Proton-neutron electromagnetic interaction.

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Nuclear energy and Coulomb's law

- It is well known that *nuclear energy* is around one *million* times more concentrated than *chemical energy,* never explained, up to now.
- The nucleon, being one million times **smaller** than an atom, its electrostatic energy is one million times **larger**, according to the **1/r** Coulomb's law.

Estimate of ^{2}H binding energy

Using the radius of the proton, R = 0.88 fm,
the deuteron binding energy
calculated from electric Coulomb's law is:

$$\frac{e^2}{4\pi\epsilon_0 R} = 1.7\ MeV$$

not far from 2.2 MeV, the measured value.

Electromagnetic interactions

- As amber (ἤλεκτρον) attracts small neutral pieces of paper, a proton **attracts** a not so neutral neutron.
- Collinear and opposite magnets (μαγνήτης) **repulse** themselves. Same phenomenon between nucleons.
- **In a nucleus the electric attraction is equilibrated by the magnetic repulsion**.

Electromagnetic interactions

- As amber (ἤλεκτρον) attracts small neutral pieces of paper, **a proton attracts a not so neutral neutron**.
- Collinear and opposite magnets (μαγνήτης) repulse themselves. Same phenomenon in the deuteron.
- **Electric attraction equilibrates magnetic repulsion.**
- no mysterious strong force needed.
- no centrifugal force and/or hard core needed.

The nuclear shell model is unable to calculate the binding energy of even a simple nucleus as ^2H.

The nuclear binding energies of ^2H and ^4He have been calculated by applying **only electric and magnetic Coulomb's laws**.

Electric charge of the proton

- It is well known that the proton contains a positive elementary electric charge
- $e = +1.6 \times 10^{-19}$ Coulomb

Electric charges in the neutron

- It is less known that the neutron contains electric charges with no net charge.
- We shall assume for the sake of simplicity that the neutron electric charges are +e and –e.
- The exact dipole formula has to be used, not $2a/r^2$, valid only when $a << r_{np}$:

$$\frac{e^2}{4\pi\epsilon_0}\left(\frac{1}{r_{np}+a}-\frac{1}{r_{np}-a}\right)$$

Neutron-proton electric interaction

'he total electric energy of 3 aligned electric charges is:

$$U_e = \frac{1}{4\pi\epsilon_0}\left(\frac{q_1 q_2}{r_{12}} + \frac{q_2 q_3}{r_{23}} + \frac{q_3 q_1}{r_{31}}\right)$$

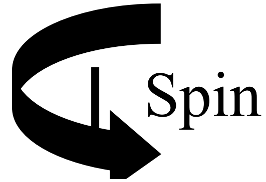
Assuming that the electric charges are +e for the proton, +e and –e for the neutron, the total electric energy is, for 3 electric charges:

$$U_e^{2H} = \frac{e^2}{4\pi\epsilon_0}\left(\frac{1}{r_{np}+a} - \frac{1}{r_{np}-a} - \frac{1}{2a}\right)$$

When the proton is far away, the energy is infinite, unphysical.
With the exact induced dipole formula for the neutron, one obtains:

$$U_e^{2H} = \frac{e^2}{4\pi\epsilon_0}\left(\frac{2}{r_{np}+a} - \frac{2}{r_{np}-a}\right)$$

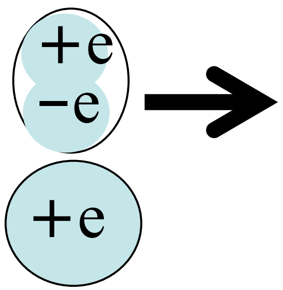
Deuteron electromagnetic structure



+e neglected (first approximation)

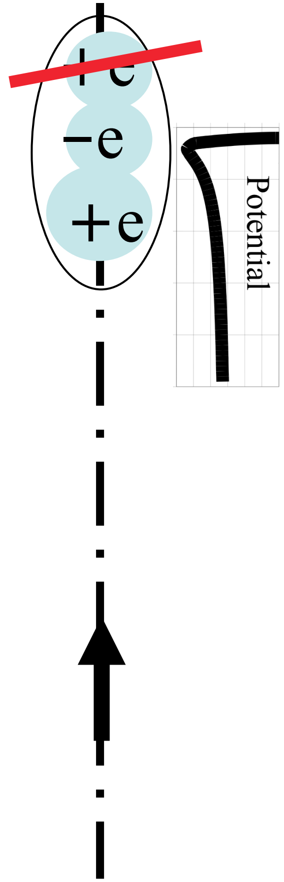
Electric charges:

Neutron dipole induced by the proton



Deuteron non-zero quadrupole

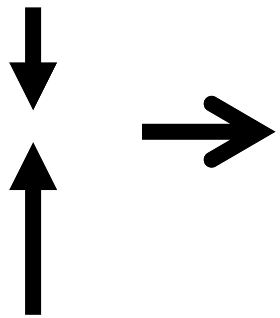
Electrostatic induction means neutron-proton attractive force



Magnetic moments:

Neutron $\mu_n < 0$

Proton $\mu_p > 0$



Deuteron magnetic moment

$\mu_D = \mu_p - |\mu_n| > 0$

Opposite magnetic moments means repulsive force

Approximate proton-neutron Coulomb potential in the deuteron

The proton positive charge attracts the neutron negative charge, equilibrated by the magnetic repulsion.

In a first approximation,
the positive charge of the neutron is neglected:

$$U_{em} = U_e + U_m = -\frac{e^2}{4\pi\varepsilon_0 r_{np}} + \frac{\mu_0 \left|\mu_n \mu_p\right|}{2\pi r_{np}^3}$$

Calculated static equilibrium distance

The potential minimum, obtained by derivation, gives the neutron-proton equilibrium distance:

$$\frac{dU_{em}}{r_{np}} = \frac{e^2}{4\pi\epsilon_0 r_{np}^2} - 3\frac{\mu_0|\mu_n\mu_p|}{2\pi r_{np}^4} = 0$$

$$r_{np} = \frac{\sqrt{6|\mu_n\mu_p|}}{ec} = 0.60 \text{ fm}$$

Using this formula, one obtains an approximation of the deuteron binding energy:

Analytical deuteron binding energy formula

Using $\mathbf{r_{np}}$ **at equilibrium** gives an approximate formula for the deuteron binding energy:

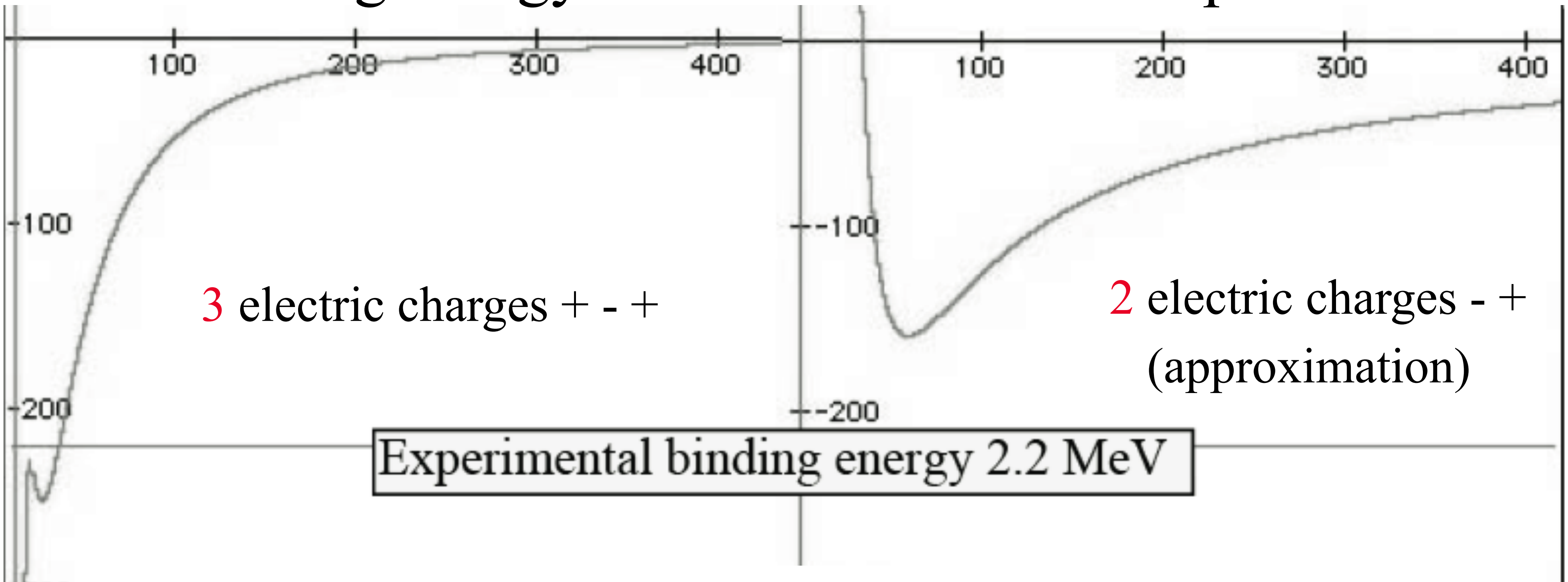
$$B = -\frac{e^3 c}{6\pi\varepsilon_0 \sqrt{6|\mu_n \mu_p|}}\, J = -\ 1.6\ \mathrm{MeV}$$

Only fundamental constants, no fit!

Experimental value : -2.2 MeV

Error evaluation of total ^{2}H binding energy

The binding energy is the minimum of the potential:



The usual dipole formula is invalid : $\mathbf{r_{np} \sim a}$

Exact dipole formula:
3 % error

$$U_{em}^{^2H} = \frac{e^2}{4\pi\epsilon_0}\left(\frac{2}{r_{np}+a} - \frac{2}{r_{np}-a}\right) + \frac{2\mu_0|\mu_n\mu_p|}{4\pi r_{np}^3}$$

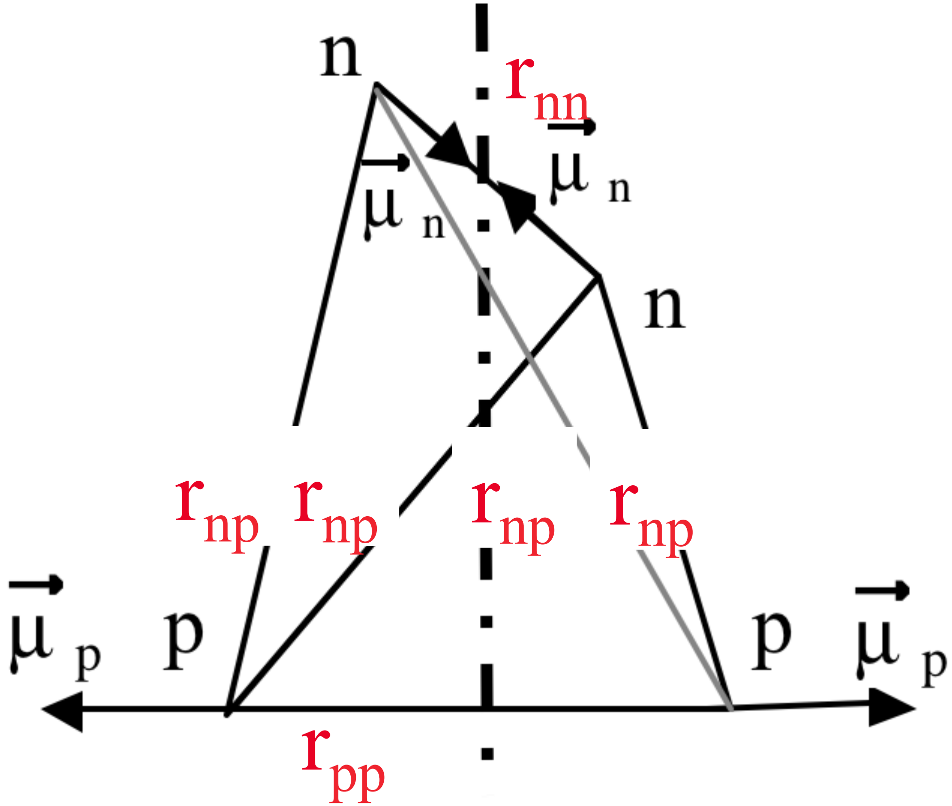
Analytical formula
without +e: 30 % error

$$U_{em}^{^2H} = -\frac{e^2}{4\pi\epsilon_0 r_{np}} + \frac{2\mu_0|\mu_n\mu_p|}{4\pi r_{np}^3}$$

α particle structure

^{4}He (2 protons and 2 neutrons) may be considered approximately as a regular tetrahedron with 60° angles.

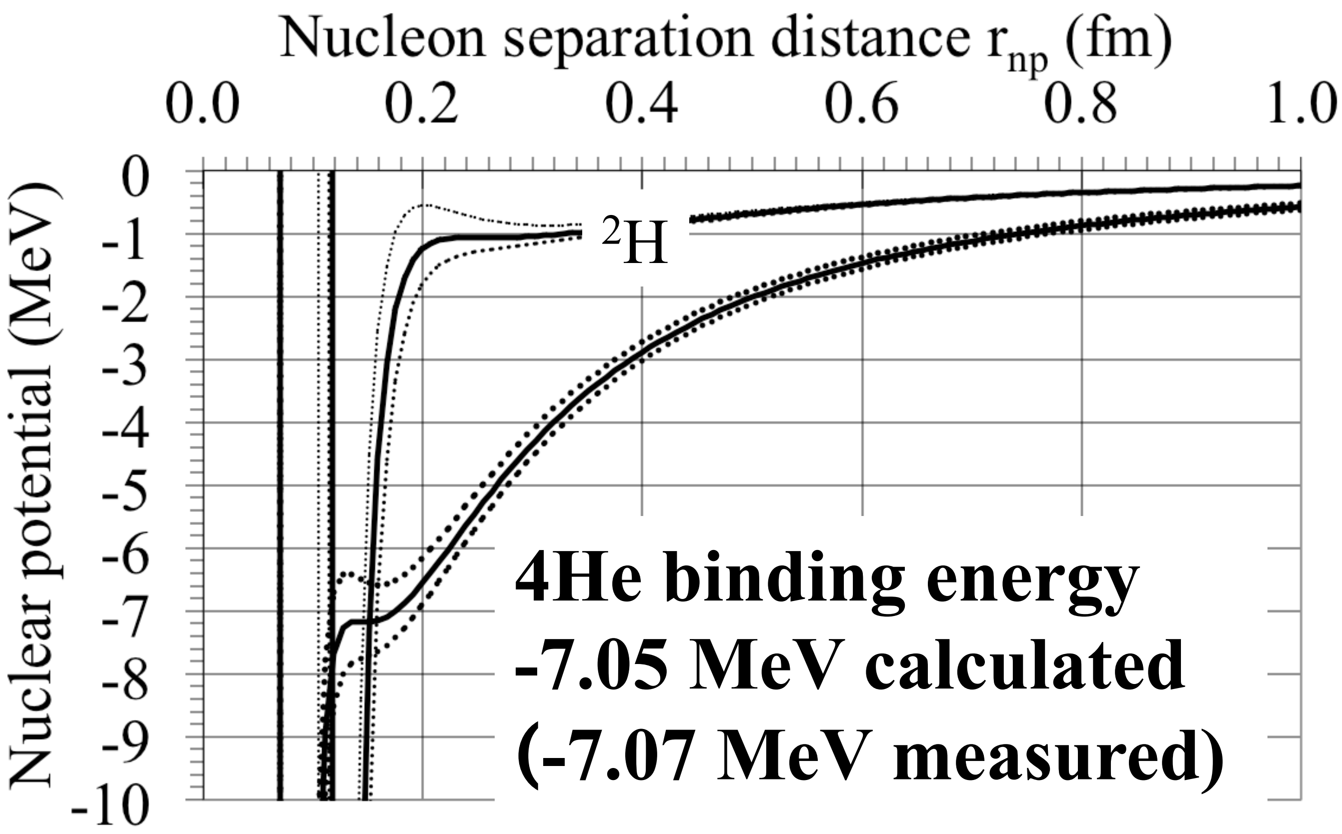
The magnetic moment of ^{4}He being zero, the magnetic moments of its nucleons have to be oppositely paired.



Helium ^{4}He potential

The simplified electromagnetic potential for the ^{4}He tetrahedron, with only the neutron-proton bonds taken into account, gives a result as good as for ^{2}H:

$$U_{em}^{^4He}/A = 2 \times \frac{e^2}{4\pi\epsilon_0}\left(\frac{2}{r_{np}+a} - \frac{2}{r_{np}-a}\right) + \frac{3}{4} \times \left(\frac{2\mu_0|\mu_n\mu_p|}{4\pi r_{np}^3}\right)$$



These local minimums are flat inflection points due to the Coulomb singularity.

^{2}H and ^{4}He binding energies per nucleon formulas compared

$$U_{em}^{^2H}/A = \frac{1}{2} \times \frac{e^2}{4\pi\epsilon_0}\left(\frac{2}{r_{np}+a} - \frac{2}{r_{np}-a}\right) + \frac{1}{2} \times \left(\frac{2\mu_0|\mu_n\mu_p|}{4\pi r_{np}^3}\right)$$

$$U_{em}^{^4He}/A = 2 \times \frac{e^2}{4\pi\epsilon_0}\left(\frac{2}{r_{np}+a} - \frac{2}{r_{np}-a}\right) + \frac{3}{4} \times \left(\frac{2\mu_0|\mu_n\mu_p|}{4\pi r_{np}^3}\right)$$

The potential energy ratio between ^{4}He and ^{2}H is

4/(3/2) = **6**

not far from the experimental ratio

7.07/1.11 = **6.4**.

Fundamental nuclear constant

$$\frac{e^2}{4\pi\varepsilon_0 R_P} = \frac{\alpha\hbar c}{R_P} = \alpha m_p c^2 = 6.84690165\ \text{MeV}$$

R_P : proton Compton radius

m_p : proton mass

α : fine structure constant

This universal constant is not far from the α particle binding energy, **7.07 MeV** characterizing the nuclear binding energy per nucleon.

H, ^{2}H and ^{4}He energies compared

- **Hydrogen atom** binding energy:

$$B^H = \frac{1}{2}\alpha^2 m_e c^2 = 13.6\ eV$$

Nuclear/chemical ratio:

- **^{2}H** binding energy per nucleon:

$$B^{^2H} \approx \frac{1}{6}\alpha m_p c^2 \approx 1.1\ MeV$$

80,000

- **^{4}He** binding energy per nucleon:

$$B^{^4He} \approx \alpha m_p c^2 \approx 7.07\ MeV$$

500,000

So called « Modern » forces replaced by electric AND magnetic Coulomb's laws

Electrostatic attraction replaces strong force.

Magnetic repulsion replaces hard core.

No orbiting nucleons.

Coulomb's laws

give the nuclear to chemical energy ratio:

$$\frac{m_p}{\alpha m_e} = 250,000$$

1/r Coulomb's law explains the nuclear/chemical energy ratio, comparable to the atom/nucleon radius ratio.

Thank you for your attention