No universal constant characterizing the nuclear force has yet been found as for gravity and electromagnetism. The neutron is globally neutral with a zero net charge. The charges contained in a neutron may be separated by the electric field of a nearby proton and therefore being attracted by electrostatic induction in the same way as a rubbed plastic pen attracts small pieces of paper. There is also a magnetic force that may repel the nucleons like magnets in the proper relative orientation. In the deuteron, the heavy hydrogen nucleus, the induced electrostatic attraction is equilibrated by the magnetic repulsion between the opposite and colinear moments of the nucleons. Equilibrium is calculated by minimizing the electromagnetic interaction potential, giving a binding energy of 1.6 MeV, not much lower than the experimental value, 2.2 MeV. No fitting parameter is used: it is a true ab initio calculation.

1. Introduction

The Greeks already knew the electrical properties of amber (elektron) and the magnetic properties of magnetite and iron. Bieler in 1924 wrote "as the angle increases, the ratio of the actual scattering to what would be expected on the inverse-square law diminishes rapidly. This suggests the existence of an attractive force at short distances from the nucleus" [1]. At that time, the neutron was not yet discovered by his colleague, Chadwick, as well as the magnetic moment of the neutron proving that it contains electrical charges. An attractive magnetic force, as imagined by Bieler to interprete his experimental results, can, theoretically, be equilibrated by a repulsive electrostatic Coulomb force but the binding is unstable, the interaction energy being positive. The electromagnetic hypothesis for the nuclear interaction was abandoned when the neutron was discovered.

In this paper it will be shown that an attractive electrostatic induction may equilibrate the magnetic repulsion between the proton and the neutron in the deuteron. The permanent dipole of an isolated neutron is negligible but it may be induced by the electrostatic induction of a nearby proton. Combined with the proton, the neutron becomes the deuteron and the induced dipole the deuteron quadrupole. The nuclear physics literature seems to have neglected the electromagnetic interaction replaced by various hypothetical forces (Wigner, Majorana, Bartlett, Heisenberg, Rosenfeld, Yukawa…) and tensor force [2] combined sometimes with a mysterious repulsive strong core. It will be shown that a simple analytical formula is able to give a reasonable value of the deuteron binding energy, using only universal electromagnetic constants such as the elementary electric charge e, the neutron and proton magnetic moments \( \mu_n, \mu_p \), the electric permittivity \( \varepsilon_0 \), the magnetic permeability \( \mu_0 \), and the light speed c or, equivalently, the fine structure constant \( \alpha \), the neutron and proton Landé factors \( g_n, g_p \), the proton mass \( m_p \) and the light speed c.

2. Principle of the calculation

2.1. Electrostatic attraction

One proton, positively charged, and one neutron containing electric charges globally neutral, without any dipole when isolated, are the constituents of the deuteron (Fig. 1). The proton, having electric field acting on the neighbouring neutron, may separate the neutron charges by electrostatic induction, creating an electric dipole. The negative charge of the dipole is attracted by the proton and the positive charge repelled. The induced electric dipole, combined with the proton electric charge, becomes the quadrupole of the deuteron \( Q = 0.288 \text{ fm}^2 = (0.54 \text{ fm})^2 \). This means that the distances between the elementary electric charges are of the order of the nucleon size. "Unfortunately, the multipole expansion is not applicable when the molecules are separated by distances comparable to the molecular dimensions" [3]. This is also true for the atomic nucleus: the far-field approximation is not applicable when the distance between the electric charges is comparable to the nucleon size.

![Fig. 1. Deuteron electromagnetic structure.](image)
The positive charge of the neutron, taken away by the positive charge of the proton, may be, in a first approximation, neglected in the calculation of the binding energy. This is justified by the fact that the Coulomb potential law is decreasing in \(1/r\) with the distance \(r\). On the opposite, the negative charge of the neutron is brought closer to the proton. The quark hypothesis needs a multibody calculation, not necessary for a first approach. Nobody having ever seen fractional electric charges, we adopt provisionally the usual elementary charge.

The deuteron is constituted of one proton and one neutron. The neutron contains electric charges with no net charge. The proton contains one elementary charge, the same of that of the deuteron. The proton attracts the negative charge and repulses farther away the positive charge. Both nucleons have magnetic moments whose algebraic sum is the magnetic moment of the deuteron. Their magnetic moments are, in the deuteron, opposite, thus repulsive. There is therefore an electrostatic attraction equilibrated by a magnetic repulsion.

### 2.2. Magnetostatic repulsion

By reason of symmetry, the neutron and the proton magnetic moments in the deuteron have to be colinear (Fig. 1). The magnetic moment of the deuteron being close to the algebraic sum of the proton and the neutron magnetic moments [2], they repulse themselves like colinear magnets with opposite polarities. Magnetic monopoles having never been observed, the distance between the magnetic charges is unknown. We may thus use the far field approximation for the magnetic interaction between the neutron and proton magnetic dipoles.

### 2.3. Binding energy

We shall first compute the interacting force and energy between two particles having electrostatic charges and colinear magnetic moments. The spins of the neutron and of the proton being colinear, they have a common axis of rotation and therefore the kinetic energy of the deuteron is already included in the rotation of the nucleons. The purpose of this calculation is to find the potential at equilibrium between electrostatic attraction and magnetic repulsion to obtain the interaction potential between the neutron and the proton and thus the binding energy of the deuteron at the equilibrium of the electrostatic and magnetic forces.

### 3. Interaction energy equation

Let us consider two particles with electrical charges \(q_1\) and \(q_2\) with magnetic moments \(\vec{\mu}_1\) and \(\vec{\mu}_2\) and their joining line \(r_{12}\). The interacting electrostatic potential is [4]:

\[
U_e = \frac{q_1 q_2}{4 \pi \varepsilon_0 r_{12}} \tag{1}
\]

The general potential of the tensor force between two magnetic moments is [5]:

\[
U_m = \frac{\mu_0}{4 \pi r_{12}^3} \left[ \vec{\mu}_1 \cdot \vec{\mu}_2 - \frac{3}{r_{12}^3} \left( \vec{\mu}_1 \cdot \vec{r}_{12} \right) \left( \vec{\mu}_2 \cdot \vec{r}_{12} \right) \right] \tag{2}
\]

When the moments are colinear, using \(\mu_0 \varepsilon_0 = 1/c^2\), the formula (2) simplifies into:

\[
U_m = -\frac{\mu_0 \mu_1 \mu_2}{2 \pi r_{12}^3} = -\frac{\mu_1 \mu_2}{2 \pi \varepsilon_0 c^2 r_{12}^3} \tag{3}
\]

where \(\mu_1\) and \(\mu_2\) are now algebraic instead of being vectorial. The electromagnetic interaction potential at a static distance \(r_{12}\) is the sum of Eqs. (1) and (3):

\[
U = U_e(r_{12}) + U_m(r_{12}) = \frac{1}{4 \pi \varepsilon_0} \left( \frac{q_1 q_2}{r_{12}} - \frac{2 \mu_1 \mu_2}{c^2 r_{12}^3} \right) \tag{4}
\]

At equilibrium, the resultant force must be zero:

\[
F = -\frac{dU}{dr_{12}} = -\frac{1}{4 \pi \varepsilon_0} \left( \frac{q_1 q_2}{r_{12}^2} - \frac{6 \mu_1 \mu_2}{r_{12}^3} \right) = 0 \tag{5}
\]

We have then

\[
r_{12}^2 = \frac{6 \mu_1 \mu_2}{q_1 q_2 c^2} \tag{6}
\]
A zero force is only possible if the condition \( q_1 q_2 \mu_1 \mu_2 > 0 \) is satisfied. Replacing \( r_{12} \) into the potential energy Eq. (4) gives the basic formula for the binding energy of two particles with electric charges and colinear magnetic moments:

\[
B = \frac{q_1 q_2}{6 \pi \varepsilon_0} \sqrt{\frac{q_1 q_2}{6 \mu_1 \mu_2}}
\]

(7)

With the condition \( q_1 q_2 \mu_1 \mu_2 > 0 \) there is equilibrium, stable or unstable. If \( q_1 q_2 < 0 \) there is stable equilibrium, that is, binding. We shall write Eq. (7) somewhat differently. The nuclear magneton is

\[
\mu_N = \frac{e h}{8 \pi m_p}
\]

(8)

where \( h \) is Planck’s constant and \( m_p \) the proton’s mass. The fine structure constant is

\[
\alpha = \frac{e^2}{2 \varepsilon_0 \hbar c} = \frac{1}{137}
\]

(9)

Using the Landé factors \( g \), we obtain an interesting formula for the binding energy between two nucleons with colinear magnetic moments

\[
B = \frac{-8 q_1 q_2}{3 e \alpha m_p c^2} \left( \frac{q_1 q_2}{6 \mu_1 \mu_2} \right) \alpha m_p c^2
\]

(10)

In this formula a pure number depending only on the geometry multiplies the mass energy \( m_p c^2 \). The parameters in the parentheses depend only on the geometry of the nucleus and on the Landé factors of the neutron and the proton. The fine structure constant \( \alpha \) is a fundamental pure number equal to 1/137 characterising the electromagnetic interaction.

4. Binding energy of the deuteron

The deuteron is made of one proton and one neutron. The deuteron magnetic moment is close to the algebraic sum of the colinear magnetic moments of the neutron and the proton. Being colinear and of opposite signs (parallel spins) there is a magnetic repulsion between the proton and the neutron. As stated above, there is, by electrostatic influence of the electric field of the proton on the neutron, separation between the positive, \( e_n^+ = e \), and negative, \( e_n = e \), charges of the neutron. The positive charge \( e_n^+ \) is pushed away by the proton and the negative charge \( e_n \) is attracted by the proton. The usual far field approximation cannot be used because the separation distance between the dipole charges is comparable to the nucleon size. The repulsion between the proton positive charge \( e_p^+ \) and the distant positive charge \( e_n^+ \) of the neutron may thus be neglected in a first approximation.

When the expression under the radical in the basic formula is positive, interaction energy exists between the electric charges and between the magnetic moments. The expression in the parentheses outside the radical should be negative in order to have a stable equilibrium. Both products \( e_e e_n^+ = e^2 \), and \( \mu_p \mu_n \) being negative, binding is possible. Let us apply numerically the basic formula to the neutron-proton interaction. We shall assume that the effective charge in the neutron is \( -e \), the same as the proton charge except for the sign. Eq. (10) becomes:

\[
B = \frac{-8}{3 \sqrt{6 \mu_e \mu_p}} \alpha m_p c^2 = \frac{-8}{3 \sqrt{6 \cdot 3.83 \cdot 5.58}} \frac{938}{137} = -1.6 \text{ MeV}
\]

(11)

This calculated binding energy is 30% lower than the experimental value, \( -2.2 \text{ MeV} \). A better value of \( -2 \text{ MeV} \) was obtained using a three-body numerical calculation but the purpose of this paper is to find an analytic formula in order to understand the nuclear interaction. The binding energy of the deuteron may thus be predicted electromagnetically. The electromagnetic potential between a neutron and a proton is shown in Fig. 2. According to the usual phenomenological theories the nuclear potential should unrealistically be 10 to 100 times the binding energy due to assumed kinetic energy. This calculation is obtained using only classical electrostatics and magnetostatics and their universal constants. There is no fitting.
This potential is simplified by the neglect of the positive charge of the deuteron. The electrostatic Coulomb potential in $1/r$ is predominant at large separation distances and the magnetic Coulomb potential in $1/r^3$ is predominant when the neutron and the proton are intermingled.

5. Nuclear and chemical energies

The typical energy needed to separate an electron from a proton is given by the Rydberg constant

$$R_r = \frac{1}{2} \alpha^2 m_e c^2 = 13.6 \text{ eV}$$

which is the binding energy of a hydrogen atom given by Bohr’s formula, very precisely equal to the experimental value of the energy of the ground state of the hydrogen atom. The electronic energy is proportional to the square of the fine structure constant $\alpha$ and the mass $m_e$ of the electron. Formula (10) shows that the nuclear interaction may be characterised by a formula similar to (12) but where $\alpha$ appears to the first power and the proton mass replaces the electron mass:

$$\frac{1}{2} \alpha m_p c^2 = 3.4 \text{ MeV}$$

The ratio of these two energies is 250,000. The electromagnetic theory is not as precise for the nucleus as for the atom, the experimental binding energy of a neutron to a proton being 2.2 MeV instead of 3.4 from (13) or 1.6 from (11). The experimental ratio between the formulas (11) and (12) is 160,000 instead of 250,000 between the experimental energy ratios of the nuclear and electronic binding energies, not too bad a result for the electromagnetic interaction.

5. Conclusion

Eq. (11) obtained from the electromagnetic hypothesis, electrostatic attraction equilibrated by magnetic repulsion, gives reasonable results for the deuteron binding energy. It seems to be the first time that the binding energy of a nucleus is calculated using universal constants only (ab initio calculation without any fitting parameter). The nuclear interaction is not only an analogue of the electromagnetic interaction: it is electromagnetic and explains why the mean nuclear energy is around $1/137$ of the mass energy and around 250,000 times the chemical energy.

REFERENCES