

Research Article

How Basic Behavior of LENR can Guide A Search for an Explanation

Edmund Storms*

LENRGY LLC, Santa Fe, NM 87501, USA

Abstract

The LENR effect was identified 27 years ago by Profs. Fleischmann and Pons as production of extra energy in a normal chemical structure, in this case PdD. Over a thousand published papers now support the discovery and the energy is shown to result from fusion of hydrogen isotopes without the need to apply energy and without energetic radiation being produced. By conventional standards, the claims are impossible. Nevertheless, a new phenomenon has been discovered requiring acceptance and understanding. The major behaviors and their present understanding are described in this paper and are used to suggest how an effective explanation might be constructed. Once again, science has been forced to either reject the obvious or accept the impossible. In this case, the normal skepticism needs to be ignored in order to determine if this promised energy source is real and can provide the ideal energy so critically needed.

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Keywords: Cold fusion, Cracks, Energy production, Hydrogen fusion, LENR, PdD, Theory

1. Introduction

Low Energy Nuclear Reaction (LENR) or Cold Fusion was introduced to the world 27 years ago by Fleischmann and Pons [1], University of Utah, with expectation of great benefit to mankind. Instead, their claim for a new kind of fusion was quickly rejected [2], an attitude that continues even today. Over the years, several thousand papers addressed the subject with a large fraction supporting the claim [3]. Mastery of about 1000 papers is now required to understand the effect. A description of all the known behaviors and all proposed explanations would require much more than a single review paper. Here, the behaviors the author considers important are examined first and then used to form the major structure of the proposed explanation.

Limits will be set using this observed behavior in order to evaluate a few proposed explanations including the one described in this paper. The new kind of nuclear interaction needed to explain LENR is expected to fall within these limits. In other words, boundaries need to be identified to keep the imagination from running wild. These limits are also based on the assumption that the LENR effect is consistent with all rules normally applied to conventional chemical and

*E-mail: storms2@ix.netcom.com.

nuclear behavior. Nevertheless, a novel mechanism is clearly operating in addition to these well understood behaviors. In other words, LENR does not conflict with conventional understanding, but instead has revealed a new, overlooked phenomenon.

Many conditions needing consideration are not quantitative or lend themselves to mathematical analysis. While frustrating to conventional scientists, these unique behaviors must be made part of a successful explanation. Quantitative behaviors can be used to expand understanding once the basic process is understood.

An effective explanation needs to solve several difficult problems. The Coulomb barrier needs to be overcome without using more energy than is normally available in a chemical structure at room temperature. Neutron formation, which has been suggested by several theoreticians [4,5], is prohibited because the required energy of 0.78 MeV and the required neutrino cannot be expected to be available at the same site at the same time.^a Once fusion has occurred, the mechanism must then dissipate the huge nuclear energy released by the process without producing local destruction of the chemical structure or energetic radiation. The mechanism must also account for various transmutation reactions known to occur. Failure to combine these events in a way that is consistent with known chemical and nuclear behavior dooms most efforts to explain the process. In contrast, a single mechanism is proposed in this paper to cause all observed behavior while being consistent with known chemical and nuclear behavior.

This paper has two parts, with the first describing the important observations on which an explanation must be based. The second part uses a few assumptions combined with these chosen behaviors to provide an explanation about how LENR can be initiated using a proposed mechanism. This mechanism is clearly much different from that causing the conventional hot fusion process. Ironically, this conflict is used to reject the claims for LENR rather than guiding a search for the cause of the difference. Consequently, this difference must be clearly understood before the novel features of LENR can be explored.

Unlike hot fusion, LENR takes place in and requires a chemical structure to operate. The role of this structure must be understood before physics is applied to understanding subsequent nuclear process. Clearly, a unique and rare condition must form in the structure in which a nuclear process can function. The nature of this condition is discussed following the discussion of hot fusion.

1.1. The nature of the hot fusion mechanism

The hot fusion mechanism uses high energy applied to plasma to overcome the Coulomb barrier by brute force. The resulting energy is dissipated as kinetic energy of the nuclear products, which are ^3He , tritium, proton, and neutron in equal amounts when deuterium is fused. This large applied energy changes the fusion rate in plasma as shown by the log-log plot in Fig. 1. The hot fusion rate is essentially zero at room temperature while the cold fusion rate can exceed 10^{12} events/s under conditions when no more than 1 eV of energy is available.

Hot fusion can also be initiated by bombarding a material by energetic deuterons. In this case, the fusion rate is slightly greater at low applied energy compared to when the same energy is applied to plasma, as can be seen in Fig. 2. Nevertheless, the fusion rate decreases as applied energy is reduced. In other words, the effective shielding of the Coulomb barrier does not increase as applied energy is reduced, even when the hot-fusion reaction takes place in a material.

Apparently the electron charge in a material can slightly lower the Coulomb barrier at the random encounters between the deuterium in the lattice and the bombarding deuteron when the applied energy is sufficiently low. While the electrons clearly help lower the barrier to achieve hot fusion, this effect alone would seem too small to explain

^aA neutrino needs to be supplied because neither an electron nor a proton contains a neutrino. Consequently, this particle needs to be supplied at the time of the reaction so that when the neutron decays later by emitting an electron and neutrino (or antineutrino), the required neutrino would be available.

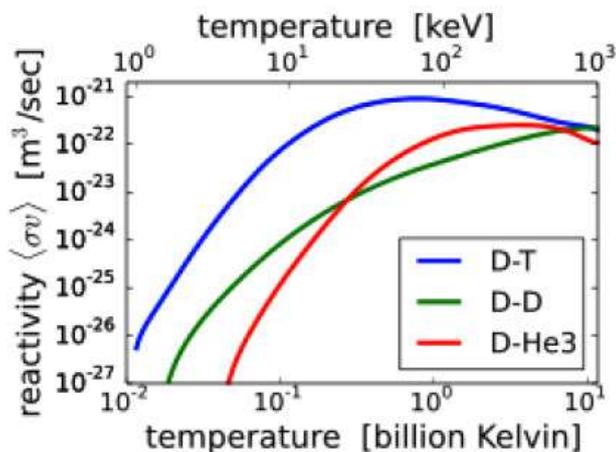


Figure 1. Effect of energy on the fusion rate in plasma for different combinations of hydrogen isotopes as result of the hot fusion process (Wikipedia).

the LENR process, although it might make a small contribution. In any case, the measured shielding effect applies only to the hot fusion mechanism. Perhaps more effective shielding during LENR might be expected if the shielding electrons were contained in a unique nuclear-active environment rather than having a random and low concentration in

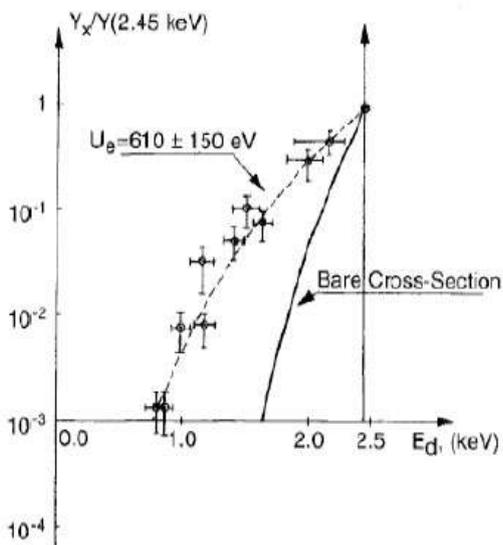


Figure 2. Comparison between the fusion rate in plasma (Bare Cross-Section) and when fusion occurs in a solid material as the result of applying energy to the bombarding D^+ ions, as shown by the X -axis. A value of unity occurs when the rate in plasma is equal to the rate using a target material [6].

the general structure where hot fusion interaction takes place. Consequently, LENR cannot be viewed as an extension of hot fusion. Instead, the process requires its own unique condition in the lattice in which a process operates that can lower the barrier without requiring extra energy.

Once the nuclei of deuterium have fused by hot fusion, the assembly breaks into fragments, which dissipate the excess mass–energy as kinetic energy. Easily detected energetic neutrons, tritium, protons, and He^3 are produced in equal amounts. This process is understood and is consistent with conventional expectations. A similar result occurs when muons are used to bring the nuclei close enough to cause fusion. In other words, no matter whether energy is used to overcome the Coulomb barrier by brute force or the separation is reduced by using the heavy muon [7–10], the same energy dissipation process results. No other method for energy dissipation as result of a fusion reaction was known to occur in nature until “cold fusion” was discovered. Clearly, the mechanisms causing hot fusion and cold fusion are significantly different because LENR does not lead to fragmentation of the nuclear products and the resulting energetic radiation.

This difference has caused much skepticism about the reality of LENR. After all, experience and teaching deny any possibility of spontaneous fusion taking place in an ordinary chemical structure without the need to apply significant energy. This apparent contradiction is resolved by proposing the cold fusion process takes place in a unique structure, called the nuclear-active-environment (NAE) where a novel mechanism might operate without conflicting with the laws that apply to the general structure. Questions about how this structure forms, where in the chemical structure this formation takes place, the nature of the unique conditions at the NAE, and the nuclear mechanism operating therein are explored later in this paper. But first, the nature of the general chemical structure is examined.

1.2. Role of chemical structure

General concepts will be explored first followed in later sections by detailed evaluation.

Because the LENR process takes place within a chemical structure, it must play by the rules such a structure imposes. This conclusion is critical to understanding the LENR process. These rules include the laws of thermodynamics and the phase rule. Local energy cannot spontaneously increase without violating the second law of thermodynamics and the local concentration of ambient energy is limited by how much energy the chemical bonds can tolerate before melting or decomposition results. Simply stated, energy cannot go up hill and its density cannot exceed the strength of the container. While these rules can be violated by random events at the quantum level, a process such as cold fusion that occurs at rates in excess of 10^{12} times/s must be consistent with the overall average behavior to which the laws apply.

If a novel mechanism is proposed to concentrate energy in order to cause nuclear fusion, why it is not found to affect chemical reactions? After all, if such a process were possible, it would be expected to operate in normal chemicals and cause chemical effects before the local energy had increased enough to cause a nuclear reaction. For example, the mechanism of energy transfer to electrons proposed by Widom and Larsen [11,12] would be expected to make many normal chemical compounds unstable. Furthermore, how such a proposed violation of the second law of thermodynamics can function in PdD needs to be justified. Similar conflicts with the laws of thermodynamics and normal chemical behavior create a similar weakness in many explanations now being proposed.

Normally, nuclear reactions of any kind are not affected by the chemical environment because the energy states are too different and local energy density cannot be increased according to the second law of thermodynamics. Apparently, the Coulomb barrier needs to be overcome by a process that does not require significant energy. This realization directs attention to the role of electron charge at the site of the fusion process. Nevertheless, the extra electron charge has to be consistent with limitations imposed by the local chemical conditions at the site.

Once fusion occurs, the structure must convert the excess mass–energy to heat without causing local melting. After all, local destruction of the active site would stop further heat production and severely limit the amount of energy

produced by LENR, which is not experienced. Once started, heat production is normally sustained for significant time. Although local melting is occasionally seen, it is not sufficient to limit the amount of power or its stability over time. Thus, the generated energy has to be dissipated well away from the fusion event and into the surrounding atomic structure as low-level heat energy. This requirement limits the form this energy release process takes and the energy of the emitted radiation.

Several different chemical structures have been found to support LENR, with PdD given the most attention. Consequently, PdD is the focus of further discussion.

1.3. The Nature of PdD

Palladium deuteride has attracted interest for about the last 100 years [13] during which time it has been studied extensively. Although the beta phase can acquire hydrogen up to about β -PdD_{0.98±0.02}, nothing about its overall behavior would suggest an ability to host a fusion reaction. The structure is face-centered-cubic (fcc) and exists in two slightly different forms having the same crystal structure based on the Pd sublattice. The alpha phase occurs between pure Pd and about PdD_{0.05}, and the beta phase forms near PdD_{0.6} when 1 atm of D₂ pressure is applied at 20°C. A two-phase region exists between these two compositions. The beta phase continues to acquire D atoms at random sites in the fcc sublattice as pressure is increased, finally reaching the upper limit of the fcc phase. Figure 3 shows the structure when all lattice sites are fully filled by deuterium. Another phase is expected to form and grow in amount as the overall D/Pd ratio increases beyond the upper limit to the beta phase, similar to the behavior of other metallic hydrides [14,15]. In other words, any composition in excess of PdD_{0.98} would be expected to be a two-phase mixture of the fcc and another phase having a different structure and increased stoichiometry. In the absence of the rare double occupancy [16,17] of normal lattice sites, the deuterium nuclei are too far apart to fuse. Achieving close approach without violating the rules of chemistry and without producing the fragmentation typical of hot fusion once fusion occurs remains a serious challenge.

Identifying where the NAE is located and what form it takes in the material has created a problem for many proposed explanations. Many explanations assume the fusion process takes place in a modification of the fcc structure when the D/Pd ratio is large. Formation of such a structure can be identified in the PdD structure because its formation would cause changes in its various properties. A search for the expected change can be made by examining several known properties, such as resistivity and lattice parameter as a function of D/Pd. The lattice parameter can be seen to have a linear [18–21] relationship to composition with no indication of a two-phase region forming within the limits of the beta phase. Both the pressure and resistivity [22] also show no sign of a change in crystal structure [23] over the composition range of interest. In every way, all properties are consistent with a normal fcc structure being present within the composition range in which LENR is found to occur.

On the other hand, Fukai [24] reported formation of a new phase when high pressure is applied at high temperature to PdH. This structure is proposed to also form under normal conditions during electrodeposition [25]. A similar structure change is proposed to be caused by deformation induced vacancies [26]. Such structures might also occur when repeated loading and unloading of PdD causes the structure to expand, producing what Storms [27] calls excess volume. Nevertheless, this condition does not explain LENR because the presence of excess volume over about 2% is found to inhibit LENR [28] rather than aid the reaction as would be expected if formation of metal atom vacancies were required to support LENR. In addition, no evidence for the Fukai phase forming when LENR is detected has been reported.

When a piece of Pd is found to be nuclear active, most of the entire batch is also found to be nuclear active. In addition, once the sample is made nuclear active, the LENR process using that piece becomes reproducible and robust. Obviously, the initial treatment of the entire batch creates stable conditions in which the LENR process can be initiated and then supported for extended times. Unfortunately, these conditions are seldom produced because their unique

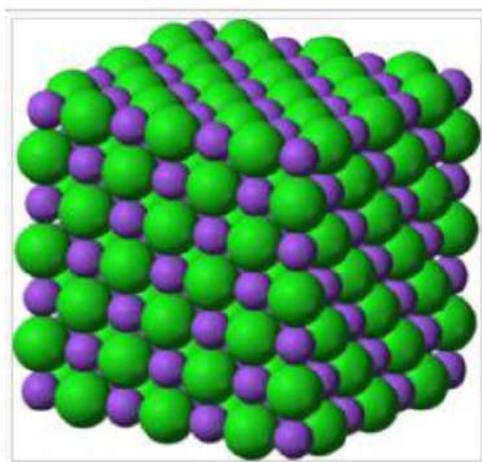


Figure 3. Crystal structure of the fcc PdD when all deuterium sites (*small purple*) are filled (Wikipedia).

characteristic is unknown and rarely formed by chance. Even when these required initial conditions are present, an additional special treatment is required before the nuclear process will start. These observations are important because they show that a treatment is possible to make large amounts of palladium nuclear active. A suggested combination of conditions is described later in this paper.

Initially, the LENR reaction was thought to take place anywhere in the PdD structure. Later studies reveal both helium [29,30] and tritium [31] form only very near the surface and not within the bulk material or on the surface where nanoparticles might be present. Transmutation products are also detected mainly in the surface region. Based on the known behavior of helium in PdH [32,33], the nuclear reactions apparently take place within a region perhaps no more than $10\ \mu\text{m}$ wide, extending from the surface into the bulk. We now need to discover the nature of the unique condition forming within this narrow band. The condition does not appear to involve a phase change, creation of vacancies in the hydride structure, creation of nanoparticles on the surface, nor does it require a high concentration of deuterium. Formation of the NAE would appear to require a unique condition present only within the surface region, which further limits the proposed nature of the NAE.

2. Important Observed Behavior

2.1. Formation of the NAE

In order for fusion to take place, the reacting nuclei must obviously be in the same place at the same time and with a critical distance between the nuclei. Normally, the D atoms are located at too great a distance to fuse. For the atoms to assemble with less distance between them, Gibbs energy must be released while the material achieves a different stable state. Generally, the atoms in a chemical structure are already close to their equilibrium condition and do not contain excess energy or have the ability to form another crystal structure unless the conditions are significantly changed. Simply increasing the D/Pd ratio does not create sufficient energy to change the structure in order to initiate the LENR process. Furthermore, for the process to be as rare and as difficult to initiate as is observed, the conditions for releasing this energy must be equally rare and difficult to create. To make the problem even more challenging, once the NAE is formed, LENR must operate at a significant rate without a further change in conditions. These conditions immediately place an important limit on any proposed condition in which LENR can take place.

Most samples of PdD do not host the LENR process regardless of the deuterium content presumably because the unique NAE is not initially present in the material. This conclusion suggests the NAE is not related to any of the features normally found in a chemical structure, such as vacancies, dislocations, and occupancy of unusual lattice sites. After all, if the NAE were related to these common features, the effect would be initiated more easily and more often. Multiple occupancy of the normal deuterium-atom vacancy must also be rejected based on this conclusion because, if such occupancy were possible, it would be present in all material under normal conditions and cause LENR with greater frequency. Nevertheless, a rare condition must form as result of some kind of treatment in order to account for occasional success. Failure to initiate LENR simply means this treatment was not successful in producing the required NAE. Once produced, the NAE appears to be stable and relatively constant in amount as indicated by production of relatively constant power.

Experience reveals another important behavior. When part of a batch of palladium can be made nuclear active, the remainder of the batch is found to be active. This activation treatment does not simply involve reaction with D but also requires extended electrolysis and/or repeated deloading and loading with D. This behavior is important because it reveals that the NAE can be created throughout an entire batch of Pd as result of a common treatment. In other words, the physical treatment of the palladium metal before reacting with deuterium affects later initiation of LENR.

Once the nuclei are assembled in the NAE, a unique process must reduce the Coulomb barrier, perhaps by a tunneling mechanism without using energy beyond that which is normally available at room temperature. Immediately, we are confronted by a problem. Normal chemical structures are known not to support nuclear reactions without significant energy being applied to bombarding ions. After all, the Coulomb barrier keeps nuclei separated and allows chemical structures to form in the first place by interaction between the electrons. The energy required to force the nuclei close enough to fuse is well in excess of the energy holding the atoms in the structure and in excess of the electron energy. This well-known and accepted behavior suggests a need to form a novel arrangement between the nuclei in the NAE designed to avoid this limitation.

In summary, two separate processes have to be considered. The first is creation of the NAE. The second is formation of a structure of H and/or D within the NAE having the ability to fuse. This nuclear process is separate from the structure of the NAE, but needs to be consistent with it. A description of the fusion process is a job for physics while identification of the NAE is a job for chemistry. Thus, we are forced to acknowledge an uncomfortable marriage between two normally independent branches of science, with chemistry being applied first to identify the NAE.

2.2. Nature of the NAE

Two different kinds of NAE have been suggested. Many researchers place the LENR process in the normal crystal structure where vacancies or dislocations might be present. Other people identify the NAE as being nanoparticles or other active sites located on the surface of the structure. These structures and flaws are normal variations in a material that for some reason becomes nuclear active.

In contrast, Storms [34] places the NAE in cracks having a critically small gap, which are separate from and chemically independent of the crystal structure. Such an environment can have properties much different from a crystal structure, including a high negative charge. Resolving this fundamental difference in proposed location of the NAE is critical to understanding the LENR process because the chosen location sets the logic on a particular path. A choice of the wrong path will result in arriving at the wrong understanding.

In order to contrast these two proposed conditions, the well documented suggestion by Hagelstein et al. [35] is explored. Hagelstein's idea is based on formation of a new phase in the normal fcc structure, such as suggested by Fukai and Okuma [36]. This phase is proposed to form on occasion after the deuterium content has exceeded $D/Pd = 0.95$ in a co-deposited material, thereby causing formation of palladium atom vacancies. Deuterium atoms fill the vacant sites and form a structure in which fusion is proposed to occur. The resulting mass–energy is dissipated by

phonons. Evidence for this proposed phase change can be obtained by searching for a discontinuity in the various physical or chemical properties. As noted above, such a search reveals no evidence for a phase change within the composition range of the beta phase. In addition, X-ray and neutron diffraction studies of the fcc structure reveal no phase change in this composition range. No evidence supports a co-deposited structure being present on the surface and helium release is not consistent with its source being so near the surface.

The NAE is apparently a feature outside of the thermodynamic behavior and its presence does not affect the measured physical properties. This conclusion is important to correctly identify the NAE.

The author, in several previous papers [37–39], identifies the NAE as residing in nano-cracks resulting from stress relief. As is required, these gaps exist outside of the chemical properties and are not influenced by limitations imposed by the chemical structure. As long as a gap having a critically small width is created, deuterons are proposed to enter the gap and to form a structure. This structure then experiences fusion by a novel mechanism. The required gap width is rarely created because most cracks would quickly become too wide to host the required hydrogen structure. Consequently, success in creating the NAE involves applying modest stress to a structure containing many weak regions having a similar ability to form small cracks. This condition might be created by accident as result of various intended and accidental treatments, thus accounting for occasional success that might even be attributed to other effects.

Although large cracks are often seen when LENR occurs, the cracks having the ability to act as the NAE are too small to be easily detected and can be overlooked. In fact, unless these structures are sought using high magnification, they would be impossible to detect. Experience shows the critical initial condition can also be created in an entire batch of material by a yet to be identified pretreatment. This realization encourages search for such a treatment.

Deciding which explanation should be explored is important because they each propose entirely different treatments to cause the LENR process. The wrong choice of explanation can lead a researcher down the wrong path with much wasted effort.

2.3. Power production

The LENR effect was first identified by its ability to produce energy in amounts greater than would be possible by any chemical reaction. The first reported success resulted when Pd was used as the cathode in an electrolytic cell containing an electrolyte consisting of $D_2O + LiOD$. When a Pd cathode is initially subjected to this treatment, the deuterium concentration in the Pd increases while energy is absorbed by the reaction, as shown in Fig. 4. Energy is absorbed because the energy used to decompose the D_2O into D_2 and O_2 is greater than is recovered when the resulting D_2 reacts with Pd, thereby causing an overall endothermic reaction.

The enthalpy of formation for deuterium can be calculated using the data in Fig. 4. For this purpose, the total amount of D reacted every six minutes is divided by the amount of energy absorbed during this time, from which the amount of energy used to decompose the D_2O is subtracted. As can be seen in Fig. 5, the electrolytic method applied to a solid piece of Pd gives values for the partial enthalpy of formation similar to the values obtained when D_2 is reacted directly with Pd nano-powder. Both reactions show that chemical energy is released when Pd reacts with D_2 and the amount decreases as the D/Pd ratio increases.

The equilibrium deuterium activity, presented as pressure, is also plotted to show the large range in values being applied to the material by the electrolytic process. The deviation from ideal behavior, called fugacity, is not taken into account.

Additional treatment was later required to start the LENR process. No additional phase forms in this composition range, such as proposed by Fukai, as indicated by the smooth unbroken variation of ΔH and pressure. Also, the smooth unbroken change in resistivity observed by McKubre et al. [22] while LENR took place is also consistent with this conclusion.

In summary, no evidence supports the claim for the NAE to result from a phase change or vacancy formation within

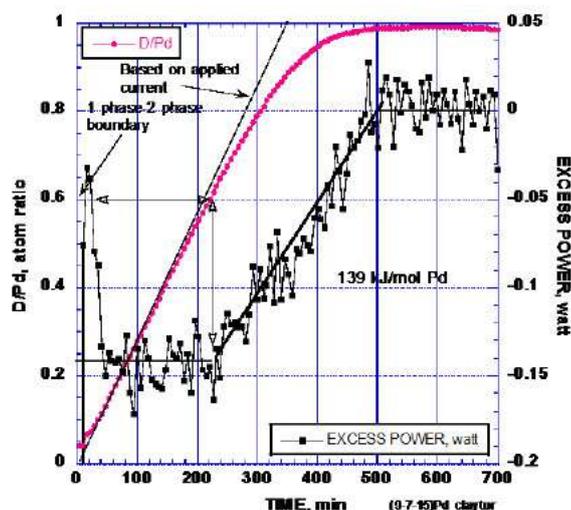


Figure 4. The D/Pd ratio and resulting power when Pd is reacted with D₂O using the electrolytic method. All D made available by the applied current initially reacts with the Pd. The amount reacted is reduced only gradually as the upper limit is reached. No excess energy is produced even after the average D/Pd ratio becomes very large. The total amount of energy/mole Pd absorbed by the process is noted. (Storms, www.LENRexplained.com).

the composition range in which excess energy production is found to occur.

The effect of temperature on power production for various D/Pd ratios is compared in Fig. 6. Samples having D/Pd = 0.80 and 0.48 produce the same amount of power at the same temperature. Removal of all deuterium stops power production. Clearly, power is not as sensitive to the deuterium content as previous studies suggest [42]. Nevertheless, some D is required for LENR to function.

The Arrhenius plot (Fig. 7), using the data in Fig. 6 (D/Pd = 0.8), shows the activation energy for the LENR process to be nearly equal to the value for diffusion of D in PdD. In other words, the rate of the fusion process is sensitive to the rate at which D can get to the site where fusion takes place and it is not sensitive to the concentration of D in the surrounding lattice. The fusion process can be proposed to rapidly convert deuterium in the NAE to fusion products, after which new D has to move relatively slowly from the surrounding lattice in order to supply additional fuel to the active sites. The rate of energy production is determined by the rate at which D can get to the NAE, not by the rate of the fusion event itself. A buildup of helium around the NAE could slow the reaction, as suggested by Hagelstein, if the diffusion rate of D⁺ were reduced by helium occupying sites the D⁺ needed for diffusion to occur. By analogy, this is similar to the speed of a car being determined by how fast gas is delivered to the engine and not related to the amount of gas in the tank or the reaction rate within each cylinder.

The resulting equation allows the power to be predicted when temperature is increased. Clearly, simply increasing temperature can produce significant power. Removing an active sample from the electrolytic cell and exposing it to D₂ gas at increased temperature would be expected to result in significantly more power than can be achieved within the 100°C limit imposed by the electrolytic cell.

2.4. Probability of forming the NAE

Figure 8 compares power produced by 157 studies reported before 2007. Notice that most studies produce power at relative low levels. On a few occasions, a large amount of power is observed with the number of reports rapidly

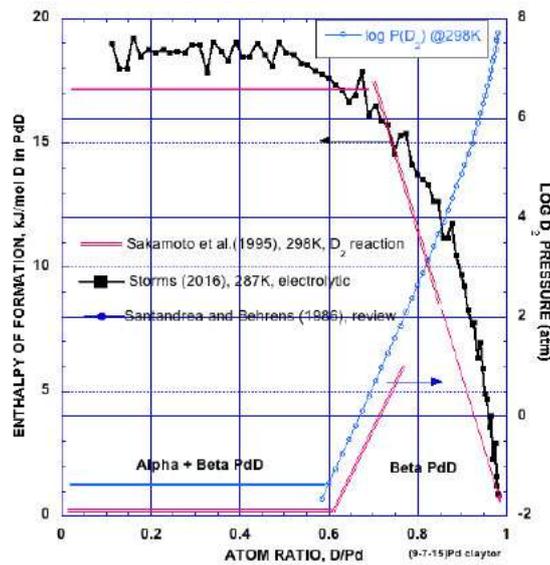


Figure 5. Enthalpy of formation calculated using the data shown in Fig. 4 based on the amount of D reacted every 6 min, the amount of power measured during this time, and the amount of energy used to decompose the D_2O from which the D results. The reaction of D_2 with Pd is exothermic. The Sakamoto et al. [40] line is obtained using their reported linear equation, which is then extrapolated from $D/Pd = 0.85$ to 0.98 , and their reported D_2 pressure. The pressure of D_2 is also obtained from the review by Santandrea and Behrens [41] (Storms, www.LENRexplained.com).

decreasing as the reported power increases. Although various size samples are used, the behavior does not seem to be related to area or volume. The concentration of the NAE seems to be the important variable, which is uniquely determined by the nature of the Pd and its treatment.

The number of reports, shown in Fig. 8 can be compared to predicted behavior based on an assumed probability of causing increased power once power production is possible. In other words, the probability of forming additional NAE once the conditions allow some NAE to form can be estimated and compared to the behavior to see if the assumption of random formation fits.

If the average power is assumed to be related only to the concentration of NAE, if 300 attempts are made to initiate LENR and the probability of producing 10 W is 0.3, the probability of producing 20 W would be 0.3×0.3 , and the probability of producing 30 W would be $0.3 \times 0.3 \times 0.3$, etc. The dashed line shows the number of predicted successful observations at each power level. The relatively good fit to the observed behavior suggests the power is caused by an increasing number of active sites whose creation is caused by a random process, with more power resulting as the number of NAE sites is increased by a process having low probability. The probability of producing any power at all would be expected to be much less than production of additional power once conditions allow some NAE to form. The data do not allow determination of the probability to form the initial NAE.

2.5. Helium production

Helium formation is the main source of power produced by LENR when deuterium is used and provides much information about the nature of the nuclear process. Sixteen measurements of the helium/energy ratio have been published. These values are compared as a histogram and plotted using $\log He/energy$ in Fig. 9. $D + D$ fusion is proposed as the source because no other nuclear reaction forming helium releases the amount of energy required to be consistent with

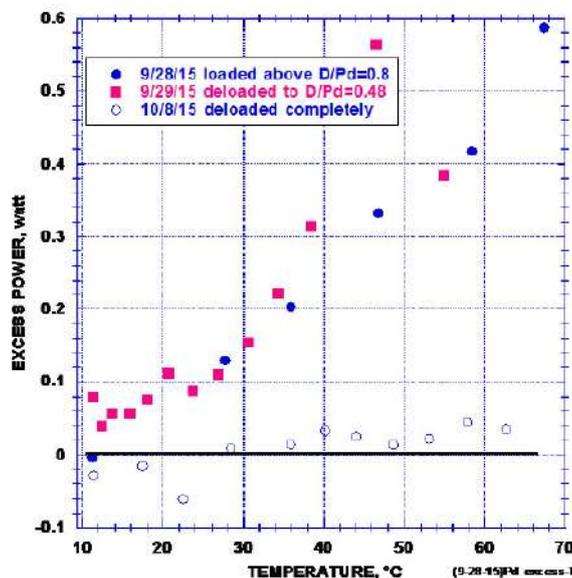


Figure 6. Effect of temperature on power production when three different amounts of deuterium are present in the sample (Storms, www.LENRexplained.com).

the measurements. Nevertheless, two reactions occurring at the same time with always the same ratio of energy and helium might account for the value. If so, one might wonder how such a combination of independent reactions just happened to give a consistent ratio nearly equal to the value produced by the $D + D$ fusion reaction.

For the helium to be detected in the gas produced by electrolysis, the source must be very near the surface. Otherwise, the helium would be retained by the PdD [32,33, 44–46]. The amount of retained He has not been determined. Nevertheless, when efforts are made to coax helium out of the metal, the total amount of helium is found to be very near the amount expected to result from the $D+D$ fusion reaction [47,48].

2.6. Tritium production

Tritium is occasionally detected when LENR is initiated by either the electrolytic or gas discharge method. Formation of this radioactive isotope of hydrogen once again demonstrates the occurrence of a very unusual nuclear process. On some occasions, the neutron flux produced by the process is also measured, which is shown as the tritium/neutron (T/n) ratio in Fig. 10. The ratio frequently reported near 10^6 suggests tritium and neutron production are correlated in a general way. As an example of possible correlation, Storms [34] suggests the neutrons result from $D+e+T$ fusion, a reaction that would increase as the concentration of tritium increased in the material, thereby creating an apparent correlation between tritium and neutron formation. The energy of the resulting neutrons would be predicted to be less than those known to result from $D+T$ fusion by the hot-fusion mechanism.

In contrast, the conventional hot fusion reaction produces a T/n ratio of 1, or zero when plotted as the log. Clearly, the ratio resulting from the LENR process does result from the hot fusion-type reaction.

The detected tritium has been shown to result from a nuclear process occurring very near the surface of the cathode when the electrolytic cell is used [31]. The rate of tritium production is also sensitive to the H/D ratio in the material [49] and Claytor (private communication) and to the nature of the material in which production takes place. Apparently,

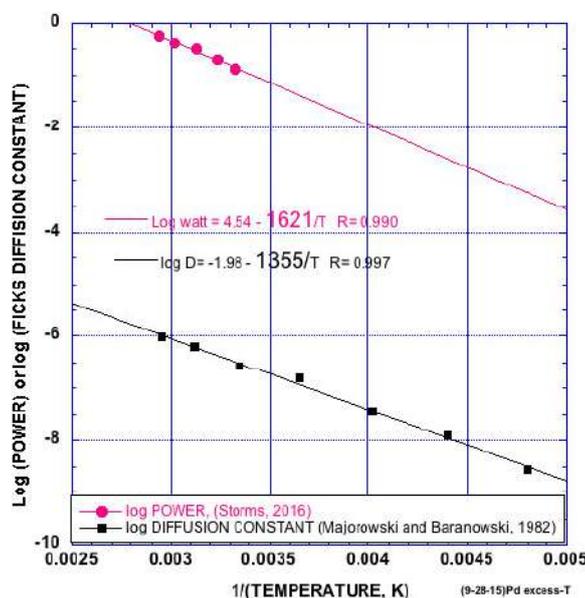


Figure 7. Comparison between the rate of diffusion of D in PdD and production of LENR power as a function of $1/T$. The similar slopes created by the data suggest both processes are affected by the same mechanism, i.e. diffusion of D through PdD [43].

production of He and tritium occur at the same location in the active material and both reactions appear to involve isotopes of hydrogen.

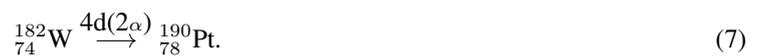
2.7. Transmutation production

Transmutation in the context of this paper is a process during which light nuclei, frequently isotopes of hydrogen, enter the nucleus of a much heavier atom, thereby producing energy and one or more nuclear products. Two kinds of transmutation are observed. The first is found to add various numbers of ^4He to the target without fragmentation of final nucleus and the second to result in fragmentation of the target after addition of some protium.

Iwamura et al. [50–52], working at Mitsubishi Heavy Industries Ltd in Japan, have studied the first type of transmutation by allowing D_2 to diffuse through a sandwich consisting of alternate layers of Pd and CaO, with the presence of CaO being important to success. The transmutation reactions occur on the surface of palladium where target nuclei have been deposited before D_2 is applied. Using X-ray fluorescence to determine the amount of material, they followed the loss of target material from the surface along with increase in the nuclear product. Examples of the various transmutation reactions are listed in Eqs. (1)–(7).

A successful explanation must show how the considerable Coulomb barrier is overcome, how excess energy resulting from the reaction is dissipated, why transmutation of Pd is not observed, and how more than one helium nucleus can be added to the target at the same time. The explanation must also show why the CaO layer can have an effect on a nuclear reaction occurring on the surface when it is separated from the surface by 40 nm of Pd. Equations (1)–(7) show the summary of the transmutation reactions reported by Iwamura et al. [50].





Miley and Patterson [53], Miley [54] as well as Srinivasan [55] report finding fragmentation products resulting from transmutation of palladium when palladium is used as the cathode in an electrolytic cell containing D_2O and/or H_2O . As can be seen in Fig 11, the Pd cathode apparently fragments into two parts in addition to experiencing addition of ${}^4\text{He}$ to the target nucleus. The platinum impurity on the cathode surface also shows evidence for similar transmutation

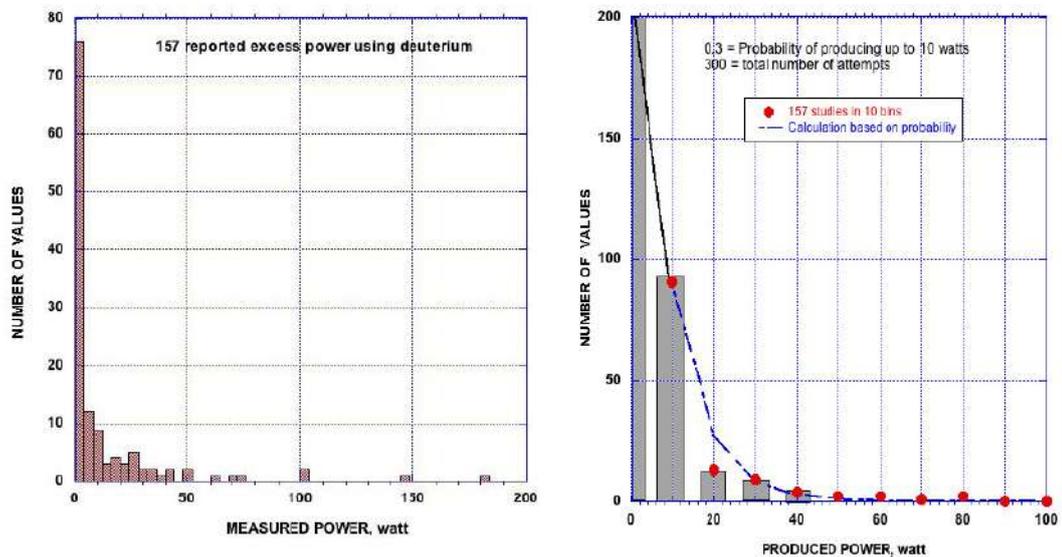


Figure 8. Histogram of power production vs. the number of reported values. A probability function, shown as the dashed line, is used to fit the data to bins at 10 W intervals.

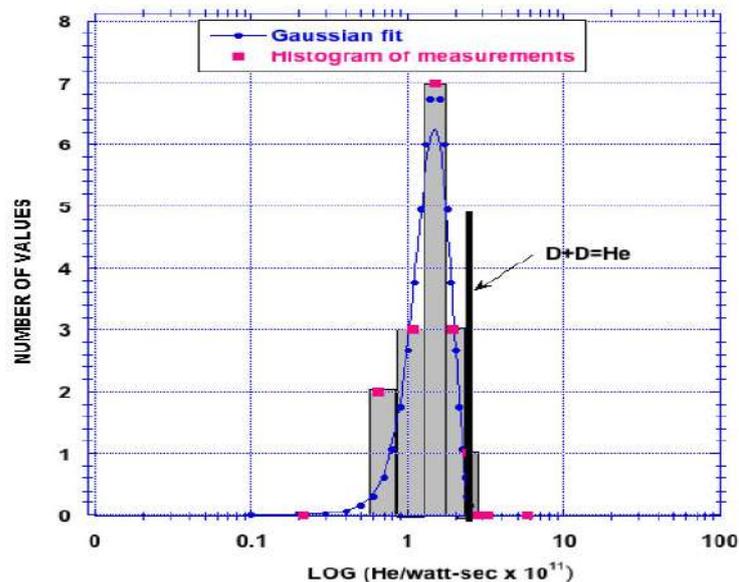


Figure 9. Histogram of reported values as a function of the log He/energy ratio as listed by Storms [30]. Many results showing no power along with no helium would fall at zero on this plot. The expected ratio produced by the $D+D = He$ fusion reaction is shown by the vertical line. A Gaussian error function is fit to the values, which gives a center value of 1.5×10^{11} He/J with uncertainty of $\pm 0.9 \times 10^{11}$ He/J.

reactions. Once again, how the large Coulomb barrier can be overcome must be explained. In this case, explaining the dissipation of energy is not a problem because it is carried by the fragments, as is expected.

2.8. Radiation production

Production of energetic radiation is a necessary result of nuclear reactions as the resulting energy is dissipated into the surrounding material. Each type of radiation responds differently to its passage through material. Photons, also called gamma rays when they are emitted by a nucleus, are reduced in number but their energy does not change as they pass through matter. Particles, such as electrons (beta rays), 4He (alpha particles), neutrons, and hydrogen nuclei all change energy as they pass through matter. In the process, their energy is converted to heat while most of the particles are quickly stopped by the material. If the energy is large, secondary radiation may be produced as the particles interact with electrons in the absorber [56–59]. Evidence for each type of radiation has been reported to result from LENR. The flux ranges from being trivial to being significant, but never sufficient to account for the energy being produced at the time. Clearly, the methods of energy dissipation are complex and handicapped by being largely hidden by being absorbed in the material surrounding the process.

In any case, the amount of radiation exposure experienced by a researcher or by commercial application is not a threat. This advantage is in sharp contrast to the situation when energy is created by hot fusion.

3. Summary of Behavior

Creating an explanation is like doing a jigsaw puzzle with some pieces missing. Nevertheless, the pieces in hand need to be fit together in the proper way in order to reveal the shape of the missing pieces. The greater the number of

successful fits, the better the missing pieces can be imagined and the more effective the search becomes. In addition, limits need to be placed on the imagination when attempts are made to describe the shape of the missing pieces. As with a jigsaw puzzle, each piece has to be consistent with other pieces and cannot be described in isolation. In other words, all the observed properties have to show consistency in their interaction and cause. The shape of the pieces now in hand can be described as follows:

- (1) The LENR reaction does not take place in a conventional chemical structure no matter how large the hydrogen content. Features normally present in conventional structures, such as vacancies of any type, dislocations, large cracks, nanoparticles, or impurities, do not host the LENR process. Instead, a unique condition called the nuclear active environment (NAE) must form. The LENR process takes place only in this unique feature and the rate of the nuclear processes is related to the number of NAE sites present.
- (2) PdD does not appear to form phases or structures besides the fcc crystal structure within the temperature, pressure, and composition range used to cause LENR.
- (3) The NAE is not normally present in a material but needs to be created by various treatments. The probability of forming the initial NAE is presently very small. Once the NAE can form, adding to the amount becomes increasingly difficult as attempts are made to increase the amount.
- (4) When an individual piece of palladium is found to form NAE and host LENR, most of the batch from which

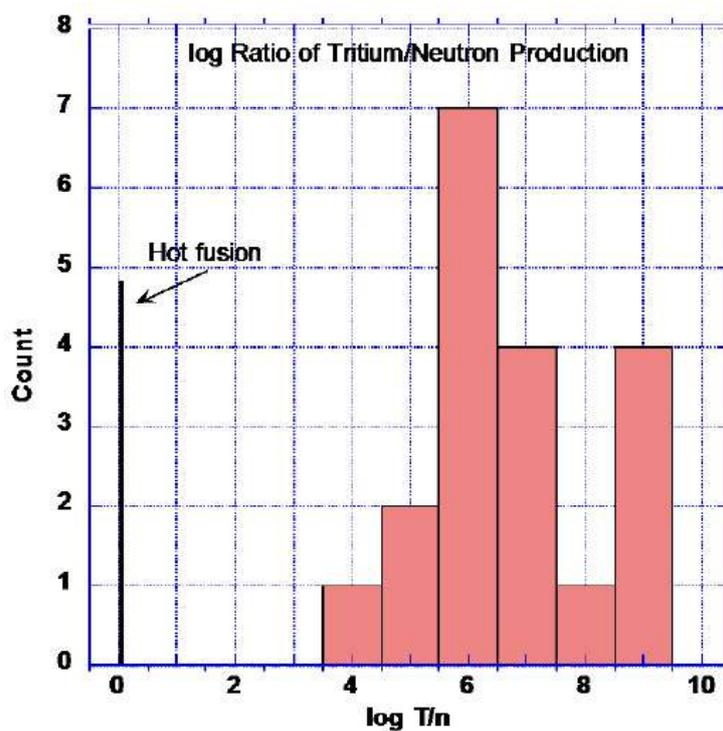


Figure 10. Histogram of the log tritium/neutron ratio resulting from the LENR process. The value for the hot fusion reaction is also shown. The spread in values is justified by the large error expected to result when the small neutron flux is measured. The source of the values is the book by Storms [3].

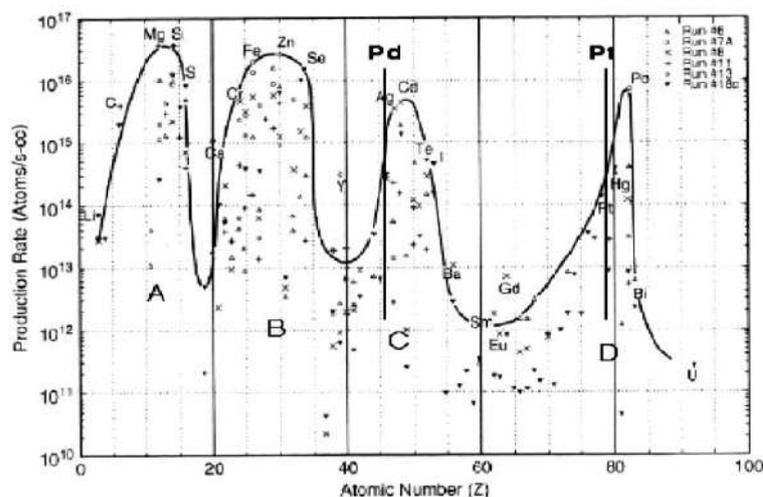


Figure 11. Spectrum of transmutation products reported by Miley and Patterson [53] and Miley [54] based on samples exposed to H₂O and/or D₂O during electrolysis. Some of the elements are expected to result from contamination, which can be ignored without changing the basic shape of the elemental distribution. The atomic number of the two major elements on the surface are noted.

the piece is obtained is also found to be nuclear active, thereby revealing the presence of a common condition and treatment being important to cause the LENR process.

- (5) Once the NAE forms, the hydrogen fuel must spontaneously assemble in the NAE by a conventional chemical process.
- (6) When electrolysis is used, the NAE forms in the material near the cathode surface where stress is concentrated and cracks are observed to form.
- (7) A process operating within the NAE lowers the Coulomb barrier and, at the same time, dissipates the excess mass–energy without fragmentation of the fusion products.
- (8) Production of at least helium-4, tritium with T/n ratio of about 10^6 , and two different types of transmutation take place in the NAE. Apparently, transmutation can also take place in biological systems [60]. Whether fusion takes place as part of this transmutation process is unknown but important to consider.
- (9) Radiation consisting of neutrons, energetic ions, photons, and electrons are produced. Most radiation has too little energy to escape from the apparatus. In each case, the detected flux intensity outside the apparatus is not correlated with energy production and is very small compared to the generated energy.
- (10) The effect of temperature on power production appears to be related to the rate of diffusion of deuterium in the material.
- (11) The effect of the D/Pd ratio on power production seems to be small.
- (12) LENR can be initiated in several different kinds of chemical structures while using different methods to initiate the process. This behavior indicates a process having universal characteristics may operate.

Each of these behaviors severely limits how imagination can be applied to finding an explanation. Each general behavior must be accounted for and be consistent with the proposed NAE and the nuclear mechanism. While many conditions and mechanisms can be and have been suggested, the search for the correct explanation requires all observed behavior to be considered, not just behavior that supports the proposed explanation. Likewise, behaviors expected but not reported also must be considered.

A theory of LENR, like a successful jigsaw puzzle, requires all the behaviors be used without forcing a fit. The missing behaviors can be identified only after their correct position in the puzzle is identified. At this stage in the search, the process is less like physics and more like solving a crime.

4. Creating a Theory

An explanation can be used to guide research and help to understand the resulting behavior. In addition, predictions can be suggested to test various assumptions. As much as possible, the explanation needs to be made consistent with all observed behavior and with the laws governing chemical behavior. Nevertheless, some assumptions must be made, which are best kept as simple as possible.

The LENR effect presents three major problems for an explanation. We need to explain how LENR works based on its observed behavior; we need to know why it works by using known physics; and we need to know how to make it work on demand by using the science of metallurgy. Each of these problems requires different kinds of information to which different approaches are applied. For example, the calculations using quantum physics have no hope of revealing how to make the effect work using real materials. The metallurgy needed to design a nuclear active material has no role in showing how the nuclear physics of the process needs to be described. The observed behavior can be used to guide the physics and metallurgy, but only when the important features are accepted as being real and meaningful. Somehow, the discussion has to address these issues as independent subjects and then combine them into a universal process. This paper focuses mainly on the logical consistency between observed behaviors using conventional chemistry and on physics to which are applied several plausible assumptions. Finally, the conclusions are applied to suggest a treatment that can cause the LENR effect.

It is important to consider LENR as a new kind of nuclear interaction. Whether a new kind of physics is required is not clear. Because the conditions and results are not consistent with experience, the LENR process defies understanding when attempts are made to apply conventional knowledge. This conflict forces consideration of new and completely novel mechanisms about how hydrogen nuclei can interact in a chemical structure. The conflict does not justify rejection of LENR.

Rather than using theory and experience based on conventional nuclear interaction or the esoteric concepts common in physics, this paper adopts a different approach [34,37,38]. No effort is made at this stage to create a mathematical description based on quantum mechanics, as is common practice. Acceptance or rejection must flow only from the plausibility of certain assumptions and the logical consequence of their application.

Think of this approach as the creation of a map based on individual reports of various explorers. A few assumptions are made about the basic topography of the land, but the details come only from a logical interpretation of available reports. The goal is to provide aid for future explorers in their search for the expected buried gold. The better the map, the fewer false paths are taken. The details of how the gold got to its location by some complex chemical and geological process is not initially important to explorers and their map. A map seeks only to show the features present on the landscape, not why they formed. Once the map is accepted, physics can be applied to understand how the process works.

5. Assumptions

Assembling the various observed LENR behaviors into a consistent picture requires several assumptions. These assumptions can be justified but not proven. They should be judged only on their plausibility. The assumptions chosen here address mainly the result, with less emphasis on the cause. Nevertheless, the result shows where the cause might be sought.

The nuclear mechanism involving LENR is unknown but it can be assumed to have certain characteristics and

consequences. Listed below are the assumptions on which its overall description is based along with reasons why these assumptions were chosen.

- (1) Creation of the NAE is assumed to follow the rules of conventional chemistry, i.e. the laws of thermodynamics apply to its formation and action. Nevertheless, its eventual role in causing a nuclear reaction would not be anticipated based only on its structure. It is important to realize, this later event is a lucky consequence made possible only because the chemical structure happens to have several unique properties.

Justification: In contrast to hot fusion and other nuclear processes, LENR requires a chemical structure in which to function. No other nuclear process has this requirement. Any change in a chemical structure, such as creation of the unique condition required of a NAE, would involve a chemical process, which in turn must follow the rules known to affect chemical reactions. Therefore, before LENR can occur, chemistry must be involved, to which the laws of thermodynamics apply. The amount of power produced is critically dependent on the amount of NAE present in the material, which at the present time is highly variable and caused by an unknown and seemingly random process (see Fig. 8).

- (2) The NAE is assumed to be a gap in the crystal structure created as a crack begins to form as result of stress relief, with a critical width near 1 nm. The gap stops being a NAE when the gap width grows too large.

Justification: The common conditions normally present in a crystal structure, such as vacancies and dislocation, are not consistent with the rare nature of LENR and its required unique characteristics. Yet, the NAE must form under a variety of conditions in a variety of materials. These requirements eliminate most features known to exist in a normal material. The nano-crack remains as a plausible possibility in which a linear molecule of hydrogen might form, as described next. Of course, only nano-cracks having access to hydrogen would become nuclear active, which would be rare under most conditions. In other words, both the NAE (in the proposed form of a nano-crack) and hydrogen isotopes must be present simultaneously in a material for the proposed nuclear process to happen.

This gap might form in any material, such as SrCeO₃ when it is used as a proton conductor [61], AlLaO₃ [62] or in the chemical support of a chemical catalyst such as when Pd is deposited on carbon [63]. A particle of Pd, regardless of its size, is not considered able to be made nuclear active when it is too small to form stress cracks.

- (3) The hydrogen atoms prior to fusion are assumed to assemble and form a chemical structure located within the NAE. The proposed structure is assumed to have the form of a linear molecule called the Hydroton. This structure has the ability to host fusion of the hydrogen atoms contained therein by a unique and unknown process.

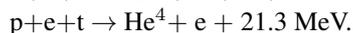
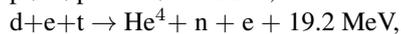
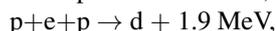
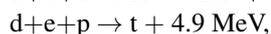
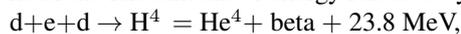
Justification: The NAE is part of a chemical structure. As such, it must play by the same rules the surrounding structure obeys. Assembly of hydrogen atoms in the NAE would involve a chemical process. For this process to be spontaneous, Gibbs energy would have to be released as the hydrogen ions move from their location in the surrounding lattice and into the NAE. In other words, the formation of a crack creates a chemical environment in which the hydrogen atom has a lower Gibbs energy than in the surrounding lattice. For the sake of this discussion, the resulting structure, called a Hydroton, is assumed to have covalent-metallic bonding in which all the atoms share the bonding electrons. These electrons along with those contributed by the surrounding Pd atoms are expected to play a role in reducing the Coulomb barrier by electron screening.

- (4) Regardless of which hydrogen isotope is present or the nature of the surrounding material, the same mechanism is assumed to cause fusion between hydrogen nuclei and dissipate the resulting excess mass–energy. Only the nuclear products are different for a different combination of hydrogen isotopes.

Justification: A phenomenon having such unique behavior and rarity would not be expected to have more than one cause. In addition, Nature is known to use as few causes as possible. For these reasons, search for

a single universal mechanism and NAE is a safe first step.

- (5) The hydrogen nuclei are assumed to fuse with an electron, as proposed by Romodanov et al. [64] This assumption is applied here to all isotopes of hydrogen. As a result, the following nuclear products and released energy are created, where d represents the deuteron, p the proton, t the triton, e the electron, and n the neutron. The amount of energy released by each reaction is noted.



Justification: Tritium is produced without significant neutron emission. The only fusion reaction able to produce this behavior requires addition of an electron when d and p fuse. Assumption #4 requires this process to create all the nuclear products regardless of which isotope of hydrogen is used. Possible involvement of the neutrino is ignored for the present. The electron (e) is captured because it is present along with the nuclei as the source of chemical bonding. As such, it is part of the energy state involved in the fusion process.

- (6) The extra mass–energy is assumed to leave gradually from each nucleus as photon radiation. This release process is ongoing and continuous after a group of hydrogen nuclei has assembled in the NAE and continues until all excess mass–energy has been lost and fusion between all the nuclei in the Hydroton is complete. While this behavior is listed as an assumption, this important idea is expanded in greater detail in Sections 6.10 and 6.11.

Justification: Somehow the excess mass–energy must be converted to heat energy. This process can be imagined to happen either before, during, or after the nuclei fuses into the predicted nuclear products. If this energy-loss process is assumed to take place during or after fusion, absence of the hot fusion products must be explained. This problem is avoided by assuming the excess mass–energy is converted gradually to heat by weak photon emission before the nuclei have become a single nucleus. The unique “magic” revealed by LENR involves this process.

- (7) Fusion is assumed to occur between adjacent nuclei when enough nuclear energy is released to form a nuclear product without additional release of mass–energy being required. This process is explained in Section 6.4.

Justification: To explain the absence of hot fusion and its energetic radiation, enough excess mass–energy must be lost from the combining nuclei to avoid fragmentation of the final nucleus. To avoid some energy remaining in the final product, this loss process is assumed to continue until the final nucleus would contain no excess mass–energy, whereupon the two nuclei would combine to form a single nucleus without release of additional energy. Failure to follow a strict equal loss from each nucleus would be unacceptable because some nuclei might end with too little or too much mass energy. Some of the extra energy expected to reside in the normally unstable 4H might be lost as photon emission before the 4H forms, thereby avoiding the expected decay by neutron emission. The emitted electron is proposed to have too little energy to be easily detected.

- (8) Two kinds of transmutations occur during LENR, but at a low rate [55,65]. Both kinds of transmutations are assumed to result from the fusion process and involve different isotopes of hydrogen. Formation of nuclei having greater atomic number than the target is assumed to result from fusion of d, during which various numbers of 4He nuclei are added to the target [66]. Because this process adds very little energy, the need for the final nucleus to fragment is avoided. Fusion products having a fraction of the target mass are assumed to result from fusion of p, during which one or more of the resulting d are added to the target, causing the nucleus to fragment into two parts to dissipate the resulting large excess mass–energy. This complex process is explained in detail by Storms in a previous publication [34].

Justification: Transmutation requires a very large Coulomb barrier to be overcome for the hydrogen to

enter the target. A chemical lattice does not contain enough energy in any form to cause transmutation. In addition, reaction with a helium nucleus has an even greater Coulomb barrier. These problems can be eliminated if transmutation involves the same process and mechanism operating when fusion of hydrogen nuclei occurs. In this way, fusion and transmutation would both take place in the NAE and involve the same method for overcoming the Coulomb barrier and release of the excess mass–energy without energetic radiation. Once again, assumption #4 is applied. In other words, fusion of hydrogen isotopes is proposed to be coupled to the transmutation reaction so that the two reactions take place in the same NAE at the same time.

6. Logical Consequences of the Assumptions

By definition, an assumption is a speculation for which justification is provided. The more plausible the justification, the more useful is the assumption. Generally, assumptions are hidden in a mathematical description, which is not the case here. Here, all the assumptions are clearly stated and justified so that the reader can decide whether they are plausible. If the assumption is believed to warrant the effort, a mathematical description favored by physicists can be used.

An assumption can only be proven by its predictions being correct or rejected if it conflicts will be accepted as laws or behavior. An effective assumption addresses many critical aspects of the phenomenon, in contrast to ad hoc assumptions that apply to only a single feature of the explanation; thereby cluttering the discussion with many ideas. Good housekeeping in theory construction favors using as few assumptions as possible.

In the end, the importance of an assumption must be based on how well it explains a significant part of observed behavior. With this understanding in mind, the consequence of the eight assumptions identified above is explored next.

6.1. Creation of the NAE

Of greatest importance is creation of the NAE. As described above, nano-cracks are proposed to be the NAE, based largely on a process of elimination of all other possibilities. Creation of such cracks requires the physical properties of the surface be exactly matched by the stress generated when the material reacts with hydrogen or with other elements. For such cracks to be produced in the surface region, the material must be brittle and contain many equally weak regions near the surface. This condition is apparently created during initial treatment of the entire batch of material.

Reaction with hydrogen creates stress as the lattice expands. The initial expansion does not cause cracks because loading subjects the surface to compression. Instead, cracks form as hydrogen is removed, which can happen by chance, if for example the current supply fails as is common during long studies. Or suitable cracks can be caused on purpose by cycling the applied power or ambient pressure.

This cycling can be initiated during electrolysis simply by stopping the power periodically or by applying a super-wave [107,108]. These treatments have all been found to improve success in causing LENR. Cycling applied gas pressure and/or temperature when gas loading is used would achieve the same result. Control of this process is difficult, but must be achieved before reliable power can be achieved.

The more difficult problem is the creation of the required initial conditions in the material. Electrolysis deposits Li, Si, O, and Pt on the surface, which might create the required conditions after an extended electrolysis without an initial treatment being necessary. As experience has shown, LENR can be caused more quickly if the required conditions were created during manufacture of the Pd or by its treatment before it is reacted with hydrogen. This required treatment has yet to be identified. The same consideration applies to the use of powder when it is exposed to H₂ or D₂. The crack might even be generated in the material on which nanoparticles of Pd or Pt are deposited, such as when a chemical catalyst is created [63]. In this case, the cracks would be present initially in the substrate and only

need to be populated by H ions formed by the particles of Pd or Pt located nearby. In other words, the NAE is not located in the nanoparticles of Pd or Pt as is the common belief. Instead, the cracks might be in the carbon or Zeolite substrates on which Pd is deposited. Consequently, care needs to be used when assumptions are made about the nature of the NAE.

6.2. Role of probability in the successful production of energy

Production of excess power first requires formation of a special condition in the material by a random process, described in general terms as the NAE. Not only does the explanation described here rests on this assumption, but the author believes this assumption is essential to understanding LENR regardless of any other assumptions that might be adopted.

We can describe this event using a probability for its formation. Obviously, the probability of creating the condition is small but the value cannot be determined using available information. On the other hand, the probability of generating various levels of power once the NAE forms can be calculated using the data in Fig. 8.

The amount of NAE determines the amount of power being produced. Therefore, the measured power can be used as a stand-in for the number of active sites. The greater the amount of power, the less likely the required number of NAE would form in a particular sample. In other words, the number of samples producing energy can be expected to be smaller the greater the amount of power because the required larger number of NAE would have a reduced probability of forming. For this limitation to be reduced the exact nature of the NAE needs to be determined and ways need to be found to create it in large amount. Thus, a critical requirement for eventual application of LENR as a commercial source of power is identified. Next, how to accomplish this goal needs to be explored.

6.3. LENR initiation first as a chemical reaction

The following description is so important; repeating the idea in different words is necessary to make sure the concept is clearly understood. No progress can be made in understanding LENR until this conclusion is accepted.

To be initiated, LENR first requires a chemical process to take place during which the ambient chemical structure is modified. After all, the LENR process is not found to take place in a large number of chemical structures when exposed to a wide range of conditions. It is rarely produced even when efforts are made to produce it on purpose. Something very rare and unusual must change in a material for the process to occur. This change must involve the chemical conditions in the structure and take place only at certain special locations in order to agree with observed behavior. In other words, a unique NAE must form.

This important conclusion leads directly to another conclusion. The laws of thermodynamics would apply to how the nuclear-active condition forms and to the process of assembling the hydrogen nuclei in the NAE prior to fusion. In other words, the rules of chemistry must be applied first before the nuclear process starts, after which the rules of nuclear physics come into play. This conclusion severely limits how and where in the material the NAE can form. A spontaneous change must involve release of Gibbs energy.

In keeping with this limitation, the NAE chosen here is assumed to be nano-cracks formed by normal stress relief. Normally, cracks have a range of gap width and random length. Larger cracks are able to pass D_2 gas from the interior of the material to the surface, thereby reducing the local deuterium content. Such wide gaps are not thought to be the NAE. On the other hand, very small gaps perhaps as small as 1 nm, are proposed to form a structure in which hydrogen atoms can fuse. The rarity of LENR results because formation of this critical gap dimension is rare and difficult to control. Conditions in the original Pd and the rate at which stress is applied as the Pd reacts with D and other elements would determine the number of cracks and their gap width. Further complexity is produced by how the stress interacts

with the crystallites in the material.^b

A linear molecule of hydrogen grows in the crack as Gibbs energy is lost, called here a Hydroton. The Hydroton is unique and not a chemical structure formed in normal material, although it can be described as a form of metallic hydrogen. It can also be described as a classic Rydberg molecule [67]. Details of how this kind of structure can form in a crack will be explored in future papers.

6.4. The nuclear process operating during LENR

Moving on to the nuclear process, we are confronted by several important questions. For example, how can helium and tritium form without large amounts of applied energy being available and without generating significant radiation? After all, both of these requirements are characteristic of conventional nuclear reactions without exception. Clearly, LENR demonstrates the need to provide unconventional answers. In this paper, the answers are based on the above-described assumptions.

During LENR, helium production clearly provides the bulk of measured energy when deuterium is used; but what role does the commonly observed tritium play? Is tritium produced by the same mechanism as helium or is it produced by a side reaction? If it is produced by the same mechanism, why is the amount so small? The additional question of how energy is produced when pure protium is used has yet to be answered by experiment. To be consistent with Assumption # 4, the reaction product would be deuterium.

According to Assumption #4, a single mechanism is proposed to operate in the Hydroton during LENR. This single mechanism is assumed to involve fusion of two nuclei of hydrogen along with an electron (Assumption #5). Consequently, tritium results from fusion between p, d, and e. How this happens is not the issue just yet. We are only exploring the consequence of these two assumptions to see how far they can take us toward an explanation of all observed behavior. Figure 12 shows the series of events expected to flow from these assumptions, as explained below. The concentration of p and d in the initial mixture of hydrogen isotopes determines the amount of energy produced and the amount of each nuclear product. The role of transmutation is not discussed here.

The initial Hydroton structure is assumed to consist of a large collection of d and p arranged in a random linear sequence. First, two of the p next to each other fuse to produce d as soon as 0.95 MeV has been lost from each nucleus by process not described here. Further energy loss allows tritium to form where a p and d are next to each other after each nucleus has lost 2.45 MeV. Finally, loss of 11.8 MeV allows the remaining d to fuse to produce H⁴. In this way, each fusion reaction takes place in sequence with the reaction requiring the smallest loss of energy occurring first. The resulting d or t might leave the Hydroton or remain to experience further fusion. The final nuclear product of H⁴ is radioactive and loses additional energy by emission of beta radiation to form helium, shown as the final event in the sequence, and as described below.

As the hydrogen in a Hydroton fuse, new hydrogen nuclei assemble in the same site and repeat the process as the hydrogen fuel diffuses to the active sites. Millions of Hydrotons are proposed to be in various stages of this process during LENR, with the measured energy being the sum of the energy contributed by each fusion event. Because the concentration of NAE is very non-uniform, some sites at the surface are hotter than others. In fact, most of the energy might result from only a few sites. A search for the NAE on the surface must consider this expectation.

Of course, if only d is present in the Hydroton, only helium can form. In contrast, a Hydroton containing only p will form only d until enough d has accumulated to produce helium and tritium. This logic predicts the use of p would

^bVarious conditions including metal and nonmetal atom vacancies, nano-particles, dislocations, and the cage in the Zeolite structure have been proposed as the NAE by other writers, each with different advantages and deficiencies. The reader can decide which is more plausible compared to the nano-crack proposed here. Regardless of the conclusion, a NAE is required and must be identified before LENR can be understood.

produce an unstable amount of power and product considerable tritium, a potentially dangerous radioactive product, as explained below.

6.5. Role of ^4H formation

Formation of the ^4H isotope would not be expected because it is unstable [68] and is proposed to emit a neutron when it is created using high energy. Beta decay has not been detected when it is formed under these conditions. Even if beta emission did occur, the lower limit to the beta energy, estimated as 17.06 MeV, would produce secondary radiation that is not detected during LENR.

For the assumptions used in this paper to be valid, the ^4H would have to form during LENR with a lower mass–energy than expected, decay with a short half-life by beta emission, and then emit the electron with much less energy than given by the above estimate. These requirements might be realized if the ^4H created by LENR had less mass than when it is created using high-applied energy. In other words, the process proposed to dissipate excess mass–energy prior to fusion is proposed to carry away some mass–energy from the H^4 , leaving less for later beta decay and with no need to emit a neutron.

6.6. Consequence of LENR using a mixture of d and p

Figure 13 shows how the reaction rates for d, He, and t formation are predicted to change as the relative amounts of d and p in the NAE change. The rate of each fusion reaction is assumed influenced only by the atom fraction of d and p in the NAE. Of course, the intrinsic reaction rate of each hydrogen isotope and especially the mixture might be different. In addition, the concentration of the isotopic ratio in the NAE will be different from that in the surrounding gas, but these details are not important at this level of analysis.

Starting first on the right-hand side of Fig. 13, the figure shows production of only helium as long as no p is present. When a small amount of p is added, some tritium and additional deuterium are proposed to form. The rate of tritium formation would be initially proportional to the atom fraction of p and then follow the dotted line in Fig. 13 until formation of deuterium becomes important. However, as the relative amount of p increases, two p would be

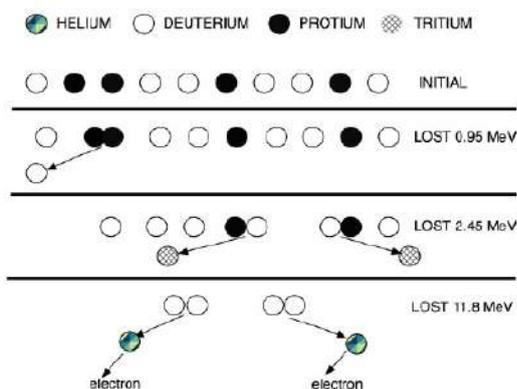


Figure 12. Sequence of events as energy is lost from the Hydroton by photon emission. The final reaction produces ^4H that rapidly decays by electron emission to ^4He . The process causing transmutation is not shown. The bonding electrons captured into the fusion product and any involvement of the neutrino are not shown. Once fusion occurs, the product might leave the Hydroton structure and join atoms in the surrounding lattice or it might remain and be fused with other hydrogen isotopes when the nuclear product is an isotope of hydrogen.

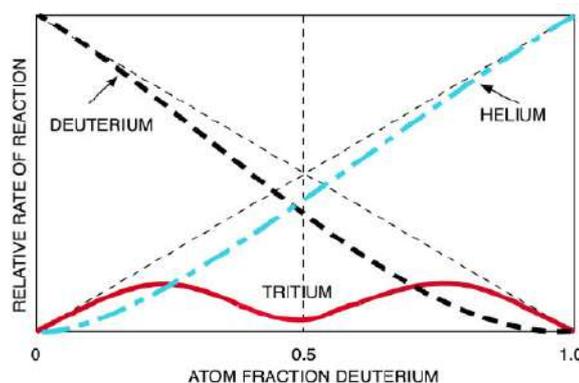


Figure 13. Relative rates of formation for deuterium, helium, and tritium as a function of $d/(p+d)$ in the NAE. The figure approximates ideal behavior when the concentration of NAE and temperature are constant. Unknown influences are expected to slightly modify the relationship. The concentration of p is 100% in the metal on the left side of the figure and d has a concentration of 100% on the right side.

increasingly found adjacent to each other, whereupon deuterium can form instead of tritium. This additional reaction would reduce the rate at which tritium forms as the d/p ratio in the NAE approaches 1.

Because fusion between two p requires loss of only 0.95 MeV from each nucleus, this fusion reaction will be completed before enough energy has been lost from the adjacent d and p for them to form tritium. Thus, the rate of formation of tritium first increases as p is added, then is reduced as the atom fraction of p in the hydrogen mixture approaches 0.5 where the deuterium and helium formation reactions dominate.

Once tritium forms, some of it would fuse with d or p (Assumption #5). When fusion takes place between t and d, a neutron is emitted, thereby accounting for the occasional detected neutron when tritium forms. This reaction will reduce the net amount of tritium, as has been occasionally claimed.

As noted previously, the resulting power is not expected to be stable when protium is used. Power will change as the deuterium concentration in the NAE builds up, allowing tritium to form followed by helium. Total power results from the sum of energy from each reaction, with formation of each He releasing 27.8 MeV^c, each tritium generating 4.9 MeV and finally each deuterium adding 1.9 MeV. The number of each nuclear reaction taking place at any time depends the amount of each hydrogen isotope present in the NAE, which is determined by how much total energy was produced up to that time by the generator. In other words, the observed behavior is expected to be influenced by the previous experience of the material.

Of the nuclear products, only tritium poses a danger, which grows as the generator continues to produce excess energy. A generator making 1 MW for one year is predicted to make as much as 20 g of tritium. This large amount would be dangerous if released into the environment, would be illegal to produce without a permit, and would have great value if captured and sold. The LENR effect would appear to be the easiest and cheapest way to make tritium for civilian and military use while also making useful energy.

This model predicts the total amount of power is influenced by the amount of NAE present, the amount of energy applied to the NAE in any form including temperature, and the isotopic composition of the hydrogen in the NAE. Further change in observed power would result if the amount of NAE and applied energy did not remain constant. Consequently, control of the process in order to generate constant and reliable energy is expected to involve significant

^cFor example, helium forms by a series of reactions that combine 4 p with 2 e. This overall process involves a mass change of 0.02979 that is equivalent to 27.75 MeV. Tritium production combines 3 p + 2e that produce a mass change of 0.00852 and 7.94 MeV.

difficulties, especially when light hydrogen is used.

6.7. Transmutation

Transmutation is the black sheep of the LENR family of nuclear products. This process involves adding one or more isotopes of hydrogen to a large target nucleus. Because transmutation is difficult to explain, the mechanism is generally ignored. Claims by Miley using PdH and Rossi [69,70] using Ni+ H₂ have focused attention on the transmutation reaction between protium and various isotopes of Pd, Ni, and lithium. Studies reported by Iwamura et al. have directed attention to transmutation when PdD is used. Two different kinds of transmutation are reported to result from use of the different hydrogen isotopes.

Normally, transmutation cannot be initiated without applying a great deal of energy in order to overcome the very high Coulomb barrier. For example, the barrier between ⁴He and Pd is 92 charge units and addition of a proton to Ni involves a barrier of 28 charge units. In contrast, fusion between hydrogen only involves a barrier of 1 unit. Even this single charge unit requires application of many keV to cause significant nuclear interaction under ordinary conditions. To add further difficulty to our understanding, we would expect a mechanism that is able to reduce the barrier would first operate to cause hydrogen fusion long before it would reach a level required to cause the more difficult transmutation. In fact as expected, when LENR occurs in PdD, fusion products are the major result with only a small amount of transmutation being detected. In contrast, Rossi has claimed the opposite behavior when NiH is used, with transmutation being the major source of energy production. This conflict points to a potential flaw in the understanding of the two systems.

A further challenge is created by having to dissipate the excess mass energy to avoid emitting energetic radiation, which is not detected. The simplest assumption to explain how the barrier is overcome, how the energy is dissipated, and how two different kinds of transmutation take place involves using the same mechanism proposed to produce fusion of hydrogen. In other words, transmutation is proposed to be a consequence of fusion and takes place as result of the fusion process. This assumption solves both problems by using the mechanism and energy involved in the fusion process to overcome the large Coulomb barrier while the same process dissipates the excess mass energy. In this way, both kinds of transmutation as well as the observed fusion products can form at the same time in the NAE. This proposed process is explained in detail by Storms in previous publications [34,37,71].

6.8. How does the fusion process work?

Now that the general landscape has been described, the next challenge is to examine the details of the fusion process. We have two problems to solve. The Coulomb barrier has to be overcome at a significant rate even though very little energy is available in the material to do the job. The second problem is to dissipate the resulting excess energy without fragmenting the resulting nucleus and without producing significant energetic radiation. These two processes have to work together in the NAE to produce all the observed nuclear products. This is a lot to ask of any known process. To simplify the description below, fusion of two D to create helium is used as an example of how the proposed process might operate, starting with the fusion mechanism.

6.9. Reduction of Coulomb barrier

Even though high energy can overcome the Coulomb barrier without any help from electron screening, the screening electrons come increasingly into play as applied energy is reduced, as can be concluded from the behavior shown in Fig 14. As applied

energy is reduced, the fusion rate increases above that measured using plasma where extra electron charge is not present. The presence of lithium [72,73] in the metal has an especially large effect on this type of enhanced fusion.

Extrapolation of the values in Fig. 14 to the amount of energy available during a typical LENR event (<0.1 eV) reveals that significant electron screening might be possible in a metal environment at low applied energy. This screening process is examined mathematically by Sinha and Hagelstein [74,75] following the work of Ichimaru [76].

How can this behavior be applied to LENR? A high electron concentration can be imagined to exist in a nano-crack, with the resulting negative charge allowing two deuterium nuclei to get close enough to fuse. Unfortunately, the fusion process is expected to quickly go to completion and release the nuclear energy by fragmentation (hot fusion) of the combined nucleus, as bombardment by the D^+ ions demonstrates [72, 77–82]. Why does this fragmentation not happen during LENR?

Ion bombardment is not like LENR because the fusion reaction is triggered at random locations in the lattice structure when the energetic ion happens to encounter a stationary ion in the lattice. In contrast, LENR takes place in rare and isolated sites where the conditions are much different from the general lattice. These sites are expected to have a much larger amount of potential electron screening along with the ability to dissipate energy in unusual ways. Such conditions would be very different from those affecting fusion during ion bombardment. Consequently, the behavior during ion bombardment only gives a hint about how electrons might reduce the barrier, but not the full story. The full story requires the NAE be identified so that its unique characteristics can be included in the description. Nevertheless, these ion bombardment studies provide evidence for significant and unexpected electron screening being available in an ordinary chemical environment.

After electron enhanced tunneling has reduced the Coulomb barrier, how can the resulting energy be dissipated without involving the normal fragmentation process?

6.10. Dissipation of excess mass energy

To answer this question, the kind of radiation carrying the excess energy needs to be identified, along with limits to its energy, and the time duration for its release. Normal nuclear reactions release the excess nuclear energy by photon emission, with a delay determined by the half-life of the process. A single photon then carries away all the excess energy stored in single a nucleus as a single event, sometimes combined with other kinds of emissions.

The LENR process is different from normal behavior. The excess energy in the nuclear product can be as high as 23.8 MeV and measurements show that the emitted photons have much less energy than this value. Consequently, we have to assume the energy is released gradually rather than being emitted as a single event after fusion has occurred. Apparently, small quanta of energy are emitted while the fusion process is underway. In other words, the LENR process can be viewed as slow fusion while the hot fusion process can be called fast fusion. This is an important conclusion that contrasts sharply with how energy is released from the hot fusion process and with the energy release process used by other kinds of nuclear reactions. A mechanism proposed to explain cold fusion needs include this slow energy release process and show how the 23.8 MeV can be broken into energy quanta that are generally too small to escape the apparatus, yet do not result in the heat energy being so concentrated to cause local melting.

This concept is so unique and important to understanding cold fusion; a more detailed description is worth considering. Apparently, a new kind of nuclear interaction can dissipate energy while the nuclear process is underway. The process can be visualized as emission of energy from a gradually forming product nucleus in which the nuclear energy states are mixed, but have not yet become characteristic of the final nuclear product. This process would normally not be detected because it would be overwhelmed when high-energy is used to initiate the nuclear process, which is the conventional method. In this case, the fusion process would be so rapid that the small window of time during which energy can be released would be too small to result in detectable energy as fractions of the main emitted energy.

The condition has been described in part by Hagelstein and Chaudhary [84] as a Lossy Spin–boson unstable state. It can also be described as an assembly of overlapping wave functions from which energy is gradually emitted as the wave function approaches that of helium. In any case, a new way for nuclei to interact has been revealed to occur in a

material when high energy is not used to cause the nuclear interaction.

Release of energy from LENR can only involve three possible methods. These are creation of phonons, coupling of energy to the surrounding electrons, or emission of photons. Only these mechanisms can carry energy from the reactants without changing the number of contained neutrons or protons. Energy would then be converted to heat as the phonons or as photons interacted with atoms in nearby material. The exact mechanism by which each of these transport methods does its job does not have to be identified just yet. We first need to understand the general consequence of each idea. Regardless of the method, when energy is released and converted to heat energy, two significant requirements have to be considered. First, the energy has to be distributed into a sufficient number of atoms to avoid causing local melting at the NAE and its subsequent destruction. Second, the energy must not be detectable as energetic radiation, either in the form of primary radiation or as secondary radiation produced when the primary radiation interacts with atoms in the material. These requirements place limits on the energy contained in each quanta of energy. Quanta with too little energy would release energy in the local material too near the source and cause local melting. When too much energy is contained in each released quanta, the radiation would escape the apparatus and be detected as energetic radiation. If too much energy were to leave the apparatus, the amount of measured heat energy would be less than expected. These limits define an energy range into which the quanta must fall.

The source of energy can be visualized as being located at the center of a sphere in which the mass–energy is converted to heat-energy. The goal is to determine the size of the sphere containing enough atoms to prevent the local temperature from rising to a destructive level when the fusion energy is deposited as heat-energy. Figure 15 shows how the number of atoms of PdD_{0.8} would change as the radius of the sphere is changed. Next, the number of atoms that would be melted by a single fusion event and by 25 such events is determined. The values are placed in Fig. 15 to show the radius of a sphere containing this number of atoms. This shows the lower limit to the sphere size above which melting would not be expected as result of this number of fusion reactions. Since the Hydroton can contain an unknown number of deuterons, the true number of fusion events taking place in each of many the Hydrotons is not known. Nevertheless, a useful estimate can be proposed that places a limit of about 0.2 μm on the sphere radius to avoid destruction of the NAE for a plausible number of reactions. This estimate can be used to identify a minimum distance of about 0.4 μm between the NAE in a material hosting d–d–e fusion to avoid destruction of the NAE. If the NAE sites were too close so that the spheres overlap, local melting might occur, as has been observed [85–87] on occasion, which would cause these Hydrotons to be immediately destroyed after which no further energy could be produced at this site. As result, an active material would quickly eliminate sites having too high a concentration of NAE and eventually achieve stable power production.

Because the diameter of the sphere required to acquire energy from d–d–e fusion is much larger than that required when p–p–e fusion occurs, use of light hydrogen would allow a much greater concentration of NAE sites to remain active. If deuterium were added to a material making energy by the p–p–e fusion process, many spheres would now overlap and cause destruction of some energy-producing locations. The reduction in power might be interpreted as poisoning of the process by deuterium. Instead, the reduction might result only from reduction in the number of NAE sites by local melting. Perhaps this is why PdD is found to make less power than the same amount of NiH even though each d–e–d fission event makes more energy than each p–e–p fusion event. Also, a generator using p would be expected to experience increased power as d is formed and increasing amounts of He and tritium are made near the end of its lifetime. A reduction in power would result when this extra energy destroyed some NAE by local melting. Clearly, the process is complex and cannot be interpreted simply by using a constant value for the energy/event

The resulting temperature in the sphere not only depends on the rate at which energy enters the sphere but also on how fast heat-energy can leave. The leaving process takes time and is affected by the temperature of the surrounding material. As observed by Szpak et al. [88], this heating–cooling process occurs in cycles with sudden heat production followed by relatively slow local cooling as the site recharges with hydrogen. During recharging, the local temperature drops as heat energy leaves the site by normal thermal conduction. This process would result in a smaller sphere

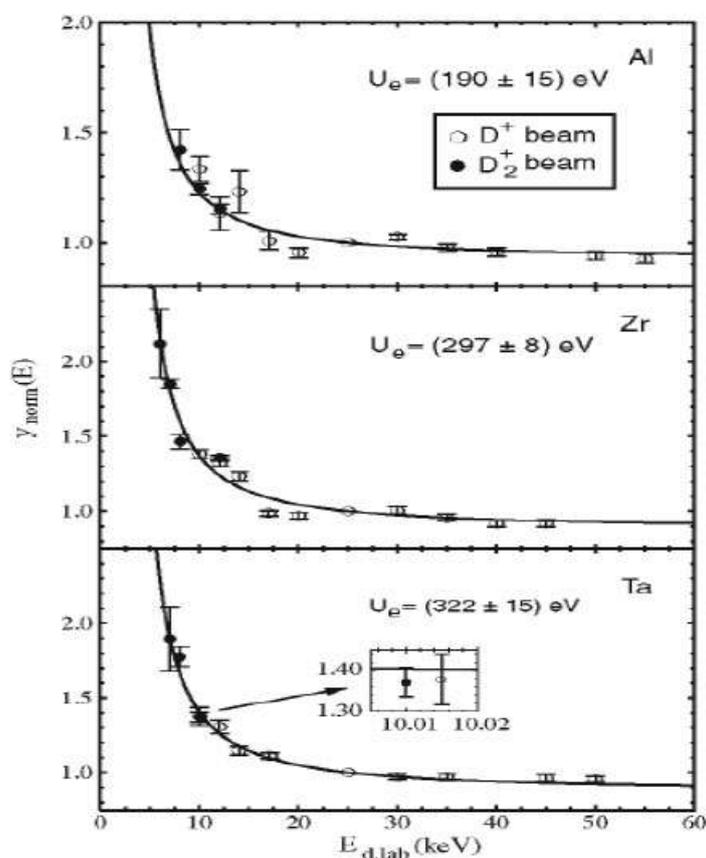


Figure 14. Enhanced fusion resulting from enhanced tunneling as the energy of the D+ ion used to bombard the indicated metal is reduced. A value of $\gamma = 1.0$ means the effect is identical to that produced when plasma is used instead of the solid metal. The rate of fusion decreases as applied energy is reduced, with the enhanced effect causing only a slight increase in the fusion rate within the studied energy range [83]. Nevertheless, the effect of electrons would be expected to be significant at the energy present during LENR. The fusion rate is obtained from the measured neutron flux.

of influence with a highly variable value determined by how easily the heat could leave and how many other active Hydrotrons were nearby. This observed behavior clearly demonstrates existence of local regions in which LENR creates energy by a cycling process. The total power results from the average of many cycles.

The average energy limit for each quantum released from the fusion process can be estimated from the radius of the sphere using the known absorption behavior of the energy carrier. This calculation is described next.

6.11. Photons as the energy dissipation method

Several methods can be proposed to dissipate the mass–energy. Emission of photons is described first, starting with how they are generated. Photon emission, called gamma, is the normal way energy is lost by all energetic nuclei. Even helium formed by the hot fusion process emits a 23 MeV gamma on a few occasions rather than fragmenting. Because this very energetic gamma is not detected during LENR, we are forced to consider any photon emitted during LENR

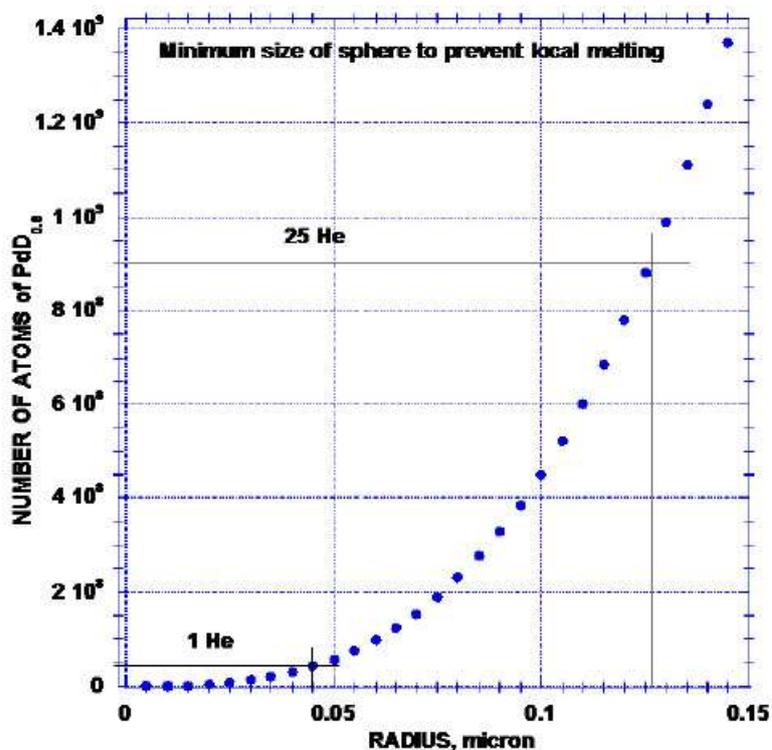


Figure 15. Estimation of the sphere of influence based on a unit cell dimension of 4.06 \AA with 7.2 atoms/unit cell for $\text{PdD}_{0.8}$. The energy to melt is estimated as $1 \times 10^{-19} \text{ J/atom}$ when each fusion releases 23.8 MeV/event.

to result from a different process. What process might be the source?

When a photon is emitted from a nucleus, spin and momentum must be conserved. With this requirement in mind, the process is proposed to involve simultaneous emission of two photons, one from each fusing deuteron with opposite spin and momentum. Because the two nuclei are coupled or entangled by the interaction, the two photons can be thought of as being emitted from the same entity. A continuous series of such pairs would be emitted until all the excess mass energy has been lost from the entity and the resulting ^4H nuclei could form with very little extra mass energy [34]. Eventual decay would result in formation of ^4He . This proposed behavior is based on applying Assumption #4 consistently and does not affect the proposed mechanism for dissipation of the nuclear energy. The proposed mechanism for energy release would be worth considering even if ^4He were formed directly without ^4H being produced. Nevertheless, search for beta radiation resulting from ^4H decay would be worth undertaking.

Photons can never be completely stopped by absorption. Instead, added absorber reduces the number of photons until the number becomes too small to measure. Thus, success in detecting photons requires use of a sensitive detector. For example, X-ray film would have a much higher sensitivity than would a GM detector, hence would be able to detect a much lower emission rate. In fact, numerous studies have detected photon emission using film placed within the apparatus [89–93]. Gozzi et al. [92] detected photon emission from small spots and placed the energy near 89 keV. Violante et al. [93] detected photon radiation between 2 and 12 keV emitted from thin films of Pd and Ni during electrolysis by using a HPGc detector. An upper limit to the photon energy of about 50 keV can be estimated based on

significant radiation not being normally detected outside the apparatus when significant energy is produced.

If each photon had energy of 50 keV, the flux of photons when 1 W was released by d–d–e fusion would be about 10^{14} photons/s at the source. Absorption by the surrounding Pyrex and the D₂O contained in the electrolytic cell combined with low efficiency of the detector would normally reduce detection to a few photons/s. The distance between the source and detector would further reduce the detectable flux. Lower photon energy would result in higher flux and greater heating at the source but fewer photons being detected outside the apparatus. These two effects place upper and lower limits on the predicted energy of any photon resulting from the nuclear process.

Because of these limitations in measuring emitted photons, we must not conclude that the LENR process produces no radiation. The process might generate considerable radiation, but at too low energy to detect using the present methods.

6.12. Electrons as the energy dissipation method

The electrons that promote tunneling through the Coulomb barrier can be proposed to acquire kinetic energy from the fusing atoms and leave the local region at high velocity. These energetic electrons carry the energy from the fusion process to the surround lattice where it is converted to heat energy. This process would generate Bremsstrahlung and X-rays. In this case, we again have to evaluate two different energy limits in order to satisfy two different requirements.

Once again, the energy dissipation process has to result in a local temperature below the melting point of the material in which the NAE is formed, resulting in a lower limit to the deposited energy density. In addition, the generated secondary photon radiation has to have an energy below a critical value to avoid being detected, resulting in upper limit to the electron energy. In other words, electron energy has to fall between two critical values to be consistent with the requirements.

The estimated radius of 0.2 μm , as discussed above, has the stopping power of 0.3 mg/cm^2 when the absorber is PdD. Based on range measurements, electrons with energy of about 10 keV would be completely stopped by this amount of material. To avoid melting the local NAE, the energy-carrying electrons would have to have energy greater than this amount.

The upper limit to electron energy is related to secondary photon production. As electrons lose energy, they generate photon emission called Bremsstrahlung. The photon energy ranges in values below the electron energy and has a maximum flux at about 1/3 this value. These X-rays would have to have an average energy below about 50 keV to avoid being detected outside the apparatus. This requirement places an upper limit to the electron energy of about 150 keV. Consequently, to satisfy the requirements, the average energy of the energy dissipating electrons would have to fall between about 10 and 150 keV. Explaining how the electron energy of proposed electron emission would remain in this range is a challenge for any explanation.

In addition, if each electron carried 10 keV of energy, 2.4×10^6 electrons would be required to carry energy from each fusion event. Given that production of 1 W requires 2×10^{11} fusion/s, an increasing large number of electrons would be affected as power production continued. These electrons would create a current flow between the region in which the NAE is located and the surrounding lattice of about 4×10^{17} electrons/s when one watt is produced. This total current of 0.07 A would produce a small local voltage gradient and magnetic field, both of which might be detected if this proposed process were to actually occur. If the energy were generated in individual particles, such as in a powder, the local charge on individual grains would increase and become obvious.

6.13. Phonons as the energy dissipation method

The term “phonon” is used to identify coherent energy carried by the vibration of atoms and electrons in a physical structure. This energy becomes heat when the vibrations become random. When molecules or crystals acquire enough

phonon energy, the bonds holding them together break and melting occurs. This process limits the amount of energy carried by a phonon as it transports energy from the fusion process. This limit can be estimated as about 1 eV, based on the energy known to hold the PdD lattice together. Thus, at least 23.8×10^6 phonons having no more than 1 eV each would have to be generated over a short period of time as two fusing deuterons approach each other and release their excess mass–energy. Even though each individual phonon would not destroy the structure, the total of so many phonons generated in a very small space would surely cause melting in a local region, thereby stopping the process at this site after a single fusion event. Consequently, this method for energy dissipation would not be consistent with observed behavior. This expectation forces rejection of the proposal by Hagelstein [94], during which the energy is proposed to be dissipated by phonon production.

6.14. Effect of laser radiation

Application of laser radiation has been reported by Letts to stimulate energy production, while the effect is sensitive to the wavelength, to the polarization angle, and perhaps to a magnetic field. A coating of gold on the cathode surface seems to be required in some cases [95–98]. Other success using laser stimulation has also been reported without the need for a gold coating [99–102].

The laser effect is explained here by assuming the light energy enters the active gap and stimulates the reaction by increasing the local temperature in each active gap. The angle of polarization is important because the wave front has to align with the gap in order for it to enter. Because stress relief caused the cracks, they are generally aligned in the same direction within the surface. The frequency is important because the wave-length must match a multiple of the gap width for the energy to enter a gap with maximum efficiency. Otherwise, the energy causes local heating in proportion to the energy being applied to the surface. An especially large effect might be produced when a location containing a high concentration of NAE is heated. In other words, because the concentration of NAE is not uniform, the exact location of the laser spot is important. Indeed, the laser spot might be used to locate where the largest amount of NAE is located, which would allow the nature of the NAE to be explored using analytical methods applied to the identified spot.

The required coating of gold is proposed to contain the active nano-cracks that are generated as the underlying PdD expands as it reacts with deuterium. In this case, the NAE is not proposed to be in the PdD.

Energy entering the gap is expected to be more effective in causing increased energy production than when energy is applied only to the surface. This is why a single laser [95,96,103] can increase energy production while a laser tuned to a gap width can cause a greater effect, thus producing the peaks in power found by Letts [98] and Letts et al. [104,105] In other words, the peaks result when the gap width and a whole fraction of the wave-length match. In this case, the matching wave-length result from a beat frequency generated as the two frequencies interact. A larger effect would be predicted when a match is achieved with the primary frequency. Consequently, use of a tunable laser is recommended as a way to determine the gap width and to explore where the NAE is located on the surface.

7. Testable Predictions

The eight assumptions described in Section 5 can be tested by the following predictions.

- (1) As shown in Fig. 13, the relative amount of deuterium, tritium, and helium produced by the LENR process is sensitive to the ratio of d/p in the material. The predicted shape of this relationship can be tested. This test must take into account the molecular form assumed by each of these reaction products in the gas phase where they are measured. Molecules of D_2 , DH, H_2 , DT, or TH can form and appear in the gas phase. The amount of each can be predicted to depend on the relative concentration of each isotope on the surface where the gas molecule forms.

Because formation of the gas is not an equilibrium process, a random probability exists for an atom finding another atom with which to combine on the surface of the material. As result, the molecular form can be highly variable and not directly related to the isotope concentration.

Because the amount of tritium is also related to the total amount of fusion taking place and to the resulting amount of energy produced, a large amount of tritium is predicted to be present after a large amount of energy is produced using protium. This tritium can be used to test the predictions while being potentially dangerous if it is not properly handled.

- (2) Addition of H₂O to D₂O is predicted to reduce the amount of power because p–p–e fusion produces much less energy than d–d–e fusion. This prediction can be tested by measuring the change in power while using various mixtures of d and p. The local concentration of p in the material will be higher than in the electrolyte or gas, which adds complexity to the measurement.

Use of protium initially is expected to result in the least amount of potential power compared to any other isotope of hydrogen or combination thereof. As the LENR process continues, deuterium forms and fuses with the p to produce tritium and increased power. Eventually, enough deuterium will form to produce helium and more power. Consequently, use of protium can be expected to result in a steady increase in power production as tritium and helium accumulate and generate some neutrons. This prediction can be tested using the behavior of the Ni–H₂ system.

- (3) When deuterium is used, the few transmutation products are expected to have a greater mass than the nuclei present in the material. When protium is used, each transmutation product will have a mass equal to only a fraction of the target nucleus because the nucleus will fragment. A mixture of p and d is predicted to produce a combination of these two kinds of transmutation products. In no case is transmutation expected to be rapid enough to generate significant energy. This prediction conflicts with the claims now being made about the behavior of NiH by Rossi.

A small amount of slightly lighter than normal proton and deuteron is predicted to exist in nature. The potential for such variable mass being possible is discussed by Davidson [106].

- (4) Successful replication requires gaining control over the stress in the material. Gaps formed by stress relief typically have a V shape with the gap widening as the surface of the material is approached. The dimension proposed to be nuclear active is close to the tip of the V. The nuclear active region is expected to be located at an unknown but small distance from the surface. Removal of increasing depths of material from the surface until the LENR process stops could be used to identify the location of the nuclear process and be used to test this description of the required condition.
- (5) A magnetic field is expected to change the rate of LENR by changing the frequency of resonance in the Hydroton. Application of laser energy is predicted to change the reaction rate of LENR by adding energy to the Hydroton in proportion to the laser frequency and to its effectiveness in being able to couple to the dimension of the nano-crack. Neither of these changes is expected to initiate the LENR effect.

Each of these predictions can be easily tested and used to evaluate the assumptions and conclusions made in this paper. In the process, this description of the LENR process can be used to guide research from which other insights can be expected to result.

8. Discussion

The LENR process consists of several unique behaviors all combined to produce a result in conflict with how nuclear reactions are normally observed to function. Eventually, each of these behaviors needs to be described using conventional mathematical methods based on quantum mechanics. Meanwhile, a model in which each process operates in

harmony with the others is required. This paper proposes such a model to which mathematical analysis will be applied in later papers.

The well documented and accepted fact that nuclear reactions cannot be initiated in a chemical environment at ambient energy needs to be acknowledged. This conflict between well-accepted expectation and observed behavior requires a unique condition be identified within the material where the observed nuclear reactions can occur, called here the NAE. Such a rare and unique site must exist outside of the normal limitations created by the chemical structure. Nevertheless, this site must form by a normal process in which a collection of hydrogen nuclei can assemble by normal chemical processes. Once assembled, these nuclei fuse without creating easily detected radiation. The unique “magic” of LENR takes place during this final phase of the process. The many observed behaviors can then be used to create a logically consistent description of the process based on these restrictions, as this paper attempts to accomplish.

The rare success in initiating LENR is consistent with there being a small probability for formation of the NAE. Experience reveals that once such sites are formed, LENR can be initiated without restrictions at high rate. This small probability makes a failed attempt the most likely outcome of a study. Success can only be improved by increasing the probability of NAE formation.

A model must start with the unique conditions in which LENR takes place. Regardless of how the NAE is proposed to form and function, its chemical characteristics would have a large effect on how the nuclear process proceeds. Consequently, LENR forces a marriage between chemistry and physics, with chemistry leading the way to understand the initial condition. This initial condition must obey the rules governing chemical behavior and be consistent with observed behavior. Only later does physics need to be applied to explain the nuclear process. Too many proposed theories start with the nuclear process and ignore the environment in which the fusion process must function. This approach has failed to help make the LENR process more reproducible.

A chemical lattice restricts the localized energy to an amount less than would break chemical bonds. This condition is not like plasma in which the energy can be increased without limit. In addition, if super heavy electrons are proposed to form [5,109,110] or if electrons were proposed to seek an orbit closer to the nucleus [111–113] as a way to reduce the Coulomb barrier, these processes would be expected to first produce changes in the chemical structure, which are not detected. Consequently, we are forced to consider only processes that would not interact with the surrounding structure, a requirement that places severe limits on a proposed process for causing LENR.

Ordinary nuclear reactions dissipate the excess mass–energy either at the time the nuclear product is formed or when extra energy is released by radioactive decay after the initial nuclear event. Apparently, the LENR process uses neither method. The nuclear product does not fragment, as is the case during hot fusion. Because the ^4H and tritium retain very little of the initial nuclear energy, they do not need to be considered as part of the main dissipation process. Instead, we are encouraged to explore a dissipation process that takes place before the fusion process is fully completed. For this unique dissipation process to be understood, the assembly of hydrogen proceeding fusion must be described in a special way. For this purpose, the assembly of nuclei is called a Hydroton. This structure might also be described as involving a Lossy Spin-boson according to Hagelstein and Chaudhary [84], a Rydberg molecule as suggested by Holmlid [67], coherent correlated states proposed to Vysotskii [114], metallic hydrogen according to Storms [34], discrete breathers suggested by Dubinko [115], Bose–Einstein Condensates as favored by Kim [116], or nuclear threads as proposed by Ivlev [117]. In addition, the hydrogen nuclei might be said to be entangled or be in a super nucleus that is gradually losing energy by complex radioactive decay, the result of which would eventually be a stable nucleus of helium, tritium, or deuterium.

Each of these descriptions, while plausible, addresses only one aspect of the problem. These proposals need to be combined and applied to the entire LENR process. Regardless of how the assembly is described at this time, a collection of nuclei must first form at a unique location in the material. The combination must experience a unique process that can lower the Coulomb barrier while dissipating the excess mass–energy as weak photon radiation. An effective theory must combine these basic requirements into a logically consistent explanation. The problem can be

reduced to two basic choices; reject the obvious or accept what appears to be impossible.

The description provided here uses the well-known behaviors of LENR to create a logically consistent mechanism based on eight assumptions. This combination of assumptions and logical consequences is like a finely tuned machine; with each assumption playing a role without which the machine could not function. The purpose is to provide a platform from which to interpret future behavior and guide research. Only lacking are the mathematical descriptions from which quantitative predictions can be obtained and from which the relationship to conventional physics can be derived. The next step requires the novel process to be explored using the mathematical tools of modern physics and for the phenomenon to take its place among the great discoveries.

When these behaviors are combined to form a unified and logical relationship, a proposed mechanism based on the behavior is forced to have only a small number of possibilities. The challenge is to identify the boundaries of this parameter space and focus on what is consistent with conventional knowledge about chemical systems and nuclear physics. Use of imagination and ad hoc explanation are only useful when all else fails.

In view of the obvious potential of LENR to produce clean, cheap, and easily available energy, the usual skepticism is best put aside until the claims are further explored. Energy of this kind is desperately needed to reduce CO₂ emissions, to purify water, and to remove the role of oil in causing international conflict. The promise can only be tested by obtaining more information about the process and by using this knowledge to create commercial energy generators. Humankind cannot afford to reject such an important gift just because it is not easy to explain or cause.

9. Summary

The LENR process produces energy as result of several nuclear reactions, all taking place in what appear to be ordinary materials under ordinary conditions. The process occurs only after a rarely formed and unique condition is created in the material. Although the process can be initiated under ambient conditions, application of additional energy, such as by increased temperature, application of laser radiation, or electric discharge can increase the rate even though these conditions do not initiate the process. All isotopes of hydrogen appear to be able to produce energy by a fusion process in a variety of materials. Transmutation also occurs and results in nuclear products that depend on the target nucleus and the hydrogen isotope present.

Once the mechanisms is understood, LENR has the potential to be the ideal source of energy required to save the world from the effects of excess CO₂, from the dangers of nuclear fission, and from the uncertain supply inherent in the other sources of energy. LENR also would be the required source of energy to make extended manned space travel possible. Let us hope these many advantages will stimulate interest in solving the difficult problems to understand and apply this source of energy.

Acknowledgement

The author is grateful to Robin Carter, Tom Grimshaw, and Carol Storms for helping to locate where the confusion was particularly concentrated and removing some of it. What remains is entirely my fault for which I ask forgiveness. This is a very complex subject with unusual emotional content as well as having many conflicts with what we were all taught. Reaching understanding with consensus is not expected to be easy.

References

- [1] M. Fleischmann, S. Pons and M. Hawkins, Electrochemically induced nuclear fusion of deuterium, *J. Electroanal. Chem.* **261** (301–308) and errata in **263** (1989) 187–188.
- [2] J. R. Huizenga, *Cold fusion: The Scientific Fiasco of the Century*, Second edn., Oxford University Press, New York, 1993, pp. 319.

- [3] E.K. Storms, *The Science of Low Energy Nuclear Reaction*, World Scientific, Singapore, 2007, 312 pages.
- [4] R.E. Godes, The quantum fusion hypothesis, *Infinite Energy* **14** (2008) 15–23.
- [5] A. Widom and L. Larsen, Ultra low momentum neutron catalyzed nuclear reactions on metallic hydride surfaces, *Eur. Phys. J. C* **46** (2006) 107.
- [6] A.G. Lipson, A.S. Roussetski, A.B. Karabut and G.H. Miley, Strong enhancement of DD-reaction accompanied by X-ray generation in a pulsed low voltage high-current deuterium glow discharge with a titanium cathode, in *Tenth Int. Conf. on Cold Fusion*, P.L. Hagelstein and S.R. Chubb (Eds.), World Scientific, Cambridge, MA, 2003, pp. 635–656.
- [7] D.V. Balin, E.M. Maev, V.I. Medvedev, G.G. Semenchuk, Y.V. Smirenin, A.A. Vorobyov, A.A. Vorobyov and Y.K. Zalite, Experimental investigation of the muon catalyzed d–d fusion, *Phys. Lett. B* **141** (1984) 173.
- [8] S.E. Jones, Muon-catalyzed fusion revisited, *Nature* (London) **321** (1986) 327.
- [9] H.E. Rafelski, D. Harley, G.R. Shin and J. Rafelski, Cold fusion: muon-catalyzed fusion, *J. Phys. B* **24** (1991) 1469.
- [10] J. Read, Muons, deuterium, and cold fusion. *Phys. Today* **63**, 10 (2010).
- [11] A. Widom, L. Larsen, Nuclear abundances in metallic hydride electrodes of electrolytic chemical cells. *arXiv:cond-mat/062472 v1*, (2006).
- [12] A. Widom and L. Larsen, Theoretical standard model rates of proton to neutron conversions near metallic hydride surfaces. *arXiv:cnucl-th/0608059v2*, (2007).
- [13] R. P. Santandrea and R.G. Behrens, A review of the thermodynamics and phase relationships in the palladium–hydrogen, palladium–deuterium and palladium–tritium systems, *High Temp. Materials Processes* **7** (1986) 149.
- [14] A.C. Switendick, Influence of the electronic structure on the titanium–vanadium–hydrogen phase diagram, *J. Less-Common Metals* **49** (1976) 283–290.
- [15] N. Boes and H. Zuchner, Electrochemical methods for studying diffusion, permeation and solubility of hydrogen in metals, *J. Less-Common Metals* **49** (1976) 223–240.
- [16] O.Y. Vekilova, D.I. Bazhanov, S.I. Simak and I.A. Abrikosov, First-principles study of vacancy–hydrogen interaction in Pd, *Phys. Rev. B* **80** (2009) 024101–024106.
- [17] A.C. Switendick, Electronic structure and stability of palladium hydrogen (deuterium) systems, PdH(D) $_n$, $1 \leq n \leq 3$. *J. less-Common Metals* **172–174** (1991) 1363.
- [18] H. Peisl, *The Metal–Hydrogen System*. G. Alefeld and J. Volkl (Eds.), Springer Series in Materials Science, Springer, Berlin, http://link.springer.com/chapter/10.1007/3-540-28883-X_5, 2005), Vol. 21.
- [19] N. Asami, T. Senjuh, T. Uehara, M. Sumi, H. Kamimura, S. Miyashita and K. Matsui, Material behavior of highly deuterated palladium, Presented at the *The Ninth Int. Conf. on Cold Fusion*, Beijing, China, Tsinghua University, 2002.
- [20] R. Feenstra, R. Griessen and D.G. de Groot, Hydrogen induced lattice expansion and effective H–H interaction in single phase PdH, *J. Phys. F, Met. Phys.* **16** (1986) 1933.
- [21] D.L. Knies, V. Violante, K.S. Grabowski, J.Z. Hu, D.D. Dominguez, J.H. He, S.B. Qadri and G.K. Hubler, In-situ synchrotron energy-dispersive X-ray diffraction study of thin Pd foils with Pd: D and Pd: H concentrations up to 1:1, *J. Appl. Phys.* **112** (2012) 083510.
- [22] M.C. McKubre and F. Tanzella, Using resistivity to measure H/Pd and D/Pd loading: Method and significance, in *Condensed Matter Nuclear Science, ICCF-12*, Yokohama, Japan, A. Takahashi, K. Ota, Y. Iwamura (Eds.), World Scientific, Singapore, 2005, p. 392.
- [23] B. Baranowski, S. Majchrzak and T.B. Flanagan, The volume increase of fcc metals and alloys due to interstitial hydrogen over a wide range of hydrogen contents, *J. Phys. F: Met. Phys.* (1971) 258.
- [24] Y. Fukai and N. Okuma, Formation of superabundant vacancies in Pd hydride under high hydrogen pressures, *Phys. Rev. Lett.* **73** (1994) 1640–1643.
- [25] Y. Fukai, M. Mizutani, S. Yokota, M. Kanazawa, Y. Miura and T. Watanabe, Superabundant vacancy–hydrogen clusters in electrodeposited Ni and Cu, *J. Alloys and Compd.* **356–357** (2003) 270–273.
- [26] M. Krystian, D. Setman, B. Mingler, G. Krexner and M. J. Zehetbauer, Formation of superabundant vacancies in nano-Pd–H generated by high-pressure torsion, *Scripta Materialia* **62** (2010) 49–52.
- [27] E.K. Storms, Measurements of excess heat from a Pons–Fleischmann-type electrolytic cell using palladium sheet, *Fusion Technol.* **23** (1993) 230.
- [28] E.K. Storms, Anomalous heat generated by electrolysis using a palladium cathode and heavy water, Presented at the American

- Physical Society, Atlanta, GA, 1999.
- [29] M. Miles, B.F. Bush, J.J. Lagowski, Anomalous effects involving excess power, radiation, and helium production during D₂O electrolysis using palladium cathodes, *Fusion Technol.* **25** (1994) 478.
- [30] E.K. Storms, The status of cold fusion (2010), *Naturwissenschaften* **97** (2010) 861.
- [31] E.K. Storms and C. Talcott-Storms, The effect of hydriding on the physical structure of palladium and on the release of contained tritium, *Fusion Technol.* **20** (1991) 246.
- [32] G.C. Abell, L.K. Matson, R.H. Steinmeyer, R.C. Bowman Jr. and B.M. Oliver, Helium release from aged palladium tritide, *Phys. Rev. B: Mater. Phys.* **41** (1990) 1220.
- [33] W.J. Camp, Helium detrapping and release from metal tritides, *J. Vac. Sci. Technol.* **14** (1977) 514–517.
- [34] E.K. Storms, *The Explanation of Low Energy Nuclear Reaction*, Infinite Energy Press, Concord, NH, 2014, 365 pages (updated e-version available at Amazon.com).
- [35] P.L. Hagelstein and I.U. Chaudhary, Phonon models for anomalies in condensed matter nuclear science, *Current Science* **108** (2015) 507–513.
- [36] Y. Fukai and N. Okuma, Evidence of copious vacancy formation in Ni and Pd under a high hydrogen pressure, *Jpn. J. Appl. Phys.* **32** (1993) L1256–1259.
- [37] E. Storms, Explaining cold fusion, *J. Cond. Matter Nucl. Sci.* **15** (2015) 295–304.
- [38] E. Storms, How the explanation of LENR can be made consistent with observed behaviour and natural laws, *Current Science* **108** (2015) 531–534.
- [39] E.K. Storms, A theory of LENR based on crack formation, *Infinite Energy* **19** (2013) 24–27.
- [40] Y. Sakamoto, M. Imoto, K. Takai, T. Yanaru and K. Ohshima, Calorimetric enthalpies for palladium–hydrogen (deuterium) systems at H(D) contents up to about [H]([D])/[Pd] = 0.86, *J. Phys.: Condens. Mater.* **8** (1996) 3229.
- [41] R.P. Santandrea and R.G. Behrens, Thermodynamic properties of alloys used in focused ion beam sources, (LANL, 1985).
- [42] M.C.H. McKubre, S. Crouch-Baker, A.M. Riley, S.I. Smedley and F.L. Tanzella, Excess power observations in electrochemical studies of the D/Pd system; the influence of loading, in *Third Int. Conf. on Cold Fusion*, Frontiers of Cold Fusion, H. Ikegami (Ed.), Universal Academy Press, Tokyo, Japan, Held at: Nagoya Japan, 1992, p. 5.
- [43] S. Majorowski and B. Baranowski, Diffusion coefficients of hydrogen and deuterium in highly concentrated palladium hydride and deuteride phases, *J. Phys. Chem. Solid.* **43** (1982) 1119.
- [44] P. Jung (Ed.), *Diffusion and Clustering of Helium in Noble Metals*, Plenum Press, NY, 1991, p. 59.
- [45] A.N. Zhiganov and A.Y. Kupryazhkin (Eds.), *Grain-Boundary Diffusion of Helium in Palladium with Submicron-Grained Structure*, Am. Inst. Phys., 2003.
- [46] J. Xia, W. Hu, J. Yang, B. Ao and X. Wang, A comparative study of helium atom diffusion via an interstitial mechanism in nickel and palladium, *Phys. Stat. Sol. B* **243B** (2006) 579–583.
- [47] M.C.H. McKubre and F.L. Tanzella, Results of initial experiment conducted with Pd on C hydrogenation catalyst materials, 1999, private communication.
- [48] M.C.H. McKubre, Review of experimental measurements involving dd reactions, *PowerPoint slides, in Tenth Int. Conf. on Cold Fusion*, P.L. Hagelstein and S.R. Chubb (Eds.), World Scientific, Cambridge, MA, 2003.
- [49] V. A. Romodanov, V.I. Savin, Y.B. Skuratnik and V.N. Majorov, The nuclear reactions in condensed media for interaction of charge particles in energy region is forming by maximum elastic losses, in *Sixth Int. Conf. on Cold Fusion, Progress in New Hydrogen Energy*, M. Okamoto (Ed.), New Energy and Industrial Technology Development Organization, Tokyo Institute of Technology, Tokyo, Japan, Lake Toya, Hokkaido, Japan, Vol. 1, 1996, p. 340.
- [50] Y. Iwamura, T. Itoh, N. Yamazaki, H. Yonemura, K. Fukutani and D. Sekiba, Recent advances in deuterium permeation transmutation experiments, *J. Cond. Matter Nucl. Sci.* **10** (2013) 63–71.
- [51] Y. Iwamura, S. Tsuruga and T. Itoh, Increase of transmutation products in deuterium permeation induced transmutation, in *Proc. JCF13*, A. Kitamura (Ed.), Japan CF-Research Soc, WincAichi, Japan, 2012, Vol. http://jcf.org/proc_jcf.html, 196–213.
- [52] Y. Iwamura, T. Itoh, N. Gotoh and I. Toyoda, Detection of anomalous elements, X-ray, and excess heat in a D₂–Pd system and its interpretation by the electron-induced nuclear reaction model, *Fusion Technol.* **33** (1998) 476.
- [53] G.H. Miley and J.A. Patterson, Nuclear transmutations in thin-film nickel coatings undergoing electrolysis, *J. New Energy* (1996) 5.
- [54] G. Miley, Characteristics of reaction product patterns in thin metallic films experiments, in *Asti Workshop on Anomalies in*

- Hydrogen/Deuterium Loaded Metals*, W.J.M.F. Collis (Ed.), Italian Phys. Soc., Villa Riccardi, Rocca d'Arazzo, Italy, 1997, pp. 77–87.
- [55] M. Srinivasan, Introduction to isotopic shifts and transmutations observed in LENR experiments, *Current Science* **108** (2015) 624–627.
- [56] P.L. Hagelstein, Neutron yield for energetic deuterons in PdD and in D₂O, *J. Cond. Matter Nucl. Sci.* **3** (2010) 35–40.
- [57] P.L. Hagelstein, Simple parameterizations of the peutron–peutron fusion cross sections, *J. Cond. Matter Nucl. Sci.* **3** (2010) 31–34.
- [58] P.L. Hagelstein, On the connection between Ka X-rays and energetic alpha particles in Fleischmann–Pons experiments, *J. Cond. Matter Nucl. Sci.* **3** (2010) 50–58.
- [59] P.L. Hagelstein, Secondary neutron yield in the presence of energetic alpha particles in PdD, *J. Cond. Matter Nucl. Sci.* **3** (2010) 41–49.
- [60] J.-P. Biberian, Biological transmutations, *Current Science* **108** (2015) 633–635.
- [61] T. Mizuno, M. Enyo, T. Akimoto and K. Azumi, Anomalous heat evolution from SrCeO₃-type proton conductors during absorption/desorption in alternate electric field, in *Fourth Int. Conf. on Cold Fusion*, T.O. Passell (Ed.), Electric Power Research Institute, 3412 Hillview Ave., Palo Alto, CA 94304, Lahaina, Maui, Vols. 2, 14, 1993.
- [62] J.-P. Biberian, Excess heat measurements in ALLaO₃ doped with deuterium, in *5th Int. Conf. on Cold Fusion*, S. Pons (Ed.), IMRA Europe, Sophia Antipolis Cedex, France, Monte-Carlo, Monaco, Vol. 49, 1995.
- [63] L.C. Case, Catalytic fusion of deuterium into helium-4, in *The Seventh Int. Conf. on Cold Fusion*, F. Jaeger (Ed.), ENECO, Salt Lake City, UT, Vancouver, Canada, Vol. 48, 1998.
- [64] V.A. Romodanov, Tritium generation during the interaction of plasma glow discharge with metals and a magnetic field, in *Tenth Int. Conf. on Cold Fusion*, P.L. Hagelstein and S.R. Chubb (Ed.), World Scientific, Cambridge, MA, 2003, pp. 325–352.
- [65] M. Srinivasan, G. Miley and E.K. Storms, Low-energy nuclear reactions: Transmutations, in *Nuclear Energy Encyclopedia: Science, Technology, and Applications*, S. Krivit, J. H. Lehr and T.B. Kingery (Eds.), Wiley, Hoboken, NJ, 2011, pp. 503–539.
- [66] Y. Iwamura, T. Itoh, N. Yamazaki, J. Kasagi, Y. Terada, T. Ishikawa, D. Sekiba, H. Yonemura and K. Fukutani, Observation of low energy nuclear transmutation reactions induced by deuterium permeation through multilayer Pd and CaO thin film, *J. Cond. Matter Nucl. Sci.* **4** (2011) 132–144.
- [67] L. Holmlid, Nanometer interatomic distances in Rydberg Matter clusters confirmed by phase-delay spectroscopy, *J. Nanopart. Res.* **12** (2010) on line.
- [68] D.R. Tilley and H.R. Weller, Energy levels of light nuclei, $A = 4$, *Nucl. Phys. A* **541** (1992) 1.
- [69] A. Rossi, *J. Nucl. Phys.*, <http://www.journal-of-nuclear-physics.com/> (2012).
- [70] A. Rossi, Method and apparatus for carrying out nickel and hydrogen exothermal reaction, EU, Patent #: WO20110005506, 2011.
- [71] E.K. Storms, Explaining cold fusion, *J. Cond. Matter Nucl. Sci.* **15** (2015) 295–304. .
- [72] J. Kasagi, H. Yuki, T. Baba, T. Noda, J. Taguchi and W. Galster, Strongly enhanced Li + D reaction in Pd observed in deuteron bombardment on PdLi_x with energies between 30 and 75 keV, *J. Phys. Soc. Japan* **73** (1998) 608–612.
- [73] J. Kasagi, Screening potential for nuclear reactions in condensed matter, in *14th Int. Conf. on Condensed Matter Nuclear Science*, D.L. Nagel and M.E. Melich (Ed.), www.LENR.org, Washington, DC, Vol. 1, 2008, pp. 318–325.
- [74] K.P. Sinha and P.L. Hagelstein, Electron screening in metal deuterides, *Trans. Am. Nucl. Soc.* **83** (2000) 368.
- [75] K.P. Sinha and P.L. Hagelstein, Electron screening in metal deuterides, in *8th Int. Conf. on Cold Fusion*, F. Scaramuzzi (Ed.), Italian Physical Society, Bologna, Italy, Lerici (La Spezia), Italy, 2000, p. 369.
- [76] S. Ichimaru, Nuclear fusion in dense plasmas, *Rev. Mod. Phys.* **65** (1993) 255–299.
- [77] R.J. Beuhler, G. Friedlander and L. Friedman, Cluster-impact fusion, *Phys. Rev. Lett.* **63** (1989) 1292.
- [78] F.E. Cecil, H. Liu and J.S. Yan, Measurements of branching ratios of low energy deuteron-induced nuclear reactions on ²H, ⁶Li, and ¹⁰B, *Phys. Rev. C: Nucl. Phys.* **47** (1993) 1178.
- [79] J. Kasagi, T. Murakami, T. Yajima, S. Kobayashi and M. Ogawa, Measurements of the D + D reaction in Ti metal with incident energies between 4.7 and 18 keV, *J. Phys. Soc. Japan* **64** (1995) 608–612.
- [80] A. Takahashi, K. Maruta, K. Ochiai and H. Miyamaru, Detection of three-body deuteron fusion in titanium deuteride under the stimulation by a deuteron beam, *Phys. Lett. A* **255** (1999) 89.
- [81] K. Czernski, A. Huke, P. Heide and G. Ruprecht, The ²H(d,p)³H reaction in metallic media at very low energies, *Europhys.*

- Letts*. **68** (2004) 363.
- [82] E.N. Tsyganov, Cold nuclear fusion, *Phys. Atomic Nuclei* **75** (2011) 153–159.
- [83] K. Czerski, New evidence of the cold nuclear fusion – accelerator experiments at very low energies, Presented at the New Advances on the Fleischmann–Pons Effect, European Parliament, Brussels, 2013.
- [84] P.L. Hagelstein and I.U. Chaudhary, Lossy spin–boson model with an unstable upper state and extension to N-level systems, *J. Cond. Matter Nucl. Sci.* **11** (2013) 59–92.
- [85] J. Ruer, Simulation of crater formation on LENR cathodes surfaces, *J. Cond. Matter Nucl. Sci.* **12** (2013) 54–68.
- [86] D.S. Silver, J. Dash and P.S. Keefe, Surface topography of a palladium cathode after electrolysis in heavy water, *Fusion Technol.* **24** (1993) 423.
- [87] A. DeNinno, A. Frattolillo, A. Rizzo, E. Del Giudice and G. Preparata, Experimental evidence of ^4He production in a cold fusion experiment, ENEA - Unita Tecnico Scientifica Fusione Centro Ricerche Frascati, Roma, 2002, RT/2002/41/FUS.
- [88] S. Szpak, P.A. Mosier-Boss, J. Dea and F. Gordon, Polarized D+ / Pd–D₂O system: hot spots and “mini-explosions”, in *Tenth Int. Conf. on Cold Fusion*, P.L. Hagelstein and S.R. Chubb (Eds.), World Scientific, Cambridge, MA, 2003, p. 13.
- [89] R.K. Rout, A. Shyam, M. Srinivasan and A. Bansal, Copious low energy emissions from palladium loaded with hydrogen or deuterium, *Indian J. Technol.* **29** (1991) 571.
- [90] S. Szpak, P.A. Mosier-Boss and J.J. Smith, On the behavior of Pd deposited in the presence of evolving deuterium, *J. Electroanal. Chem.* **302** (1991) 255.
- [91] M. Miles and B.F. Bush, Search for anomalous effects involving excess power and helium during D₂O electrolysis using palladium cathodes, in *Third Int. Conf. on Cold Fusion*, Frontiers of Cold Fusion, H. Ikegami (Ed.), Universal Academy Press, Tokyo, Japan, Nagoya Japan, 1992, pp. 189–199.
- [92] D. Gozzi, F. Cellucci, P. L. Cignini, G. Gigli, M. Tomellini, E. Cisbani, S. Frullani and G.M. Urciuoli, X-ray, heat excess and ^4He in the D/Pd system, *J. Electroanal. Chem.* **452** (1998) 251–271.
- [93] V. Violante, P. Tripodi, D. Di Gioacchino, R. Borelli, L. Bettinali, E. Santoro, A. Rosada, F. Sarto, A. Pizzuto, M.C.H. McKubre and F. Tanzella, X-ray emission during electrolysis of light water on palladium and nickel thin films, in *The 9th Int. Conf. on Cold Fusion, Condensed Matter Nuclear Science*, X.Z. Li (Ed.), Tsinghua Univ. Press, Tsinghua Univ., Beijing, China, 2002, pp. 376–382.
- [94] P.L. Hagelstein, On the phonon model in cold fusion/LENR, *Infinite Energy* **19** (2013) 12–17.
- [95] D. Letts and D. Cravens, Laser stimulation of deuterated palladium: past and present, in *Tenth Int. Conf. on Cold Fusion*, P.L. Hagelstein and S.R. Chubb (Eds.), World Scientific, Cambridge, MA, 2003, pp. 159–170.
- [96] E.K. Storms, Use of a very sensitive Seebeck calorimeter to study the Pons–Fleischmann and Letts effects, in *Tenth Int. Conf. on Cold Fusion*, P.L. Hagelstein and S.R. Chubb (Eds.), World Scientific, Cambridge, MA, 2003, pp. 183–197.
- [97] D. Letts and P.L. Hagelstein, Simulation of optical phonons in deuterated palladium, in *14th Int. Conf. on Condensed Matter Nuclear Science*, D.L. Nagel and M.E. Melich (Eds.), Vol. 1, Washington, DC, 2008, pp. 333–337.
- [98] D. Letts, Highly reproducible LENR experiments using dual laser stimulation, *Current Science* **108** (2015) 559–561.
- [99] J. Tian, L.H. Jin, B.J. Shen, Z.K. Weng and X. Lu, Excess heat triggering by 532 nm laser in a D/Pd gas loading system, in *ICCF-14 Int. Conf. on Condensed Matter Nuclear Science*, D.L. Nagel and M.E. Melich (Eds.), Vol. 1, Washington, DC, 2008, pp. 328–332.
- [100] M. Apicella, E. Castagna, L. Capobianco, L. D’Aulerio, G. Mazzitelli, F. Sarto, A. Rosada, E. Santoro, V. Violante, M.C. McKubre, F. Tanzella and C. Sibilìa, Some recent results at ENEA, in *Condensed Matter Nuclear Science, ICCF-12*, A. Takahashi, K. Ota, Y. Iwamura (Eds.), World Scientific, Yokohama, Japan, 2005, pp. 117–132.
- [101] V. Nassisi, Experimental studies of a XeCl laser having UV preionization perpendicular and parallel to the electrode surfaces, *Appl. Phys. B* **53** (1991) 14–18.
- [102] V. Nassisi and M.R. Perrone, Double XeCl laser and lateral UV preionization, *Appl. Phys. B* **51**, 254 (1990).
- [103] D. Letts and D. Cravens, Laser stimulation of deuterated palladium, *Infinite Energy* **9** (2003) 10.
- [104] 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, J. Marwan and S. Krivit (Eds.), Oxford University Press, Oxford, 2009.
- [105] D. Letts, D. Cravens, P. L. Hagelstein, Thermal changes in palladium deuteride induced by laser beat frequencies, in *ACS Symposium Series 998, Low-Energy Nuclear Reactions Sourcebook*, J. Marwan and S.B. Krivit (Eds.), American Chemical Society, Washington, DC, 2008, pp. 337.

- [106] M. Davidson, Theories of variable mass particles and low energy nuclear phenomena, *Found. Phys.* **44** (2014) 144–174.
- [107] I. Dardik, H. Branover, A. El-Boher, D. Gazit, E. Golbreich, E. Greenspan, A. Kapusta, B. Khachatorov, V. Krakov, S. Lesin, B. Michailovitch, G. Shani and T. Zilov, Intensification of low energy nuclear reactions using superwave excitation, in *Tenth Int. Conf. on Cold Fusion*, P.L. Hagelstein and S.R. Chubb (Ed.), World Scientific, Cambridge, MA, 2003, p. 61.
- [108] O. Azizi, A. El-Boher, J.-H. He, G.K. Hubler, D. Pease, W. Isaacson, V. Violante and S. Gangopadhyay, Progress towards understanding anomalous heat effect in metal deuterides, *Current Science* **108** (2015) 565–573.
- [109] D. Das and M.K.S. Ray, Fusion in condensed matter – a likely scenario, *Fusion Technol.* **24** (1993) 115.
- [110] F. Parmigiani and P.G. Sona, Theoretical considerations on the cold nuclear fusion in condensed matter, *Nuovo Cimento Soc. Ital. Fis. D* **11** (1989) 913.
- [111] N.V. Samsonenko, D.V. Tahti and F. Ndahayo, On the Barut–Vigier model of the hydrogen atom, *Phys. Lett. A* **220** (1996) 297.
- [112] R.L. Mills and W.R. Good, Fractional quantum energy levels of hydrogen, *Fusion Technol.* **28** (1995) 1697.
- [113] K.P. Sinha and A. Meulenberg Jr., Lochon catalyzed D–D fusion in deuterated palladium in the solid state, *National Acad. Sci. Lett.* **30** (2007) 243.
- [114] V.I. Vysotskii and M.V. Vysotskyy, Coherent correlated states of interacting particles – the possible key to paradoxes and features of LENR, *Current Science* **108** (2015) 524–530.
- [115] V.I. Dubinko, Low-energy nuclear reactions driven by discrete breathers, *J. Cond. Matter Nucl. Sci.* **14** (2014) 87–107.
- [116] Y.E. Kim, Bose–Einstein condensate theory of deuteron fusion in metal, *J. Cond. Matter Nucl. Sci.* **4** (2011) 188–201.
- [117] B. Ivlev, Nuclear threads. *arXiv:1312.6561* (2014).