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Electromagnetic Interactions in an Atomic Nucleus

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Electromagnetic Interactions in an Atomic Nucleus

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Abstract

Repulsive Coulomb forces are known in heavy nuclei. Electric or magnetic, attractive or repulsive, Coulomb interactions exist in all nuclei. A proton attracts a not so neutral neutron as amber attracts small neutral objects. The magnetic moments of atomic nuclei interact as magnets. The electromagnetic energies, falsely assumed to be negligible in an atomic nucleus, are of the same order of magnitude as the nuclear binding energies. In this paper, the electromagnetic potential energies of the deuteron ^{2}H and the alpha particle ^{4}He are calculated statically, without fitting, by the bare application of the Coulomb's and Poisson's laws. The binding energies have been obtained by solving graphically the electromagnetic potentials.

Keywords: Electromagnetic interaction, Neutron, Proton, Deuteron, Helium, Alpha particle, Nuclear energy, Nuclear interaction.

Introduction

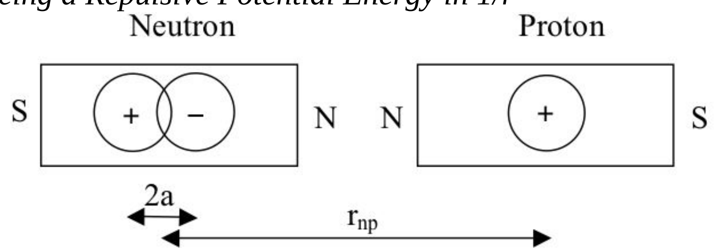
The electric and magnetic interactions have been discovered two millenaries ago by the ancient Greeks. The electromagnetic laws were discovered by Coulomb [1] and Poisson [2] two centuries ago. The proton, having a positive charge +e, is able to attract a neutron having electric charges with no net charge as a rubbed plastic pen attracts small neutral pieces of paper: “The positive charge attracts negative charges to the side closer to itself and leaves positive charges on the surface of the far side. The attraction by the negative charges exceeds the repulsion from the positive charges, resulting in a net attraction.”[3]. The magnetic moments of ^{2}H are collinear and opposite by reason of symmetry as shown on figure 1. The collinear and opposite magnetic moments of nucleons of the same kind may annihilate the resultant magnetic moment of ^{4}He (fig. 2).

Principle of the Calculation

The permanent dipole of an isolated neutron is negligible but a nearby proton induces an electric dipole in a neutron containing electric charges with no net charge. Combined with the proton, the neutron becomes the deuteron and the induced dipole the deuteron quadrupole. The potential energy between electrostatic charges and between magnetic moments of nucleons in the deuteron and the α particle are calculated.

Only electric and magnetic Coulomb-Poisson laws with associated fundamental constants are used (elementary electric charge e, neutron and proton magnetic moments μ_n, μ_p, vacuum electric permittivity ε_0, magnetic permeability μ_0, light speed c).

Figure 1. *Schematic Deuteron Structure. - The Proton Containing only one Electric Charge, Assumed to be Punctual in a First Approximation, its Electrostatic Proton Potential Energy is in 1/r. The Neutron Contains Electric charges with no Net Charge. Because of the Proximity of a Neutron and a Proton in a Nucleus, there is a Dissymmetry Causing an Attraction as in any Electrostatic Induction [3]. The Magnetic Moments of the Neutron and of the Proton are Opposite (North Poles Near Contact or Vice-Versa) and Collinear, Thus Producing a Repulsive Potential Energy in $1/r^3$*



Electromagnetic Interaction Potential Energy in a Nucleus

The sum of the electromagnetic potential energies of particles i and j, with electric charges e_i and e_j, magnetic dipoles μ_i and μ_j is, according to the Coulomb and Poisson formulas combined [1, 2, 5, 6, 7]:

$$U_{em} = \sum_i \sum_{i \neq j} \frac{e_i e_j}{4\pi\epsilon_0 r_{ij}} + \sum_i \sum_{i \neq j} \frac{\mu_0}{4\pi r_{ij}^3} \left[\mu_i \cdot \mu_j - \frac{3(\mu_i \cdot r_{ij})(\mu_j \cdot r_{ij})}{r_{ij}^2} \right] \quad (1)$$

r_{ij} is the separation distance between electric charges or magnetic moments. r_{ij} is the internucleon vector between the centers of the nucleons. This formula shows that the Coulomb potential energy is attractive or repulsive depending on the sign of the product of the electric charges. The Poisson magnetic potential energy is attractive or repulsive depending on the orientation and position of the magnetic moments of the nucleons.

Electric Charges in the Neutron

The non-zero magnetic moment of the neutron indicates that it is not an elementary particle, as it carries no net charge but still interacts with a magnetic field. If the neutron had no charge, its electrostatic potential energy would be zero. The proton containing one elementary charge +e, its electrostatic potential energy is, for a radius r = 1 fm, not far from the deuteron ^2H binding energy:

$$U_e^p(r) = \frac{e^2}{4\pi\epsilon_0 r} = 1.44\ MeV \quad (2)$$

The proton (938.272 MeV) should be heavier than the neutron (939.565 MeV) by nearly the same quantity. The sign is wrong: the proton is lighter than the neutron [1] by approximately the same quantity 1.29 MeV as in equation (2). A rough explanation is that the neutron contains two opposite elementary electric charges +e and −e. Its mass energy exceeds that of the proton nearly by the electrostatic potential energy of the proton. We may therefore assume that the neutron contains two electric charges, one electron −e, and one positron +e in a first approximation.

Electromagnetic Potential Energy of the Deuteron

Deuteron Electrostatic Potential Energy

An induced electric dipole may be created in a neutron by electric induction from a nearby proton. In a first approximation, the electric charge +e of a proton attracts the negative charge −e of the neutron and repulses its positive charge +e. According to Coulomb potential energy [1, 2] in 1/r from formula (1), the negative charge is more attracted than the positive charge is repulsed, resulting in a net attraction as has been shown by Feynman [3]: ”A net force can arise if a negative charge of one piece is closer to the positive than to the negative charges of the other piece". The usual dipole potential formula, in $1/r^2$, is an approximation that cannot be used here because the separation distance 2a between the neutron electric charges is of the same order of magnitude as the neutron-proton separation distance r_{np}. The exact electric dipole formula has to be applied, to obtain the most precise result. The total interaction potential energy between the proton and the neutron is the sum of the potential energy of an isolated dipole plus the potential energy needed to create it, thus twice the potential energy of an isolated dipole [4]:

$$U_e^{2H} = \frac{e^2}{4\pi\epsilon_0}\left(\frac{2}{r_{np}+a} - \frac{2}{r_{np}-a}\right) \tag{3}$$

where r_{np} is the distance in fm between the centers of the proton and the neutron (figure 1). 2a is the separation distance between the positive and negative elementary charges of the neutron, assumed to be punctual. The total electric potential energy between the three electric charges +e of the proton, −e and +e of the neutron is negative, thus attractive, contradicting the assumption that the Coulomb force is zero in the deuteron although it contains both positive and negative charges in equal quantities.

Deuteron Magnetic Potential Energy

According to formula (1), the magnetic potential energy of the deuteron is, from Poisson formula [2]:

$$U_m^{2H} = \frac{\mu_0}{4\pi r_{np}^3}\left[\vec{\mu}_n \bullet \vec{\mu}_p - \frac{3\left(\vec{\mu}_n \bullet \vec{r}_{np}\right)\left(\vec{\mu}_p \bullet \vec{r}_{np}\right)}{r_{np}^2}\right] \tag{4}$$

The magnetic potential energy is positive, repulsive because the magnetic moments of the proton and of the neutron in the deuteron are collinear and opposite as it is well known ($\vec{\mu}_n \bullet \vec{\mu}_p < 0$, North poles in contact) as shown on figure 1. The coefficient in the brackets is thus equal to $2|\mu_n\mu_p|$:

$$U_m^{2H} = \frac{2|\mu_0\mu_n\mu_p|}{4\pi r_{np}^3} \tag{5}$$

^{2}H total Potential Energies Combined

Adding the electrostatic (3) and magnetostatic (5) components of the Coulomb-Poisson electromagnetic potential energy, formula (1) becomes:

$$U_{em}^{2H} = \frac{e^2}{4\pi\epsilon_0}\left(\frac{2}{r_{np}+a} - \frac{2}{r_{np}-a}\right) + \frac{2|\mu_0\mu_n\mu_p|}{4\pi r_{np}^3} \tag{6}$$

There are two parameters in this equation, the neutron-proton distance r_{np}, in fm, and the distance 2a between the neutron positive and negative charges (fig. 1).

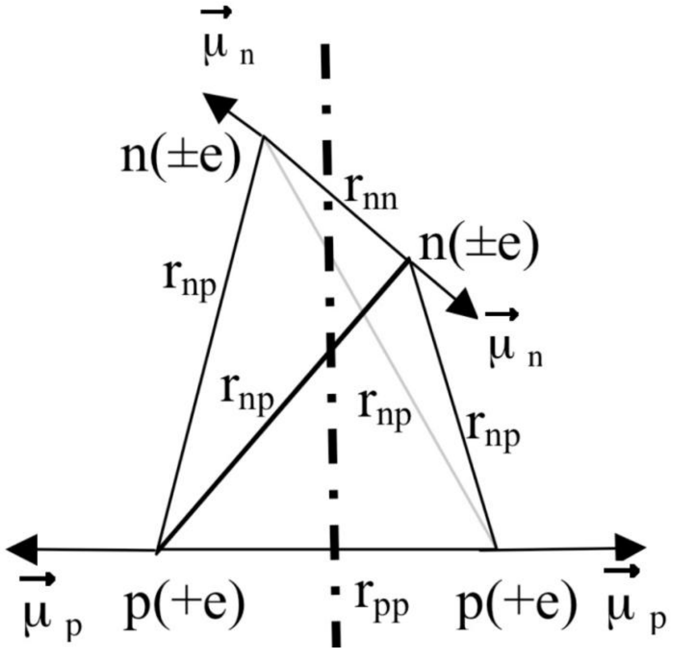
Deuteron Potential Energy per Nucleon

Dividing by A = 2, we obtain the potential energy per nucleon of the deuteron (fig. 3):

$$U_{em}^{^2H}/A = \frac{e^2}{4\pi\epsilon_0}\left(\frac{1}{r_{np}+a} - \frac{1}{r_{np}-a}\right) + \frac{|\mu_0\mu_n\mu_p|}{4\pi r_{np}^3} \tag{7}$$
$$= 1.442\left(\frac{1}{r_{np}+a} - \frac{1}{r_{np}-a}\right) + \frac{0.0849}{r_{np}^3}\ MeV$$

The binding energy should correspond to a minimum of the potential, but, due to the Coulomb singularity, there is no minimum. Instead, there is a horizontal inflection point, a saddle point, corresponding to the binding energy of ^2H and ^4He (fig. 3).

Figure 2. *Tetrahedral ^4He. − The Magnetic Moment of the α Particle Being Zero as it is Well Known, the Magnetic Moments of the Nucleons are Paired, Collinear and Oppositely Oriented by Reason of Symmetry. Therefore, There is a Single Magnetic Repulsion between Protons and Another one between, Negligible in a First Approximation in Comparison with the Four Neutron-Proton Bonds. The Main Magnetic Interaction is the Repulsion between Neutrons and Protons whose Projections on their Common Edge are Oppositely Oriented both Outward (or both Inward).*



Electromagnetic Potential Energy of Helium 4

We shall calculate the total α particle (^4He) potential energy by comparison with that of the deuteron ^2H.

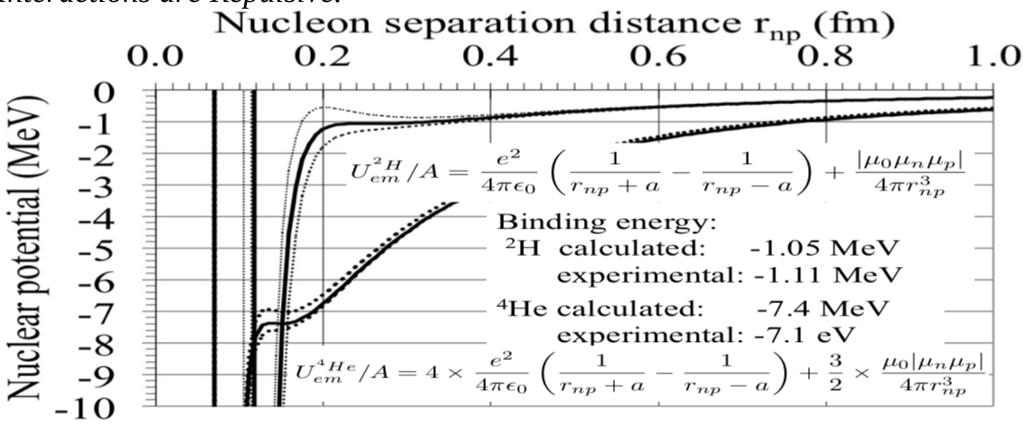
^4He, being made of 4 nucleons, is a tetrahedron that we shall assume to be regular by approximation. The proton-proton and neutron-neutron interactions are single, compared with the four neutron-proton bonds. Therefore they may be neglected in a first approximation. The magnetic moments are collinear and oppositely oriented along the neutron-neutron and the proton-proton vectors by reason of symmetry (fig. 2). Therefore, the total magnetic moment is zero.

One ^4He nucleus bond is, except for the inclination, made of 4 deuteron bonds. The number of bonds is equal to the number of nucleons. Therefore, its binding energy per nucleon is twice that of the deuteron. Each proton being connected to two neutrons, the binding energy is again multiplied by two. Therefore, the binding energy per nucleon of ^4He is thus **4** times larger than that of the deuteron. This would be exact without the inclination at 60° of the two magnetic moments, multiplying by **1/4**, cosine 60° squared, according to formula (4). Also according to formula (4), there is a coefficient **3/2**=1.5, increasing the binding energy by 50%. Finally, the magnetic energy term per nucleon is **4×1/4×3/2** = 3/2 that of the deuteron, giving the formula:

$$U_{em}^{4He}/A = 4 \times \frac{e^2}{4\pi\epsilon_0}\left(\frac{1}{r_{np}+a} - \frac{1}{r_{np}-a}\right) + \frac{3}{2} \times \frac{|\mu_0\mu_n\mu_p|}{4\pi r_{np}^3}$$
$$= 5.78\left(\frac{1}{r_{np}+a} - \frac{1}{r_{np}-a}\right) + \frac{0.1274}{r_{np}^3}\ MeV \qquad (8)$$

This potential is shown on figure 3; the horizontal inflection point is a saddle point corresponding with the α particle binding energy although with a lower precision than for ^2H because the neutron-neutron and proton-proton interactions are neglected. More precise results should be obtained by taking also into account the neutron-neutron and proton-proton interactions responsible for a less regular tetrahedron.

Figure 3. *Graphic of ^2H and ^4He Ectromagnetic Potential Energies per Nucleon. - The Horizontal Inflection Point is not a Real Minimum, due to the Coulomb Singularity. for Each Nucleus there is only one Horizontal Inflection Point Obtained by Adjusting 2a, the Neutron Electric Charges Separation Distance. The Calculated Binding Energy is Stronger than the Experimental Values because the Neglected Neutron-Neutron and Proton-Proton Interactions are Repulsive.*



Deuteron and Alpha Binding Energies

The ^{4}He binding energy is around 6 times greater than that of the deuteron ^{2}H because the deuteron has only one bond for two nucleons and the α particle two bonds per nucleon (fig. 2), thus multiplying the binding energy per nucleon by 4. Last by not least, the magnetic moment of ^{4}He being inclined by 60°, the magnetic potential is 1.5 times larger than that of ^{2}H. Therefore the magnetic repulsion being lower, the binding energy is enhanced by 50%, explaining the coefficient 6 between the binding energies of ^{4}He and ^{2}H.

Conclusions

The nuclear binding energies of the two simplest nuclei, the deuteron ^{2}H and the α particle ^{4}He have been calculated successfully by the bare application of electric and magnetic Coulomb-Poisson laws only. Indeed the so-called ”Coulomb force”, repulsive between protons, inexistent in the deuteron, is not the only electromagnetic interaction in a nucleus. The electrostatic attraction exists between a proton and a neutron as in the deuteron, equilibrated by the magnetic repulsion, explaining its binding energy. The nuclear energy corresponds to the equilibrium between electric and magnetic forces in the nucleus.

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