13}Al + ^4_2He \rightarrow ^{30}_{15}P^* + 1n$

1934 Hans Bethe

liquid drop model and mass formula

1938 Otto Hahn, Lise Meitner & Fritz Strassmann

discover nuclear fission

1948 Maria Goeppert-Mayer & J. Hans D. Jensen

develop the nuclear shell model
Brief historical overview
in search of the building blocks of the universe

1953 Aage Niels Bohr, Ben Roy Mottelson, Leo James Rainwater
developed the collective nuclear model

1956 Frederick Reines & Clyde L. Cowan
discovery of the neutrino

1983 Carlo Rubbia
discovery of the W and Z Boson

1998 Takaaki Kajita & Arthur B. McDonald
discovery of neutrino oscillations ➞ neutrinos must have some mass
So ... Where Do We Start?

We need a point of reference to start discussing nuclear physics.
Nuclear units and physical constants

Nuclear units

- **length unit:**
  Fermi = femtometer = fm = \(10^{-15} \text{[m]}\)

- **energy unit:**
  MeV = \(10^6\) eV = \(10^6 \cdot 1.602 \cdot 10^{-19}\) CV = \(1.602 \cdot 10^{-13}\) [J]

- **mass unit:**
  \(1\ u = 1/12 \cdot \text{m}^{12}\text{C} = 931.49432\ \text{MeV}/c^2 = 1.66054 \cdot 10^{-27}\) [kg]

- **time unit:**
  [s] or [fm/c] ≈ \(3 \cdot 10^{-24}\) [s]

Constant of nature relevant to nuclear physics

- speed of light in vacuum, \(c = 2.99792458 \cdot 10^8\) [m/s]
- Planck’s constant / \(2\pi = \hbar = 6.58211889 \cdot 10^{-22}\) [MeV s] = \(1.054 \cdot 10^{-34}\) [J s]
- \(\hbar c = 197.3269602\) [MeV fm]
- fine structure constant (dimensionless), \(\alpha = e^2/(\hbar c) = 1/137.0359976\)
  \(\rightarrow e^2 = \alpha \cdot \hbar c = 1.4399643929\) [MeV fm]
- **elementary charge**, \(e = 1.602 \cdot 10^{-19}\) [C] or \(e = 1.1999851636\) [\(\sqrt{\text{MeV fm}}\)]
- rest energy of proton, \(m_p c^2 = 938.27231\) [MeV]
- rest energy of neutron, \(m_n c^2 = 939.56563\) [MeV]
- rest energy of electron, \(m_e c^2 = 0.51099906\) [MeV]
- Avogadro’s number, \(N_A = 6.0221367 \cdot 10^{23}\) /mol

- E – p relationship: \(E^2 = p^2 c^2 + m_0^2 c^4\)
- Kinetic energy: \(T = E - m_0 c^2 = m_0 c^2 (\gamma - 1)\)
The atom

- atom is a neutral system

atomic excitations
\(~ 1-10^5 \text{ eV}~

caused by transitions between electronic states

\(~ \sim 10^{-10} \text{ m} ~\)
Bohr atomic model
absorption spectrum
Bohr atomic model
emission spectrum

Helium emission spectrum
The atomic nucleus

nuclear excitations
\(~ 10^5-10^8\) eV

caused by transitions
between nuclear states

excitations can be caused
by individual nucleons or
as a collective motion of
the nucleus

nuclear shell model
Inside the atomic nucleus

proton

neutron

protons and neutrons are very similar, they can be classified as the same object: the nucleon

Nucleons are quantum mechanical objects:

- They are spin ½ Fermions
- Radius: $r \sim 1 \cdot 10^{-15}$ m, or 1 fm (fermi)
- Charge: $p \rightarrow +e$
  $n \rightarrow 0$
- Mass: $p \rightarrow 938.27$ MeV/$c^2$
  $n \rightarrow 939.56$ MeV/$c^2$
- Isospin: $|p> = | -1/2 >$
  $|n> = | +1/2 >$
Structure of nucleons

proton
\( u, u, d \)

neutron
\( u, d, d \)

“Up” (\( u \))
- \( m = 2.4 \text{ MeV}/c^2 \)
- \( q = +\frac{2}{3} \)

“Down” (\( d \))
- \( m = 4.8 \text{ MeV}/c^2 \)
- \( q = -\frac{1}{3} \)

particle excitations
\( > 10^9 \text{ eV} \)
Elementary particles of the standard model

QUARKS
- u → up, mass ≈ 2.3 MeV/c², charge 2/3, spin 1/2
- c → charm, mass ≈ 1.275 GeV/c², charge 2/3, spin 1/2
- t → top, mass ≈ 173.07 GeV/c², charge 2/3, spin 1/2
- d → down, mass ≈ 4.8 MeV/c², charge -1/3, spin 1/2
- s → strange, mass ≈ 95 MeV/c², charge -1/3, spin 1/2
- b → bottom, mass ≈ 4.18 GeV/c², charge -1/3, spin 1/2
- γ → photon

GAUGE BOSONS
- e → electron, mass 0.511 MeV/c², charge -1, spin 1/2
- μ → muon, mass 105.7 MeV/c², charge -1, spin 1/2
- τ → tau, mass 1.777 GeV/c², charge -1, spin 1/2
- Z → Z boson, mass 91.2 GeV/c²
- W → W boson, mass 80.4 GeV/c²

LEPTONS
- ν_e → electron neutrino, mass <2.2 eV/c², charge 0, spin 1/2
- ν_μ → muon neutrino, mass <0.17 MeV/c², charge 0, spin 1/2
- ν_τ → tau neutrino, mass <15.5 MeV/c², charge 0, spin 1/2

Higgs boson → mass ≈ 126 GeV/c²
**Terminology**

A – mass number gives the number of nucleons in the nucleus

Z – number of protons in the nucleus (atomic number)

N – number of neutrons in the nucleus

\[ A = Z + N \]

In nuclear physics, nucleus is denoted as \( \frac{A}{Z}X \), where X is the chemical element
e.g. \( ^1H \) - hydrogen, \( ^{12}C \) - carbon, \( ^{197}Au \) - gold.

Different combinations of \( Z \) and \( N \) (or \( Z \) and \( A \)) are called nuclides

- nuclides with the same mass number \( A \) are called isobars
- nuclides with the same atomic number \( Z \) are called isotopes
- nuclides with the same neutron number \( N \) are called isotones
- nuclides with equal proton number and equal mass number, but different excited states are called nuclear isomers

\[
\begin{align*}
17N, 17O, 17F \\
12C, 13C, 14C \\
13_6C, 14_7N \\
180Ta, 180mTa
\end{align*}
\]

The most long-lived non-ground state nuclear isomer is tantalum-180m, which has a half-life in excess of 1000 trillion years
The Chart of Nuclides
- the “Playground” for Nuclear Physics

**chart of nuclides:**
- representation of isotopes in the Z-N plane
- isotope: atom (nucleus) of an element with different number of neutrons

- **black:** stable isotope
- **red:** $\beta^+$-unstable isotope
- **blue:** $\beta^-$-unstable isotope
- **yellow:** $\alpha$-instable isotope
- **green:** spontaneous fission
The Chart of Nuclides
- the “Playground” for Nuclear Physics

chart of nuclides:
- representation of isotopes in the Z-N plane
- isotope: atom (nucleus) of an element with different number of neutrons

different modes of radioactive decay

- $\beta^-$
- $n$
- $\beta^+$
- $\alpha$
- $\gamma$

The chart shows the distribution of isotopes in the Z-N plane, with different colors representing various isotopes and their properties. The grid highlights different modes of radioactive decay, including electron capture ($\beta^-$), positron emission ($\beta^+$), neutron emission ($n$), and alpha decay ($\alpha$).
The Chart of Nuclides
- the “Playground” for Nuclear Physics

*chart of nuclides:*
- representation of isotopes in the Z-N plane
- isotope: atom (nucleus) of an element with different number of neutrons
Questions: Chart of Nuclides

1. How are the *isotopes* of an element arranged on the chart?
2. Nuclides with the same number of neutrons are called *isotones*. How are they arranged on the chart?
3. Nuclides with the same mass number are called *isobars*. What would be the orientation of a line connecting an *isobaric* series?
4. Begin with the following radioactive parent nuclei, $^{235}\text{U}$, $^{238}\text{U}$, $^{244}\text{Pu}$, trace their decay processes and depict the mode and direction of each decay process on the chart. What are the final stable nuclei?

Solar abundance \( (\text{Si}^{28} = 10^6) \)

**open questions:**

- Why is Fe more common than Au?
- Why do the heavy elements exist and how are they produced?
- Can we explain the solar abundances of the elements?
Nucleosynthesis in the r-process

JINA
Joint Institute for Nuclear Astrophysics 2002

Movie: H. Schatz, National Superconducting Cyclotron Laboratory
Calculation: K. Vaughn, J.L. Galache, and A. Aprahamian, University of Notre Dame
Model: B. Meyer, Clemson University and R. Surman, North Carolina State

Temperature: 1.50 GK
Time: 2.7e-14 s
Nuclear Fission: Energy and Engineering

![Diagram of nuclear fission energy and engineering](image)

- **Z**, number of protons
- **N**, number of neutrons

Legend:
- Probability values for different states:
  - 6.08E-1
  - 6.21E-2
  - 6.34E-3
  - 6.47E-4
  - 6.61E-5
  - 7.03E-8
  - 7.17E-9
  - 7.32E-10
  - 7.47E-11

- **235U**
- **N=126**
- **Z=82**
- **N=82**
- **Z=50**
- **N=50**
- **Z=28**
- **N=28**
- **Z=20**
- **N=20**
- **Z=8**
- **N=8**

Unknown states are indicated by a gradient.

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Nuclear matter has exotic properties

- Nuclear matter is extremely heavy \(2.3 \cdot 10^{17} \text{ kg/m}^3\)

  for comparison:
  - sea water: \(1.0 \cdot 10^3 \text{ kg/m}^3\)
  - tin oxide: \(1.6 \cdot 10^3 \text{ kg/m}^3\)
  - steel: \(1.1 \cdot 10^4 \text{ kg/m}^3\)
  - lead: \(2.5 \cdot 10^4 \text{ kg/m}^3\)
  - core of the sun: \(1.5 \cdot 10^5 \text{ kg/m}^3\)

- Although we know nuclear matter only in small portions inside atoms, it exists in nature also in big portions:
  - Neutron Stars have a diameter of typically 10 km

- Nuclear structure physics investigates the response of the nucleus as a function of:

\[
\rho = \frac{Am_p}{4/3 \pi R^3} = \frac{m_p}{4/3 \pi r_0^3} = \frac{1.66 \cdot 10^{-27} \text{ kg}}{4/3 \pi (1.2 \cdot 10^{-15} \text{ m})^3}
\]
## Properties of stable nuclei

### Radius & shape
- size: nuclear radius \( (R = 1.2 \cdot A^{1/3} \text{ fm}) \)
- shape: spherical / deformed (prolate / oblate)

### Density & mass
- constant nuclear density \( (\rho = 10^{17} \text{ kg/m}^3) \)
- nuclear mass & valley of stability

### Nuclear states
- quantum numbers spin \( S \), parity \( P \), magnetic moments
- shell structure: valence-nucleons, collective excitations

### Nuclear reactions
- binding energy: fusion & fission, nuclear astrophysics
- special reactions: exchange / transfer