Comments on Storms' Ideas About the Location and Mechanism for Low Energy Nuclear Reactions

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Character and Role of Theory

Storms' view of where and how low energy nuclear reactions (LENR) occur has been called a theory, so we begin with an examination of the character of a scientific theory. A compact summary about theory in any science is available in Wikipedia: "A scientific theory is a well-substantiated explanation of some aspect of the natural world, based on a body of facts that have been repeatedly confirmed through observation and experiment. Scientists create scientific theories from hypotheses that have been corroborated through the scientific method, then gather evidence to test their accuracy. As with all forms of scientific knowledge, scientific theories. . .aim for predictive and explanatory force."

The Wikipedia article continues, "The strength of a scientific theory is related to the diversity of phenomena it can explain, which is measured by its ability to make falsifiable predictions with respect to those phenomena. Theories are improved as more evidence is gathered, so that accuracy in prediction improves over time. . .Scientific theories are the most reliable, rigorous and comprehensive form of scientific knowledge. This is significantly different from the word 'theory' in common usage, which implies that something is unproven or speculative."

Scientific theories are unavoidably quantitative. Notice the emphasis on "accuracy" in the above discussion of theory. There is a sequence of steps for the development and testing of a theory. An idea comes first. Then, equations that embody the notion must be written down. Computational evaluation of those equations then yields values that can be compared with past measurements or used to design experiments to test the theory, possibly falsifying it.

We will compare Storms' idea about where and how LENR occur with these aspects of theories after a brief synopsis of the current status of LENR and a summary of Storms' viewpoints on the sites and dynamics of LENR.

Low Energy Nuclear Reactions

The overall situation regarding LENR seems quite clear. It is an active and challenging field of science. Experimentally, there is substantial and robust evidence for the ability to produce nuclear reactions using chemical energies. However, the experiments are neither adequately reproducible nor reliably controllable at this time. This is largely due to the fact that LENR are not understood. None of the few dozen theories has satisfactorily explained the mechanisms involved in LENR and their dependence on materials and other characteristics. Despite the experimental and theoretical shortfalls, a few companies are now engineering prototypes of energy generation products based on LENR, which they hope to bring to market in the near future. There is a remarkable degree of hype associated with the promises of products and their potential impacts.

The absence of understanding of LENR is not due to a lack of theoretical effort. Many ideas have been advanced in efforts to understand the fundamentals of these reactions. The Chechin *et al.* paper entitled "A Critical Review of Theoretical Models for Anomalous Effects in Deuterided Metals," which was published in 1994, listed and commented on more than 25 models. A large fraction of the papers at each of the last few International Conferences on Cold Fusion have been theoretical in nature. Because LENR theories are in diverse stages of development, some being only ideas, it is hard to determine where to stop counting. However, there are roughly three dozen theories in circulation. Some are no longer under development due to the passing of their authors. Others are being pushed vigorously. The credentials of the people putting forward LENR theories vary widely. Many of the authors are well trained in the physics and chemistry relevant to LENR. Very few of the theories have produced numerical predications, especially reaction rates. And, there has been scarcely any solid comparison of numerical results based on LENR theories with available experimental data.

Storms' Ideas About the Location and Mechanism of LENR

An examination of Storms' ideas on requirements for and production of LENR should not be confined to a review of his paper published in this issue. Earlier, he published a much longer article with 162 references in the *Journal of Condensed Matter Nuclear Science* (Vol. 9, pages 86-107, 2012, http://www.iscmns.org/CMNS/JCMNS-Vol9.pdf#page=91) with the title "An Explanation of Low Energy Nuclear Reactions (Cold Fusion)." The paper lists five "proposed requirements" that must be satisfied by a theory for LENR. It then goes on to compare some of the available theories with the list of requirements, stating which requirements are violated by which theories. The long paper is a good example of Storms' knowledge of the relevant literature and logical approach to an understanding of LENR. Judging from his writings and comments on the web, Storms has studied many, maybe most, of the theories on LENR. Comments on the new paper in this magazine are informed by what is in the earlier paper, as will be noted.

In both papers, especially the long article, Storms presents evidence and arguments for LENR occurring on the surface, and not within the bulk of materials. He then says, since LENR are not commonplace, they must depend on relatively rare conditions on the surface. That is, they are not prone to occurring on ordinary surfaces, many of which can be relatively simple structurally. However, it has to be recognized that surfaces in anything other than ultra-high vacuum conditions are chemically complex due to adsorbed layers, even if the underlying substrate is atomically smooth. Storms believes that "small" cracks on surfaces satisfy both the ideas that LENR occur on surfaces and in rare circumstances, which are largely uncontrollable. It is noteworthy that Storms does not explicitly quantify what he means by small.

Storms presents two interesting lists in the long paper. The first is a set of three "principles" that have to apply to LENR. The first of these principles states that a nuclear active environment (NAE) must form, and obey the known laws of physics and chemistry. The second is insertion of a hydrogen isotope into the NAE. And, the third is the actual nuclear reaction. This sequence seems reasonable. The second list, also with three items, deals with the major variables that determine the amount of energy generated by LENR. They are the concentration of the NAE, the concentration of protons or deuterons in the NAE, and the locally available energy to trigger the LENR. These points might be true, but it would be very useful to write out the coupled kinetic equations based on them, and then evaluate those equations using some reasonable parameters.

The paper in this issue by Storms posits three sequential steps for the production of LENR, which are more detailed than his list in the long paper. These go beyond the locations where LENR occur and essentially provide ideas about the fundamental mechanism for such reactions. The steps are (a) cracks form and are filled with protons or deuterons, (b) a resonant process happens to induce LENR and (c) the produced energy is carried off as coherent photons with characteristic energies. Each of these suggestions involves problems. While cracks on the surfaces of materials, including the materials in LENR experiments, are common, there is no direct evidence for cracks being the locations of nuclear reactions. The idea that cracks are the NAE was arrived at by a process of elimination. But, cracks have been found experimentally to degrade or defeat attainment of high loading of deuterons into palladium in electrochemical LENR experiments. Such high loading is known from experiments to be a necessary condition for observation of excess heat.

The occurrence of a "resonance process" is also speculative, and has even less support than the centrality of cracks for occurrence of LENR. Resonances are common in both electrical and mechanical phenomena. Mechanical structures from atomic lattices to the entire earth have resonances. In the current case, Storms envisions that, "Nuclei of hydrogen (all isotopes) might be confined by a crack structure in a special way. These nuclei can be imagined as floating equidistant between the walls of the crack supported by the charge present on each wall." This statement gives a rough calibration of the size scale of the cracks of interest, namely small enough for both walls to provide confinement. There is no suggestion in Storms' paper of the frequencies of the resonances. However, it seems clear that the frequencies have to be near or comparable to phonon frequencies (THz) because of the small size of the contemplated arrangements of nuclei.

Storms also wrote, "When a line of 'floating' hydrogen nuclei, each separated by an electron, is created in a crack, this structure has the ability to resonate along its axis." The statement that a "line" of atoms is involved is particularly interesting. An ordinary crack, which has a ribbon-like structure, could support a sheet, but not a line of atoms, unless only the bottom of the crack has dimensions small enough to do what Storms envisions. Then the line might run roughly parallel to the surface of the material. If the bottom of the crack is not the region of interest, then there would be no single line of atoms, no clean vibration frequencies and no preferred direction for escape from the solid of part of the energy from LENR.

If the existence of a line of atoms is accepted, a question arises about the contemplated separation of the nuclei by electrons. It is possible that the positive charges on the nuclei are neutralized by nearby electrons either in the crack or in the walls of the crack. That is, the electrons will not be solely between nuclei, but will have spatial distributions dependent on the local arrangements of protons or deuterons and the host material. The wave functions of electrons in solids do include regions between ions, but they are also extended in other directions.

The next problem is how the "resonance" of a line of atoms could induce nuclear reactions. The motions of the H or D nuclei in a crack are not unlike the motions of the same entities in a lattice, although they might be somewhat closer to each other. That is, their separations would not be determined by the host lattice, but by the electro-dynamics of the protons or deuterons and the nearby electrons in the crack.

Finally, where does the energy released by LENR go? Storms presents some possibilities, but they also are quite speculative. That is not to say they are wrong, but there is very little experimental basis for his surmises. Storms wrote in the published long paper, "As this resonance takes place, coherent photons (X-rays) are emitted, similar to what takes place in a laser. In this case, the energy does not come from outside sources, but from gradual conversion of hydrogen nuclei into another element, with the intervening electron being absorbed into the final nucleus. . .This unconventional relationship is forced on the system by the walls of the crack in which the process occurs." Later in the same paper, Storms wrote, "Analysis using mathematical tools will follow if the suggested model is found to be correct." This seems backwards, since the mechanism cannot be shown to be correct without prior computations (analysis) and comparison of their results with experiments.

Regarding the envisioned X-ray emission, Storms wrote in the paper in this magazine that, "Momentum is conserved by two coupled photons being emitted in opposite directions along the axis of the crack." Further, he states, "Since in each case the radiation is coupled to a resonance process, it will be coherent and act like an X-ray laser." There is no basis for assuming that the energy released by LENR will be photons in the X-ray region of the spectrum. And, there is no indication in either paper of the energy of such emissions. The basis for the envisioned X-ray photons being "coupled" and coherent is unclear. That they might originate at the same time does not make them coupled, as are the entangled photons in modern action-at-a-distance experiments. Low energy directed X-ray emission has been reported by Karabut for glow-discharge plasma loading LENR experiments. However, it cannot be due to laser action because of insufficient energy densities. The statement "act like an X-ray laser" is bothersome because lasers in all regions of the spectrum act by stimulated emission. That process certainly does not play a role in the emission of the imagined counter-propagating photons.

What is in Storms' model of where and how LENR occurs is only part of the situation. What is missing from his presentation is also important. Most basically, there is no clear picture of the atomic arrangements that might be held by the walls of crack and driven into resonant motion, presumably thermally. There are no equations describing the motions, which could lead to computations of the energetic and kinetics predicted by the model. In fact, his model is essentially descriptive and not quantitative. The picture offered by Storms does not satisfy the most basic quantitative aspects of a scientific theory, as stated in the opening paragraphs above. Storms' concepts could be the beginning of a thoroughly developed theory, but they are no more than ideas now.

Before finishing a critique of Storms' papers on the locations and mechanisms for LENR, it should be noted that he is entirely focused on fusion of light nuclei. His long paper tabulates and discusses specific nuclear reactions involving isotopes of hydrogen. Many scientists in the field think that experimental evidence for transmutations of much heavier nuclei requires more than a fusion-centric approach to understanding LENR.

Further Technical Comments

Since cracks are central to Storms' concept of where LENR occur, it is reasonable to consider the various types of cracks in which the reactions might occur. Cracks are ordinarily openings in a surface, which have a relatively small width and depth, and usually extend for longer distances along the surface. The widths and depths of cracks can vary in size from nanometers, that is, a few atoms on the low end to about a millimeter on the large end. The extent along the surface commonly ranges from something under millimeters to dimensions limited by the size of the piece of material, sometimes many centimeters.

It is also possible to have what might be called cracks that do not extend significant distances along the surface. They would have openings on the surface that are more or less equiaxed, that is, of comparable dimensions in both directions parallel to the surface. Their depth could vary from a small fraction of the dimensions of the opening parallel to the surface to many times deeper. It would be more natural to think of these features as holes in the surface, rather than cracks.

The geometry of ordinary cracks and holes in surfaces can vary widely. One possibility is to have flat and parallel sides orthogonal to the surfaces, with flat bottoms roughly parallel to the surface. Another is to have interior sides that slope almost smoothly from the opening downward to meet at a line or point in the bottom, essentially a "V" shape. Many intermediate possibilities exist, with sides stepped on an atomic scale.

A limiting case is a hole in the surface that is due to removal of only one string of atoms in the lattice. It might intersect the surface at a wide range of angles. However, we can consider it as perpendicular to the surface for purposes of discussion. Such a hole (not a crack in the usual sense of the word) would have an opening with dimensions on the order of interatomic separations, that is, fractions of a nanometer. It would be larger than the region immediately along the edge of a dislocation that emerges from a surface, but similar in having a structure with size comparable to atoms.

With these considerations of the range of possible crack geometries and sizes, we can examine them as possible sites for LENR. In any crack with dimensions larger than about one nanometer, hydrogen or deuterium atoms can have three kinds of relations to the solid. Some will coat the interior surface of the cracks, much like they coat the overall surface of the material. Others will be in more-or-less linear regions where the surfaces within a crack meet, possibly near the bottom of the crack, or else on atomic-scale ledges in the interior wall of the crack. The third possibility is for the H or D atoms to simply fill the crack without being in contact with the solid. That case would be similar to those entities in the electrolyte over the surface in an electrochemical experiments or the gas above a surface in a gas loading experiment. There might be nothing special about the first or third cases.

The main case of interest is the second possibility, namely H or D atoms or molecules being simultaneously in contact with two facets of a substrate along a linear structure of some possibly-long length. That is, lines of H or D atoms could form either in holes in a surface that are due to the removal of only one or a few strings of lattice atoms, or along much more likely ledges within cracks. It must also be noted that any surface of a crystal that is not parallel to some low-index lattice plane will contain ledges against which H or D atoms could also be in contact with the substrate atoms on two "sides." Hence, cracks into a surface are not necessary to produce a line along a surface where H or D atoms can contact metal atoms in two directions. In fact, cracks might be very undesirable, because they can serve as "leaks" from which H or D loaded into a lattice escape.

It is easy to contemplate ledges on the surfaces or the walls of the cracks of materials. The ledges have been observed with atomic force microscopes in experiments with ultra-high vacuum conditions. It is not possible to keep the surface of a substrate free of adsorbate atoms in most cases with a vacuum greater than about 10^{-9} torr. However, all electrochemical experiments, those for LENR included, have dense electrolyte in contact with the surface, and a very dynamic situation right at the surface. At the cathode in an electrochemical cell, H_2 or D_2 molecules are split into H or D atoms, which can either enter the cathode or recombine to form molecules. Diverse chemical reactions and depositions occur on or very near to the solid surface. That surface is very unlike the textbook picture of the surface of a solid. The same is also true for LENR gas loading experiments. Such experiments all have atmospheres near or well beyond one atmosphere, with unknown concentrations of unknown impurities in the atmospheres.

If it is assumed that lines of H or D ions form within cracks or along ledges on the surface of materials, the dynamics of the structures are likely to be very complex. The atoms near the hydrogen isotopes will be in thermal motion as phonons impinge on the surfaces. It seems unlikely that any mechanical (positional) excitations along the line of hydrogen isotopes would propagate over significant distances because of the orthogonal jostling of the nearby substrate atoms. H or D ions might either be ejected from the linear arrangement, or join it if there is an opening in the line. Substrate atoms will also be moving due to random diffusion on the surface. Their arrival at a ledge, or departure from a ledge, might disturb the line of the H or D ions.

There is the further question of the strength of bonding of the line of hydrogen isotopes to the nearby substrate atoms. That strength will largely determine the stability of the linear structure and its dynamics, including the resonance that Storms thinks leads to fusion. Of the several types of bonding in and on solids, it seems that some type of induced polarization, like a van der Waals force, might determine the bond strength. However, this is only an unsupported surmise now. Electronic structure computations with a code like Quantum Esspresso, might indicate the nature of the bonding and its strength. Molecular dynamics simulations of the linear H or D arrangements could exhibit the dynamics of the line of hydrogen isotopes, including its formation, stability and frequencies.

In summary, the lines of H or D ions that Storms apparently envisions can occur in different structures: (a) the bottoms of cracks, (b) ledges in the walls of cracks, (c) ledges on the surfaces of materials, even in the absence of cracks and (d) very small holes into the surface of a material. It is noted that there may not be a substantial database for the existence of the small holes with cross sections on the order of one nanometer or less. A literature search needs to be done to determine if such holes have been observed with atomic force microscopes or other tools of nanotechnology.

Given these geometries, it is possible to make simple estimates of the required densities for cracks and nano-holes by using the excess energies observed in LENR experiments. In the case of a line of H or D ions in the bottom of a crack or on ledges, we seek to estimate possible numbers of the LENR per sec cm^2 to produce specified powers. Assume that an experiment produces 100 mW of excess power for a cathode area of 5 cm^2. That is equivalent to 20 mW/cm^2 or about 5×10^9 24 MeV reactions/sec cm^2. Using 10^{10} reactions per sec cm^2, there would have to be a rectangular grid with 10^5 reactions/sec in orthogonal directions within the 1 cm^2. Since 1 cm = 10^7 nm, this power density would require one LENR within an area of $(100\ nm)^2$ each second. If the LENR occurred along linear structures of H or D ions, this estimate implies a very high density of cracks or ledges. If there is a lower density, then correspondingly more nuclear reactions per second would have to occur in at least some of the cracks. Similarly, if the LENR occur in lines of H or D within nanometer-scale holes in the surface, there would have to be a very high areal density of those holes.

Importantly, Storms wrote in the long paper that, "The puzzle still lacks a clear description of the mechanism operating within the crack. Once a mechanism is found to apply, later mathematical analysis can be used to further support the model and generate other predictions." I largely, but not completely, agree with both parts of this statement. An adequate model for the production of LENR in cracks has yet to be offered. And, once such a model for a mechanism is available (and prior to its being "found to apply"), it will be necessary to write down the governing equations and evaluate them to obtain numbers for comparison with experiments. Both the energetics and the kinetics (rates) should result from the "mathematical analysis."

Non-Technical Perspective

The technical comments just offered are a normal part of critical discussion in science. Beyond those, I have a non-technical complaint about the title of the article by Storms in this issue. He wrote ". . .from a Chemist's Point of View." That bothers me for two reasons. The first is the fact that the field of LENR has been plagued by inter-disciplinary hostilities from the outset. Continuing to emphasize disciplinary differences tends to perpetuate such problems. The field is intrinsically, inevitably interdisciplinary, so scientists with different backgrounds should collaborate on attacking the basic problem of understanding LENR. Storms actually acknowledges this. When commenting on the differences between physics and chemistry, he wrote in the long paper, "The phenomenon of LENR requires a marriage between these two fields of science."

The other reason that part of the title bothers me is concern about the larger question of being a scientist, independent of discipline. Certainly, one's academic and professional backgrounds influence and even determine how problems are approached. Storms has every right to be proud of his academic and professional backgrounds in chemistry. I am pleased with my training and work in physics (even though that subject often comes with a deficit of humility). Storms has served the field much more broadly than practicing chemistry. He is a scientist who has learned other disciplines, as required. In some sense, he does himself, as well as the field, a disservice in prominently emphasizing one discipline, no matter how essential that discipline is to studying LENR.

Storms' Contributions to the Science of LENR

My scientific and personal views above on Storms' two papers on the location of where LENR occur and the mechanisms leading to LENR are quite negative. However, my critical concerns about aspects of his ideas for the mechanism behind LENR are far from my overall perspective on the capabilities and contributions of Storms to the science of LENR. He has been and remains one of the most important contributors to the field.

We should pause to appreciate the three steps that Storms has taken to get to a point of being able to offer ideas about the locations of and mechanisms for LENR. He has (a) read thoughtfully much of the literature on LENR, (b) analyzed the implications of many measurements and ideas and (c) routinely interacted with the global scientific community, especially through the CMNS Google Group. His attention to LENR theories has had two effects. Storms has provided comments on many, though not all, of the theories regarding LENR. Most of those comments are criticisms of the flaws he perceives in the examined theories of LENR. And, recently he has developed his own concepts of the physical mechanisms that produce LENR. Now, Storms is further developing his ideas with the expectation of later mathematical analyses and experimental tests.

However his foray into theory turns out, Storms is a virtuoso experimentalist. His abilities to design, build, calibrate and employ sophisticated experiments are well documented in his many papers. He is skilled in glass blowing, electronics, mechanics, calorimetry, data acquisition and other capabilities needed for LENR experiments. Storms has done sophisticated engineering design, fabrication and testing of calorimeters and complex experiments. Photographs of some of his devices and set-ups are on the web at http://lenr-canr.org/?page_id=187. He is clearly much more than a chemist, as is necessary to grapple with LENR experimentally. Storms is a skilled scientist and engineer with very broad laboratory capabilities.

The results of Storms' studies of the experimental papers are useful complications of quantities and references, as presented in his book and elsewhere. The book is *The Science of Low Energy Nuclear Reaction*, published in 2007 by World Scientific. Overall, Storms is one of the best informed, most critical and consistently interactive of the scientists in the field. There is a need for more people to be like him. It is good news that he has decided to adventure beyond experiments to critique and develop theories for LENR.

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