Nuclear Physics

Atomic nucleus

History. First experimental facts: radioactivity, 1896, Henry Becquerel, following Wilhelm Conrad Roentgen who discovered X-rays in 1895. But X-rays are emitted by atomic e, α, β, γ particles are emitted by the nucleus.

In 1911 the Nobel prize Ernst Rutherford discovered the nucleus.

More than 99.99% of atomic mass **big mass means big energy**

Diameter of the order of 2 fm.

Existence of nuclear forces, much stronger than elmgn ones.

1931 Wolfgang Pauli predicted the **neutrino**

In 1932 James Chadwick discovered the **neutron the nucleus contains protons and neutrons; isotopes**

1939 Hahn and Strassman discovered **Uranium fission**

Construction of **particle accelerators**, **nuclear reactions**, other **elementary particles**.

Important properties of nuclei

All the nuclei may be divided in *stable* and *instable or radioactive*.

Characteristics:

- **mass number *A*** ***number of protons and neutrons***
- **atomic number *Z*** ***number of protons***
- **mass *M* and Binding energy**
- **Radius**
- **spin *I***
- **magnetic momentum**
- **Type of radioactivity (**α, β, γ**)**

Notation X_A^Z with Z atomic no. and A mass no.

Atomic number Z is: the no of e in the atom, the number of protons in the nucleus, the position in the Mendeleev table.

Mass no A is the number of nucleons (protons and neutrons) in the nucleus.

Mass of the nucleus

Atomic and nuclear masses are measured in *atomic mass units*.

$$1 \text{ a.m.u.} \equiv 1 \text{ u} = 1.660539040(20) \times 10^{-27} \; kg$$

Definition: one twelvth of the mass of a neutral atom of C^{12}. To each mass corresponds a rest energy:

Particle	Rest mass (kg)	Rest energy
electron	$9.11 \cdot 10^{-31}$	0,511 MeV
proton	$1.57 \cdot 10^{-27}$	938.27 MeV
neutron	$1.67 \cdot 10^{-27}$	939.56 MeV
amu	$1.66 \cdot 10^{-27}$	? MeV
1 kg	1	$9 \cdot 10^{16}$ J

Masses are measured using *mass spectrometers*, precisions 10^{-8}.

Mass defect and binding energies

The mass of the nucleus is always less than the sum of the individual masses of the protons and neutrons which constitute it. The difference measures the nuclear binding energy

$$\Delta M c^2 = \Delta E = Z m_p + (A - Z) m_n - M_{nucleus} \qquad (1)$$

For an *alpha* particle:

$M_\alpha = 4.00153\ u$, m_p=1.00728, m_n=1.00866,

$\Delta M = 0.0304\ u$, $\Delta E = 28.3\ MeV$

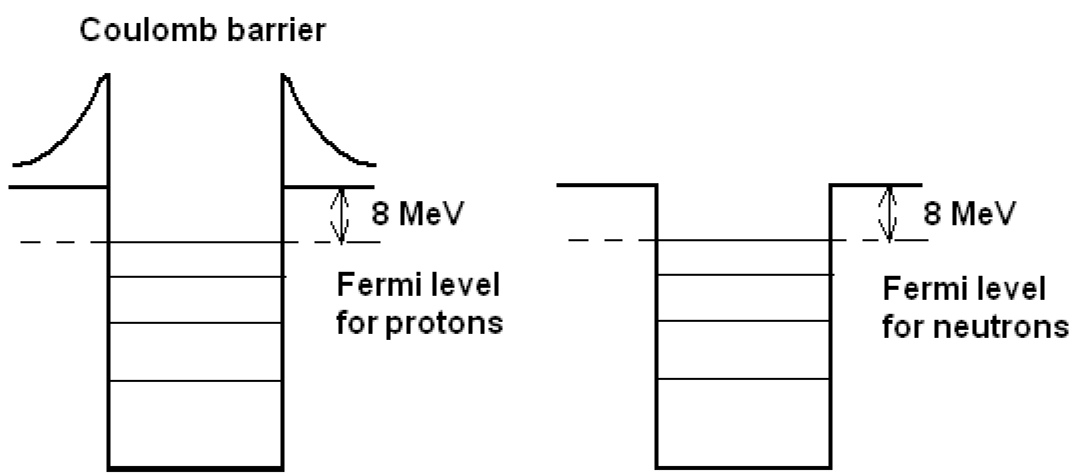
Comparison with the *e* in an atom: 10 eV.

Dimensions of thye nucleus:

$$R=R_0A^{1/3} \qquad (2)$$

with $R_0=1.4\cdot10^{-15}$ m. the density of the nuclear material is 10^{17} kg/m^3.

The potential well of the nucleus



Magnetic momentum of the nucleus

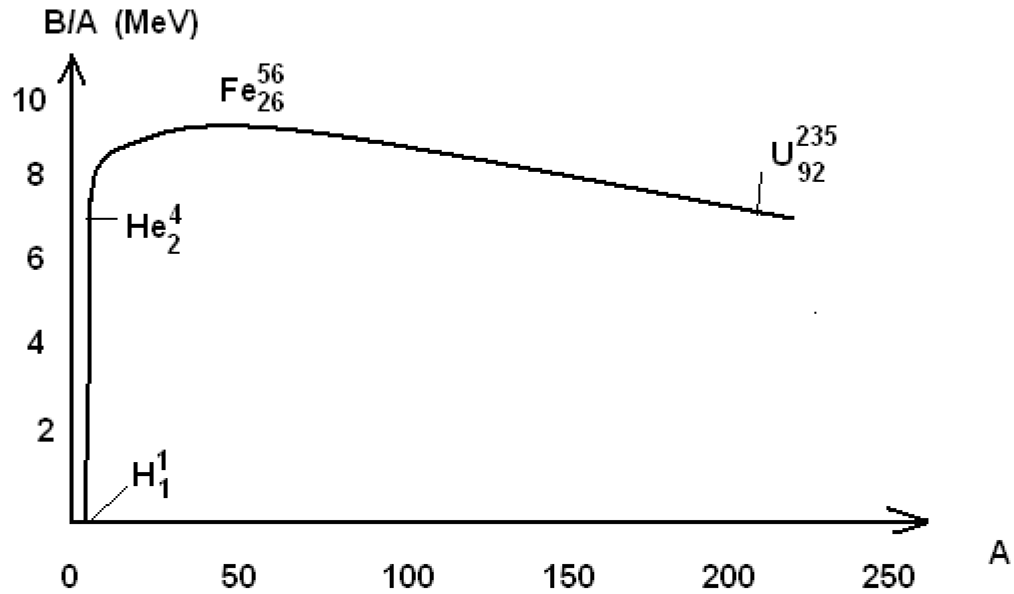
The nuclear analogous of the Bohr magneton is

$$\mu_{nucl} = \frac{e\hbar}{2m_p} = \frac{\mu_B}{1836} \qquad (3)$$

The proton has $\mu_p = +2.79\mu_{nucl}$ and the neutron $\mu_n = -1.91\mu_{nucl}$

These are signs of an internal structure of the nucleons

The nuclear binding energy curve

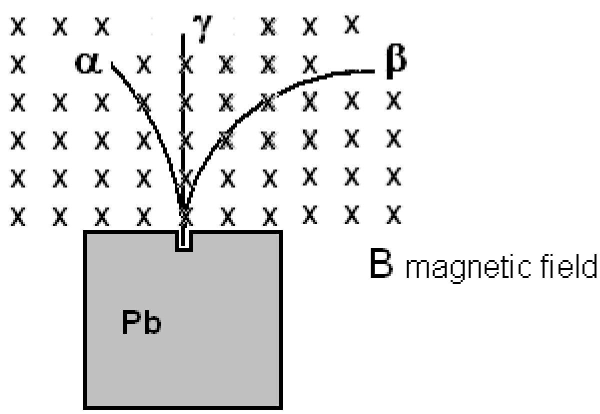


Nucleus	H_1^1	He_2^4	Fe_{26}^{56}	Ni_{28}^{62}	U_{92}^{235}
B/A (MeV)	**?**	**7**	**8.790**	**8.794**	**7.7**

Most tightly bound: Ni_{28}^{62}, Fe_{26}^{56} 8.8 MeV/nucleon (they are even-even nuclei). **Fission and fusion can yield energy**, 5 MeV/nucleon for fusion, 1 MeV/nucleon for fission

Radioactivity

Radioactive nuclei are instable and emit particles. The type of the nucleus may change, i.e. a type of atom changes towards another type of atom, the initial element transforms in another element, ocupying another case in the Mendeleev table **transmutation**. The most common types of radioactivity are named α, β, γ . They were discovered by Becquerel in 1896 and studied by Rutherford, Pierre and Marie Curie and others.



Alpha rays: nuclei of He_2^4, very heavy particles (7350 times the mass of the *e*). They interact heavily with materials and are stopped by a few mm of air or some tenths of mm in condensed materials. Usual decay of heavy nuclides. Theoretical model is based on a tunnel process.

$$X_Z^A \rightarrow Y_{Z-2}^{A-4} + \alpha_2^4 \qquad (4)$$

Beta rays: electrons (β^-) or positrons (β^+). They are stopped by a few cm of air or a few mm of Al.

$$X_Z^A \rightarrow Y_{Z+1}^A + e^- + \tilde{\nu} \qquad X_Z^A \rightarrow Y_{Z-1}^A + e^+ + \nu \qquad (5)$$

- Search in *Hyperphysics* what are e^+, ν and $\tilde{\nu}$

Gamma rays: photons of high energy, with wavelength smaller of 10^{-10} m. They are stopped by more than 20 cm of lead or by 1 m of concrete.

$$X_Z^{A*} \rightarrow X_Z^A + \gamma \qquad (6)$$

Radioactive law

Assume we study a certain radioactive species of nuclides. The initial no. of radioactive nuclei is N_0=$N(0)$. In time they decay towards a stable type of nuclei. The number of nuclides disintegrated in the time dt is dN. It is proportional to dt and $N(t)$: $dN \propto -Ndt$, or $dN = -\lambda Ndt$, where λ is a constant called *radioactive constant*. By integration we find

$$N(t) = N(0)e^{-\lambda t} \qquad (7)$$

Obviously $[\lambda] = s^{-1}$.

The *half-life* is the time required for a quantity to reduce to half its initial value. *The radioactive half-life* $T_{1/2}$ is the time required for a number of radioactive nuclides to reduce to half its initial value $N(0)$: $N(T_{1/2}) = N(0)/2$.

Exercice 1: Show that $T_{1/2} = \dfrac{0.693}{\lambda}$.

Exercice 2: How many radioactive nuclides remains after t_1=2$T_{1/2}$? But after t_2=10$T_{1/2}$? How many nuclei were disintegrated after t_1 and t_2 ?

Nuclear fission chain reaction. A nucleus U_{92}^{235} absorbs a neutron, splits in two lighter nuclei and produces 3 neutrons. During the fission a huge amount of energy is released. Even if two neutrons are lost, the third could collide with another U_{92}^{235} nucleus and the reaction continues with a termendous release of energy. See *Hyperphysics*