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The “Renaissance” in Nuclear Physics: Low-Energy Nuclear Reactions and Transmutations

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ABSTRACT

Nuclear structure theory has recently undergone an unexpected “renaissance” that can be attributed to two factors: (a) Since 1989, experimental findings have indicated isotopic anomalies in “chemical systems” at energies well below the expected ~10 MeV nuclear level. (b) Since 2007, remarkable *ab initio* super-computer calculations of nuclear properties have been made under the assumption that nucleons have well-defined intranuclear positions ($x \leq 2$ fm). Assuming a magnetic structure of nucleons consistent with classical physics, we have made related lattice calculations of nuclear binding energies and magnetic moments. Our results compare favorably with results from other Copenhagen-style nuclear models.

***Keywords*:** Nuclear physics, Classical physics, Low-energy nuclear reactions, Transmutations, Biot-Savart law, Magnetic attraction, Nuclear binding energies

1. INTRODUCTION

Nuclear structure theory has recently undergone an unexpected “renaissance” that can be attributed to two factors:

(a) since 1989, a steady stream of experimental findings has been reported indicating isotopic anomalies in “chemical systems” at energies well below the expected ~10 MeV nuclear level;

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(b) since 2007, remarkable *ab initio* super-computer calculations of nuclear properties have been made under the assumption that nucleons have well-defined intranuclear positions in a nucleon lattice ($x \leq 2$ fm).

Unresolved problems in nuclear structure theory have remained since 1932. Most textbooks in nuclear physics fully acknowledge that there are contradictions among the liquid-phase, gaseous-phase, and molecular cluster models of nuclear structure theory, and reluctantly acknowledge that a unified theory remains to be developed (Figure 1). There are 60+ articles in the nuclear physics literature on a unified, solid-phase lattice model of nuclear structure.

Discoveries of low-energy nuclear phenomena since 1989 have indicated that conventional nuclear theory is incomplete. Starting in 2004, Ulf Meissner and colleagues developed a new tool in nuclear physics: "Nuclear Lattice Theory". Using "Nuclear Lattice Effective Field Theory" (NLEFT), they have done *ab initio* supercomputer calculations of nuclear properties assuming that *nucleons are located at the vertices of a solid-phase lattice*.

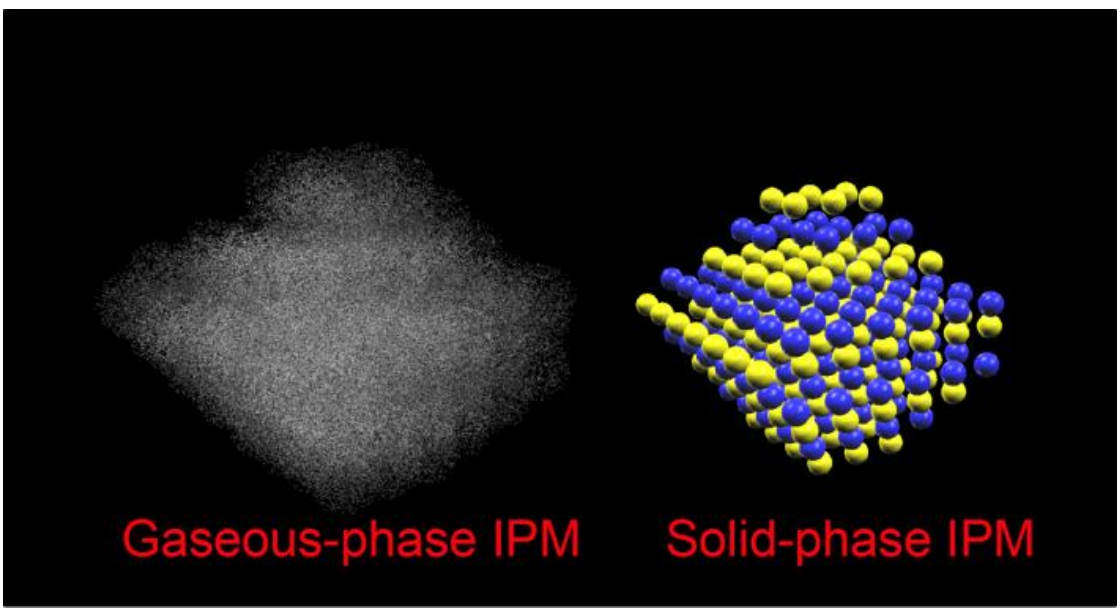

Figure 1. Mean-field assumptions about the nuclear force *vs* complex (but computable) solid-geometry.

The NLEFT runs contrary to the long-established dominance of the Copenhagen interpretation of quantum mechanics [1]. Although a "nuclear lattice" is not compatible with the Copenhagen interpretation of quantum mechanics, calculations using a lattice of nucleons produce unprecedented precision. Meissner's "Nuclear Lattice Theory" has opened the gates in conventional nuclear theory for discussion of the femto-level structure of individual isotopes. Similar to the revolution in chemistry (~1850), nuclear theorists have begun to study the internal geometry of the nucleus.

By assuming the localization of nucleons to rather small intranuclear volumes ($x < 2$ fm), the Copenhagen interpretation implies a very low uncertainty in position associated with high uncertainty in angular momentum. In other words, it is not only the capability to *measure* simultaneously conjugate variables that is restricted, but there are restrictions on what properties the particles themselves might have.

As a consequence, non-Copenhagen theoretical assumptions that have previously been considered "unconventional", at best, and "pre-modern", at worst, are now routinely made as a computational necessity in NLEFT. Moreover, the award by the European Physical Society of the Lise Meitner Award in Nuclear Physics to Ulf Meissner in 2016 for such theoretical work [2] is a clear indication that rigorous, numerical reproduction of experimental data trumps all considerations of philosophical "purity".

We have followed Meissner's lead in making unconventional lattice calculations of nuclear binding energies and magnetic moments, and found good results that compare favorably with far more (but unnecessarily) complex theoretical results from nuclear models that are consistent with the Copenhagen interpretation of quantum mechanics.

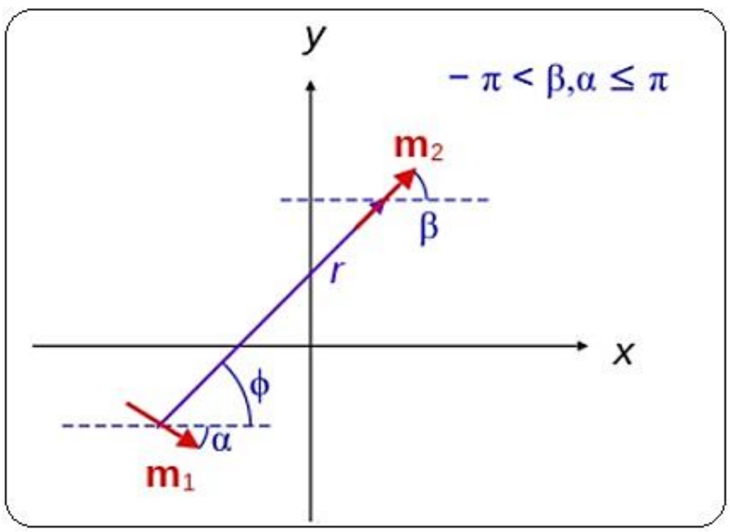

Figure 2. Calculations from classical electromagnetic theory applied to the nucleon dipoles in the n-body problem of nuclear structure [3].

The new developments in nuclear physics are a "renaissance" because low-energy nuclear phenomena can be explained using classical electromagnetic theory. The symmetries of an fcc lattice of nucleons are identical to those of the well established IPM. Distances and angles among all pairs of nucleons are known. This means that it is possible to:

i) calculate nuclear binding energies from the local interactions among nucleons;

ii) calculate excited states from transitions of nucleons from one lattice site to another;

iii) calculate the magnetic dipole and quadrupole moments of all even-odd, odd-even and odd-odd isotopes.

The theoretical tools of electromagnetism can be used to reconstruct nuclear structure theory:

a) *nuclear binding energies*: near-neighbor ($1^{st} \sim 7^{th}$) magnetic effects of ~ ± 0 - 5 MeV per nucleon-nucleon bond suffice to account for nuclear binding energies across the periodic chart;

b) *nuclear magnetic moments*: the summation of proton and neutron magnetic dipoles in a lattice reproduces the known nuclear magnetic moments.

The quantum mechanical description of all nucleon states is identical in both models, but the lattice model has explicit geometrical constraints that are not found in a gas. Every nucleon in the fcc lattice has a unique set of Cartesian coordinates, from which its unique set of quantum numbers can be calculated.

The known nucleon radius and the known density of nucleons in the nuclear interior have structural implications for the "independent-particle model" (IPM). By taking each nucleon to be a magnetic dipole of known strength, nuclear binding energies and nuclear magnetic dipoles can be calculated (Figure 2).

2. THE NUCLEAR CASE

Following the work on the "in-phase Biot-Savart magnetic attraction between rotating fermions" [4-6], we have calculated:

1) the nuclear binding energies of all stable/near-stable isotopes;

2) the magnetic moments of all stable odd-even, even-odd, and odd-odd isotopes whose magnetic moments have been experimentally measured.

By specifying the positions of nucleons within a close-packed nucleon lattice, every nucleon is assigned a set of quantum numbers (*n, l, j, m, i, s*, and parity) based solely on its Cartesian coordinates. This quantal description of nucleons in the lattice is isomorphic with the symmetries known from the independent-particle model (IPM, ~shell model) of conventional nuclear structure theory. A realistic nuclear force is typically modeled in NLEFT using 40-50 adjustable parameters, but the magnetic interaction between nucleons can be modeled with just 2 parameters, leading to vast improvements in nuclear binding energy and magnetic moment predictions, relative to the traditional shell model calculations.

Finally, we show that LENR transmutation data on Lithium, Nickel, and Palladium isotopes can be simulated using the nuclear lattice and the magnetic nuclear force. Because of the identity between the gaseous-phase IPM and the fcc lattice [7-9], lattice explanations of transmutation effects provide a direct link to conventional nuclear theory (Figure 3).

Neighbor in fcc Lattice	Type of Bond (isospin and spin)	Lattice Distance	Nuclear Distance (in femtometers)
1st	NN↑↓ PP↑↓ PN↑↓ PN↑↑	$\sqrt{8}$ = 2.828427	2.02620
2nd	NN↑↑ PP↑↑	$\sqrt{16}$ = 4.0	2.86548
3rd	NN↑↓ PP↑↓ PN↑↓ PN↑↑	$\sqrt{24}$ = 4.898979	3.50948
4th	NN↑↑ PP↑↑	$\sqrt{32}$ = 5.656854	4.05240
5th	NN↑↓ PP↑↓ PN↑↓ PN↑↑	$\sqrt{40}$ = 6.324555	4.53072
6th	NN↑↑ PP↑↑	$\sqrt{48}$ = 6.928203	4.96316
7th	PN↑↓ PN↑↑	$\sqrt{54}$ = 7.348469	5.26422

Figure 3. Lattice dimensions [9].

We conclude that funding of LENR research should focus on the basic experimental science of isotopic transmutation effects, regardless of their possible technological utility. Once the empirical data are unambiguous, *ab initio* computational simulations become possible.

The phase-state of nuclear matter remains a controversial topic. Already in the 1930s, a "Fermi gas" model of nuclear structure was suggested, followed by the liquid-drop model (LDM) of Bohr, Gamow and Wheeler. Also in the 1930s, the first alpha-cluster models for 4n-nuclei (^{4}He, ^{8}Be, ^{12}C, ^{16}O) were published, eventually including all of the other, stable 4n-nuclei (^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}A and ^{40}Ca). By the late 1940s, the implicitly gaseous-phase independent-particle model (IPM) had become the central paradigm in nuclear structure theory, while liquid- and solid-phase models retained advantages for certain nuclear phenomena.

While these three classes of model each has its numerical strengths, the notion that the atomic nucleus is simultaneously a liquid, gas and a molecular solid was an obvious absurdity that has not disappeared from textbook discussions of nuclear structure in subsequent decades. Although not advocated explicitly as a model of nuclear structure "per se", it is of some interest that in 1937 Wigner pointed out that the symmetries of the nuclear Hamiltonian (i.e., the full set of nucleon states as specified in the nuclear version of the Schrödinger wave equation) are those of a particular (face-centered-cubic) crystalline lattice, effectively adding a fourth (solid-phase) model of the texture of nuclear matter (N=Z).

Unlike the amorphous structures implied by liquid- or gaseous-phases, the nucleon lattice specified by Wigner implies that the relative positions and orientations of all nucleons in stable nuclei are precisely defined and, in principle, that the subnuclear geometry can be used to calculate various nuclear properties. We have, in fact, developed the fcc lattice of nucleons as a model of nuclear structure, and shown that its numerical results concerning nuclear size, shape, density, etc. compare well with the 30+ other models of nuclear structure developed throughout the 20th century.

Today nuclear "modeling" has the rather well-deserved reputation of being little more than "data-fitting", i.e., the adjustment of model parameters, isotope-by-isotope, to reproduce experimental data, while contributing little or nothing to the fundamental, unresolved issue of the nature of the nuclear force that holds nuclei together. In the present paper, we address the question of the nuclear force acting between nucleons in a close-packed nuclear lattice.

3. THE NEW WAY TO USE THE BIOT-SAVART LAW

The Biot-Savart law allows one to calculate the magnetic field generated by electric currents. A possible magnetic origin of the nuclear force is typically dismissed as unimportant since the potential energy derived from the Biot-Savart law is one or two orders of magnitude smaller than required. Because of the effects of the inverse of the distance between coils, this gap is not altered even when the higher-order terms in the Biot-Savart expansion are included.

Using that law, the mutual force between coils is obtained as due to the contribution of infinitesimal length elements, *ignoring any phase relation between the currents*.

If, however, phase relations are brought into consideration, the situation changes radically. Considering the magnetic force between two coils with currents having a definite phase relation in the same approximation of large distances between the coils, we get a modified potential energy.

4. TECHNICAL DETAILS

We consider two circular coils (1) and (2), in which circulate the currents i_1 and i_2, respectively. Let R be the common radius of the coils that are placed within a canonical orthogonal Cartesian coordinate system (xyz). We consider two cases:

(a) the coils in two parallel planes;

(b) the coils in the same plane.

(a) Coil 1 lies in the plane (xz), while coil 2 is in a parallel plane at a distance y. The circulating current in circuit 1 generates in the surrounding space a magnetic field (by the Biot-Savart law) given by:

$$\vec{B}_1 = \frac{\mu_0\, i_1}{4\pi} \int_{C_1} \frac{d\vec{l} \times \vec{r}}{r^3} \tag{1}$$

where r is the distance between the infinitesimal vector ***dl*** of the circuit and the point at which the field ***B*** is estimated. Circuit 2, under the action of field $\boldsymbol{B}_1$, is affected by the force (for the Laplace law):

$$\vec{F} = i \int_{C} d\vec{l} \times \vec{B} \tag{2}$$

Considering Eqs. (1) and (2), the force perceived at coil 2 under the action of the field generated from coil 1 is given by:

$$\vec{F}_{12} = \frac{\mu_0\, i_1\, i_2}{4\pi} \int_{C_2} d\vec{l}_2 \times \int_{C_1} \frac{d\vec{l}_1 \times \vec{r}_{12}}{r_{12}^3} \tag{3}$$

Let $P_1 = (x_1, 0, z_1)$ be a generic point of the coil 1 and $P_2=(x_2, y, z_2)$ a generic point of the coil 2 (Figure 4). In the chosen reference system, considering the axes versors $\boldsymbol{i}$, $\boldsymbol{j}$, $\boldsymbol{k}$ and the vector property:

$$\vec{a} \times \left(\vec{b} \times \vec{c}\right) = (\vec{a} \cdot \vec{c})\vec{b} - \left(\vec{a} \cdot \vec{b}\right)\vec{c}\ , \tag{4}$$

Eq. (3) can be rewritten in the form:

$$\vec{F}_{12} = \frac{\mu_0\, i_1\, i_2}{4\pi} \int_{C_1}\int_{C_2} \frac{d\vec{l}_2 \cdot \vec{r}_{12}}{r_{12}^3}\, d\vec{l}_1 - \frac{d\vec{l}_2 \cdot d\vec{l}_1}{r_{12}^3}\, \vec{r}_{12}\ . \tag{5}$$

The first part of Eq. (5) is zero, being the integral of a gradient extended to a closed line. It remains therefore:

$$\vec{F}_{12} = -\frac{\mu_0\, i_1\, i_2}{4\,\pi} \int_{C_1}\int_{C_2} \frac{d\vec{l}_2 \cdot d\vec{l}_1}{r_{12}^3}\, \vec{r}_{12} \quad . \tag{6}$$

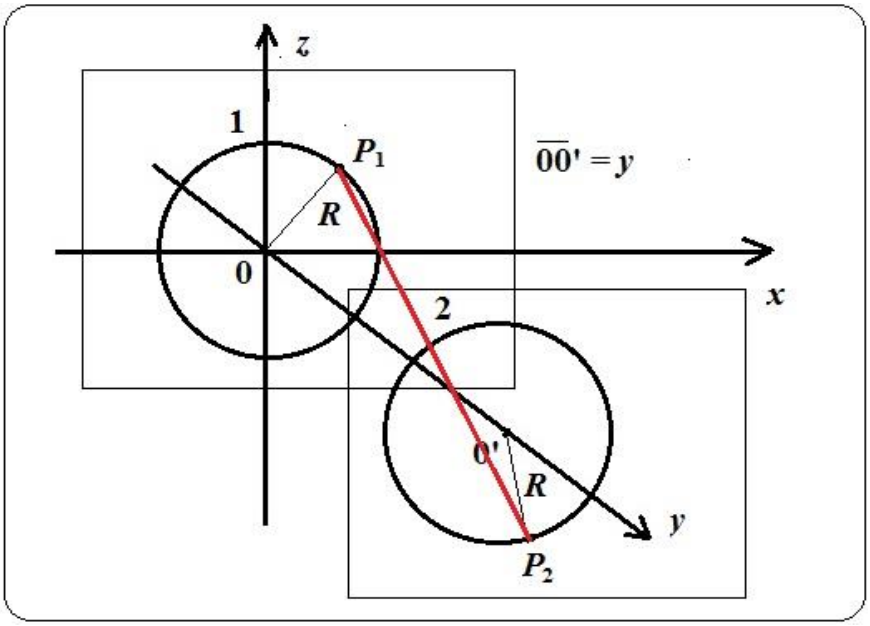

Figure 4. The case of coils in parallel planes.

With further algebra it is possible to rewrite Eq. (6) in the form:

$$\vec{F}_{12} = -\frac{\mu_0\, i_1\, i_2}{4\,\pi} \Big(\vec{i} \int_{C_1}\int_{C_2} \frac{(x_2 - x_1)\,(dx_1\, dx_2 + dz_1\, dz_2)}{\left((x_2 - x_1)^2 + y^2 + (z_2 - z_1)^2\right)^{3/2}} + $$
$$+ \vec{j} \int_{C_1}\int_{C_2} \frac{y\,(dx_1\, dx_2 + dz_1\, dz_2)}{\left((x_2 - x_1)^2 + y^2 + (z_2 - z_1)^2\right)^{3/2}} + \vec{k} \int_{C_1}\int_{C_2} \frac{(z_2 - z_1)\,(dx_1\, dx_2 + dz_1\, dz_2)}{\left((x_2 - x_1)^2 + y^2 + (z_2 - z_1)^2\right)^{3/2}} \Big) \quad . \tag{7}$$

Considering now cylindrical coordinates and the binomial series of the denominator, up to the first order, we can write:

$$\frac{1}{(y^2 + 2\,R^2\,(1 - \cos(\phi_1 - \phi_2)))^{3/2}} \cong \frac{1}{y^3}\left(1 - \frac{3\,R^2}{y^2}\,(1 - \cos(\phi_1 - \phi_2))\right) \quad , \tag{8}$$

then Eq. (7) becomes:

$$\vec{F}_{12} = -\frac{\mu_0\, i_1\, i_2}{4\,\pi}\, \frac{6\,\pi^2\, R^4}{y^4}\, \vec{j} \; . \tag{9}$$

The force (9) has intensity:

$$\left|\vec{F}_{12}\right| = \frac{3}{2}\frac{\mu_0\, i_1\, i_2\, \pi\, R^4}{y^4} \quad . \tag{10}$$

If we consider now Eq. (7) in the hypothesis that the two currents are in phase (Figure 5), the same calculation gives the results:

$$\vec{F}_{12\,ph} = -\frac{\mu_0\, i_1\, i_2\, \pi\, R^2}{y^2}\,\vec{j} \quad ; \tag{11}$$

$$\left|\vec{F}_{12\,ph}\right| = \frac{\mu_0\, i_1\, i_2\, \pi\, R^2}{y^2} \quad . \tag{12}$$

The comparison between Eqs. (10) and (12) gives:

$$\left|\vec{F}_{12\,ph}\right| = \frac{2}{3}\left(\frac{y}{R}\right)^2 \left|\vec{F}_{12}\right| \quad . \tag{13}$$

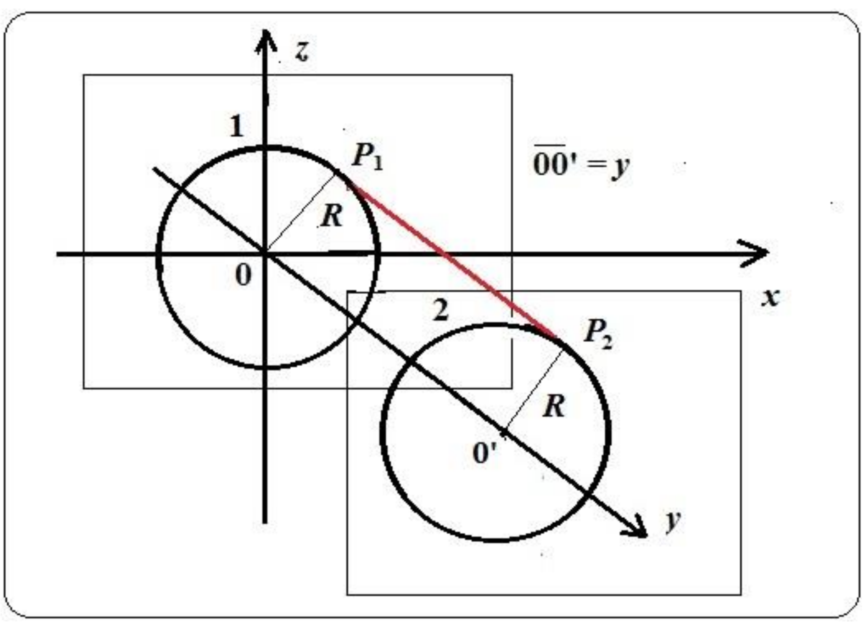

Figure 5. The case of coils in parallel planes with currents in phase.

(b) We consider the two coils placed in the same plane, for example (*xz*). If P_1 is the generic point of coil 1 and P_2 that of coil 2, and *d* is the distance between the two centers, it is $x_1 = R\cos\phi_1$, $z_1 = R\sin\phi_1$, $x_2 = d + R\cos\phi_2$, $z_2 = R\sin\phi_2$ (Figure 6).

Using the same procedure as the case (a), we get:

$$\left|\vec{F}_{12}\right| = \frac{3\,\mu_0\, i_1\, i_2\, \pi\, R^4}{d^4}\;; \tag{14}$$

$$\left|\vec{F}_{12\,ph}\right| = \frac{\mu_0\, i_1\, i_2\, \pi\, R^2}{d^2}\;; \tag{15}$$

$$\left|\vec{F}_{12\,ph}\right| = \frac{1}{3}\left(\frac{d}{R}\right)^2 \left|\vec{F}_{12}\right|\,. \tag{16}$$

The corresponding energies are respectively:

(a) coils on two parallel planes:

$$E = \frac{\mu_0\, \mu_1\, \mu_2}{2\,\pi\, y^3}\,, \tag{17}$$

$$E_{ph} = \frac{\mu_0\, \mu_1\, \mu_2}{\pi\, R^2\, y}\,. \tag{18}$$

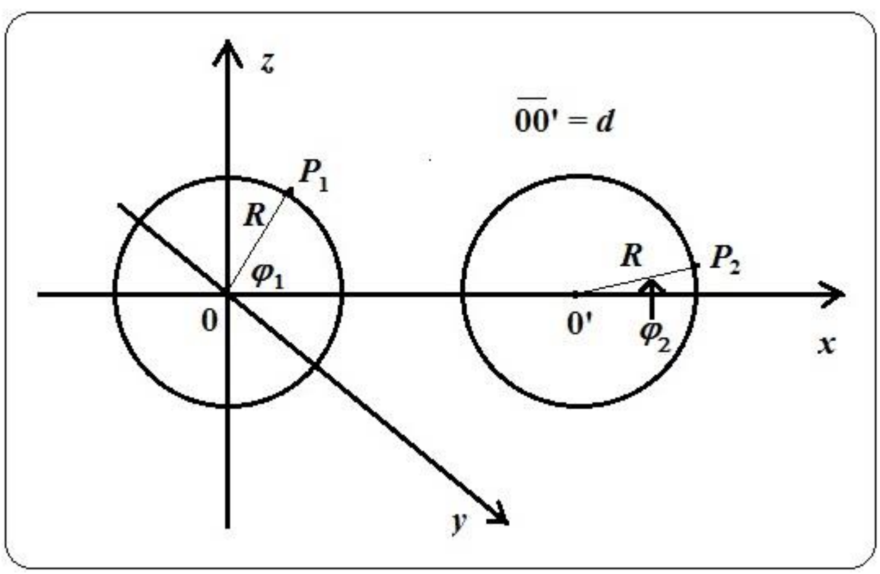

Figure 6. The case of coils in the same plane.

(b) coils in the same plane:

$$E = \frac{\mu_0\, \mu_1\, \mu_2}{\pi\, x^3}\,, \tag{19}$$

$$E_{ph} = \frac{\mu_0\,\mu_1\,\mu_2}{\pi\,R^2\,x}\,, \tag{20}$$

with in evidence the magnetic moments [4].

5. RESULTS AND DISCUSSION

As first example, we consider the case of two nucleons placed at a distance y = 2 fm; keeping into account the nuclear magneton value $\mu_N = 5.0432 \cdot 10^{-27}$ J/T and considering the nucleon radius R = 0.5 fm, energies (17,18) are respectively:

$$E\;=\;3.97\text{ KeV};\qquad E_{ph} = 0.127\text{ MeV}.$$

Introducing an appropriate exponential phase factor, of the form “exp (- l r)”, Eqs (18) and (20) can be rewritten as:

$$E_{ph}(r) = \frac{\mu_0\,\mu_1\,\mu_2}{\pi\,r^2\,y}\,e^{-\lambda r}\,, \tag{21}$$

$$E_{ph}(r) = \frac{\mu_0\,\mu_1\,\mu_2}{\pi\,r^2\,x}\,e^{-\lambda r}\,. \tag{22}$$

In Table 1 we have summarized the values of E_{ph} for different combinations of values of x, y and R.

Table 1. Values of E_{ph} corresponding to different R of coils and distances x and y.

Case (a)			Case (b)		
y (fm)	R (fm)	E_{ph} (MeV)	x (fm)	R (fm)	E_{ph} (MeV)
0.5	0.2	1.98	2	0.1	3.19
1	0.2	1.59	2	0.2	0.80
1.5	0.2	1.06	2	0.3	0.35

In Table 2 we calculated the tuning factor values (in absolute value) for fixed R, binding energies and distance among coils.

Table 2. Tuning factor values for fixed *R*, binding energies and distance among coils.

Case (a)				Case (b)			
y (fm)	*R* (fm)	*Binding energy* (MeV)	*Tuning factor* (m^{-1})	*x* (fm)	*R* (fm)	*Binding energy* (MeV)	*Tuning factor* (m^{-1})
1.0	0.2	3.0	3.18×10^{15}	2.0	0.2	3.0	6.65×10^{15}
1.0	0.4	2.0	4.04×10^{15}	2.0	0.4	2.0	5.78×10^{15}
1.0	0.6	1.0	2.89×10^{15}	2.0	0.6	1.0	4.05×10^{15}
1.0	0.8	0.5	2.02×10^{15}	2.0	0.8	0.5	2.89×10^{15}

Clearly, an attractive magnetic energy of only 4 keV obtained from the classical Biot-Savart interaction without consideration of the phase relation would be only a small contribution to nuclear binding energies, but 0.13 MeV between nearest neighbors is already a significant percentage of the mean nuclear binding in either the context of the LDM or the fcc lattice.

Specifically, default structures for ^{90}Zr, ^{200}Hg, and ^{238}U lattice nuclei have, respectively, 370, 865, and 1036 nearest-neighbor interactions, corresponding to mean energies of 2.1, 1.8, and 1.7 MeV (per nearest-neighbor "bond"). In other words, the "untuned" magnetic effects are only one (not three) orders of magnitude too weak to account for nuclear binding energies.

The "tuned" magnetic effects obtained by adjusting the factor in the phase relation between the rotating charges allows for magnetic attraction of several MeV. Clearly, the validity of the results depends crucially on the three variables *R*, *x*, *y*. Note that a center-to-center internucleon distance of approximately 2.0 fm gives a core nuclear density of 0.17 nucleons/fm^3. This value is the nuclear core density that is normally cited in the textbooks since the electron-scattering experiments of Hofstadter in the 1950s, but somewhat larger values (0.13 ~ 0.16) for the "mean" density (core plus skin region) are also cited in the literature [10]. Similarly, the nucleon RMS radius for both protons and neutrons is known experimentally to be ~ 0.88 fm [7]. Nevertheless, the nuclear dipole that results in the magnetic moments of 2.79 and -1.91 μ, respectively, might have dimensions somewhat different from the matter distribution within the nucleon, so that calculations of magnetic force effects over a broad range of dipole sizes are relevant.

If we consider now the case (a) (analogous calculations can be made for case (b)) and make the assumption about the nucleon dipole:

$$R = y = 0.2333 \text{ fm},$$

it follows that the magnetic interaction between two protons, two neutrons, or one proton and one neutron is 5 MeV; the short-range nuclear force with various spin and isospin combinations can explain the basic trend in nuclear binding energies.

With the adjustement above, we can conclude that the magnetic nuclear force is sufficient to explain nuclear binding. Binding effects (5MeV) among neighboring nucleons are enough to achieve binding for 273 isotopes built in the fcc software, implying that a magnetic nuclear force is consistent with the lattice model [9].

6. CONCLUSIONS

Funding of LENR research should focus on the basic experimental science of isotopic transmutation effects, regardless of their possible technological utility. Once the empirical data are unambiguous, *ab initio* computational simulations should become possible.

We have developed the fcc lattice of nucleons as a model of nuclear structure, showing that its numerical results concerning nuclear size, shape, density, etc. compare well with the 30+ other models of nuclear structure developed throughout the 20th century. To date, "nuclear modeling" contributes little or nothing to the fundamental unresolved issue of the nature of the nuclear force holding nuclei together. In the present work, we addressed the question of the nuclear force acting between nucleons in a close-packed nuclear lattice. The validity of results depends crucially on the three variables R, x, y. A center-to-center internucleon distance of approximately 2.0 fm gives a core nuclear density of 0.17 nucleons/fm^3, nuclear core density normally cited in the textbooks since the electron-scattering experiments of Hofstadter in the 1950s (somewhat larger values (0.13 ~ 0.16) for the "mean" density (core plus skin region) are also cited in the literature).

Similarly, the nucleon RMS radius for both protons and neutrons is known experimentally to be ~ 0.88 fm. Nevertheless, the nuclear dipole that results in the magnetic moments of +2.79 and -1.91 μ, respectively, might have dimensions somewhat different from the matter distribution within the nucleon, so that calculations of magnetic force effects over a broad range of dipole sizes are relevant.

The followed way, with the novelty of the "particular use" of the Biot-Savart law, is therefore a possible solution to the 80 years old problem of the nuclear force [11].

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Biography

Paolo Di Sia is currently adjunct professor by the University of Padova (Italy). He obtained a bachelor in metaphysics, a master in theoretical physics and a PhD in theoretical physics applied to nanobiotechnology. He interested in classical-quantum-relativistic nanophysics, theoretical physics, Planck scale physics, metaphysics, mind-brain science, history and philosophy of science, science education. He is author of 260 works to date (papers on national and international journals, international book chapters, books, internal academic notes, works on scientific web-pages, popular works, in press), is reviewer of two mathematics academic books, reviewer of 12 international journals. He obtained 13 international awards, has been included in Who's Who in the World every year since 2015, selected for 2017 and 2018 "Albert Nelson Marquis Lifetime Achievement Award", is member of 10 scientific societies and of 32 International Advisory/Editorial Boards.
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