J. Condensed Matter Nucl. Sci. 26 (2018) 15–31

Research Article

# Expectations of LENR Theories

David J. Nagel*

*The George Washington University and NUCAT Energy LLC, 725 23rd Street NW, Washington DC 20052, USA*

**Abstract**

The mechanisms that cause Lattice Enabled (or Low Energy) Nuclear Reactions (LENR) are still not understood, even though much is known empirically about LENR. We provide list of 24 observations from almost three decades of LENR experiments. These observations require theoretical explanations. This paper deals with two aspects of the many theories about the mechanisms. The first is the *theories themselves*, i.e., their characteristics and results. The few dozen available theories on LENR mechanisms are diverse and complex. Only a lengthy paper could properly summarize their essence, including all assumptions and implications. Such a thorough review of extant LENR theories would be challenging to write. Here, we merely indicate reviews and other sources of information on LENR theories. The second focus of this paper is the *status of development* of LENR theories, specifically, the completeness of their elaboration. It is possible to detail what is expected of LENR theorists by experimentalists, teachers, students, developers and other interested personnel. We provide and discuss ten questions for LENR theoreticians about the description (characteristics) and status (development) of their ideas. The nearly three decades of theoretical work on LENR has resulted in remarkably few well-developed theories. None of them has yet been adequately tested and widely accepted. There remains a great opportunity for some theoretician to provide the basic understanding of LENR. That understanding would enable or speed the commercialization of this new, clean, promising and much needed energy source.


*Keywords:* Empirical observations, Heat–He correlation, LENR, Low energy nuclear reactions, Theory

## 1. Introduction

There are two large opportunities for fame and fortune available in the field of LENR, understanding and exploitation. When scientific understanding of LENR has been achieved, the mechanisms active to produce LENR and their characteristics, notably their rates, will be known. It is likely that the person or team, which eventually provides that understanding, will be feted for their accomplishment.

Experiments have shown that LENR can provide high power and energy gains, with much more thermal energy coming out of LENR cells than is put into them electrically. Further, operation of LENR does not produce dangerous prompt radiation, significant radioactive waste or greenhouse gases. Commercial LENR generators are expected to be relatively small, so they can be distributed and independent of the grid. Their use in homes would give consumers

*E-mail: nagel@gwu.edu.

© 2018 ISCMNS. All rights reserved. ISSN 2227-3123

control over their energy generation, similar to how they now control their energy usage. Such generators would not be subject to brown or black outs, or other grid-related problems. Because of their gains and other favorable characteristics, safe and reliable generators based on LENR should be very cost-effective and attractive to customers. Hence, commercial exploitation of the features of LENR ought to be very remunerative. That is why over 20 small companies in at least nine countries [1] are seeking to develop prototypes of LENR generators even before the mechanisms that produce power and energy are understood.

Because understanding of LENR will solve a current major scientific riddle, and because that understanding will promote earlier and better commercialization, we focus on theories for LENR in this paper. Section 2 summarizes many of the empirical observations, which have come from over a quarter of a century of experiments. It is possible that some of those observations are either wrong or irrelevant. However, most of those observations will withstand the test of time. The entire body of empirical knowledge constrains and tests the activities of theoreticians. Put another way, the items listed in the next section challenge theoretical developments aimed at understanding LENR.

Section 3 is a summary of earlier reviews of the actual content of LENR theories. Those studies are important milestones on the road to eventual understanding of LENR. Section 4 is the body of this paper. It provides and discusses the 10 questions for LENR theoreticians. Those questions seek to determine the characteristics and status of the diverse theories. Section 5 gives a summary of the primary points of this paper, and adds some comments on what is needed to speed the theoretical and quantitative understanding of LENR. Appendix A provides a possible scenario for correlations between heat and helium generation beyond conventional single-step fusion reactions.

## 2. Empirical Observations of LENR Characteristics

The history of science has instances where it has taken decades for ideas to be verified or observations to be explained. Wegner put forward the idea of plate tectonics in 1912 [2], but observational evidence for its correctness did not emerge for about forty years [3]. Einstein published the equations for stimulated emission in 1917 [4]. However, it was not until demonstration of the MASER by Townes in 1954 that those equations were shown experimentally to be correct [5]. In both of those cases of theory-before-observation, the core ideas were relatively simple, and the needed observational or laboratory techniques had to be developed. The reverse also happens. Onnes discovered superconductivity in 1911 [6], but it was not understood until 1957 [7]. That phenomenon was found in many materials in the decades between the initial discovery and the elucidation. However, the core problem was relatively simple, namely how could electrical resistance go to zero at suitably low temperatures? The situation with LENR seems to be more complex, with very many types of experiments and diverse findings. But, the major observations can be stated simply. That is done in the rest of this section.

The central finding from thousands of LENR experiments over almost 30 years is the following: it is possible to use chemical energies on the scale of electron volts to release nuclear energies in the range of mega electron volts. It has to be emphasized that the ability to release nuclear energies by using chemical energies enables high energy gains. That is, it is possible conceptually, and has been demonstrated experimentally, that much more thermal energy can be gotten from an LENR experiment than is put into it to cause the nuclear reactions. The gain is defined as the ratio of the output thermal energy to the input electrical energy. LENR gains were summarized in a recent paper [8]. There is strong experimental evidence for gains as high as 26. The largest reported LENR gain, which is neither verified nor reproduced, is 800 [9].

A schematic perspective of barriers to reactions, and both chemical and nuclear energy gains, is given in Fig. 1. In chemical reactions, the barrier energy is on the order of the reaction energy on a scale of electron volts. The barrier arises from the energy needed to take apart the existing reactant molecules to produce new arrangements in the products. In nuclear reactions, the barrier is a significant fraction of a mega electron volt, and the reaction energy is commonly greater than one mega electron volt. That barrier is due to the electrostatic repulsion of two positive nuclei,

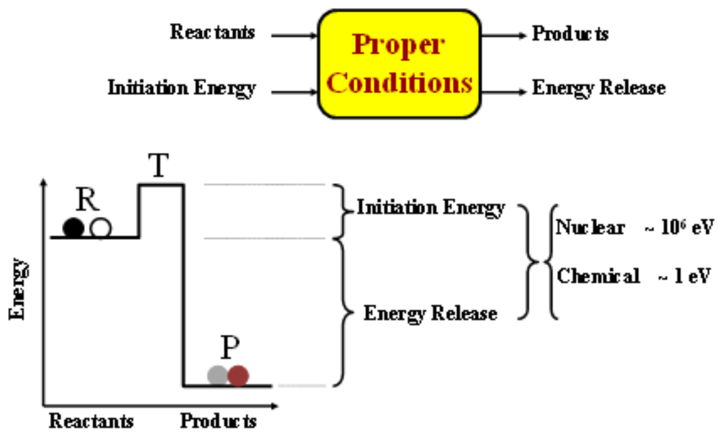


**Figure 1.** *Top*: Schematic of the flows of matter and energy into and out of a reaction, either chemical or nuclear. *Bottom*: Diagram showing the energy levels for the Reactants (R) in their initial and Transition (T) states, and the energy level of the resulting Products (P). As noted, the energy scale for nuclear reactions is roughly one million times larger than the energy scale for chemical reactions.

the so-called Coulomb barrier. The remarkable and still mysterious aspect of LENR is that chemical energies can turn nuclear reactants into nuclear products.

Even modest LENR gains, say, less than 10, would have great impact. Electricity generation is not efficient due to the multiple necessary steps. Currently, the chemical energy in fossil fuels is first converted to thermal energy, and then to mechanical energy, and then, finally, to electricity. Each step has inefficiencies due to various losses, such as conductive losses and friction, on top of the inescapable thermodynamic (Carnot) losses. Only about 40% of the energy in coal or gas can be converted to electricity [10]. And, a significant fraction of the electrical energy is lost in transmission from large generation facilities to users. The electricity transmission losses in the US average 7–8% [11]. There are over 7000 electrical generation plants in the US [12]. Hence, transmission inefficiencies waste the power generated by about 500 of them. The ability of LENR to (a) provide significant gains from (b) small distributed generators of heat and electricity would make electrical power more cost effective.

It is noted in passing that the largest current hot fusion experiment is seeking a gain of 10. The International Thermonuclear Experimental Reactor (ITER) is being built in the south of France for over $20B. The project is expected to take over 20 years. It will not necessarily result in the design for a large and costly practical power station. Yet another, similarly large experiment will be needed prior to commercialization of power from hot fusion. Ultimate hot fusion power stations will be large and expensive, with transmission losses. An investment in research and development for LENR at even 10% of the level of hot fusion funding could result in understanding and commercialization on a time scale as short of half of the time for the ITER construction and testing.

In addition to the central gain characteristic of LENR, there are many other empirical observations that must addressed by LENR theoreticians. Lists of empirical observations have been given by several authors. Storms 2007 book has a list of 12 observations [13]. The organizers of ICCF-14 provided 10 high-level statements about the results of many LENR experiments [14]. Recently, Hubler provided another list of experimental LENR observations that beg explanation [15]. There are other lists, but those three cover most of the salient points. The following list is an integration of the points made by those and other authors, with our wording.

(1) Nuclear reactions (MeV output) can be initiated by using chemical energies (eV input).

(2) There are many ways to produce LENR and to measure their results.
(3) Diverse solid materials have been shown to produce LENR (Pd, Ni, Ti, alloys, etc.)
(4) Both protons and deuterons can be involved in LENR under some circumstances.
(5) Many conditions can result in LENR, with lattices in liquids or gases.
(6) Initiation times for production of LENR vary widely in different experiments.
(7) Disequilibrium conditions, with high proton or deuteron fluxes, favor LENR.
(8) Some LENR occur in small and distinct regions on or near the surface of materials.
(9) A few measurements show that LENR can occur during sub-millisecond times
(10) High power and energy gains have been measured in diverse experiments.
(11) High power densities and energy densities, and energy per atom values, are possible.
(12) High temperatures are not needed to produce LENR, but rates increase with temperature.
(13) For electrochemical experiments, high ratios of deuterons to Pd atoms favor LENR.
(14) Excess power has also been measured with lower ratios of deuterons to Pd atoms.
(15) Cathode surface texture, roughness and impurities significantly influence LENR
(16) Application of laser light, magnetic fields and some other effects increases LENR.
(17) Different outputs from LENR experiments are measurable with diverse instruments
(18) Production of large heat, tritons and helium indicate that nuclear reactions occur.
(19) Heat »tritium »neutrons, so LENR are not due to conventional D–D fusion.
(20) Fe, Zn and Cu are the most common transmutation products (fission occurs?)
(21) Some evidences show that living organisms can cause nuclear transmutations.
(22) Heat production has sometimes been correlated with nuclear products, especially helium.
(23) Little prompt radiation or radioactive waste, and nearly zero green house gases come from LENR.
(24) LENR, when understood, reproducible and controllable, might provide the basis for new, clean, commercial, cost-effective, distributed energy generators.

It must be noted that some of these empirical observations are not consistent with each other. Items 13 and 14 on the loading of deuterons (D) into palladium (Pd) provide an example. Clear evidence has been presented that achieving a high ratio of D/Pd is necessary (but not sufficient) for production of LENR energy [16]. However, in contrast, Storms found that "…excess power is independent of the D/Pd ratio and applied electrolytic current, being only sensitive to temperature." [17] These statements, and the diversity of the entire list of empirical information, challenge those who seek to understand LENR. It is likely that full verification of these observations and their quantitative understanding will take many years to achieve.

An informed and diligent reviewer could take each of the two dozen observations listed above, and assemble a collection of publications to back up every observation. That is, these empirical "facts" are not the result of singular papers or other reports. This list, the result of over one-quarter of a century of careful experimentation, is a very stern challenge to LENR theoreticians.

Imagine a matrix that lists each of the above 24 empirical observations against each of the dozens of LENR theories. Many (most??) of the theories would be eliminated by one or more of the listed observations. Unfortunately, many LENR theories fail at the conceptual level, as will be discussed in Section 3.

## 3. Milestones in Evaluation of LENR Theories

There are dozens of theories about what causes LENR. Most are incompatible with other LENR concepts. Theories are ultimately in competition with each other. Understanding and assessing the *characteristics* and *status* of each theory is a major first step toward down selecting theories. Those goals motivate this paper.

There have been a few more or less thorough reviews of LENR theories since the 1989 Fleischmann–Pons announcement. Those reviews summarized papers on LENR theory and their content. We note the few such reviews in the rest of this section.

### 3.1. 1994 Paper by Fleischmann, Pons and Preparata [18]

The originators of the LENR field had a strong and abiding interest in explanations of what they and others measured. Because of that, they developed a close relationship with Preparata, a leading LENR theoretician. This paper resulted from their shared interests and collaboration. The paper includes a review of the energetics of the dissolution of hydrogen isotopes in palladium. It contains the list of seven observations that have to be explained by LENR theories, which were already noted in the last section. The authors provide a list of types of "Possible Models" and "Impossible Models" for each of those seven phenomena. The abstract for the paper follows:

- We review some of the key facts in the phenomenology of Pd hydrides usually referred to as "cold fusion". We conclude that all theoretical attempts that concentrate only on few-body interactions, both electromagnetic and nuclear, are probably insufficient to explain such phenomena. On the other hand we find good indications that theories describing collective, coherent interactions among elementary constituents leading to macroscopic quantum-mechanical effects belong to the class of possible theories of those phenomena

It is noted that, while this paper references many of the existing LENR theories in 1994, it is not a review of such theories. Rather, it provides constraints on LENR theories, given the noted observations.

### 3.2. 1994 Review paper by Chechin et al. [19]

This paper was an actual review of LENR (CF) theories by theoretical physicists. The abstract for the paper follows:

- We briefly summarize the reported anomalous effects in deuterated metals at ambient temperature, commonly known as "Cold Fusion" (CF), with an emphasis on important experiments as well as the theoretical basis for the opposition to interpreting them as cold fusion. Then we critically examine more than 25 theoretical models for CF, including unusual nuclear and exotic chemical hypotheses. We conclude that they do not explain the data.

The authors were outspoken in their criticism of extant LENR theories. They wrote the following in their Conclusion section:

- We conclude that in spite of considerable efforts, no theoretical formulation of CF has succeeded in quantitatively or even qualitatively describing the reported experimental results. Those models claiming to have solved this enigma appear far from having accomplished this goal. Perhaps part of the problem is that not all of the experiments are equally valid, and we do not always know which is which. We think that as the experiments become more reliable with better equipment, etc., it will be possible to establish the phenomena, narrow down the contending theories, and zero in on a proper theoretical framework; or to dismiss CF. There is still a great deal of uncertainty regarding the properties and nature of CF.

  Of course, the hallmark of good theory is consistency with experiment. However, at present because of the great uncertainty in the experimental results, we have been limited largely in investigating the consistency of the theories with the fundamental laws of nature and their internal self-consistency. A number of the theories do not even meet these basic criteria. Some of the models are based on such exotic assumptions that they are almost untestable, even though they may be self-consistent and not violate the known laws of physics. It is imperative that a theory be testable, if it is to be considered a physical theory.

It would be worthwhile to revisit each of the 25 theories considered in the review by Chechin et al. in order to (a) see which of them are no longer being actively developed, and (b) learn the status of each of those theories that have been advanced since 1994.

### 3.3. 2007 [20] and 2014 [21] books by Storms

Both of the books on LENR from Storms contain chapters on theoretical ideas. They are written from the perspective of a thoughtful experimentalist, rather than that of theoreticians. Chapter 8 of the 2007 book provides a list of four restrictions on LENR theories. It then discusses "Plausible Models and Expectations" for the production of heat, helium and transmutation products. That material references many of the ideas to explain LENR, but does not cover all of them. Storms then considered some potential approaches to fusion involving deuterons and other reactions with protons. He concludes that chapter by noting that "all theories have one or more major flaws".

Chapter 4 of Storms' 2014 book is a more systematic classification and review of LENR theories. Storms listed seven classes of LENR theories. They are (with the number of theories in each class in parentheses): Cluster Formation (5), Resonances (6), Neutron Reactions (4), Special Electron Structures (3), Transmutations (2), Tunneling (1) and Cracks and Special Structures (2). The 23 theories span most, but not all of the ideas that were and are competing for understanding of LENR. Overall, this chapter is the best summary of LENR theories in one source in recent years, and is very useful.

### 3.4. 2008 Matrix of theories presented at ICCF-14 [22]

The Proceedings of ICCF-21 contain a matrix of the 22 theoretical presentations given at that conference vs the characteristics of those theories. See Table 1. The features of the theories were noted in response to these questions:

(1) What is the form of the reaction(s) considered?
(2) Does the paper deal with the Coulomb barrier?
(3) Does the paper deal with energetic particles?
(4) What is the conceptual foundation of the theory?
(5) Has the concept been reduced to equations?
(6) Have numerical results been provided?
(7) Have the results been applied?

The matrix is copied on a following page. That format is meant to provide a facile way to compare different ideas about the mechanism(s) behind LENR. It would be useful to broaden this matrix to include theories not given at that conference and to add additional features, such as the calculation of LENR rates.

### 3.5. 2009 Review by Krivit and Marwan [23]

This paper includes a history of the study of LENR, and a survey of experiments and results. It also contains a review of thirteen LENR theories, and mentions a few others. The authors summarize their review of LENR theories by stating "There is no lack of effort to explain LENR. There are also very few comprehensive, qualitative evaluations of LENR theories." They also note that "Cyclical patterns have occurred in the views that have attempted to explain LENR." This is true for some theories that have been developed over several years.

### 3.6. 2013 Issue of Infinite Energy Magazine [24]

Issue number 112 of the magazine contained nine papers by the authors of various LENR theories [25]. They include, in the order of publication, Hagelstein, Dallacasa and Cook, Storms, Meulenberg and Sinha, Vysotskii and Vysotskyy, Kozima, Meulenberg and, finally, Sinclair. Hence, these articles were not a "third party" review of such theories, as was the case for most of the compilations noted above in this section. However, the individual articles provide more depth for each of the theories than is usually available in reviews of various theories.

Biberian suggested this issue reviewing "Theoretical Models of Cold Fusion". In the introduction, he listed six criteria and questions about such theories and papers describing them:

(1) The papers are intended for experimentalists as further guidance on producing experiments.
(2) The papers should be short (maximum of 4000 words).
(3) The papers should make clear the initial assumptions of the theory.
(4) What experimental results are explained by the theory?
(5) What are the predictions of the theory?
(6) What should experimentalists do to produce successful experiments?

This listing of reviews of LENR theories is not exhaustive. There are some other examinations of multiple theories. However, these reviews give a fairly comprehensive listing and discussion of LENR theories as of the dates of their publications (see Table 1).

This paper is a related, but different, approach to the dozens of LENR theories. It is not a review or evaluation of LENR theories. Rather, it offers questions, the answers to which would enable people interested in LENR to understand the nature and situation for various theories. Presentation of those questions and comments on them constitute most of the rest of this paper.

## 4. Questions about LENR Theories

The topic of hypotheses and theories in science has a long and rich history. Our approach here is less philosophical and more practical. We simply ask developers of LENR theories about the *characteristics* and *status* of their ideas. A different view of LENR theory has been presented by Hagelstein, a sophisticated LENR theoretician [26]. Ten questions will be presented and discussed in Sections 4.1–4.10.

### 4.1. Q1. How is your theory connected to LENR?

Some concepts presented at LENR conferences have no stated or evident connection to LENR. It is reasonable to ask if a given idea seeks to explain everything about LENR, or just some aspect of what was measured. Some works on nuclear structures and on nuclear reactions, which are presented in LENR conferences, do not get as far as making a clear connection to LENR. That is not to say they are unscientific, or else, science not worth attention. However, it should be possible for a theoretician to state clearly which of the many empirical observations listed in Section 2 they seek to explain.

### 4.2. Q2. What is the key idea or concept of your theory?

All theoretical developments must start with some idea or concept about what is happening to make it possible to induce nuclear reactions with chemical energies. LENR theoreticians ought to be able to state unambiguously their core idea (or ideas) and *the associated assumptions*, which are adopted at the outset of a specific theoretical development. Without such clarity, it is impossible for the theoretician to develop their theory, or to explain it to interested people, especially experimentalists.

**Table 1.** Characteristics of theories presented at ICCF–14.

| Authors | Which LENR? | Coulomb Barrier | Hi-energy Particles | Concept | Equations? | Numerical Results? | Use of Results? |
|---|---|---|---|---|---|---|---|
| Adamenko and Vysotskii | Transmutation | N/A | NA | Magnetic monopoles | Yes | Approx. bounds | No |
| Alexandrov | e+P $\rightarrow$ N+$\nu$ | Neutrons | No | Band theory, effective mass | Yes | Yes | Applied to semicond. |
| Bass and Swartz | D Fusion | No | No | Control theory | Computer Simula-tion | Yes | Future work |
| Breed | 4D $\rightarrow \alpha + \ldots$ | Yes | Yes | Band theory, effective mass, resonance | Yes | No | NA |
| S. Chubb | D+D $\rightarrow {}^4$He+heat | Yes | Yes | Nonlocal quantum effects, resonance | Yes | Yes | No |
| T. Chubb | Various | Yes | Yes | "Ion band states" | No | No | NA |
| Cook | Transmutation | No | NA | Lattice model of nuclei | Yes | Yes | Compared with expt. |
| Dufour et al. | Pd+D, D+D | Yes | Indirectly | New force | No | No | NA |
| Fou | D+D fusion | Yes | No | Neutron exchange, electrostatic fields | No | No | NA |
| Frisone | D plasma oscillations | Yes | NA | Gamow and Preparata Theory | Yes | Yes | No |
| Godes | e+P $\rightarrow$ N+$\nu$ | Neutrons | No | Various | No | No | NA |
| Hagelstein and Chaudhary | D+D $\rightarrow {}^4$He+24 MeV | Yes | Yes | Coupling two-level systems to phonons | Yes | Quali tative | NA |
| Hagelstein, Melich and Johnson | Various | Yse | Yes | Various | NA | NA | NA |
| Hagelstein et al. | Various | No | No | Existing theory | Yes | No | NA |
| Kim | D+D $\rightarrow {}^4$He+heat | Yes | Yes | Bose–Einstein condensate | Yes | Yes | Yes |
| Kozima | Not stated | No | No | Cellular automata, recursion equations | No | No | NA |
| Kozima and Date | Transmutation | Neutrons | No | "Neutron drops" | No | No | NA |
| Li et al. | P+D+e $\rightarrow$ ${}^3$He+e+$\nu + \nu^-$ | Neutrons | Indirectly | Resonance, tunneling | Yes | Yes | No |
| Sinha and Meulenberg | D fusion | Yes | No | Screening via local $e^-$ pairs | Yes | Yes | No |
| Swartz | D fusion | No | No | Relations between operating parameters | Yes | Approx-imately | Yes |
| Swartz and Forsley | D Fusion | No | No | Relations involving operating parameters | Computer calculations | Qualitative | Yes |
| Takahashi | 4D $\rightarrow {}^8$Be* $\rightarrow 2\alpha$ | Yes | No | "Tetrahedrally symmetric clusters" | Yes | Yes | No |

### 4.3. Q3. What is (are) the foundation(s) of your concept?

This question asks: what is the basis in physics, chemistry, biology, materials science, electromagnetics and other sciences of the mechanism(s) at the core of a theoretical idea? What advanced knowledge of which sciences is needed to proceed? Developing a theory, understanding a theory, and using a theory require expertise in particular disciplines. It is likely that physics will turn out to be the core discipline needed to fully understand LENR. However, the complexity of both LENR experiments and their results make it very likely that serious expertise in other disciplines will also needed. That is especially true of Chemistry and Materials Science.

### 4.4. Q4. Does your mechanism involve only one step or more than one step?

There is a general issue in the field of LENR that is very fundamental and unresolved. It is whether there is only one nuclear reaction or a sequence of two or more nuclear or other reactions. In fact, the situation is even more complex than that. Some LENR theories involve the formation of "compact objects", which have sizes and binding energies intermediate between those of atoms and nuclei. A recent review of such theories is available [27]. The formation of such objects would not involve nuclear reactions, and could be responsible for part, or even all of the heat seen in LENR experiments. However, compact objects might, after formation, go on to participate in nuclear reactions. There is a precedent for such behavior in muon-catalyzed fusion, an understood process [28]. So, LENR might occur by a two-step process, the first without any nuclear reaction and the second being a nuclear reaction.

Even more fundamental, there are three types of possible reactions relevant to LENR: chemical, exotic and nuclear. Chemical reactions include electrochemical and solid-state mechanisms, which are needed to create Nuclear Active Environments in Nuclear Active Regions. Exotic reactions include the formation of compact objects or other entities by neither ordinary chemical nor nuclear reactions. Nuclear reactions include any mechanism which produces changes in the nuclei that are involved in the reactions, whether fusion, fission, transmutations or other changes in a nucleus.

If production of a Nuclear Active Environment is always the initial step, then all LENR experiments involve two steps. That initial "reaction" is probably chemical in nature, and sets the stage for a nuclear reaction. Hence, there are two likely sequences needed for production of LENR: (a) Chemical, then Nuclear, or (b) Chemical, then Exotic and, finally, Nuclear. However, this does not exhaust possibilities. The number and sequence of multiple reactions can vary greatly. As noted above, some LENR theories do not involve nuclear reactions at all.

The number and type of reactions during LENR experiments is rarely discussed. This is a major deficiency in the theoretical side of the field. One paper by Widom and Larsen does have a discussion of possible sequential nuclear reactions, assuming the availability of lithium and of sufficient numbers of "ultra-low-momentum" neutrons [29]. The Appendix to this paper considers two sequential nuclear reactions leading to production of both heat and helium, and their correlation.

### 4.5. Q5. Are the equations that embody your concept written out?

If this is not done, the "theory" is nothing more than a concept, which is untestable, and has no value for either explaining past experiments or designing new experiments. The challenge is to have all the needed equations to embody the basic concept. Additional equations beyond those that are necessary can be counterproductive.

### 4.6. Q6. If the equations are written, have they been evaluated by reduction to numbers?

There is no way to know from equations alone if the idea(s) behind them is (are) correct, or if the equations are complete and correct. Science is all about numbers, and stopping at the equations stage is like preparing for and starting a race, only to quit part way through it. There are many choices and challenges in the computational part of a theoretical program. Choices include the source of needed parameters, what algorithms to use, what computer language to employ, what machine to use for the calculations, and how to store and use the results. Each of these choices can influence the results of the calculations based on the starting set of equations. Post–calculation analyses are sometimes valuable, and they also require making several choices on what to do and how to do it.

### 4.7. Q7. How does your mechanism relate to experimental observations?

Comparison of the results of theoretical developments with experiment, and the design of experiments to test the results of theories, are critical to understanding of LENR. Hence, this and the remaining three questions have to do with the intersection of theories and experiments.

The list of empirical observations from LENR experiments in the second section is quite clear and challenging. However, some aspects are worth additional comments because they are both remarkable and important to applications

Power gains in excess of 25 have been observed in a few experiments [30]. Values of generated energy (in eV/atom of the metal catalyst) in excess of 2000 have been observed in LENR experiments [31]. Power densities exceeding those within nuclear fission fuel rods by about 50 times have been measured [32].

Materials are especially critical to production of LENR, including high loading, surface orientation and morphology, the presence of impurities and other unknown factors. When LENR are understood, the key materials parameters will be known, along with their range of acceptable values. Put another way, LENR theories ought to provide guidance on the composition and structure of materials that will lead to LENR. That is rarely the case.

It is known that application of external stimuli to LENR experiments can initiate (trigger) or increase (stimulate) such reactions, and their generation of energy and products. Figure 2 is a schematic relationship between LENR experiments, the various input stimuli that have been applied to them (left column) and the diverse attempted output measurements from them (right column) [33]. LENR theories ought to be able to explain the actions of applied stimuli, as well as the type and magnitude of measured quantities. There are very many challenges of this type.

For example, Radio Frequency (RF) has been applied to LENR experiments and increased excess power was observed. In other LENR experiments, RF emissions from LENR experiments were measured, both without and with the production of measurable excess power. A complete LENR theory ought to be able to rationalize the RF frequencies used to increase LENR reaction rates and the RF frequencies measured during LENR experiments, as well as the RF powers involved. A recent review of the overlap between LENR experiments and RF inputs or outputs is available [34].

### 4.8. Q8. What time histories and reaction rates are (quantitatively) predicted?

Reaction rates that come out of LENR theories are especially important and deserve separate attention for two reasons. First, empirical rates can be obtained from carefully designed and calibrated experiments, so they are testable. Second, reaction rates are the basis of applications. Whether or not LENR will turn out to be the foundation of practical commercial energy generators will depend on what reaction rates can be produced, controlled and sustained.

Many LENR experiments have shown the production of energy and reaction products to be uncontrolled and highly variable during a run. Understanding such variability, and achieving full control of power output, is another challenge to LENR theoreticians.

As discussed under Question 4, LENR might always, or at least often, involve at least two reaction steps. Hence, it must be asked, for theoretical mechanisms involving more than one step, which step is rate limiting? If there are two reactions, their rates can compare in only three ways, one or the other is dominant, or they are comparable.

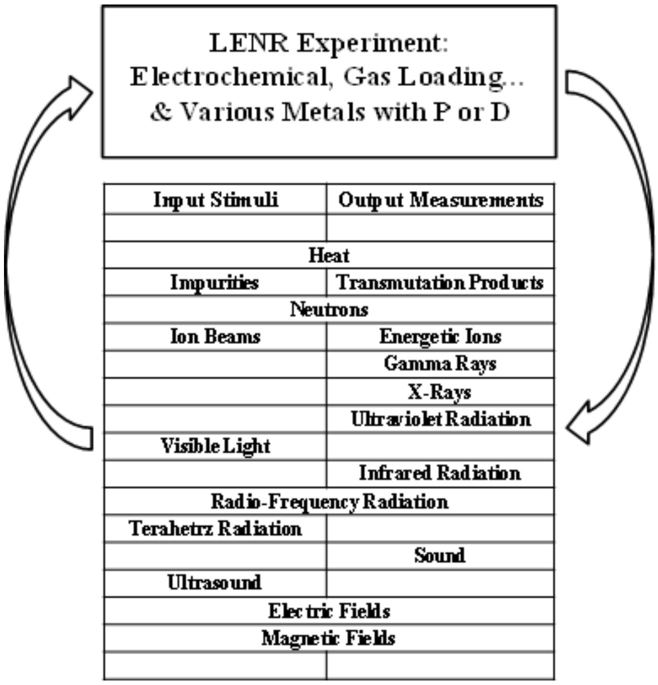


**Figure 2.** Stimuli that have applied to LENR experiments (*left column*) or measured from such experiments (*right column*). P stands for protons and D for deuterons. Blanks in the columns are possibilities that have not yet been applied or measured.

### 4.9. Q9. Can one theory explain all LENR observations?

LENR experiments have produced a remarkable great variety of observations. The question of whether only one or, rather, multiple theories are needed to explain the diversity of observations from LENR experiments. Again, a summary of those observations is in Section 2. This question is like the question on there being one or more steps when LENR occur, critical but rarely discussed. No paper on this issue is known to this author.

Theories and mechanisms are conceptually separable. That is, one could have multiple explanations for one mechanism. So, there is another question. Are all observations due to one mechanism, or are multiple mechanisms needed to understand all of the data? If the latter, what controls the pathway and outcome of any given experiment? Will a single theory be able to embrace multiple mechanisms?

### 4.10. Q10. The ultimate question: Is your theory testable?

It is widely accepted that failure to achieve the results predicted theoretically does not rule out a theory, because the experiments might have some type of unknown or unrecognized flaw. Agreement between quantitative theoretical predictions and the numerical results of measurements increases the probability that a theory is correct, but even this could be accidental and worthless.

The explicit comparison of the results of LENR theories with experiments is a rarity in the field. This author knows of only three parametric comparisons of measured and computed results from the past 28 years. They will be briefly noted here, and reviewed in detail in a forthcoming paper [35].

The first direct comparison of a LENR theoretical prediction with the results of an LENR experiment, known to this author, was published in a paper on ultra-low momentum neutrons by Widom and Larsen in 2006 [36]. They compared their theoretical neutron scattering lengths with the transmutation rates published by Miley and his collaborators [37], both as a function of atomic mass. The theoretical curve showed peaks where multiples of the neutron wavelength within nuclear matter fit the size of the mass-dependent nucleus. The experimental transmutation rates also showed peaks as a function of atomic mass. The positions of the computed and measured peaks are similar for all five peaks in both data sets. In a subsequent study, they were found to be statistically correlated [38].

Another direct confrontation of LENR laboratory data with theory comes from experiments performed by Letts, Cravens and Hagelstein [39]. Their cathode was irradiated with THz electromagnetic radiation from heterodyning two lasers, which could be varied in frequency (wavelength). Three main peaks in the production of LENR power were observed at specific frequencies. The authors associated the frequencies of two of the peaks with optical phonon frequencies in palladium hydride. An alternative explanation of the same data was offered later by Vysotskii and Vysotskyy in support of their Coherent Correlated States theory of LENR [40].

The two examples just reviewed basically involved comparison of LENR data with the results of quantum mechanical calculations. A third example, published in 2013, was qualitatively different. It involves measured excess powers from 40 experiments with the pair of lasers used to produce the THz frequency-dependent excess power noted in the last paragraph. Letts provided an equation involving several parameters relevant to those experiments [41]. He computed excess power as a function of frequency and compared the numerical results with the measured excess powers. The empirical and computational results were in remarkable agreement over a frequency range from below 5 up to 22 THz and excess power range from near zero up to 1.4 W.

## 5. Conclusion

Theory and related hypotheses really have only two primary functions: to explain the past or to predict the future. There is a large volume of good data from LENR experiments, which begs quantitative, or even qualitative, understanding. That is, there is ample opportunity for more theoretical explanations of what has already been observed. Reaction rates present a sterling opportunity for explaining measured results. The assumptions basic to any theoretical approach and physical constants are needed for computation of LENR reaction rates.

The three cases cited under Q10 involved theoretical explanations of earlier data. But, theory can also precede measurements. Design of experimental tests of theories and hypotheses is a time-honored and useful approach in the sciences. The chance to design LENR experiments and predict their outcome is also wide open. This author knows of only one program in which experiments have been designed to test a theory about LENR. It is reviewed next.

Hagelstein has been working for many years on reciprocal mechanisms for energy sharing between nuclear levels (MeV energies) and phonon states (meV energies) [42]. In one direction, he deals with the partition (fractionization) of high energy quanta in the MeV range (from nuclear reactions) into many low energy quanta in the meV range (due to phonons). In the other direction, his theoretical work considers the addition of many phonon (vibrational) energies to produce the much higher nuclear energies. If successful, the closely related mechanisms for down- and up-conversion will explain deuteron–deuteron nuclear reactions, which are able to avoid the Coulomb barrier and occur without emission of energetic radiation. In the recent past, Hagelstein and his team have been performing mechanical vibrational experiments and searching for the emission of X-ray energies associated with very low-lying nuclear states [43]. This is not a direct test of a theory on LENR, but rather a test of the mechanism that is central to an LENR theory.

Almost all extant LENR theories fall short of what is desirable, and actually necessary, in terms of their completeness. It could happen that, if all available LENR theories are carried to numerical completion and then compared with experiments, there would be no compelling agreement. That is, it is not certain that the theories now in play will prove to be adequate for understanding LENR. It is also possible that a new LENR theory will appear and provide the desired understanding. Further, it is conceivable that the solutions of the challenge of understanding LENR will come from outside of the field, either from a new theory or even a theory that already exists. One possibility is given in the next paragraph.

The experimental work of Cardone and his large team has shown that it is possible to induce nuclear reactions by using ultrasound to excite liquid mercury at room temperature [44]. Three minutes of insonification turns the silvery liquid into a dark powder, which contains many new elements. That group interprets their results in terms of what is called Deformed Space Time (DST). A substantial body of theory on DST exists [45]. Is it possible that DST will (a) prove to be a correct explanation of the transmutation results in the ultrasound experiments and (b) explain what is seen in very different LENR experiments?

A discussion of how to down select LENR theories has been published [46]. Part of it reads:

- There is little evidence of convergence toward the few ideas that are most worthy of attention and funding. Of course, it is the nature of science that an individual researcher can work on whatever they want to pursue within funding constraints. However, having a limited number of LENR theories as a focus might speed the achievement of the desired ultimate understanding. If the mechanisms active in LENR were understood, the scientific development of the field could accelerate. And, importantly, the development of commercial products would proceed much faster and with greater assurance of success. There are problems associated with the evaluation, prioritization and down-selection of theories about LENR. One of them is the natural tendency of scientists, theoreticians included, to want others to pay favorable attention to their work. Another is the fact that some of the concepts are not clearly documented. Another challenge is due to the fact that many of the ideas are still evolving because of recent activities of their originators

It must be noted, even emphasized, that there has been much unpublished material and discussion about LENR theories on the internet. That is especially true for postings on the CMNS Google Group. For example, in April and May of 2016, there were 100 postings in a thread on LENR theories. It is difficult to reference such material for two reasons. First, that discussion is privileged to members of the group. And, even if it were not private, it is not accessible to others and, hence, cannot be referenced. The ideas in this paper were influenced by unpublished posting about LENR theory, but are solely the current views of the author.

This paper has focused on deficiencies in LENR theories. However, it is also true that many LENR experiments, and reports on what was done and found in a laboratory, are less than satisfactory. Experimental setups and materials are often not as good as they might be, in terms of modern equipment and software, and available materials science and engineering. Such shortfalls are usually due to insufficient funds. Analysis of data from LENR experiments is commonly not as thorough as is desirable. For example, few authors perform Fourier Transformations on time series data to obtain the distribution of frequencies (the spectrum) from the measurements. Such transformations are essentially trivial with modern software. Finally, many reports on LENR experiments are not adequately complete. This is especially bothersome if another scientist seeks to reproduce an earlier experiment. Overall, there are too many deficiencies in LENR experiments and papers. However, despite these problems, we have still learned a great deal about LENR in laboratories, as noted in Section 2.

The explanation(s) of the existence and many facets of LENR remains for some time in the future. It could be achieved soon, or only after many more years of struggling with the numerous experimental characteristics from diverse LENR experiments. Whatever and whenever the outcome, the discovery, experimental elucidation and theoretical understanding of LENR will constitute a significant chapter in the history of science.

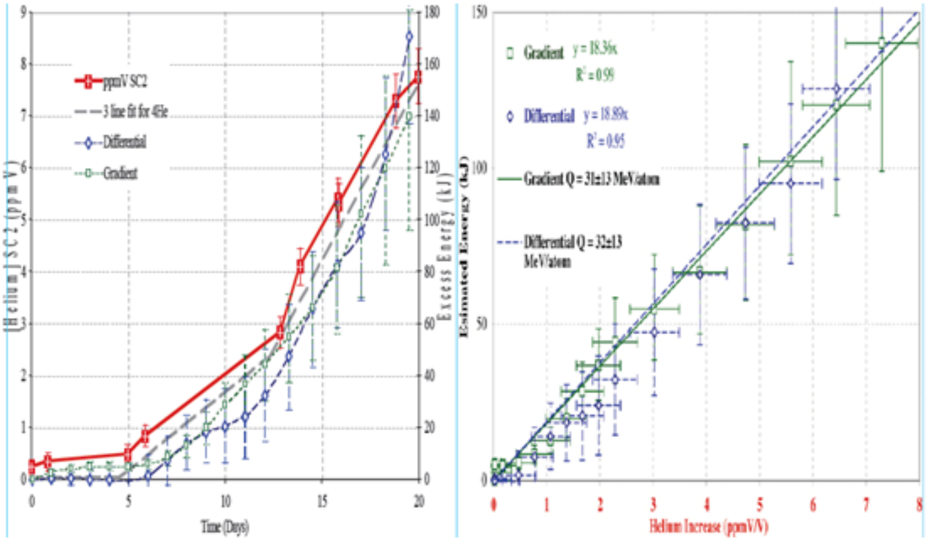


**Figure 3.** Helium production in an LENR experiment at SRI International. *Left*: Time history of the helium concentration in Parts per Million by Volume. *Right:* The excess energy in kJ vs the helium concentration. Fitting the data by different means gave approximately 31–32 MeV per helium atom produced.

## Acknowledgements

Provision of information and comments by Peter Hagelstein, Dennis Letts, Michael McKubre, Andrew Meulenberg and Vladimir Vysotskii is much appreciated. A reviewer provided comments that improved this paper. William Collis is thanked for his organization of the 12th International Workshop on Anomalies in Hydrogen Loaded Metals, at which this paper was presented.

## Appendix A. The Correlation of Heat Generation and Helium Production

The correlation of excess energy with the number of helium atoms, both produced in the same LENR experiment, was discovered by Miles [47]. Helium generation, and that correlation, were reviewed recently [48]. The best example of the linear relationship between heat and helium production was published by McKubre and his colleagues [49]. It is shown in Fig. 3. There are two notable characteristics of those data. The first is that the helium levels exceeded the 5.2 ppm level of helium in the atmosphere. Hence, the measured helium was not produced by a leak from the atmosphere into the experiment. The other significant characteristic of the results is the slope of the correlation curve, namely 31 or $32 \pm 13$ MeV/atom. Those values are close to the energy of the 23.8 MeV gamma ray, which is emitted in the rare $(10^{-7})$ branch of conventional D–D fusion.

There has been much discussion about that result. Some scientists rationalized the difference by noting that some of the helium might be trapped in the palladium materials of the experiments, and hence not measured. If that were the case, then the measured heat to helium ratios would be higher than the actual values.

There are also ideas that helium might be due to two (or more) nucleon or nuclear reactions in sequence [27]. The total energy $E_{\mathrm{T}}$ from two sequential nuclear reactions can be written simply. The equation for two reaction steps 1 and 2 is

$$E_T = N_1\,E_1 + N_2\,E_2,$$

where $N_1$ and $N_2$ are the number of each type of reaction and $E_1$ and $E_2$ are the associated energies. Define $F$ as the fraction of the first reactions that also produce a second reaction, so $N_2 = F\,N_1$. $F$ can be taken as 1 for the purpose of this discussion. That is $N_1 = N_2$. Then, if each of the terminal second reactions produces a helium atom, $N_1 = N_2 =$ He, so the ratio of heat to helium is

$$E_T/\text{He} = E_1 + E_2.$$

That is, the slope of the correlation in the right part of Fig. 3 would be the sum of two reaction energies. In principle, the $E_1$ could be negative, that is, the first nucleon or nuclear reaction could be endothermic. But, then the first reaction would be unlikely. It is more probable that both of the energies $E_1$ and $E_2$ are exothermic, so they would add. In that case, the slope of a heat vs helium graph could be greater than expected from simple one-step hot fusion D–D reaction, as it is in Fig. 3.

Helium is a remarkably stable nuclear entity. If we assume that it forms during the second reaction, then 31.5–23.8 MeV = 7.7 MeV = $E_1$. This analysis is very simple. It is provided to illustrate the difficulty in interpreting the data in Fig. 3 as evidence of a single-step fusion process.

This present scientific uncertainty about the number and nature of the reactions involved in LENR certainly does not take away the strong evidence that both helium and heat are produced and are correlated, at least in experiments such as that reported by Miles, SRI International and others.

## References

[1] G.W. Draper and F.H. Ling, LENRaries. A New Era of Renewable Energy, Anthropocene Institute, http://www.anthropoceneinstitute.com/wp-content/uploads/2017/02/LENRaries.pdf (2017).

[2] http://www.ucmp.berkeley.edu/geology/techist.html and Henry R.*Frankel, The Continental Drift Controversy: Volume 1, Wegener and the Early Debate,* Cambridge University Press, Cambridge, pp. 152, 584 (2012). ISBN 978-0-521-87504-2.

[3] http://www.ucmp.berkeley.edu/geology/tecmech.html and http://geography.unt.edu/~mcgregor/Earth_Science/plate.tectonics.revise.pdf.

[4] http://web.ihep.su/dbserv/compas/src/einstein17/eng.pdf and https://www.aps.org/publications/apsnews/200508/history.cfm.

[5] https://journals.aps.org/pr/abstract/10.1103/PhysRev.99.1264 and https://en.wikipedia.org/wiki/Charles_H._Townes.

[6] https://en.wikipedia.org/wiki/History_of_superconductivity.

[7] https://en.wikipedia.org/wiki/BCS_theory.

[8] D.J. Nagel, Energy gains from lattice enabled nuclear reactions, *Current Science* **108** (2015) 641–645.

[9] T. Mizuno and Y. Toriyabe, Anomalous energy generation during conventional electrolysis, in A. Takahashi, K.-O. Ota and Y. Iwamura (Eds.), *Proc. 12th Int. Conf. on Cold Fusion*, World Scientific, Singapore, 2006, pp. 65–74.

[10] http://www.mpoweruk.com/fossil_fuels.htm.

[11] http://www.mpoweruk.com/energy_efficiency.htm.

[12] https://www.eia.gov/tools/faqs/faq.php?id=65&t=2.

[13] E. Storms, *The Science of Low Energy Nuclear Reaction*, World Scientific, Singapore, 2007, p. 175.

[14] D.J. Nagel and M.E. Melich, Preface, page xi in D.J. Nagel and M.E. Melich (Eds.), *Proc. 14th Int. Conf. on Condensed Matter Radiation Sciences*, http://www.iscmns.org/iccf14/ProcICCF14a.pdf_ (2008).

[15] G. Hubler, Private Communication, 2015.

[16] M.C.H. McKubre, F.L. Tanzella, I. Dardik, A. El Boher, T. Zilov, E. Greenspan, C. Sibilia and V. Violante, Replication of condensed matter heat production, in *Low-Energy Nuclear Reactions Sourcebook*, J. Marwan and S.B. Krivit (Eds.), American Chemical Society, 2008, pp. 219–247.

[17] E. Storms, Anomalous energy produced by PdD, *J. Condensed Matter Nucl. Sci.* **20** (2016) 81–99.
[18] M. Fleischmann, S. Pons and G. Preparata, Possible theories of cold fusion, *Nuovo Cimento* **107** (1994) 143–157.
[19] V.A. Chechin, V.A. Tsarev, M. Rabinowitz and Y.E. Kim, Critical review of theoretical models for anomalous effects in deuterated metals, *Int. J. Theoret. Phys.* **33** (1994) 617–670. www.lenr-lanr.org/acrobat/ChechinVAcriticalre.pdf and arXiv:nucl-th/0303057v2.
[20] E. Storms, *The Science of Low Energy Nuclear Reaction*, World Scientific, Singapore, 2007.
[21] E. Storms, *The Explanation of Low Energy Nuclear Reaction*, Infinite Energy Press, Concord, NH, 2014.
[22] R.W. Johnson, Introduction to theory papers in D.J. Nagel and M.E. Melich (Eds.), *Proc. 14th Int. Conf. on Condensed Matter Radiation Sciences*, p. 476, http://www.iscmns.org/iccf14/ProcICCF14b.pdf_ (2008).
[23] S.B. Krivit and J. Marwan, A new look at low-energy nuclear reaction research, *J. Environmental Monitoring* **11** (2009) 1731–1746.
[24] C. Frazier, *Infinite Energy Magazine*, Issue 112, pp.12–48 ((November/December 2013).
[25] P. Hagelstein, V. Dallacasa, N. Cook, E. Storms, A. Meulenberg, P.K. Sinha, V.I. Vysotskii, M.V. Vysotskyy, H. Kozima and D. Sinclair, Theoretical models of cold fusion, *Infinite Energy Magazine*, Issue 112 (2013). http://www.infinite-energy.com/iemagazine/issue112/index.html.
[26] P.L. Hagelstein, on theory and science generally in connection with the F–P experiment, *Infinite Energy Magazine*, Issue 108, pp. 5–12 (March/April 2008).
[27] D.J. Nagel and R.A. Swanson, LENR excess heat may not be entirely from nuclear reactions, *J. Condensed Matter Nucl. Sci.* **15** (2015) 279–287.
[28] https://en.wikipedia.org/wiki/Muon-catalyzed_fusion.
[29] A. Widom and L. Larsen, Ultra low momentum neutron catalyzed nuclear reactions on metallic hydride surfaces, *Eur. Phy. J.* **46** (2006) 107–111. DOI:10.1140/epjc/s2006-02479-8.
[30] I. Dardik, T. Zilov, H. Branover, A. El-Boher, E. Greenspan, B. Khachaturov, V. Krakov, S. Lesin and M. Tsirlin, Excess heat in electrolysis experiments at energetics technologies, in condensed matter nuclear science, *Proc. 11th Int. Conf. on Cold Fusion,* J.-P. Biberian (Ed.), World Scientific, New Jersey, 2006, pp. 84–101.
[31] M.C.H. McKubre, Presentation at Short Course prior to the 10th Int. Conf. on Cold Fusion, Cambridge, MA, 24 August 2003.
[32] G. Preparata, Everything you always wanted to know about cold fusion calorimeter, in *Proc. 6th Int. Conf. on Cold Fusion,* M. Okamoto (Ed.), 1996, pp. 136–143.
[33] D.J. Nagel, Questions about lattice enabled nuclear reactions: experiments, theories and computations, *Infinite Energy Magazine*, Issue 119, p. 18 (January/February 2015).
[34] F. Scholkmann, D.J. Nagel and L. F. DeChiaro, Electromagnetic emission in the kHz to GHz range associated with heat production during electrochemical loading of deuterium into palladium: a summary and analysis of results obtained by different research groups, *J. Condensed Matter and Radiation Sci.* **19** (2016) 325–335.
[35] D.J. Nagel, LENR Theories vs LENR experiments, in preparation.
[36] A. Widom and L. Larsen, Nuclear abundances in metallic hydride electrodes of electrolytic chemical cells, https://arxiv.org/pdf/cond-mat/0602472.pdf (2006).
[37] G.H. Miley, Possible evidence of anomalous energy effects in H/D-loaded solids – low energy nuclear reactions (LENR), *J. New Energy* **2**(3–4) (1997) 6–13 and G.H. Miley and J.A. Patterson, Nuclear transmutations in thin-film nickel coatings undergoing electrolysis, *J. New Energy* **1** (3) 5–13 (1996) and G.H. Miley, On the reaction product and heat correlation for LENRs, in F. Scaramuzzi (Ed.), *Proc. of the 8th Int. Conf. on Cold Fusion*, Lerici, Italy, 2000, pp. 419–424.
[38] F. Scholkmann and D.J. Nagel, Statistical analysis of transmutation data from low-energy nuclear reaction experiments and comparison with a model-based prediction of Widom and Larsen, *J. Condensed Matter Nucl. Sci.* **13** (2014) 485–494.
[39] D. Letts, D. Cravens and P.L. Hagelstein, Dual laser stimulation and optical phonons in palladium deuteride in low-energy nuclear reactions sourcebook, Vol. 2, American Chemical Society, Washington DC, 2009, pp. 81–93. and P.L. Hagelstein, D.G. Letts and D. Cravens, Terahertz difference frequency response of PdD in two-laser experiments, *J. Condensed Matter Nuclear Sci.* **3** (2010) 59–76.
[40] V.I. Vysotskii and M.V. Vysotskyy, Coherent correlated states and low-energy nuclear reactions in non-stationary systems, *Euro. Phys. J.* A **49** (2013) 99 and DOI 10.1140/epja/i2013-13099-2.

[41] D. Letts, A method to calculate excess power, *Infinite Energy magazine*, Issue 112, pp. 63–66 (November/December 2013).
[42] P.L. Hagelstein, Current status of the theory and modeling effort bases on fractionation, *J. Condensed Matter Nucl. Sci.* **19** (2016) 98–109.
[43] F. Metzler, P.L. Hagelstein and S. Lu, Observation of non-exponential decay in X-ran and gamma emission lines from Co-57, *J. Condensed Matter Nucl. Sci.*, in press (2018).
[44] F. Cardone, G. Albertini, D. Bassani, G. Cherubini, E. Guerriero, R. Mignani, M. Monti, A. Petrucci, F. Ridol, A. Rosada, F. Rosetto, V. Salazz, E. Santoro and G. Spera, Deformed spacetime transformations in Mercury, *Int. J. Modern Phys*. B **31** (2017) 1750168, DOI: 10.1142/S0217979217501685.
[45] F. Cardone and R. Mignani, *Deformed Spacetime*, Springer, Dordrecht, The Netherlands, 2007.
[46] D.J. Nagel, Questions about lattice enabled nuclear reactions: experiments, theories and computations, *Infinite Energy Magazine*, Issue 119, p. 28 (January/February 2015).
[47] M.H. Miles, R.A. Hollins, B.F. Bush, J.J. Lagowski and R.E. Miles, Correlation of excess power and helium pproduction during $D_2O$ and $h_2o$ electrolysis using palladium cathodes, *J. Electroanal. Chem.* **346** (1993) 99.
[48] A. Lomax, Replicable cold fusion experiment: heat/helium ratio, *Current Science* **108** (2014) 574–577.
[49] M.C.H. McKubre, F. Tanzella, P. Tripodi and P. Hagelstein, The emergence of a coherent explanation for anomalies observed in D/Pd and H/Pd system: evidence for $^4$He and $^3$He production, in F. Scaramuzzi (Ed.), *Proc. 8th Int. Conf. on Cold Fusion*, Lerici Italy, Italian Physical Society, 2000.