Electromagnetic Nature of the Nuclear Interaction

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Nuclear interaction

- Strong force

- Orbiting nucleons

- Electromagnetism

Proton-neutron electric attraction

Electrical attraction discovered by the Greeks who observed that rubbed amber (elektron in greek) attracts neutral particles.

Magnetic interaction between nucleons

Magnetic attraction was also observed by the Greeks with magnetite (from the magnesia region)

- Magnetic repulsion was probably observed much later

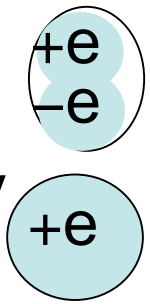
Neutron-proton equilibrium

The deuteron (heavy hydrogen) is made of one proton and one neutron. There is electromagnetic equilibrium between the electrostatic attraction and the magnetic repulsion.

To calculate it we need to know the deuteron electromagnetic structure

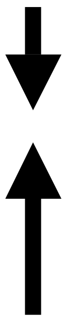
Deuteron electromagnetic structure

Neutron dipole induced by the proton



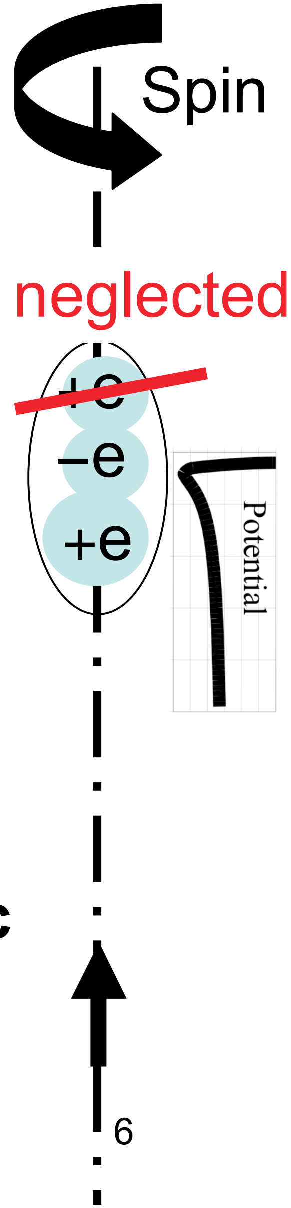
Neutron $\mu_n < 0$

Proton $\mu_p > 0$



Electrostatic induction means neutron-proton attractive force

Opposite magnetic moments means repulsive force



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

Electromagnetic nuclear interaction

$$U_{em} = \sum_i \sum_{i \neq j} \frac{e_i e_j}{4\pi\varepsilon_0 r_{ij}} + \sum_i \sum_{i \neq j} \frac{\mu_0}{4\pi r_{ij}^3} \left[\vec{\mu}_i \bullet \vec{\mu}_j - \frac{3\left(\vec{\mu}_i \bullet \vec{r}_{ij}\right)\left(\vec{\mu}_j \bullet \vec{r}_{ij}\right)}{r_{ij}^2} \right]$$

- Or, equivalently

$$U_{em} = \alpha m_p c^2 \sum_i \sum_{i \neq j} \left[\frac{e_i e_j R_P}{e^2 r_{ij}} + \frac{|g_i g_j|}{16} \left(\frac{R_P}{r_{ij}} \right)^3 S_{ij} \right]$$

$$S_{ij} = cos\left(\vec{\mu}_i, \vec{\mu}_j\right) - 3\ cos\left(\vec{\mu}_i, \vec{r}_{ij}\right) cos\left(\vec{\mu}_j, \vec{r}_{ij}\right)$$

Deuteron potential

- The preceding formulas give, for the deuteron

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

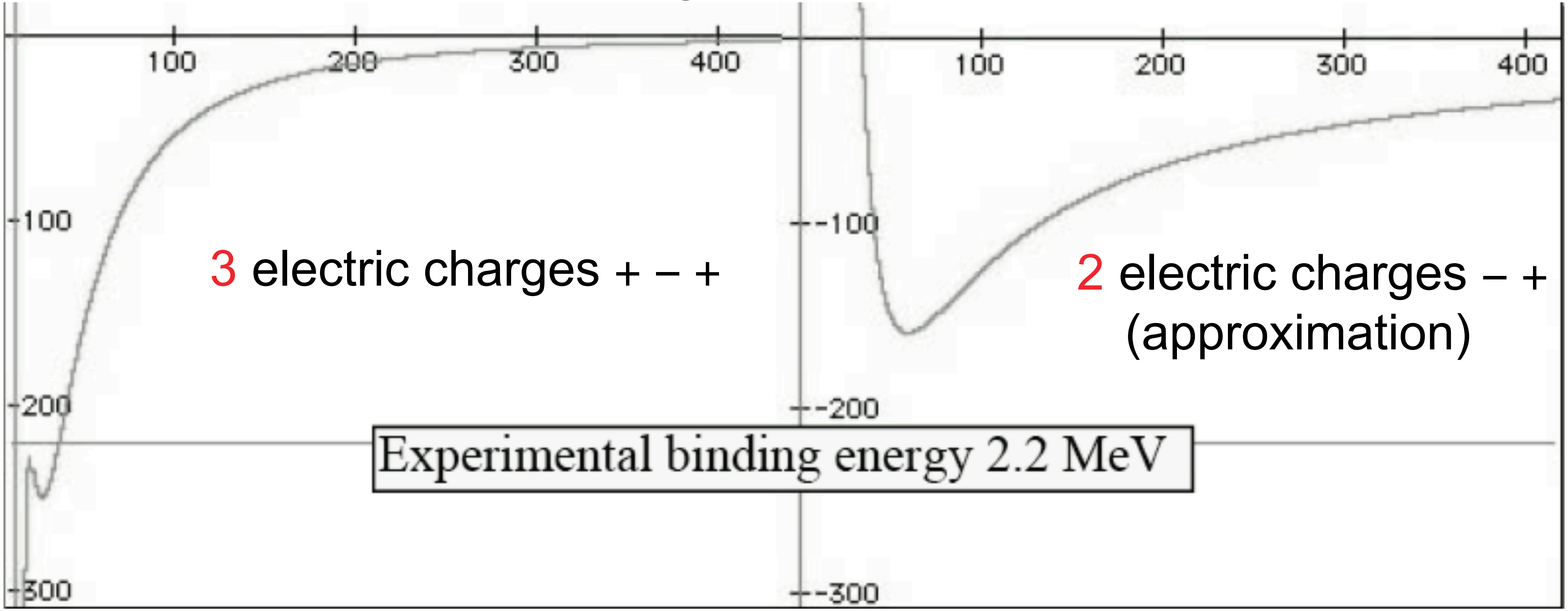
There are three electrostatic terms and one magnetostatic

The first two correspond to the interactions between the proton and the positive and negative charges of the neutron
The third one is the varying energy of the proton induced dipole which
has to be zero for infinite r_{np}.

The last term is the magnetic repulsion between the nucleons

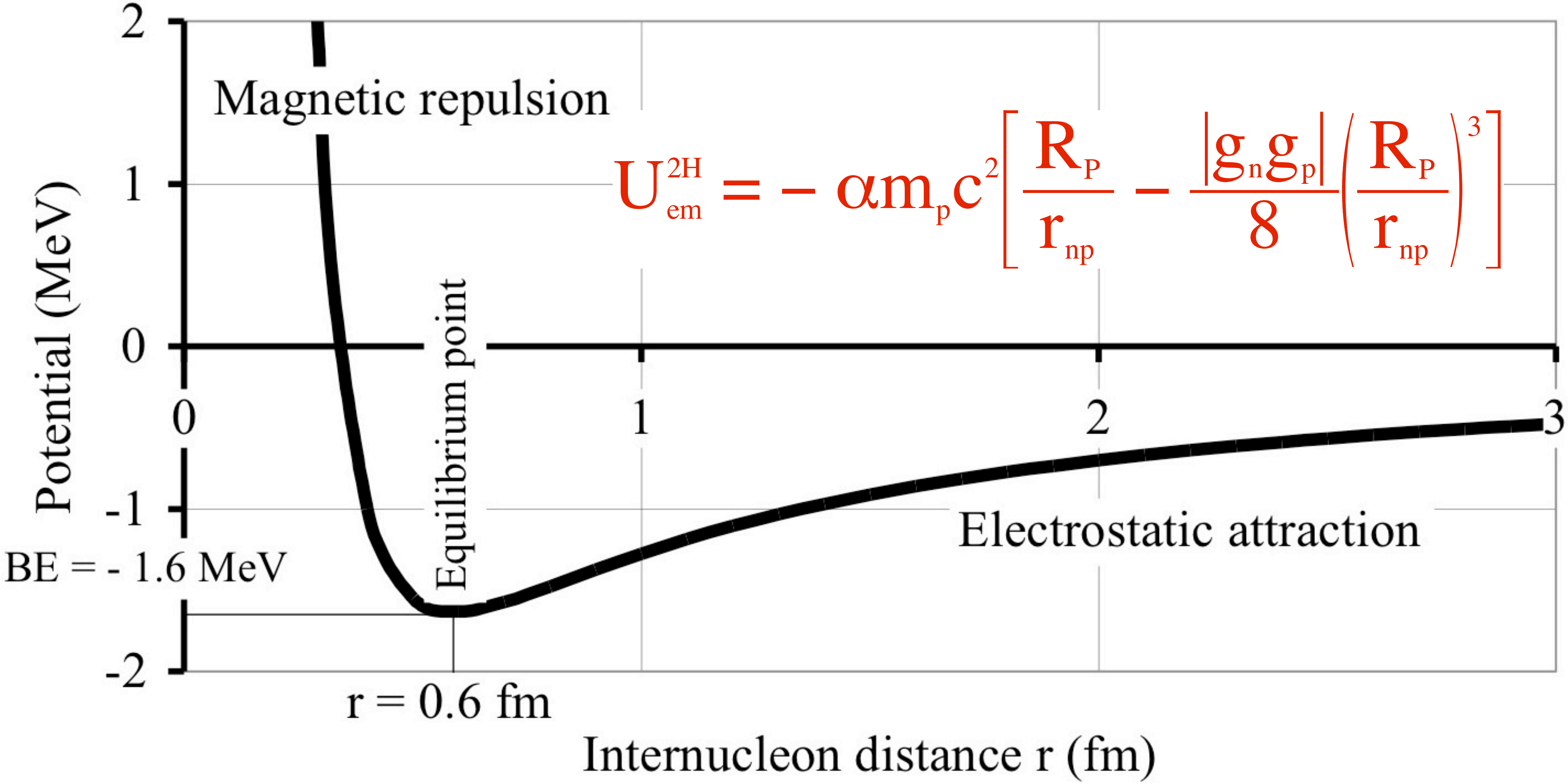
Deuteron binding energy

from Coulomb laws of electrostatics and magnetostatics



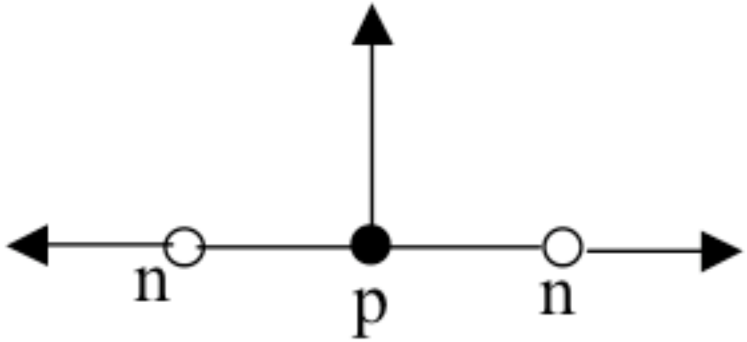
The experimental binding energy is in satisfying accord with the experimental value when using the preceding formula.
However, in order to obtain an analytical formula the positive charge of the neutron is neglected, giving a binding energy 30 % too weak.

Simplified deuteron electromagnetic potential



B. Schaeffer, J. Fusion Energy (2011) 30:377-381

Triton ^{3}**H**

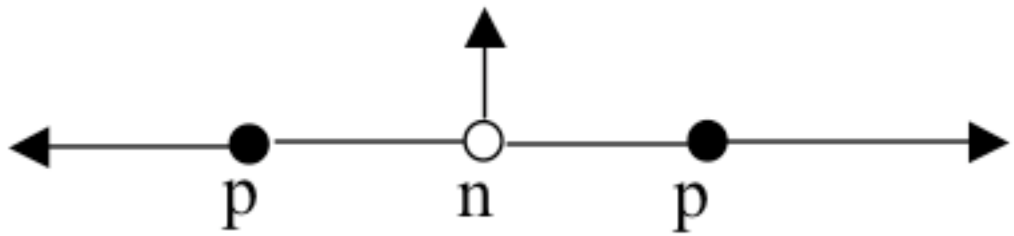


Experiment : 3H **8.5 MeV**

Calculated **triton** binding energy:

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

Helion ^{3}**He**



Experiment : 3He **7.7 MeV**

Swithing round g_n by g_p gives the calculated **helion** binding energy :

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

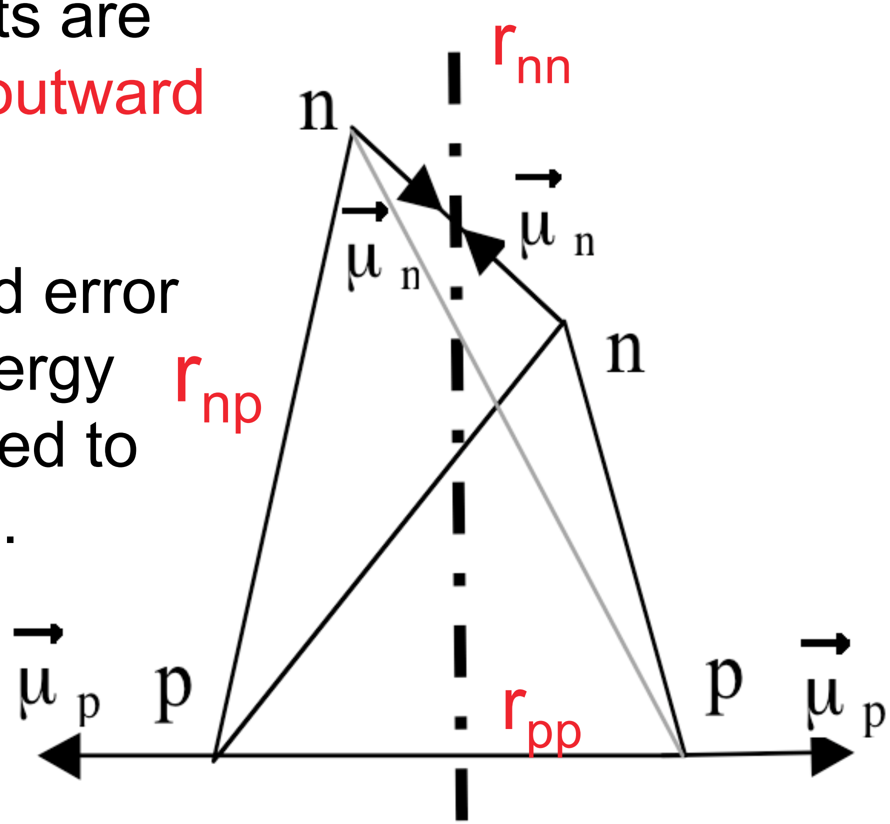
^{3}H has a higher binding energy than ^{3}He due to the lower magnetic repulsion between neutrons than between protons

Alpha particle potential

The electromagnetic potential for the tetrahedral structure of ^{4}He is

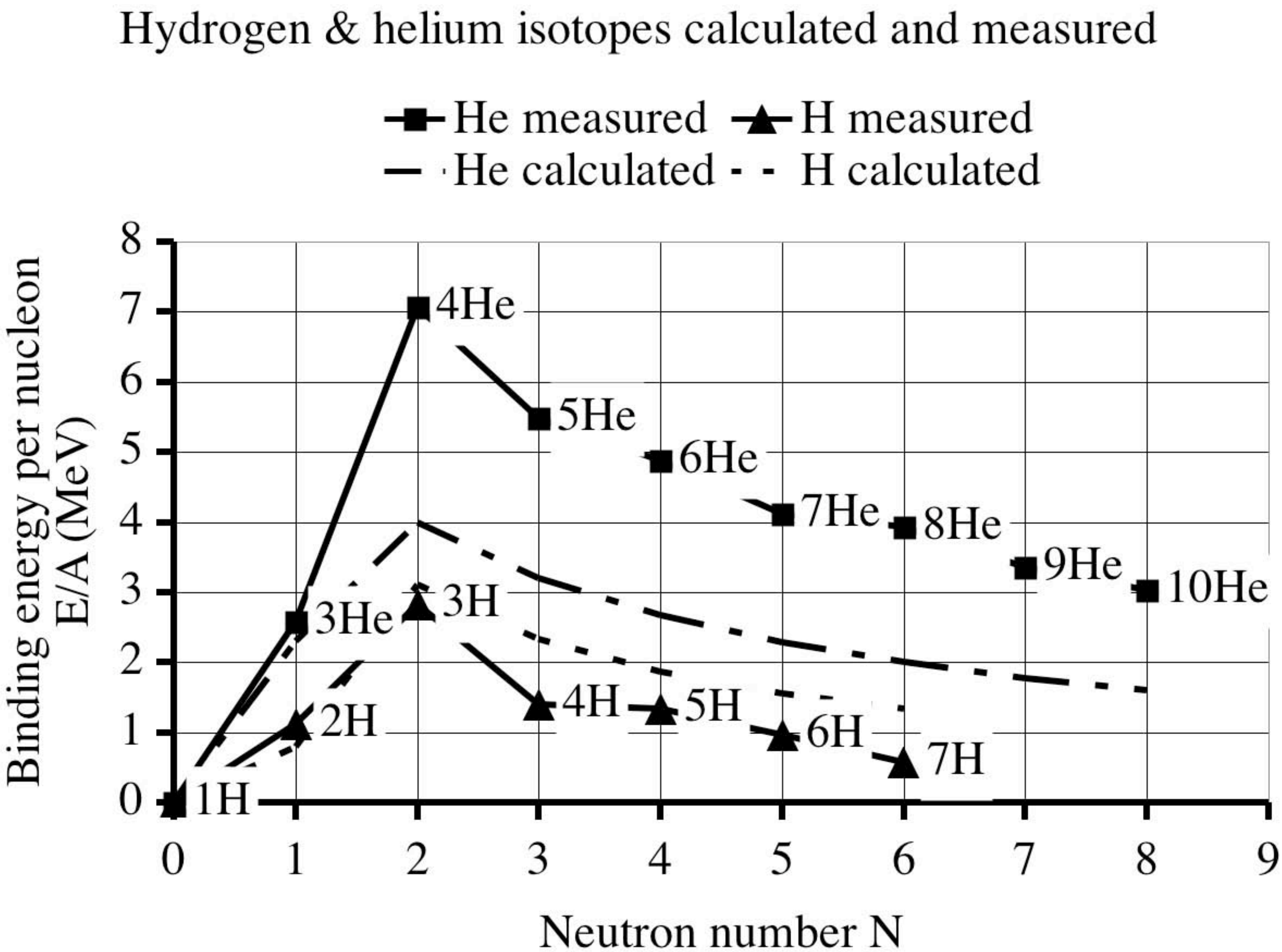
$$\alpha m_p c^2 \left\{ \left[\frac{R_P}{r_{nn}} + \frac{g_n^2}{8} \left(\frac{R_P}{r_{nn}} \right)^3 \right] + \left[\frac{R_P}{r_{pp}} + \frac{g_p^2}{8} \left(\frac{R_P}{r_{pp}} \right)^3 \right] - 4 \left[\frac{R_P}{r_{np}} + \frac{|g_n g_p|}{16} \left(\frac{R_P}{r_{np}} \right)^3 \frac{3 r_{nn}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

The magnetic structure of the alpha particle being unknown the magnetic moments are assumed to be opposite and inward-outward oriented as shown on the drawing



Solving the above equation by trial and error for the 3 variables the total binding energy of the alpha particle has been calculated to be 17 MeV instead of 28 experimental.

As for the deuteron, this result is not very precise, due to the neglect of the neutron positive charge.



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 (deuteron) :

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
- Soft core -> magnetic repulsion
- Nuclear energy ≈ αmc^2 ≈ 1 % of mass
- Nuclear/chemical energy $\frac{1}{2}\frac{m_p}{\alpha m_e}$ = **120,000**

Thank you for your attention