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Research Article

LENR and Nuclear Structure Theory

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Abstract

The significance of LENR research for understanding nuclear structure is discussed. In stark contrast to atomic-level Quantum Electrodynamics (QED), nuclear theory has remained a collection of mutually exclusive "models" lacking a rigorous foundation. We argue that LENR indicates the way forward to a quantitative theory of nuclear structure, Quantum Nucleodynamics (QND).

Keywords: LENR, Nuclear structure theory, Piezonuclear fission, Quantum nucleodynamics

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1. Introduction

The technological potential of LENR remains strong and progress in achieving experimentally stable LENR environments has recently been reported. Those developments are to be welcomed and should eventually lead to the long-awaited funding required for both basic and applied research. But, in light of experimental progress, the theoretical implications of LENR research for nuclear physics, in general, also deserve some attention.

LENR theorists have devoted most of their efforts to the explanation of mechanisms that would allow for the phenomena of "cold fusion." What has not yet been studied is the significance of LENR for conventional nuclear physics. Here, we argue that LENR already indicates the direction in which progress in nuclear structure theory can be anticipated.

Three distinct aspects of nuclear theory are examined: (1) unanswered questions in conventional nuclear theory related to the nuclear force, (2) certain experimental findings in LENR research, and (3) the integration of LENR findings into conventional nuclear structure theory in the form of Quantum Nucleodynamics (QND).

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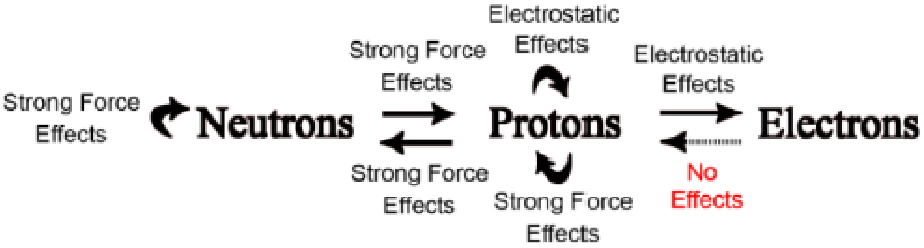


Figure 1. The central dogma of atomic physics (ca. 1932), where proton-electron attraction could be explained in terms of classical electrostatic theory, while the strong force effects were essentially new and inexplicable.

2. The Nuclear Force

No topic in nuclear physics is as important as that of the nuclear force. Already by the early 1930s, it was apparent that an extremely strong binding force allows for the stability of nuclei containing numerous positively charged protons. In contrast, the peripheral electrons were found to interact predominantly with the nuclear protons through the much weaker electrostatic force. These indubitable facts led to the so-called "central dogma" of atomic physics (Fig. 1).

Starting in the 1950s with the growing availability of particle accelerators capable of focusing beams of particles on nuclei at high energies, it became possible to characterize the nuclear force with great precision.

Theoretical reconstruction of the nuclear potential measured in nucleon-nucleon scattering experiments has typically resulted in Lennard–Jones type potentials (Fig. 2), where there is a strongly repulsive force (at least several hundred MeV) at short distances (<1 fm), a weaker attractive force (50–100 MeV) at 1–2 fm, and only weak effects beyond 3 fm. These characteristics have been formalized in the so-called Argonne, Paris and Bonn potentials. As of today, their approximate validity (and their spin-, isospin- and distance-dependence) is well-established.

It is relevant to note, however, that the powerful nuclear potential contrasts markedly with what is known from relatively low-energy experiments on the structure of stable nuclei. Specifically, the total binding energies of the 800+ stable isotopes indicate an average binding energy of less than 8 MeV per nucleon. Moreover, the average energy per nucleon implies a nearest-neighbor nucleon–nucleon interaction of less than 3 MeV in the high-density nuclear core (the region inside the arrow in Fig. 2). In other words, MeV-range nucleon interactions in stable nuclei are many orders of magnitude *weaker* than the effects measured in high-energy scattering experiments and many orders of magnitude *stronger* than the average eV interactions of electrons with their nuclei.

While there is still no consensus concerning the theory of the nuclear force, the essence of the "central dogma" of atomic physics throughout the 20th century was two-fold: (1) protons have strong effects on the peripheral electrons (but not vice versa), and (2) neutrons have little direct contact with the extra-nuclear world (Fig. 1). In fact, a weak chemical influence on nuclear decay rates had also become known by the early 1960s [2–5], but generally the nuclear realm and the atomic (electron) realm are still thought to be energetically distinct. That dogma is directly challenged by LENR findings and, today, the primary obstacle to the acknowledgement of the experimental evidence for induction of nuclear reactions at low energies is the *dogmatic* assertion that extra-nuclear effects on nuclear dynamics are theoretically impossible.

Unrelated to the issues of LENR, we have developed a lattice model of nuclear structure that was initially an attempt to integrate the diverse threads of modern nuclear structure theory [1, 6–8]. The implications of the lattice model for nuclear structure theory per se have been published many times, and are briefly summarized in the Appendix. Of direct relevance to LENR are the dimensions of the lattice and its implications regarding the nuclear force. That is,

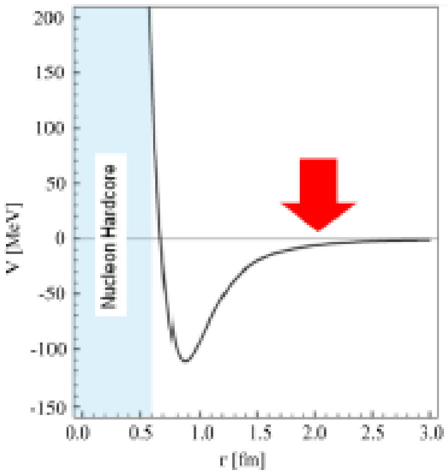


Figure 2. A realistic Lennard–Jones type nuclear potential deduced from nuclear scattering experiments. Small differences in the height, depth and distance of the potentials due to spin and isospin are known, but all such potentials have no effects beyond 3 fm. There is no doubt that the nuclear force is "short-range."

in a lattice of nucleons, nucleon interactions are fixed within a narrow range of 1.0–3.0 fm. At that range, we have found a significant magnetic effect that is a microscopic (femtometer-scale) version of the Biot–Savart law of magnetic attraction between parallel currents (Fig. 3).

Under the assumption that the magnetic moments of the proton and neutron are consequences of the rotation of a *single* positive or negative valence charge, respectively, a significant magnetic contribution to nuclear binding energies is found. The main difference from the Biot–Savart law of classical electromagnetic theory is that, in copper wire coils containing continuous streams of electron charges, phase effects of the movement of individual charges need not be considered. With only one charge in each nucleonic "coil," however, the magnetic interaction will necessarily depend strongly on the positions (phase relationship) of the two revolving charges – as they travel parallel or antiparallel relative to one another in their intra-nucleonic orbits. In effect, not only the distance and relative orientations of the magnetic poles, but also the phase relationship of the charge flow, determine the strength of the femto-scale magnetic interaction [9].

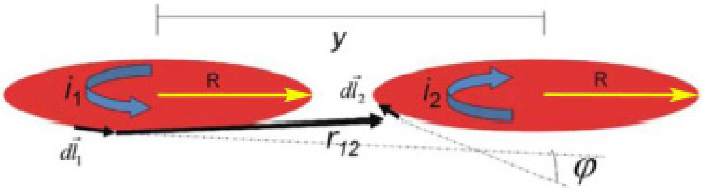


Figure 3. The magnetic force acting between two revolving charges depends not only on the distance and orientation of the electric currents, but also on their relative phases, φ [9].

The magnetic effects are attractive and repulsive for first and second neighbors in the lattice, respectively. That finding is consistent with the fact that the lattice model requires an *antiferromagnetic* ordering of nucleons in each isospin layer. Between layers of different isospin, there are necessarily both parallel and antiparallel nucleon pairs and differences in orientation of the magnetic dipole result in magnetic effects of varying magnitude. In this view, the magnetic force between nucleons is fundamentally short-range, because the dephasing of the charge "coils" with distance reduces the magnetic effects among distant neighbors. In effect the attractive magnetic force acts as a form of "strong screening" between like charges. These properties can be expressed by the force between two coils as, where ***r***12 designates the center-to-center distance between the coils and ***R*** is the coil radius.

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

In cylindrical coordinates

$$\vec{F}_{12} = \frac{\mu_0 i_1 i_2}{4\pi} \vec{j} \int\int \frac{yR^2 \cos(\varphi_1 - \varphi_2) d\varphi_1 d\varphi_2}{\left[(y^2 + 2R^2(1 - \cos(\varphi_1 - \varphi_2))\right]^{\frac{3}{2}}}$$

Note phases between currents

Expansion of the denominator

$$\left[(y^2 + 2R^2(1 - \cos(\varphi_1 - \varphi_2))\right]^{-\frac{3}{2}} = \frac{1}{y^{3}}(1 - \frac{3R^2}{y2}(1 - \cos(\varphi - \varphi)) + \ldots\ldots)$$

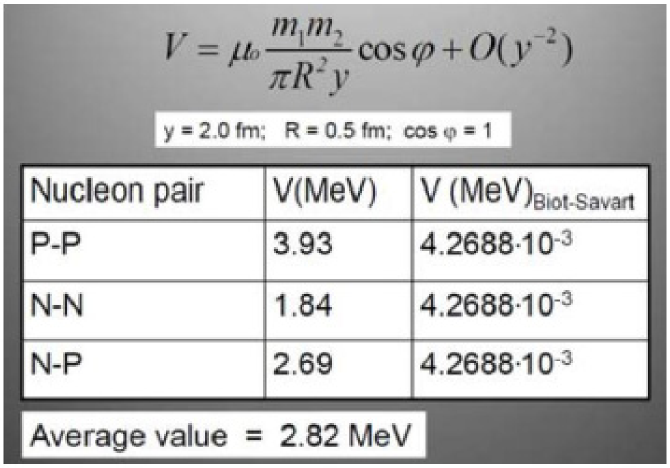
As summarized in Fig. 4, consideration of phase produces a strong increase well above the classical, Biot–Savart magnetic interaction between two circulating charges – leading to net attraction (repulsion) on the order of a few MeV at realistic internucleon distances of 1–3 fm. As we have previously reported [1], the mean nuclear binding force of nearest neighbor nucleons in the lattice is only 2.75–2.79 for nuclei as different as calcium, palladium and uranium. We therefore conclude that, regardless of the reality of pion-exchange binding effects and/or quark contributions, the magnetic effect alone is of sufficient strength to account for nuclear binding energies.

By definition, the clockwise rotation of negative charge gives an upward north pole, whereas similar rotation of a positive charge gives an upward south pole. The permutations of spin (up and down) and isospin (proton and neutron) result in the six fermi-level magnetic interactions shown in Fig. 5.

3. LENR

3.1. Magnetic effects

Some of the most interesting – and yet unexplained – findings in LENR research are indications that external magnetic fields can have a strong influence on heat generation. Letts and colleagues have reported [10] the ability to turn LENR excess heat-generation on-and-off simply by 90^o rotation of the cathode (not anode) with respect to an external magnetic field of 500 Gauss. The significance of that effect lies in the fact that, in terms of conventional physics, a magnetic field of that strength should have little influence on intranuclear dynamics, being orders of magnitude weaker than nuclear



$$V = \mu_o \frac{m_1 m_2}{\pi R^2 y} \cos\varphi + O(y^{-2})$$

$y = 2.0$ fm; $R = 0.5$ fm; $\cos\varphi = 1$

Nucleon pair	V(MeV)	V (MeV)$_{\text{Biot-Savart}}$
P-P	3.93	$4.2688 \cdot 10^{-3}$
N-N	1.84	$4.2688 \cdot 10^{-3}$
N-P	2.69	$4.2688 \cdot 10^{-3}$

Average value = 2.82 MeV

Figure 4. Summary of the strength of the magnetic attraction between nucleon pairs separated by 2.0 fm and lying in the same plane (as in Fig. 3). The classical Biot–Savart effect is weak, but, when phase is considered, there is an increase of three orders of magnitude in the strength of the magnetic interaction.

force effects. To the contrary, however, relatively low-energy changes in the magnetic environment have been shown to influence heat generation in LENR.

Questions remain unanswered concerning the location of the LENR effects that produce excess heat (the nuclear active environment, NAE, proposed by Storms [11]) and the mechanism of their susceptibility to magnetic fields, but manipulations of magnetic fields are clearly a promising direction for future LENR research.

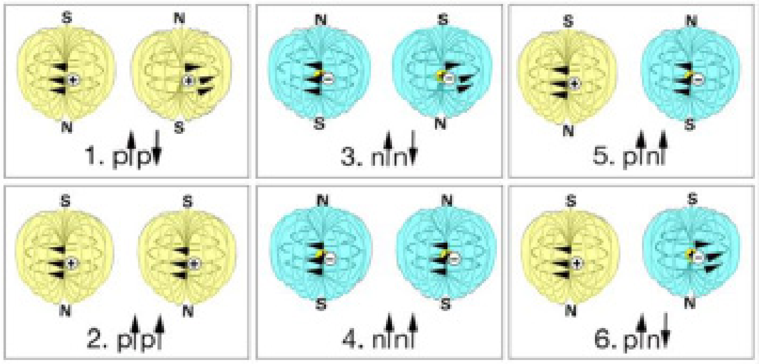


Figure 5. The six permutations of spin and isospin. The upper and lower rows show the attractive and repulsive magnetic interactions, respectively, at a center-to-center internucleon distance of 2.0 fm.

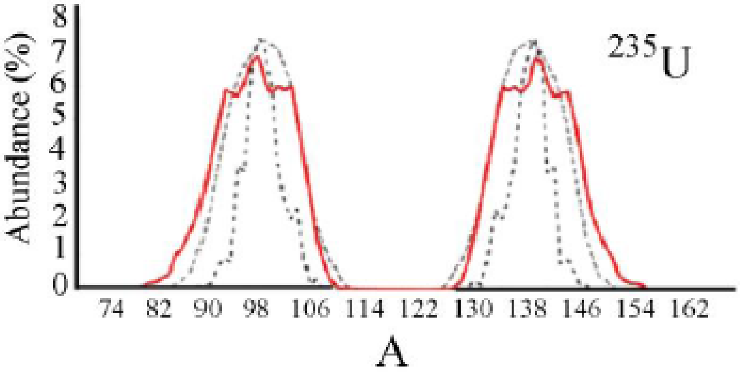


Figure 6. Results of the lattice simulation of thermal fission of ^{235}U. Lattice coordinates for nucleons in the nuclear core were fixed, while surface positions were occupied at random. The fission process was undertaken for each configuration along all available lattice planes and repeated for statistical study. The red lines are the experimental data, the dotted lines are the results of lattice simulations [1,19].

3.2. Transmutations

The most unambiguous indications of specifically nuclear involvement in "cold fusion" experiments are findings of nuclear transmutations. The appearance of elements in a reaction system where they are originally absent and/or measurement of abnormal isotopic ratios are decisive indications of nuclear effects [12,13]. As was true of early experiments on the fission of uranium in the 1930s, the possibility of contaminants must first be excluded, but the presence of unnatural isotopic ratios is alone indication of nuclear reactions. Both unnatural isotopic ratios and the presence of unanticipated elements in uncontaminated LENR experiments have been reported in several dozen LENR

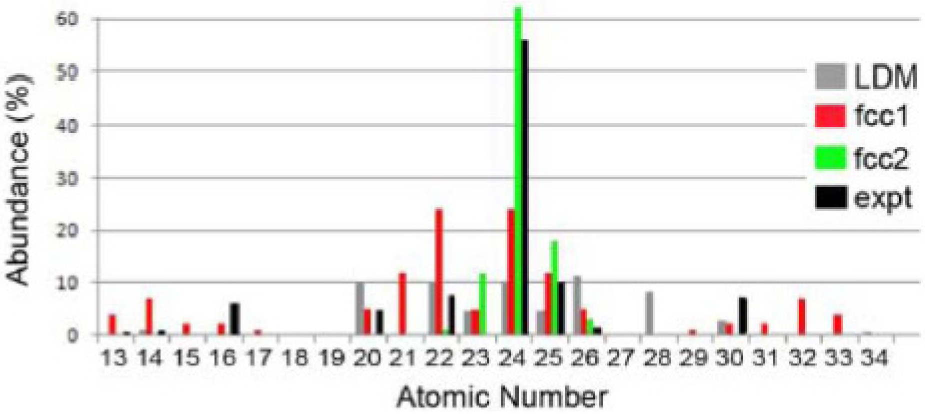


Figure 7. A comparison between the experimental findings on the low-energy fission of palladium and several theoretical models [1]. The liquid-drop model (LDM, grey lines) fails to account for the dominance of fragments at Z = 22 to 25. Qualitatively better results are obtained in lattice simulations where the deuterium triggers the fission but does not bind to either fragment (fcc1, red lines) and where the deuterium triggers the fission and binds to fragments (fcc2, green lines). Experimental data (black lines) from Mizuno [12].

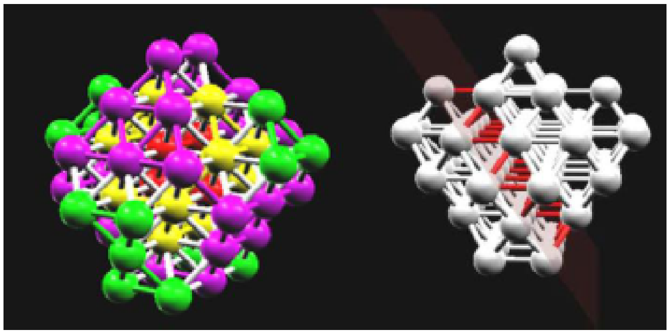


Figure 8. The lowest-energy lattice structure of ^{56}Fe that is consistent with the known IPM structure of this isotope. On the left is shown the color-coded ^{56}Fe nucleus (16 green nucleons on the surface of the doubly-magic ^{40}Ca nucleus). On the right is shown the lattice simulation of a low-energy fission plane, leading to stable daughter isotopes (^{27}Al and ^{29}Si). (The NVS software is available at [27].)

studies [11]. Unfortunately, the physical mechanisms underlying nuclear transmutations in LENR remain obscure and, primarily because of political, rather than experimental difficulties, their implications for nuclear structure theory have not been thoroughly explored. But the obvious needs to be stated: if nuclear transmutations can be elicited in the experimental conditions of LENR research, much of modern nuclear structure theory will need to be rewritten.

3.3. Piezonuclear fission

Over the past four years, Carpinteri and colleagues have reported on a new form of LENR. On the basis of geological findings and laboratory experimental studies, they have argued that a previously unknown type of solid-state nuclear fission has occurred in iron-containing rocks over geological time, and can be induced in high-impact compression experiments [14–18]. They report that a 2–4-fold increase in neutron emission over normal background levels has been consistently found in otherwise-conventional experiments on the tolerance of granite and other familiar rocks subjected to high pressure impact. Insofar as background neutron radiation is normally produced by the spontaneous fission of small amounts of radioactive elements, Carpinteri surmised that the non-radioactive elements in their samples were undergoing fission due to compression.

That hypothesis was confirmed in subsequent laboratory tests in which both neutron emission and nuclear “ash” suggestive of the fission of iron were found. Carpinteri has emphasized the geological significance of their findings and,

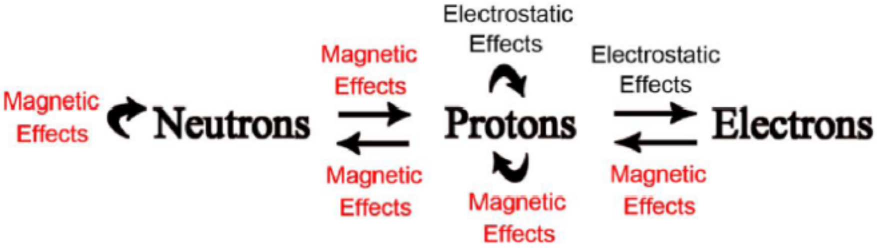


Figure 9. The modern “central dogma” of atomic physics implied by lattice calculations of magnetic effects [9] and magnetic field manipulations in LENR experiments [10].

like most LENR researchers, he has not speculated on the underlying nuclear mechanisms, but again the implication is that nuclear reactions can be induced at relatively low energies. Clearly, if low-level fission of the elements in the Earth's crust has occurred over geological time, there should be indication of elemental and isotopic changes. That is indeed the case in well-established geological findings on the distribution of elements on the Earth's surface. Specifically, a depletion of iron isotopes, together with an excess of magnesium, aluminum and silicon isotopes, in certain geological locations is circumstantial evidence of low-energy fission of iron nuclei, with the accumulation of nuclear "ash" corresponding to the binary fission of iron. Confirming results were then obtained along the compression fissures in rock samples undergoing laboratory tests: increases in background neutron counts, a decrease in the abundance of iron isotopes, together with an increase in magnesium, silicon and potassium isotopes. Their conclusion is that LENR effects – unrelated to the more usual palladium and nickel electrolytic findings of cold fusion research – result in the fission of iron, and the deposit of daughter fragments. An understanding of the significance of the Carpinteri results for both geology and LENR has only recently begun.

4. Putting LENR and the Magnetic Nuclear Force Together

While the focus of most experimental and theoretical LENR research has, for obvious reasons, been on the factors that lead to the production of excess heat in "table-top" LENR experiments, the *theoretical* implications of LENR are potentially revolutionary for nuclear structure physics, in general. Alone, the reconfiguration of nuclear structure theory within the framework of a lattice model (a "frozen liquid-drop") would appear to have little relevance for theoretical developments in LENR, but the nuclear force properties that are implied by the lattice may be important.

The original claim of the lattice model was simply that a mathematical isomorphism exists between the entire set of nucleon states (as described in the independent-particle model, IPM) and a specific lattice (see the Appendix for a summary and literature references). The significance of the isomorphism lies in the fact that, unlike the gaseous phase models of the nucleus (the conventional Fermi gas, shell model and IPM), there is a precise geometrical configuration of nucleons in the lattice version of the IPM. As a direct consequence of that geometry, any quantum mechanical nuclear state that can be described in the IPM necessarily has a structural analog in the lattice. That fact, in turn, implies that the entire set of local nucleon-nucleon interactions for any given number of protons and neutrons in the lattice can be calculated. It is the precise, quantitative nature of nucleon interactions that distinguishes the lattice version of the IPM from the gaseous version.

Although the relevance to LENR studies is not obvious at first glance, there are two main arguments that suggest a deep connection between the lattice model and LENR. The most important point, in terms of nuclear structure theory, is the fact that the lattice IPM lends itself to implementation of a fully realistic nuclear force at the dimensions of the lattice, with no need to postulate a gaseous nuclear interior or a fictitious, long-range "effective" nuclear force unlike the force that is known experimentally. Since a nearest-neighbor internucleon distance of 2.026 fm in the lattice gives the nuclear core density of 0.170 nucleons/fm^3 and reproduces nuclear charge radii and binding energies [1], the magnitude of the nuclear force at specifically 2.0 fm becomes crucial. Examination of magnetic effects at that scale (Section 2) clearly shows the relevance of femto-magnetic phenomena for explaining total nuclear binding energies.

The second, more direct, connection between the lattice model and LENR is found in the simulation of LENR phenomena using the lattice structures for specific nuclei, notably palladium and iron isotopes. While the energetic basis for all forms of LENR remains a theoretical puzzle, the specific types of nuclear "ash" that have been reported find relatively straight-forward explanations in terms of fission products, as deduced from systematic severing of nuclei along lattice planes.

Lattice simulations began with the thermal fission of uranium and plutonium isotopes [19], where the lattice structures were shown to produce asymmetrical fission fragments close to the 3:2 ratio that is known experimentally (Fig. 6). Notably, unlike the conventional liquid-drop and shell model explanations of asymmetrical fission, the lattice results are produced *without* the use of an "asymmetry parameter" or other adjustable parameters of the nuclear potential well that are typically used to reproduce experimental findings. On the contrary, the asymmetrical fragments produced in the lattice model are a direct consequence of the lattice geometry itself, insofar as certain oblique planes passing through the actinide structures are energetically favored because they contain fewer nearest-neighbor bonds that cross the fission plane than vertical or horizontal planes.

Using the same lattice fission technique as used for the actinides, the simulation of the fission of the palladium isotopes (with a deuteron added at random to surface positions) produces approximately symmetrical fission fragments (Fig. 7). The rough agreement with the transmutation data published by Mizuno [12] is apparent. Again, "fission parameters" adjusted to reproduce the experimental data are *not* needed. While the energetic basis for the presumed fission of palladium remains unclear in LENR, the findings on the masses of the isotopes in the nuclear "ash" are consistent with the lattice model.

Finally, the newest of the LENR fission results are those of Carpinteri and colleagues [14–18]. Their basic finding is that there is a depletion of iron isotopes specifically along the fracture planes that are revealed in the high-pressure compression "failure" of granite and similar rocks. Together with isotopic analysis that reveals an excess of magnesium, aluminum and silicon along those same planes, they have argued that there is strong circumstantial evidence for the piezonuclear fission of iron (Z = 26), the production of daughter fragments (Z = 12 to 14) and low-level neutron radiation. Again, questions about mechanisms remain unanswered, but the phenomenology is consistent with nuclear fission.

Using the lattice model for the fission of iron isotopes, prediction of the high- and low-probability planes along which nuclear fission may occur is straightforward. As shown in Fig. 8, the lowest energy (maximal compactness) lattice structure for ^{56}Fe that is consistent with the lattice model can be fractured along 17 lattice planes that pass through or near the nuclear center. Already at this relatively gross level, the lattice model indicates an abundance of $Z = 12$ to 4 stable isotopes as the products of fission along nuclear lattice planes. Simulation results are summarized in Table 1.

Table 1. The main products generated by fission of ^{56}Fe along lattice planes using the NVS software

Fragment 1			Fragment 1			Interfragment effects	
Z	N	A	Z	N	A	Q (MeV)	Bonds
13	14	27	14	15	29	53.21	38
11	12	23	16	17	33	52.98	38
19	20	39	8	9	17	43.42	32
14	14	28	14	14	28	53.88	40
19	22	41	7	8	15	42.50	36

The current status of the lattice model in the realm of nuclear structure theory is approximately equivalent to the status of LENR in the realm of experimental nuclear physics. Conventional nuclear theorists are vociferous that the many models of the atomic nucleus are, if mutually contradictory, nonetheless "complementary" and suffice to explain nuclear phenomena. Similarly, experimental nuclear physicists are vociferous that the empirical claims in LENR research for excess heat and nuclear transmutations cannot possibly be true in light of the "central dogma" of atomic physics, and must reflect experimental error and/or wishful thinking. In other words, both the theorists' and the experimentalists' rejection of LENR are based upon the presumed inviolability of the nucleus via relatively low-energy mechanisms. There are, however, both experimental and theoretical grounds for skepticism concerning such dogma.

5. Conclusions

The experimental finding that initiated the “cold fusion” revolution was the generation of heat in electrolytic experiments far in excess of what could be explained conventionally on a chemical basis. Subsequent work indicated nuclear products – including low-level radiation and nuclear transmutations. Two decades of further experimentation has not led to theoretical clarity, but the involvement of the atomic nucleus in various ostensibly chemical phenomena is now unambiguous [11]. Significantly, conventional nuclear theory does *not* predict the phenomena of LENR and many conventional physicists remain unconvinced of the reality of LENR since the energy domains of chemistry and nuclear physics remain so far apart. The negative bias with regard to LENR is clearly a consequence of the familiar, but apparently incomplete, theoretical framework of the “central dogma” of atomic physics from the 1930s. Our own calculations (strictly within the realm of nuclear structure theory) indicate a previously unrecognized magnetic contribution to nuclear binding energies. Time, concerted effort and low-level funding for basic research will eventually tell what mechanisms are important, but it is already clear that a revision of the dominant “dogma” of atomic physics is in the making (Fig. 9).

Appendix A.

Details of the lattice model have been published in the physics literature [e.g., 6,7, 19–26], summarized in spreadsheets and PowerPoint presentations available over the internet [8,27], illustrated in cross-platform software that is freely available [27,28], and thoroughly discussed in a recent monograph [1]. The model has been advocated as a possible *unification* of nuclear structure theory – a field notorious for its continuing use of numerous, mutually-contradictory macroscopic analogies – the notorious gaseous, liquid, and cluster models of nuclear theory. Unfortunately, despite the widely acknowledged disarray of nuclear “modeling,” the argument for the unification of nuclear theory within the lattice model has fallen on deaf ears in light of the many successful applications of nuclear energy over the course of many decades. It may indeed be true that the many modern applications of nuclear phenomena are too numerous to discredit the entire field, but developments in LENR have again brought the “completeness” of current nuclear orthodoxy into question. Not only have unanticipated, low-energy nuclear phenomena been detected, but the reconfiguration of the central paradigm of nuclear structure theory, the IPM, within a lattice suggests the form in which a modern theory of quantum nucleodynamics (QND) might eventually take [29].

Whatever the ultimate outcome of current theoretical debates, it can be said that the central pillar in support of the lattice model – largely unappreciated, but uncontested by conventional theorists – is that the antiferromagnetic fcc lattice uniquely reproduces the entire “independent-particle texture” of the nucleus, as originally described in the IPM (ca. 1950). The mathematical identity between the lattice and the standard view of nuclear quantum mechanics means that the quantal states of nucleons (***n, l, j, m, s, i*** and ***parity***) can be deduced solely from nucleon coordinates in the lattice, and vice versa [7]. That fact is illustrated in the following seven equations:

$$\boldsymbol{n} = |x| + |y| + |z| - 3)/2, \tag{A.1}$$

$$\boldsymbol{l} = |x| + |y| - 2)/2, \tag{A.2}$$

$$\boldsymbol{j} = |x| + |y| - 2)/2, \tag{A.3}$$

$$\boldsymbol{m} = |x|^*((-1) \wedge ((x-1)/2)/2, \tag{A.4}$$

$$\boldsymbol{s} = (-1) \wedge ((x-1)/2)/2, \tag{A.5}$$

$$\boldsymbol{i} = (-1) \wedge ((x-1)/2), \tag{A.6}$$

$$\boldsymbol{parity} = \mathrm{sign}(x^* y^* z), \tag{A.7}$$

where nucleon coordinates (x, y, z) are the odd-integers that define a face-centered cubic lattice. The simplicity of the equations is self-evident, and leads to various nuclear-level geometrical symmetries of the nuclear shells and subshells (spherical ***n***-shells, cylindrical ***j***-shells, conical ***m***-shells, orthogonal layering of spin and isospin). Even the non-classical concept of nucleon ***parity*** finds a geometrical definition in the lattice. *A priori,* it is not obvious which version of the independent-particle model – a lattice or a gas – is a more suitable description of nuclear reality, and further research is still needed.

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