Electromagnetic Theory of the Nuclear Interaction. Application to the Hydrogen and Helium Isotopes

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The neutron is not so neutral

The strong force is not so strong

The electromagnetic interaction is not so feeble

The nuclear interaction may be electromagnetic

Estimate of ^{2}H binding energy

At an internucleon distance of R = 0.65 fm the electrostatic potential energy is equal to the binding energy of the deuteron :

$$U_{em}^{np} = \frac{e^2}{4\pi\varepsilon_0 R} = 2.2\ \mathrm{MeV}$$

This calculation proves that the electromagnetic interaction is not so feeble as it is incorrectly assumed.

Deuteron nuclear potential

electrostatic attraction
between a neutron and a nearby proton is due to the well known electrostatic induction

+

magnetic repulsion
between nucleons is due to opposite and collinear magnetic moments

Shell model useless

No orbital movement of the nucleons exists in the deuteron and in the α particle ground states

where $\ell = 0$

Dipole and polarizability formulas

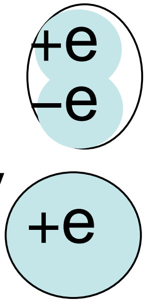
The dipole and polarizability formulas are valid only in a uniform electric field

The electric field is not uniform within a neutron near to a proton

It is better to use the original
Coulomb law
for point charges

Deuteron electromagnetic structure

Neutron dipole induced by the proton



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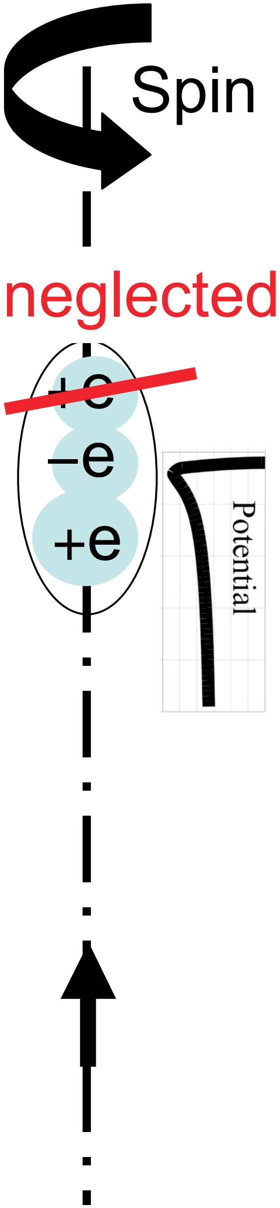
Deuteron non-zero quadrupole

Electrostatic induction means neutron-proton attractive force



Neutron
$\mu_n < 0$

Proton
$\mu_p > 0$

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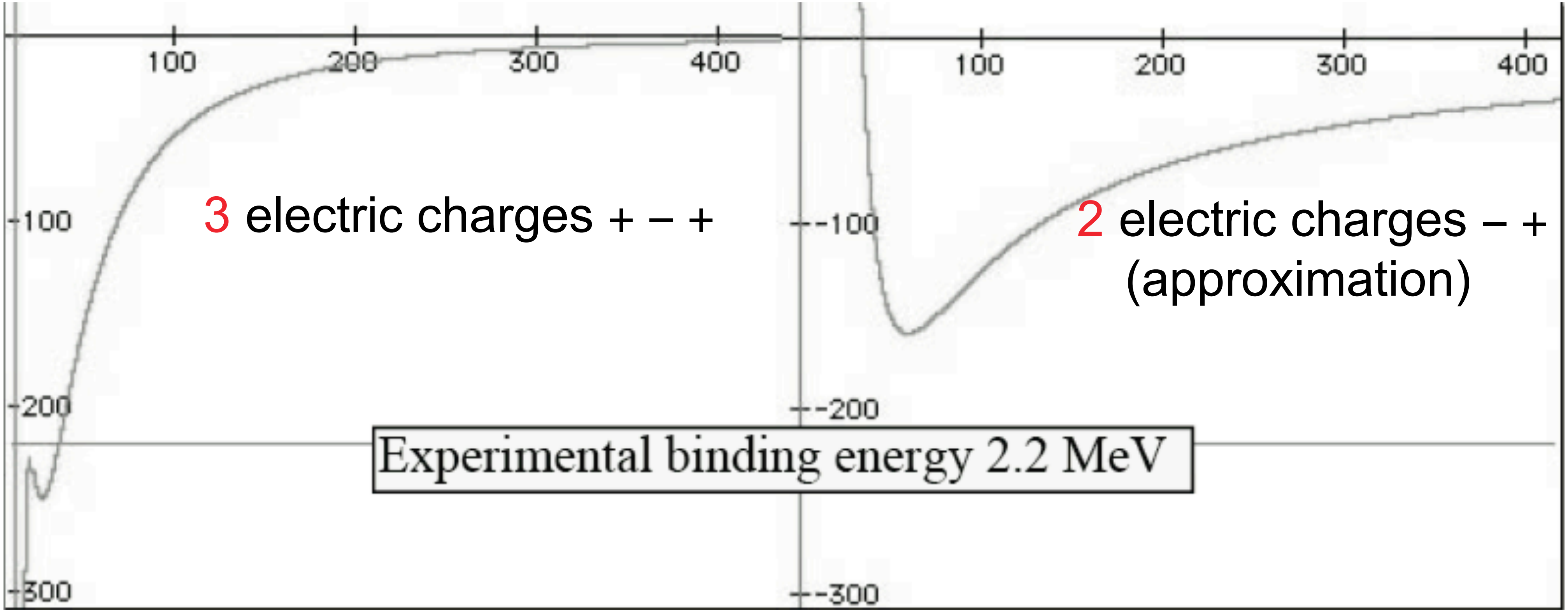
Deuteron magnetic moment
$\mu_D = \mu_p - |\mu_n| > 0$

Opposite magnetic moments means repulsive force

Deuteron binding energy
from laws of electrostatics and magnetostatics



3 electric charges + − +

2 electric charges − + (approximation)

The experimental binding energy is intermediate between the two graphically obtained binding energies.

This justifies the 2 point charge approximation

Electromagnetic interaction between the proton and the neutron in the deuteron

The neutron has a **locally effective** **negative charge –e** due to the neglect of its positive charge, farther away from the proton.

Summing the Coulomb attractive charge-charge potential and the magnetic repulsive dipole-dipole potential gives the deuteron potential :

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

Calculated equilibrium distance

The minimum potential (without orbital kinetic energy: $\ell = 0$) gives the binding energy at equilibrium (force = 0) :

$$F = -\frac{dU_{em}(r_{np})}{dr_{np}} = -\frac{e^2}{4\pi\varepsilon_0 r_{np}}\left(1 - \frac{6|\mu_n\mu_p|}{e^2c^2r_{np}^2}\right) = 0$$

This gives the neutron-proton equilibrium distance :

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

Phenomenological potentials give also values around 0.6 fm

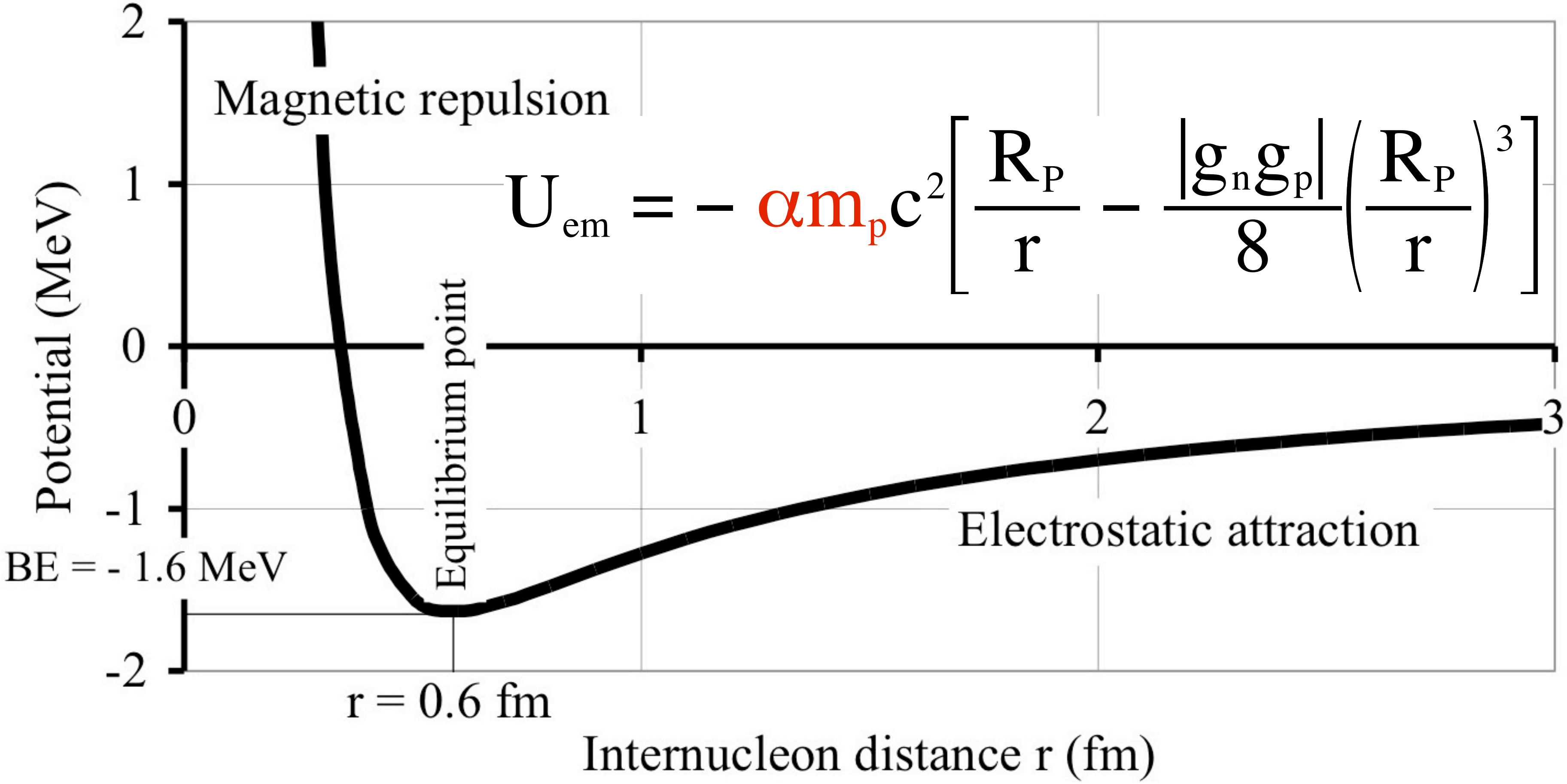
Deuteron binding energy

Replacing r_{np} at equilibrium in the potential gives the binding energy of the deuteron :

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

Experimental value : 2.2 MeV

Deuteron electromagnetic potential



$$U_{em} = -\alpha m_p c^2 \left[\frac{R_P}{r} - \frac{|g_n g_p|}{8} \left(\frac{R_P}{r} \right)^3 \right]$$

α : fine structure constant

m_p : proton mass

c : light speed

R_P : proton Compton radius

g_n, g_p : Landé factors

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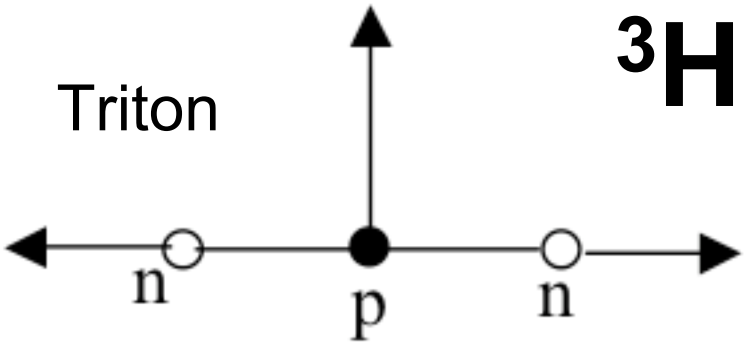
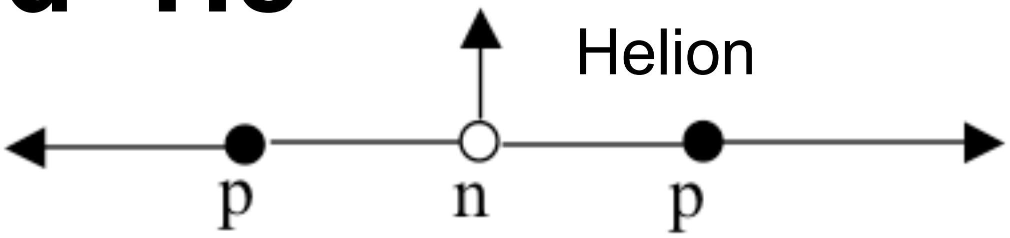
^{3}H and ^{3}He





Experiment : 3H **8.5 MeV**

3He **7.7 MeV**

Calculated triton binding energy:

$$B_{em}^{3H} = -\frac{4\sqrt{2}}{|g_n|}\alpha\, m_p c^2 = -\mathbf{10\ MeV}$$

Replacing g_n by g_p gives the helion binding energy :

$$B_{em}^{3He} = -\frac{4\sqrt{2}}{|g_p|}\alpha\, m_p c^2 = -\mathbf{6.9\ MeV}$$

^{3}H has a higher binding energy than ^{3}He due to the lower magnetic repulsion between neutrons than between protons

^{4}He potential

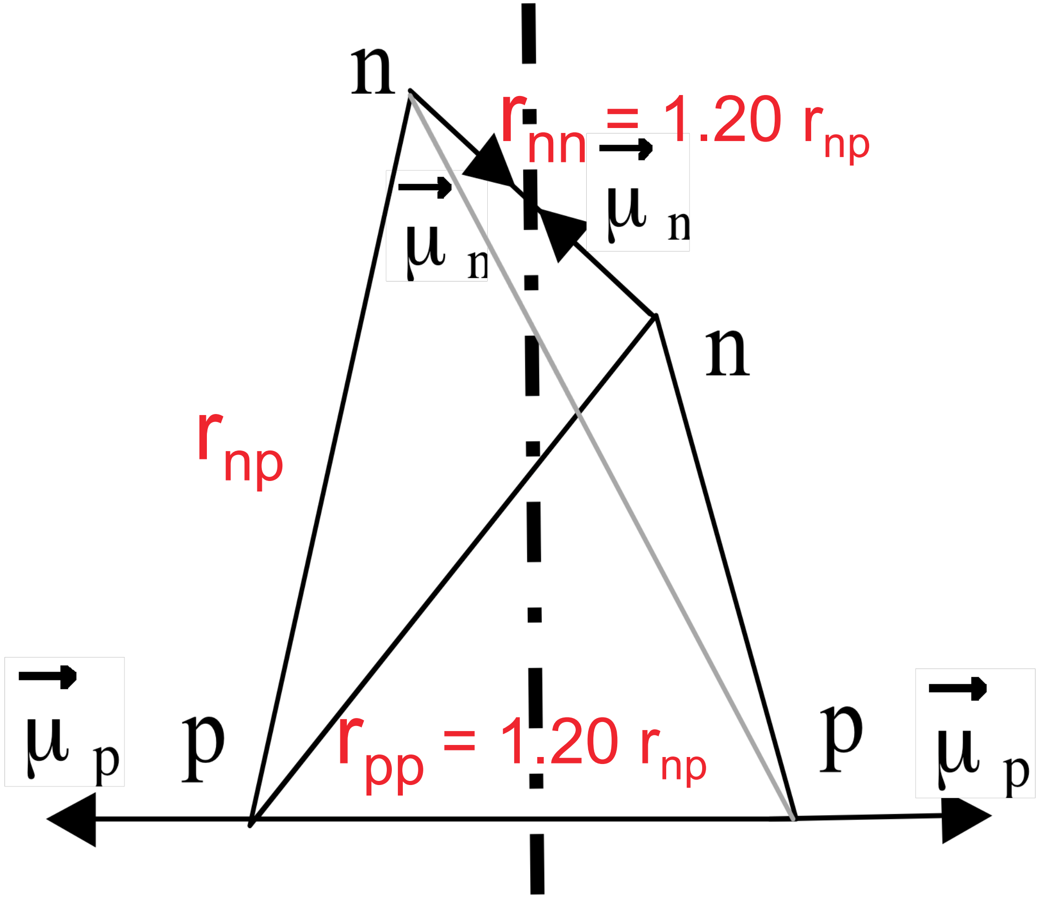
The electromagnetic potential for an almost regular tetrahedron is :

$$U_{em}^{^4He} = \alpha m_p c^2 \left(\frac{R_P}{r_{nn}} + \frac{g_p^2}{8}\frac{R_P^3}{r_{nn}^3} + \frac{R_P}{r_{pp}} + \frac{g_n^2}{8}\frac{R_P^3}{r_{pp}^3} - \frac{R_P}{r_{np}} - \frac{3|g_n g_p|}{16}\frac{R_P^3}{r_{np}^3} \right)$$

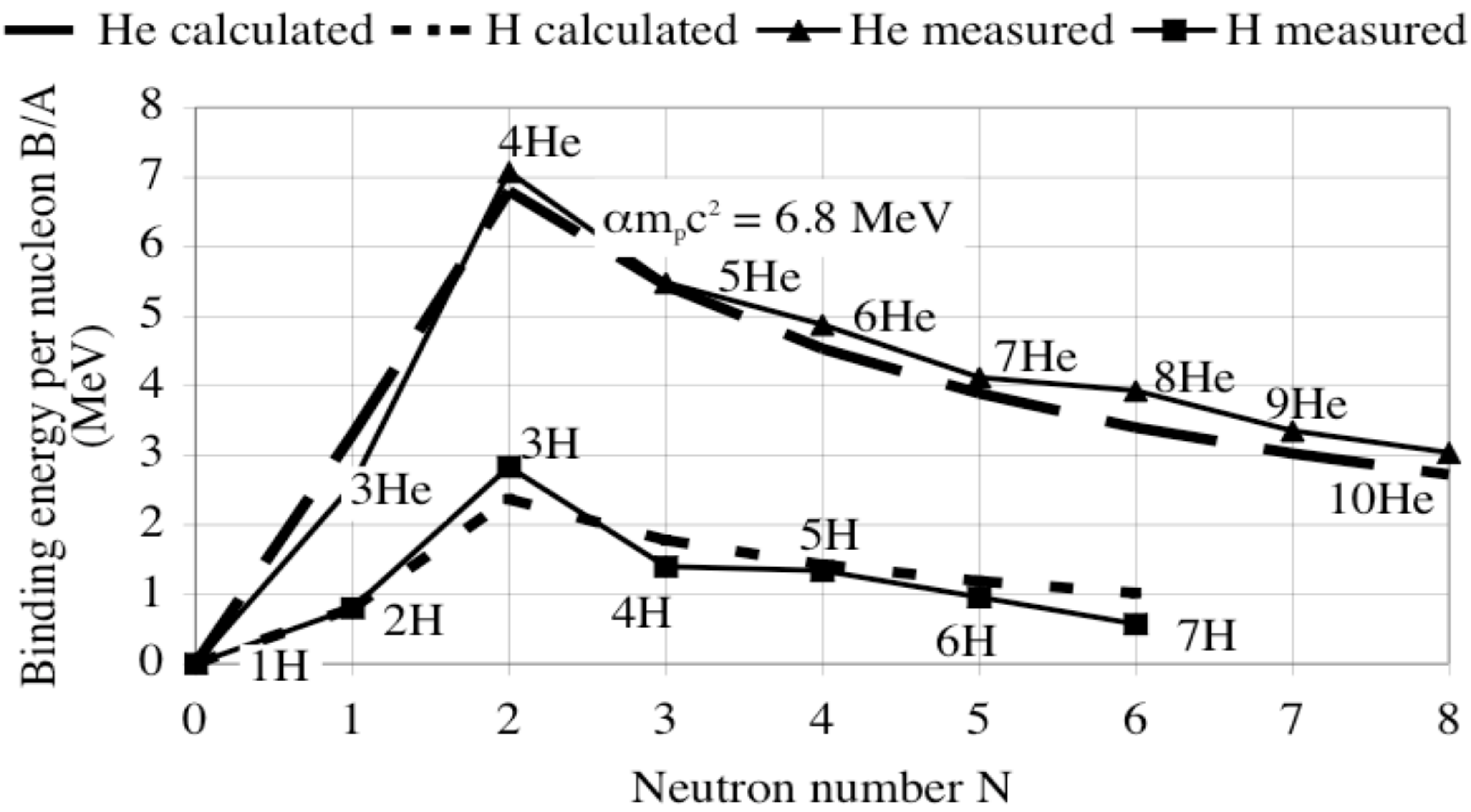
The structure of ^{4}He being unknown the magnetic moments are assumed to be opposite but inward-outward and the ^{4}He tetrahedron 20 % flattened:

$r_{nn} = r_{pp} = 1.20\, r_{np}$.

This gives the binding energy of ^{4}He : – 28 MeV.



Calculated and experimental binding energies B/A of the H and He isotopes



Total binding energy of the N > 2 isotopes assumed to be constant

Nuclear and chemical energies

Chemical energy is the electron-proton separation energy:

$$-R_y = -\frac{1}{2}\alpha^2 m_e c^2 = -13.6\ \mathrm{eV}$$

Nuclear energy is the neutron-proton separation energy

$$-\frac{1}{4}\alpha\, m_p c^2 \sim -1.6\ \mathrm{MeV}$$

Ratio nuclear / chemical energy :

Calculated

$$\frac{1}{2}\frac{m_p}{\alpha m_e} = \frac{1.6\ \mathrm{MeV}}{13.6\ \mathrm{eV}} = 120{,}000$$

Experimental

$$\frac{2.2\ \mathrm{MeV}}{13.6\ \mathrm{eV}} = 160{,}000$$

Electromagnetism clarifies:

- Strong force : electrostatic attraction
- Hard core : magnetic repulsion
- Ratio nuclear / chemical energy :

$$\frac{1}{2}\frac{m_p}{\alpha m_e} = 120{,}000$$

Thank you for your attention