Questions About Lattice Enabled Nuclear Reactions: Mechanisms and Materials

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Abstract — Questions serve to focus discussions of research problems and engineering challenges. This is the first of three papers, which will pose and address technical questions about Lattice Enabled Nuclear Reactions (LENR). It deals with theoretical mechanisms and key materials in LENR experiments and potential power generators.

1. Introduction

Scientists have two jobs, learning new things and communicating them. Without learning, there is no science. Without communication, what is the use of learning? The desire to learn is commonly driven by curiosity. But, there are other motives for doing research to gain knowledge. Sometimes, scientists simply enjoy the pleasure of performing research. This is often the case when they are just exploring some topic, not necessarily driven by any questions. Nonetheless, seeking to answer questions is one of the most basic reasons for doing research, no matter the origins of the questions.

Posing and addressing scientific questions is a skill that requires balance. Working on questions that are too easy consumes time and resources. And, the answers to such questions provide little progress for a field. At the other extreme, working on questions that are really hard may not be wise. They, and the fame that comes from solving them, can be very attractive. But, there are also drawbacks. Relatively large amounts of time and money are usually needed to answer tough questions. And, success is far from guaranteed. These considerations are broadly applicable in science. They are certainly germane to the study of Lattice Enabled Nuclear Reactions, since it is a field of science.

Compiling and commenting on the scientific and related questions about LENR has two motivations. First, it seems useful to have several such questions in one place. Many of them are related. Second, when LENR becomes accepted as a legitimate field of scientific inquiry, there will be programs funded by government agencies and large companies, which are aimed at developing more understanding of LENR for both scientific and practical reasons. This paper seeks to serve as an early program planning tool of use, hopefully, in the not-so-distant future.

The present compilation and comments are inevitably limited, being the views of only one person. Other scientists would make a list of questions and write associated comments with some commonalities, but serious differences. It must be noted that there is continual email discussion of basic questions about LENR on the CMNS GoogleGroup moderated by Haiko Lietz.[1] Those discussions are very valuable, but are not integrated into a larger picture of issues about LENR, as this paper attempts to do. It is hoped that this summary will stimulate others to provide additional questions and viewpoints regarding the science and applications of LENR.

One dozen fundamental questions about mechanisms and materials for LENR are the focus of this first paper. These are some of the really fundamental unresolved questions that burden and enliven the study of LENR. The second paper will deal with experimental and computational questions that are significant to the advancement of the science of LENR. Many of those questions are closely related to the questions in this paper. The final set of questions about LENR, which will constitute the third paper, has mainly to do with the engineering, applications and commercialization of LENR generators of thermal or electric power and energy. These practical questions are inevitably related to the science of LENR, since a basic understanding of LENR would impact the answers to them. And, as the more practical questions regarding LENR are answered, the resulting knowledge should feed back into the science of the subject.

In 2002, Beaudette published a brochure containing questions and answers about LENR.[2] Many other technical and non-technical questions regarding LENR were posed and answered by this author in 2009.[3] Most of those answers remain true now. In a recent paper, McKubre and two colleagues listed and discussed significant questions that go beyond the science of LENR.[4]

The following questions are numbered simply for identification. That is, the numbering does not indicate any relative importance. It is hoped that these questions will be discussed in much more detail, so having identification numbers for them could be useful. The two largest technical problem areas in the study of LENR are theory and materials for experiments. Hence, this first paper addresses them. The next two sections are devoted to the topics of mechanisms and materials. For each question, there is a statement about why it is being asked, and some comments on what might be done to answer the question. The concluding section offers some additional perspectives. It also summarizes evidence for the nuclear nature of LENR.

2. Questions on Mechanisms

The most urgent questions about LENR center on what happens during such reactions. Why do LENR occur? If this were known, it might be relatively straightforward to produce conditions that will lead to reproducible, controllable and reliable energy production by LENR. It might even be possible to influence which specific reactions occur, and hence optimize the production of heat or other desired products.

Q1. ***Is there only one, or more than one, basic physical mechanism(s) active in LENR experiments to produce the diverse measured results?***

This question is motivated by the wide variety of results obtained in LENR experiments, as well as by a desire for fundamental understanding. Large thermal power releases and high energy gains[5]; output processes as fast as microseconds[6]; nuclear products ranging from tritium and helium through elements with intermediate masses to heavy elements[7]; fast particles, especially neutrons,[8-10] charged particles[11] and energetic photons[12,13]; and other effects such as emission of radio-frequency[14] and infrared radiation[15,16] and sound,[17] have all been measured. In addition, there is empirical evidence for the occurrence of fissioning of heavy elements in LENR experiments.[18]

It is conceivable that all of these results could be explained by one fundamental mechanism for LENR, or by a single mechanism that is followed by other reactions. However, it is also possible that different experiments access different parts of some overall parameter space, which favor the actions of different mechanisms. The lack of many correlations between different experimental outputs from LENR experiments would seem to favor the operation of two or more mechanisms, either simultaneously or sequentially. However, there are many more potential correlations between products of LENR than have been sought experimentally to date. These are relevant to Q7 below, where there is additional discussion of potential correlations.

Among the more remarkable observations in many LENR experiments are the small amounts of prompt and residual radiations. A central challenge to the question on LENR mechanisms is to explain both the low levels of energetic (gamma) radiation during experiments (such as seen in hot fusion), and the very low levels of radioactivity in materials after experiments (in contrast to fission).

This question on mechanisms is essentially a question on how the electrostatic (Coulomb) repulsion between two nuclei can be overcome or avoided, so that they can experience the wave function overlap that is prerequisite to their reaction. It will not be answered until a fundamental understanding of what happens in such experiments is achieved by a combination of theory and experiment. Achieving that understanding is difficult. Multiple steps are needed: (a) the development of theoretical concepts, (b) their reduction to equations, (c) computations based on the equations, and (d) comparison of the numerical results with experimental data. A review of "cold fusion" theories in 1994 critiqued the many ideas then in circulation.[19] Over three dozen theoreticians had already offered ideas about the mechanism causing "cold fusion," which the authors organized into 20 categories, some of them related. Many of those early concepts have become dormant or modified over the years, and other ideas have been added. Recently, Storms reviewed 23 LENR theories in seven categories.[20] The discovery of the mechanism(s) needed to answer this question will have great scientific and practical importance.

Q2. ***Is excess heat from electrochemical loading and gas loading experiments due to the same basic mechanism(s)?***

There are four fundamental approaches to creating conditions that result in LENR by bringing together hydrogen or deuterium with solid materials. They involve the use of electrochemical, gas, plasma and other methods, including beams and chemical preparation of hydrides and deuterides. Of these, electrochemical and gas loading have gotten the most attention. It is widely believed that electrochemical approaches are primarily good for scientific studies. However, gas loading will be used in the earliest commercial LENR generators because of its relative simplicity. Here, as with the first question, it is possible that different mechanisms are active in these two major branches of the field. The experimental setups, materials, protocols and results are often very different. But, it would be simpler if the same mechanism(s) were active in both approaches to loading. This is one statement of Occam's Razor.[21]

It might be possible to address this question by the use of the same materials in both types of experiments. Imagine cylindrical rods of some material that are coated, several at a time in the same equipment, with a thin film of a material conducive to producing LENR, maybe containing Pd or Ni. The composition, thickness, surface properties and other possibilities, such as having embedded nanoparticles, could vary widely. Once prepared and characterized, some of the rods could be used as electrodes in electrochemical experiments and others put into gas loading experiments. Comparison of the results obtained with the two methods of loading might provide an answer to this question, although that is not the only potential outcome. It remains possible that the same mechanism(s) occur for both methods of loading, but differences in the two techniques would lead to divergent results.

Q3. ***Are protons and deuterons interchangeable in at least some effective heat producing experiments?***

It is clear from experiments that LENR can be induced using either protons or deuterons from water and other liquids, gases and other materials containing them. The hydrogen isotopes introduced into LENR experiments can be varied in several ways. Some experiments are done with water or gases containing relatively small fractions of the unwanted isotope, either protons or deuterium. In those experiments, the light or heavy water, or the gas used, is very pure. In other cases, less pure substances are used. For example, most light water experiments have been done with water containing the natural abundance of deuterons (1 deuteron per 6420 protons in the earth's oceans).[22]

In many experiments, especially early in the field, dual cells were run simultaneously (often in series), one with light water and the other with heavy water. The light water experiment was thought to be a control, which would not produce power. The H_2O experiments proved that proper calorimetry was being done because the measured thermal output power was equal to the input electrical power.[23]

Most of the successful electrochemical experiments, that is, those that produced thermal power, have been done with heavy water. Dozens of examples could be given. We will cite only one of the best known, where the ratio of the thermal energy out of the electrochemical cell to the electrical energy put into it was 26.[24] Unpublished experiments by McKubre at SRI International involved addition of H_2O to cells with D_2O electrolytes, which were producing power.[25] The cells contained 3 mm diameter Pd cathodes. The excess power declined to zero over several days, delays much longer than the times required for diffusive equilibration of the H within the Pd. The causes of the slow change are not known.

There have been several light water electrochemical experiments for which production of excess heat was reported. Mills and Kneizys published the results of an experiment with an H_2O and K_2CO_3 electrolyte in 1991.[26] They reported an energy gain of 37, the largest such report at the time. That work stimulated a similar experiment in Japan by Notoya and Enyo. Excess power was observed at 2.7 to 3.4 times the input power, which ranged up to 2 W.[27] The same laboratory had a second paper on light water electrolysis at ICCF-3.[28] Four different cathode metals (Ni, Au, Ag and Sn) were used with two carbonate and two sulphate electrolytes. Only Sn with K_2SO_4 produced excess power (0.91 W) during a 65 hour run. A third publication from Notoya and her colleagues using light water in the electrolyte gave more evidence of the production of excess power.[29] They achieved excess powers up to 169% of the input power, which was 0.54 W.

In some electrochemical experiments, the ratio of protons to deuterons was varied during the course of the run. Bush and Eagleton performed many light water LENR experiments during the period 1990 to 1994. In one early report, Bush gave the results of several runs with different carbonate electrolytes in light water with nickel cathodes.[30] They reported LENR powers up to 5.9 W, and total energies as high as 0.75 MJ. That power level was gotten 24 hours after addition of 2 ml of heavy water to the cell, which was earlier operating with only light water in the electrolyte. The excess power of 5.9 W represented a power gain of 27.3%. The addition by Swartz of heavy water to another light water experiment with a nickel cathode showed increases in the production of power. In that case, the rate of power production was doubled to 0.5 W by the addition of 7.4% of D_2O.[31]

No electrochemical experiments are known to this author in which both light and heavy water were used in different proportions for entire experiments. Given the results with the mixed D_2O and H_2O electrolytes, it seems reasonable to conduct experiments with the relative amounts of heavy and light water as a parameter. They would have to be run with relatively small fractions of light water. Fleischmann stated in a letter to Miles that little H_2O in D_2O would stop the excess heat effect. The light water is preferentially electrolyzed, so that 1% of it in D_2O resulted in protons being 10% of the hydrogen isotopes within the Pd cathode.[32] One of the challenges for such a set of experiments would be to have enough cathodes with adequately similar performance in the multiple electrochemical cells.

Gas loading of protons onto and into nickel is economically attractive. Water and gases containing protons are much cheaper than similar deuterated materials, and nickel is much less expensive than palladium. Hence, it is widely expected that initial commercial LENR generators will involve gas loading of protons onto nickel. Further, gas loading is experimentally simpler than electrochemical loading. Early in the history of LENR research, Piantelli experimented with gas loading of nickel and other materials.[33] Many such experiments have been performed since then.

There was also substantial early interest in gas loading of deuterons into Pd. Arata and Zhang produced excess power by inserting deuterons into nanoparticles of Pd and Pd coated with zirconia.[34] That work was done with their "double structure" cathodes within electrochemical cells. Deuterons were produced on the outside of the hollow cathodes and diffused to the interior, creating a high pressure for gas loading of the Pd materials in the central void. In 1998, the two researchers reported the generation of LENR power up to 10 W during an experiment that ran for 8500 hours or almost one year. Their double structure cathode was immersed in an electrolyte that had two parts of D_2O and one part H_2O by weight.

In recent years, a team of researchers from Kobe University and Technova has studied both H and D loading from gases into a wide variety of nano-materials. Some materials gave high loading ratios (H or D per metal atom) and high heats of formation for both isotopes of hydrogen.[35] In other experiments at high temperatures, they measured excess powers of 5 W per gram of Ni, which lasted for a few days.[36] Another material gave 15 W for three days, and then increased by 10 W over three weeks. The excess energy corresponded to about 100 eV per Ni atom. In their most recent paper, the team reported that they observed excess energies of "several hundred eV/Ni-atom" in experiments above 500°C.[37]

As is the case with electrochemical loading experiments, there does not seem to be any reports where the composition of the gaseous atmosphere was varied continually from pure hydrogen to pure deuterium. Such parametric experiments, for both electrochemical loading and gas loading, could result in an answer to this question. It might happen that LENR can occur with either hydrogen isotope, but not as well when they are mixed, because of the need to establish some kind of a vibratory or other resonance with a single frequency.

It should be noted that a few of the many theories of mechanisms for LENR apply to either isotope.[38] Others require either one or the other of H and D, but cannot embrace both. Hence, the answer to this question has the potential to weed out some of the theories for LENR, or at least to constrain the breath of their applicability.

Q4. *Over what time scales do LENR release energy, that is, what is the time history of power generation by LENR?*

The time scales over which energy is generated in LENR experiments are important for both scientific and practical reasons. The time history of energy releases might help in understanding what is happening at a fundamental level, if the experimental time resolution is sufficient. It is important to learn if significant energy releases, which require the near-simultaneous occurrence of numerous LENR, are the result of many uncorrelated events, or are due to some type of a fast cascade of reactions, possibly a chain reaction. The concept of a LENR chain reaction was discussed in a paper in 1996 by Arata and Zhang.[39]

The energy released in LENR experiments and generators is unavoidably pulsatile on the scale of atoms. This is because an amount of energy is released during each LENR event at some point in time and space. If there are many LENRs occurring simultaneously, the power production on mesoscopic and macroscopic levels can occur in bursts. Or, if there are numerous LENRs occurring sequentially, the power production can have an apparently continuous and almost smooth time history. So, there are four basic modes of uncontrolled energy release: (a) a constant rate (ignoring shot noise), (b) a slowly-varying (pseudo-steady) rate, (c) bursts of various durations and magnitudes, and (d) a mix of the more-or-less steady output plus the occurrence of some bursts.

There is a great deal of experimental evidence on the time histories of energy releases from LENR. It falls into two cate-

gories, direct heat measurements with calorimeters and other types of measurements. Calorimeters can be sensitive devices, but they generally have long time constants.[40] Hence, it is usually not possible to follow the temporal histories of events that occur on time scales of minutes or faster. The response times of most calorimeters used for LENR studies are in the range of several minutes to hours. Consider how long it takes a cup of hot coffee to equilibrate with the ambient temperature. Very fast, that is, high power releases of energy are integrated by the calorimeters, so only the total energy generated within a short time is obtained.

There are many reports of highly variable excess power production in LENR experiments, where the output power changes over time scales of hours or more. One of the more interesting is the observation by Kozima and his colleagues that the frequency of excess power bursts varied inversely with their magnitude.[41] Miles found that power production in the Pd-D electrochemical system varied relatively continuously and smoothly at temperatures below about 60°C.[42] Above that temperature, bursts were more common due to the onset of significant positive feedback. Relatively slow variations in output power may be more important for applications of LENR power than for scientific understanding.

The formation of craters on the surfaces of cathodes during electrochemical LENR experiments provides circumstantial evidence of fast energy releases. The craters show evidence of melting, which indicates that high temperatures existed during the formation of craters. There is no way known to obtain experimental measurements of the times scales of the energy releases that produce craters. The locations and times of crater formation are not known in advance. Only if the site of an expected crater were known, some particular area on a cathode could be watched to observe a crater form. So, dynamic measurements of crater formation are not feasible. However, it is possible to use the crater sizes, and estimates of formation energies, with thermal analyses or simulations to obtain estimates of energy release times.

Craters from electrochemical LENR experiments have diameters generally in the range of 1 to 100 micrometers. Two methods have been used to estimate the energies that would be necessary to produce the observed craters, simple calculations and the scaling of crater sizes and energies.[43] The two techniques were in rough agreement. They showed that crater energies range from about 1 nJ (for 1 μm diameter) to about 1 mJ (for 100 μm diameter). Assuming that each LENR produces 20 MeV of energy, those energy values imply that between 1200 (1 μm diameter) to 1200 million (100 μm diameter) reactions occurred within a very small spatial region. The emission times for releases of such energies have been estimated by use of an analytical model of crater formation.[44] They varied from nanoseconds to microseconds.

Other types of measurements with instrumentation that responds faster than calorimeters are useful to, at least, set empirical limits on energy release times due to LENR. A recent study compiled published data from measurements of sound, radio-frequency emission, infrared emission, x-ray emission, and production of neutrons and energetic ions.[45] The results for the fastest signals found in each category are summarized in Table 1. It would be valuable to obtain time-resolved spectral information for sound, RF, IR and x-ray data. However, such measurements are limited by the total available intensity for each of these values.

The last column indicates work that would be valuable for improving such data. High speed data on emissions from LENR experiments will probably be of great use scientifically. They should serve to guide and constrain theories about the mechanisms that lead to LENR. This may be most true for the fastest energy releases, which set upper limits on the durations of energy release events. Fast recordings might indicate something about the difference between near-simultaneous reactions and cascaded (chain?) reactions. It is also likely that bursts of power that occur over much longer times, including those resolvable with calorimetry, will be important. The use of LENR generators for myriad applications will be influenced by large power variations on longer time scales. It is already clear that the ultimate disposition (as heat, sound, radiation, etc.) of the energy released from nuclear binding energies by LENR will be significant, at least scientifically, and probably practically. Such energy branching ratios are needed.

Q5. *Do LENR occur exclusively as individual uncoupled events, or is it possible to have cascades of LENR, in which one reaction makes more likely the occurrence of more LENR?*

Many LENR must occur to release significant amounts of energy. One MeV of energy might seem to be a large value, but it is equivalent to only 1.6×10^{-13} J. Hence, even if a single LENR reaction releases 20 MeV, it takes 3×10^{11} such reactions to result in one joule of excess energy. That release in 1 second supplies 1 W of power. Such a small power can have many applications, depending on the size and cost of the equipment needed to produce it. But, most contemplated applications of LENR require powers on the order of kW. Heating a residence is one such application. Hence, LENR rates near 10^{14} Hz are of great interest.

It is possible that all LENR reactions occur individually, not influenced by similar reactions in their proximity. However, it is also possible that the occurrence of one reaction will

Table 1. The shortest time responses from empirical data for each of the listed measurables.

Observations	Shortest Time	Needed Research
Sound	About 20 msec	Additional measurements with faster acoustic system
RF Emission	A few seconds	Additional measurements with faster RF system
Infrared Emission	<< 1 second	Additional measurements with faster IR system
X-Ray Emission	About 2 μsec	Additional measurements with faster x-ray system
Neutrons	< 64 μsec	More fast measurements with stronger neutron sources.
Energetic Ions	About few min.	New designs that permit ions to reach fast detectors

either decrease or increase the likelihood of similar reactions. These prospects are examined in the following paragraphs.

If all LENR reactions are uncoupled, it is instructive to estimate their average spatial separation. Power densities in excess of 1 kW/cm^3 have been reported from LENR experiments.[46,47] One kW is equivalent to 3 x 10^{14} reactions per second, again using 20 MeV per reaction. Assuming that the reactions are uniformly distributed on a cubic grid 1 cm^3 in size within a nuclear active region, they are separated by about 100 nm. If the reactions all occurred in a two-dimensional region, that is, on a surface, the spacing between reaction sites would be less than 1 nm. Essentially, each surface atom position would be the site of a LENR each second. For both 2D and 3D cases, LENR products, that is, the nuclei that result from the LENR, would be produced with similar separations each second. The reaction products might have energy that enables them to move away from where they were created. However, that does not ameliorate the potential problem of the accumulation of reaction products, and their possibly deleterious effects on occurrence of further LENR. Hence, the production of heat by LENR in a small spatial region may decrease the likelihood of further energy production. The reconstitution of the active materials in a LENR generator might be necessary.[48]

During energy production by nuclear fission, the proximity of fuel nuclei is necessary, if neutrons released by prior reactions are to be efficiently captured to produce further fissions. That leads to the question of whether or not similar effects might operate during the production of energy by LENR. That is, are cascaded or chain reactions operable during production of heat by LENR? There has been very little discussion of this possibility in the field to date.[39,49] The answer to this question will ultimately depend on understanding of the basic mechanism(s) that produce LENR, as already discussed. If the occurrence of individual LENR events damages or destroys the efficacy of the nearby region for production of later LENR events, practical means to renew or replace active materials will be needed. In some sense, that would be similar to a large fire using the oxygen available in a region, and not being able to burn further, even though fuel remains.

There is indirect experimental evidence for the nearly simultaneous occurrence of numerous LENR in small spatial regions. As noted above, craters have been observed on the surface of cathode materials after many electrochemical LENR experiments. Estimates of the energy releases needed to produce measured crater diameters range from 1 nJ to 1 mJ.[43] And, analytical calculations of crater formation times are in the range of nanoseconds to microseconds.[44] These numbers imply that numerous MeV-scale reactions are closely located in both space and time. However, that evidence alone does not indicate whether the reactions are independent of each other or occur in causal sequences.

There does not seem to be a clear experimental path to answering the question about whether LENR are separate or coupled events, and the related question of whether they improve or degrade chances for subsequent events. Possibly, the use of materials having layers with nanometer-scale thicknesses would be instructive. However, resolution of these issues will probably occur only when the fundamental mechanism(s) of LENR are understood. The answer to the question of potential cascades of LENR, and their possibly negative effects on further production of energy and transmutation products, is very central to the commercialization of LENR.

Q6. *Is the excess heat due entirely or only partially to nuclear reactions, and, if partially, what other mechanism contributes to the heat output?*

It was clear to Fleischmann and Pons that the excess heat they measured in the 1980s could not be due to chemical reactions. They and others thought that the only alternative explanation was nuclear reactions. However, there was and remains the possibility that there is some entity between nuclei and atoms in both size and energy, which can be formed with the release of energy, that is, without requiring nuclear reactions.

Randell Mills postulated early in the 1990s the existence of a deeply bound form of hydrogen, which he called the hydrino.[50] The least binding energy, and hence the energy that might be released during formation of the entity, was thought to be 41 eV. More tightly bound levels were postulated to have higher energies. If such bound energy levels existed, they should be evidenced in spectra and, possibly, in electron scattering experiments. The spectral evidence for the hypothetical levels is not compelling.[51] And, the scattering experiments do not seem to have been done. Hence, the existence of Mills' envisioned deeply bound energy levels in hydrogen is still an open question.

Since then, other theorists have postulated "compact objects," the formation of which would yield keV-scale energies, rather than nuclear MeV energies. Such entities supposedly involve one of the hydrogen isotopes as nuclei and also orbital electrons. They would have sizes much smaller than atoms. The idea is that some or all of the released heat in what are called LENR is not due to nuclear reactions, but comes from the formation of these compact objects. Because of their small size and electron shielding, the protons or deuterons at the center of these objects can move closer to other nuclei in materials, which increases the probability of later true nuclear reactions. The effect is similar to muon-catalyzed fusion,[52] but the detailed mechanism is different. In this LENR scenario, the nuclear reactions that lead to transmutation products and energetic particle emissions are entirely subsequent to the main heat production mechanism. The ancillary nuclear reactions are thought to be exothermic, so they do contribute some unknown fraction of the measured excess heat. In such a case, correlations between heat production and conventional nuclear reaction products are possible, but not required.

There are several theories about compact objects. Each of those theories is briefly reviewed below. For reference, we note that the radii of a hydrogen atom, with a muon in place of the normal electron, is 285 fm.[53] This small radius leads to increased fusion rates because the distance over which tunneling must occur to result in a nuclear reaction is much smaller than for normal atoms. Hence, the tunneling probabilities and associated nuclear reaction rates are greatly increased (catalyzed). It is not possible to produce power practically by use of muon-catalyzed fusion for two reasons. The energy to produce muons exceeds the fusion energy that can be generated during their short lifetime of 2.2 microseconds.[54] And, each muon has a 1% chance of staying with an alpha particle created by a fusion reaction, preventing it from catalyzing further reactions.

There were two papers by Maly and Vavra on compact

objects in the 1990s, stimulated by cold fusion.[55] They dealt with "deep Dirac levels" in various atoms. Those levels are solutions of the Dirac equation, the relativistic analog of the Schrödinger equation in Quantum Mechanics. The papers give their energies and charge distributions. The binding energies fall in the range of 300 to 500 keV and the orbital radii are on the scale of femtometers. The authors of the papers considered experiments to test for the existence of these levels. They point to calorimetric evidence from LENR experiments as (indirect) evidence of the levels they computed.

In the mid-1990s, Dufour proposed the existence of bound states that result from equilibrium between the attractive electrostatic force and the repulsive electro-weak force.[56] He termed the entities Hydrex and Deutex, depending on whether a proton or deuteron was involved. The radii of various energy levels of the Hydrex were computed to be in the range of 1.78 to 3.47 fm. Their binding energies varied widely from about 393 keV for the lowest (n = 1) quantum level to 36 keV for n = 20 and beyond to small energies for higher quantum numbers. Dufour envisioned the Hydrex as a composite with oscillatory behavior between a proton with a very close electron and a neutron-neutrino pair.

Another theory on compact objects by Heffner was discussed on the internet in 2007 and published during the next year.[57] He wrote of weakly bound pairs of electrons in the same state with opposed spins. In his concept, the existence of these electron pairs increases the probability of creation of a "deflated paired state." In that state, the two electrons have wavelengths sufficiently small to exist "in the nucleus."

In 2011, Mayer and Reitz published an article entitled "Electromagnetic Composites on the Compton Scale."[38] They postulated a three body entity, called a tresino. Such particles would consist of a central proton or deuteron, plus two orbital electrons with aligned spins. Computations based on a simple Schrödinger equation gave 3.7 keV for the binding energy for a tresino and 386 fm for the orbital radius of the two electrons. Assuming that tresinos can form, Mayer and Reitz argued that they might explain two major current scientific riddles, the heating of the earth in geology[58] and dark matter in astronomy.[59] The two researchers applied the concept of the composite particles to explain aspects of LENR. The heat observed in calorimetric experiments is attributed to tresino formation. Note that the tresino mechanism does not require nuclear reactions for the production of energy.

Meulenberg and Sinha have also addressed the mechanism of LENR by consideration of compact objects. Their approach also involves a short-term composite of two electrons and either a proton or deuteron, along with a bare proton or deuteron.[60] However, their mechanism is the formation of such an object, followed by D-D fusion. That is, the approach necessarily involves nuclear reactions. They envision that the non-uniform lattices in heavily loaded Pd involve localized and high-frequency phonon modes. Those vibrations produce dynamic electrostatic fields that interact strongly with electrons in the materials. The resultant "potential inversion" causes the formation of "lochons," that is, local-charged-boson-electron pairs, giving deuterons compact screening and a net negative charge. That removes the coulomb barrier, leading to the D-D fusion. In a recent paper,[61] Meulenberg summarized the related work by Naudts.[62] He arrived at an energy of the rest mass of the electron times the fine structure constant, specifically, 511 keV/137 = 3.7 keV and a radius of about 390 fm.[63] These values are essentially identical to those for tresino formation.

Recently, in response to reports of high LENR powers from the Ni-H system, Dufour hypothesized the existence of a new composite system, which he terms the Hypole.[64] He envisions a Ni nucleus about 1.9 picometers from a proton, with an electron orbiting the combination. Both the proton and electron are within the electron shells of the Ni atom. Dufour gives the Hypole formation energy as 10.5 keV. Because of the picometer separation of the Ni nucleus and proton, Dufour applies the new term "pico-chemistry" to LENR reactions that follow formation of Hypoles.

The compact object theories just surveyed are all essentially concepts with some supporting computations. It is natural to ask why such compact objects have not been observed previously. The answer might be that very special conditions are needed for their formation in observable numbers. For example, Mayer and Reitz envision spin alignment of the two electrons in a tresino. Having two aligned electrons simultaneously near each other and either a proton or deuteron is required. That might be a very rare circumstance because of chemical and thermal effects.

If it occurs, a two-step process might explain the relatively small production of tritium and neutrons, and the occurrence of transmutations. That is, if the secondary nuclear reactions are rare for any reason (low tunneling probability or dearth of nearby reaction partners), very few nuclear products might result. A two-step scenario could also have something to do with the difficulty in producing heat and its erratic behavior, if very specific conditions are required to make the compact objects.

It is simple to compute the implications of the formation of compact objects, and possible, but not assured subsequent nuclear reactions.[65] If the formation of compact objects is indeed the initial step in the production of excess heat, the total amount of excess energy E_T depends on the number N_C of reactions that form compact objects, the energy E_C released per formation of a compact object, the fraction f_N of the compact object formation events that lead to subsequent nuclear reactions, and the energy E_N released per nuclear reaction: $E_T = N_C\{E_C + \Sigma f_N E_N\}$. The summation is over the number of subsequent distinct exothermic nuclear reactions. The values of f_N can range from zero (no secondary nuclear reactions) to unity (when a particular energetic nuclear reaction follows each compact object formation event). The fraction of the excess heat due to nuclear reactions, namely $(\Sigma f_N E_N/E_T)$, can be as low as zero or as high as nearly unity. So, the generated energy can be due entirely to non-nuclear events or dominated by nuclear reactions.

Storms has postulated the existence of a "nuclear active environment" of still unknown composition and structure in which LENR occur.[66] If the initial reactions are not nuclear, but are instead the exothermic formation of a compact object, a nuclear active environment is not a requirement. However, in that case, it is probably still necessary to have a particular combination of material (composition and structure) and ambient (sonic, magnetic or other fields) conditions favorable to the formation of compact objects.

Resolution of this question about the source of excess heat will probably not come from any clear yes-or-no experiments. It is conceivable that, under some conditions, all of

the excess energy is indeed due to nuclear reactions and, under other conditions, little of it is nuclear. Intermediate situations could also exist. Much additional quantitative experimental and theoretical work will be necessary to determine what actually happens for various conditions.

Q7. *Do other results from LENR, including transmutation products, fast particles, photons and craters, arise from the heat producing reactions?*

This question is closely related to the question on the origin of products from LENR experiments, which was just discussed. It has two parts that are similar, first about transmutation products and then about fast particles. These are addressed in turn. In all cases, the central issue is the temporal correlation between various outputs during LENR experiments, or the post-run correlation of quantitative aspects of the measured results.

It might be that all of the touted transmutation products are due to nuclear reactions that produce heat. Hence, one can expect a quantitative correlation between the amounts of heat in joules and amounts of transmutation products, that is, their number of atoms. In most cases, chemical analyses for transmutation products have been done before or after LENR experiments. That is, there is no temporal information on when the products were produced, but there is still the opportunity for quantitative correlations after an experiment.

In electrolysis experiments, it is possible to withdraw and analyze part of the electrolyte during an experiment. However, this has rarely been done. Doing so is not guaranteed to be instructive, because the concentration of new elements might be small compared to the amounts already present. And, the transmutation products might be on or in the cathode and not accessible to analysis.[67] In gas loading experiments, real time analyses might be carried out by proper connection of a differentially-pumped mass spectrometer to the experiments. However, here again, the transmutation products might not be in the sampled atmosphere. No experiments of this type are known to this author.

Early in the field, it was thought that the measured excess heat was due exclusively to fusion of two deuterons with the production of ^{4}He nuclei. Miles and his coworkers were the first to measure both the heat and helium. They observed a correlation consistent with the amount of energy (about 24 MeV) known to be released during one of every ten million conventional (hot) fusion reactions.[68] Later, McKubre and his colleagues did extensive research on the production of heat and helium in a gas loading experiment.[69] They reported a correlation between the two products with the energy per reaction of 31 or 32 +/- 13 MeV. Others did heat and helium measurements in the same experiments, which were reviewed in two papers.[70]

Tritium and ^{3}He have been reported in multiple LENR experiments. But, no correlations with the excess heat are published. Light elements are not the only reported transmutation results from LENR. There is a vast literature on the production of heavier elements.[71] Only one correlation between the heat produced and the number of new atoms from the LENR is known.[72] In that work, Dufour and his colleagues reported the production of Mg, Cu and Zn atoms with a Pd electrode and Lu, Hf, Yb and Pb atoms with an electrode of U. They gave values for the MeV measured per atom produced in the range of 150 to 400 MeV for the various reaction products. Those reaction energies span the energies from neutron-induced fission of heavy isotopes.[73]

If fast particles and photons are the result of the nuclear reactions that generate all of the excess heat, then (a) the particles should be diagnostic of the heat-producing reactions and (b) there should be a correlation between the number of particles and the heat. Conversely, if the nuclear reactions that produce the fast particles are only subsequent to the initial and dominant heat-producing reactions, the relationship might be different. The nuclear reactions could generate anything from a small to a large fraction of the overall excess heat, as discussed in response to Q6 above.

Temporal and quantitative correlations between excess heat and both fast particles and photons have been sought in a few cases. Such experiments are challenging. First, there has to be production of excess power, which is not always possible to achieve. Even when there is excess power production, it is commonly unsteady as a function of time. Good equipment for measurement of energetic particles is relatively expensive and not widely available. It is well known that the number of fast neutrons or charged particles emitted from LENR experiments is generally small. Hence, it can be necessary to count for relatively long times (minutes to hours) to obtain adequate statistics. The time variations of the power production might occur on different time scales, making correlations difficult

The potential for correlations among measurable quantities from LENR experiments can be appreciated by examining Figure 1. It lists the dozen kinds of observables that have been reported at least twice from LENR experiments. Only one report of sound from an LENR experiment is known.[17] There are 66 possible pairwise comparisons among all of these dozen quantities. Clearly, there remain many opportunities to seek correlations between observables in experiments in the hope of understanding the fundamental mechanisms that produce LENR.

This is another case where the question will be resolved only by experiments. Having a source of excess power that

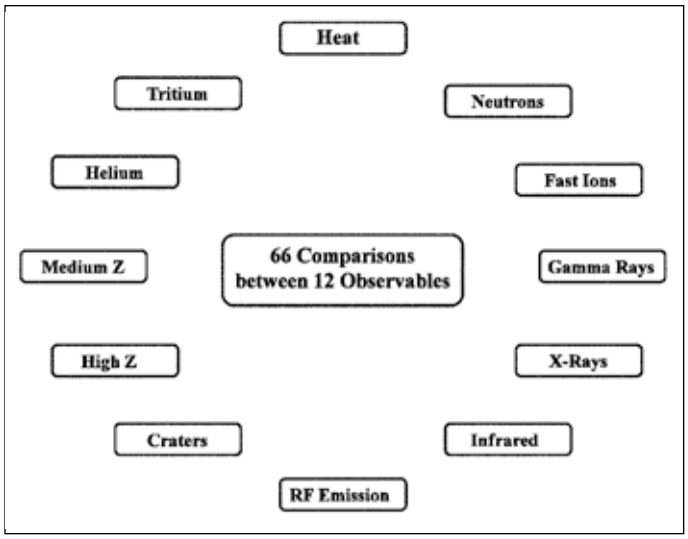

Figure 1. Quantities that have been measured during and after LENR experiments. Reaction products range from tritium and helium to heavy elements. Particles measured include neutrons and fast ions. Observed photons span four regions of the electromagnetic spectrum, from gamma rays to RF emissions. Craters are indicative of localized fast heat generation.

runs relatively steadily for long periods of time would be very useful for such experiments. It would be best to use radiation detectors that have large acceptance solid angles and high stopping power for radiations, which also provide information on the energies (spectra) of the particles.[74]

3. Questions on Materials

The core difficulty in achieving reproducible and controllable production of heat and other products in LENR experiments is due to some aspect of the materials used in the experiments. The chemical compositions and atomic structures of those materials can vary widely. Quantification of the numbers and positions of the key atoms in experimental materials is challenging and expensive. That is particularly true of impurities with low concentrations. But, impurities could be central to the production of LENR. It might also be important that any given piece of material, such as the cathode in an LENR electrochemical experiment, is not uniform in its composition and atomic structure. That is, there can be spatial variations in the details of materials on nanometer scales, which might be important to production of LENR. And, the key characteristics of materials generally vary with time during an experimental run or during the use of a LENR power generator.

Control and characterization of materials, and then their testing in LENR experiments, requires many years of research by a competent team. Such a program has been pursued by the Italian group lead by Violante in collaboration with researchers in the U.S.[75] They found that specific characteristics of Pd cathodes lead to improved production of LENR power in electrochemical experiments. There is a great need for such systematic and thorough research. The number of potentially-relevant materials parameters is large. For example, additives to materials in LENR experiments can vary widely in type and concentrations. Similarly, there are many opportunities for application of sonic, magnetic, electromagnetic and other fields of diverse magnitudes and combinations to LENR experiments.

Q8. *What are the keys to making and maintaining materials that produce excess heat regarding both composition (notably impurities) and structure (vacancies, dislocations, cracks, etc.)?*

There are five things needed for any LENR experiment: (1) equipments to house and power the experiment, and to measure what happens, (2) materials that go into the experiment, (3) protocols, which specify what gets done, when and how, (4) the laboratory where the experiment is setup and run and (5) the experimenter. There are very many options for each of these. All but one can be determined and known in considerable detail. That exception is materials. The details of materials necessary for the occurrence of LENR must be tightly related to the mechanisms by which such reactions occur.

As already noted, determining the chemical composition and the atomic structure of materials in adequate detail is both time-consuming and expensive. It requires sophisticated and well calibrated analytical equipment in the hands of technicians skilled in using it. Even if such materials characterization is done for the cathode or other materials before an electrochemical experiment, the materials change during the experiment. Those changes can be necessary to the production of LENR. For example, achieving a high ratio of deuterons to metal atoms, that is, high loading, in electrochemical experiments is necessary to reliably get excess heat.[76] It is possible to determine changes in materials during experiments in some cases. Using the resistance ratio to determine loading is a good example.[77] However, it is not possible to follow during LENR experiments the variations in all chemical and structural properties that might be important.

It is thought by many people that subtle, but critical variations in materials within LENR experiments are what make production of excess power challenging, and also account for variations in both reproducibility and output power. It was realized over 15 years ago that low level impurities could produce modest excess powers in LENR experiments, if the impurities were reactants.[78] Rarely are the levels of impurities in materials well known prior to experiments. Even if impurities are not actually fuel, they might be needed to produce nuclear active regions in which LENR can occur. Basically, if very particular combinations of composition and structure are needed to produce LENR, and if the acceptable variations in those conditions are small, then finding the right conditions in the multi-parameter space is difficult. Such challenges are common in electrochemical experiments. That also appears to be the case for gas loading experiments, including those that are now moving toward commercialization.

Very many physical and chemical processes have been employed to prepare the interior bulk and exterior surfaces of materials for LENR experiments. Most of them have been used prior to insertion of the Pd, Ni or other materials into an experimental chamber. As one example, Arata and Zhang employed plasma spraying to coat a nickel rod with a layer of Pd.[79] The resulting complex surface was full of "microdefects," which lead to highly reproducible LENR behavior. There is a good argument for preparing the active materials *in situ*, that is, in the chamber within which the LENR will be produced. That approach avoids contamination of the surface from the external atmosphere. In recent work, Mizuno and his colleagues used a cyclic process for preparation of Ni and Pd surfaces within their reaction chambers.[80] The metals were first heated in vacuum, then subjected to a glow discharge plasma, then heated in the reactant gas, and finally heated in vacuum again. This cycle was repeated four or five times prior to experiments. Excess power was achieved in approximately three-fourths of the experiments.

A massive amount of materials science and engineering research is needed to discover and optimize ways to prepare materials for LENR experiments. Development of a quantitative and predictive theory for production of nuclear active regions might resolve this question. However, it is also possible that only very careful parametric experiments, in which key factors are both varied willfully and characterized in detail, will suffice to solve the materials riddle.

Q9. *Do LENR occur on or near surfaces or in the bulk of materials or at any locations on or in a material?*

This is another question closely related to the issue of what mechanisms cause LENR. It matters greatly, both scientifically and practically, if LENR occur on or very near to surfaces of materials, in their bulk or in both types of locations. Surface sites, including cracks that extend to the surface, are readily accessible from the surrounding liquid or gaseous atmosphere. Hence, they have either zero or small diffusion lengths (and times). It takes longer to load hydrogen iso-

topes at high levels into the bulk of materials, especially if they have dimensions on the order of millimeters or more. Similarly, thicker materials require more time to reject reaction products, such as He, which can impede further energy production.[48] The ratio of surface area to bulk volume depends on the sizes and shapes of material particles.[81] Hence, hydrogen isotope access to sites for the occurrence of LENR should influence the geometries of materials that are needed in experiments and generators. Maintenance of the desired shapes and sizes might limit the lifetime of fuels in LENR generators, depending on diffusion and sintering.

Some clean surfaces can be classified as flat and smooth, if the shapes of the atoms and molecules that constitute the surface are ignored. But, usually surfaces are structured with various geometries of different size scales. Surfaces are commonly covered with diverse layers, which are generally complex in both their composition and structure. This is especially true for the environments in electrochemical cells. The layers on surfaces can be enabling or disabling for the chemical or nuclear reactions of interest. The bulk of a material can be even more complicated than the surface because of the various types of defects, and their different dimensionalities, which are possible.[82]

Even the definition of a surface or near-surface region can be complex, especially for contoured surfaces. Electronic structure calculations made for layers of atoms parallel to the clean surface of a crystal provide useful guidance on what constitutes a surface. They show that the band structure and density of states for the single surface layer of atoms is markedly different from those of bulk layers. This is due to the absence of bonds on one side of atoms in the surface layer. However, the second layer has an electronic structure that is very much like that of bulk layers. So, the surface and near-surface regions can be reasonably defined as just the top one or two layers of atoms on a clean surface. That is, the width of the surface and near-surface region is on the scale of 1 nanometer or even less in thickness. However, diffusive and other more energetic processes can affect depths extending 1 micrometer or more into the bulk of a material.

There is evidence from electrochemical, and from gas loading and permeation LENR experiments, that the reactions occur near the surface of the usually-ordered solid materials involved in the experiments. A few workers have found that excess power scales with the electrical current density through the surface of the cathode.[83] Others showed that shining a laser on a cathode in an electrochemical cell increases the rate of power production.[84] The skin depth for the laser-solid interaction is on the order of 50 nanometers.[85] Arata and Zhang used Pd black in their hollow (double structure) cathodes, which had a high pressure of deuterium gas inside of the cathodes.[34] In such finely-divided Pd, most of the atoms are near the surfaces of the nano-particles. The gas permeation transmutation experiments by Iwamura and his colleagues show the reaction products occur within about 10 nm of the surface.[86] In his first book, Storms cites evidence for the occurrence of LENR on surfaces.[87] Included are the appearance of tritium in the gas above an active cell (rather than in the cathode) and the surface-sensitive open circuit voltage in power-producing cells. The production of LENR power from cathodes with very thin layers of active materials indicates that LENR can occur on or near surfaces.[88]

Celani and his colleagues at the Italian INFN-LNF and other laboratories spent many years studying the effect of surface conditions on the electrolytic production of LENR power. In 2003, they wrote that "we are confident that most of the observed effects occur at the interface between the solution and the Pd bulk."[89] A systematic study of Pd material characteristics in relationship to their ability to produce excess power was conducted by Violante and his coworkers at the Italian ENEA laboratories.[90] It was found that power generation was more likely if the surface crystallites had a (100) orientation, and if the spatial frequency of the surface roughness was in the range of 10^6 to 10^7 m^{-1}. That is, surfaces with structures in the sub-micrometer (nanometer) scale favored the production of LENR power. It is worth noting that materials prepared *in situ* by co-deposition of Pd and D give excess powers that are not in proportion to their very large surface areas.[91]

Besides the evidence for LENR occurring on surfaces, just reviewed, there are also indications of the scaling of LENR power with volume. The first long paper by Fleischmann and Pons showed excess power varying with cathode volume.[92] Early work by Miles agreed with that publication.[93] There also remains a question about LENR occurring on surfaces that are buried within the volume of cathode and other materials. If that occurs, there could be an apparent scaling with volume even if the LENR all occurred on interior surfaces.

In summary, there is substantial empirical evidence of varying quality which indicates that LENR occur on or near the surface of solids. However, the case for where LENR occur is certainly not closed. Additional data are needed both from reproductions of experiments already run, and from new types of measurements, such as Raman scattering. It is possible that parametric experiments in which the surface area and bulk volume are separately varied will resolve the important question of where LENR occur. A simpler experiment to prove that LENR occur on surfaces would be to introduce a solution of some material into a cell that is producing excess energy, which would deposit on the surface of the cathode. If all the LENR were occurring on the surface, then the new solute could effectively and quickly poison the nuclear active region and rapidly reduce production of excess power. However, if the LENR were occurring within the cathode, excess power might be reduced only slowly or not at all.

The location of LENR has important practical, as well as scientific, implications. If LENR occur on surfaces, it will be dramatically easier to bring reactants together and to remove products compared to reactions occurring within materials. It will also be easier to reconstitute nuclear active reactions on the surfaces of materials.

Q10. *Are nano-scale structures or particles sizes necessary for occurrence of LENR?*

This question is motivated by considerable experimental data and some theoretical perspectives. We cited some evidence just above for LENR occurring mainly on or near the surfaces of materials. If that is the dominant situation, then nanometer-scale structures could be fundamental to the occurrence of LENR. That is due to the fact that the surface and nearby regions on materials are generally on the order of 1 nanometer or less in thickness. As the size of material particles decreases toward the nanometer-scale, the surface-to-volume ratio increases.[81] And, the fraction of the interior

(bulk) atoms close to a surface also grows. That decreases the times for protons or deuterons to access all the atoms in a material by diffusion.

The assertion by one theory that LENR occur in micrometer-scale patches on surfaces[94] would, if correct, mean that LENR happen in structures that are on nanometer scales in at least one dimension. That dimension is limited by the surface thickness. A recent theory asserts that LENR occur due to a different one-dimensional structure, namely lines of protons or deuterons within cracks in materials.[95] These theories have yet to be validated. It might be necessary to have structures with nanometer scales in two or three dimensions, in order to cause LENR.

Preparation of deuteron-loaded Pd by codeposition techniques results in materials that have features on millimeter, micrometer and nanometer scales. It is not clear if the effectiveness of codeposited materials in giving excess power is due to their dramatically increased surface-to-volume ratios, or due to the presence of nanometer-scale particles. The design of experiments to separate these two variables would be challenging.

There is a significant body of research on LENR that involves particles with dimensions on the order of nanometers. It began with the work of Arata and Zhang.[34] As already noted, they used nanoparticles of Pd within a double structure cathode in electrochemical experiments. Electrolysis produced protons and deuterons, which migrated through the walls of the cathode and pressurized the region containing the Pd nano-particles (Pd black) up to 10 atmospheres. The effectiveness of those experiments in producing excess heat and ^{3}He reaction products prompted a great deal of attention to nano-particles in gas-loading LENR experiments.

The use of nano-particles at elevated temperatures is problematic because diffusion and sintering of the particles leads to their growth and loss of nanometric character. To combat agglomeration, Arata and Zhang turned to using nano-particles of Pd coated with ZrO_2.[96] Excess powers as high as 10 W were measured for hundreds of hours. Oxide coated nanoparticles are also being used in gas loading experiments by another Japanese collaboration.[35,36] Substantial excess powers were measured for various materials. In other experiments, particles of Pd as small as 1 nanometer were embedded in zeolites, and then cycled between atmospheres of either H_2 or D_2 and vacuum.[97] The use of D_2 apparently produced excess heat, although there remains the possibility that it is of chemical origin. A generic problem with experiments containing substantial numbers of atoms and molecules other than the active metals (such as Pd or Ni) is accounting for the energetics. That is, chemical interactions involving the numerous non-active materials can involve energies that approach and exceed the energies released by relatively small numbers of LENR on or in the active metals.

There has been some work published on the production and use of surfaces that have nanometric structures on or embedded in them prior to experiments. Such surfaces can be made by a wide variety of physical and chemical techniques. For example, ion bombardment leads to roughening of smooth surfaces of materials. The character and size scales of the roughness depends on the target material and its crystal orientation, and on the ions used, their angle of incidence, their energies, the dose and the atmosphere in which the bombardment occurs. It is also possible to employ physical or chemical material *deposition* processes to produce rough surfaces. Physical or chemical etching (material *removal*) processes can also be used to generate rough surfaces. As with ion bombardment, there are several important parameters, the values of which determine the final structures and scales of the surface roughness.

There have been several recent studies in which physical or chemical processes have been used to produce micrometer-scale and smaller structures on the surfaces of materials for gas-loading LENR experiments.[98] Work has begun on the employment of very short pulse lasers to produce structures on both micro- and nano-meter scales on the surfaces of materials to be used as cathodes in LENR experiments.[99] Significant work on surface preparation of cathodes by templating and other means has been performed, but not documented.[100] Mizuno and his colleagues recently reported on the use of glow discharge plasmas to produce fine-scale structures on the surfaces of metals.[80]

It must be noted that particles with exterior dimensions on the scale of nanometers are often highly defective. That is, they can contain many vacancies, dislocations and planar defects. Further, the smallest nanometer-scale particles have dimensions on the same scale as common materials defects. So, if defects play a role in the causation of LENR, the demonstrated efficacy of nano-scale particles may be due to their highly-disordered character rather than their external dimensions. Miley has stated that the size of defects is more important than the size of particles. A summary of many of his views appeared in this magazine.[101]

In order to resolve the necessity and effects of nano-scale structures on causation of LENR, there are three potential, albeit difficult, approaches. All the methods would depend on the ability to make and characterize specific kinds of materials, be they Pd or Ni or other compositions. The starting point would be the ability to make surfaces with similar densities of particles of the same sizes and geometrical shapes on them. If the spacing of those structures were varied first, experiments might show what separation scale would be the best for producing LENR. The second approach is similar, but would involve particles of the same spacing and shape but varying size. Finally, the separations and sizes of the particles could be held constant, and their shapes varied. A series of experiments as similar as possible, save for the particle densities, dimensions and shapes, might provide indications of the role of nano-structures in LENR.

Q11. *What is the role of oxide-metal and other interfaces in LENR experiments?*

The presence of oxides or other compounds on or in materials in LENR experiments has already been shown to have significant effects. They can impede the diffusion of hydrogen isotopes through materials. The reason for the slower hydrogen or deuterium diffusion in compounds, especially ionic compounds, compared to diffusion in metals seems clear. Protons or deuterons are very small compared to atomic sizes and inter-atomic spacings. Unlike all other elements, the hydrogen isotopes need not carry bound electrons with them inside of most solids. That is, they have sizes on the order of nuclei (femtometers) rather than sizes on the order of atoms (nearly nanometers). Hence, the diffusion coefficients of hydrogen isotopes in materials are relatively

high.[102] Once inside a metal, the positive charges of protons and deuterons are shielded (charge neutralized) by available electrons, some of which are highly mobile. However, in most compounds, the bonding electrons are not mobile. They are localized on the anions in solids with ionic bonding, like oxides, or between atoms in materials with covalent bonding, notably organic materials. Localized (bound) electrons cannot move freely with either protons or deuterons, which are slowed by their unavailability.

Oxides, sometimes buried in metals and sometimes coating nano-particles, have been an important part of many successful LENR experiments. There are two particularly noteworthy instances in which oxide layers played a central role in LENR experiments. Iwamura and his colleagues did deuterium permeation experiments in which the Pd foils had buried within them five oxide layers, each 100 nm thick.[103] They reported the transmutation of many elements when the layers were made of CaO, but did not measure transmutations when MgO was employed. The layers of oxides were near the entrance side of the Pd foils, that is, the side into which the permeating deuterons entered. They probably influenced (impeded) the motion of deuterons through the foils.

For different reasons, Arata and Zhang used oxide coated Pd nanoparticles in some experiments.[34] As noted, if uncoated nanoparticles are used in gas-loading experiments, they rapidly sinter together and lose their nanometric size scales. To defeat such sintering, Pd particles embedded in ZrO_2 were used. The oxide is a compound with a high heat of formation and relatively low atomic mobility compared to the pure Pd. The Pd particles were about 50 nanometers in diameter. Excess powers of 2-10 W were observed for 1600 hours using those materials.

A recent paper by Biberian *et al.* reviewed LENR experiments in which oxides played a role.[104] The authors note that running electrochemical LENR experiments in Teflon or polymer coated cells does not produce excess heat. However, the use of glass cells does lead to oxide formation on the cathodes, and excess heat in many cases. Slow dissolution of the glass puts ions into the electrolytes, which deposit on the cathode. Those might block absorption of deuterons in some of the areas of a cathode, and restrict the active electrochemistry to smaller areas with necessarily higher current densities. Or, conceivably, they might play a role in supplying reactants.

It was found experimentally that addition of 0.25-0.75% boron to Pd lead to reliable production of excess heat.[105] That performance was attributed to reduced cracking of the Pd, and less subsequent deuterium escape. Reaction and removal of oxygen during the preparation of such alloys might occur and be important. In contrast, Biberian and his colleagues note that it is also possible that boron added to Pd promotes superficial oxide formation and leads to quicker production of excess heat. Those authors note that oxide coatings cause high electric fields at the oxide-metal interface. However, it cannot be said now if that leads to LENR, or specifically where LENR reactions occur.

Resolution of questions about the role of oxide layers and other interfaces in LENR experiments is highly desirable, both scientifically and practically. It is possible that the use of specially designed cathodes for electrochemical experiments, and tailored permeation foils for gas loading experiments, will help produce answers. Cathodes with partial coatings, and permeation foils that have areas which are either covered or not with layers or interfaces, might be useful. The fraction of the covered area could be the variable parameter in such experiments.

Q12. *What are the roles of the surroundings of active materials in LENR experiments?*

One of the most well-established aspects of the study of LENR is the need to bring together either protons or deuterons with solid materials, which are almost always in the form of a crystalline lattice. There are a few cases in which that juxtaposition of the hydrogen isotopes and the lattice is done chemically prior to insertion of the materials into a LENR experiment. This approach is called "preloading." However, in most LENR experiments, the protons or deuterons start in a phase outside of the lattice, and are then brought onto the surface or into the interior of the key material. The light isotopes can originate in the liquid state in conventional electrochemical experiments, in a gaseous form in gas loading experiments, in a plasma in glow discharge and arc experiments, or in an ion beam, if loading is done by implantation in a vacuum. The point here is that the ambient phases in contact with the key materials in a LENR experiment play the role of supplier of the protons or deuterons. Hence, the motions of protons or deuterons from within those phases to the surface of the materials, and what happens when the H or D arrive at the surfaces, must be of interest.

An important fact is that the surroundings of the solid materials in a LENR experiment contain molecules, atoms or ions of elements other than hydrogen. In principle, the effects of those other elements can vary greatly. At one extreme, they can poison desirable surface reactions. Other, less drastic changes are also possible. For example, in electrochemical experiments, adding Hg to the electrolyte can make the electrode surface impervious to the passage of protons or deuterons. This has been used to seal hydrogen isotopes within cathode materials.[106] At the other extreme, molecules, atoms or ions from the ambient surroundings of the solid material in an experiment can produce nuclear active regions in which LENR occur. It is also possible that those quanta supply reactants for LENR.

Soon after the Fleischmann and Pons announcement, two groups experimented with changing the composition of the electrolyte during LENR experiments. Shirai and colleagues were running a cell with a D_2O solution containing 0.1 M DCl and 0.01 M $PdCl_2$ for three days.[107] The cell had a current within the Pd cathode, in addition to the electrolysis current. The cell temperature sensor read about 20°C. Then, they replaced the electrolyte with an H_2O solution containing 0.1 M LiOH. The temperature in the cell increased by over 50°C. During the following days, they varied the currents within the cathode and the electrolysis current. Depending on the combinations of the currents, the temperatures ranged between about 20 and 70°C. That is, there was some degree of control over the thermal power output from LENR.

The second group included Appleby and coworkers. They conducted electrochemical loading experiments, which produced modest excess powers.[108] The results of one experiment of about 150 hours are in Figure 2. It is seen that the signal-to-noise ratio exceeded 10 for the highest output powers. This experiment had four interesting features. The first

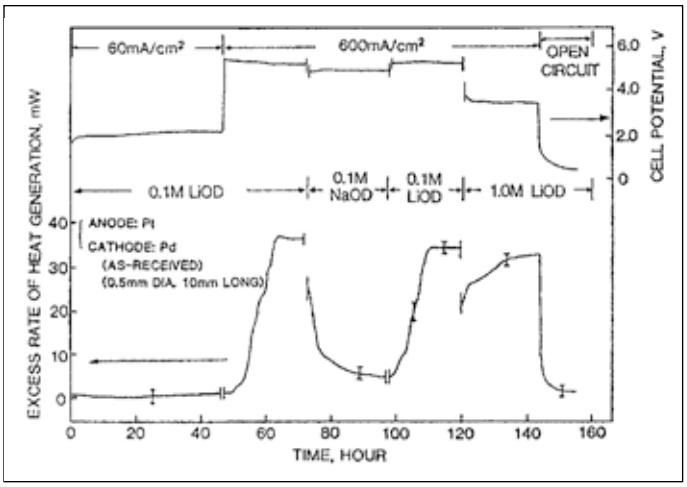

Figure 2. Time history of applied current density, excess power generation and cell potential with a Pd wire cathode and varying electrolyte chemistry and concentrations.

was the power balance at the start of the run when the current density was low. Increasing the current by a factor of 10 caused the production of excess power, when the electrolyte was 0.1 M LiOD. The second noteworthy feature is that the LENR power declined toward zero after the electrolyte was changed to 0.1 M NaOD. Returning to the 0.1 M LiOD caused the return of the excess power at nearly the original level. The third feature of interest was the behavior when the concentration of the LiOD was increased by a factor of ten. The excess power declined to about half of its value with the more dilute LiOD electrolyte, and then started to recover. Finally, the time constant for changes in the excess power was several hours in these experiments. It is not known if the role of the Li atoms in Appleby's experiments was "merely" to create conditions for LENR, without the Li participating in the reactions, or if the Li atoms were actually reactants in energy-producing LENR. In any event, the experiments show that lithium and sodium had very different effects on the production of LENR power. There is a clear need for more experiments in which the composition and concentration of the electrolyte (or gaseous atmosphere) is varied during a run.

4. Conclusion

The posing of numerous scientific and other questions about LENR should not leave the impression that little is known about the subject. While there remains much to be learned, great progress has been made empirically in the past quarter century. A long paper could be written on those advances. Here, only the most important empirical facts will be briefly summarized. Prime among them is the observation that it is possible to induce nuclear reactions by the use of chemical energies. While specific conditions are not fully known, it is clear that LENR require both a solid and either protons or deuterons. Importantly, the evidence for the occurrence of nuclear reactions is robust. Output energies from LENR experiments have exceeded what is possible from chemical reactions by factors of over 1000 in some cases. The appearance of the products of nuclear reactions is indisputable. Evidence for the production of tritium, a radioactive isotope with a short half lifetime, which is relatively easy to measure, is especially strong. Neutrons and fast particles cannot result from chemical reactions. By themselves, they show that nuclear reactions occur in LENR experiments. Other empirical evidence, such as the appearance of craters in the surfaces of materials in LENR experiments, can only be explained by the release of nuclear energies.

There are many other scientific and practical questions about LENR. A recent paper by McKubre, which addresses questions and criticisms of research on LENR, is available.[109] He considered three questions: (a) What do we think we know? (b) Why do we think we know it? (c) Why do doubts still exist in the broader scientific community? Certainly, one of the most important non-technical questions is what will be required for the subject to be accepted as a legitimate field of science, regardless of its practicality. There are two primary difficulties to overcome. One is ignorance by most scientists of the strong experimental data for the occurrence of LENR. Even researchers who are working on ways to better produce, handle and use energy do not pay attention to the status and attractive prospects of LENR. Another problem is active opposition by some former scientists to the acceptance of LENR as a field of science. How much of that opposition is ego or ignorance or due to funding by vested energy interests is unknown, and will remain so.

There are three possibilities which might lead to the acceptance of LENR by the scientific and broader communities. One is the development, testing and widespread acknowledgement of a clear theoretical explanation. This will not happen soon because of the many theories, their generally poor states of quantitative development and the lack of experiments designed to test their predictions. Another breakthrough possibility is a report of very strong experimental results, for example, the controllable production of power at the kilowatt level. However, a paper of this type with strong test results from E-Cat systems appeared in May of 2013.[110] It did not even make the mainstream press. A new report on E-Cat testing does not seem to be having a broad impact either, at least not yet.[111] A third possibility is the appearance of LENR power generators in stores for purchase by the public. That will require several stages, including the development of reliable and controllable prototypes, beta testing, design and production of products, and their safety and regulatory clearances. So, this approach to legitimizing LENR research and development will not happen soon.

The second paper in this trilogy will appear in Issue 119 of this magazine. It will deal with questions about scientific experimental and computational procedures for LENR. The final paper is slated for Issue 120. Its focus will be on engineering, commercialization and applications of LENR power generators.

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