SCIENCE SET
OPEN ACCESS PUBLISHERS

ISSN: 3066-7194
Research Article

Novel Journal of Applied Sciences Research

The Lawson Criterion for Low Energy Nuclear Reactions

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Submitted: 18 November 2025 **Accepted:** 25 November 2025 **Published:** 23 December 2025

https://doi.org/10.63620/MKNJASR.2025.1058

Citation: *Bowen, N. L. (2025). The Lawson Criterion for Low Energy Nuclear Reactions. Nov Joun of Appl Sci Res, 2(6), 01-07.*

Abstract

The Lawson Criterion is a figure of merit used in nuclear fusion research, which compares the rate of nuclear energy being generated in the reactor to the rate of energy loss from the reactor. Low Energy Nuclear Reactions (LENR) are nuclear reactions that take place at lower energies and temperature ambient conditions. Conversely, hot fusion is a type of nuclear fusion reaction that takes place at several hundreds of millions of degrees Kelvin. These hot temperatures are used to overcome the electrical repulsion of the Coulomb barrier between two charged nuclei. In both cases, LENR or hot fusion, if the rate of energy being released by the nuclear reactions is greater than the rate of energy loss from the reactor, then the reactor is said to be "self-sustaining". This self-sustaining reaction is the goal of both LENR and hot fusion. This paper examines the ability of an LENR reactor to achieve a self-sustaining condition, without the extreme high temperatures that are used by hot fusion. Comparisons between LENR and hot fusion are also made, where appropriate.

Keywords: Lawson Criterion, LENR, Fusion, Energy Balance.

Introduction

Introduction to Lawson Criterion

The Lawson equations were first developed by John D. Lawson and published in 1957. As originally formulated, the Lawson equations are energy balance equations, stating that when the rate of energy production is higher than the rate of energy loss, then the system will be able to self sustain its own reaction. The conditions are easily stated, but difficult to achieve. Later analysis, specific to hot fusion, modified the Lawson Equation, giving a minimum required value for the product of the electron plasma density, ne, and the energy confinement time, τE, and the plasma temperature Tp. This figure-of-merit is called the triple product for hot fusion, the product of density ne, confinement time τE, and plasma temperature Tp. It must be higher than a certain value, for hot fusion to occur.

The energy balance equations, as first outlined by Lawson, do indeed apply to LENR reactors. However, the assumptions and approximations used to modify the energy balance equations for hot fusion, such as the triple product, do not apply. The purpose of this study is to examine the Lawson Equations for the parameters of LENR, to determine if such reactions can meet the requirements outlined by these energy balance equations.

Introduction to Low Energy Nuclear Reactions

The term "Low Energy" does not refer to the output of the nuclear reaction. Rather, it refers to the ambient temperature of the reactions. If LENR is defined as a nuclear reaction that does not require an ambient temperature of several hundreds of millions degrees, then it is correct to say that LENR has been around for a long time. Low energy nuclear fusion, wherein the ambient temperature was not hundreds of millions of degrees, occurred for the first time in the 1934, when Mark Oliphant, a student of Ernest Rutherford, first bombarded fast deuterium ions on to deuteron-loaded metal targets, using a particle accelerator. This was the first demonstration of nuclear fusion [1].

Similar to the experiment by Oliphant, LENR typically uses deuterium (an isotope of hydrogen 2H, often denoted as D) as the fuel, whereas hot fusion typically uses a mixture of both deuterium and tritium (an isotope of hydrogen 3H, often denoted as T). LENR could also use a mixture of tritium and deuterium, but the extreme high price of tritium has inhibited such research. LENR also uses a metal lattice for the host material of the core. This is either palladium, nickel, or an alloy of similar metals. This host metal is then forced to absorb a high density of the hydrogen isotope, D within the metal lattice--by either high pressure, high temperature, electrolysis, or other similar means. Due to the presence of this host lattice material, LENR is often called Lattice-Assisted Nuclear Reactions (LANR).

Introduction to Ignition, a Self-Sustaining Reaction

When a nuclear reaction occurs and releases energy, the energy is in the form of kinetic energy of the child products, or in the form of gamma radiation, or both. For all reactors types-- fission, hot fusion, or LENR--if enough of that released kinetic energy is captured by the reactor's fuel, such that a subsequent reaction is induced within the reactor core, then the reactor becomes self-sustaining. In other words, the reactor produces enough energy from its own nuclear reactions to self-sustain its own nuclear reactions. This phenomenon, called "ignition", occurs when enough of the released nuclear energy from the reaction is kept within the reactor core, rather than being lost from the core.

The Methodology and Understanding of the Energy Balance Equations

In that first fusion experiment, the resultant fusion process did not have a net output energy, due to the large amount of input energy used by the particle accelerator to accelerate the deuterons. Also, this reaction was not self-sustaining. For a better understanding of why this was the case, an examination of the two energy balance equations is appropriate.

The Energy Balance Equations for Net Output Energy

A net output energy means that there is more energy is coming out of the reactor than what is being put in as input energy. This net energy increase is due to the released energy of the nuclear reactions occurring, as shown in Eq. 1.

$$Energy_{net} = Energy_{out} - Energy_{in} \quad \text{Eq.1}$$

However, this net output energy can often be ambiguous, since there are several definitions of input energy. One definition is that input energy can mean the energy that actually enters into the core of the reactor in the form of heat, magnetic energy, electrical energy, or laser light. For example, if a laser light shines on the reactor core, the input energy to the reactor is simply the amount of heat from the laser light.

Another definition of input energy can be the energy being drawn from the power grid to meet the reactors input requirements. Due to equipment inefficiencies, this second type of input energy is generally much larger than the actual energy going into the reactor. Again, using the laser light as an example, if many large lasers are used to generate the input energy going into a fusion reactor, then the energy being drawn from the power grid is much larger, by a factor of roughly 1000, than the energy going into the reactor, due to the large inefficiencies of the lasers.

A third definition is the energy from the raw fuel burned by the power plant, in the form of coal, oil, or other fuels, in order to produce the electrical energy going into the grid. Again, due to the many inefficiencies, much more energy is burned than what is delivered to the electrical outlets. Thus, this input energy, from the burned fuel, is much larger. Given the different definitions of input energy, the definition of net output energy is similarly ambiguous.

The Energy Balance Equations for a Self-Sustained Reaction

The energy, Efusion, is the energy released from the fusion reaction. It depends on the density of the fuels involved, their cross sections, the distance wherein they interact, and the energy released by each reaction. The energy released is the total number of fusions, $Number_{fusion}$, times the energy released by each fusion reaction, $E_{ReleasedPerReaction}$. This can be mathematically represented as shown in Eq. 2:

$$E_{fusion} = \left(Number_{fusion}\right)\left(E_{ReleasedPerReaction}\right) \quad \text{Eq.2}$$

The number of fusions that occurs depends on the density of the two fuels, in number per unit volume, times the reaction cross section, times distance wherein the two nuclides are able to interact, $distance_{interaction}$. This is shown in Eq. 3.

$$Number_{fusion} = (\rho_{fuelA})(\rho_{fuelB})(\sigma_{AB}(T))(distance_{interaction})$$

Eq.3

where:

ρ_{fuelA} is the number density of fuel A

ρ_{fuelb} is the number density of fuel A

σ_{AB} is the nuclear reaction cross section between fuels A and B

distanceinteraction is the distance wherein an interaction between fuel A and fuel B might occur.

The "interaction distance" term is the distance wherein the two fuels might interact. For example, the two fuels must be together in one space, traveling with a relative velocity, with respect to each other. For example, imagine a cube, 20 cm per side, filled with fuel-A. The other fuel, fuel-B, is traveling at a velocity relative to fuel-A. A particle of fuel-B enters the cube, and the two fuels cross paths within that confined space for a certain distance--in this example, 20 cm. Within that distance, the two fuels can interact with each other. That distance, wherein they might interact, is the interaction distance, distanceinteraction. If the particle of fuel-B continues on its journey outside of the space where fuel-A resides, then the interaction distance is still only that space wherein they interacted.

Note that Eq. 3 describes the total number of released fusions occurring in the reactor; it is not the reaction rate, which is the number of reactions per second. To get the reaction rate, the total number of fusions is divided by time on both sides of Eq. 3. This results in another one of the Lawson Equations, the number of fusions per second per unit volume, f, as shown in Eq. 4:

$$f = (\rho_{fuelA})(\rho_{fuelB})(\sigma_{AB}(T))(velocity_{relative}) \quad \text{Eq.4}$$

where velocityrelative is the relative velocity between the two fuels. This equation is very useful for determining the number of reactions, the released energy from a fusion reactor, the amount of heat generated, and the energy balance within the reactor.

For hot fusion, it is assumed that fuel-A, deuterium D, and fuel-B, tritium T, have the same temperature. For hot fusion, the fusion reaction that occurs is the reaction between T and D, with the resultant child products of helium-4 and a neutron, shown in Eq. 5:

$T+D \rightarrow {}^4He+neutron$ Eq. 5

It is assumed, in hot fusion, that there are no other ions present other than the fuel ions. It is further assumed that D and T are present in an optimal 50-50 mixture. With these assumptions, the ion number density then equals electron number density. The energy density of both electrons and ions together, according to the ideal gas law, is given by W=3nT, where W is the energy density, T is the temperature in electron-volts (eV) and n is the particle number density.

These assumptions are not correct for LENR. An examination of these assumptions, one at a time, is necessary, to determine how and why they differ for LENR.

For LENR, fuel-A is deuterium at room temperature, (0.026 eV) and fuel-B is energetic deuterium, at a much higher temperature, (several MeV). Thus, the hot fusion assumption that fuel-A and fuel-B have the same temperature is hugely incorrect for LENR. Also the assumption that the two fuels are in a 50-50 ratio is incorrect. In LENR there is a huge number of cold deuterons, with densities around 6x1022 per cm3, and a much smaller number of the high-energy deuterons, with densities around 1010 per cm3. Thus, the two fuels--the room temperature deuterons and the energetic deuterons--are at vastly different temperatures and densities within the metal lattice.

Also incorrect for LENR is the assumption that there are no ions present other than fuel ions. In LENR, there are four reactions occurring, instead of only one reaction [2]. The two primary reactions are shown in Eqs. 6 and 7:

$D+D \rightarrow T+proton$ Eq. 6

$D+D \rightarrow {}^3He+neutron$ Eq. 7.

These two reactions naturally occur in a 50-50 ratio. The child products of these primary reactions, specifically T and 3He, become the fuel for the secondary reactions. The two secondary reactions are shown in Eqs. 8 and 9:

$D+T \rightarrow {}^4He+neutron$ Eq. 8

$D+{}^3He \rightarrow {}^4He+proton$ Eq. 9

When released from the primary reactions, the T and the 3He are at a high energy of several MeV, and are able to overcome the Coulomb barrier without difficulty, to cause the secondary reactions. As a result of these four reactions occurring within an LENR reactor, there is also a significant amount of T, 3He and 4He, protons, and neutrons in the lattice. Most predominantly, of course, are the atoms of the lattice metal, which is either nickel, palladium, or a similar alloy.

The assumption in hot fusion that the ion density equals electron density is also incorrect for LENR. For deuterons in a LENR lattice, the number of electrons is much more than the number of D ions. This is because the lattice is a conducting metal, and many electrons are inherently in the conduction band from the lattice, more than one electron per lattice atom.

Next, another assumption, used in hot fusion, is that the energy density of both electrons and ions together follows the ideal gas law. This is incorrect for LENR. In a metal lattice, the energy density of the ions and electrons does not relate to the ideal gas law, and the equation simply does not apply. Rather, for a metal lattice, the energy is the summation of the energy of all of the atoms, ions, and free electrons in the reactor core. Unfortunately, this is not easily expressed in a simple formula. Rather, the energy density is the summed energy of all particles in the lattice, plus the energy of the lattice itself, then divided by the volume of the material. In other words, the energy density would be related to the temperature of the lattice, plus the energy of the thermalized deuterons, plus the energy of all the high-velocity ions and neutrons.

As a result of these many differences between LENR and hot fusion, the assumptions and approximations used by hot fusion reactors to describe the energy balance do not apply to LENR. Rather, for LENR, it is essential to start with the original energy balance equation and understand how they relate to the nuclear reactions occurring under the conditions of LENR.

The Lawson Criterion for LENR

As discussed previously, the volume fusion rate, typically denoted by the letter f, is the number of fusion reactions per second per unit volume. Eq. 4 for the fusion rate, can be modified for hot fusion, using a plasma moving in a continuous circular motion. The resultant volume rate of fusion, f, is shown in Eq. 10:

$$f = n_d n_t \langle \sigma v \rangle = \frac{1}{4} n^2 \langle \sigma v \rangle \quad \text{Eq.10}$$

where σ is the fusion cross section, v is the relative velocity between the two fuels, and the < > brackets denote an average of the Maxwellian distribution velocity times the cross section at that velocity, over the relevant temperature range of interest. For this hot fusion equation, nd is the number density of deuterons, in number per cm3, and nt is the number density of tritons, in number per cm3. Since nd is assumed to be equal to nt for hot fusion, it follows that nd=nt=½ n, where n is the total number of ions. Given these assumptions, the equation shown in Eq. 4 then transforms to the equation shown in Eq. 10. However, for LENR, these assumptions are not correct and nor is the equation, Eq. 10.

Also, this equation in Eq. 10 is an approximation, because of that average <σv> term. This term is the cross section, which is a function of energy, times the velocity at the same energy, averaged over all relevant temperatures. It also assumes a Maxwellian distribution for the velocity and temperature of the ions. These approximating assumptions are not accurate for LENR fusion. The correct way to calculate this equation would be to integrate σv over the entire energy range of interest. Since this is a difficult integral to evaluate in closed form, the next best choice is to perform a step-wise summation, in a numerical integration.

LENR does not have a Maxwellian distribution of temperature. Rather, for LENR, the child product particles are at the exact same temperature upon being released from a reaction, with no Maxwellian distribution of energy. Then, they loose energy during the collisions with other nuclides. This type of collision process within a lattice creates more of a multi-humped distribution. Another complication in LENR is that there are four reactions involved. To calculate this equation correctly for LENR, numerical integration should be used instead of the non-applicable approximation, used for hot fusion. This correct approach is shown in Eq. 11.

$$f = \rho_A \rho_B \sum_{i=1}^{n_{steps}} \sigma(T) \times (v_{relative}) dT \quad \text{Eq.11}$$

where ρA is the number density of reactant-A, ρB is the number density of reactant-B, and nsteps is the number of steps for the numerical integration. T is absolute temperature, and Vrelative is the relative velocity of the two reactants, and dT is the step size.

One of the most critical parameters for the Lawson criterion is the fuel density. For hot fusion, the density is on the order of 1016 ions per cm3. For LENR, the density is typically between 6x1022 and 7x1022 deuterons per cm3. This is a difference of six to seven orders of magnitude improvement, for LENR, as compared to hot fusion. This extremely significant increase in the density helps to compensate for the lower ambient temperature.

The Volume Heating Rate

The Volume Heating Rate from Neutrons

For hot fusion, the volume rate of heating by fusion reactions is the fusion rate, f, times the energy of the charged fusion products, Echarged. In hot plasma fusion using magnetic confinement, the uncharged neutrons do not contribute the heating of the plasma, since they will not circle within the magnetic field. Rather they escape the reactor plasma core, going out from the core in straight-line paths like a spherical explosion in three dimensions. Thus the entire kinetic energy of the neutrons is lost energy (as it is defined by the Lawson Criteria) and it does not contribute to the volume heating rate.

For LENR, the neutrons contribute heat to the volume rate of heating, since they do not escape from a hot circulating plasma. Rather, the kinetic energy of the neutrons is largely contained within the lattice, and is thus is very important for LENR. As long as the kinetic energy of the neutrons stays in the lattice core, then volume heating from the neutrons occurs. Thus for LENR, as opposed to hot fusion, the neutron energy contributes to the volume heating rate and for the ignition of the reaction. The kinetic energy of the neutrons that do escape the core is considered as lost energy. This fraction of escaped neutrons can be minimized by the geometry of the core and the optimal design of the reactor--using techniques similar to those using fission reactors to keep the neutrons within the core as much as possible.

For both hot fusion and LENR, any neutron that does escape the reactor core can still create useable heat within the reactor apparatus, but outside of the reactor core. This occurs if the neutrons are involved in reactions with other elements, such as boron or lithium. Hot fusion reactors are able to generate more heat in this manner, via the reactions of the escaped neutrons. Although this heat from neutron reactions does not contribute to the volume heating rate, it is still heat that can be used for the purpose of power generation.

In the case of the D-T reaction, the energy of the 4He is 3.5 MeV. This value cannot be changed by any manipulation of core geometry or reactor design. For LENR, both Echarged and Eneutron are of interest, since they are equally important for LENR. As such, the energy for that fraction of neutrons that do not escape, Eneutrons, must be included in this calculation. This fraction does depend on the geometry, size, and the deuterium density within the lattice core; thus an exact number is not possible. However, a reasonable estimate is that about 70% of the neutron kinetic energy will be dissipated as heat in the reactor core, contributing to the volume heating rate. The transfer of this kinetic energy comes in the form of collisions between the energetic neutrons and the atoms of the deuterium and metal in the core.

The released energy that stays in the reactor core, EVolumeHeating, is the energy that contributes to the volume heating rate. Given this estimate of 70% for the neutronic kinetic energy, then the overall energy EVolumeHeating can be determined. Any energy that is not part of the volume heating rate is, according to the Lawson Criteria, an energy loss. For LENR, the volume rate of heating is the sum of the energies for the charged particles plus that fraction from the neutrons. This yields, EVolumeHeating = Echarged + (0.70) x Eneutron. (This energy does not include the neutron reactions that may occur outside of the core.)

The Total Volume Heating Rate from Charged particles

Considering the charged particles, an examination is done of how much energy contributes to the volume heating, for every 100 D+D primary reactions in an LENR reactor. Of these 100 reactions, 50% of them are D+D-->T+n, and 50% of them are D+D-->3He+p. Also, about 76% of the child-product tritium reacts with another deuterium, which means that for every 100 primary D+D reactions, there is a secondary T+D reaction about 38% of the time. Similarly, about 40% of the child product Helium-3 will react with another deuterium, which means that for every 100 primary D+D reactions, there is a secondary 3He+D reaction 20% of the time. For LENR, the four reactions described in Eqs. 3-6 are of interest. All of the energy from the charged particles and 70% of the neutron energy goes into the volume rate of heating by fusion. This is much better energy retention than what a hot fusion reactor achieves for its volume rate of heating, largely due to its 80% energy loss of the neutrons. LENR releases energy from four reactions instead of just one, and it doesn't have that inherently large energy loss for its neutrons.

The Total Volume Heating Rate

Table 1a and 1b are two tables comparing how much energy is lost for both LENR and hot fusion. As can be seen, only 14.07% of the energy is lost for lattice-assisted LENR, compared to the 80% of the energy that is lost for hot plasma fusion.

Table 1a: LENR

Reaction	Child product of reaction	Relative reaction rate per 100 reactions	Energy of child product (MeV)	Released energy for every 100 D+D reactions (MeV)	% of energy for this child product that is lost	Lost energy (MeV) for every 100 D+D reactions	NOT lost energy (MeV) for every 100 D+D reactions)

D + D → T + p	T	50	1.01	50.5	0	0	50.5
	p		3.03	151.5	0	0	151.5
D + D → He^3 + n	He3	50	0.8175	40.9	0	0	40.9
	n		2.4525	122.6	30	36.7875	85.8125
D + T → He^4 + n	He4	38	3.518	133.7	0	0	133.7
	n		14.072	534.7	30	160.4208	374.2792
D + He^3 → He^4 + p	He4	20	3.68	73.6	0	0	73.6
	p		14.72	294.4	0	0	294.4
Totals				1401.9		197.2	1204.7
Percentage of energy that is lost:						14.07%	

Table 1b: Hot Fusion

Reaction	Child product of reaction	Relative reaction rate per 100 reactions	Energy of child product (MeV)	Released energy for every 100 D+T reactions (MeV)	% of energy for this child product that is lost	Energy lost (MeV) for every 100 D+T reactions	Energy NOT lost (MeV) for every 100 D+T reactions
D + T → He^4 + n	He^4	100	3.518	351.8	0	0	351.8
	n		14.072	1407.2	100	1407.2	0
Totals				1759		1407.2	351.8
Percentage of energy that is lost:					80%		

Tables 1a and b, a comparison of released and lost energy for a.) LENR and b.) hot fusion.

The energy that is not lost from the core, $E_{VolumeHeating}$, is the energy that comes from the reaction and stays in the core. This energy, $E_{VolumeHeating}$, is the critical energy for the Lawson Criteria--to be used either for self-heating, as is the case for hot fusion, or for initiating a subsequent reaction, as in the case of LENR. For LENR, $E_{VolumeHeating}$ is 1204.7 MeV for every 100 D+D reactions, as seen in the table above, highlighted in blue on the bottom right. For hot fusion, $E_{VolumeHeating}$ is 351.8 MeV for every 100 D+T reactions. As can be seen, a substantial amount of energy is lost in the hot fusion reactors as compared to the LENR reactors. This lost energy needs to be minimized in order to maintain the reactor in a self-sustaining condition, and the minimization of $E_{VolumeHeating}$ is key to meeting the Lawson Criteria, as discussed in the next sub-section.

The Lawson Criterion for Volume Heating in LENR

The Lawson Criterion requires that fusion heating, which is f x $E_{VolumeHeating}$, exceeds the power losses, as shown in Eq. 12.

$$f \times E_{VolumeHeating} \geq P_{loss} \quad \text{Eq.12}$$

This equation is the requirement for a reactor to self-sustain its own reactions. For hot fusion, one can rewrite Eq. 12 by substituting in known quantities. This yields Eq. 13:

$$\frac{1}{4} n^2 \langle \sigma v \rangle E_{VolumeHeating} \geq \frac{3nT}{\tau_E} \quad \text{Eq.13}$$

This equation Eq 10 is valid only for hot plasma fusion, and it is incorrect for LENR, for the many reasons mentioned previously.

Starting with the unmodified energy-balance equation, Eq. 12, it can be properly modified for LENR. The left side of Eq. 12 is the released power of the reactions that stays in the core: the fusion rate times the volume heating energy. This power must be greater than the right side of the equation, which is the power lost from the core. For the power of the reactions released into the core is $P_{released}$. For the power lost from the core is P_{loss}. For LENR, $P_{released}$ is the sum of the four LENR reactions (Primary1, Primary2, Secondary1 and Secondary2), as shown in Eq. 14.

$$P_{released} = P_{reaction\_P1} + P_{reaction\_P2} + P_{reaction\_S1} + P_{reaction\_S2}$$

Eq.14

The power, P_{loss}, is the energy per second, that is lost from the system—either as heat, or radiation, or the kinetic energy of particles that escape the core. This power loss largely depends on the confinement time of the energy.

The Confinement Time of the Volume Heating Energy

The confinement time, τE, measures the rate at which the core loses energy to its environment. The faster the rate of loss of energy, the shorter the energy confinement time. For all forms of fusion, the confinement time is the energy contained within the system, divided by the power loss. A comparison is made for both hot fusion and LENR.

Confinement Time for Hot Fusion

For a plasma hot fusion reactor to operate in steady state, the fusion plasma must be maintained at an extremely high temperature. In order to maintain the fusion conditions, the thermal energy must be added to the plasma at the same rate as the energy is lost. For a hot fusion reactor without a plasma, the important energy balance is that for every reaction, there is enough energy remaining in the core to invoke a similar subsequent reaction. For example, in laser-induced hot fusion, this means that the released energy helps give enough kinetic energy to the D and T ions to overcome the Coulomb barrier. For every one D+T reaction that occurs, a subsequent D+T reaction must occur, as a direct result of the released energy of the previous reaction. For this to occur, it is important that the density of the D and T within the pellet is high enough for a subsequent reaction to occur, before the energy is lost to unwanted radiation--such as heat, light, or Bremsstrahlung radiation.

Confinement Time for LENR

Similar to a laser hot fusion reactor, these high-density conditions are needed for an LENR reactor. Specifically, that for every reaction there are enough energetic deuterons in the lattice core, with enough kinetic energy to overcome the Coulomb barrier, such that at least one subsequent reaction occurs, before the energy is lost to unwanted heat radiation. The released kinetic energy from the D+D reaction can interact with the thermal deuterons in the lattice, transferring enough of their kinetic energy to these deuterons to allow for a subsequent reaction. For each previous reaction that occurs, there need be only one subsequent reaction. Thus, there need be only a few of the deuterons that are hot enough to overcome the barrier, just enough for one subsequent reaction for every previous reaction.

The released energy from the D+D reaction is the kinetic energy of the child products from both the primary and secondary reactions. This additional energy from the secondary reactions is important. (Historically, it was previously thought that LENR could not sustain its own reactions, because the released energy of these secondary reactions was not properly taken into consideration.) Through the process of collisions with the deuterons in the lattice, the thermal deuterons are energized to high velocities. If the transferred kinetic energy is enough to overcome the Coulomb barrier, a subsequent reaction can occur. For an LENR reactor, the deuteron fuel density must be high enough for a subsequent reaction to occur, before the energy is lost in the form of low-temperature heating.

Low-Temperature Heating in LENR and Its Mitigation

For LENR, this low-temperature heating is the most significant energy loss, even though this loss goes into the core itself. Although the lattice core is the recipient of this low-temperature heating, this energy does not contribute to a subsequent reaction. This type is energy loss is characterized by numerous collisions with the electrons of the lattice, dispersing the kinetic energy to these numerous electrons, rather than to the deuterons. The electrons become the recipients of the kinetic energy, preventing the transference of kinetic energy to the nuclei in the lattice.

Certain types of lattices can assist in reducing this type of low-temperature energy loss, through a process known as "ion channeling" [3, 4]. Ion channeling can give the energetic ions a longer confinement time before losing their energy to low-temperature heating. For this to occur, it is important is that the electrons have a significant reduction in their thermally-induced kinetic energy. This, in turn, allows the nuclear stopping power to be greater than the electronic stopping power at lower energies. If this shift in stopping power, from electrons it nuclear, occurs within the energy range of the energetic ions, then this type of low-temperature energy loss can be strongly mitigated.

For example, this type of electron behavior is often seen in superconducting materials. In order for the fusion reactor to be more effective, it is currently believed that the lattice metal core of the reactor should have similar properties of superconductivity. The materials of PdDx (where x is the deuterium loading ratio) have such superconductive properties. Other hydrogen loaded metals, such a NiDx and other similar alloys, also have some of the properties of super conductors. For the core material of the fusion reactor, it is believed that the superconductive property has the ability to decrease the electron stopping power within that material, thereby increasing the range of the energetic charged ions. This, in turn, increases the reaction probabilities, allowing for an enhanced fusion reaction rate. Such behavior is related to the lattice confinement of the deuterium.

This mitigation of electron stopping is also seen in palladium hydrides, such as PdD and PdH, (as well as in other similar alloys.) For PdDx, the electronic thermal heating coefficient is decreased significantly, by as much as a factor of 6 reduction [5], when x is above 85%. When this behavior occurs, the electronic stopping power is reduced, relative to the nuclear stopping power. This, in turn, means that the energized ions are not slowed down by the many small collisions with electrons, but rather by the larger collisions with the other deuteron nuclei in the lattice [6, 7, 8, 9]. As a result of the reduction of electron collisions, the low-temperature energy loss is significantly reduced.

This is why, for LENR, it is not just the density of the deuterium fuel that matters. The behavior of the electrons in the lattice must also be taken into consideration, and this is why LENR is often called "lattice-assisted nuclear reactions" or "Solid State Fusion".

Discussion and Results

The released power, $P_{released}$ is the power coming out of the nuclear reactions of both the primary and secondary reactions. These reactions occur because of the kinetic energy of the deuterons, imparted to the deuterons from the energetic child products of the previous reaction, is sufficient to overcome the Coulomb barrier. The input power, P_{input}, is the kinetic energy of the deuterons, which must be sufficient to overcome the Coulomb barrier. The P_{loss} is the sum of the power going to the surrounding water bath, plus the power loss due to the neutrons and gamma radiation that escape the metal core. The resulting energized deuterons then cause a subsequent D+D reaction, sustaining the reaction. There must be enough energetic deuterons in the metal core to keep the nuclear reaction occurring. Currently for LENR, this is also a delicately balanced process and relatively misunderstood. However, when everything is configured correctly, the LENR reactor maintains the number of energetic deuterons in such a way as to sustain the reactions, as has been experimentally shown through hundreds of successful LENR experiments, yielding a self-sustained reaction with a net energy output [10].

The Energy Balance Equations for lattice assisted LENR can be met, due to the high density of the fuel ions, which is several orders of magnitude higher than what is proposed for hot fusion. Also, the confinement time of the energy in the core of the LENR reactor is much longer than otherwise expected, due to the mitigation of electron stopping power, provided by the lattice. As a result, even at the much lower temperatures typically seen in Low Energy Nuclear reactions, self-sustaining reaction are possible under these conditions.

Conclusions

The heart of the Lawson Equations is the balance of the various energies--E_{input}, $E_{released}$, $E_{VolumeHeating}$, and E_{loss}--for nuclear reactions. These energies, and their underlying conditions, are quite different for hot fusion and LENR. For a hot plasma reactor, these energy balance equations have been extensively modified for the particular assumptions relevant to hot plasma fusion. For LENR, these assumptions and modifications do not apply. However, the original energy balance equations of the Lawson Equations are still relevant.

The lack of a high ambient temperature for LENR is not important, as long as the energized ions and neutrons within the lattice core are able to initiate a subsequent reaction for every previous reaction that occurs. In this paper, it has been shown that the amount of volume heating energy within the LENR reactor is than that for hot plasma fusion reactor. However for LENR, some of the volume heating is actually considered as lost energy, if it is in the form of low-temperature heating due to electron stopping. For this reason, in the LENR reactors, the lattice assistance provided by the host material is critical to initiate a subsequent reaction. When the released energies from the reactions are able to transfer enough kinetic energy to enough fuel deuterons, then a subsequent reaction can occur. A self-sustaining reaction occurs, due to the lattice-assistance of the reactor core. A better understanding of how and why this lattice assistance occurs is essential to a better understanding of how and why LENR can occur, without the need for extreme high temperatures. The extreme high-density of the deuterons in LENR is important, along with the longer confinement times which are afforded to the energetic ions, due to the mitigation of electronic stopping within certain critical energy ranges for the ions. Low Energy Nuclear Reactions can and do meet the requirements of the Lawson energy-balance equations.

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