

A Lattice-Assisted Conventional Explanation for LENR, Part II

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Abstract:

This paper is part II of a three-part series of papers. In part I of these companion papers, an explanation of the LENR (Low Energy Nuclear Reactions) mechanism is given, using lattice assistance and conventional explanations. All of the so-called “miracles” of LENR are explained using detailed explanations, calculations, and equations. This three-part series of papers show that an LENR reactor is able to create a continuous self-maintained reaction. It is recommended that the reader first examines the Part I paper to gain a better understanding of the mechanisms involved in this explanation. [1]

This mechanism, by which the reactor is able to maintain its reaction, is briefly described as follows. A palladium (Pd) host metal is loaded with the hydrogen isotope of deuterons (^2D), to a high ratio, such that for every atom of palladium there is at least 0.8 atoms of deuterium in the lattice. In a steady-state condition within the LENR reactor, a subsequent nuclear reactions can occur, when the Coulomb barrier is overcome by the transference of kinetic energy from the energetic child products of the previous reactions to the cold ^2D fuel. This transference of kinetic energy is achieved via the collisions of the energetic child products with the cold ^2D . With this increased kinetic energy transferred to the ^2D , no unconventional behaviors are needed to overcome the Coulomb barrier between this newly energized ^2D and another ^2D in the lattice.

Historically, there have been two objections to using conventional models to explain the behavior of LENR. The first objection is the obstructive and hampering effects of electron stopping on reaction rates. The second objection is the experimentally low rate of neutron detection. Part I of this set of papers has addressed the details, mechanism, and mathematics of a self-sustaining reaction, using the assumption that electron stopping was not a major influence. In this Part II paper, the reason why electron stopping is not a strong influence in lattice-assisted nuclear reactions is addressed. Part III addresses the issue of neutron detection.

Answering and eliminating this first objection—that of the detrimental effects of electron stopping—is the purpose of this Part II paper.

In the next third Part III paper, there is an examination of the number of neutrons that scatter and react within the entire apparatus. There is also an examination how many neutrons escape the apparatus, how many enter the detector, how many are detected, and how the moderator-tube might affect the neutron detection. Gamma radiation is also examined.

Keywords—LENR, LANR, electron stopping, nuclear stopping.

1. Introduction

The outline of this paper is as follows:

- Section 1: Introduction
- Section 2: Review of Part I Paper
- Section 3: Overview of Electron and Nuclear Stopping Theories
- Section 4: Unusual Properties of the PdD_x metal hydride
- Section 5: The Mitigation of Electron Stopping in a PdD_x Lattice
- Section 6: Electron Stopping and the Two Most Important Charged-Particle Reactions
- Section 7: Summary and Conclusion

There are numerous reactions that occur within the reactor, categorized in this series of papers as primary reactions, secondary reactions, and tertiary (third in order) reactions. The two primary reactions are $^2\text{D}+^2\text{D}\rightarrow^3\text{T}+\text{p}$ and $^2\text{D}+^2\text{D}\rightarrow^3\text{He}+\text{n}$. The two secondary reactions are $^2\text{D}+^3\text{T}\rightarrow^4\text{He}+\text{n}$ and $^2\text{D}+^3\text{He}\rightarrow^4\text{He}+\text{p}$. The tertiary reactions occur outside of the reactor core, but still within the reactor apparatus. (Note: the term “apparatus” includes everything that is part of the experimental setup--the metal palladium core, the surrounding electrolyte, the borosilicate glass container for the electrolyte, the surrounding water bath, and the second borosilicate glass container around the water bath. The term “apparatus” may also include any insulation or any other materials--such as wood, aluminum, or steel--contained within the experimental setup.) A fourth set of reactions may occur, both within the reactor core and the reactor apparatus, but these reactions occur in such small numbers as to be negligible, and are not discussed.

In this paper “A Lattice-Assisted Conventional Explanation for LENR, Part II”, there is a brief overview of electron stopping theory, as well as providing convincing experimental evidence that this electron stopping force is mitigated at lower ion energies in a PdD_x lattice. Other than this one reasonable assumption, no other unusual or unconventional physics is needed to explain LENR.

2. Review of Part I

In the companion paper, “A Lattice-Assisted Conventional Explanation for LENR, Part I”, detailed and rigorous mathematical calculations are performed, using conventional equations and conventional nuclear reactions. In the Part I companion paper, a typical example electrolytic LENR reactor is used to show that a self-sustaining reaction can be produced. However, if the reactions are taking place without the benefit of a surrounding metal lattice, the self-sustained subsequent reactions cannot occur. There are many beneficial effects of the lattice that assist in the reaction rate of the nuclear reactions--such as electron screening, a decrease in the specific heat coefficient of PdD_x, convey electrons, changes in magnetic properties, and ion channeling. Due to this lattice-assistance, the nuclear reactions are enhanced to the point where at least one subsequent ²D-to-²D reaction occurs for each previous ²D-to-²D reaction. In the parlance of nuclear reactors, this is called the “reactivity” of the reactor, a property which must be greater than zero for the reactor to self-maintain its own reactions. The condition is such that the reactor is using part of its own nuclear output energy to induce a subsequent reaction, in a manner similar to a fission reactor. Part I also discusses the desired condition of a self-maintained continuous reaction, and it is rigorously and mathematically demonstrated in that paper.

This mechanism is: that palladium (Pd) host metal is loaded with the hydrogen isotope of deuterium, to a high loading ratio of at least 0.8 atoms of deuterium for every Pd atom. In a steady-state condition within the LENR reactor, a subsequent nuclear reaction occurs when the Coulomb barrier is overcome by the transference of kinetic energy from the energetic child products of the previous reactions to the cold ²D fuel. This transference of kinetic energy is achieved via the collisions of the energetic child products with the cold ²D. With this increased kinetic energy for the ²D, no unconventional behaviors are needed to overcome the Coulomb barrier.

An example reactor was used to demonstrate and test this mechanism, both conceptually and mathematically. The example reactor was a typical electrolytic LENR reactor, with a Pd host metal and deuterium as the hydrogen isotope fuel.

In this example reactor of Part I, the total power emitted by this electrolytic LENR reactor is approximately 3.4 watts, with contributions from the primary, secondary, and tertiary reactions. The power for the tertiary reactions is low is because most of the tertiary reactions for the neutrons at 14.07 MeV are endothermic, meaning they absorb energy rather than emitting energy. Another reason for the low power of the tertiary reactions is due to the relatively low amount of released energy, only 2.2 MeV, from the ¹H+n → ²D reaction. Thus, the energy of the tertiary reactions may or may not be experimentally measured by the calorimetry, depending on how the calorimeter is configured.

3. Overview of Electron and Nuclear Stopping Theory

When traveling through a solid, energetic ions slow down and transfer their kinetic energy by two distinct phenomena: energy transferences due to interactions with electrons and energy transferences due to interactions with atomic nuclei in the target material. These are termed electronic and nuclear stopping, respectively. Typically, electronic stopping is the dominant mechanism for projectiles in the 10 MeV–GeV energy range. In the lower energy ranges, such as below 100 keV, nuclear stopping dominates the slowing down of heavy ions. In the intermediate energy ranges, between 10 MeV and 100 keV, either phenomenon may be dominant, depending on the material, the ion, and the behavior of the electrons.

Shown in Figure 1 is an illustration of the electron and nuclear stopping powers for aluminum ions impacting aluminum material. Note how the nuclear stopping power is dominant at lower energies, while the electron stopping power is dominant at higher energies. The point where in the two energies crossover is the energy wherein the stopping power changes from being dominated by electron stopping to nuclear stopping. Also note how the electron stopping power is much larger than the nuclear stopping in its magnitude.

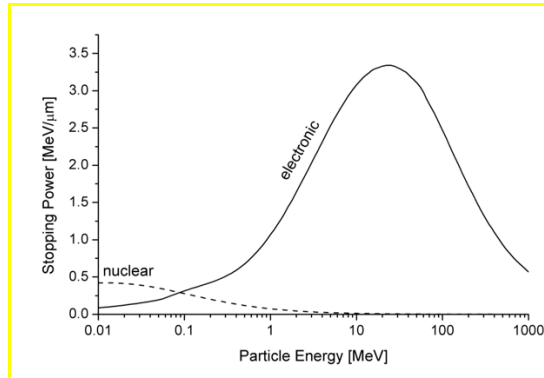


Figure 1. Plot of the stopping power, for electron stopping and nuclear stopping, versus ion energy. This illustrates the relative placement of the two effects with respect to each other, for aluminum ions bombarding aluminum. In this plot, the crossover energy of these two effects is at 0.1 MeV.

Shown in Figure 2 is a similar curve between the host of a silicon-dioxide with gold ions injected into it. Notice the shift in the relative position of the two curves.

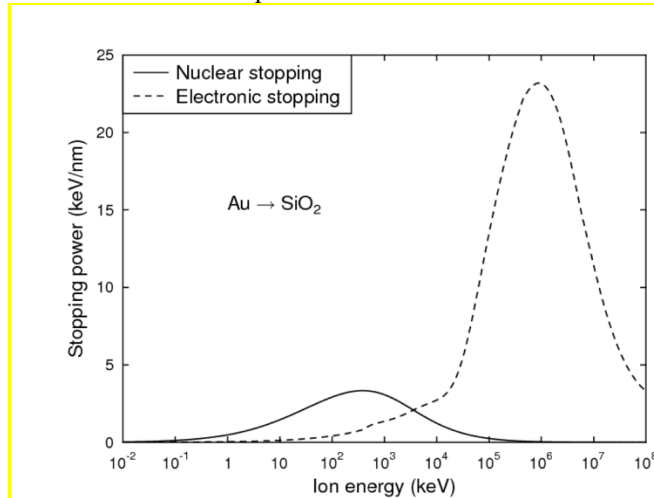


Figure 2. Plots of the stopping power for electron stopping and nuclear stopping for gold ions onto silicon-dioxide, illustrating the relative placement of the two effects, versus energy. For this combination, the crossover energy is at 5 MeV.

3.1 Electron Stopping Theory for Charged Particles

Electron stopping is like a drag or friction on the ion, but the electron stopping force does not tend to deflect the ion's path in any way. Thus, the ion tends to travel in a straight-line path while slowing down. When the ions are slowed down by nuclear stopping, they traverse a chaotic and zigzag path. The ions will not travel in a straight-line path; rather, the ions will scatter at relatively large angles. Thus, this straight-line path of travel on the ion is not demonstrated when nuclear stopping is the predominant stopping force on the ion.

The electrons surrounding an atom are involved with the slowing of energetic ions. For high energy ions, this effect is dominant. The main theoretical understanding of this phenomenon is described by the Bethe formula for ion particle stopping power. The term "stopping power" is a misnomer, since the actual attribute being calculated is a force, rather than a power. A more accurate term would be to call it a "stopping force". This so-called "stopping power" is the force that the electrons impose on the high energy ions to slow them down, very much like the force of friction. As the high energy ions traverse through the material, they will strip off the electrons from the atoms they collide with. This is a kinetic energy loss for ions. For non-relativistic speeds, as is the case for the ions produced in an LENR reactor, the equation for the stopping power force is shown in Eq. (1). This force is represented as the incremental change in energy, dE , divided by the incremental change in distance, dx —in other words, $-dE/dx$. The negative sign indicates that the force is a retarding force.

The notation in Eq. (1) is the notation normally seen in descriptions of this Bethe formula for the stopping power force, wherein the stopping power force is assigned the symbol S. The formula notation was derived originally with relativistic terms included for particles that may be traveling at velocities close to the speed of light:

$$F_{\text{stopping power}} = S = -\frac{dE}{dx} = \frac{4\pi k^2 z^2 e^4 n}{mc^2 \beta^2} \left[\ln \left(\frac{2mc^2 \beta^2}{I(1-\beta^2)} \right) - \beta^2 \right] \quad (1)$$

Since the particles are not travelling at relativistic speeds, this equation can be simplified, and it is re-written below in Eq. (2):

$$F_{\text{stopping power}} = S = -\frac{dE}{dx} = \frac{4\pi k_0^2 z^2 e^4 n}{mv^2} \left[\ln \left(\frac{2m_e v^2}{I} \right) \right] \quad (2)$$

where:

S is the “stopping power” force,

dE/dx is the incremental change in energy E per incremental change in distance x,

k is Coulomb’s constant=8.99x10⁹ in MKS units,

z is the atomic number of the high energy ion, in this case it is 1,

e is the elementary charge of a proton, 1.602x10⁻¹⁹ coulombs,

n is the number of electrons per unit volume in the medium,

m is the electron mass,

v is the electron velocity,

β is v/c, the velocity divided by the speed of light,

I is the mean excitation energy of the medium.

When using this equation for a medium of dense gas, heavy water, or a dense plasma of deuterons, it is shown that the high energy ions quickly lose energy due to their interaction with free electrons. Thus, the energy loss due to the electrons is much larger than the energy loss due to the nuclides in the medium. This interaction with the electrons significantly reduces the distance that an ion can travel, as well as the ability of an ion to transfer its kinetic energy to another deuterium atom. Therefore, if electron stopping is strongly present within a deuterated medium, such as heavy water, the chance of a chain reaction becomes essentially impossible.

3.2 Nuclear Stopping Theory for Charged Particles

When a Pd atom in the solid lattice receives significant recoil energy by an energetic ion, (also known as scattering or a collision) the Pd nucleus will become displaced and removed from its lattice position. Similarly, when an interstitial deuterium atom receives significant recoil energy by an energized ion, a substantial amount of the ion’s kinetic energy is transferred to the deuterium nucleus, causing the target deuterium nucleus to become a highly-energized deuteron ion. Also, it causes the projectile ion to scatter in a relatively large angle. For two charged particles, the projectile and the target, this type of interaction is called Rutherford scattering. Rutherford scattering causes the trajectory of the original projectile ion to be a non-straight, chaotic path through the material. As a result, the total distance that these ions travel inside the host material is not necessarily related to the size of the host material. Also, if the deuteron’s energy is high enough to overcome the Coulomb barrier between itself and another deuteron, the two ions may also react with one another. Much energy is released, in the form of kinetic energy of the child products, and the process repeats. For a more mathematical analysis of Rutherford scattering, please see the Part I paper. [1]

The SRIM (Stopping and Range of Ions in Matter) software package is widely used for the calculation of ion implantation depth, as well as the standard displacements per atom of an ionic radiation dose. The SRIM code provides an implementation of both electron and nuclear stopping for any given ion in an amorphous target material. For any material that is not amorphous, but rather having a crystal structure, such as a metal, the use of this software may not apply. This is because neither the calculation of the nuclear nor the electron stopping power includes any spatial information--such as crystal ordered lattice structure or orbital electron structure. For example, it is known that the calculations fail systematically for channeled ions. There are several situations wherein the values obtained from SRIM carry numerous uncertainties, and deuterated metals such as highly loaded PdD_x are very likely to encounter a faulty analysis from such software. The SRIM code is only a rough estimate for non-amorphous materials or highly unusual metals, such as PdD_x, since the actual answers depend on the lattice involved, the materials involved, and other characteristics of the non-amorphous substance.

4. Unusual Properties of the PdD_x Metal Hydride

It has frequently been documented that there are one or more attributes within the lattice that allow for the subsequent ²D-to-²D reaction to occur. That is why LENR is often called Lattice-Assisted Nuclear Reactions, or LANR. There are many theories examining the various ways in which the lattice can affect the reaction, including theories involving: phonon-electron interaction [2, 3], correlated coherence [4, 5], Bose-Einstein condensate [6], and electron screening [7, 8]. What is critical to understand is that LANR is a nuclear reaction that takes place in a unique metallurgic lattice environment. This very significant aspect of the lattice-assistance cannot be overlooked or ignored, for an understanding of LENR.

4.1 The Unusual Behaviors of Palladium Hydrides

Palladium hydride is one of the most-studied interstitial metal hydrides, due to the many unusual, unexplained, and theoretically-unpredictable changes in its physical behaviors [9]. These include:

- Ordered phases
- Anomalous properties at temperatures below 100 °K
- A superabundant-vacancy phase with stoichiometry Pd₃D₄ formed at high temperature and pressure
- Quenching of the enhanced Pauli para-magnetism of palladium
- Superconductivity at 10 °K without external pressure
- An inverse isotope effect in its superconductive properties
- An anomaly in the low-temperature specific heat, called the “50-K anomaly”
- Non-linear anomalies in its electrical resistivity
- An unusual hysteresis effect in resistivity during loading and unloading.
- Anomalies in the Hall effect
- Thermal expansion
- Ordering of interstitial deuterium
- Unpredictable superconducting transition temperature
- Anharmonicity of the hydrogen-site potential of its superconducting properties
- Unexplained phonon band structure, due to the lack of a realistic understanding of its anharmonicity.
- The high transition temperature, T_{critical}, for any metal hydride not subject to extreme hydrostatic pressure.

4.2 Internal Resistance and Similarities to Superconductivity

One of the more interesting phenomenon listed above is the anomalies in the internal friction, also known as resistivity, of palladium hydride and palladium deuteride as a function of x. Internal resistance anomalies in palladium hydride and palladium deuteride (PdH_x and PdD_x) are observed as non-linear changes in electrical resistance during hydrogen phase transitions. These anomalies are generally linked to the hydrogen-to-palladium ratio (x=H/Pd) between the α and β phases. The key changes of the internal resistance to consider include a non-linear response of the resistivity versus x. As x is increased, the resistivity does not increase linearly with hydrogen content but rather exhibits a maximum resistivity at x=0.7, which is the alpha/beta phase transition. Above that, the resistivity drops sharply as x approaches one. This is shown in Figure 3.

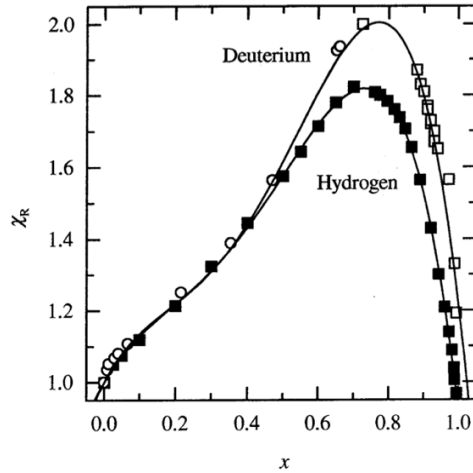


Figure 3. The R/R_0 resistance ratio χ_R versus x , where x is the loading ratios for H/Pd and D/Pd. Data taken from Zhang et al., [10] and references therein.

In a superconducting material in its superconducting state, the conduction electrons possess only a slight amount of thermal energy motion, due to the fact that the temperature is near absolute zero. For a superconductor, this is why the electrons pass through the lattice with essentially no resistance. This same phenomenon--a strong reduction in internal resistance--occurs in PdD_x simply by adding more hydrogen into the lattice. The extreme cold temperatures are not necessary, because of the significantly lower electronic specific heat coefficient, C_e . The electronic specific heat is lowered by a factor of six, meaning that the conduction electrons are not vibrating as much as normal, which sharply reduces the resistivity.

5. The Mitigation of Electron Stopping in a PdD_x Lattice

5.1 The Effect of Ion Channeling on Scattering and Reaction Rates

In a lattice, the phenomenon of nuclear scattering is much more complex and difficult to calculate than the Rutherford scattering equation suggests. The many positive nuclei in the lattice alter the positions and electric fields of the conduction electrons. Thus, the electric field is not as simplistic as in Rutherford scattering, where only one projectile and one target are considered.

Many physical phenomena occur when a charged ion traverses through a solid target. When the target material is monocrystalline, as for palladium, the reaction rates of these physical processes are dependent on the direction of ion travel, relative to the crystalline planes. Thus, the stopping power is much lower in certain directions than in others, an effect commonly called "channeling". When channeling occurs, the ions travel much further without losing energy to the lattice. In condensed-matter physics, channeling is the process that constrains the path of a charged particle within a crystalline solid, focusing the ions between the crystalline planes.

Channeling leads to deeper penetration of the ions in the material, an effect which is experimentally verified [11, 12, 13]. This would, in turn, increase the ability of the ions to either react or scatter within the lattice.

5.2 The Effect of Magnetic Susceptibility on Scattering and Reaction Rates

The term "magnetic susceptibility" describes the response of a material to an external magnetic field. As the palladium lattice PdD_x is loaded with deuterium, its magnetic susceptibility changes significantly as a function of x , going from paramagnetic to diamagnetic. The magnetic susceptibility of any material is strongly dependent on the behavior of the electrons in the material. Thus, when this unusual change of going from paramagnetic to diamagnetic occurs, it is an indication that the electrons in the PdD_x material are undergoing changes with regards to their spin and magnetic alignment, as a function of loading. These changes in the electronic behavior are another indication of unusual conditions within the PdD_x lattice that might affect electron stopping.

5.3 The Effect of Convey Electrons on Scattering and Reaction Rates

Another interesting phenomenon is an effect where the projectile ions transport or "convey" electrons as they travel through a lattice. When an ionic projectile is moving through a host lattice slowly enough for the free electrons

to follow it, it has been shown that this transport of electrons may occur. In other words, the free ion transports a free electron in a quasi-bonded state, as it travels through the lattice [14]. Two benefits are achieved. First, these electrons screen the ion, reducing the ability of the ion to penetrate an electron cloud of the lattice material; this in turn promotes the channeling effect, described above. Second, these convey electrons reduce the effective Coulomb barrier that the projectile ion encounters for a target ion [15]. Thus, due to these convey electrons, the charged projectile ions will tend to interact more with a nucleus, rather than with the electrons. The threshold velocity for this behavior is dependent upon how easily the electrons can follow the ion at a given energy. If the free electrons are not as thermally active within the lattice, then they can follow the projectile ion more easily. In other words, the thermal activity of the electrons is important. If there is less electron thermal activity present in the lattice, then the electrons are able to become convey electrons for fast ions, at ion energies higher than normal. A reduction in the thermal activity of electrons is important.

5.4 The Effect of Electronic Specific Heat on Scattering and Reaction Rates

Another property of PdD_x that changes significantly as a function of x is the electronic specific heat coefficient, denoted as C_e . For the electronic specific heat coefficient, this is a metallic property dependent on the electron density of states. For pure palladium, C_e is 9.5 (millijoules per mole kelvin squared). When deuterium is added to the Pd, the electronic heat coefficient drops significantly. For the loading range of $x = 0.83$ to $x = 0.88$, the electronic specific heat coefficient is six times smaller than for pure Pd. For a given temperature, this means that the electrons do not move around as much as normal. When C_e is low, most of the thermal energy is lattice vibration.

As mentioned previously, in a superconducting material in a superconducting state, the electrons possess very little thermal energy motion, essentially moving with only the slower motion of the applied electric current.

Because of the reduction of the specific heat coefficient, this same phenomenon occurs in PdD_x , simply by adding more deuterons into the lattice. The extreme cold temperatures are not necessary, because of the significantly lower C_e . The electronic specific heat is lowered by a factor of six, meaning that the conduction electrons are not vibrating as much as they normally would.

Given this condition within the PdD_x lattice, it can be easily understood why the electron stopping process might be beneficially shifted, with respect to the ionic stopping process, to allow for longer ionic travel distances in the lattice. As a result, the reaction rate would be higher in an ordered PdD_x lattice, than it would be for the same density of targets in an amorphous non-structured material. This change in the electronic specific heat coefficient occurs at the same loading range, x , that is required for the super-conduction of the PdD_x lattice, suggesting a strong relationship.

5.5 The Effect of PdD_x Superconductivity on Scattering and Reaction Rates

Experimental evidence implies that when an energetic ion passes through a superconductor, the stopping force on that ion, in a superconductor, is dominated by nuclear stopping rather than electron stopping. As mentioned above, PdD_x is a superconductor, and its behavior is dependent on the loading ratio x . Ishikawa et al. [16] found that when ion projectiles, with energies less than 2 MeV, traversed through certain superconducting materials, the defect production rate in the lattice of the superconductor was proportional to the nuclear stopping power, rather than electron stopping. The defect production rate has two contributions: the effect via elastic displacement due to nuclear collisions, and the effect due to electron stopping. These researchers found that for ions with energies less than 2 MeV, the defect production rate was proportional to the nuclear stopping power, rather than electron stopping. The contribution from electron stopping only became apparent for extremely high ion energies, over 80 MeV. Quoting from the text:

“For low energy (≤ 2 MeV) ion irradiation, $(\Delta c/c_0)/\Phi$, which corresponds to the defect production rate, is proportional to the nuclear stopping power, S_n . On the other hand, for high energy (80 MeV-3.8 GeV) ion irradiation, the contribution of electronic excitation to $(\Delta c/c_0)/\Phi$ is precisely estimated by assuming that the observed $(\Delta c/c_0)/\Phi$ value is the sum of the contribution of elastic displacement and that of electronic excitation.”

Other researchers have found similar results when studying superconductive materials. Baubour et al. [17] found that the damage in the lattice of superconductors is created by elastic collisions, which indicates that the nuclear stopping power S_n is the dominant stopping power. Quoting from the text:

“For ions with energies less than several MeV, the dominant mechanism causing irradiation-induced degradation of T_c is collisional damage.”

This agrees with previous experiments [18]:

“The defect production rate, which is obtained from the initial slope of the resistance–fluence curve, is almost proportional to the nuclear stopping power, S_n . The T_c depression due to irradiation is also nearly proportional to S_n . These results indicate that the defect production process is dominated by elastic displacement. ... In high- T_c superconductor $\text{EuBa}_2\text{Cu}_3\text{O}_y$ irradiated with 2 MeV electrons and 0.5–2.0 MeV ions, the normal-state resistance changes and T_c depression due to irradiation are nearly proportional to S_n , indicating that the elastic displacement is a dominant damage production process.”

In other words, these behaviors of the lattice follow this same conclusion--that nuclear stopping S_n dominates at ion projectile energies below several MeV. For superconducting materials, there is a behavior occurring within the lattice which mitigates the electron stopping power at energies below several MeV.

Other researchers have found similar results when studying superconductive materials--that the damage in the lattice is created by elastic collisions, a condition indicative of the nuclear stopping power S_n being dominant [19, 20]. Thus, for superconducting materials, the dominant mechanism causing irradiation-induced degradation is nuclear collisional damage, for ions with energies less than 2 to 3 MeV. In other words, the electron stopping power is shifted with respect to the nuclear stopping power.

6. Electron Stopping and the Charged-Particle Nuclear Reactions in PdD_x

For ion irradiation below several MeV, the creation of defects in the lattice is due to the elastic collisions of the projectile ions with the nuclei in the lattice, rather than collisions with the electrons. Thus, experimental data implies that the effects of electron stopping of energetic ions inside of a superconductor lattice are strong reduced. Unfortunately, no data has been taken about the ionic damage in the superconductor of PdD_x . However, if PdD_x is similar to other superconducting materials, for which such data has been collected, then these data suggest that the dominant cause of crystal damage is due to nuclear stopping power, rather than by electronic excitation. It is quite reasonable to assume that the superconducting material of PdD_x has some unusual and unexplained electronic behaviors, one of which would be that the behavior of PdD_x is similar to other superconducting materials, with regards to electron stopping power, wherein the electron stopping is shifted with respect to the nuclear stopping.

More examples of how these two curves might be positioned relative to each other are shown in Figure 4. The leftmost curve shows the generic curve with the crossover at about 0.1 MeV, similar to Figure 1. The second one shows the two curves with a crossover at 5 MeV, similar to Figure 2. The last curve on the right in Figure 4 shows the crossover at 10 MeV. This last curve is hypothesized to be similar to the curve that might occur for a superconductor, such as deuterated PdD_x with a high loading, wherein the crossover energy is relatively high.

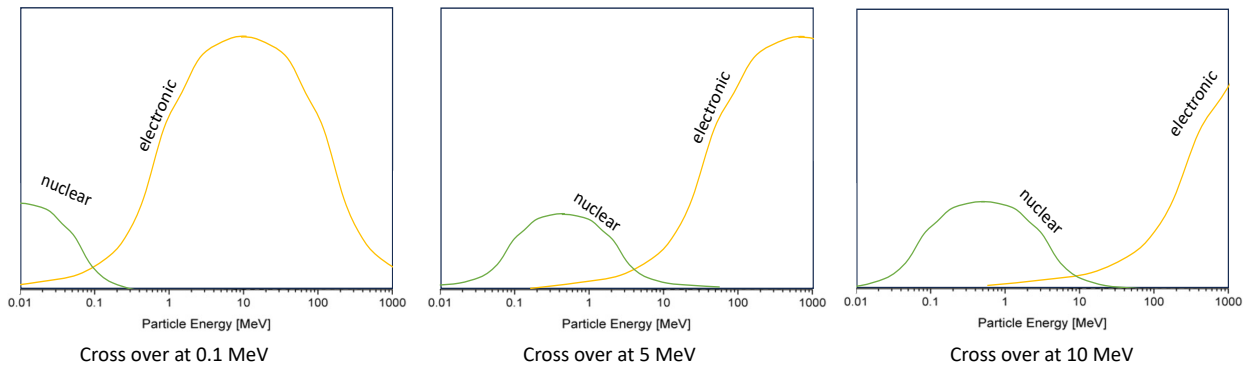


Figure 4: Plots of the stopping power for electron stopping and nuclear stopping shown as three generic diagrams, illustrating the relative placement of the two effects, with respect to each other, versus energy. Note the crossover energies are at 0.1 MeV, 5 MeV, and 10 MeV. The 10 MeV crossover energy might be the hypothetical relative placement for superconductors, such as PdD_x .

If the ion energy is higher than the crossover energy, then electron stopping dominates, and the ion will travel in a relatively straight-line path until it slows down below the crossover energy. After it has slowed down below the crossover energy, nuclear stopping dominates, and the path of the ion is highly chaotic, scattering in three dimensions, often with relatively large deflection angles. If the angle is large, the energy transfer to the target nucleus is large. This is shown in Figure 5 below.

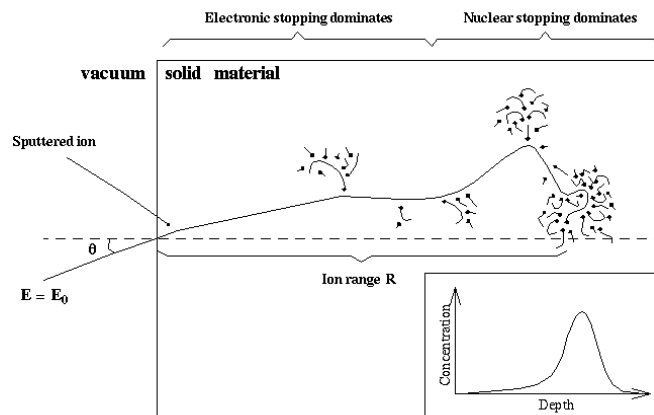


Figure 5: Illustration of an energetic ion traversing through an amorphous material.

As shown in Figure 5, the ion enters from the left with an initial energy, E_0 , and it travels in a relatively straight line. Once it slows down below the crossover energy, nuclear encounters then become dominant, and the ion scatters in a chaotic manner, tracing a random three-dimensional zigzag path. When moving in this zigzag path, the overall accumulated distance traveled by the ion is relatively long—on the order of centimeters. However, the net penetration depth into the lattice is relatively short, just a few tenths of a millimeters. Thus, a long distance can be traversed by an ion within a relatively thin sample of palladium, when the nuclear stopping force is dominant.

During this time when the nuclear stopping force is dominant, the energetic deuteron ion transfers its energy to the many fuel deuterons in the lattice. Since the Pd atoms are so much heavier than the D ions, very little energy is transferred to the Pd atoms.

6.1 The Tritium-to-Deuterium Reaction

Of the charged-particle nuclear reactions occurring in an LENR, there are two important reactions for producing a self-sustaining reaction. The first reaction to be discussed in this sub-section is the reaction between a deuterium atom and an energetic tritium, the ${}^2\text{D}+{}^3\text{T}\rightarrow{}^4\text{He}+\text{n}$ reaction. The second important reaction is the deuteron-to-deuteron reaction, discussed in sub-section 6.2.

Upon its formation as a child product, the tritium has an energy of 1 MeV. The electron stopping force becomes dominant at energies typically higher than 1 MeV or so. However, this crossover transition from nuclear stopping to electron stopping is dependent on several properties of the lattice and the projectile ion.

As discussed above, for PdD_x material, the electron stopping force is not presumed to be dominant at 1 MeV ion energy. Thus, the tritium, which is released from the reaction with an energy of 1 MeV, would then be dominated by the nuclear stopping force, and as a result it will not trace a straight path through the loaded PdD_x lattice. Rather it will scatter, tracing a chaotic zigzag path through the material. When it reaches the slower energy of 0.1 MeV, it has the highest probability of a reaction with another deuterium atom in the lattice. Solving for the probability of a reaction, it is found that about 80 to 90% of the tritium will react in a secondary reaction, when there is high loading of deuterium in the Pd [1].

Even for the situation wherein the electron stopping force might be dominant at an energy of 1 MeV, the electron stopping would not be the dominant stopping force for the slightly lower energies, such as in the 0.5 MeV to 0.1 MeV range. This is the energy range where most of the T+D reactions occur. If it is the situation where the electron stopping is dominant at 1 MeV, the tritium would travel only a short distance in the material at 1 MeV, quickly slowing down due to the electron stopping. Then, once the tritium reaches a slightly lower kinetic energy, its behavior would become dominated by the nuclear stopping, and it would trace out the rest of its path as a chaotic zigzag track through the material. The tritium would eventually react or stop. The electron stopping force makes

very little difference to tritium, since its reaction rate peaks at energies lower than the typical crossover for most materials.

For a 90% reaction rate and with 100% loading, the average distance that a tritium ion has to travel is between 8 and 9 cm. This analysis is done using numerical integration to calculate this complicated path, which is made of thousands of short zigzag increments. This analysis is not something that can be easily determined with one or two simple equations. Rather, numerical integration is needed, using the appropriate cross sections for the incremental energy ranges.

For many reasons, related to the unusual metallurgic behavior and the associated unusual electronic behaviors in PdD_x, it is believed that electronic stopping is not the dominant stopping force for an ion at 1 MeV energy. However, even if it is, it is very unlikely to be dominant at 0.5 MeV--in which case the T+D reaction still achieves a higher than 90% rate. Although the tritium does travel along a total path that is longer than the dimensions of the sample, the pathway is chaotic and zigzag--not a linear single-directional path. Thus, the ion easily stays inside the sample, until it either reacts or thermalizes.

6.2 The Deuterium-to-Deuterium Reaction

The second important reaction for producing a self-sustaining reaction is when the newly-energized deuterons react with the non-energized deuterium. The newly-energized deuterons are energized from collisions with energetic child-product neutrons of the primary and secondary reactions. As can be seen in Table 1, most of these newly-energized deuterons are a result of collision with neutrons [1]. The neutrons cause over 62% (29.27+34.04) of the energy in the newly-energized deuterons, as shown in the right-most column. This is for a PdD_x reactor with 100% loading, and electron stopping only at energies above 14 MeV.

Projectile	Number of energetic 2D TARGETS, for this projectile	Average energy for successful scattered TARGETS, in MeV	Total Number Times Average Energy	Percentage of total energy of the newly-energized deuterons contributed by this child product
3T, Primary1	3.4112E+11	0.20917	7.135E+10	1.38
3He, Primary2	2.8556E+11	0.19778	5.648E+10	1.09
proton, Primary1	1.0547E+12	0.27510	2.901E+11	5.62
neutron, Primary2	2.5807E+12	0.58588	1.512E+12	29.27
proton, Secondary2	2.3192E+12	0.40831	9.470E+11	18.33
4He, Secondary2	6.2769E+11	0.29652	1.861E+11	3.60
4He, Secondary1	1.1743E+12	0.29311	3.442E+11	6.66
neutron, Secondary1	3.0520E+11	5.76016	1.758E+12	34.04
Sum=	8.69E+12		5.17E+12	

Table 1: Amount of energy of newly-energized deuterons, from collisions with the child-products of the primary and secondary reactions.

Such behavior regarding the importance of neutrons has also been noted by other researchers. Several quotes are shown below, taken from a NASA study in which photo-induced high-energy neutrons (created by using gamma radiation) were used to initiate nuclear reactions in a deuterated metal [22]. These quotes indicate that the transference of the kinetic energy of the neutrons to the fuel deuterium is of utmost importance for establishing a reactor that can achieve and self-sustain nuclear reactions.

“We show that neutrons are far more efficient than energetic charged particles, such as light particles (e^- , e^+) or heavy particles (p , d , α) in transferring kinetic energy to fuel nuclei (D) to initiate fusion processes.”

“We then demonstrated the superior efficiency of the kinetic energy transfer by energetic neutrons on the target deuteron nuclei resulting in subsequent nuclear reactions. Such a process is a key ingredient in achieving and sustaining nuclear reactions.”

“We show that neutrons are far more efficient than energetic charged particles, such as light particles (e^- , e^+) or heavy particles (p , d , α) in transferring kinetic energy to fuel nuclei (D) to initiate fusion processes. We provide a theoretical framework for d -D nuclear fusion reactions in high-density cold fuel nuclei embedded in metal lattices, with a small fraction of fuel activated by hot neutrons...”

This concept, of high energy neutrons being essential for a self-sustained reaction, is in very strong agreement with the model discussed in this set of papers, “A Lattice-Assisted Conventional Explanation for LENR”, wherein the high

energy neutrons are the predominant and most important vehicle for energizing the deuterium fuel nuclei, a process which is needed to sustain the nuclear reaction.

Even if the energetic protons from the $D+D \rightarrow {}^3\text{He}+p$ reaction are briefly slowed down by the electron stopping, it would make only a minor difference. Similarly, the other charged-particle collisions contribute only a very small number of energized deuterons, and these reactions can easily be disregarded as making only a small contribution to the end result. The collisions with the neutrons is the cause that dominates the number of the newly-energized deuterons.

To prove this point, further computer analysis calculations have been done. Table 2 shows the results of the LENR reactor behavior if the electron stopping becomes dominant at ion energies higher than 14 MeV, and at ion energies higher than 1 MeV, and at energies higher than 0.2 MeV. All of these calculations are for 100% loading of the ${}^2\text{D}$ in the Pd, with a Pd sample size of 2 cm^2 . These numbers are for a reactor running at 1 watt total for the two primary reactions—in other words, with 1.71×10^{12} primary reactions occurring in the reactor per second.

Cross-over energy wherein the electron stopping becomes dominant.	Average overall energy of the energetic ${}^2\text{D}$, in MeV	The number of energetic hot ${}^2\text{D}$	The ratio for the subsequent reaction rate (Must be greater than 1 for a self-sustaining reaction.)	The reactivity of the reactor (Must be a positive number for a self-sustaining reaction.)
14 MeV	0.5948	$8.68\text{E}+12$	1.15	0.150
1 MeV	0.6937	$5.81\text{E}+12$	1.14	0.138
0.2 MeV	0.586	$1.51\text{E}+12$	0.32	-0.675

Table 2: The changes in the reactor behavior if the crossover energy, where the electron stopping becomes dominant, is shifted in value.

The analysis shown in Table 2 is very interesting. The top row shows the numbers for electron stopping crossover energy above 14 MeV. The second row shows the numbers for electron stopping crossover energy at 1 MeV. The third row shows the numbers for electron stopping crossover energy at 0.2 MeV. When the electron stopping crossover energy is at 14 MeV, the average energy of the energetic ${}^2\text{D}$ is about 0.5948 MeV, and there are about 8.68×10^{12} energetic ${}^2\text{D}$ in the reactor. The reactivity of the reactor is positive at +0.150, as seen in the last column to the right. The reactivity must be a positive number, for the reaction to be self-sustaining. If the electron stopping becomes dominant at a lower energy, such that the crossover energy is at 1 MeV, the average energy of the deuterons is slightly higher, and the number of energetic deuterons is slightly lower. However, the reactivity is still positive at +0.138, meaning that a self-sustaining reaction would still occur in the reactor. If the electron stopping crossover energy is at a lower energy, of 0.2 MeV, then the reactor is not able to self-sustain a reaction, with a negative reactivity of -0.675.

To reiterate, the two most important charged-particle reactions are the T+D reaction and the D+d reaction, which both occur at relatively low energies. Thus, these two reactions would still take place even if the electron stopping crossover energy in PdD_x is at 1 MeV.

That being said, there is strong evidence that crossover energy for the electron stopping is indeed at a higher value for PdD_x than it is for Pd. The experimental evidence suggests that the electron stopping curve is positioned further to the right of the neutron stopping curve—such that the nuclear stopping curve dominates for most, if not all, of the energies involved. That moderately minor change—a shift in the relative position of the two curves—is the only change that is needed to allow for a self-sustaining D+d reaction to occur at room temperature.

The subsequent D+d reaction is very important to the self-sustaining reaction. When calculating the number and average energy of these newly-energized deuterons, their average energy is 0.257 MeV [1], for a PdD_x loading of about 80%. If the hypothesis about the relative crossover energy for electron and nuclear stopping is correct, then this 0.257 MeV energy is well below the energy range for the dominance of electron stopping. Thus, the electron stopping force is not the dominant determination of the length of the path. At this energy, the projectile is slow enough, such that the nuclear stopping dominates, the ions continue to travel through the lattice, tracing a zigzag path in the material. In this case, these ions would still react with a high enough probability to maintain a self-sustained reaction. Even if there were some electron stopping at the beginning of the ion's path, a self-sustaining reaction would still be the resulting outcome.

The energetic neutrons, because they are electrically neutral, are not affected by electron stopping. Furthermore, the neutrons activate the majority of newly-energized deuterons for the subsequent reaction. Also, there is strong theoretical and experimental evidence that for the T+D reaction and the D+d reactions, which both occur at relatively lower energies, are not strongly affected by electron stopping. Even if electron stopping dominates at the high end of the energy range, once the ions slow down slightly, then the nuclear stopping will dominate. Nuclear stopping still takes place at the lower energies, causing a zigzag path, allowing for a longer total distance through the material, longer than the actual dimensions of the material itself. This in turn allows for high probability of a subsequent reaction to occur.

Other host materials, such as nickel-deuteride NiD_x , exhibit some of the same behaviors as PdD_x . Nickel-deuteride has some of the similar material changes when it is loaded with deuterium; however, these changes typically occur at higher temperature and higher pressures. The requirement for higher temperature and pressures means that a nickel host material would not work in a normal electrolytic reactor. The experimental data agree with this prediction--there are no electrolytic experiments, to date, supporting the idea that NiD_x works equally as well as PdD_x in electrolytic experiments. Rather NiD_x experiments require higher temperatures and pressures to produce excess heat.

Recently there have been several papers that indicate the unusual metallurgical behaviors of PdD_x may, indeed, be directly responsible for the beneficial lattice-assistance for self-sustained the nuclear reactions in the PdD_x electrolytic system. Recently, experimenters at the University of Missouri Research (MURR) reactor discovered some unusual behaviors regarding tritium production in a metallic sample of deuterated titanium. [24]. Quoting from the paper:

“Tritium production from TiD_2 in the cyclotron vault at MURR, where the neutron spectrum was completely energetic with almost no thermal neutrons, was a factor of 2.9–5.1 times higher than predicted from simulations using known nuclear reactions.”

In other words, when the researchers used energetic neutrons, the experiments yielded 3 to 5 times more nuclear reactions than predicted. This unpredicted result implies that there is an unexpected phenomenon occurring inside the deuterated TiD_x lattice, one that was not simulated by the computer programs. The transference of the neutron's kinetic energy to the fuel deuterium would be expected. However, it was not expected that the energized deuterons would traverse far enough through the TiD_x lattice to react with other deuterons and thereby creating tritium. Conventional simulations for electron stopping would claim that the energized deuterons would slow down too quickly, and would not be able to produce a subsequent reaction. Finding 3 to 5 times higher reaction rates than predicted is a result that implies, in these experiments, the electron stopping was not the dominant stopping force at these energies. (It should be mentioned that TiD_x is also a superconductor, and it exhibits somewhat similar unusual behaviors when loaded. [24])

These researchers at MURR also point out that the measurement of screening potentials through accelerated d–D collisions in various materials has revealed values around 25 eV in gaseous D_2 , approximately 50 eV in deuterated insulators, semiconductors, and noble metals (Cu, Ag, Au), roughly 180 eV in Be, and about 800 eV in Pd. In other words, the electron screening phenomenon is relatively small for gaseous deuterium, but it is 32 times larger in lattice materials, such as palladium, strongly suggesting that the structure of the lattice is assisting the reaction in a way that the amorphous materials cannot do. Quoting again from the same paper:

“This indicates the likelihood of an additional mechanism, such as collision-induced fusion in the solid state, increasing the credibility in the results from Steinetz et al.”

“Recently, a novel type of collision-induced, solid-state fusion reaction was reported in titanium deuteride and erbium deuteride by Steinetz et al., and theoretically analyzed by Pines et al.”

The Steinetz experiment is research from 2020 from NASA [25]. The researchers used gamma to bombard deuterated targets of (TiD_2 , ErD_3), producing neutrons that transferred their kinetic energy to energize a small portion of the fuel deuterium, creating fast-moving deuteron ions. That, in turn, allowed for some of these energetic deuterons to react with other fuel deuterium in the lattice. This resultant D+d reaction releases more neutrons, with an even higher kinetic energy than the initial neutrons. Because of the increase in the released energy given to these neutrons, more deuterons are energized, and the subsequent reaction rate is higher. These results would not be seen in an amorphous material, with no lattice-assistance. Other researchers have found similar results, that by increasing

the loading of deuterium into a Pd lattice, the reaction rate increases substantially [26]. The lattice is allowing the reaction to be more probable than otherwise expected or predicted.

These results imply that the lattice-assistance of highly-deuterated metals allows nuclear reactions to occur at a rate higher than what conventional predictions might suggest. There are numerous anomalous changes in a deuterated metal lattice such as PdD_x —changes in the electron behavior, reduction in the number of conduction band electrons, Fermi-level changes, magnetic behavior, non-linear resistivity, and channeling, as well as changes in the coefficient of electronic specific heat, the electron screening, and its superconductivity. The unexpected increase in the reaction rate of deuterated metals is likely due to a combination of any of these metallurgical anomalies.

7. Summary and Conclusion

As discussed above, the assistance of the lattice for nuclear reaction rates is critical. For example, consider heavy water, wherein there is no lattice structure. Because of this lack of structure, even though there is a high concentration of deuterium, a nuclear reaction cannot take place. Heavy water has 6.68×10^{22} ions per cm^3 , which is comparable to the density of fuel within the palladium lattice; however, nuclear reactions of $^2\text{D}+^2\text{D}$ do not occur in heavy water, and a ^2D -to- ^2D chain reaction does not occur. The reason the $^2\text{D}+^2\text{D}$ reaction cannot take place in materials, such as heavy water, is due to the electron stopping force that the electrons impose upon the projectile ions. If it is assumed that for high values of x in the PdD_x lattice, the electron stopping power is shifted to higher energies, then these reactions can occur. Such mitigation is due to a combination of one or more of the following phenomena: ionic channeling, convey electrons, changes in magnetic susceptibility, reduction in thermal electronic vibrations, electron shielding, and/or superconductivity. All of these effects in combination contribute an important role in increasing the reaction rates within the lattice.

In summary, **with the one very reasonable assumption that the crossover energy for the dominance of electron stopping power is shifted to higher energies, such that electron stopping is not dominant in the energy range where most of the nuclear reactions occur in a PdD_x lattice, then LENR can then be explained by conventional nuclear explanations.** The nuclear reactions are able to occur due to the ionic transference of kinetic energy, allowing the Coulomb barrier to be overcome by kinetic energy, in a conventional manner. For every previous reaction in the LENR reactor, a subsequent reaction is able to occur, allowing for a self-sustaining nuclear reaction at temperatures well below those needed for the conditions of hot fusion.

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