A Lattice-Assisted Conventional Explanation for LENR, Part III

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Abstract:

This paper is part III of a three-part series of companion 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 and Part II papers to gain a better understanding of the mechanisms involved in this explanation. [1, 2]

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 (^{2}D), 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 reaction 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 ^{2}D fuel. This transference of kinetic energy is achieved via the collisions of the energetic child products with the cold ^{2}D. With this increased kinetic energy transferred to the ^{2}D, no unconventional behaviors are needed to overcome the Coulomb barrier between this newly energized ^{2}D and another ^{2}D in the lattice.

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 the Part II paper, the reason why electron stopping is not a strong influence in lattice-assisted nuclear reactions was addressed. This Part III paper addresses the issue of neutron detection.

In this third Part III paper, there is an examination of the number of neutrons scatter and react within the entire apparatus. There is also an examination of 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, neutron emission, neutron detection, gamma emission, gamma detection.

1. Introduction

The outline of this paper is as follows:

Section 1: Introduction
Section 2: Brief Review of Part I and Part II
Section 3: Neutron Scattering and Absorption
Section 4: Gamma Radiation from the Apparatus
Section 5: Neutron Detection
Section 6: 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 reactions. The two primary reactions are $^2D+^2D\rightarrow{}^3T+p$ and $^2D+^2D\rightarrow{}^3He+n$. The two secondary reactions are $^2D+^3T\rightarrow{}^4He+n$ and $^2D+^3He\rightarrow{}^4He+p$. 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 the second paper "A Lattice-Assisted Conventional Explanation for LENR, Part II", there was 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.

In this Part III paper, it is also shown that the low level of neutron detection is explained as being due to neutron scattering and reactions within the apparatus, as well as the fact that high energy neutrons are difficult to detect, especially if they are not expected as child products from the experimental reactions. This calculation for neutron detection is done with rigorous mathematical calculations, to make this an accurate quantifying analysis. The estimated number of neutrons that are emitted, as well as the estimated gamma radiation, are determined. The results are in good agreement with experimental data.

2. Brief Review of Part I and Part II

2.1 Review of A Lattice-Assisted Conventional Explanation for LENR, Part I

In the companion paper, "A Lattice-Assisted Conventional Explanation for LENR, Part I", detailed and rigorous mathematical calculations are performed and described, using conventional nuclear reactions. In "A Lattice-Assisted Conventional Explanation for LENR Part I", a typical example reactor is used to show that a chain reaction can be produced in a LENR. However, if the reactions take place without the benefit of a surrounding metal lattice, the subsequent reactions cannot occur. Due to the effects of the lattice—such as electron screening, a decrease specific heat coefficient of PdD_x, and ion channeling—the nuclear reactions are enhanced to the point where one subsequent ^{2}D-to-^{2}D reaction occurs for each previous ^{2}D-to-^{2}D reaction. This is called the "reactivity" of the reactor, which must be greater than one for the reactor to self-maintain its own reactions. This requires that the reactor uses part of its own nuclear energy to induce a subsequent reaction, similar to a fission reactor.

The total power emitted by this example reactor is approximately 3.4 watts, with contributions from the primary, secondary, and tertiary reactions. The heat energy of the tertiary reactions may not be experimentally measured by the calorimetry, depending on how it is configured.

2.2 Review of A Lattice-Assisted Conventional Explanation for LENR, Part II

When a high energy ion exists inside of a metal lattice, the electrons in the metal quickly slow down the ion. For high ion energies, this effect, called electron stopping, is dominant. The main theoretical understanding of this phenomenon is described by Bethe formula for ion particle stopping power. This stopping force that the electrons impose on the high energy ions is very much like a friction force, and it is an energy loss for ions. For non-relativistic speeds, the equation for the stopping power force is shown in Eq. (1). This force is represented as the incremental change in energy divided by the incremental change in distance, -dE/dx. The negative sign indicates that the force is a retarding force.

$$F_{stopping\ power} = S = -\frac{dE}{dx} = \frac{4\pi k_0^2 z^2 e^4 n}{mv^2}\left[ln\left(\frac{2m_e v^2}{I}\right)\right] \qquad Eq.(1)$$

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=8.99×10^9 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, 1.602×10^{-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, for ^{2}D gas, 13.4 eV.

When using this equation for an amorphous medium like heavy water, the high-energy ions quickly lose energy due to their interaction with free electrons. Therefore, when electron stopping is dominant within a deuterated amorphous medium, a subsequent reaction is not possible.

It is claimed that there are certain attributes within the lattice allowing a subsequent ^{2}D-to-^{2}D reaction to occur. There are many theories examining the various ways that the lattice affects the reaction. In part II of this series, it is postulated that the electron stopping force is not dominant at the ion energies in the Pd lattice. Rather, the electron stopping power is shifted with respect to the nuclear stopping power in a PdD_x lattice. With this one assumption,

LENR can then be explained by conventional explanations. The nuclear reactions occur due to the transfer of ionic kinetic energy to the fuel deuterium, allowing the Coulomb barrier to be overcome in a conventional manner.

3. Neutron Scattering and Absorption

The neutron emission from the LENR reactor is examined in this section. An analysis is made for energetic neutrons at 14.07 MeV and 2.45 MeV, as well as room temperature neutrons—which are also known as "thermal neutrons". Energetic neutrons have a high scattering rate in the electrolyte and water bath. When a neutron scatters with a deuteron, it loses roughly half its energy. When a neutron scatters with proton, it loses roughly two thirds of its energy. An examination of the mathematics involved in this scattering process is provided, and a calculation is made to determine how many neutrons escape a typical LENR example apparatus.

Here are the assumptions and parameters for a typical LENR example apparatus.

- One watt of power total from the two primary reactions. This requires 8.55×10^{11} reactions for both the primary reactions, for a total of 1.71×10^{12} primary reactions.
- From Part I, it was determined that about 75.8% of the ^{3}T reacts with ^{2}D in the secondary1 reaction.
- Energetic neutrons are the child product of the secondary1 reaction, with 14.07 MeV.
- There are 6.48×10^{11} neutrons per second, at an energy of 14.07 MeV, from the secondary1 reaction.
- The electrolyte is in a cylindrical borosilicate glass container with an inner radius of 2.5 cm, and it is 25 cm tall. The outer radius is 3 cm.
- There is 1 mole/liter of lithium in the heavy water electrolyte, with the natural abundance of ^{6}Li and ^{7}Li.
- The two borosilicate glass beakers are made with the natural abundance ratio of ^{10}B and ^{11}B.
- The thermal water bath extends 30 cm (about 12 inches) beyond the first beaker. (The water bath could be replaced by polyurethan insulation, or some other type of material with a high hydrogen density. Typically, if an LENR experiment does not have a water bath surrounding it, it instead has some type of insulation with a high H density. The effect on the scattering and reaction is similar.)
- The water bath is surrounded by the second borosilicate glass beaker, which is 0.5 cm thick.
- The whole apparatus has a radius of 33.5 cm.
- The total output power coming out of the reactor is 3.40 watts.

This example reactor is similar to the example reactor used in the companion paper, "A Lattice-Assisted Conventional Explanation for LENR Part I".

3.1.1 Equations for Neutron Scattering and Reactions

If a collimated beam of mono-energy neutrons is traveling through a material, the intensity as a function of distance, I(x), is dependent on the initial intensity, I_0, and the total mean-free path between interactions, λ_{total}. This is shown in Eq. (2), [3].

$$I(x) = I_0 \, exp(-x/\lambda_{total}) \qquad Eq.(2)$$

The total mean-free path λ_{total} is the average distance travelled before any interaction, shown in Eq. (3).

$$\lambda_{total} = \frac{1}{\left(\frac{1}{\lambda_{scatter}}\right) + \left(\frac{1}{\lambda_{reaction}}\right)} \qquad Eq.(3)$$

where $\lambda_{scatter}$ is the mean-free path for scattering from all elements, and $\lambda_{reaction}$ is the mean-free path for all neutron-induced reactions, for all elements in the material. For each element within that material, the density of that element is multiplied by its scattering cross section, for the neutron energy being examined. This is summed for all elements in the material. The mean-free path for scattering is the reciprocal of that summation of products. Eq. (4) is an example of the mean-free path for scattering of neutrons in water:

$$\lambda_{scatter_H2O} = \frac{1}{\left[\left(\sigma_{scatter_H}\right)\left(\rho_H\right) + \left(\sigma_{scatter_O}\right)\left(\rho_O\right)\right]} \qquad Eq.(4)$$

where $\sigma_{scatter_H}$ is the cross section for hydrogen and ρ_H is the density of hydrogen, in atoms per cm^3, and $\sigma_{scatter_O}$ and ρ_O are similarly defined for oxygen.

For the reaction cross sections, a corresponding equation for $\lambda_{reaction}$ is used. However, since the various isotopes have different reaction rates, this calculation accounts for the various isotopes of each element, shown in Eq. (5).

$$\lambda_{react_H20} = \frac{1}{\left[\left(\sigma_{react_H1}\right)\left(\rho_{H1}\right) + \left(\sigma_{react_H2}\right)\left(\rho_{H2}\right) + \left(\sigma_{react_O16}\right)\left(\rho_{O16}\right) + \left(\sigma_{react_O17}\right)\left(\rho_{O17}\right) + \left(\sigma_{react_O18}\right)\left(\rho_{O18}\right)\right]} \quad Eq.(5)$$

For Eq. (5), the sum of all the various neutron reaction cross sections, for a given energy, is σ_{react}. In other words, the reaction cross sections in this equation encompass all neutron reactions between a neutron and the isotope, at the specified energy.

3.2 High Energy Neutrons at 14.07 MeV

The neutrons at 14.07 MeV are examined first. We want to determine how many of these neutrons scatter, react, or escape the apparatus. For the 14.07 MeV neutrons in this example calculation, the initial number, I_0, is 6.48×10^{11}, (calculated from Part I of this paper). As these neutrons slow down, the scattering cross section becomes larger; thus, they are more likely to scatter successively, numerous times. As a result, very few of them escape the reactor apparatus. Using the total mean-free path of Eq. (3), the intensity as a function of distance can be determined. This calculation is shown in Table 1.

There are five sections of the apparatus, listed in column A, on the left side of Table 1. These are the core, the electrolyte, first borosilicate beaker, the water bath, and the second borosilicate beaker. For each of these five sections, the 2 or 3 elements within that section are separated out: D and Pd for the core; D, O, and Li for the electrolyte; etc. For each element, the scattering and reaction cross sections are determined [4] at 14.07 MeV neutron energy. These cross sections are shown in the columns B-G. The densities of the atoms within that section are shown in columns H-J. Next, the scattering mean-free path, the reaction mean-free path, and the total mean-free path are determined in the columns, K-M. The distance the neutron travels is in column N. The results are given in columns O-R, on the right side of the table.

For the 14.07 MeV neutrons, note the value in the bottom row of column Q is 1.78×10^{10} neutrons. This is the number that escape the apparatus; this is $(1.78 \times 10^{10})/(6.48 \times 10^{11})$=2.75% percent that escape the reactor apparatus, without scattering or reacting.

However, some of the neutrons that scattered inside the apparatus may still escape, as they continue through the apparatus. After this first scattering, there are several different energies of these neutrons, all at a lower energy.

If a neutron scatters, then for the first instant immediately after that scatter, the neutron is still in the same section of the apparatus that it was in prior to the scatter. However, after the scatter, it goes in a new direction and at a lower energy. The neutron has another chance to react or scatter again in that same section of the apparatus. That first scatter was the first interaction. Table 1 is for the neutrons going through the apparatus in interaction #1. After this first interaction, the neutron has its second interaction.

For those neutrons that scattered off of either Pd, Si or O, during interaction #1, this same calculation is repeated, but now at the new lower energy, the energy in the range between 13.8 to 12.4 MeV. The number of these neutrons at this energy is known from Table 1, as 3.18×10^{11}, which is the sum of all the neutrons that scattered off of either a Pd, Si, or O atoms, in the various sections of the apparatus. A new calculation table, called table 1a, is made for this energy range. It is similar to Table 1, for the energy range of 13.8 MeV to 12.44 MeV. As before for Table 1, the number of neutrons that scattered, reacted, or escaped is calculated during this interaction. However, this table 1a is not shown, but rather the results are summarized in Table 2.

For those neutrons that scattered off of either Li or B, in interaction 1, this same calculation is repeated, but now for the energy in the range between of 11.8 MeV to 10.4 MeV. The number of these neutrons at this energy is known, from Table 1, as 1.65×10^{9}, the sum of all the neutrons that scattered off of either a Li or B atom, in all of the apparatus. A new calculation table, called table 1b, is made for this energy range, similar to Table 1, for the energy range of 11.8 MeV to 10.4 MeV. This table 1b is not shown, but the results are summarized in Table 2.

For those neutrons that scattered off of D, in interaction 1, this same calculation is repeated, for the energy in the range of 6.8 MeV. The number of these neutrons at this energy is known, from Table 1. It is 5.55×10^{10}, the sum of all neutrons that scattered off a D atom, within the apparatus. A new table is made, called table 1c, similar to Table 1, for the energy of 6.8 MeV. This table 1c is not shown, but the results are summarized in Table 2.

For those neutrons that scattered off of ^{1}H, in interaction 1, this same calculation is repeated, at an energy of 5.2 MeV. The number of these neutrons at this energy is known, from Table 1, as 3.2×10^{11}, the sum of all the neutrons that scattered off of ^{1}H atom, in the apparatus. A new table is made, called table 1d, similar to Table 1, for the energy of 5.2 MeV. This table 1d is not shown, but summarized in Table 2.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Section	Scattering Cross Section			Reaction Cross Sections			Density of Atoms			Mean Free Paths			Distance		Results		
		In barns.			In barns.		In number of atoms/cm^3				In cm		In cm				
Inside the Core: the Pd and D2	Scatter cross section with D2	Scatter cross section with Pd		Total neutron reaction cross section with D2	Total neutron reaction cross section with Pd		Density of D2 in core	Density of Pd in core		Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through core	Percent probability of a neutron interacting in core	Number of neutrons that interact in core	Number that have not yet interacted and go into electrolyte	Number that react in core
	0.635	2.50		0.17000	0.603		5.4E+22	5.7E+22		5.68	23.07	4.56	0.78	15.7	1.02E+11	5.46E+11	2.16E+10
Inside the electrolyte: the deuterium, oxygen, and lithium	Scatter Cross section with D2 in electrolyte	Scatter Cross section with O in electrolyte	Scatter Cross section with Li in electrolyte	Total neutron reaction cross section with D2	Total neutron reaction cross section with O	Total neutron reaction cross section with Li	Density of D2 atoms in electro-lyte	Density of O atoms in electro-lyte	Density of Li atoms in electro-lyte	Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through electrolyte	Percent probability of a neutron interacting in electrolyte	Number of neutrons that interact in electrolyte	Number that have not yet interacted and go into first glass beaker	Number that react in electrolyte
	0.635	1.000	0.997	0.17000	0.700	0.74	6.7E+22	3.3E+22	6.0E+20	13.08	28.41	8.95	1.72	17.5	9.55E+10	4.51E+11	3.21E+10
Inside the first glass beaker: boron, oxygen, and silicon	Scatter Cross section with B in first glass beaker	Scatter Cross section with O in first glass beaker	Scatter Cross section with Si in first glass beaker	Total neutron reaction cross section with B	Total neutron reaction cross section with O	Total neutron reaction cross section with Si	Density of all B atoms in first glass beaker	Density of all O atoms in first glass beaker	Density of all Si atoms in first glass beaker	Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through first glass beaker	Percent probability of a neutron interacting in first glass beaker	Number of neutrons that interact in first glass beaker	Number that have not yet interacted and go into water bath	Number that react in first glass beaker
	0.815	1.000	0.750	0.585	0.700	1.150	5.7E+21	4.7E+22	1.9E+22	15.23	17.24	8.09	0.50	6.0	2.70E+10	4.24E+11	1.29E+10
Inside the water bath: hydrogen and oxygen	Scatter Cross section with H1 in water bath	Scatter Cross section with O in water bath		Total neutron reaction cross section with H1	Total neutron reaction cross section with O		Density of H1 atoms in water bath.	Density of O atoms in water bath.		Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through water bath	Percent probability of a neutron interacting in water bath	Number of neutrons that interact in water bath	Number that have not yet interacted and go into second glass beaker	Number that react in water bath
	0.700	1.000		#######	0.700		6.7E+22	3.3E+22		12.46	42.74	9.65	30.00	95.5	4.05E+11	1.89E+10	2.14E+11
In the second glass beaker: boron, oxygen, and silicon	Scatter Cross section with B in second glass beaker	Scatter Cross section with O in second glass beaker	Scatter Cross section with Si in second glass beaker	Total neutron reaction cross section with B	Total neutron reaction cross section with O	Total neutron reaction cross section with Si	Density of all B atoms in second glass beaker	Density of all O atoms in second glass beaker	Density of all Si atoms in second glass beaker	Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through second glass beaker	Percent probability of a neutron interacting in second glass beaker	Number of neutrons that interact in second glass beaker	Total number that have not yet interacted and escape	Number that react in second glass beaker
	0.815	1.000	0.750	0.585	0.700	1.150	5.7E+21	4.7E+22	1.9E+22	15.23	17.24	8.09	0.50	6.0	1.13E+09	1.78E+10	5.41E+08
																Total that react during first pass =	2.81E+11
																Number that did not escape or react during this first pass =	3.50E+11
																Percentage that escape during first pass =	2.74

Table 1: Intensity of 14.07 MeV neutrons as they travel through the various sections of a typical LENR apparatus. This is interaction #1 for these 14 MeV neutrons.

All of this data from Tables 1, 1a, 1b, 1c, and 1d are summarized in Table 2.

Summary of all neutrons originally at 14.07 MV		
Description	Number	Comments
Original number of 14.07 MeV neutrons =	6.48E+11	
Number that escaped for first interaction =	1.78E+10	
Number that escape for range of 12.5 - 13.8 MeV =	1.16E+10	
Number that escape for range of 10.43 - 11.86 MeV =	4.09E+07	
Number that escape for range of 6.8 - 5.2 MeV =	1.98E+09	
Estimated number that escape from third interaction =	5.67E+09	
Sum of escaped neutrons from 1st, 2nd, and 3rd interaction =	3.70E+10	This is the number of neutrons, originally at 14.07 MeV, that escape. 5.71% escape the apparatus.
Number reacted for first interaction =	2.81E+11	
Number that react in second pass for 13.8 - 12.5 MeV range =	1.55E+11	
Number that react in second pass for 11.9 - 10.4 MeV range =	5.42E+08	
Number that react in second pass for 6.8 - 5.2 MeV range =	2.41E+10	
Estimated number that reacted in third interaction	6.92E+10	
Adding up reacted neutrons from first and second passes =	5.30E+11	This is the number of neutrons, originally at 14.07 MeV, that react. 81.69% react.
Remaining number that thermalize in the set-up =	8.17E+10	This is the number of neutrons, originally at 14.07 MeV, that thermalize. 12.6% thermalize.

Table 2. Summary of the neutrons originally released from the D+D→^{3}T+n reaction, at 14.07 MeV energy. This table shows all of the neutrons that scattered (and stay inside the apparatus), escaped the apparatus, or reacted in the apparatus.

Only 5.71% escape the apparatus, and about 82% react. The rest of these neutrons thermalize to ambient temperature and will eventually react or decay. The first row of Table 2 is the original number of 14.07 MeV neutrons for this example reactor. The second row is the number that escaped during the first interaction through the apparatus. The next three rows are the number that escape for the various energy ranges of the neutrons during the second interactions. The next row is the estimated number from the third interaction. The sum of these three interactions is below, giving an estimate of the number of 14 MeV neutrons that escape the apparatus. This is 5.71% of the original number. Also shown in Table 2 is the number of neutrons that reacted, which is 5.30×10^{11} or 81.69%. The estimated number that remains in the apparatus is 8.17×10^{10} or 12.6%.

3.3 Neutrons at 2.45 MeV

The 2.45 MeV neutrons from the primary2 reaction are considered next, in a similar manner to the 14.07 MeV neutrons above. For Table 3, the initial intensity, I_0, is 8.55×10^{11}. For Table 3, the descriptions of the columns are the same as for Table 1, but the values are for 2.45 MeV neutrons.

To clarify, for those neutrons that originated as child products from the D+D→^{3}He+n reaction, this same calculation is repeated, but with a starting energy of 2.45 MeV for interaction #1. As before for Table 1, a calculation is made for how many neutrons scattered, reacted, or escaped during their interaction #1. This Table 3 is shown below.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Section	Scattering Cross Section			Reaction Cross Sections			Density of Atoms			Mean Free Paths			Distance		Results		
		In barns.			In barns.		In number of atoms/cm^3			In cm			In cm				
Inside the Core: the Pd and D2	Scatter cross section with D2	Scatter cross section with Pd		Total neutron reaction cross section with D2	Total neutron reaction cross section with Pd		Density of D2 in core	Density of Pd in core		Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through core	Percent probability of a neutron interacting in core	Number of neutrons that interact in core	Number that have not yet interacted and go into electrolyte	Number that react in core
	2.4	2.70		0.00001	0.050		5.4E+22	5.7E+22		3.54	352.67	3.51	0.78	19.9	1.71E+11	6.84E+11	1.89E+09
Inside the electrolyte: the deuterium, oxygen, and lithium	Scatter Cross section with D2 in electrolyte	Scatter Cross section with O in electrolyte	Scatter Cross section with Li in electrolyte	Total neutron reaction cross section with D2	Total neutron reaction cross section with O	Total neutron reaction cross section with Li	Density of D2 atoms in electro-lyte	Density of O atoms in electro-lyte	Density of Li atoms in electro-lyte	Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through electrolyte	Percent probability of a neutron interacting in electrolyte	Number of neutrons that interact in electrolyte	Number that have not yet interacted and go into first glass beaker	Number that react in electrolyte
	2.4	0.800	1.7	0.00001	0.00005	0.2	6.7E+22	3.3E+22	6.0E+20	5.31	8144.7	5.31	1.72	27.7	1.89E+11	4.95E+11	1.45E+08
Inside the first glass beaker: boron, oxygen, and silicon	Scatter Cross section with B in first glass beaker	Scatter Cross section with O in first glass beaker	Scatter Cross section with Si in first glass beaker	Total neutron reaction cross section with B	Total neutron reaction cross section with O	Total neutron reaction cross section with Si	Density of all B atoms in first glass beaker	Density of all O atoms in first glass beaker	Density of all Si atoms in first glass beaker	Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through first glass beaker	Percent probability of a neutron interacting in first glass beaker	Number of neutrons that interact in first glass beaker	Number that have not yet interacted and go into water bath	Number that react in first glass beaker
	2.500	0.800	2.000	0.050	0.00005	0.0005	5.7E+21	4.7E+22	1.9E+22	11.13	3368.3	11.10	0.50	4.4	2.18E+10	4.73E+11	7.35E+07
Inside the water bath: hydrogen and oxygen	Scatter Cross section with H1 in water bath	Scatter Cross section with O in water bath		Total neutron reaction cross section with H1	Total neutron reaction cross section with O		Density of H1 atoms in water bath.	Density of O atoms in water bath.		Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through water bath	Percent probability of a neutron interacting in water bath	Number of neutrons that interact in water bath	Number that have not yet interacted and go into second glass beaker	Number that react in water bath
	2.620	0.800		0.00003	0.00005		6.7E+22	3.3E+22		4.95	257787	4.95	30.00	99.8	4.72E+11	1.10E+09	5.51E+07
In the second glass beaker: boron, oxygen, and silicon	Scatter Cross section with B in second glass beaker	Scatter Cross section with O in second glass beaker	Scatter Cross section with Si in second glass beaker	Total neutron reaction cross section with B	Total neutron reaction cross section with O	Total neutron reaction cross section with Si	Density of all B atoms in second glass beaker	Density of all O atoms in second glass beaker	Density of all Si atoms in second glass beaker	Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through second glass beaker	Percent probability of a neutron interacting in second glass beaker	Number of neutrons that interact in second glass beaker	Total number that have not yet interacted and escape	Number that react in second glass beaker
	2.500	0.800	2.000	0.050	0.00005	0.0005	5.7E+21	4.7E+22	1.9E+22	11.13	3368.3	11.10	0.50	4.4	4.86E+07	1.05E+09	1.64E+05
																Total that reacted=	2.16E+09
																Total that did not react or escape =	8.52E+11
																Percentage that escape during first pass =	0.12

Table 3: Intensity of 2.45 MeV neutrons as they travel through the various sections of a typical LENR apparatus. This is interaction #1 for these 2.45 neutrons.

For the neutrons originally at 2.45MeV, Table 3 shows how the neutrons behave for their interaction #1. A calculation is done for how the neutrons behave similar to what was done for the 14.07 MeV neutrons. For these 2.45 MeV neutrons that scattered off either Pd, Si, O, B or Li in their interaction #1, a calculation is done for interaction #2, but now at this new lower energy range. The new range, for interaction #2 for these neutrons, is 2.40 MeV to 1.82 MeV. The number of these neutrons, within this energy range of 2.4 MeV to 1.82 MeV, is 4.11×10^{11}. (This number was derived from Table 3 above; calculations not shown.) A new table is made, table 3a, which is similar to Table 3, but for the energy range of 2.40 MeV to 1.82 MeV. As before, a calculation is made for how many neutrons scatter, react, or escape during this interaction. This table 3a is not shown, but is summarized in Table 4. Similarly, the values for table 3b, with lower energy levels from 1.2 MeV to 0.9 MeV, are calculated but not shown. The results are summarized in Table 4. For the neutrons that were originally at 2.45 MeV, a summary of their second pass through the apparatus is shown in Table 4. This is similar to Table 2 in description, but for the different energy ranges. All of the data from Tables 3, 3a, 3b are summarized in Table 4.

Summary of all neutrons originally at 2.45 MeV		
Description	**Number**	**Comments**
Original number of 2.45 MeV neutrons =	8.55E+11	
Number that escaped for first pass =	1.05E+09	
Number that escape in second pass for 2.4 - 1.8 MeV range =	1.55E+08	
Number that escape in second pass for 1.2 - 0.9 MeV range =	1.44E+05	
Adding up escaped neutrons from first and second passes =	1.21E+09	This is the number of neutrons, originally at 2.45 MeV, that escape. 0.14% escape the apparatus.
Total that reacted for first pass only =	2.16E+09	
Number that react in second pass for 2.4 - 1.8 MeV range =	1.78E+09	
Number that react in second pass for 1.2 - 0.9 MeV range =	1.34E+09	
Adding up reacted neutrons from first and second =	5.28E+09	This is the number of neutrons, originally at 2.45 MeV, that react. 0.62% react.
Remaining number that thermalize in the set-up =	8.49E+11	This is the number of neutrons, originally at 2.45 MeV, that thermalize. 99.24% thermalize.

Table 4. Summary of the neutrons originally released from the D+D→^{3}He+n reaction, at 2.45 MeV energy. This table shows all of the neutrons that escaped or reacted. Only 0.14% escape the apparatus, and only about 0.62% react. The rest of the neutrons thermalize within the water bath, to reach ambient temperature.

There are 2 large tables just for the first interaction, one for 14.07 MeV neutrons and one for 2.45 MeV neutrons: Table 1 and Table 3. There are 4 large tables just for the second interaction for the neutrons that were originally at 14.07 MeV: tables 1a, 1b, 1c, and 1d. These are not shown. There are 2 large tables just for the second interaction, for the neutrons that were originally at 2.45 MeV: tables 3a, 3b. These are not shown. Thus there are 6 tables total for the second interactions, all at different energies. For each of these 8 tables (1, 1a, 1b, 1c, 1d, 3, 3a, and 3b) the number of neutrons that escape the apparatus is estimated. For the neutrons are at lower energies, most of the neutrons stay in the water bath and eventually thermalize.

As can be seen in Table 4, very few neutrons escape. Rather, these neutrons stay in the reactor, scattering and lowering their energy, until they thermalize. As the energy of the neutrons continues to shift into lower energy ranges, the neutrons reach a temperature close to ambient temperature, wherein several predominant reaction rates increase, and the apparatus begins to absorb the neutrons via reactions. An examination of the room temperature neutrons within the apparatus is done next.

3.4 Low Energy Neutrons at 26 milli-eV Thermal neutrons.

When the neutrons are thermalized at room temperature, they react more readily with the other elements and isotopes in the apparatus, such as the palladium, boron, lithium, and hydrogen ^{1}H. In some of these reactions, more ^{4}He and more heat are released. In other reactions, gamma radiation is released.

The number of neutrons remaining in the reactor, after they have reached 0.9 MeV or less, is determined from the bottom rows of Tables 2 and 4. The sum is $8.17 \times 10^{10} + 8.49 \times 10^{11} = 9.31 \times 10^{11}$. Using this approximation, this value is used to determine how many neutrons react or escape at the energy of 26 milli-eV. Also, additional calculations are done to determine how much gamma radiation is emitted from the apparatus.

For thermal neutrons outside the core, but still in the reactor apparatus, there are three main tertiary reactions of importance. These are: $^{6}Li+n \rightarrow {}^{4}He+{}^{3}T$, $^{10}B+n \rightarrow {}^{4}He+{}^{7}Li$, $^{1}H+n \rightarrow {}^{2}D+\gamma$.

The lithium reaction is often used in hot fusion reactors to prevent the neutrons from escaping, due to its very large cross section of 941 barns. Lithium is typically used as an electrolytic in LENR apparatuses. Any neutron that reacts with lithium ^{6}Li will result in the child product of ^{4}He and ^{3}T. These reaction by-products are often seen, experimentally, being emitted from the electrolyte of LENR reactors.

Another important reaction is that of boron ^{10}B with a room temperature neutron. This removes thermal neutrons due to its a huge cross section of 3840 barns. For a reactor apparatus that contains any borosilicate glass, (such as Pyrex or Dewars) the room temperature neutrons will react with the boron, in the reaction $^{10}B+n \rightarrow {}^{4}He+{}^{7}Li$.

The third room temperature neutron reaction of importance occurs in the water bath surrounding the LENR apparatus, which contains a high density of hydrogen. Hydrogen ^{1}H this is a moderator for fission reactors, and it is also used in most LENR apparatuses as the thermal water bath. The reaction is $^{1}H+n \rightarrow {}^{2}D+gamma$, with a cross section of about 0.332 barns. Even though the cross section is much smaller in size compared to those of ^{6}Li and ^{10}B, the density of the ^{1}H in the water bath is quite high. The result is that very few thermal neutrons escape the water bath of the typical LENR apparatus.

In a steady-state situation, the number of neutrons being emitted from the core is equal to the number of neutrons either escaping the apparatus or reacting with the materials in the apparatus. In this steady-state situation, there will be a certain number of neutrons emitted from the core, a certain number of neutrons escaping or reacting, and a certain number contained within the reactor apparatus. The number of neutrons being emitted from the core for this example, is 1.50×10^{12} per second, as calculated in the companion paper, Part I. In steady state, the number of neutrons contained within the apparatus is, by definition, a constant. Thus, as a first assumption, the number of thermal neutrons reacting in the reactor apparatus is equal to the number of neutrons being emitted minus the number of neutrons that react or escape.

For the apparatus in this example, the total volume of the apparatus is 88,141 cm^3. (The apparatus contains a borosilicate glass beaker holding the electrolyte and the core, and this beaker has an outer radius of 3 cm. The borosilicate glass beaker for the water bath extends 30 cm beyond the electrolyte beaker, such that the inner radius of the water bath beaker is 33 cm. The thickness of the water bath beaker is 0.5 cm, such that the outer radius of the entire apparatus is 33.5 cm. The water bath is 25 cm high. The total volume of the apparatus is 88,141 cm^3.)

Assuming in steady state, there are approximately 9.31×10^{11} thermal neutrons, as determined above. If it is assumed that these neutrons are evenly distributed within the volume of the reactor apparatus, then this gives a density of 1.11×10^{7} thermal neutrons per cm^3. Unlike the energetic neutrons of 14.07 MeV and 2.45 MeV, these thermal neutrons are not moving in a straight path inside the apparatus, rather they are moving in random Brownian motion, with only a very short distance between interactions.

The thermal neutron interaction rates can be determined by using Eq. (2). This is calculated in Table 5 for thermal (0.026 eV) neutrons. For this table, the neutrons in each of the 5 sections are assumed to be evenly distributed throughout the apparatus, and the number in each section is proportional to volume of the section. This condition of thermal neutrons occurs after approximately 34 scattering interactions with a ^{1}H nucleus. Table 5 also shows information for gamma radiation. Also included in Table 5, is the amount of unscreened gamma radiation that is released, calculated columns R, S, T, and U. This is the gamma that is released by the reactions, it is not the gamma energy that comes out of the apparatus, since the apparatus itself does provide some screening and shielding.

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Section	Scattering Cross Section			Reaction Cross Sections			Density of Atoms			Mean Free Paths			Distance		Results	
		In barns.			In barns.		In number of atoms/cm^3				In cm		In cm			
Inside the Core: the Pd and D2	Scatter cross section with D2	Scatter cross section with Pd		Total neutron reaction cross section with D2	Total neutron reaction cross section with Pd		Density of D2 in core	Density of Pd in core		Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through core	Percent probability of a neutron interacting in core	Number of neutrons that interact in core	Number that react in core
	4.3	5		0.0006	0.3		5.4E+22	5.7E+22		1.94	58.68	1.88	0.78	34.0	7.17E+06	2.79E+05
Inside the electrolyte: the deuterium, oxygen, and lithium	Scatter Cross section with D2 in electrolyte	Scatter Cross section with O in electrolyte	Scatter Cross section with Li in electrolyte	Total neutron reaction cross section with D2	Total neutron reaction cross section with O	Total neutron reaction cross section with Li	Density of D2 atoms in electro-lyte	Density of O atoms in electro-lyte	Density of Li atoms in electro-lyte	Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through electrolyte	Percent probability of a neutron interacting in electrolyte	Number of neutrons that interact in electrolyte	Number that react in electrolyte
	4.3	4	0.9	0.0006	0.0002	66	6.7E+22	3.3E+22	6.0E+20	2.37	25.13	2.17	1.72	54.8	2.78E+09	3.36E+08
Inside the first glass beaker: boron, oxygen, and silicon	Scatter Cross section with B in first glass beaker	Scatter Cross section with O in first glass beaker	Scatter Cross section with Si in first glass beaker	Total neutron reaction cross section with B	Total neutron reaction cross section with O	Total neutron reaction cross section with Si	Density of all B atoms in first glass beaker	Density of all O atoms in first glass beaker	Density of all Si atoms in first glass beaker	Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through first glass beaker	Percent probability of a neutron interacting in first glass beaker	Number of neutrons that interact in first glass beaker	Number that react in first glass beaker
	4.5	4	2	800	0.0002	0.20	5.7E+21	4.7E+22	1.9E+22	3.99	0.22	0.21	0.50	91.0	2.15E+09	2.12E+09
Inside the water bath: hydrogen and oxygen	Scatter Cross section with H1 in water bath	Scatter Cross section with O in water bath		Total neutron reaction cross section with H1	Total neutron reaction cross section with O		Density of H1 atoms in water bath.	Density of O atoms in water bath.		Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through water bath	Percent probability of a neutron interacting in water bath	Number of neutrons that interact in water bath	Number that react in water bath
	30	4		0.330	0.0002		6.7E+22	3.3E+22		0.47	45.27	0.46	30.00	100.00000	8.95E+11	4.34E+11
In the second glass beaker: boron, oxygen, and silicon	Scatter Cross section with B in second glass beaker	Scatter Cross section with O in second glass beaker	Scatter Cross section with Si in second glass beaker	Total neutron reaction cross section with B	Total neutron reaction cross section with O	Total neutron reaction cross section with Si	Density of all B atoms in second glass beaker	Density of all O atoms in second glass beaker	Density of all Si atoms in second glass beaker	Mean free path for scatters	Mean free path for reactions	Total mean free path	Distance an average neutron travels through second glass beaker	Percent probability of a neutron interacting in second glass beaker	Number of neutrons that interact in second glass beaker	Number that react in second glass beaker
	4.5	4	2	800	0.0002	0.2000	5.7E+21	4.7E+22	1.9E+22	3.99	0.22	0.21	0.50	91.0	2.51E+10	2.47E+10
															Total that reacted=	4.61E+11

Table 5a. Summary of the thermalized neutrons at 26 milli-eV energy. This table shows all of the neutrons that reacted, columns A through Q.

Columns A through Q are similar to the columns in Tables 1 and 3. As can be seen for column O for the water bath row, 100.000000% of the neutrons that are in the water bath will react in the water bath, at this thermal energy. Any neutrons that were in the second borosilicate glass react at 91%. Although a few may escape, this is a negligible amount; most neutrons scatter and react in the apparatus. These assumptions can be used as a reasonable approximation to determine how much gamma radiation is released from the reactions, and how much is subsequently emitted from the apparatus.

A	R	S	T	U
Section	Calculating Gamma emission			
Inside the Core: the Pd and D2	Energy of one n+Pd reaction, in MeV	Energy of all of these n+Pd reactions, in MeV.	Energy of all n+Pd reactions, in Joules	Energy of only the gamma emitting reactions, in Joules
	9.50	2.65E+06	4.24E-07	4.24E-07
Inside the electrolyte: the deuterium, oxygen, and lithium	Energy of one n+Li reaction, in MeV	Energy of all of these n+Li reactions, in MeV.	Energy of all n+Li reactions in Joules	Energy of only the gamma emitting reactions, in Joules
	4.783	1.61E+09	2.57E-04	0
Inside the first glass beaker: boron, oxygen, and silicon	Energy of one n+B reaction, in MeV	Energy of all of these n+B reactions, in MeV.	Energy of all of these n+B reactions in Joules	Energy of only the gamma emitting reactions, in Joules
	0.477	1.01E+09	1.62E-04	1.47E-04
Inside the water bath: hydrogen and oxygen	Energy of one n+H reaction, in MeV	Energy of all of these n+H reactions, in MeV.	Energy of all n+H reactions in Joules	Energy of only the gamma emitting reactions, in Joules
	2.224	9.65E+11	1.54E-01	1.54E-01
In the second glass beaker: boron, oxygen, and silicon	Energy of one n+B reaction, in MeV	Energy of all of these n+B reactions, in MeV.	Energy of all n+B reactions in Joules	Energy of only the gamma emitting reactions, in Joules
	0.477	1.18E+10	1.89E-03	1.72E-03
			Gamma Energy Total =	0.156

Table 5b. Continuation of Table 5. Summary of the thermalized neutrons at 26 milli-eV energy. This table shows all of the gamma energy is released from those reactions, columns R through U.

Rows R through U in Table 5 are for the purpose of determining gamma radiation. Column R gives the energy of one reaction. Column S is the total of all such reactions, the product of column R times column S, in MeV. Column T is that same energy converted to Joules, and column U is only the energy that is released as gamma radiation. A bit more explanation is needed for column U. The reaction with ^{10}B releases part of its energy as kinetic energy and part of the energy a gamma radiation. For the two sections in the apparatus with the borosilicate glass, the value listed in Column R, for the energy of one reaction, is only the gamma energy, not the kinetic energy. For room temperature neutrons interacting with boron, 90% of the reactions result in the release of gamma energy. For the section with the electrolyte, essentially none of the reactions emit gamma radiation. For the sections with the Pd core and water bath sections, all of the released energy is gamma.

Tables 1 through 5 represent an accurate estimate of how many neutrons escape from or react in the LENR apparatus. These numbers are not some overly-simple or quick estimate. By examining these five tables (Tables 1-5) in detail, it can be seen that only a small percentage of the neutrons escape, mostly in the higher energy ranges. Most of the neutrons are captured in the water bath and react therein. Most of the gamma radiation comes from the tertiary reaction of the thermalized neutrons within the water bath reacting with ^{1}H. By combining the information from Tables 1 through 5, it can be determined that the total sum of all the neutrons that escape the apparatus is 3.82×10^{10}. The total number that thermalized within the apparatus is 9.3×10^{11}.

The calculated detection rate and dosage rates for neutrons are calculated in Section 5. The calculations for gamma radiation are done next in Section 4. These calculations also include the gamma shielding done by the apparatus, and the effective dose that a typical person might get if they stand next to one watt reactor for one hour.

4. Gamma Radiation Emitted from the Apparatus

There is no beta decay in the set of reactions occurring within an LENR. Therefore, the most common way that gamma radiation can occur from an LENR is via neutron absorption, wherein an element, with a baryon mass A, absorbs a neutron and transforms into a different isotope of that same element, with a baryon mass A+1. This reaction is accompanied by a release of gamma radiation. This type of reaction is shown in Eq. (6), where X is the generic symbol for the given element.

$$ {}^{A}_{Z}X + n \rightarrow {}^{A+1}_{Z}X + \gamma \qquad Eq.(6) $$

4.1 Calculation and determination of gamma radiation

Using the numbers and values that have already been obtained in this paper, a calculation of the amount of gamma radiation is shown in Table 6.

Description	Amount	Comments
Source of the gamma by reaction type		
Gamma from primary reactions	0	No gamma. All energy is released as kinetic energy of child products.
Gamma from secondary reactions	0	No gamma. All energy is released as kinetic energy of child products.
Gamma from tertiary reactions	0.160	All gamma is created by the tertiary reactions.
Source of the gamma by energy of the neutrons		
Gamma from 14 MeV neutrons	0	No gamma. These are all endothermic reactions.
Gamma from 2.45 MeV neutrons	0.003	Joules/sec. There is just a small amount of gamma from the boron reactions.
Gamma from all other neutrons at other energies	0.156	Joules/sec. The room temperature reactions are dominant.
Total	0.160	
By energy of the created gamma		
Amount of 0.477 gamma, unscreened	0.003	Joules/sec
Amount of 2.225 gamma, unscreened	0.157	Joules/sec
Total gamma after being screened by apparatus	0.04828	Joules/sec. This is the gamma that comes out of the apparatus.
Energy absorbed by a person 1 meter from source	1.92E-03	Joules/sec
Dosage, assuming the average person weighs 70 kg.	2.74E-05	Joules/sec/kg
Dosage, per watt of reactor output power	7.80E-06	Joules/sec/kg, per watt of reactor output power
Dosage for 1 hour, 1 meter away from a 1-watt reactor	0.0281	Joules/kg, per watt of output power, after 1 hour, at 1 meter away.
Fraction of a lethal dose	(1/178)th	After 1 hour, for 1 Watt of excess heat, standing 1 meter away.

Table 6: Gamma radiation emitted from the reactor.

As shown in Table 6, there is no gamma being released by any of the primary or secondary reactions. Only the tertiary reactions release gamma. Also, there is no gamma released by any of the tertiary reactions occurring from the 14.07 MeV neutrons, since these reactions are all endothermic. Most of the gamma radiation comes from the tertiary reactions involving low energy neutrons, near room temperature. These have been grouped together in Table 6 and summed as 0.160 Joules/second. This number is also the sum of all gamma at 0.477 MeV and at 2.224 MeV, unscreened by the apparatus. Because these gamma particles are emitted randomly in three dimensions, they must pass through the reactor apparatus to get into the air. On average, the gamma rays pass through about 13 cm of water and 0.5 cm of borosilicate glass, for the numbers in this example reactor. The materials within the apparatus screen the gamma radiation as the average gamma rays traverse outward. The equation for screening the gamma intensity is an exponential function of distance x, which includes what is known as a "linear attenuation coefficient", μ. This is shown in Eq. (7).

$$ I = I_0 exp(-\mu x) \qquad Eq.(7) $$

The linear attenuation coefficient is dependent on the gamma energy and on the material, and can be obtained from experimental data tables [5]. In units of cm^{-1}, the linear attenuation coefficient, μ, for water is 0.078 for gamma energy at 0.477 MeV, and for 2.224 MeV, it is 0.052. For borosilicate glass, the linear attenuation coefficient is 0.155 for 0.477 MeV gamma, and it is 1.05 for 2.224 MeV gamma. For 0.477 gamma going through 13 cm of water and 0.5 cm of borosilicate glass, this gives a combined attenuation factor of 0.336. This is shown in calculation Calc. (1).

$$ For\ 0.477\ MeV\ gamma\text{:}\ \frac{I}{I_0} = [exp(-0.078 \times 13)]\ \times [exp(-0.155 \times 0.5)] = 0.336 \quad Calc.(1) $$

For the 2.224 MeV gamma, the combined attenuation factor is 0.301, as shown in calculation Calc. (2), below.

$$For\ 2.224\ MeV\ gamma: \frac{I}{I_0} = [exp(-0.052 \times 13)] \times [exp(-1.05 \times 0.5)] = 0.301 \quad Calc.\ (2)$$

When multiplied by the initial intensities for the two energies of gamma radiation, the resulting gamma intensity that comes out of the apparatus is 0.04828 Joule/sec. This is the gamma energy coming outward from the entire apparatus in a spherical distribution. (Recall that the term "apparatus" is the entire reactor setup, including the core, the electrolyte, the glassware, and the water bath.) For a human, with an approximate cross sectional surface area 0.5 meter^2, who is one meter away from the reactor core, the energy absorbed is shown in the next row down, as 1.92×10^{-3} joules/sec. This is divided by the mass of the average human, of 70 kg (154 lb.), for an energy of 2.74×10^{-5} joules/sec/kg of weight, shown in the next row down as the radiation dosage. These numbers are for a reactor running at 3.4 watts of output power, for this example. For a reactor running at one watt of excess output power, this is 7.8×10^{-6} joules/sec/kg. The next line down shows the dosage that an average-sized person would get, if he stood for one hour, one meter away from the LENR reactor, which was running at one watt output power. That person will receive a dose of 0.0281 joules/kg. This unit of joules/kg is also known as a "Gray". One Gray is considered harmful, and five Grays is considered lethal. Most experimental LENR reactors do not run at that one watt of power, and most people do not stand that close to the reactor for that long. Even if they did, this is about $(1/178)^{th}$ of a lethal dose of gamma radiation.

For comparison, consider a hypothetical reactor, wherein the only reaction is $^2D + {}^2D \rightarrow {}^4He$+gamma. Then for one watt of excess power being released, the intensity of gamma radiation would be 2.6×10^{11} gamma rays per second, at an energy of 23.8 MeV. Essentially all of the released energy is gamma; thus, it releases one joule/sec of gamma radiation. The screening of this gamma is much less, due to its very high energy. At 23.8 MeV the screening is negligible, and essentially all of the gamma goes through the apparatus unscreened. For this hypothetical reactor, a human, standing one meter away for a one-hour would receive 2.04 joules/kg from this hypothetical reactor, or almost half of a lethal dose. Fortunately, an actual (non-hypothetical) LENR reactor does not produce this much gamma—due to the behaviors of the primary, secondary, and tertiary reactions that occur within it. Rather, most of the released energy in an actual LENR reactor is kinetic energy of the child particles, which turns into usable heat.

4.2 Summary of Gamma radiation calculations

There are four reasons causing the gamma radiation to be so much lower than the overly-simple calculation:

1. The primary and secondary reaction do not produce gamma radiation.
2. The neutrons that react in the energy range of 14.07 MeV to 5.2 MeV produce only a very tiny amount of gamma radiation. This is because most of the reactions involved within this energy range are endothermic and do not produce gamma radiation.
3. The remaining neutrons, which are at the lower energies, will react in reactions that mostly produce low energy gamma radiation, mostly in the range of 0.447 MeV to 2.224 MeV, rather than producing gamma predominantly in the higher energy range of 23.8 MeV.
4. The intensity of the gamma radiation produced in the reactor apparatus will be screened and attenuated by the materials of the apparatus. These materials, particularly the water bath (or the insulation if that is being used instead), will screen a large percentage of the gammas. Also, if higher density materials—such as lead or steel—are part of the apparatus, they will further attenuate the intensity of the gamma radiation.

Thus, the actual amount of gamma radiation seen from a reactor depends on the output power being generated by that reactor, the size of the apparatus, and the materials contained within the apparatus.

There are very few LENR experiments that have all of the necessary conditions for detecting gamma radiation. If all five of these conditions are not met, then no gamma will be detected. These conditions are:

- The LENR reactor was an electrolytic or gas loaded reactor, using palladium and deuterium.
- There was a large water bath surrounding the reactor, configured in such a way so that there are several centimeters of water between the Pd core and the gamma detector.
- The gamma detector was sophisticated enough to detect high energy gamma, higher than 2 MeV. Unsophisticated or outdated gamma detectors cannot be used.
- The reactor was producing upwards of 100 mW of excess power, determined via calorimetry.

There is no experimental data, to date, that meets the four above criteria of properly detecting gamma radiation. However, there are two LENR experiments, found in the LENR library, that come close. For one, there was no

water between the Pd metal core and the detector, and even the heavy water electrolyte had evaporated off the top part of the Pd metal core [6]. Heavy water, ^2D_2O, does not react with neutrons to produce gamma. Another experiment did not have the gamma detector turned on when the LENR reactor was actively producing heat [7].

This model predicts that if a gamma detector is properly used and the experiment does meet the four criteria, then the gamma flux will be much smaller than what might be expected from a naïve calculation. Also, the gamma energy will be in a much lower in energy. As a result, for a low output power LENR reactor, less than 1 watt, the gamma radiation is far from being a lethal dose.

5. Neutron Detection

In this section, a calculation is made for the number of neutrons that are detected by a typical He-3 detector, but with no moderator tube in front of the detector.

5.1 Geometric considerations

The whole apparatus has a total radius of 33.5 cm from the center of the core to the outer radius. Let's assume that the aperture of the He-3 neutron detector is placed 1.5 cm away from that outer radius, which gives 35 cm for the core-to-aperture distance.

From Table 2 of this paper, the estimated number of neutrons, originally at 14.07 MeV, that escape the apparatus is 3.70×10^{10}. From Table 4, the estimated number of neutrons, there were originally at 2.45 MeV, escape the apparatus is 1.21×10^{9}. The sum of these is 3.82×10^{10}. As mentioned previously, these estimates are calculated for mono-energy collimated neutrons. However, the neutrons coming out of the core are not collimated, rather they are in spherical distribution surrounding the core. If there were a spherical apparatus, rather than cylindrical, then the number that would come out of this spherical apparatus would be the same as that calculated above, 3.82×10^{10}, but the neutrons would be distributed in a sphere rather than a column. For an aperture 5 cm diameter for the neutron detector, the fraction of neutrons that enter the aperture is the ratio of the two areas: the area of the aperture opening divided by the surface area of a sphere with a radius of 35 cm. This is also called the solid angle of the detector opening. For the values of this example, this is shown in Eq. (8).

$$Fraction_{EnteringTube} = \frac{Surface\ area\ of\ aperture}{Surface\ area\ of\ sphere} = \frac{\pi r_{aperture}^2}{4\pi\, r_{sphere}^2} = \frac{2.5^2}{4 \times 35^2} = 784 \qquad Eq.(8)$$

Also, it is assumed that the neutron detector is placed as close as possible to the core, aimed directly at the core, and that it is not oriented at some funny angle, or placed with an offset. Under these circumstances, the fraction of 14 MeV neutrons that enter the neutron detector is $(3.70 \times 10^{10}/784) = 4.72 \times 10^{7}$, for our example cylindrical reactor. (This number of 784 is only for the geometry and distances of this example. Equation 9 shows how to calculate this for other geometries and distance.) Of the neutrons that enter the neutron detector, the number of neutrons that were originally at 14.07 MeV is 4.72×10^{7}, and the number there were originally at 2.45 MeV is 1.54×10^{6}. These numbers are used in calculations below for the determination of how many neutrons are detected.

5.2 Other Factors to Consider for Neutron Detection

The experimenter must check the manufacture's specifications to obtain the number of detected neutrons that are required for one count. This is called the "detection efficiency". Again, the experimenter must obtain this detection efficiency from the manufacturer of the detector. For a He-3 neutron detector, this is the ratio of the number of room-temperature neutrons that go directly into the He-3 gas chamber, compared to the number of counts that the detector produces. If a research paper only describes the number of "counts per second", then that detection efficiency must also be included to convert that value of "counts per second" into the number of room temperature neutrons entering the detector per second. Also, the research paper should include the ratio of the area of the aperture of the moderator tube on the detector and the distance that the aperture opening was from the reactor core, also known as the solid angle subtended by the detector face.

5.3 Considerations of the Moderator Tube

It is recommended that any LENR experiments do not use a moderator tube in front of the neutron detector. If there is historical LENR data that needs to be reinterpreted, data which was taken with a moderator tube in front of the detector, then the data is valuable to prove that neutrons were emitted, however, it is irrelevant in terms of

neutron count. To get a meaningful accurate number of the neutrons that were emitted from the reactor, the experiment would have to be re-done, and the data would have to be re-taken without the moderator tube.

Moderator tubes are no longer recommended for use with a neutron detector for that reason. When trying to detect neutrons, it is recommended that experimenters do not use a moderator tube in front of the neutron detector. A moderator sphere that completely covers the detector may be a more reasonable configuration, and it has the ability to detect more neutrons than does a tube, but the calibration calculations are still more difficult than using a detector without any moderator. The calculations without any moderator between the apparatus and the detector are more straight-forward.

5.4 Moderator Tube Size versus Neutron Detection

The diameter of the moderator tube has a strong effect on the number of neutrons that are able to enter the He-3 gas chamber. Fig. 1 is a Log-Linear plot of the number of neutrons that enter the He-3 chamber versus the diameter of the moderator tube, for 2.45 MeV neutrons.

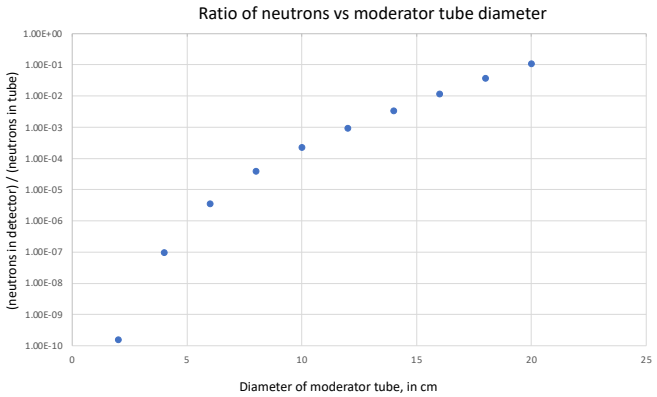

Fig. 1. The $\log_{10}$ of the ratio of the neutrons that enter the He-3 gas chamber divided by the neutron that enter the moderator tube. This is plotted in a log-linear plot, versus the radius of the moderator tube. The ratio changes by over 8 orders of magnitude as the moderator tube radius changes from 2 cm to 20 cm, an enormous variation.

As the radius of the moderator tube changes from 2 cm in diameter to 20 cm in diameter, the number of neutrons that enter the He-3 gas chamber changes by a factor of over 8 orders of magnitude of the 2.45 MeV neutrons, and over 14 orders of magnitude of the 14.07 MeV neutrons. The number of neutrons that pass through the moderator tube and enter the chamber is strongly dependent on the width of the tube. This is an enormously strong dependence on the size of the moderator tube, and it is something that many experimentalists might not consider. This large variation is not due to the solid angle subtended by the moderator tube face, but rather this significant loss is caused by loss due to neutrons scattering within the moderator tube and escaping.

The length of the moderator tube also affects the number of neutrons that are detected, but the dependency is not as strong. If the moderator tube is too short, the neutrons pass right through without being affected. If the moderator tube is too long, the neutrons get stuck in the tube and react, without ever reaching the detector's He-3 gas chamber.

5.5 Variations in Experimental Data.

Regarding the experimental data, there is a large variation for the number of neutrons per watt of excess heat [8]. In this calculation, it has been demonstrated that the number of neutrons detected depends on the geometry of the apparatus, the geometry of the detector placement with respect to the core, the materials within the apparatus, the type of detector, the geometry of the moderator tube, and materials of the moderator tube, and the type, size, and density of gas in the detector's gas chamber. Therefore, unless the apparatuses and the neutron detectors are exactly identical in every aspect, then there would be very little, if any, correlation between excess heat and neutron count. As a result, this analysis predicts a large variation between excess heat and neutron count—in complete agreement with the experimental results. It can now be understood why this large variation exists. This large variation is not due to some as-yet-undiscovered physics occurring inside of an LENR reactor. Rather it is due to the minor and seemingly inconsequential differences in the experimental apparatuses, differences which have a surprisingly strong effect on the neutron detection count.

5.6 The Meaning of Calibration.

Detector efficiency in neutron detectors is defined as the ratio of detected signals to the incident radiation. If no active nuclear fissions or fusions are occurring near the detector, and if an experimenter measures the neutron count under this circumstance, then the measurement consists of two things: the number of background neutrons in the environment and the noise floor electronics in the detector. If an experimenter claims that they calibrated their neutron detector simply by measuring the background neutron radiation, then that is an incorrect claim.

For a proper calibration of a neutron detector, what is needed is to use a neutron source, with a known quantity of neutrons at the expected energy of interest. These neutrons should be emitted in a spherical pattern. Then such neutron source must be placed inside of a typical LENR reactor apparatus. Then the rate of neutron detection from that known source should be measured, using the same detector and moderation tube used in the experiment.

For LENR experiments, no He-3 detectors have been calibrated in this manner. Experimentalists may think that they are calibrating the neutron detector, but all they are doing is measuring meaningless noise. Similarly using neutrons from a radioactive source, such as ^{252}Cf, is not calibration. The neutrons from this source have a range of energies, but most probable energy is 0.7 MeV, much lower than the expected energies, 14.1 MeV and 2.45 MeV, of the neutrons being emitted from the LENR reactor. To properly calibrate the neutron detector, the neutron energies should be the same as those expected from the reactor. Otherwise, the detection efficiency can be off by several orders of magnitude.

Detector efficiency is a crucial factor that is influenced by the detector's material properties, the detector's geometry, and the specific counting setup. It is a complex characteristic that also varies greatly with neutron energy and the overall detection geometry. **A well-calibrated system using known sources, with a known intensity and with the expected energy of the neutrons. This is absolutely necessary for accurate measurements.** Without this proper calibration, the results for neutron detection data are not meaningfully accurate.

5.6.1 Neutron Calibration by EuroFusion Scientists

In 2018, the EuroFusion group, working in conjunction with ITER, performed a proper calibration of a neutron detector, for high energy neutrons. This calibration process required a considerably large amount of research time and money to perform. Fortunately, they scientists at EuroFusion knew that the energy of the neutrons from the reactions would be at 14.1 MeV, and they also knew it is extremely difficult to detect 14 MeV neutrons, thus they did not attempt some poorly-considered overly-quick calibration.

The first task for the EuroFusion group was to build a high-energy neutron generator [9]. The T+D → ^{4}He+n reaction produces 14.1 MeV neutrons. Thus, ideally, the neutron source would be a mono-energy source of neutrons at 14.1 MeV. However, there are no long-lived radioactive materials that decay with such high-energy neutrons, especially with a mono-energy. Thus, they could not simply calibrate the detector using piece of Am-Be in the reactor vessel, as the result would be inconclusive. Rather, the scientists at EuroFusion had to build a neutron generator that produced neutrons with a mono-energy of 14.1 MeV. To do this, they used an ion beam, with T/D beam with a 50/50 ratio, accelerated to an energy of 100 keV. The bean bombards a titanium target containing T/D, also at a 50/50 ratio. This produces beam-target fusion reactions, at 14.1 MeV.

To make sure the neutron generator is producing a constant and steady output of neutrons, multiple monitoring detectors are used: a Single Crystal Diamond Detector with a Si diode, and a set of activation foils. Neutron detection in a Single Crystal Diamond Detector is based on electrons and holes being generated by charged particles in the detector active volume. These charged particles are produced via neutron-induced nuclear reactions on the diamond, ^{12}C. The main reaction is an endothermic reaction: ^{12}C+n → α+^{9}Be, with a threshold energy of 6.18 MeV. This reaction represents a reasonable detection channel for 14 MeV neutrons, since any neutron below the threshold is not detected. The activation foils also use endothermic reactions for detecting the neutrons, employing aluminum, magnesium, iron, and niobium. When a high energy neutron impinges on these foils, the resulting nuclear reaction creates a radioactive element with a relatively short half-life. Upon decay, a gamma is emitted, and the gamma can then be detected. These foil detectors are not real time detectors due to the inherent delay in decay of the radioactive materials.

The monitoring detectors have to be attached to the neutron generator in the same fixed positions during the calibration and characterization campaign, and also during the in-vessel calibration. In this way, the active monitoring detectors can be “absolutely calibrated” in their operating conditions. However, the monitoring detectors will experience a different neutron spectrum during the in-vessel calibration due to the presence of neutrons scattered by the vessel. This effect is taken into account by neutronics simulations to correct for the different operating conditions.

Extensive neutronics analyses were required to derive the needed calibration factors, related to deploying the neutron generator inside the vessel, and to take into account the many particular circumstances of the system. A detailed Monte Carlo simulation was performed.

After successfully building this high-energy neutron generator, they used it to perform an in-vessel calibration of their detector and system [10]. For this calibration, the scientists knew the energy of the neutrons, the flux of the neutrons, and the angular of distribution of the neutrons. The neutron generator was placed inside the actual apparatus, in vessel, to determine how many neutrons were detected by the neutron detectors. Using this information, they were able to determine how many neutrons were emitted, based on the counts in the detector. The answer they obtained was that for every one count from the detectors, approximately 400 million, (4.13×10^8), neutrons were emitted from the source. This is an overall detection efficiency of 2.4×10^{-9} counts per neutron emitted from the reactor. These values are for specialized detectors that were specially constructed for detecting high-energy neutrons. A cheaper detector, such as an He-3 detector, would exhibit an even higher number for the neutrons per count. Furthermore, if a moderator tube is used with the He-3 detector, the number of neutrons/count would be even higher, by several orders of magnitude.

This detailed and extensive procedure is exactly what must be done to determine how many 14 MeV neutrons are actually emitted from a reactor core. There has never been an LENR experiment that has properly calibrated the neutron detectors in this manner.

A simple gamma dosimeter or a simple He-3 neutron detector with a moderator tube is not a valid way to determine the number of neutrons being emitted from a reactor. Rather, the team at EuroFusion spent extensive effort and analysis to calibrate the neutron detectors and determine their efficiency factor.

This extensive and very thorough research, done by the EuroFusion team of scientists for the calibration of a 14 MeV neutron detector, is experimental proof that that high energy 14 MeV neutrons are extremely difficult to detect. Furthermore, the resulting detection efficiency is extremely small, as is predicted. However, the poor detection efficiency is generally not known by non-nuclear scientists trying to perform nuclear experiments. As a result, the LENR community has had a long-held unawareness of exactly how small the detection efficiency is, for 14 MeV neutrons. Furthermore, the LENR experimenters did not expect 14 MeV neutrons to be emitted from a reactor. Nevertheless, this is the energy of the vast majority of the neutrons escaping from the apparatus. For decades, this unawareness has been the most problematic source of confusion for the science of LENR. When an LENR researcher detects one count per second for a reactor running at 1 watt of excess power, this is a commensurate rate of neutron generation within the reactor. While this extremely small detection efficiency is not an intuitive result, the nuclear scientists at EuroFusion knew this. The LENR scientists should pay attention to this result, and understand the implications of it.

5.6.2 Calibration by NASA Scientists

There have been some partially-successful calibration processes done by LENR scientists. The first one to mention was done by the NASA scientists in 2020 [11]. These scientists used two neutron detectors: a stilbene detector and an EJ309 detector. Both of these detectors are much better than an He-3 detector for high energy neutrons. However the NASA scientists did not expect neutrons higher than the 2.45 MeV energy. They were also extremely cautious about any false-positives for neutron detection, and strongly filtered the data to remove any such false positives.

They performed the neutron detection fairly well, breaking down the various factor that might influence the detection. They included the intrinsic detection efficiency and the geometric factors, both of which need to be included. Although the two detectors were capable of detecting neutrons up to 15 MeV, the detection efficiency vs. neutron energy is not a constant, and since they were not expecting 14 MeV neutron, they did not take this into consideration.

Also, they used Am-Be and ^{252}Cf as the neutron sources for calibration, both of which have a wide range of neutron energies, going down as low as 0.1 MeV with the most probable peaks being at a fairly low energy. Because this calibration was not done with a mono-energy neutron source, the detection efficiency that was measured would be over estimated, since it would be skewed for detecting the lower energy neutrons. That factor is difficult to predict, but it probably reduces the actual detection efficiency for 14 MeV neutrons by about 10 to 20.

This neutron detector calibration was one of the better performed by an LENR experimental team, but there were still some imperfections in the procedure. It is not clear in the text that they considered the geometrical factors, which would cause several orders of magnitude lower overall detection efficiency. This team used the stilbene and the EJ309 neutron detector, which are well suited for high energy neutrons, and used Am-Be and 252Cf as their calibration sources. With this set of instrumentation, they determined the overall detection efficiency was 7×10^{-6} and 2 × 10-6 for 2.45 MeV neutrons, for the two detectors. For 14 MeV neutrons, this would be a much lower

detection efficiency. Also, for other types of neutron detectors, such as He-3 detectors, the result would be an even lower detection efficiency by several orders of magnitude.

5.6.3 Calibration by Scientists at Università di Roma

The other partially-successful neutron calibration was done by a team of scientists at the University of Rome [12]. They used an He-3 neutron detector with a spherical moderator surrounding the detector. When performing the calibration, they used a neutron source to measure the detection efficiency, as should be done.

However, they used an Am-Be source for neutrons, which is not a mono-energy source of neutrons, at the expected energy of 14 MeV. The neutrons from an Am-Be source are in a wide range of energies, ranging from 0.1 MeV to 7 MeV, with an average of 4 MeV. Using a neutron source with a wide range of low energies can cause an inherent error in the calculated detection efficiency, especially for a moderated He-3 neutron detector trying to detect 14 MeV neutrons.

To determine the geometric factor, the scientists positioned an Am-Be source at the same distance from the detector as the palladium electrode. However, they did not do an in-vessel calibration. This means that any absorption of neutrons by the apparatus was not considered, thus causing a significant error. However, coming out of the Pd core of the reactor, about half the neutrons are at 2.45 MeV and the other half are at 14 MeV. Most of the 2.45 MeV neutrons are caught in the water bath, and do not emerge from the apparatus. Since this experiment had a water bath, the 2.45 MeV neutrons did not escape, and were not getting detected at all. Essentially all of the detected neutrons are at 14 MeV of energy. However about 90% of these 14 MeV neutrons get absorbed or react in the water bath. Thus, when the experimenters were measuring the detector efficiency without doing an in-vessel calibration, these factors were not taken into account. The calibration needs to be done in-vessel, with the exact some materials between the neutron source and the detector.

Confounding this even more, these 14 MeV neutrons are not detected with the same detector efficiency as the broad spectrum of lower energy neutrons coming from the Am-Be source. Rather, the 14 MeV neutrons, the ones that did escape the water bath, would be detected at a much lower detection efficiency. The 14 MeV neutrons are the ones most likely to emerge from the water bath from an LENR reactor.

This team determined a detection efficiency of 5E-5 counts/neutron for the Am-Be source, or one count for every 20,000 neutrons. This number of 20,000 is much larger than what some experimentalists might expect. Unfortunately, there is an often-made naïve assumption is that one count is close to being equal to one neutron emitted from the reactor—and assumption which ignores the geometrical factor, the detector efficiency, the absorption of neutron by the apparatus, and the large variations of detection efficiency as a function of neutron energy.

5.6.4 Background counts.

Background counts are not a calibration. Rather the background count simply needs to subtract out from the experimental count. Background counts may be neutrons at room temperature, at 0.026 eV, with a cross section that is 38,000 times higher than the 14 MeV neutrons. As a result, almost background thermal neutrons get detected.

Another possibility is that the background counts may be simply the electrical noise of the detector, and it hence has no meaning, other than that it should be subtracted out of the experimental results.

For example, if the detector counted 1 count/second of background neutrons, this is about 1 neutron per second of the thermal 0.026 meV neutrons. And if during the experiment, the detector detected 11 counts, then the actual number of neutrons that these 11 counts represent can be calculated. For 14 MeV neutrons that detection efficiency is smaller by that factor of 38,000. Subtract the one neutron of background from the 11 counts, and that makes 10 counts that were detected during the experiment. For 14 MeV neutrons the detector efficiency is 38000 times lower than for thermal neutrons. In other words, only one out of 38,000 14 MeV neutrons get counted. Here is where confusion often occurs.

The experiment did not detect only 10 neutrons. Those 10 extra counts that occurred during the experiment represent 38,000 times more neutrons than that one background count. The experiment detected 10 counts per second, so 380,000 neutrons, at 14 MeV, entered the detector. If the detector subtends a solid angle of (1/1000)th, then the number of neutrons that escaped the apparatus was 380,000,000 neutrons/sec. If the number of neutrons that escaped the apparatus was only (1/10)th of what was emitted from the core, then the core produced 3,800,000,000 neutrons/second. (For ease of understanding this example, this calculation does not take into account the manufacturer's stated efficiency of the detector for room temperature neutrons, which should also be included as a factor.)

The naïve experimenter might say that the number of counts they detected from the detector was not commensurate with the number of neutrons that should have been emitted from the Pd core. They are mistaken. The core did not just emit 10 neutrons. It emitted 3.8 billion neutrons/second. If the experimenters put a moderator tube in front of the detector, then they would not even measure those few 10 counts per second. The only neutrons that would enter the detector would be the background neutrons, and they would think there were no neutrons being emitted by the reactor. The naïve experimenters would conclude that the LENR reactors do not produce neutrons. For over 35 years, we have been confused about neutron calibration.

5.7 Experimental Evidence of High Neutron Emissions.

There is a large variation of neutron detection values in the LENR experimental data, and as might be expected, there are also experimental validations of high-flux neutron readings. For example, in a summary of LENR experiments by Hagelstein [13], he reports on experiments done by Karabut et al. [14]. In these experiments, the Karabut et al. use a scintillation detector with no moderator. Readings of 10^6 neutrons per second were detected. These experiments involved using a glow discharge to load a Pd foil in D_2 gas, at 10 torr, with a 400 V discharge current. Quoting from Hagelstein:

> "After about 100 seconds after the start of the discharge, neutron emission is observed (a huge signal, reaching up to 10^6 neutrons/sec in some experiments). The neutron detection described in their earlier work was done using RUP-1 silver activated ZnS scintillation detectors and type SNM-18 gas discharge (^{3}He) detectors. The 10^6 (1×10^6) neutron/sec signal appeared in the scintillation detector as 2000 counts/sec at a distance of 1 meter; the signal showed up as 10,000 pulses/second at a distance of 30 cm on the SNM-18 detector. No emission was observed using a hydrogen discharge."

Another example of high neutron detection was recorded by Pam Mosier-Boss [15]. She reports damage to the gamma detectors, caused by excessive exposure to neutrons, which occurred during the experiments. The neutrons flux was not measured, but the gamma flux was measured. Furthermore, the damage to the gamma detectors was caused by the neutrons, during these measurements. Below are quotes from the reference.

> "On 2-28 at 08:30, the 40K line fits to a single Gaussian line. By 2-29 at 11:14, the 40K line has lost intensity and shows a tail on the low frequency side. This peak fits to two Gaussians…. The changes observed in the gamma ray lines are consistent with neutron damage to a HPGe detector."

To clarify, the gamma detector was damaged by an extremely high flux of neutrons as it was attempting to measure the gamma radiation. In trying to determine the energy of the neutrons that caused this damage, the researchers concluded that the damage was caused by neutrons from the uranium calibration material, as well as from neutrons at 2.5 MeV and neutrons at 14.1 MeV. Again quoting from the paper:

> "It is worth noting that the observed PdD spectrum likely consists of fission neutrons derived from the U witness material, and 2.5 MeV DD fusion neutrons and 14.1 MeV DT fusion neutrons."

Thus not only did the researchers find evidence of a large flux of neutrons, but they also found evidence of very high energy neutrons, in the 14 MeV range. These researchers also found other evidence of high energy neutrons, in the CR-39 detectors. Again quoting from the paper:

> "Figure 3.4-8d shows an asymmetric track observed in an Au/U/Pd/D co-deposition experiment as well as a corresponding DT neutron generated asymmetric track. Examples of symmetric triple tracks are shown in Figure 3.4-9. As discussed above, triple tracks in CR-39 detectors are diagnostic of >9.6 MeV neutrons."

As described from this text, the neutron flux was so high that it damaged the gamma detectors. Also, the energy of the neutrons was determined to be higher than 2.45 MeV, which is the for neutrons energy that occur from the $D+D \rightarrow {}^3He + n$ reaction. These high energies of these detected neutrons are a very strong indication that the $T+D \rightarrow {}^4He+n$ reaction was also occurring.

These examples illustrate that when neutron detection is done in a more diligent and correct manner, then high neutron readings can be and have been obtained. If there was a detector that was 100% efficient for all neutron energy ranges going up as high as 14 MeV, and if the reactor was running at one-watt excess power, with a relatively large detector aperture radius of about 20 cm^2, with no moderator tube in between, then the detector

should detect about tens of millions of neutrons/second being detected, maybe even 100's of millions. However, there is no such thing as a neutron detector that is 100% efficient for all neutron energies, going up to 14 MeV neutrons. Nor are the neutron efficiencies the same across the range of energies. For example, if a He-3 neutron detector is 20% efficient for room temperature neutrons, then its efficiency is only 0.000526% efficient for 14 MeV neutrons. Instead of detecting millions of neutrons per second, the detector would detect more like 70 neutrons per second, for a one-watt reactor. This value is well within the range of what is seen experimentally.

5.8 Calculation of Exposure Dosage to Neutron Radiation:

Similar to the calculations for gamma radiation for this example reactor, the calculations for neutron radiation exposure and dosage can be estimated. Referring to Tables 2 and 4, at the bottom right of these tables, is the number of neutrons that escape the apparatus and go into the surrounding air. The number of neutrons that escape the apparatus are 1.78×10^{10} for the 14.07 MeV neutrons and 1.05×10^{9} for the 2.45 MeV neutrons. When these intensities are multiplied by the neutron energies and then summed together, the total neutron energy is 2.53×10^{11} MeV, coming out of the apparatus in a spherical distribution. This is 4.05×10^{-2} Joules. For a human, with an approximate cross sectional surface area 0.5 meter^2, who is standing one meter away from the reactor core, the energy absorbed is 1.61×10^{-3} joules/sec. To convert this to Grays, this value is divided by the mass of an average human being, 70 kg, for an energy of 2.30×10^{-5} joules/kg of body weight per second.

Recall, these numbers are for a reactor running at 3.4 watts of output power. For a reactor that is running at one watt of output power, an average size person, standing for one hour at a distance of one meter away from the reactor, will receive a dose of 0.0244 joules/kg per second. This unit of joules/kg is also known as a "Gray", and 1 Gray is considered harmful. As mentioned earlier, most experimental LENR reactors do not run at that one watt of power, and most LENR researchers do not stand that close to the reactor for that long. Even if they did, this is about 41 times less than a harmful dose of neutron radiation. This is for the parameters of this example reactor. For larger reactors with a high excess output, these calculations must be re-done.

5.9 Summary of Neutron Detection Section:

A low neutron detection count is predicted. In a typical LENR electrolytic reactor apparatus, with a typical He-3 neutron detector and moderator tube, 1.5 trillion neutrons per second are generated for a 3.4-watt output LENR. There is an extremely vast difference between the number of neutrons detected compared to the number that are generated from the reactor core—dependent on the exact apparatus size and materials, the water bath size, and the moderator tube size. Large variations are expected for other sizes and materials.

Previous LENR experiments have not properly calibrated the neutron detectors by using a known quantity of neutrons, at the expected energy of interest, going through the same materials and same geometry of the apparatus.

This lack of proper calibration of neutron detection has been a source of confusion for over 35 years, which has unfortunately spawned many types of unconventional explanations for LENR. These unconventional explanations are quickly discarded, by conventional physicists, as being invalid. This, in turn, has kept LENR as being viewed as a pseudoscience by the conventional nuclear scientists, for over 35 years.

6. Summary and Conclusion

In the companion paper, "A Lattice-Assisted Conventional Explanation for LENR, Part I", conventional explanations, calculations, and equations, were used to determine that a self-sustaining chain reaction was possible in a palladium-deuteride electrolytic low energy nuclear reactor. For that self-sustaining reaction to occur, the palladium lattice played an important role, specifically in separating the relative regions of neutron energy in which electron stopping and nuclear stopping were predominant. With this explanation, all of the so-called "miracles" of LENR are explained.

In the companion paper, "A Lattice-Assisted Conventional Explanation for LENR, Part II" a discussion is made regarding the lattice assistance of the PdD_x lattice for nuclear reactions. Of critical importance is an explanation as to why the cross-over energy of the dominance of electron stopping versus nuclear stopping is shifted in a PdD_x lattice. This cross-over energy is very likely shifted to higher energies, well above 1 MeV. Even at 1 MeV, the self-sustaining reaction within the PdD_x lattice is still able to occur. This Part II paper has provided a detailed mathematical analysis of neutron behavior, a better understanding of the material science of the lattice, and how this lattice environment affects the reaction rates and scattering rates of nuclides. These understandings of neutron behavior and material science are required to understand this LENR phenomenon. If the PdD_x lattice is, indeed, able to mitigate the electron stopping, then no highly unusual or novel physics is needed. When there is assistance from

the material characteristics of the lattice to help with the reaction, Low Energy Nuclear Reactions are theoretically possible and can be understood from an established scientific viewpoint.

This is the third paper in this series of papers, discussing the behavior, characterization, detection, and dosage of neutrons and gamma radiation, specifically for PdD_x electrolytic LENR reactors.

It should be noted that this model does not attempt to analyze or explain all of the various types of LENR experiments that have been performed—for example, gas phase experiments using nickel and hydrogen with no water bath. Other more unusual types of LENR experiments are also not described by this paper, such as cavitation, Lattice Energy Convertors, high-voltage stimulation, or solid-state electrolytes. Rather, the primary intent of this paper is to explain the electrolytic-type palladium and deuterium systems. This paper is meant to provide a quantitative analysis, one that is closely related to conventional physics and explanations than those that have been given for LENR in the past.

The questions of neutron emission and gamma emission were examined, calculated, and discussed. It is confirmed mathematically that a typical LENR apparatus does not emit high quantities of either neutrons or gamma radiation, even though they are both formed within the reactor. Recall that the term "apparatus" includes every part of the experimental setup—the metal core, the surrounding electrolyte, the surrounding water bath, and the borosilicate glass containers around the electrolyte and water bath. Also included is any insulation, wood, aluminum, steel, or other materials in the setup. The "apparatus" is not simply the palladium core, but rather it is anything within the experimental setup that might interact with a neutron or a gamma.

Within the apparatus, the neutrons are scattered, slowed, and absorbed within the typical reactor apparatus before the majority of neutron emission can escape the system. Also, there is only a small fraction of neutron absorption reactions, wherein gamma radiation is released, that occur. Of this gamma radiation, a large fraction of the gamma is absorbed by the apparatus itself.

The absence of neutron and gamma radiation from the reactor apparatus can be explained as being due to neutron scattering, neutron absorption, neutron shielding, and gamma shielding. This exemplification has been done with rigorous and detailed mathematical calculations, involving thousands of computer calculations, in order to make this analysis. This is not a quick or superficial mathematical calculation. Rather the estimated number of neutrons that are emitted is mathematically determined, as well as the estimated gamma radiation intensity. In addition to these rigorous and detailed calculations for neutron behavior, also shown is a graph for the computer calculated behavior of the number of neutrons that might be detected, when using a moderator tube in front of the detector.

The proper understanding of neutron behavior is needed to understand how to optimize an LENR. High-energy neutrons are indeed emitted from the reactions, but they are extremely difficult to detect in a typical LENR apparatus. Only a small percentage of neutrons are able to escape the apparatus and even fewer pass through the moderator tube, if one is used. The results of this mathematical analysis are in good agreement with the LENR experiments, giving a wide variation in the experimental data, with very few neutrons detected.

Reviewing the various aspects of neutron detection and this model:

- This model predicts a very small fraction of the emitted neutrons would escape from the typical reactor, and even fewer will be detected, strongly dependent on the geometry and detector.
- Most experimentalists are quite incorrect in the misconceived belief that neutrons are not released in an LENR reactor. Neutrons are released. They scatter. They slow down. They react. However, they are not easily detected.
- If the neutron detector is not properly calibrated with a known number of neutrons, at the expected neutron energy going through an identical apparatus, then the ability of an experimenter to determine the actual number of emitted neutrons within the LENR is not possible.
- Measuring detector noise or background radiation is not a proper calibration.
- Neutron detection is especially difficult:
    - if the thermal water bath is large
    - if the excess power of the reactor is low
    - if there is an abundance of neutron-absorbing materials in the apparatus.
    - If there is a moderator tube or sphere in front of the detector
- Most LENR experiments have not focused on the accurate detection of neutrons, especially in terms of proper calibration of the neutron detector.

These detailed mathematical analyses predict a large variation in this estimated number, and this large variation is also seen experimentally. The analysis made in this paper indicates that such large variation is due to the strong dependency of neutron detection on the geometry of the apparatus and the exact materials used within it. In the past, this strong dependency might not have been expected or anticipated, especially by experimentalists who do not have

a strong background in nuclear science. As a result, the variations in the geometry and the materials of the apparatus and the detector were not given as much consideration as was needed, in terms of understanding how their nuclear behaviors may affect the outcome.

In conclusion, the lack of neutron detection in LENR experiments has been explained and analyzed mathematically. The science of LENR is real, experimentally validated by hundreds of experiments, and it is explained in the context of lattice-assisted reactions, and conventional nuclear physics.

For the entire series of papers, a model of LENR has been provided, and it is shown that a self-sustaining reaction can indeed occur, by using the released energy of the reactions to deliver enough kinetic energy to the fuel deuterons to overcome the Coulomb barrier, which allows for a subsequent reaction. In order for this to occur, the electron stopping crossover energy must be high enough to prevent the sudden slowing of the energized ions. This is done with only a relatively minor shift in the electron and nuclear stopping curves, relative to each other. This is the assistance from the palladium-deuteride lattice. The resulting high-energy child product neutrons that are emitted from the PdD_x core are not easily detected. Rather the are easily scattered, easily absorbed by the materials in the apparatus, and easily transported through a detector without causing a count.

Thus, a conventional explanation of LENR is given. No novel and unconventional physics are required. The laws of thermodynamics or energy conservation are not broken. No “miracles” remain unexplained. Low Energy Nuclear Reactions are explained using conventional nuclear physics.

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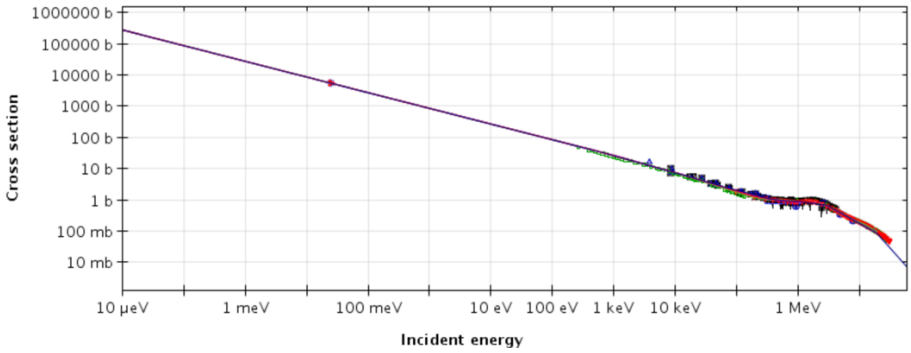
Appendix: Tutorial for a simplified calibration of a He-3 neutron detector.

When not using a moderator tube, there are 4 numbers needed to convert the number of neutrons coming out of the reactor core to the number of neutrons that are detected by an He-3 detector. Using these four numbers, a very good estimate of this conversion factor can be made. An example detector with an example LENR PdD_x electrolytic reactor is discussed.

1.) **The manufacturer's stated detection efficiency of the He3 detector.** This efficiency number is the percentage of room temperature neutrons, that enter the He3 gas chamber, compared to the number of neutrons that actually react in the chamber. This number is typically 20 to 30%. This number varies from detector to detector, and it must be obtained from the manufacturer. For this example, let's say it is 30%, or 0.3 stated as a fraction. The numbers highlighted in bold will be used to determine the total calibration factor.

2.) **The cross-section ratio**. For the reaction of $^3He+n \rightarrow {}^3H+p$ reaction, this is the ratio of the cross section for 14.07 MeV neutrons compared to the cross section of the 26 milli-electron-volts neutrons. Smiilary the ratio of the cross section for 2.45 MeV neutrons to the 26 meV neutrons, for the same reaction.

Notice the log-log scale. There is a huge variation of cross section with regards to neutron incident energy.



Cross section of 14.07 Mega eV	0.140 barns
Cross section of 2.45 Mega eV	0.750 barns
Cross section of 26 milli eV	5300 barns
Ratio of cross sections = 5300/0.140 =	**38,000.**
Ratio of cross sections = 5300/0.75 =	**7,067.**

3.) **The area ratio of the solid angle.** This is the ratio of the aperture area of the detector compared to the surface area of a virtual sphere, with the radius equal to the distance between the core and the detector. The aperture radius, r, is something that must be measured for each He3 detector, since it varies from detector to detector.

$$Area_{aperture} = \pi r^2$$

For this example, let's say the He3 detector has a radius of 1 cm. So the aperture area is 3.14 cm^2. For this example, let's say that the detector is 30 cm away from the Pd core of the reactor. Call this R. The surface of a sphere with this radius R=30 cm, is:

$$Area_{SurfaceOfSphere} = 4\pi R^2$$

For this example, the ratio of areas is = **3,600**.

Note, the equations for these first three numbers are irrefutable. The equations can not be claimed to be incorrect. For different sizes and geometries, the formulas can be used by inserting the numbers for the particular apparatus—radii, detector efficiency, etc.

4.) **Fraction of escaped neutrons.** This last number is the estimate the fraction of neutrons. escaping from the LENR apparatus. For an electrolytic LENR with a water bath, most of the apparatus is water. For this simplified estimate, we ignore the other materials in the apparatus. The equation for the number of neutrons that escape is shown below.

$$Fraction_{that\ escapes} = Exp\left(-(DistanceTraveled_{inWater})/(MeanFreePath_{total})\right)$$

where the total mean-free-path is:

$$MeanFreePath_{total} = \frac{1}{\left(1/MeanFreePath_{reaction}\right) + \left(1/MeanFreePath_{scatter}\right)}$$

As before, these are valid equations, not debatable. The only approximation here is claiming that the reactions are due only to the water bath, thereby ignoring the rest of the set up. However, this is a good approximation.

Here are the experimental cross sections and resulting mean-free paths for 14.07 neutrons water.

- The mean-free path for reactions, $\text{MeanFreePath}_{\text{reaction}}$, is 42.74 cm, at 14.07 MeV.
- The mean-free path for scattering, $\text{MeanFreePath}_{\text{scattering}}$, is 12.46 cm, at 14.07 MeV.
- The total mean free path for water is 9.65 cm.

The shortest distance between the core and the outside edge of the water bath is 30 cm. Using this equation, the fraction that escapes the water bath:

$$Fraction_{\,that\ escapes} = EXP\left({}^{-(30)}\!/_{(9.65)}\right) = 0.0446$$

The fraction that escapes is 0.0446, for this example. However, some of the neutrons scattered. For the ones that scattered, a number of those may escape the apparatus at a lower energy. For a reasonable estimate of that number, let's multiply by 2. (This is based on the more complex calculations in the attached paper.) Thus, it is estimated that the fraction of 14.07 MeV neutrons is 0.0892, that escape the apparatus, **0.09** when rounded.

Repeating this for the 2.45 MeV neutrons:

- The reaction-mean-free path for reactions in water is 260,000 cm, at 2.45 MeV.
- The scattering-mean-free path for scattering in water is 4.95 cm, at 2.45 MeV.
- The total-mean-free-path for 2.45 neutrons in water is: 4.95 cm.
-

$$Fraction_{\,that\ escapes} = EXP\left({}^{-(30)}\!/_{(4.95)}\right) = 0.0023$$

Again, for this rough estimate, this is multiplied this by 2. Thus, it is estimated that the fraction of 2.45 MeV neutrons is **0.0046**, that escape the apparatus in this example.

Now we have all the numbers we need to make an estimate of how many neutrons we will detect. We assuming that one count from the detector electronics is equal to one reaction in the He3 gas chamber. For each count of the detector, the number of neutrons emitted from the core is calculated below:

$$Number_{NeutronsPerCount} = \frac{[(\text{cross section ratio})(\text{area ratio})]}{[(\text{fraction of escaped neutrons})(\text{He3 detector efficiency})]}$$

For this example, number of 14.07 MeV neutrons per count = (38,000)(3600) / (.3) (0.09) = 5.1×10^9 neutrons per count. Said another way, if the reactor core releases 5.1 billion neutrons with an energy of 14 MeV, then only one will be counted. The detector efficiency for 14.07 neutrons is one over this number, 2.0×10^{-10}.

Repeating this for the 2.45 MeV neutrons:

$\text{Number}_{\text{NeutronsPerCount}}$ = [(7067)(3600)] / [(.3) (0.0046)] = 1.8×10^{10} neutrons per count, and the detector efficiency for 2.45 neutrons is one over this number, 5.56×10^{-11}.

If a moderator tube is used, both of these detection numbers are even smaller, by several orders of magnitude, depending on the geometry of the moderator tube. Moderator tubes are not recommended.

For the numbers of neutrons per count, the weighted average of both, is 1.9×10^{10} neutrons per count. In other words, for this example, one count from the detector means that 1.9×10^{10} neutrons were released in the reactor core. The overall detection efficiency is 8.4×10^{-11}.

Note, the equations for these first three numbers of this estimate are irrefutable. Only this last number, the percentage of neutrons that escape, is an estimate. However, this analysis is a relatively good estimate when there is a large water bath surrounding the reactor.

Thus, only a few percent of the neutrons escape the reactor apparatus. Since another apparatus might have a different radius for the water bath or it might use different materials around the reactor, such as polyurethan insulation, then that value and those materials should be used in the formula. If something other than water is used to surround the reactor, then the calculations would involve these other materials and include more details.

The final result, for this example of a typical LENR reactor, is that for every 1.9×10^{10} neutrons released in the reactor, there will be only one count from the detector. If this result is off by a factor of 2 or 3 or even 10, it is not important, compared to the other huge factors involved with detecting high-energy neutrons.

The reason why only a few neutrons are detected is readily seen by this example calculation. For this typical LENR electrolytic reactor, for every 1.9×10^{10} neutrons generated by the reactor, there is only 1 count from the He3 detector. A researcher will only see a few counts per second, for a typical electrolytic apparatus and set-up with no moderator tube or moderator sphere. Experimentally, there is a very large variation in this number, which is of course due to the variations of the setups and detectors.