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 $^2\text{H}$ binding energy

At an internucleon distance of $R = 0.65 \text{ fm}$ the electrostatic potential energy is equal to the binding energy of the deuteron:

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

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 $\alpha$ 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

Electrostatic induction means neutron-proton attractive force

Opposite magnetic moments means repulsive force

Deuteron dipole induced by the proton

Neutron dipole induced by the proton

Deuteron non-zero quadrupole

Neutron dipole induced by the proton

Deuteron magnetic moment

\[ \mu_D = \mu_p - |\mu_n| > 0 \]

Neutron
\[ \mu_n < 0 \]

Proton
\[ \mu_p > 0 \]
Deuteron binding energy from laws of electrostatics and magnetostatics

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:

\[
U_{em} = U_e + U_m = -\frac{e^2}{4\pi\varepsilon_0 r_{np}} + \frac{\mu_0|\mu_n\mu_p|}{2\pi r_{np}^3}
\]
Calculated equilibrium distance

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

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

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 :

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

Experimental value : 2.2 MeV
Deuteron electromagnetic potential

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

- \( \alpha \): 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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\[ B_{\text{em}}^{\text{H}} = -\frac{4\sqrt{2}}{|g_n|} \alpha \ m_p c^2 = -10 \text{ MeV} \]

\[ B_{\text{em}}^{\text{He}} = -\frac{4\sqrt{2}}{|g_p|} \alpha \ m_p c^2 = -6.9 \text{ MeV} \]

\(^3\text{H}\) has a higher binding energy than \(^3\text{He}\) due to the lower magnetic repulsion between neutrons than between protons.
The electromagnetic potential for an almost regular tetrahedron is:

\[ U_\text{em}^{4\text{He}} = \alpha m_pc^2 \left( \frac{R_P}{r_{nn}} + \frac{g_p^2 R_P^3}{8 r_{nn}^3} + \frac{R_P}{r_{pp}} + \frac{g_n^2 R_P^3}{8 r_{pp}^3} - \frac{R_P}{r_{np}} - \frac{3 |g_ng_p| R_P^3}{16 r_{np}^3} \right) \]

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

\[ r_{nn} = r_{pp} = 1.20 r_{np} \]

This gives the binding energy of $^4\text{He}$: $-28 \text{ MeV}$. 
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:

\[- R_y = - \frac{1}{2} \alpha^2 m_e c^2 = - 13.6 \text{ eV}\]

Nuclear energy is the neutron-proton separation energy:

\[- \frac{1}{4} \alpha m_p c^2 \sim - 1.6 \text{ MeV}\]

Ratio nuclear / chemical energy:

Calculated
\[\frac{1}{2} \frac{m_p}{\alpha m_e} = \frac{1.6 \text{ MeV}}{13.6 \text{ eV}} = 120,000\]

Experimental
\[\frac{2.2 \text{ MeV}}{13.6 \text{ eV}} = 160,000\]
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