

# What is real about cold fusion and what explanations are plausible?

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**Abstract.** Experimental observations are now available to test rational theories and models about the cold fusion effect. Some of this information is summarized and used to draw logical inferences. Requirements a plausible theory must meet are suggested and a model based on the role of so-called super-clusters is proposed.

Keywords: Cold fusion, cluster, nuclear reaction, fusion

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## INTRODUCTION

The field of study commonly called cold fusion started in 1989 with the announcement by Profs. Fleischmann and Pons[1] of unusually large heat production in an electrolytic cell containing deuterium. At the time, the reported experimental results were too general to give much confidence in the claims for a fusion reaction between deuterons in palladium. Over the last 20 years, this situation has changed remarkably thanks to steady research in over 8 countries. The question now is which part of this large data set can be believed and used to understand the mechanism that results in fusion and transmutation reactions.

To explain the anomalous results, a successful theory or model must be related to a unique physical and/or chemical environment because the nuclear reaction cannot occur without this condition being present. Once this novel condition forms, a nuclear reaction can release its energy into the environment by several different processes including emission of energetic radiation. This radiation has been difficult to detect because most is absorbed before reaching a detector. Nevertheless, various nuclear products accumulate in the material and these have been detected in significant amounts.

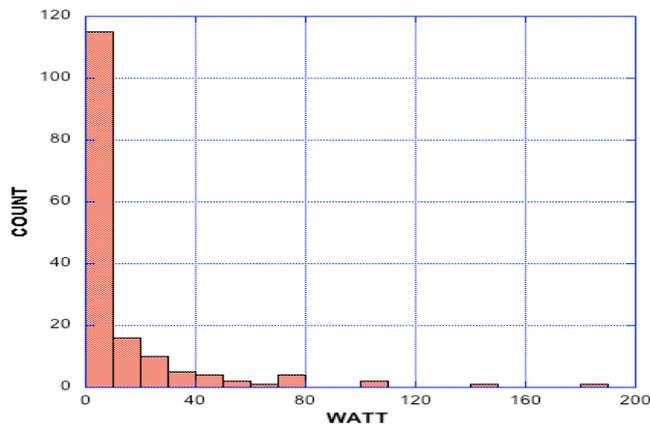
This is not a review or evaluation of proposed theories. Hopefully, the approach used in this paper will encourage theoreticians to evaluate their own ideas. In addition, this paper accepts the effect as being real and is not a critique or review of published work. A few well-documented studies are cited to provide a general understanding of the cold fusion effect. Each of these observations suggests several questions that must be addressed and logically connected by any theory. A mechanism is described that meets this requirement.

## DISCUSSION

Several indications of a novel process have been discovered. These have a range of acceptance and importance, with heat generation being the most accepted and important. However, for this energy to result from a nuclear reaction, nuclear products must be found. At the present time, these products include, helium-4, tritium, transmutation products from various target elements, and energetic radiation. These are listed and discussed in the order of decreasing amount. So far, only helium production is quantitatively related to heat production. Other radiation products may be present in amounts consistent with heat production but are difficult to detect due to their limited range in experimental conditions.

### Heat

Energy production in excess of any known chemical reaction is the major indication of a novel nuclear reaction taking place. The number of successful efforts is too large to list here, but can be found in the book by Storms[2]. The histogram below (Fig. 1) summarizes the amount of heat produced using the electrolytic method pioneered by Fleischmann and Pons. While many studies produced only a few watts of extra power, a significant number produced large and easily measured amounts of power. Furthermore, each paper in the histogram is only counted once even though many successful results are described in each paper. “What kind of reaction can generate MJ of energy in a simple chemical system along with production of radiation and additional elements”? This question is addressed in a later section.



**FIGURE 1.** Histogram of power production from the electrolytic method.

Where in a sample is this energy produced? McKubre et al. used the following equation to describe excess power (EP) obtained from wire cathodes in a Fleischmann-Pons electrolytic cell. [3, 4]

$$EP = M*(x-x_0)^2*(i-i_0)*dx/dt,$$

where  $x_0$  = critical average D/Pd of the bulk cathode,  $x$  = actual average composition,  $i$  = actual average current density,  $i_0$  = critical average  $I/cm^2$ ,  $dx/dt$  = variation in composition. This equation can be expanded by

$M = n * A$  where “A” is the number of nuclear active sites having ‘n’ efficiency.

The heat producing reaction favors locations where the deuteron concentration is greatest, which is affected to some degree by applied current density and rate of composition change. This location exists at the surface of the cathode in an electrolytic cell and on the surface of nanoparticles. The deuterium concentration becomes especially great on the surface of a cathode as the bulk composition approaches unity and on the surface of nanoparticles as they become smaller. In fact, the composition at the surface of a cathode has been measured[5, 6] and the D/Pd ratio is found to be at least 1.5, which indicates the presence of another phase having a perfect lattice D/Pd ratio greater than unity — perhaps as great as 2.[7] Abrupt changes in the temperature coefficient of resistivity at D/Pd = 1 also indicate the presence of another phase having a higher ideal lattice composition.[8, 9] The surface of an electrolytic cathode contains a much greater D/Pd ratio than the bulk material as well as lithium[10] and other advantageous impurities. Consequently, a theory based on  $\beta$ -PdD in bulk material is not addressing the true active environment, which is a complex alloy containing Li, Pd, D and other elements of unknown kind and amount with a very non-uniform distribution. Such surfaces also frequently contain significant oxygen because the stability of the Li-O bond prevents reduction by hydrogen generated at the electrode.

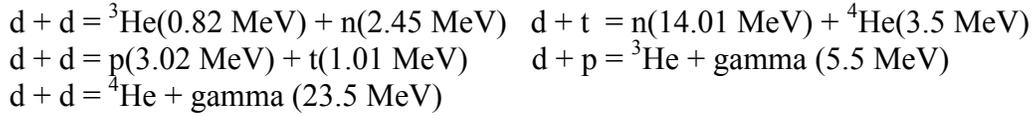
### **Products of Nuclear Reactions**

Although some anomalous energy is produced when ordinary hydrogen[11] or water[12] is used, the d-d fusion reaction has been and continues to be the center of attention. Many laboratories investigating cold fusion searched for products expected from hot fusion, but without success. For example, the expected neutrons are occasionally detected, but these are not associated with heat production either in time or in magnitude. Tritium is occasionally detected in small quantity, but again it is not associated with heat production.

A nuclear reaction between two nuclei must produce at least two products, which are required to carry away the energy and momentum. Fusion reactions involving deuterons are known to result in the paths listed in Table 1, with each producing the required two products. The first two reaction paths are found in equal amount when enough energy is applied to force two deuterium nuclei through the Coulomb barrier, i.e. hot fusion.

According to the third possible reaction path, if helium were formed by a conventional reaction, 23.5 MeV gamma radiation would be produced and easily detected. Failure to find this radiation supported considerable skepticism, but did not stop a search for helium at a few laboratories.

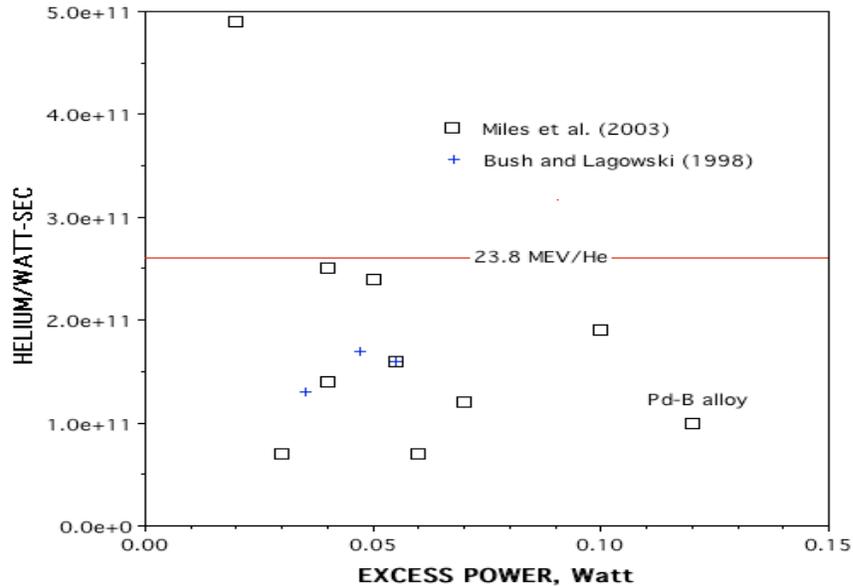
**TABLE 1.** Reactions resulting from fusion involving deuterons



*Helium*

Helium has been detected on many occasions in cold fusion cells, in both the gas and the palladium cathode, and shown to have a relationship to the amount of heat measured. Two independent measurements are compared in Fig. 2. Many other studies show a clear correlation between heat and helium production, but without giving quantitative values. To properly understand these measurements, a few qualifications must be accepted. Only the amount of He released into the gas stream is measured. McKubre et al.[13] and Matsunaka et al.[14] show that this quantity represents only part of the total amount of He produced since it omits any helium captured in the solid Pd cathode. Although the amount captured can be variable, depending on how deep into the surface helium forms, the round number value is about 50%. Both studies compared in Fig. 2 are consistent with this 50% value within expected uncertainty. Taking all measurements into account and applying this potential loss of helium, Storms[2] proposed a value of  $20 \pm 5$  MeV for the energy produced by formation of each helium nucleus, which is consistent with the expected energy produced by a d-d fusion reaction.

Alternative explanations have been suggested that involve addition of deuterons, protons, or neutrons to isotopes of lithium to generate helium. None of these reactions produce enough energy per He atom to be consistent with the measurements.



**FIGURE 2.** Helium atoms/Joule vs Excess power. Two independent studies are compared.

## *Tritium*

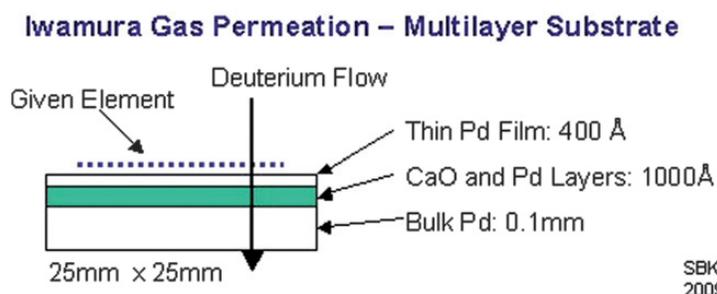
Many examples of tritium production have been reported occasionally in electrolytic cells and during gas discharge,[15, 16] as reviewed by Storms[2]. While more success may have occurred than was reported, because the isotope is seldom measured, production is nevertheless rare. The amount when found is always too small to generate detectable heat, but sufficient to demonstrate an unexpected nuclear process. When the neutron/tritium ratio is measured, it is always found to be very small – in the range between  $10^{-9}$  and  $10^{-6}$ . Consequently, tritium does not result from the normal hot fusion reaction.

Bockris [17] reported interruption of tritium production when the electrolytic cell was shaken, suggesting the source is dendrites on the cathode surface that are removed by agitation. These later reformed to continue production. Surface examination showed deposits of copper from wires within the cell. Claytor et al.[16] have been increasingly successful in producing tritium using pulsed DC discharge between alloys of palladium in deuterium gas. This process is very sensitive to the composition of the alloy and also generates dendrites.

Tritium is unique because it is one of the very rare radioactive elements produced by the process. A useful theory must account for its occasional presence.

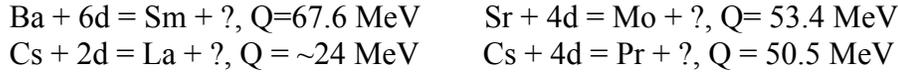
## *Transmutation*

Isotopes and elements not present in the initial environment are reported.[2] While the elements or isotopes may have been present initially as contamination, this argument cannot be applied successfully to all such claims. Two studies stand out in showing that clusters of deuterons might be involved in such transmutation reactions. Iwamura et al.[18-22], in a series of papers, claimed to detect the reactions shown in Table 3. Clusters containing as many as 6 deuterons are required to enter the nucleus as a unit. However, several aspects of this work require explanation. As shown in Fig. 3, the target nuclei are deposited on a 400 Å thick surface layer of palladium which lies on a layer of CaO, a presumed catalyst. How does the cluster get from the catalyst to the target and why do the clusters not react completely with the intervening palladium? How is the significant energy communicated to the environment? Clearly, something must be emitted that is not detected, as indicated by the question mark.



**FIGURE 3.** Simplified cross-section representation of the Iwamura experiment. Figure provided by Steve Krivit.[23]

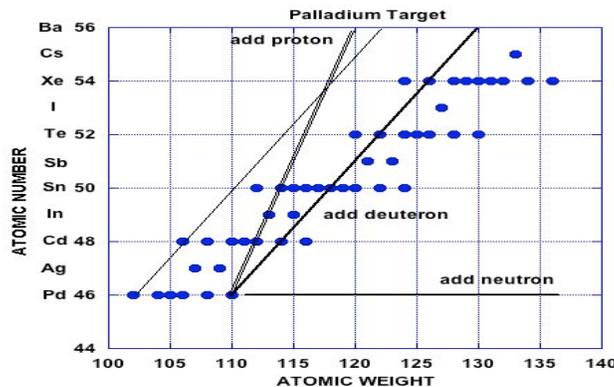
**TABLE 3.** Observed transmutation reactions reported by Iwamura et al.



The second study involves the work of Miley et al.[24, 25]. His experiments employ SIMS, AES, EDX and NAA for analysis. The work is based on the use of thin films of nickel and/or palladium deposited on an inert substrate, with a small amount of platinum as an impurity from the anode and perhaps a little sulfur as an impurity from the electrolyte. The electrolyte contained  $\text{Li}_2\text{SO}_4$  in  $\text{H}_2\text{O}$ . Elemental analysis was made before and after electrolytic action. Although it is safe to assume some of the detected elements resulted either from contamination or from error in analysis, the general pattern appears to be real — showing a region of atoms having high concentration from about mass 106 (Pd) to mass 130; from mass 195 (Pt) to mass 210; and from about mass 25 (S?) to mass 32. The region around nickel (58) shows elements on both the high mass and the low mass sides of this potential target element. Transmutation requires addition of something to the target, which leaves elements on the low-mass side unexplained. Possible addition of neutrons, protons or deuterons to Pd is explored next.

Figure 4 shows the position of the stable isotopes near palladium with respect to their atomic number and atomic weight. If neutrons are added to palladium, the resulting isotopes would follow a horizontal line on the figure and eventually produce beta emitters. These have half-lives that decrease from minutes to milliseconds as more neutrons are added. To produce the observed elements near mass 130, a series of decays from parent to daughter would have to take place over a significant length of time as each isotope decayed to another radioactive isotope with gradually increasing atomic number. In addition, the expected radioactivity is rarely detected even though this would be an easy measurement. Therefore, it is possible to conclude that transmutation does not result from neutron addition from any source.

If protons are added to palladium, the resulting isotopes would follow a line parallel to the one shown on the figure for protons. The mass of the heaviest stable isotope is 114 before unstable isotopes are produced, which is not high enough to explain the full range reported.



**FIGURE 4.** Stable elements as a function of atomic weight and atomic number near palladium. Lines show the result of adding neutrons, protons, or deuterons to palladium.

Only addition of deuterons, as indicated by the line labeled “add deuteron”, results in the full range of observed stable isotopes. This same process can be applied to nickel, platinum and sulfur to give the same conclusion in spite normal water containing only about 7000 ppm deuterium being used. Apparently, only deuterons, regardless of their concentration, produce active clusters.

In the case of elements having a mass lower than nickel, these cannot result from a reaction with deuterons or any other particle. These elements might result from fission of nuclei after addition of deuterons to palladium, as has been suggested by other authors. Because the resulting nuclei are at and near iron, additional energy can be released by formation of these very stable nuclei. Consequently, a certain fraction of nuclei resulting from addition of deuterons to Pd may split into two parts during the transmutation process and may account for the frequent reports of iron on palladium cathodes. The consequence of this proposed process is summarized in Table 5. Since no radioactive isotopes have been found to result from transmutation, it is safe to assume only stable isotopes are formed by the fission process. These are shown in bold. Notice, except for Ag, stable isotopes result only by the addition of an even number of deuterons up to 10. No stable isotopes are formed by larger additions. However, a few unstable isotopes, shown in italic, can release additional energy by splitting into the elements listed at the bottom of the table. In other words, stable isotopes remain whole and certain unstable (radioactive) isotopes fission while conserving total mass and total atomic number. The quantity of each transmutation or fission product is determined by the abundance of the target isotope and unknown selection rules.

TABLE 5. Summary of isotopes made by adding deuterons to palladium.

Element	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe	Cs	Ba	La	Ce
Atomic Number	46	47	48	49	50	51	52	53	54	55	56	57	58
#D	0	1	2	3	4	5	6	7	8	9	10	11	12
Atomic Weight	102	<b>104</b>	<b>106</b>	<i>108</i>	<i>110</i>	<i>112</i>	<i>114</i>	<i>116</i>	<i>118</i>	<i>120</i>	<i>122</i>	<i>124</i>	<i>126</i>
	104	<b>106</b>	<b>108</b>	<b>110</b>	<b>112</b>	<b>114</b>	<b>116</b>	<b>118</b>	<b>120</b>	<b>122</b>	<b>124</b>	<b>126</b>	<b>128</b>
	105	<b>107</b>	<b>109</b>	<b>111</b>	<i>113</i>	<b>115</b>	<b>117</b>	<b>119</b>	<b>121</b>	<i>123</i>	<b>125</b>	<i>127</i>	<b>129</b>
	106	<b>108</b>	<b>110</b>	<b>112</b>	<b>114</b>	<b>116</b>	<b>118</b>	<b>120</b>	<b>122</b>	<b>124</b>	<b>126</b>	<b>128</b>	<i>130</i>
	108	<b>110</b>	<b>112</b>	<b>114</b>	<b>116</b>	<b>118</b>	<b>120</b>	<b>122</b>	<b>124</b>	<b>126</b>	<b>128</b>	<b>130</b>	<b>132</b>
	110	<b>122</b>	<b>114</b>	<b>116</b>	<b>118</b>	<b>120</b>	<b>122</b>	<b>124</b>	<b>126</b>	<b>128</b>	<b>130</b>	<b>132</b>	<b>134</b>
Fission path				Ti+ Co	2 Mn Ti+Ni Fe+Cu	Fe+ Mn	2 Fe	Fe+Co	2 Co	Ni+ Co	2 Ni	Ni+ Cu	2 Cu

#D = number deuterons added

bold – stable isotopes

*italic* – radioactive and produces stable isotopes after fission

**normal** – radioactive and produces radioactive isotopes after fission.

Although this approach does not prove elements near iron result from fission, it does show such a process is consistent with the atomic numbers and weights resulting after deuteron addition to palladium. One of many examples of experimental evidence for this process is shown in Fig. 5, based on an electrolytic study by Mizuno[26, 27] who used a Pd cathode, Pt anode, and an electrolyte containing D<sub>2</sub>O. These elements

are located within a few tens of microns of the surface and seriously hide the underlying palladium.

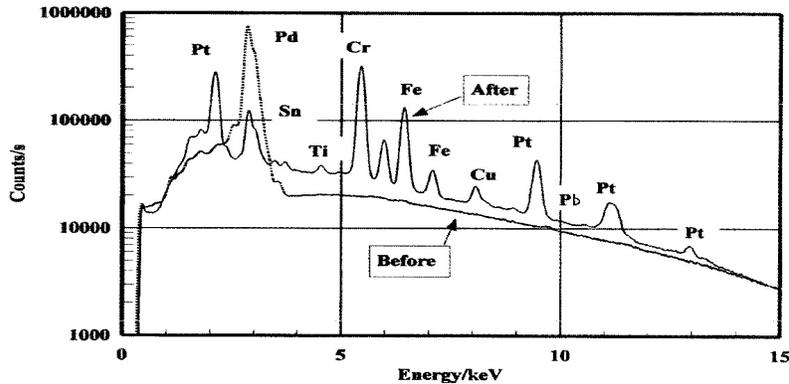


FIGURE 5. EDX examination of a palladium cathode before and after electrolysis.[26]

## Energetic Radiation

Nuclear reactions are expected to produce radiation that can be used to determine the nature of the reaction. For many years, failure to detect expected radiation was a reason for skepticism and frustration. At the very least, X-ray radiation should be detected from the slowing-down process of energetic particle emission and gamma radiation. Both should be detectable well away from the source using simple detectors such as film or Geiger-Mueller counters.

Charged particles have a much shorter range and must be sought very close to the source. Until CR-39 was used, detection was not possible in electrolytic cells although such radiation was found during gas discharge using other kinds of detectors. The apparent absence of such radiation encouraged people to propose mechanisms that did not require energetic emissions. The characteristics of detected radiation must now be examined carefully to determine whether these mechanisms are necessary and to discover exactly how the nuclear energy is dissipated. Because different energy is applied and different detectors are used, radiation from electrolysis and gas discharge will be discussed separately.

### *X-ray emission during electrolysis*

Electrolysis involves so little energy that emission of X-radiation is unexpected, yet such radiation has been reported many times. This provides one more clear indication of a nuclear reaction being the source of the anomalous energy.

X-ray emission from electrolytic cathodes using dental X-ray film revealed a point source that appeared to be well focused.[28] When X-ray energy is measured, the results are consistent with K- $\alpha$  radiation from elements present on the surface along with some Bremsstrahlung.[29-31] The radiation flux correlates with the amount of heat being produced.[32, 33] However, the measured flux is very low, no doubt caused by absorption in the cell wall as calculated by Violante et al.[34] Bursts of radiation reveal the erratic nature of the process, a fact that is not visible in the heat

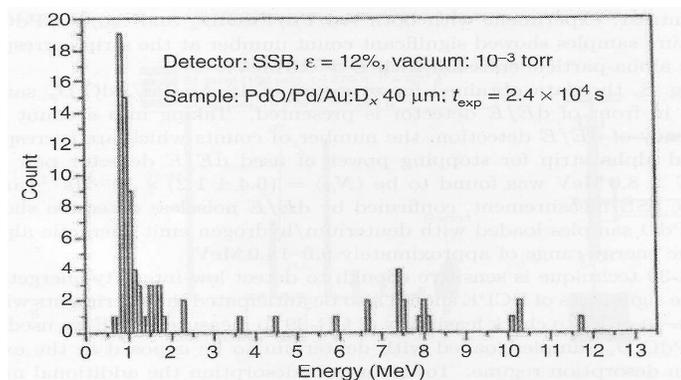
measurement because of the large time constant typical of calorimeters. What process can eject an electron from a K- $\alpha$  state, which for Pd requires about 3 keV.

### *Particle emission during electrolysis*

After many failed attempts, particles of various kinds having a range of energy are found during electrolysis using D<sub>2</sub>O. Because their range is very short, detection requires placing CR-39 very close to the cathode. Passage of energetic particles modifies the plastic, producing a pit where some plastic is dissolved away by concentrated NaOH. The energy and type of radiation can be estimated from the size and shape of the pit.

Mosier-Boss et al.[35] found pits on pieces of CR-39 after they were exposed to radiation from cathodes made of three different metals. Each was subjected to electrolysis in D<sub>2</sub>O + LiCl + PdCl<sub>2</sub> in the same cell while Pd deposited on each metal surface. The front side of the CR-39 shows the effect of what are identified as alpha particles with energy near 1 MeV and pits on the backside are produced by radiation identified as neutrons. The silver cathode (Ag), which readily absorbs neutrons, did not generate radiation that is able to penetrate to the backside.

A cathode was made by oxidizing Pd and plating one side with gold (Lipson et al.[36]). This was reacted with deuterium using the electrolytic method and placed next to a silicon barrier detector while under vacuum. The energy of particles emitted during removal of deuterium is shown in Fig. 6. Notice most particles have energy near 0.7 MeV, with a rapid drop in number at higher values. Lower energies might be present, depending on where the lower detection-limit was set. Some of the peaks near 8 MeV might be caused by radon. Although the particles were identified as alpha, this conclusion is questionable, which also raises doubts about the assigned energy. Nevertheless, the emitted particles appear to have a range of energy with most at low energy.



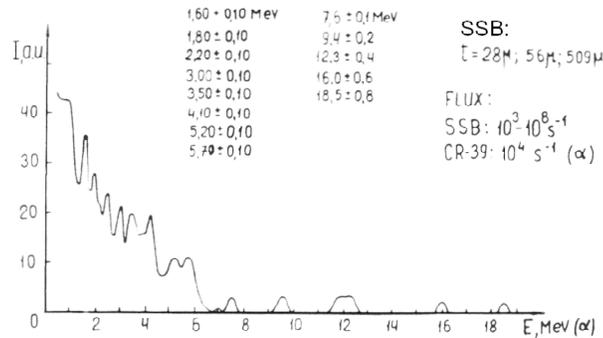
**FIGURE 6.** Particles emitted from PdD as deuterium is removed.

In contrast to evidence for conventional particles having relatively low energy, Oriani and Fisher[37, 38] used CR-39 to detect particles able to cause secondary reactions well outside of the apparatus. These are detected within the electrolytic cell as well as up to 8 cm from the cathode after they passed through electrolyte and glass. As suggested by Kowalski[39], these might be energetic neutral particles emitted from an unconventional source.

### *Particle emission during gas discharge*

Particles emitted from the cathode during and after low-voltage gas discharge in  $D_2$  have been detected using a silicon barrier detector (SBD), from which energy can be determined after the kind of particle is identified using absorbers. Energy is reduced by an amount proportional to the absorber mass-density and the kind of particle being detected. Alphas are easy to identify this way but protons and deuterons are more difficult to differentiate from each other because they have similar absorption characteristics.

Karabut et al.[40] produced a discharge in  $D_2$  using a Pd cathode and less than 500 V. Immediately after the discharge was stopped, the spectrum shown in Fig. 7 was recorded using a silicon barrier detector. The radiation at 3.5 MeV was identified as alpha using absorbers. Presumably, this radiation resulted from d-d fusion as the deuterium content slowly decreased from the level produced by the discharge.



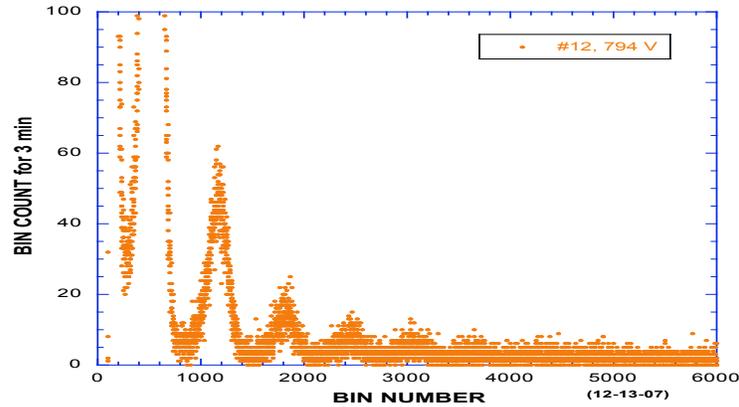
**FIGURE 7.** Energy of particles emitted immediately after discharge in  $D_2$  was stopped. [40]

Too much electrical noise prevented the spectrum from being recorded during discharge. This delayed reaction, so called life-after-death, was explored by Savvatimova[41] by measuring the total current produced by emitted ions and by observing exposure of X-ray film. Evidence for strange radiation having extraordinary penetrating power was also found, similar to reports by Oriani and Fisher,[42] Matsumoto[43], and Lochak and Urutskoev[44].

Storms and Scanlan[45] (Fig. 8) observed an energetic particle spectrum during discharge in  $D_2$  at 794 V using a silicon barrier detector. The particles were tentatively identified as deuterons and distinguished from electrical noise using absorbers. The lowest energy that could be measured was about 0.5 MeV, with decreasing numbers of particles with greater energy, similar to the behavior found by Karabut et al.[40]. The question is, “What process produces this type of energy spectrum”?

## **GENERAL REQUIREMENTS OF THEORY**

A comprehensive theory has been slow to develop because several ad hoc assumptions are required to explain the “impossible”. Now that the field has a large body of experimental data, a rational basis exists to reject or accept many proposed theories. This understanding is summarized below.



**FIGURE 8.** Spectrum of particles emitted during discharge at 794V in D<sub>2</sub>. [45]

The nuclear reactions occur where deuterium concentration is the greatest, which includes the surface of electrolyzing cathodes and the surface of nano-particles of certain metals and alloys. These environments have very little relationship to the properties of  $\beta$ -PdD, which have been used as the basis for many mechanisms. In addition, the nuclear-active environment (NAE) has additional unknown features that allow it to form only rarely.

The major heat producing reaction is unconventional fusion between deuterons to produce helium-4, which can occur at rates in excess of  $10^{12}$  He/second as bursts. Helium results in preference to the other products because a mechanism is available in a solid to dissipate the resulting energy and achieve a product having the lowest energy. The only mechanism available in plasma to create helium requires emission of gamma radiation, which is forbidden. Consequently, the other less-energetic paths are taken because they can use energetic particles to dissipate energy.

Other possible but rare reactions involve additions of multiple deuterons to nuclei of various elements in the NAE, i.e. transmutation and production of tritium. Formation of radioactive elements other than tritium is rare but not impossible. Neutrons do not play a role in these reactions, neither as reactants nor as products. Protons have a limited role and deuterons are the main reactant.

Energy is released from these reactions by energetic particles without gamma emission. The energy of these particles is smaller than expected to result from the proposed source reaction and is too small to allow detection except very close to the source. Some energy might be absorbed directly into the lattice, but this process has no direct evidence and might have no importance once all of the particle emission has been identified. Some of the particles have strange properties and have not been identified.

Regardless of the reaction, the resulting particle energy can produce secondary reactions, resulting in neutron and/or gamma emission, if their energy is above critical values. Failure to detect significant amounts of such radiation indicates existence of a mechanism that can reduce most energies below these values. Measurements show particle energy well below energy released by a fusion or transmutation reaction. This realization places emphasis on the low end of the energy range as location of

important particle energy and indicates need for a process to reduce energy to these values.

A plausible theory must also be consistent with general scientific understanding. To get over a barrier, energy must be concentrated to a level equal to the barrier height. If the concept of tunneling is used, the energy must be high enough to produce the observed reaction rate. Accelerating the nuclei, as used to produce hot fusion, can achieve this result. In contrast, the concentration process in cold fusion has to be done in small steps because so little energy is available in the environment and the overall structure will not tolerate local high-energy. These small steps must involve an exothermic reaction for the process to be spontaneous and must be localized on a group of deuterons, called the active structure (AS). Such a group or cluster is required for multiple deuterons to enter a nucleus at the same time and cause the observed transmutation. This assumption leads to several logical consequences. As energy is lost from the AS, electrons in the AS become more stable, hence increasingly less affected by the presence of a nearby nuclear charge. This allows them to remain fixed in locations, orbits, or energy levels that can hide the combined nuclear charge of the AS. Once this total charge is sufficiently hidden, the AS can approach and enter another nucleus, whether this is a deuteron or a heavier element. In other words, a two-step process is required. The first step involves incremental loss of energy until a special structure is sufficiently stable to overcome a Coulomb barrier. This process gives off energy that accelerates the reaction without requiring additional energy from the environment. Once this structure forms, a nuclear reaction can take place with a large release of energy that further accelerates the process. What type of mechanism might be consistent with these requirements?

## **PROPOSED MECHANISM**

Two basic questions, in addition to the requirements noted above, need to be addressed by any theory. These are, "How can multiple deuterons enter a nucleus with high atomic number and how is the energy resulting from this reaction dissipated into the environment"? One possible answer is the involvement of deuterium clusters in both processes. While involvement of small clusters has been suggested in the past by several authors, this model solves a couple of problems by proposing the clusters have a large number of members. This concept is applied first to the transmutation reaction and then to fusion.

Up to 10 deuterons apparently can enter a nucleus. For this to happen as a single event, all must be at the same place at the same time. This condition describes what can be called a super-cluster. For all members of the cluster to enter at the same time, they must be located close together compared to nuclear dimensions and their nuclear charge must be hidden from the target nuclei. These requirements imply existence of an unusual bonding state that can form within a group of deuterons. The nature of this state will not be discussed here, but will be a subject for future papers.

Clusters of deuterons are proposed to form by an exothermic reaction requiring a catalyst or template. Once the basic structure of the cluster has formed on the surface of this special material, it detaches and diffuses in random directions within the solid lattice. Initially, this seed structure cannot cause fusion or transmutation because it has

not released enough energy. Energy is released in small units as each deuteron is added, causing the effective nuclear charge of the assembly to be hidden by a greater amount. For example, in the Iwamura study, cluster seeds form on the surface of the CaO and these diffused through 400 Å of Pd to the surface where target nuclei have been deposited. During the trip, the seeds grow in number-size as they encounter an increasing concentration of deuterons streaming in the opposite direction. A transmutation reaction is only possible after the number-size has increased enough to hide the nuclear charge of the assembly and to reduce the physical size comparable to that of the target nucleus. Presumably, in the Iwamura study, clusters do not become active until they reach the deposited targets, where reaction with the deposited targets as well as with the much more numerous palladium nuclei become possible. A similar process might occur in studies [46-53] during which deuterium is simply allowed to diffuse through palladium, which produces a small amount of heat and transmutation products.

This special material is rare so that cold fusion occurs infrequently only when and where it is present. The observed delay in starting power production is proposed caused by slow formation of this material and slow growth of clusters to a reactive number-size. The rate of cluster growth is influenced by the concentrations of AS and deuterons. Therefore, nuclear reactions will have the highest rate where deuteron concentration is greatest. This concentration determines how fast cluster size increases and the probability of an active cluster finding a deuteron with which to fuse one of its members.

The AS is slow to form because it is a complex combination of certain atoms that seldom result in the require structure. Several different combinations of several different elements are probably active, all in the form of nanoparticles. Consequently, the NAE is located on the surface of nanoparticles that are formed on a surface or present after having been placed in the apparatus fully formed. Naturally, not all such particles are active. As a result, the amount of power produced by a cell is highly variable, as is observed. Power output will also be highly variable over short and long times, as observed, because active clusters will be destroyed by energy release and new ones will have to form by a random process. The challenge is to identity the nature of the active nanoparticle and to make these in large amounts. Only then can the effect be made reproducible and a source of significant power.

Once a cluster reacts with a target nucleus, how is the considerable energy dissipated? If the cluster has more members than can be fully absorbed by the target, the extra members are proposed to carry away the energy. The number of extra members would have to be large enough so that the energy of each emitted deuteron is too small to cause significant secondary reactions. Furthermore, a transmutation reaction would have to be impossible before this large number had been achieved to prevent this requirement from being violated. Therefore, the nuclear charge must be increasingly hidden as the number increases and a critical number, determined by the charge on the target nuclei, must be reached before reaction is possible.

The probability of a fusion reaction between a cluster and a deuteron is expected increase as number-size increases, resulting in competition between further increase in number-size and the fusion reaction. Therefore, fusion will have a higher rate than does transmutation and compete with transmutation by removing clusters that might

grow enough members to cause transmutation. However, even a fusion reaction will require the cluster to be large enough to avoid secondary reactions. Because a random range of number-sizes are expected to react, energy of emitted deuterons is expected to have a range of values, from ones that are difficult to detect to a few that are energetic enough to produce secondary reactions, similar to the spectrum of particle energy shown in Figs. 6, 7, and 8. This range is expected to be sensitive to conditions and applied energy, which might explain the observed wide range of reported energies for detected particles. Also, some of the emitted particles might be neutral or be a fragment of the original cluster, which would complicate identification and measurement of energy. A cluster fragment, if it retained the unique bonding characteristics, might not be stopped easily by matter and could explain the behavior of the reported “strange” radiation.

The proposed model is still very incomplete and ignores many observations. Nevertheless, the logic suggests a new way to look at the problem that might be helpful in development of more complete models. While many questions remain, the approach has many ways it can be tested and suggests how the cold fusion effect might be increased.

## REFERENCES

1. Fleischmann, M., S. Pons, and M. Hawkins, *Electrochemically induced nuclear fusion of deuterium*. J. Electroanal. Chem., 1989. 261: p. 301 and errata in Vol. 263.
2. Storms, E.K., *The science of low energy nuclear reaction*. 2007, Singapore: World Scientific. 312.
3. McKubre, M.C.H., et al. *Concerning reproducibility of excess power production*. in *5th International Conference on Cold Fusion*. 1995. Monte-Carlo, Monaco: IMRA Europe, Sophia Antipolis Cedex, France.
4. McKubre, M.C., et al., *Replication of condensed matter heat production*, in *ACS Symposium Series 998, Low-Energy Nuclear Reactions Sourcebook*, J. Marwan and S.B. Krivit, Editors. 2008, American Chemical Society: Washington, DC. p. 219.
5. Storms, E.K. *Relationship between open-circuit-voltage and heat production in a Pons-Fleischmann cell*. in *The Seventh International Conference on Cold Fusion*. 1998. Vancouver, Canada: ENECO, Inc., Salt Lake City, UT.
6. Yanokura, M., et al., *An approach to the cold fusion through hydrogen isotopes analysis by the heavy ion Rutherford scattering*. Chem. Lett., 1989: p. 2197.
7. Storms, E. *The nature of the energy-active state in Pd-D*. in *II Workshop on the Loading of Hydrogen/Deuterium in Metals, Characterization of Materials and Related Phenomena*. 1995. Asti, Italy.
8. Spallone, A., et al. *An overview of experimental studies on H/Pd over-loading with thin Pd wires and different electrolytic solutions*. in *11th International Conference on Cold Fusion*. 2004. Marseilles, France: World Scientific Co.
9. McKubre, M.C. and F. Tanzella. *Using resistivity to measure H/Pd and D/Pd loading: Method and significance*. in *Condensed Matter Nuclear Science, ICCF-12*. 2005. Yokohama, Japan: World Scientific.
10. Asami, N., et al. *Material behaviour of highly deuterium loaded palladium by electrolysis*. in *Sixth International Conference on Cold Fusion, Progress in New Hydrogen Energy*. 1996. Lake Toya, Hokkaido, Japan: New Energy and Industrial Technology Development Organization, Tokyo Institute of Technology, Tokyo, Japan.
11. Focardi, S., et al. *Evidence of electromagnetic radiation from Ni-H systems*. in *11th International Conference on Cold Fusion*. 2004. Marseilles, France: World Scientific Co.
12. Mizuno, T., et al., *Production of heat during plasma electrolysis*. Jpn. J. Appl. Phys. A, 2000. 39: p. 6055.
13. McKubre, M.C., F. Tanzella, and P. Tripodi, *Evidence of d-d fusion products in experiments conducted with palladium at near ambient temperatures*. Trans. Am. Nucl. Soc., 2000. 83: p. 367.
14. Matsunaka, M., et al. *Studies of coherent deuteron fusion and related nuclear reactions in solid*. in *The 9th International Conference on Cold Fusion, Condensed Matter Nuclear Science*. 2002. Tsinghua Univ., Beijing, China: Tsinghua Univ., Beijing, China.

15. Alekseev, V.A., et al., *Tritium production in the interaction of dense streams of deuterium plasma with metal surfaces*. Tech. Phys. Lett., 1995. 21: p. 231.
16. Claytor, T.N., D.D. Jackson, and D.G. Tuggle, *Tritium production from a low voltage deuterium discharge of palladium and other metals*. J. New Energy, 1996. 1(1): p. 111.
17. Chien, C.-C., et al., *On an electrode producing massive quantities of tritium and helium*. J. Electroanal. Chem., 1992. 338: p. 189.
18. Iwamura, Y., et al., *Detection of anomalous elements, X-ray and excess heat induced by continuous diffusion of deuterium through multi-layer cathode (Pd/CaO/Pd)*. Infinite Energy, 1998. 4(20): p. 56.
19. Iwamura, Y., et al. *Correlation between behavior of deuterium in palladium and occurrence of nuclear reactions observed by simultaneous measurement of excess heat and nuclear products*. in *Sixth International Conference on Cold Fusion, Progress in New Hydrogen Energy*. 1996. Lake Toya, Hokkaido, Japan: Lake Toya, Hokkaido, Japan.
20. Iwamura, Y., et al., *Detection of anomalous elements, X-ray, and excess heat in a D<sub>2</sub>-Pd system and its interpretation by the electron-induced nuclear reaction model*. Fusion Technol., 1998. 33: p. 476.
21. Iwamura, Y., et al. *Observation of nuclear transmutation reactions induced by D<sub>2</sub> gas permeation through Pd complexes*. in *ICCF-11, International Conference on Condensed Matter Nuclear Science*. 2004. Marseilles, France: World Scientific.
22. Iwamura, Y., et al. *Observation of surface distribution of products by X-ray fluorescence spectrometry during D<sub>2</sub> gas permeation through Pd cathodes*. in *Condensed Matter Nuclear Science, ICCF-12*. 2005. Yokohama, Japan: World Scientific.
23. Krivit, S.B. and J. Marwan, *A new look at low-energy nuclear reaction research*. J. Environ. Monit., 2009. 11: p. 1731.
24. Miley, G.H. and J.A. Patterson, *Nuclear transmutations in thin-film nickel coatings undergoing electrolysis*. J. New Energy, 1996. 1(3): p. 5.
25. Miley, G. *Characteristics of reaction product patterns in thin metallic films experiments*. in *Asti Workshop on Anomalies in Hydrogen/Deuterium Loaded Metals*. 1997. Villa Riccardi, Rocca d'Arazzo, Italy: Italian Phys. Soc.
26. Mizuno, T., *Nuclear transmutation: The reality of cold fusion*. 1998, Concord, NH: Infinite Energy Press. 151.
27. Mizuno, T., et al., *Confirmation of the changes of isotopic distribution for the elements on palladium cathode after strong electrolysis in D<sub>2</sub>O solutions*. Int. J. Soc. Mat. Eng. Resources, 1998. 6(1): p. 45.
28. Szpak, S., P.A. Mosier-Boss, and J.J. Smith, *On the behavior of Pd deposited in the presence of evolving deuterium*. J. Electroanal. Chem., 1991. 302: p. 255.
29. Iwamura, Y., et al. *Characteristic X-ray and neutron emissions from electrochemically deuterated palladium*. in *5th International Conference on Cold Fusion*. 1995. Monte-Carlo, Monaco: IMRA Europe, Sophia Antipolis Cedex, France.
30. Violante, V., et al. *X-ray emission during electrolysis of light water on palladium and nickel thin films*. in *The 9th International Conference on Cold Fusion, Condensed Matter Nuclear Science*. 2002. Tsinghua Univ., Beijing, China: Tsinghua Univ. Press.
31. Bush, R.T. and R.D. Eagleton. *Experimental studies supporting the transmission resonance model for cold fusion in light water: II. Correlation of X-Ray emission with excess power*. in *Third International Conference on Cold Fusion, "Frontiers of Cold Fusion"*. 1992. Nagoya Japan: Universal Academy Press, Inc., Tokyo, Japan.
32. Szpak, S., P.A. Mosier-Boss, and J.J. Smith, *On the behavior of the cathodically polarized Pd/D system: Search for emanating radiation*. Physics Lett. A, 1996. 210: p. 382.
33. Szpak, S. and P.A. Mosier-Boss, *Nuclear and thermal events associated with Pd + D co-deposition*. J. New Energy, 1996. 1(3): p. 54.
34. Violante, V., et al. *Search for nuclear ashes in electrochemical experiments*. in *Tenth International Conference on Cold Fusion*. 2003. Cambridge, MA: World Scientific Publishing Co.
35. Mosier-Boss, P.A., et al., *Detection of energetic particles and neutrons emitted during Pd/D co-deposition*, in *ACS Symposium Series 998, Low-Energy Nuclear Reactions Sourcebook*, J. Marwan and S.B. Krivit, Editors. 2008, American Chemical Society: Washington, DC. p. 311.
36. Lipson, A.G., et al. *Energetic charged particles emission from hydrogen-loaded Pd and Ti cathodes and its enhancement by He-4 implantation*. in *11th International Conference on Cold Fusion*. 2004. Marseilles, France: World Scientific Co.
37. Fisher, J.C. *External radiation produced by electrolysis - A work in progress*. in *8th International Workshop on Anomalies in Hydrogen/Deuterium Loaded Metals*. 2007. Catania, Sicily, Italy: The International Society for Condensed Matter Science.
38. Oriani, R.A. and J.C. Fisher. *Nuclear reactions produced in an operating electrolytic cell*. in *11th International Conference on Cold Fusion*. 2004. Marseilles, France: World Scientific Co.

39. Kowalski, L. *On emission of nuclear particles caused by electrolysis*. in *8th International Workshop on Anomalies in Hydrogen/Deuterium Loaded Metals*. 2007. Catania, Sicily, Italy: The International Society for Condensed Matter Science.
40. Karabut, A.B., Y.R. Kucherov, and I.B. Savvatimova, *Nuclear product ratio for glow discharge in deuterium*. Phys. Lett. A, 1992. 170: p. 265.
41. Savvatimova, I. *Reproducibility of experiments in glow discharge and processes accompanying deuterium ions bombardment*. in *8th International Conference on Cold Fusion*. 2000. Lerici (La Spezia), Italy: Italian Physical Society, Bologna, Italy.
42. Oriani, R.A. and J.C. Fisher. *Energetic charged particles produced during electrolysis*. in *Tenth International Conference on Cold Fusion*. 2003. Cambridge, MA: World Scientific Publishing Co.
43. Matsumoto, T., *Experiments of underwater spark discharge with pinched electrodes*. J. New Energy, 1996. 1(4): p. 79.
44. Lochak, G. and L. Urutskoev. *Low-energy nuclear reactions and the leptonic monopole*. in *11th International Conference on Cold Fusion*. 2004. Marseilles, France: World Scientific Co.
45. Storms, E.K. and B. Scanlan. *Detection of radiation from LENR*. in *ICCF-14*. 2008. Washington, DC: [www.LENR.org](http://www.LENR.org).
46. Li, X.Z., et al. *"Super-absorption" - correlation between deuterium flux and excess heat*. in *The 9th International Conference on Cold Fusion, Condensed Matter Nuclear Science*. 2002. Tsinghua Univ., Beijing, China: Tsinghua Univ. Press.
47. Qiao, G.S., et al., *Nuclear transmutation in a gas-loading system*. J. New Energy, 1997. 2(2): p. 48.
48. Qiao, G.S., et al. *Nuclear products in a gas-loading D/Pd and H/Pd system*. in *The Seventh International Conference on Cold Fusion*. 1998. Vancouver, Canada.
49. Wei, Q.-M., et al. *Element analysis of the surface layer on the Pd and Pd-Y alloy after deuterium permeation*. in *8th International Workshop on Anomalies in Hydrogen/Deuterium Loaded Metals*. 2007. Catania, Sicily, Italy: The International Society for Condensed Matter Science.
50. Tian, J., et al. *Anomalous heat flow and its correlation with deuterium flux in a gas-loading deuterium-palladium system*. in *The 9th International Conference on Cold Fusion, Condensed Matter Nuclear Science*. 2002. Tsinghua Univ., Beijing, China: Tsinghua Univ. Press.
51. Wu, W., et al. *Anomalous heat effect during permeation of deuterium gas through the palladium tube*. in *The 9th International Conference on Cold Fusion, Condensed Matter Nuclear Science*. 2002. Tsinghua Univ., Beijing, China: Tsinghua Univ. Press.
52. Liu, B., et al. *"Excess heat" induced by deuterium flux in palladium film*. in *Condensed Matter Nuclear Science, ICCF-12*. 2005. Yokohama, Japan: World Scientific.
53. Liu, B., et al. *"Excess heat" in a gas-loaded D/Pd system with pumping inside palladium tube*. in *8th International Workshop on Anomalies in Hydrogen/Deuterium Loaded Metals*. 2007. Catania, Sicily, Italy: The International Society for Condensed Matter Science.