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Status of cold fusion (2010)

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Abstract The phenomenon called cold fusion has been studied for the last 21 years since its discovery by Profs. Fleischmann and Pons in 1989. The discovery was met with considerable skepticism, but supporting evidence has accumulated, plausible theories have been suggested, and research is continuing in at least eight countries. This paper provides a brief overview of the major discoveries and some of the attempts at an explanation. The evidence supports the claim that a nuclear reaction between deuterons to produce helium can occur in special materials without application of high energy. This reaction is found to produce clean energy at potentially useful levels without the harmful byproducts normally associated with a nuclear process. Various requirements of a model are examined.

Keywords Cold fusion · CMNS · LENR · Heat production · Transmutation · Review

Introduction

Cold fusion is one name given to a source of energy based on a process similar to nuclear fusion but occurring at low applied energy in special materials. Discovery of the process in 1989 is attributed to Profs. Fleischmann and Pons (F–P) (Fleischmann et al. 1989) while they worked at the University of Utah. Since then, the subject continues to be investigated in more than eight countries and has resulted in several thousand published papers in peer-reviewed journals. Unfortunately, many studies are only available in the

Proceedings of the International Conference on Cold Fusion, thanks to the difficulty in getting such studies published in many journals. The cited conference papers are available as full text at www.LENR-CANR.org and, in some cases, in the bound version published by World Scientific available from www.amazon.com. The field of study, now called condensed matter nuclear science (CMNS), has expanded beyond the knowledge obtained 21 years ago on which most popular opinions are based. A person interested in the subject is invited to read the in-depth discussion and summary of the literature provided by Storms (2007).

The unique process is proposed to involve a reaction between deuterons, resulting in ^4He and small amounts of occasional tritium and neutrons without significant harmful radiation. In addition, reactions can apparently occur between deuterons or protons and various target elements to produce changes in elemental and isotopic compositions, which are called transmutation. All of these reactions are thought to occur on or near the surface of certain special materials containing hydrogen isotopes. In contrast to hot fusion, the process requires very little energy beyond that supplied by the normal environment, although some benefit results from additional energy being applied in various forms.

The process has been initiated using several different methods. Initially, F–P used special palladium as the cathode in an electrolytic cell containing $\text{D}_2\text{O}+\text{LiOD}$. Similar results have been reported using low-voltage gas discharge in D_2 , low-voltage plasma generated in D_2O , bubble collapse on various metals in D_2O using ultrasound, and exposure of various special materials to deuterium gas at modest pressure. Even various single-cell organisms have been reported to produce nuclear products when grown in D_2O as well as in H_2O , but in the latter case with less evidence supporting the claims.

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These reports are difficult to accept, especially when viewed as isolated experiences. But when a large collection of work shows similar and reproducible behaviors, the claims become more plausible even though a satisfactory explanation is still lacking. In some cases, individual studies were done with such care; credible evidence is provided without replication, although replication is required to give the final proof. Even though this is not a complete review of all known behaviors, enough compelling evidence is summarized to support the credibility of some claims, to justify further study, and to show a potential importance to science and industry. In addition, many proposed explanations can be eliminated from further consideration or given increased support by using this published collection of observations. This review is not intended to resolve the ongoing conflict within the field between the various explanations or which dataset should be rejected or accepted. Much more information than is presently available is required to compile a picture most people in the field can agree is correct. Instead, this paper intends to show a fraction of what appears to be sufficiently well supported to encourage further investigation and new thinking about how the process might work. Of course, the opinions are those of the author and do not represent a consensus within the field. As expected, such a young and complex subject generates considerable controversy and debate even among people within the field. Skeptics of the general claims are not the only people who can recognize error and have strong opinions about the cause.

Initially, the claim that a nuclear process is involved was based on the unusually large magnitude of the observed anomalous energy. A search for the required nuclear product was rewarded with helium production being identified as the major reaction. In addition, tritium and neutrons were also occasionally reported along with various transmutation products, showing on some occasions abnormal isotopic composition changes. These nuclear products, while important, are roughly 10^{10} less abundant than helium, making their production a side issue to understanding the main cold fusion process. Radiation with the expected energy and intensity has not been found, although enough radiation of various kinds has been detected to demonstrate unexpected nuclear processes. Just how the observed radiation relates to the measured nuclear products and heat production is still not clear.

Conventional theory is based on experience obtained from the hot-fusion process when initiated using high energy, generally in plasma. This process makes energy by forming tritium and neutrons at equal rates, largely independent of the environment. In contrast, the reaction called cold fusion makes mostly helium, which requires a solid environment to form. A transition between these two types of reaction is expected as applied energy is increased. Consequently, a condition called warm fusion can be

imagined, but this distinction will not be labored here. Suffice to understand that the term cold fusion describes a large number of nuclear reactions having a wide range of rates, with helium production being the reaction having the greatest rate. These reactions are produced at low applied energy only in special environments, called the nuclear active environment (NAE). While features of this environment have been suggested, it has not yet been fully described. At the present time, this concept is used mainly to direct attention to the important role played by the atomic environment. In contrast, hot fusion is not very sensitive to the environment but instead is influenced mainly by the amount of applied energy. Nevertheless, the influence of atomic environment on the hot-fusion process is being explored and will be discussed in a later section as it relates to cold fusion.

Energy from hot fusion is now produced on an industrial scale in plasma (the planned International Thermonuclear Experimental Reactor in France) or by a laser (National Ignition Facility in USA). This arguably well-understood process provides a starting point for discussing cold fusion. The goal is to show that cold fusion has very little relationship to the hot-fusion process, in contrast to the conventional belief. This early and continued coupling of hot and cold fusion has been a major mistake and a source of unwarranted skepticism applied to cold fusion.

Products produced by hot fusion are listed in Table 1 and compared to products found using cold fusion. Different reaction products are expected because two different processes must occur for the Coulomb barrier to be overcome or penetrated. Hot fusion does this by using high energy, i.e. brute force. Cold fusion appears to involve a process similar to that used by a catalyst. Different environments are used, different amounts of energy are applied, and different nuclear products result. Consequently, the observed behavior of hot fusion should not be used to evaluate the expected behavior of cold fusion. These events need to be viewed as being caused by two entirely different kinds of nuclear processes but related to a fusion-type reaction.

Discussion

The various anomalous behaviors are examined, starting with energy production. Energy in this context is considered anomalous if it has a magnitude greater than can be supplied by a plausible chemical source, is produced under conditions that are not expected to result in energy production, or can be correlated with production of a nuclear product, including radiation. Nevertheless, the source cannot be proven to be nuclear without additional information.

Table 1 Reactions that result when D+D fusion occurs

	Reaction	MeV	Hot-fusion fraction	Cold-fusion fraction
Environment: <i>Hot-Fusion</i> plasma or high energy, <i>Cold-Fusion</i> special condensed matter at low energy	D+D= ⁴ He+energy	23.8	<1%(γ -ray)	>99.9%(no γ -ray)
	D+D=Tritium+proton	4.03	50%	Rare
	D+D=neutron+ ³ He	3.27	50%	Extremely rare

Abnormal energy

Energy is measured by first determining the heating power (Watts) using a calorimeter. This power is multiplied by the time during which abnormal power is produced to obtain the energy expressed as Joules. When power is applied to the calorimeter, for example to cause electrolysis or to produce gas discharge, this added power is subtracted, and any remaining power is considered to be abnormal. Energy resulting from known chemical reactions is also taken into account.

What appears to be abnormal energy can result from errors in measuring the power or from unexpected chemical reactions. Evaluation of claims must examine each possibility. Once these errors are understood and eliminated, science requires a claimed phenomenon be replicated with sufficient frequency to eliminate the role of the experimenter in causing the effect. Further confidence in the claim can be obtained if some of the variables that affect behavior show consistent patterns of behavior within and between different studies. Each of these issues will be addressed. Frequent failure to replicate is not relevant because absence of unusual energy can result from lack of knowledge about the necessary conditions or unintentional failure to create these conditions. When the required conditions are identified, success always improves, as studies of this phenomenon have demonstrated. This is why rejection of claims based on negative results is illogical and not useful. Nevertheless, negative results can be used to identify conditions worth avoiding in future studies.

The chemical systems in which the effects are observed are relatively simple, which reduces the likelihood chemical reactions are the source of energy. Nevertheless, contributions by plausible chemical processes during electrolysis were examined by the students of Prof. Bockris at Texas A&M University (Kainthla et al. 1989) and found to be insignificant. Since electrolysis must be continued for a week or more before abnormal heat production begins, some people speculate that during this time, potential chemical energy might slowly accumulate in the cell at power levels too low to be detected. This energy would later be rapidly released and falsely identified as anomalous. Nevertheless, many cold-fusion experiments have produced far more energy and for a longer time than any plausible chemical storage mechanism can accumulate.

The challenge to the initial work of F–P was made easier because they chose a novel type of calorimeter in which the temperature of the D₂O electrolyte was used to calculate the rate of heat flow through the walls of a Dewar-type enclosure. The method was prematurely criticized by Miskelly et al. (1989) by proposing that temperature gradients within the electrolyte invalidated claims for heat production. Later, the method was carefully analyzed by Hansen (1991) at the request of the State of Utah and by Wilson et al. (1992) at General Electric. Both examinations concluded the measurements of F–P were less accurate than claimed but nevertheless showed the presence of a real source of abnormal heat. Other plausible criticisms followed and were answered. Holst-Hansen and Britz (1995) addressed and rejected the possibility that current fluctuations in applied electrolytic power might be mistaken for the apparent energy. Jones et al. (Hansen et al. 1998; Jones et al. 1995) argue that uncertain recombination of the O₂ and D₂ gases generated by electrolytic action is a cause of apparent heat. This idea was rejected by Will (1997) and more recently by Storms (2006). This source of uncertainty is completely eliminated when a catalyst is placed in the cell to recombine all gas, as is now common practice during many successful studies (the electrolytic process produces D₂ at the cathode and O₂ at the anode that must be recombined back to D₂O to keep the chemical energy of this process within the calorimeter. If this recombination is not complete and the amount is unknown, an error will result. Various methods are used to determine the amount of recombination). Storms (2006) addressed and rejected a number of errors proposed by Shanahan (2005, 2006). Most of these initial rejections of claimed anomalous heat now have been answered by using calorimeters with a variety of designs, including isoperibolic, flow, and Seebeck (Storms 2004). No single source of error applies to all methods, which adds credibility when similar results are obtained using different designs, as has been the case.

Mckubre et al. (1994, 1998) at Stanford Research International (SRI) set out to make measurements of heating power so carefully that issue of error in the method would be eliminated. They used a flow calorimeter, shown in Fig. 1, that captured 99.3% of the energy produced in the cell. This high recovery allowed power to be measured based on the flow rate, the heat capacity of cooling fluid, and the change in temperature of the fluid when it passed through the calorimeter, without making corrections for

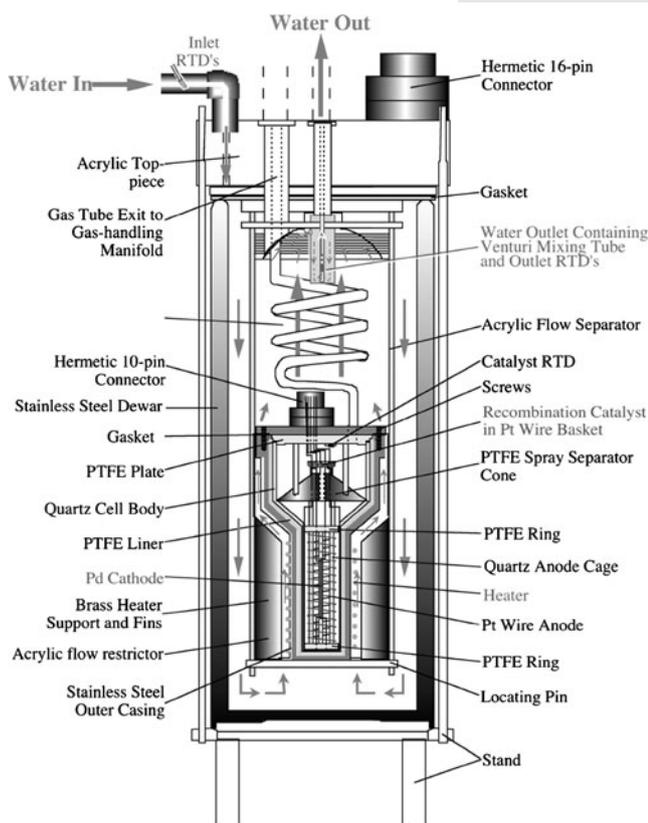


Fig. 1 Flow-type calorimeter used by McKubre et al. (1994) at SRI. The cell was isolated from the atmosphere and contained a recombining catalyst. The average D/Pd ratio was determined by measuring the resistance of the Pd wire cathode. An electric heater kept internal temperature constant and provided a means for calibration

heat losses from the cell. Nevertheless, the calorimeter was periodically calibrated using an internal resistor and the maximum error was determined to be ± 50 mW. In addition to observing abnormal energy well above the expected error from 19 different samples, two important variables were discovered. They observed that the rate of heat production is determined by applied current (Fig. 2) and by the average D/Pd ratio of the cathode (Fig. 3). A similar correlation between these variables and energy production has been observed in every subsequent study done worldwide when such measurements are made. This consistency in the behavior of two independent variables shows that in many cases, the anomalous energy is not the result of error in measurement.

Over the years, many attempts to make energy by the electrolytic process have been attempted with occasional success. Figure 4 shows two histograms showing the number of reported values having the plotted heating power. This representation underreports the total number because only the largest heating power obtained in a study reporting several successes is used. A wide range of heating power is expected because the active samples can be

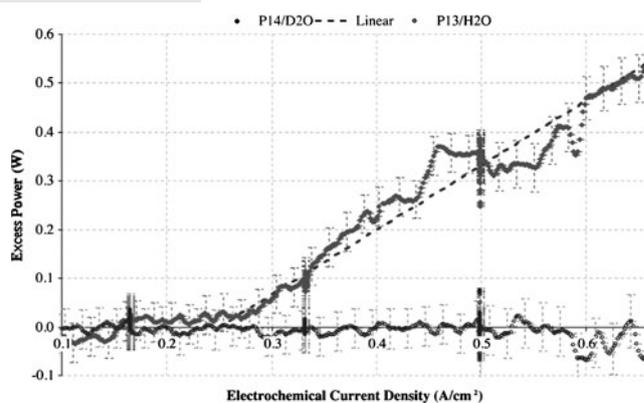


Fig. 2 Effect of current density at the cathode on excess power production. The absence of an effect when D₂O is replaced by H₂O. (Source: McKubre et al. 1994)

expected to contain a variable number of active sites from which the heat originates. Many failures are experienced when no active sites are present, some of which have been reported but most have not. These failures are frustrating and not generally useful unless the reason why active sites were not produced is obvious. Failure to apply electrolytic current for a time sufficient to achieve the required deuterium composition and presence of unwanted impurities known to stop the effect, such as light hydrogen, are two known reasons for failure. Many other reasons are slowly being identified.

The electrolytic method has been shown to produce abnormal energy at the surface of the cathode. This surface is a complex and non-uniform mixture of various materials that are gradually deposited from the electrolyte (lithium, oxygen, deuterium), the anode (platinum (Pt)), and the Pyrex container (silicon and boron). As a result, the required nature of the active material, i.e., the NAE, is not known and is produced largely by chance only in certain locations. The characteristically long delay before abnormal

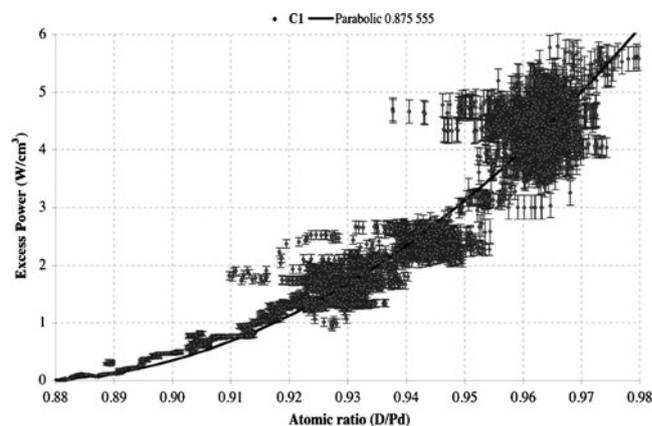
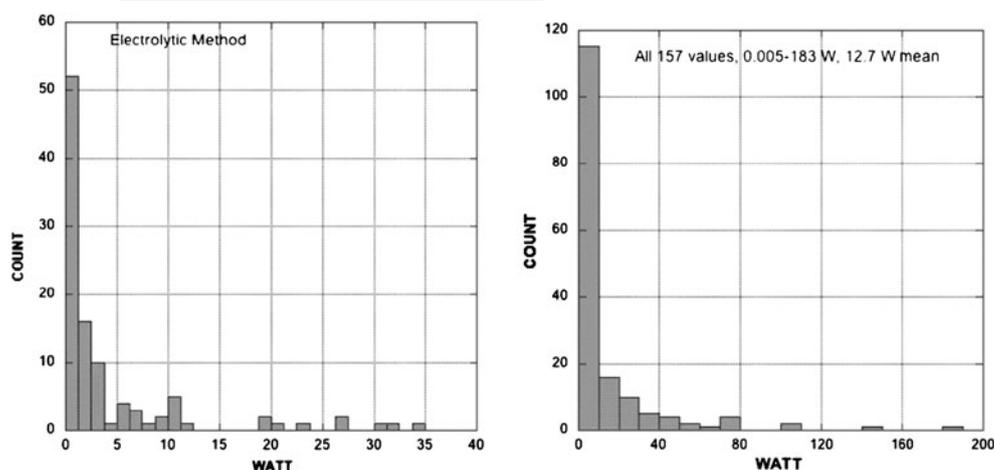


Fig. 3 Relationship between average D/Pd ratio of the cathode and excess power over that applied to the calorimeter. (Source: McKubre et al. 1994)

Fig. 4 Histograms of reported abnormal energy using the electrolytic method (*left*) and 157 values based on all methods (*right*) using data from 1989 to 2004. Note that occasionally, large amounts of power are generated. (Storms 2007)



energy is detected appears to be related to slow creation of this complex layer and subsequent increase in the deuterium concentration at the surface. The required high deuterium content at the surface can only be achieved if the underlying palladium has the exceptional ability to reach an average composition in excess of about $\text{PdD}_{0.85}$. These extraordinary and difficult to create conditions partially explain the frequent failure to replicate when using the electrolytic method. A significant effort by Violante et al. (2008) at ENEA (Italy) in collaboration with the Naval Research Laboratory (USA) was able to produce palladium that has the ability to achieve high loading of deuterium. This material resulted in the expected improved success in making excess power (Dardik et al. 2007; McKubre et al. 2008). In contrast to these usual experiences, Storms (2000) found that a platinum cathode started making extra energy when electrolyzed for a long time in a typical F–P cell, and Swartz and Verner (2003) observed extra energy using clean palladium when the electrolyte was very pure D_2O . These one-of-a-kind experiences further restrict how the nature of the NAE might be described and suggest neither palladium (Storms) nor lithium (Swartz and Verner) is necessary to produce anomalous energy.

Most successful studies using the electrolytic method were applied to palladium wire or sheet. Other methods involving palladium have been also found to work. For example, Arata and Zhang (1999a, b, c, 2000) and Case (McKubre et al. 2000a, b, c) exposed nano-sized palladium to deuterium gas to initiate helium and heat production. Starting in 1993, Arata and Zhang pioneered a study of nano-sized palladium by placing a selected sample of palladium-black in a sealed palladium tube and generating high pressure D_2 gas within the tube by subjecting the tube to electrolysis in $\text{D}_2\text{O}+\text{LiOD}$. As pressure increased, they found anomalous heat and helium to increase. Figure 5 shows the behavior of extra power production as electrolysis continued during which time the internal pressure increased as electrolysis continued. Use of H_2O instead of D_2O did not

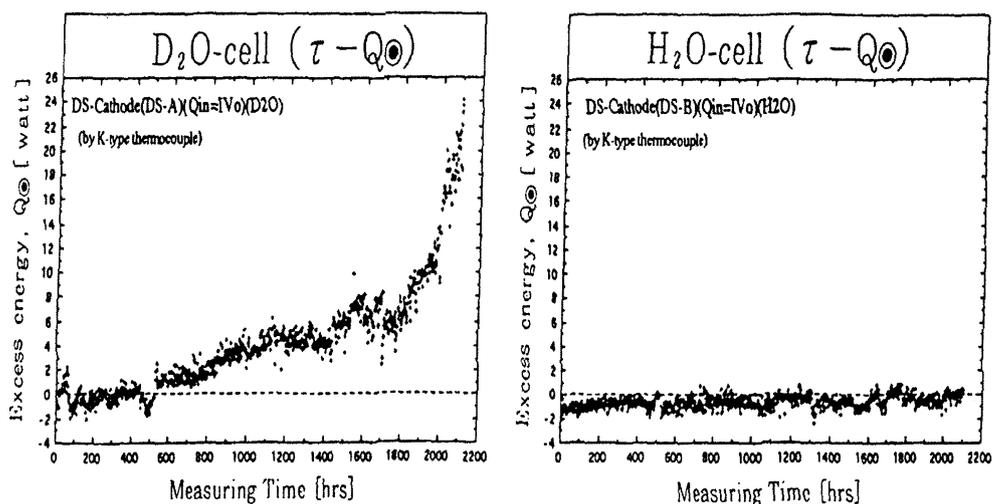
result in abnormal heat, thus eliminating the source being a chemical reaction. The sample was claimed to be active when again exposed to deuterium by the same method even after the container had been stored for years. McKubre et al. replicated this behavior, as shown in Fig. 6, using samples supplied by Arata and Zhang but with a different calorimeter. In this study, current is increased, causing an increase in plotted applied power, which caused an increase in internal pressure, extra energy, and helium. Once again, use of H_2O resulted in no extra energy. As is common in this field, some efforts to replicate this observation have failed.

Arata and Zhang (2002) later explored several methods of making finely divided palladium in a form that would not sinter and become deactivated at higher temperatures as easily as did the palladium-black. A sample made by oxidizing an alloy of $\text{Zr}+\text{Pd}$ is claimed to make anomalous energy when exposed to D_2 pressure. The oxidation process is intended to create isolated nanoparticles of impure palladium within the oxidized zirconium. This and similar materials are being studied in laboratories in China, Japan, and USA.

Case (1998) reported production of extra energy by nano-particles of palladium on the surface of charcoal when the material was exposed to D_2 gas at temperatures up to 175°C . Once again, the nature of the material was very important. McKubre et al. (2000a, b, c) replicated the claims with the help of Case only after an important and previously unpublished pretreatment of the material was used. This experience reinforces the need to work closely with people who have reported successful results when replications are attempted. The gradual increase in extra energy was accompanied by helium production. Other people have failed to replicate this observation using similar commercial catalysts, probably because the required nanostructure was not present; a condition that is very difficult to produce.

These few successful studies of palladium at the nano-size level have opened a new and potentially useful way to initiate the energy-producing reaction and reveal another

Fig. 5 Heat production as pressure is increased over a period of time in a palladium tube containing palladium-black. A flow calorimeter was used. (Arata and Zhang)



important aspect of the NAE. Although too few replications have been successful to have confidence in the importance of the same materials used by Arata–Zhang or Case, interest in the method has encouraged a study of these and similar materials. If the method can be mastered, it would provide a very simple and safe way to produce nuclear energy on a small scale while providing a convenient environment in which to study the mechanism.

Karabut and coworkers at “LUCH” in Russia (Karabut 2005, 2007; Karabut et al. 1991; Savvatimova et al. 2007) have explored low-voltage discharge in deuterium gas for many years and report production of heat, helium, and transmutation products at a palladium cathode. This method gives insight into the role of applied energy in influencing the nuclear process and allows radiation produced by the reaction to be easily explored, as described in a later section. A few partial replications can be cited (Dufour et al. 2000; Miley et al. 2005; Mizuno et al. 1998a,b; Narita et al. 2005; Storms and Scanlan 2007). Claytor et al. (1992, 1996, 1998) have explored tritium production using this method for many years. Success is very dependent on the nature of the palladium alloy used as the cathode and to

some extent by the applied voltage even though this voltage is well below that required to cause hot-fusion or “normal” nuclear interaction. These experiences give additional evidence for initiation of various nuclear reactions at low-energy provided a suitable material is present. Identification of this special material is the main challenge facing science at the present time.

Energy–helium relationship

Fleischmann and Pons initially assumed the observed heating power resulted from one or more of the expected hot-fusion reactions. Gradually, absence of significant neutrons and tritium focused attention on the reaction that produces helium. However, absence of the expected gamma radiation argued against this reaction as the source of energy. Despite this objection, helium was sought and quickly found by Miles and Bush (Bush et al. 1991) in the evolving gas and by Morrey et al. (1990) in the palladium metal. Other measurements have been made since these initial observations with increasing accuracy in measuring the relationship between energy and helium generation.

Helium can be made by several different nuclear reactions besides fusion, as listed in Table 2, so an accurate value for the MeV/He ratio is essential to decide which of these reactions is the main source of energy. Observing an energy–helium relationship in a variety of chemical systems containing different elements also helps in this identification. For example, lithium, which is present in most electrolytic cells, is not present in the environments used by Case, Arata–Zhang, Swartz, or during gas discharge where helium is also produced. This observation reduces the possibility that lithium is a major source of helium and energy. The only elements known to be common to all heat- and helium-producing methods are deuterium and oxygen.

Many people feel that the correlation between heat and helium is the strongest evidence for cold fusion. Errors can

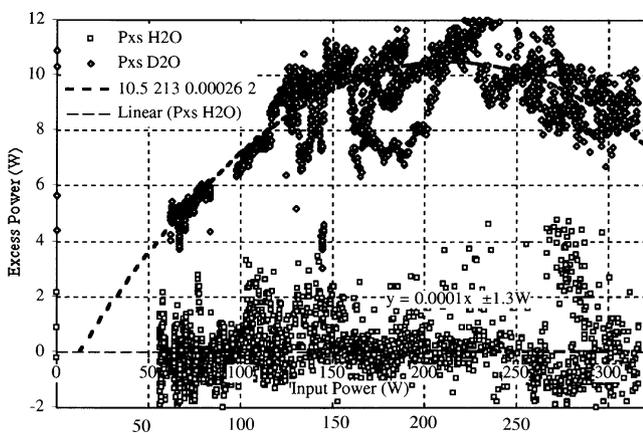


Fig. 6 Replication of Arata–Zhang work by McKubre et al. at SRI

Table 2 Proposed reactions producing helium from materials expected to be present in cold-fusion environments

	Reaction	MeV/He	He atoms/J	
Involvement of neutrinos and radioactive decay products are ignored	$D+D=^4\text{He}+\text{energy}$	23.8	2.6e11	
	$4D=^8\text{Be}=2^4\text{He}$	23.8	2.6e11	
	$D+T=\text{neutron}+^4\text{He}$	17.5	3.6e11	
	$D+^6\text{Li}=^8\text{Be}=2^4\text{He}$	11.2	5.6e11	
	$H+^7\text{Li}=^8\text{Be}=2^4\text{He}$	8.4	7.4e11	
	$2H+^7\text{Li}=^9\text{B}=2^4\text{He}+p$	8.4	7.4e11	
	$n+^7\text{Li}=^8\text{Li}=\text{}^8\text{Be}+\text{beta (13 MeV)}=2^4\text{He}$	13.4	4.7e11	
	$n+^6\text{Li}=T+^4\text{He}$	4.3	14.5e11	
	H proton, D deuteron, T triton	Transmutation	3–6? from alpha	

be made in either the heat or helium measurement, but the energy/helium ratio is extremely unlikely to show a plausible and consistent value. A correlation can be said to exist if helium is detected when extra energy is produced and helium is absent when energy is not produced. The latter condition can also result when the cold-fusion process is not actually initiated, which is often the case. Such studies involving helium are rare because its accurate determination is difficult and requires use of either an expensive mass spectrometer to separate the mass of ^4He (4.002603) from the mass of D_2 (4.028203) and/or equipment to remove all D_2 without changing the helium concentration. Also, the equipment must be air-tight because air contains 5.24 ppm He that can contaminate a sample. Fortunately, an air leak delivers argon along with helium, which can be easily detected. A helium concentration greater than the air background eliminates air as the source, which has been achieved on a few occasions. Overall, 12 correlations and four quantitative studies have been reported as described below.

Miles and coworkers (Bush et al. 1991; Miles and Bush 1992; Miles et al. 1991, 1994) at the China Lake Naval Weapons Center (USA) were the first (1990) to show helium production in an electrolytic cell while it was making energy. Pyrex flasks were used to collect the gases ($\text{D}_2+\text{O}_2+\text{D}_2\text{O}+\text{He}$) evolving from the cell but the resulting values for the amount of helium in the gas were crudely measured. Even so, a clear presence of helium was found when heat was produced and no helium was detected when heat was absent. Although many critiques (Miles and Jones 1992; Miles 1998) were offered at the time to reject the results, subsequent studies support their conclusion that helium is produced by a typical F–P electrolytic cell when it makes extra energy. Additional evidence for an unexpected nuclear process was provided at the time by finding low-level radiation emitting from the cell, as detected using X-ray sensitive film. Similar radiation has been detected during studies in other laboratories using other techniques, as described in a later section.

Chien et al. (1992) at Texas A&M University (USA) electrolyzed palladium as the cathode in D_2O and occa-

sionally found tritium in the electrolyte and helium in the palladium metal at 2–100 times background. When the cathode was cut into different pieces, variations in helium concentration showed a very non-uniform distribution with a maximum of 1.7×10^{11} atoms of helium in a piece cut from a location near the cathode surface. Heat production was not measured.

Karabut and coworkers (Karabut et al. 1992; Savvatimova et al. 1994) at LUCH in Russia studied gas discharge in D_2 using 100–500 V. Heat, radiation, and transmutation products were detected along with an increase in helium at 4–100 times background. Heat production as well as transmutation products were detected during later work, but a quantitative relationship was not reported. This work has continued to the present time with similar results being reported.

Zhang et al. (1992) at universities in Chengdu (China) detected helium in a titanium (Ti) cathode using a Ga^+ ion source for secondary ion mass spectrometry (SIMS) analysis of the surface after the metal had been electrolyzed in D_2O . They used the negative ion spectra to avoid interference by D_2^+ and H_2D^+ . The amounts of heat and helium were found to be related, but a quantitative measurement was not reported.

Stringham (2003) in the USA has developed a novel method to initiate nuclear reactions by subjecting a metal, usually palladium, to intense sonic radiation in D_2O . Plasma of ionized D_2O is injected into the metal surface as bubbles generated by the sonic wave collapse on the surface. Extra heat, transmutation products, and helium as high as 1.2×10^{18} atoms have been detected. A titanium target produced a background level of less than 10^{15} atoms of helium when no extra heat was detected.

Aoki et al. (1994) Univ. of Tsukuba University (Japan) produced up to 27 W in a typical F–P electrolytic cell and the helium was separated from the other gases by gas chromatography. A net rate of production in excess of that produced by cells containing H_2O (as a null) was $(0.5\pm 2.1)\times 10^{10}$ atoms/s when 4.8 ± 0.5 W was produced in the cell containing D_2O . This uncharacteristically low helium

production rate could have resulted from loss of helium in the gas chromatograph column or retention of a greater than normal amount by the palladium, as the authors suggest.

Arata and Zhang (1995a, b, 1996a, b, 1997a, b, 1999a, b, c, 2000) at Osaka University (Japan) pioneered a study of nano-sized palladium powder by placing it in a sealed tube of palladium through which D_2 diffused while the tube was electrolyzed in D_2O , as described in the section about heat production. Helium was detected in the D_2 gas contained in the tube and in the Pd-black. Use of light hydrogen produced no helium. This method has also been found to produce tritium (Clarke et al. 2001; McKubre 2003).

Botta and coworkers (1995, 1996) at Univ. of Torino (Italy) passed current through a palladium sheet in D_2 gas at 2.7 bar while measuring energy and helium. An amount of helium equal to $(5.3 \pm 0.7) \times 10^{18}$ atoms was measured above an undetectable background after excess power was produced. Although a correlation was found between heat and helium, a quantitative relationship was not reported.

Takahashi and coworkers (Takahashi 1998; Isobe et al. 2000, 2002; Matsunaka et al. 2002) at Osaka University (Japan) measured helium production by electrolysis. Four successful runs gave values between 8.8×10^{14} to 7.0×10^{16} atoms with a background of about 5×10^{15} atoms.

Gozzi and coworkers (1993a, b) at Univ. of Rome, La Sapienza (Italy) studied a complex palladium cathode electrolyzed in D_2O , reported first in 1993. A series of papers were published about the same work with a final corrected version provided in 1998 (Gozzi et al. 1998). The data do not allow determination of a quantitative relationship between energy and helium. On some occasions more helium was measured, based on the energy being produced, than would result from a reaction giving the expected value of 23.8 MeV/He. On other occasions, a lesser amount than expected was detected. The helium appeared to be emitted in bursts with a delay after energy was created, which compromised the conclusion.

Apicella et al. (2005) in Italy constructed a very advanced system for analyzing helium and report preliminary values after the cathode in an energy-producing electrolytic was exposed to a laser. The largest value reported is 1.05×10^{16} atoms compared to a background of 0.75×10^{16} atoms of helium. The background is from helium initially present in the mass spectrometer.

De Ninno and coworkers (2004, 2008) at ENEA-Frascati (Italy) electrolyzed a long thin film of Pd deposited on Al_2O_3 . Although only $(8.1 \pm 0.2) \times 10^{14}$ atoms of helium were made, heat and helium were clearly correlated even though the amount of helium measured was about 12 times the expected amount. This difference, as acknowledged by the authors, was mainly caused by difficulties in measuring the correct amount of heat.

The 12 studies summarized above are consistent in showing that helium is associated with energy production when electrolysis, gas discharge, sonofusion, and gas loading are used with deuterium and palladium. A few of these studies could be wrong, but the probability that all 12 are wrong and the apparent correlation is caused by error in each study is very small. The next problem is to determine the quantitative relationship between helium and energy production. Because this kind of measurement is difficult, only a few values are available (Table 3).

Following the first study (Bush et al. 1991; Miles et al. 1993), as noted above, a new study by Miles et al. (1994) was made using stainless steel pipes and an isoperibolic calorimeter, similar to the one used previously. Nine values, including one outlier that is ignored here, were reported. Later, a single palladium cathode containing boron was studied and found to produce helium at a concentration 10 times background (Miles et al. 2000).

Bush and Lagowski (1998) at Univ. of Texas, while collaborating with SRI (USA), report three values using a Seebeck calorimeter and an all stainless steel system. The paper provided insufficient information to check the claimed values, so the values in Table 3 are based on detailed information communicated to Storms by Bush in 1998 (Storms 1998).

McKubre and coworkers (2000a, b, c) at SRI examined the claim made by Case (1998) using a typical but carefully selected sample of commercial hydrogenation catalyst consisting of palladium on charcoal. Extra energy and helium were found when the catalyst was exposed to deuterium gas at 170–250°C and 1–3 atm D_2 . This effect proved to be very sensitive to the nature of the catalyst and the procedure used, which has made the claim difficult to reproduce. An inline, high-resolution mass spectrometer was used to study helium production during the entire run. In most cases, the concentration of helium rose and eventually exceeded that in the laboratory atmosphere. The value listed in Table 3 is based on the average of 13 individual values for helium concentration. The authors conclude:

1. No helium or heat is produced when H_2 is used
2. When D_2 is used, a slow approximately exponential increase in helium concentration with time is observed.
3. Some cells show a delay in helium production followed by an approximately linear increase of helium with time.

Energy production was correlated with helium production using an isoperibolic-type calorimeter from which a MeV/He value of 32 ± 13 was reported based on the differential method of calibration. This is equivalent to $(1.9 \pm 0.8) \times 10^{11}$ He/J as listed in Table 3.

Table 3 Summary of the measured relationship between energy and helium production

Author	Method	Number of values	He/J average	He/J standard deviation
Miles and Bush (1994)	Electrolysis	8	1.6e11	0.7e11
Bush and Lagowski (1998)	Electrolysis	3	1.5e11	0.2e11
Miles et al. (2000)	Electrolysis	1	1.0e11	
McKubre et al. (2000a, b, c)	Gas loading	13 Data points	1.9e11	0.8e11

A measurement involving palladium must take into account the amount of helium retained by the metal when helium is created by an energetic process on or within the metal near its surface. If helium is being emitted as alpha particles or is diffusing in all directions in a random way, approximately one half of the produced helium will move or be radiated toward the interior and be trapped within the palladium. Experience using palladium loaded with ^3He obtained from tritium decay shows that such trapped helium can be removed from the metal only at temperatures near the melting point (Abell et al. 1990; Camp 1977; Chrzan and Wolfer 1991). The other half of the emitted helium would go in a direction toward the electrolyte or surrounding gas and be detected. Such a correction needs to be applied to the values in Table 3 for helium produced by electrolysis. In contrast to the behavior of solid palladium, McKubre was able to coax retained helium out of nano-sized Pd by loading and unloading it with deuterium, which resulted in the expected value for the MeV/He ratio. When corrections for this missing helium are applied to the data in Table 3, Storms (2007) obtained a probable value for MeV/He equal to 25 ± 5 , which is close enough to the expected value of 23.8 to be considered support for a D–D fusion-like reaction being the main source of energy. However, this does not mean the process involves direct fusion of two deuterons to make helium. The process or the mechanism is obviously complex and is not revealed by this measurement.

Production of transmutation products

When one or more deuterons or protons enter the nucleus of an element, the process is called transmutation. Transmutation is observed to occur over a range of energy conditions. These conditions can be assigned to three broad categories, which are (1) low-energy (2) medium-energy, and (3) high-energy. Examples of the first condition are electrolysis, gas-loading, gas-diffusion, low-voltage discharge, and biological. Conventional nuclear reactions result when high energy is applied, some of which are typical of hot fusion. Because these energy regions produce different behaviors, different mechanisms apparently apply and need to be explained separately. The low-energy region typical of cold fusion is discussed first.

Since the very large Coulomb barrier of the target normally prevents such reactions at low energy, the claims have been difficult to accept and explain. Consequently, the experimental results must be examined with care to avoid being misled by contamination or analytical error. However, even though a complete evaluation is not possible in this paper, so many examples of transmutation have been published, as summarized by Storms (2007); the claim must be given serious consideration. A few especially compelling studies are described, and the consequence to theory is discussed assuming transmutation is a real process.

Absolute proof is not yet available because replication is difficult, and many obvious sources of errors torment the measurements. Various methods have been used to determine the presence of these transmutation products, each with its own but different source of error. Consequently, all claims cannot be rejected based on the error in one method, such as the existence of overlapping molecular species when SIMS is used. As will become apparent, the possibility of transmutation being real and related to the fusion process is not as difficult to explain as it might first appear.

The most common target is Pd because this metal is frequently used as the cathode during electrolysis and gas discharge, the two methods most studied for transmutation production. A summary of many reports using a histogram based on the number of reports for each element is shown in Fig. 7. The location of common targets is noted at Pd and Pt, with the Pt being normally transferred to the cathode from the anode. Zinc and copper (Cu) are the most common products followed by iron (Fe), Ti, and aluminum. Radioactive products are seldom found. Copper and iron are common elements in many environments and could result from contamination because they can deposit on the cathode when they are present in the electrolyte. However, zinc and especially titanium and aluminum are not common in the materials used to construct such cells. Surprisingly, all of these elements have an atomic number less than the expected target. This unexpected result is discussed in a later section. In contrast, a few elements heavier than the expected targets are produced, suggesting protons or deuterons could have been added to the target nuclei. Miley and Shrestha (2008) have summarized studies done

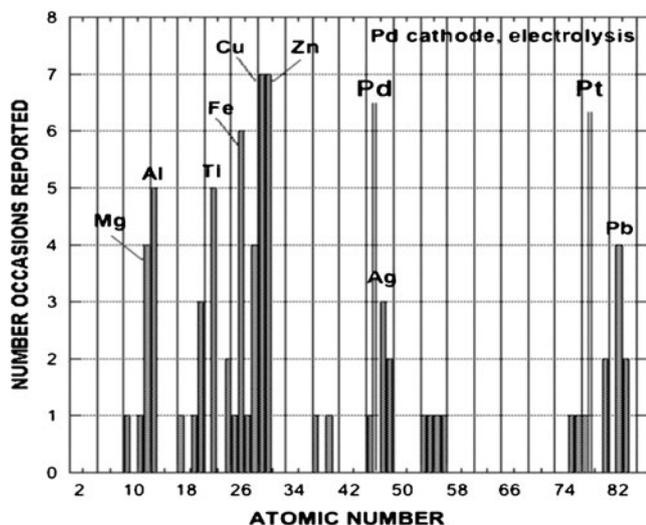


Fig. 7 Histogram showing the number of reports of anomalous elements found on a cathode surface having the plotted atomic number

at the University of Illinois and results obtained by other people. Elements heavier than ten mass units compared to palladium apparently can be produced at detectable concentrations. This mass limit is important as described later.

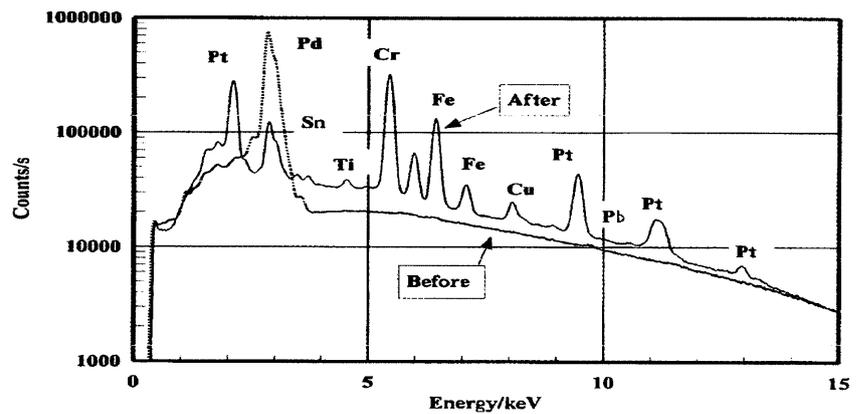
Mizuno and coworkers (1996a, b, 1998a, b) of Hokkaido Univ., Japan, provide an important individual study worth examining in detail because they used very pure and carefully analyzed materials. Electrolysis was done at 150°C under pressure in an electrolyte containing D₂O + LiOH after it had been pre-purified for 7 days by electrolysis using sacrificial platinum electrodes. The stainless steel cell was sealed and protected by a thick coating of Teflon. Electrolysis was continued for 32 days, after which the palladium cathode was analyzed using energy dispersive X-ray spectrometry (EDX), Auger electron spectroscopy, SIMS, and electron probe microanalyzer. Figure 8 shows the result obtained using EDX. The other analytical methods confirmed this analysis and found other elements such as As, Ga, Sb, Te, I, Hf, Re, Ir, Br, and Xe, several of which had abnormal isotopic ratios. A skeptic might find grounds to dismiss many of the claimed transmutations as contamination. For example, the chromium (Cr) and Fe might come from exposed stainless steel. However, this cannot explain the Cu and Ti, which were not found initially in the materials, and which showed abnormal isotopic ratios. This kind of uncertainty reveals the difficulty of arriving at a firm conclusion based on a single study. A final conclusion can only be gradually accepted as many individual studies showing similar results become available from different methods. For example, Karabut (2004) report that the transmutation products shown in Fig. 9 resulted when a palladium cathode is exposed to gas discharge in D₂ using applied voltage between 1,000 and 2,000 V. The collection of elements is similar to those found after electrolysis. Once

again, some elements can be assumed to result from contamination, but not all. In the past, before the cold fusion claims focused attention on such results, all anomalous elements would have been completely ignored as contamination. Perhaps, now, more attention will be given to separating true contamination from products of a nuclear reaction.

An important investigation of transmutation involving chosen targets and careful analysis of the results has been in progress since 1997 at Mitsubishi Heavy Industries, Japan by Iwamura and coworkers (2002a, b, 2003, 2004, 2005). They passed D₂ through a heated (70°C) sandwich consisting of alternating thin layers of CaO and Pd (Fig. 10). Various elements that were previously deposited as a thin layer on the upstream side of the diffusion barrier were found to experience changes in elemental composition as deuterium diffused through the material. These changes were determined in situ and in real time using X-ray photoelectron spectroscopy. As the concentration of the target element decreased, the amount of product element increased. The rate also increased when the sample temperature was increased, resulting in a greater flux of deuterium. In contrast, this effect did not occur when CaO was replaced by MgO or when H₂ was used even though other conditions remained unchanged. The product element resulted from addition of multiple deuterium atoms, with the number depending on the target element. In one case, the amount of ¹³³Cs on the surface decreased at the rate of about 1.9 × 10⁹ atoms/s while the ¹⁴¹Pr increased by about the same rate. Conversion of cesium to praseodymium involves addition of four deuterons with release of 48.4 MeV/Cs. This process would have generated about 0.015 W, which is small compared to most reported values resulting from cold fusion but easily detectable using modern calorimetry. However, no attempt was made to determine the amount of energy produced during this study. Attempts to replicate this work have had mixed success. Takahashi (2005a, b) was able to show conversion of Sr to Mo by diffusing D₂ through a Pd–CaO sandwich on which Sr was deposited, similar to the results reported previously by Iwamura et al. using the same method. Naval Research Laboratory (NRL, USA), in collaboration with Iwamura, failed to achieve what workers at NRL consider to be a replication of the Cs–Pr conversion.

This work is important because it shows that clusters of deuterons are involved in the transmutation process and the cluster contains at least six deuterons. This conclusion is also consistent with many of the reported transmutation results. In addition, the design of the study shows that the required clusters were formed at the CaO layer, and they had to diffuse through 400 Å of Pd in order to reach the target without reacting with the intervening palladium. This requirement reveals important information about the

Fig. 8 Result of EDX examination of a cathode before and after discharge. (Mizuno and co-workers)



process that is discussed in a later section. While the transmutation products typically are detected on the surface during this study, their concentration is not uniform but located at certain sites. Dash (2004) and other investigators have made the same observation about transmutation products being present in special locations when other methods are used. These rare sites apparently contain the special characteristics of the NAE required to initiate a nuclear process.

Starting in 1963, Kervran (1963, 1972, 1980) proposed that living organisms could create elements they needed by transmuting available elements. This idea was widely rejected for lack of believable data and because it seemed impossible. In 1993, Thompkins and Byrd (1993) expanded on the idea in the book “The Secret Life of Plants.” In 1992, Komaki (1992, 1993) at the Biological and Agricultural Research Institute in Shiga-ken, Japan undertook a study of molds and yeasts when the organisms were denied essential elements in their culture. They attempted to determine if the necessary elements could be created by

transmutation. Using modern analytical tools, these living organisms were shown to increase the concentrations of potassium, magnesium, iron, and calcium in their cells over the amounts available. Vysotskii and coworkers at Kiev Shevchenko University, Ukraine (Vysotskii and Kornilova 2003; Vysotskii et al. 1996a, b, 2001; 2008) carried the work further by making Fe⁵⁷ from Mn⁵⁵ when a collection of bacteria were grown in D₂O. The Fe⁵⁷ was detected using the Mossbauer effect, which is uniquely sensitive to this one isotope and could be used to monitor the reaction rate. The process also has been found to accelerate radioactive decay of some elements. Consequently, bacteria are being explored as a way to rapidly decontaminate soil. While such claims are hard to accept, evidence for them is mounting. If real, the claim adds one more process an explanation must address. In particular, an explanation must account for how the resulting large nuclear energy is released without killing the organism; otherwise, the claimed ability obviously could not have been developed by evolution. Further simplification of an explanation can be achieved by assuming the initiation process and the method of energy release used by life forms applies to all cold-fusion reactions regardless of the products or experimental conditions.

The author realizes that many people find a claim for occurrence of nuclear reactions in living cells hard to accept and that many more replications are required before the claim can be fully justified. Nevertheless, the evidence is growing and needs to be debated in the context of cold fusion.

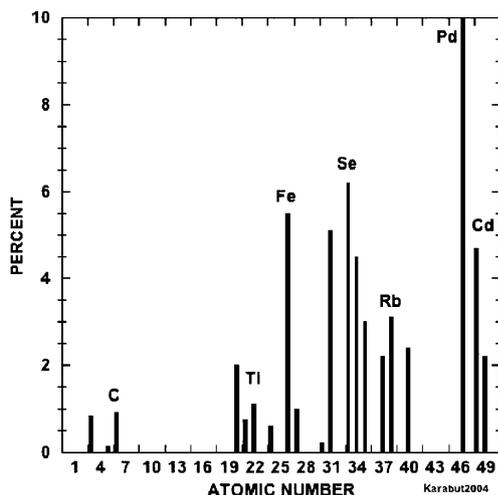


Fig. 9 Elements found on a palladium cathode after gas discharge using 1–2 keV in D₂. (Karabut 2004)

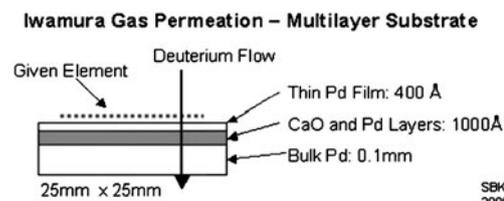


Fig. 10 Simplified drawing (Krivit) of sample used by Iwamura et al.

Production of tritium

Tritium is a radioactive isotope of hydrogen having a half-life of 12.33 years by beta decay. It is rarely produced in cold-fusion environments and has no correlation to heat and helium generation. The largest amount measured in a single study is 10^{16} atoms, (Kaushik et al. 1990; Wolf et al. 1990) which is an amount easy to detect. Most studies report much less (Storms 2007). Tritium is barely detectable in the environment and is not present in palladium (Cedzynska and Will 1992) or cell construction materials. Consequently, its presence cannot result from contamination at the concentration frequently reported. The only process known to increase tritium in an electrolytic cell results from preferential loss of D_2 to the gas, which makes the naturally occurring tritium in D_2O appear to have a higher concentration. Corrections are made for this effect when open cells are used.

Chien et al. (Bockris et al. 1992; Chien and Huang 1992) at Texas A&M University (USA) measured a rate of tritium production equal to 10^8 atoms/s from which power production of 6×10^{-5} W can be calculated from the known value of 4.03 MeV/T, provided the tritium results from D–D fusion. Because this rate of production is typical when such measurements have been made, the result gives an approximate contribution to measured power. Clearly, this small potential contribution to energy production can be safely ignored.

The concurrent neutron flux is more than a million times less than the tritium production rate. Therefore, tritium must be produced without enough energy to initiate a D–T fusion reaction and the resulting neutron. This means the triton does not result from the same mechanism that operates during hot fusion. Tritium has also been detected using ordinary H_2O in electrolytic cells (Notoya 1994; Sankaranarayanan et al. 1996), which suggests a novel production process not requiring more deuterium than contained in ordinary water. Apparently in both cases, a NAE is required and the released energy does not appear mainly as energetic products. This behavior suggests a similar mechanism but one involving different reactants and products.

As is the case with all of the cold fusion reactions, this one is also sensitive to conditions on the cathode surface where tritium originates. These rarely formed conditions handicap a study but are a blessing if cold fusion is used to generate energy, where the presence of tritium would not be welcome, but could be eliminated by preventing formation of the required NAE.

Production of radiation

Radiation is always associated with conventional nuclear processes as the resulting energy and momentum are released

and communicated to the environment. To conserve momentum, conventional nuclear reactions produce at least two products when two nuclei react to cause fusion or transmutation. For example, when two deuterons fuse under hot-fusion conditions to make helium, the second particle is a photon (γ -ray), a product that is not detected when helium is made under cold-fusion conditions. Consequently, it is difficult to explain how helium is made by cold fusion without emission of significant radiation. Hagelstein (Hagelstein and Chaudhary 2008; Hagelstein 1992) and the Chubbs (Chubb 2009; Chubb and Chubb 1991) over the years have attempted to describe mechanisms that might couple the energy and momentum directly to the surrounding atoms in the atomic lattice. However, as suitable detectors have been applied to the problem, some radiation has been detected, consisting mainly of X- and gamma-radiation along with some energetic particles. Consequently, not all energy is communicated to the lattice. This radiation was largely missed in the past because it has low intensity and, in the case of the charged particles, has very limited range.

The energetic particles are now detected using CR-39, a plastic that suffers local damage by passage of a charged particle or neutron. This damage can be revealed as a small pit after suitable treatment, the shape and size of which gives information about the energy and type of particle. Such particle radiation can be detected because the CR-39 allows placement very near the source of radiation. Although the method is immune to many spurious signals, pits caused by chemical attack when the plastic is exposed to certain electrolytes can introduce confusion. In spite of this potential problem, pits caused by particles can be identified and show a wide range of energy values from below 1 to 16 MeV. This amount of energy is less than that produced by the expected source reactions. This conclusion is further supported by Mosier-Boss and coworkers (Mosier-Boss et al. 2008; Szpak et al. 2009) at the SPAWAR Systems Center in San Diego. They used CR-39 having a thickness of about 1 mm to observe energetic particle radiation with energy determined to be near 1 MeV, resulting when palladium was plated from palladium chloride on various metal cathodes in the same cell. The two sides of a piece of Cr-39 are shown in Fig. 11. All of the cathode materials generated radiation that made pits on the front side and, in two cases, on the back side as well. When the deposit was applied to a silver cathode, no radiation originating from the silver penetrated through the plastic to the backside. Radiation reaching the backside had the characteristics of neutrons having energies up to 14.1 MeV (Mosier-Boss et al. 2010) even though neutrons are not expected to result from a cold-fusion reaction. Since CR-39 accumulates the effect, the flux and the time during which this radiation was produced are impossible to determine. Nevertheless, these and similar observations

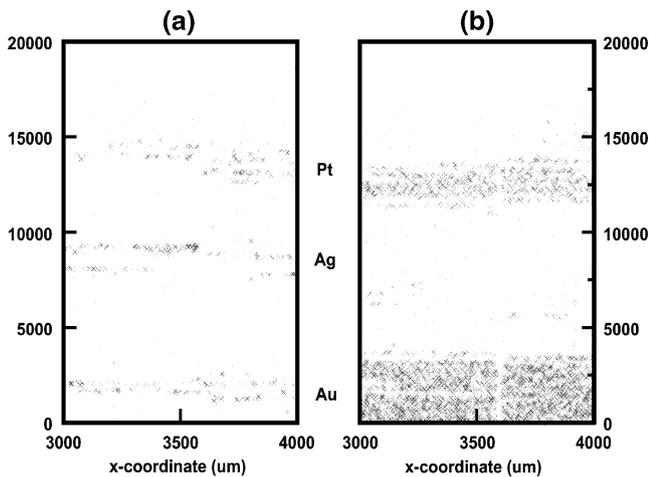


Fig. 11 Front side (a) and back side (b) of CR-39 exposed to an electrolytic cell while palladium is plated on different metal wires. The radiation produced at the silver cathode did not penetrate through the plastic. The images were made by computer analysis of the surface. The front-side tracks in some areas were too copious for computer recognition

reveal release of some energy as energetic particles. Still unknown is the relationship of this radiation to heat+helium production.

Radiation with unexpected properties has been detected, which adds another curiosity to the process (Lochak and Urutskoev 2004; Matsumoto 1993; Oriani and Fisher 2004; Savvatimova and Dash 2002). These claims raise a question about how much of the detected radiation is a new kind or simply results from changes in conventional radiation. For example, if the emitted nuclei are not missing their electrons as is normally the case, i.e. are neutral, they will interact with detectors in unexpected ways. These possibilities need to be considered when studies are made of the radiation.

Theory and explanations

If the observations described above are basically correct, how can they be explained? Since 1989, hundreds of attempts have been published (too many to discuss in detail here). At the risk of ignoring clever and potentially important insight, only the most general ideas are included. The first step is to identify the basic requirements a useful mechanism must have. These requirements allow some proposed explanations to be rejected outright while others can be explored in more detail.

To participate in a nuclear reaction within a solid, a deuteron must appear to have a greatly reduced nuclear charge when viewed from the nucleus of another element. Many ways have been proposed to achieve this condition. For example, electrons might concentrate between the nuclei to hide the charge, local energy might push the nuclei through the barrier (tunneling); wave-like behavior might lower the effective nuclear charge; an electron might

enter the deuteron to make a dineutron; Bose–Einstein condensates of nuclei might form, thereby allowing the strong force to operate between the nuclei; or clusters of atoms might form in which the bonding electrons could hide the nuclear charge. If transmutation is accepted, the mechanism must be able to cause fusion to make helium as well as react with other elements. This requirement places severe limits on proposed mechanisms unless several independent mechanisms occur, which, in view of the unique requirements, seems unlikely. But, this requirement is only part of the problem.

When a deuteron reacts with a target nucleus, considerable energy is released and only one nuclear product can be clearly identified, i.e. the resulting new element. Since a single product is not able to carry away the resulting energy and momentum, this momentum and energy must be communicated to other particles. The energy of these particles must be in range limited by the measured values and by energy too small to make detectable secondary reactions, as evaluated by Hagelstein (2010). Details are provided by Hagelstein in Vol. 3 of JCMNS (<http://www.iscmns.org/CMNS/publications.htm>). Secondary reactions, if they occur, can be detected because the reaction products have enough energy to leave the system and become visible to conventional radiation detectors. These requirements mean that the 23.8 MeV generated by formation of helium must be communicated to many atoms immediately upon its release. Mechanisms to directly communicate energy to the lattice have been suggested (Chubb 2009; Chubb and Chubb 1991; Hagelstein and Chaudhary 2008), but clearly, these processes do not transfer all energy because some energetic particles are detected. It is still too early to know how much of the resulting energy is emitted as particles, many of which might defy present detection methods. Nevertheless, clearly, the energy resulting from helium formation is distributed, not as gamma emission as produced during hot fusion but as disturbances within the NAE and as ejected energetic particles. Just how this process operates remains to be discovered.

If clusters are involved, how might they reduce the energy of emitted particles and couple energy to the lattice? Storms and Scanlan (2010) and Toimela (2004, 2007) provide similar answers that require assumptions be made about the size of the cluster and its characteristics. If the cluster contains more deuterons than are able to react with the target, the remaining deuterons might participate in release of energy by being accelerated away from the reaction site, as shown in Fig. 12, by a mini-explosion. Each additional deuteron would carry away its fraction of the nuclear energy and momentum either as an ion or neutral fragment of the original cluster. While this mechanism has not been explored in detail, it is consistent with the observations and allows clusters to be involved in the entire process from lowering the Coulomb barrier at the start of process, as described

above, to dissipating energy as particles after the reaction has occurred. In contrast to this proposal, Miley et al. (2007) with various co-authors propose the process involves creation of a large nucleus at 306X126 by addition of a large cluster to a target element. This resulting nucleus is proposed to fragment into all the observed isotopes by a complex fission reaction. The challenge for the physics community is to explain how a cluster having the required properties and large size can form. At the present time, the Rydberg cluster (Åman and Holmlid 1992; Badiei et al. 2009; Bendkowsky et al. 2009) is known to have some of the properties required of this process.

The difficulty in replication can be used to reject the claims as being impossible or it can be used instead to show that rare and difficult to create conditions are required to initiate the nuclear reactions, the so-called NAE. The latter belief will be accepted here for the sake of further discussion. Consequently, success is related more to understanding how materials science applies to the processes than to a model based only on nuclear physics. Apparently, once the required conditions are created, the nuclear process occurs without further assistance. A search for these special conditions thus becomes the goal without a need to first understand the subsequent nuclear process. In other words, in this case, chemistry leads and physics follows in the effort to make the effect larger and more reproducible.

This means a proposed mechanism must acknowledge the atomic structure. In the past, attention has focused on the atomic structure of beta-PdD (fcc) containing a high

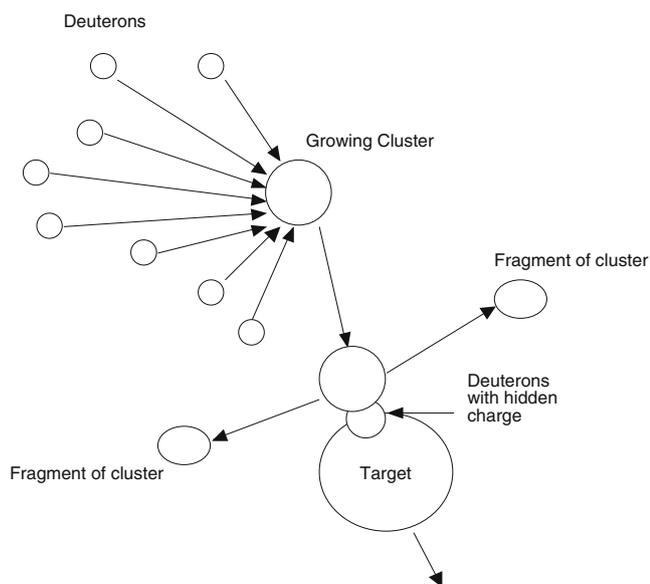


Fig. 12 Growth and destruction of a cluster causing transmutation. The cluster is proposed to grow on the surface of special materials until it contains over 100 deuterons, a few of which enter into nuclear reactions. The many fragments produced by a nuclear reaction between the target and part of the cluster can contain one or more deuterons with zero to many missing electrons. The circular shape of the cluster is for illustration purposes only

concentration of deuterium. However, the surface of electrolytic cathodes, where the nuclear reactions are now known to occur, is a complex alloy containing sometimes a minor amount of palladium. In addition, the recent discovery that nano-size is important has shifted attention to the surface of particles where the atomic arrangement of unexpected absorbed elements can be very complex. This new understanding further restricts the kind of mechanism that is consistent with observation. When this requirement is added to the other requirements discussed above, the required conditions become sufficiently well defined to allow most suggested mechanisms to be rejected. Even the mechanisms that remain after this evaluation involve “miracles” that need to be resolved before the field can advance. An additional review is required to address this problem.

Many ideas suggested during the early history of the field are best ignored because they were based on too little experimental information and too little consideration about the novel relationship between hot and cold fusion. Preparata (1991, 1993) and Rabinowitz (1993) have done a good job of evaluating many of these ideas. Takahashi (2005a, b) has reviewed more recent attempts and summarized experimental information needing explanation.

For the sake of history, the model proposed by Fleischmann et al. (1994) is worth examining in detail. These authors made the following assumptions as quoted from their papers:

1. Deuterons in β -PdD are “virtually” unbound, act like classical oscillators, and form clusters or ordered domains containing perhaps three members in the lattice, especially at high D/Pd ratio.
2. Special domains are anticipated to form dense plasma in which energy can concentrate by collective oscillations.
3. A hot-fusion-like, many-body reaction is proposed to occur, from which neutrons and tritium are expected to result.

Preparata (1993, 1994) refined the theory to include the following assumptions as paraphrased from his paper:

1. Condensed matter contains “ensembles of identical charge and mass oscillating around equilibrium positions with a typical frequency.”
2. Electrons entering the palladium lattice with the deuterons are “delocalized,” allowing them to occupy the volume between the positive deuterons.
3. The deuterons occupy octahedral and tetrahedral positions where they form local regions of coherent plasma.
4. The deuteron plasmas at two adjacent sites interact and the intervening electrons cause enough screening to allow fusion between adjacent deuterons to occur.

In other words, the process is proposed to involve a process that concentrates both energy and electrons and this combination provides the necessary shielding of the

Coulomb barrier. This approach has been expanded by at least 75 published papers by various authors describing various forms of electron screening and concentration of energy.

Several very important facts are ignored when models based on the local concentration of energy and/or electrons are proposed. First, Nature resists the spontaneous concentration of energy. This conclusion is contained in the Second Law of Thermodynamics, one of the cornerstones of modern science. Second, most electrons in a solid lattice of atoms are arranged so as to create a stable structure. When this arrangement is changed, the structure is affected and will change. This change will absorb energy, thereby resisting the proposed change in the electron concentration or energy. In other words, the chemistry of the system will resist changes required by such models, unlike conditions in plasma on which hot-fusion theories are based. A successful model for overcoming the Coulomb barrier must describe a process that does not change the basic electron structure or overall energy within the lattice to avoid these conflicts with universal experience. This requirement suggests formation of the NAE is a spontaneous process that precedes the nuclear reactions after suitable elements have been properly assembled. Details of its form determine which nuclear reaction will be permitted. The number of such sites in a material determines the gross rate of each reaction and the heat flux resulting from the sum of these reactions. Consequently, the wide range of measured power results because the material contains different amounts of the NAE, not because the material has a different physical volume or area as first proposed. Presumably, only a very small amount of NAE is present in active material. The challenge is to increase the amount without increasing the gross size of the supporting material.

The recent and well-demonstrated work of Iwamura et al., described above, has directed attention toward the role of clusters. Success would appear to depend on having conditions that allow these clusters to form. Several processes and environments have been suggested to result in cluster formation including Bose–Einstein condensate (Kim 2010; Takahashi and Yabuuchi 2008), hydrino formation (Mills et al. 1994), and Rydberg molecules (Bendkowsky et al. 2009; Holmlid et al. 2009; Wan and Holmlid 2002). A proposed description of the deuteron cluster must include its ability to react with target nuclei to cause transmutation as well as helium formation and meet all the requirements described above. For such reactions to occur, the cluster must be mobile and simultaneously hide the charge of at least 10 deuterons from the charge of the target nuclei. In addition, the size of the reacting part of the cluster must be similar in size compared to the target nucleus for these deuterons to enter the target as a unit. Since anomalous power is found to increase as temperature

is increased, the mechanism that forms reactive clusters would be expected to become more active as temperature is increased, thereby resulting in an increased number of nuclear reactions.

If clusters are involved, what will be the consequences of their reactions? When transmutation occurs, the atomic weight and atomic number of the target will increase. As can be seen in Fig. 13, adding deuterons to ^{110}Pd produces stable isotopes where the line marked “add deuterons” intersects a dot. This happens only when even numbers are added at and below 10 deuterons. When more than 10 deuterons are added, all the resulting isotopes will be radioactive, which is seldom detected. Stable elements are also produced when deuterons are added to the other isotopes of palladium but the upper limit of element stability is reduced. Addition of protons also produces stable elements, but the upper limit is much less than when deuterons are added. This diagram can be used to predict which isotopes are expected to result from transmutation of the Iwamura-type. Occam’s razor suggests that whatever mechanism is involved in transmutation, it also causes the helium-producing and tritium-producing reactions, which narrows the range of plausible mechanisms and eliminates many suggested explanations. If this assumption were made, cluster formation would be expected to precede all nuclear reactions within the NAE. The next challenge is to discover the nature of the NAE. Electron screening is one of its many possible characteristics.

Electron screening has been studied by bombarding a material containing deuterium with energetic deuterons. Such studies apply energy far exceeding that involved in normal cold fusion. The reaction rate is measure using neutron emission and this rate is compared at the same applied energy to the known behavior of hot fusion. Therefore, such studies can be said to use a low applied energy to determine how the concentration of electrons in a solid influence the typical hot-fusion reaction paths.

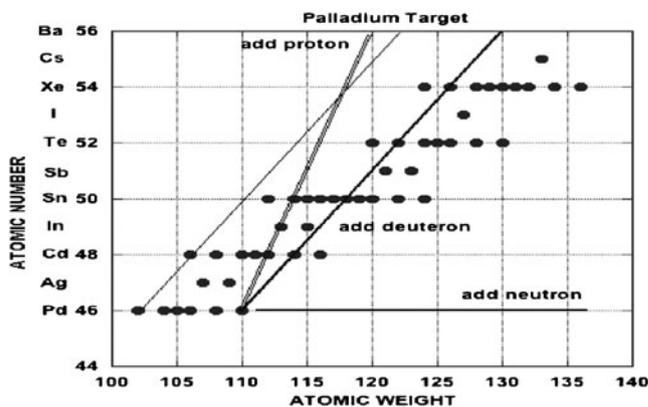


Fig. 13 Relationship between atomic number and atomic weight of stable isotopes between palladium and cesium based on the periodic chart of the elements. (Storms and Scanlan 2010)

(Czerski et al. 2004; Huke et al. 2008; Kasagi 2008; Kasagi et al. 1998a, b; Lipson et al. 2005; Yuki et al. 1997) Pure Pd has a smaller enhancement (Fig. 14) compared to when its surface is covered with PdO, a compound containing extra electrons. Presence of lithium causes an especially large enhancement compared to fusion rates in plasma (Kasagi et al. 1998a, b). However, this behavior has no clear relationship to cold fusion because energy is delivered to the reaction by the bombarding particle and the resulting energy is dissipated by emission of two energetic particles having the expected energy. These conditions and behaviors do not exist during cold-fusion. In addition, the hot-fusion reactions have very small rates at these low applied energies and are not significantly increased by screening. In other words, this is an interesting effect, but it has no practical significance to explain the high reaction rates achieved during heat production by cold fusion. Such rates equal 10^{12} helium/s when 1 W is produced. Nevertheless, it is fair to say that studies of hot fusion, when done in a solid rather than in plasma, can reveal aspects of electron shielding that might exist in the transition region between hot and cold fusion. This transition could be called warm fusion.

What would happen if a special NAE were created in a solid that is subjected to bombardment by moderate-energy deuterons. This situation has been explored by Claytor and coworkers (1992, 1996, 1998) for many years while looking for enhanced tritium production. They find that tritium production can be significantly increased at pulsed applied energy of a few keV if certain alloys containing palladium are used as the cathode. The neutron emission rate is apparently not increased. In other words, if applied

energy is sufficiently small, the three known fusion paths can be modified by using different NAE. Neutron production can be increased when the material contains extra electrons, a very simple NAE; tritium production can be significantly increased when certain alloys of palladium are used, a more complex NAE; and the helium-producing reaction can be made the dominate fusion path without emission of gamma rays when a very special NAE is created. Normal hot fusion at high energy produces a t/n ratio equal to 1 while this ratio is $\sim 10^{6-9}$ at the very low energy characteristic of cold fusion. Consequently, the amount of calculated enhancement would depend on whether emitted neutrons or tritons were used to determine the reaction rate. In other words, cold and hot fusions are not actually separate processes but are part of a continuum based on applied energy and the characteristics of a NAE. Proper placement of these reactions in this range of variables is important to understanding the basic process.

A few authors have suggested and shown evidence for involvement of novel particles such as a new stable and massive hadron called a Erzion (Bazhutov et al. 1982), a cluster of electrons called EVO (Shoulders 2006; Shoulders and Shoulders 1996), a new particle with a rest mass of 2–26 times that of the electron called a Iton (Matsumoto 1990), a super-heavy electron (Widom and Larsen 2006), a particle having a fractional charge (McKibben 1995, 1996/1997, 1997, 1998), polyneutrons (Fisher 2007), and the magnetic monopole (Adamenko and Vysotskii 2005; Lochak and Urutskoev 2004; Rambaut 2004; Schwarzchild 2006). None of these novel particles can explain all observed behavior, although some might play a small role under unusual conditions.

Addition of neutrons, as several authors have suggested (Fisher 2007; Kozima 2000; Widom and Larsen 2006), is not consistent with observation because long chains of beta decay must occur after multiple neutron addition before the observed elements are formed. The required delay in producing the final stable element and resulting radioactivity are not observed.

Conclusion

Where does the field of study stand at present? First of all, a large number of studies (Storms 2007) reporting production of large amounts of power and energy are now available for evaluation. Some of the individual results far exceed the energy from any conceivable chemical or mechanical source. Second, nuclear products including helium, tritium, neutrons, and transmutation products have been reported by numerous laboratories using a variety of methods of production and detection. Helium and heat production are found to be correlated based on a significant number of

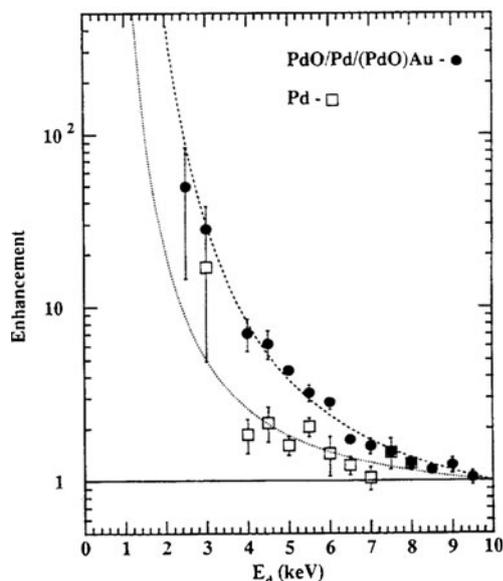


Fig. 14 Enhancement over the free-space hot-fusion rate vs energy of bombarding deuterons (source: Kasagi et al. 1998a, b)

studies. In addition, the measured values for the ratio between energy and helium production rates show good internal consistency and a close relationship to the value expected when two deuterons combine to produce helium. Third, radiation has been detected that can only be produced by nuclear processes. While some of the measurement could be influenced by error, contamination, or misinterpretation, the large and growing collection cannot be fully explained this way. Therefore, the claimed occurrence of unusual nuclear reactions under conditions thought not to cause such reactions is supported. The challenge now is to discover what mechanism or mechanisms can produce all of the different nuclear products and how the process can be made more reproducible so that it might be more easily studied and developed as a source of energy.

The absence of a useful theory is presently a major handicap to progress. Especially troubling is the tendency of some people to promote ideas that are in direct conflict with a basic understanding of how Nature is known to behave based on well-established observation. The cold-fusion effect may be novel but it exists in the context of a large and well-developed understanding of nuclear interaction that needs to be included in any useful theory. The first stage in this process requires the nature of the required environment, the NAE, to be identified. At the very least, the almost universal assumption that palladium is uniquely involved needs to be reexamined. Indeed, when palladium is used, the active region is not palladium deuteride but a very inhomogeneous and complex alloy. The location of the NAE in this region is not known.

If a NAE can exist in living cells, the consequence is huge. This would allow environmental contamination to be reduced using bacteria and mean that the abundance of elements on earth has been modified by the presence of life. The conditions known to exist in living cells also might severely restrict the nature of the NAE in nonliving matter, an insight that could help define the NAE. The challenge to the imagination is obvious.

What are the consequences of this phenomenon being real? The answer to this question involves science, energy policy, and politics. Clearly, if the rate of the energy-producing reaction can be increased, controlled, and sustained for long periods, this energy source has the potential to replace all other sources. In many ways, cold fusion produces the ideal energy because the easily extracted fuel (deuterium) exists in inexhaustible amounts in all water, the process of extraction and energy generation appear to create no harmful products, and the generator can be small enough to power individual dwellings. Ordinary hydrogen (protium) may even be a source of nuclear energy under certain conditions. General application can be expected to have important consequences, both good and bad. At the very least, this energy may offer a

solution to the global warming problem. At the worst, economic distress will result as the present energy infrastructure is replaced. From a scientific point of view, the ability of “normal” materials, including living organisms, to apparently initiate nuclear reactions shows that present knowledge about nuclear interaction is painfully inadequate. Efforts to improve this understanding can be expected to reveal other amazing and useful phenomena. The stakes are enormous and attention needs to be paid to the possibilities, no matter how remote they may seem. In a rational world and in the face of growing ecological disaster from using carbon-based fuels, every possible energy source would be explored, no matter how unlikely. Why is cold fusion the only proposed source that is widely ignored at the present time?

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References

- Abell GC, Matson LK et al (1990) Helium release from aged palladium tritide. *Phys Rev B: Mater Phys* 41(2):1220
- Adamenko S, Vysotskii V (2005) Observation and modeling of the ordered motion of hypothetical magnetically charged particles on the multilayer surface and the problem of low-energy fusion. *Condensed Matter Nuclear Science, ICCF-12*. World Scientific, Yokohama
- Åman C, Holmlid L (1992) Hydrocarbon clusters from a foil diffusion source. *J Clust Sci* 3:247
- Aoki T, Kurata Y et al (1994) Helium and tritium concentrations in electrolytic cells. *Trans Fusion Technol* 26(4):214
- Apicella M, Castagna E et al (2005) Some recent results at ENEA. *Condensed Matter Nuclear Science, ICCF-12*. World Scientific, Yokohama
- Arata Y, Zhang Y-C (1995a) Achievement of solid-state plasma fusion (“cold fusion”). *Proc Japan Acad* 71(Ser B):304
- Arata Y, Zhang Y-C (1995b) Achievement of solid-state plasma fusion (“cold fusion”). *Koon Gakkaishi* 21(6):303 (in Japanese)
- Arata Y, Zhang Y-C (1996) Achievement of solid-state plasma fusion (“cold fusion”). *Sixth International Conference on Cold Fusion, Progress in New Hydrogen Energy, Lake Toya, Hokkaido, Japan, New Energy and Industrial Technology Development Organization, Tokyo Institute of Technology, Tokyo, Japan*
- Arata Y, Zhang Y-C (1996b) Deuterium nuclear reaction process within solid. *Proc Japan Acad* 72(Ser. B):179
- Arata Y, Zhang Y-C (1997a) Solid-state plasma fusion (“cold fusion”). *J High Temp Soc* 23:1–56 (special volume)
- Arata Y, Zhang Y-C (1997b) Helium (^4He , ^3He) within deuterated Pd-black. *Proc Jpn Acad, Ser B* 73:1
- Arata Y, Zhang Y-C (1999a) Anomalous production of gaseous ^4He at the inside of ‘DS cathode’ during D_2O -electrolysis. *Proc Jpn Acad, Ser B* 75(10):281
- Arata Y, Zhang Y-C (1999b) Critical condition to induce ‘excess energy’ within [DS- H_2O] cell. *Proc Jpn Acad, Ser B* 75(Ser. B):76
- Arata Y, Zhang Y-C (1999c) Observation of anomalous heat release and helium-4 production from highly deuterated fine particles. *Jpn J Appl Phys* 2 38(7A):L774

- Arata Y, Zhang Y-C (2000) Definite difference among [DS-D₂O], [DS-H₂O] and [Bulk-D₂O] cells in the deuterization and deuterium-reaction. 8th International Conference on Cold Fusion, Lericci (La Spezia), Italy. Italian Physical Society, Bologna
- Arata Y, Zhang Y-C (2002) Formation of condensed metallic deuterium lattice and nuclear fusion. *Proc Jpn Acad Ser B* 78 (Ser B):57–62
- Badii S, Andersson PU et al (2009) Fusion reactions in high-density hydrogen: A fast route to small-scale fusion? *International J Hydrogen Energy* 34:487
- Bazhutov Y, Khrenov BA et al (1982) About one opportunity of second shower spectrum interpretation observed at small depth underground. *Izv AN USSR, ser Phys* 46(9):2425
- Bendkowsky V, et al (2009) Novel binding mechanism for ultra-long range molecules. arXiv:0809.2961v1
- Bockris J, Chien C et al (1992) Tritium and helium production in palladium electrodes and the fugacity of deuterium therein. Third International Conference on Cold Fusion, "Frontiers of Cold Fusion", Nagoya Japan. Universal Academy Press, Tokyo, pp 231–240
- Botta E, Bracco R et al (1995) Search for ⁴He production from Pd/D₂ systems in gas phase. 5th International Conference on Cold Fusion, Monte-Carlo, Monaco, IMRA Europe, Sophia Antipolis Cedex, France, pp 233–240
- Botta E, Bressani T et al (1996) Measurement of ⁴He production from D₂ gas-loaded Pd samples. Sixth International Conference on Cold Fusion, Progress in New Hydrogen Energy, Lake Toya, Hokkaido, Japan, New Energy and Industrial Technology Development Organization, Tokyo Institute of Technology, Tokyo, 29–35
- Bush BF, Lagowski JJ (1998) Methods of generating excess heat with the Pons and Fleischmann effect: rigorous and cost effective calorimetry, nuclear products analysis of the cathode and helium analysis. The Seventh International Conference on Cold Fusion, Vancouver, Canada. ENCO, Salt Lake City, 38–42
- Bush BF, Lagowski JJ et al (1991) Helium production during the electrolysis of D₂O in cold fusion experiments. *J Electroanal Chem* 304:271–278
- Camp WJ (1977) Helium detrapping and release from metal tritides. *J Vac Sci Technol* 14:514–517
- Case LC (1998) Catalytic fusion of deuterium into helium-4. The Seventh International Conference on Cold Fusion, Vancouver, Canada. ENCO, Salt Lake City, pp 48–50
- Cedzynska K, Will FG (1992) Closed-system analysis of tritium in palladium. *Fusion Technol* 22:156–159
- Chien C-C, Huang TC (1992) Tritium production by electrolysis of heavy water. *Fusion Technol* 22:391–394
- Chien C-C, Hodko D et al (1992) On an electrode producing massive quantities of tritium and helium. *J Electroanal Chem* 338:189–212
- Chrzan DC, Wolfer WG (1991) Helium bubble growth by the dislocation pipe diffusion mechanism. Sandia National Laboratory, Livermore, pp 91–8671
- Chubb SR (2009) Overcoming the coulomb barrier and related effects through resonant electrostatics and quantum mechanics in the Fleischmann–Pons excess heat effect. In: Marwan J, Krivit S (eds) *Low-energy nuclear reactions sourcebook*, vol 2. Oxford University Press, Oxford (in press)
- Chubb TA, Chubb SR (1991) Cold fusion as an interaction between ion band states. *Fusion Technol* 20:93–99
- Clarke BW, Oliver BM et al (2001) Search for ³He and ⁴He in Arata-style palladium cathodes II: Evidence for tritium production. *Fusion Sci Technol* 40:152–167
- Clayton TN, Tuggle DG et al (1992) Evolution of tritium from deuterided palladium subject to high electrical currents. Third International Conference on Cold Fusion, "Frontiers of Cold Fusion", Nagoya Japan. Universal Academy Press, Tokyo, pp 217–229
- Clayton TN, Jackson DD et al (1996) Tritium production from a low voltage deuterium discharge of palladium and other metals. *J New Energy* 1(1):111–118
- Clayton TN, Schwab MJ et al (1998) Tritium production from palladium alloys. The Seventh International Conference on Cold Fusion, Vancouver, Canada. ENCO, Salt Lake City, pp 88–93
- Czerski K, Huke A et al (2004) The 2H(d,p)3H reaction in metallic media at very low energies. *Europhys Lett* 68:363
- Dash J (2004) Research at Portland State University, 1989–2004 on the interaction of metals with hydrogen isotopes. ASTI-5, Asti, Italy, www.iscmns.org/
- Dardik I, Zilov T et al (2007) Report on electrolysis experiments at energetics technologies, International Conference on Condensed Matter Nuclear Science, ICCF-13, Sochi, Russia, p. 325
- De Ninno A, Del Giudice E et al (2008) Excess heat and calorimetric calculation: evidence of coherent nuclear reactions in condensed matter at room temperature. In: Marwan J, Krivit SB (eds) *Low-Energy Nuclear Reactions Sourcebook*. American Chemical Society, Washington, DC, pp 127–158
- DeNinno A, Frattolillo A et al (2004) ⁴He detection during H/D loading of Pd cathodes. ASTI-5, Asti, Italy, www.iscmns.org/
- Dufour J, Murat D et al (2000) Hydrex catalyzed transmutation of uranium and palladium: experimental part. 8th International Conference on Cold Fusion, Lericci (La Spezia), Italy. Italian Physical Society, Bologna, 153–158
- Fisher JC (2007) Outline of polyneutron theory. 8th International Workshop on Anomalies in Hydrogen/Deuterium Loaded Metals, Catania, Sicily, Italy, The International Society for Condensed Matter Science, pp 70–91
- Fleischmann M, Pons S et al (1989) Electrochemically induced nuclear fusion of deuterium. *J Electroanal Chem* 261:301–308, and errata in Vol 263:187–188
- Fleischmann M, Pons S et al (1994) Possible theories of cold fusion. *Nuovo Cim* 107A(1):143–156
- Gozzi D, Caputo R et al (1993) Excess heat and nuclear product measurements in cold fusion electrochemical cells. Fourth International Conference on Cold Fusion, Lahaina, Maui, Electric Power Research Institute 3412 Hillview Ave, Palo Alto, CA 94304:2–1 to 2–31
- Gozzi D, Caputo R et al (1993) Helium-4 quantitative measurements in the gas phase of cold fusion electrochemical cells. Fourth International Conference on Cold Fusion, Lahaina, Maui, Electric Power Research Institute 3412 Hillview Ave, Palo Alto, CA 94304: p. 6–1 to 6–19
- Gozzi D, Cellucci F et al (1998) Erratum to "X-ray, heat excess and ⁴He in the D/Pd system". *J Electroanal Chem* 452:251–271
- Hagelstein PL (1992) Coherent and semicoherent neutron transfer reactions I: The interaction Hamiltonian. *Fusion Technol* 22:172–180
- Hagelstein PI (2010) Constraints on energetic particles in the Fleischmann–Pons experiment. *Naturwissenschaften* 97(4): 345
- Hagelstein PI, Chaudhary I (2008) Models relevant to excess heat production in the Fleischmann–Pons experiments. In: Marwan J, Krivit SB (eds) *Low-Energy Nuclear Reactions Sourcebook*. American Chemical Society, Washington, DC, 1503:249–267
- Hansen WN (1991) Report to the Utah State Fusion/Energy Council on the analysis of selected Pons Fleischmann calorimetric data. Second Annual Conference on Cold Fusion, "The Science of Cold Fusion", Como, Italy. Societa Italiana di Fisica, Bologna, pp 491–527
- Hansen LD, Jones SE et al (1998) A response to hydrogen+oxygen recombination and related heat generation in undivided electrolysis cells. *J Electroanal Chem* 447:225–226

- Holmlid L, Hora H et al (2009) Ultrahigh-density deuterium of Rydberg matter clusters for inertial confinement fusion targets. *Laser Part Beams* 27(3):529
- Holst-Hansen P, Britz D (1995) Can current fluctuations account for the excess heat claims of Fleischmann and Pons? *J Electroanal Chem* 388:11–16
- Huke A, Czerski K et al (2008) Enhancement of the deuterium-fusion reactions in metals and its experimental implications. arXiv: 0805.4538v1
- Isobe Y, Uneme S et al (2000) Search for coherent deuteron fusion by beam and electrolysis experiments. 8th International Conference on Cold Fusion, Lerici (La Spezia), Italy. Italian Physical Society, Bologna, pp 17–22
- Isobe Y, Uneme S et al (2002) Search for multibody nuclear reactions in metal deuteride induced with ion beam and electrolysis methods. *Jpn J Appl Phys* 41(3):1546–1556
- Iwamura Y, Itoh T et al (2002a) Nuclide transmutation device and nuclide transmutation method. Mitsubishi Heavy Industries, Patent No. US2002/0080903 A1 and EP 1 202 290 A2
- Iwamura Y, Sakano M et al (2002b) Elemental analysis of Pd complexes: effects of D₂ gas permeation. *Jpn J Appl Phys A* 41(7):4642–4650
- Iwamura Y, Itoh T et al (2003) Low energy nuclear transmutation in condensed matter induced by D₂ gas permeation through Pd complexes: correlation between deuterium flux and nuclear products. Tenth International Conference on Cold Fusion. World Scientific, Cambridge, pp 435–454
- Iwamura Y, Itoh T et al (2004) Observation of nuclear transmutation reactions induced by D₂ gas permeation through Pd complexes. ICCF-11, International Conference on Condensed Matter Nuclear Science, Marseilles, France, World Scientific, pp 339–350
- Iwamura Y, Itoh T et al (2005) Observation of surface distribution of products by X-ray fluorescence spectrometry during D₂ gas permeation through Pd cathodes. Condensed Matter Nuclear Science, ICCF-12. World Scientific, Yokohama, pp 178–187
- Jones JE, Hansen LD et al (1995) Faradaic efficiencies less than 100% during electrolysis of water can account for reports of excess heat in 'cold fusion' cells. *J Phys Chem* 99:6973–6979
- Kainthla RC, Szklarzyk M et al (1989) Eight chemical explanations of the Fleischmann–Pons effect. *Hydrogen Energy* 14(11):771–775
- Karabut AB (2004) Excess heat production in Pd/D during periodic pulse discharge current in various conditions. 11th International Conference on Cold Fusion, Marseilles, France, World Scientific Co, pp 178–193
- Karabut AB (2005) Research into low-energy nuclear reactions in cathode sample solid with production of excess heat, stable and radioactive impurity nuclides. Condensed Matter Nuclear Science, ICCF-12, Yokohama, Japan, World Scientific, pp 214–230
- Karabut AB (2007) Excess heat power registration in high voltage electrolysis and discharge systems. International Conference on Condensed Matter Nuclear Science, ICCF-13, Sochi, Russia, Tsiolkovsky Moscow Technical University, pp 225–236
- Karabut AB, Kucherov YR et al (1991) The investigation of deuterium nuclei fusion at glow discharge cathode. *Fusion Technol* 20:924
- Karabut AB, Kucherov YR et al (1992) Nuclear product ratio for glow discharge in deuterium. *Phys Lett A* 170:265–272
- Kasagi J (2008) Screening potential for nuclear reactions in condensed matter. ICCF-14, International Conference on Condensed Matter Nuclear Science, Washington, DC, www.LENR.org
- Kasagi J, Yuki H et al (1998a) Strongly enhanced Li+D reaction in Pd observed in deuteron bombardment on PdLix with energies between 30 and 75 keV. *J Phys Soc Japan* 73:608–612
- Kasagi J, Yuki H et al (1998b) Anomalously enhanced D(d, p)T reaction in Pd and PdO observed at very low bombarding energies. The Seventh International Conference on Cold Fusion, Vancouver, Canada. ENECO, Salt Lake City, pp 180–185
- Kaushik TC, Shyam A et al (1990) Preliminary report on direct measurement of tritium in liquid nitrogen treated TiDx chips. *Indian J Technol* 28:667–673
- Kervran CL (1963) *Transmutations biologiques, metabolismes aberrants de l'asote, le potassium et le magnesium*. Librairie Maloine S A, Paris
- Kervran CL (1972) *Biological transmutations*. Swan House, Brooklyn
- Kervran CL (1980) *Biological transmutation*. Beekman, Woodstock
- Kim YE (2010) Bose–Einstein condensate theory of deuteron fusion in metal. Purdue University, West Lafayette, Report No. PNMBTG-1-10
- Komaki H (1992) Observations on the biological cold fusion or the biological transformation of elements. Third International Conference on Cold Fusion, "Frontiers of Cold Fusion", Nagoya Japan. Universal Academy Press, Tokyo, pp 555–558
- Komaki H (1993) An Approach to the Probable Mechanism of the Non-Radioactive Biological Cold Fusion or So-Called Kervran Effect (Part 2). Fourth International Conference on Cold Fusion, Lahaina, Maui, Electric Power Research Institute 3412 Hillview Ave, Palo Alto, CA 94304: Vol 4, 44–1 to 44–12
- Kozima H (2000) Neutron drop: condensation of neutrons in metal hydrides and deuterides. *Fusion Technol* 37:253–258
- Lipson AG, Miley G et al (2005) Enhancement of first wall damage in ITER type Tokamak due to LENR effects. Condensed Matter Nuclear Science, ICCF-12, Yokohama, Japan, World Scientific, pp 325–335
- Lochak G, Urutskoev L (2004) Low-energy nuclear reactions and the leptonic monopole. 11th International Conference on Cold Fusion, Marseilles, France, World Scientific Co, pp 421–437
- Matsumoto T (1990) Prediction of new particle emission on cold fusion. *Fusion Technol* 18:647–651
- Matsumoto T (1993) Cold fusion experiments with ordinary water and thin nickel foil. *Fusion Technol* 24:296–306
- Matsunaka M, Isobe Y et al (2002) Studies of coherent deuteron fusion and related nuclear reactions in solid. The 9th International Conference on Cold Fusion, Condensed Matter Nuclear Science. Tsinghua Univ, Beijing, pp 237–240
- McKibben JL (1995) Can cold fusion be catalyzed by fractionally-charged ions that have evaded FC particle searches. *Infin Energy* 1(4):14–23
- McKibben JL (1996/1997) Strange-particle catalysis in the production of COH₂ gas or iron. *Infin Energy* 2(11):37–37
- McKibben JL (1997) Catalytic behavior of one (or two) subquarks bound to their nuclear hosts. *Infin Energy* 3(13/14):103–105
- McKibben JL (1998) Recent observations that yield information on catalytic particles. *Infin Energy* 4(20):70–72
- McKubre MCH (2003) Review of experimental measurements involving dd reactions, PowerPoint slides. Tenth International Conference on Cold Fusion, Cambridge, MA, World Scientific Publishing Co
- McKubre MCH, Crouch-Baker S et al (1994) Isothermal flow calorimetric investigations of the D/Pd and H/Pd systems. *J Electroanal Chem* 368:55–66
- McKubre MCH, Crouch-Baker S et al (1998) Energy production processes in deuterated metals. EPRI, Palo Alto, Report No. TR-107843-VI
- McKubre MC, Tanzella F et al (2000a) Evidence of d-d fusion products in experiments conducted with palladium at near ambient temperatures. *Trans Am Nucl Soc* 83:367
- McKubre MCH, Tanzella FL et al (2000b) Finite element modeling of the transient calorimetric behavior of the MATRIX experimental apparatus: ⁴He and excess of power production correlation through numerical results. 8th International Conference on Cold Fusion, Lerici (La Spezia), Italy. Italian Physical Society, Bologna, pp 23–27
- McKubre MCH, Tanzella FL et al (2000c) The emergence of a coherent explanation for anomalies observed in D/Pd and H/Pd

- system: evidence for ^4He and ^3He production. 8th International Conference on Cold Fusion, Lericci (La Spezia), Italy. Italian Physical Society, Bologna, pp 3–10
- McKubre MC, Tanzella F et al (2008) Replication of condensed matter heat production. ACS Symposium Series 998, Low-Energy Nuclear Reactions Sourcebook (Marwan, J. Krivit, S. B., eds.) American Chemical Society
- Miles MH (1998) Reply to 'An assessment of claims of excess heat in cold fusion calorimetry'. *J. Phys. Chem. B* 102:3648
- Miles M, Bush BF (1992) Search for anomalous effects involving excess power and helium during D_2O electrolysis using palladium cathodes. Third International Conference on Cold Fusion, "Frontiers of Cold Fusion", Nagoya Japan. Universal Academy Press, Tokyo, pp 189–199
- Miles M, Jones CP (1992) Cold fusion experimenter Miles responds to critic. *21st Century Sci & Technol.* (spring issue) p 75
- Miles MH, Bush BF (1994) Heat and helium measurements in deuterated palladium. *Trans Fusion Technol* 26(4):156–159
- Miles M, Bush BF et al (1991) Heat and helium production in cold fusion experiments. Second Annual Conference on Cold Fusion, "The Science of Cold Fusion", Como, Italy, Societa Italiana di Fisica, Bologna, Italy, pp 363–372
- Miles MH, Hollins RA et al (1993) Correlation of excess power and helium production during D_2O and H_2O electrolysis using palladium cathodes. *J Electroanal Chem* 346:99–117
- Miles M, Bush BF et al (1994) Anomalous effects involving excess power, radiation, and helium production during D_2O electrolysis using palladium cathodes. *Fusion Technol* 25:478
- Miles M, Imam MA et al (2000) Excess heat and helium production in the palladium-boron system. *Trans Am Nucl Soc* 83:371–372
- Miley G, Shrestha P (2008) Transmutation reactions and associated low-energy nuclear reactions effects in solids. In: Marwan J, Krivit SB (eds) *Low-Energy Nuclear Reactions Sourcebook*. American Chemical Society, Washington, DC, pp 173–218
- Miley G, Yang Y et al (2005) Intense non-linear soft X-ray emission from a hydride target during pulsed D bombardment. *Condensed Matter Nuclear Science, ICCF-12*. World Scientific, Yokohama, pp 314–324
- Miley G, Hora H et al (2007) Cluster reactions in low energy nuclear reactions (LENR). 8th International Workshop on Anomalies in Hydrogen/Deuterium Loaded Metals, Catania, Sicily, Italy, The International Society for Condensed Matter Science, pp 235–251
- Mills RL, Good WR et al (1994) Dihydrino molecule identification. *Fusion Technol* 25:103–119
- Miskelly GM, Heben MJ et al (1989) Analysis of the published calorimetric evidence for electrochemical fusion of deuterium in palladium. *Science* 246:793–796
- Mizuno T, Ohmori T et al (1996a) Anomalous isotopic distribution in palladium cathode after electrolysis. *J New Energy* 1(2):37–44
- Mizuno T, Ohmori T et al (1996b) Anomalous isotopic distribution of elements deposited on palladium induced by cathodic electrolysis. *Denki Kagaku oyobi Kogyo Butsuri Kagaku* 64:1160 (in Japanese)
- Mizuno T, Akimoto T et al (1998a) Neutron and heat generation induced by electric discharge. *J New Energy* 3(1):33–45
- Mizuno T, Akimoto T et al (1998b) Confirmation of the changes of isotopic distribution for the elements on palladium cathode after strong electrolysis in D_2O solutions. *Int J Soc Mat Eng Resour* 6(1):45
- Morrey JR, Caffee MW et al (1990) Measurements of helium in electrolyzed palladium. *Fusion Technol* 18:659
- Mosier-Boss PA, Szpak S et al (2008) Detection of energetic particles and neutrons emitted during Pd/D co-deposition. In: Marwan J, Krivit SB (eds) *Low-Energy Nuclear Reactions Sourcebook*. American Chemical Society, Washington DC, pp 311–334
- Mosier-Boss PA, Dae JY et al (2010) Comparison of Pd/D co-deposition and DT neutron generated triple tracks observed in CR-39 detectors. *Eur Phys J Appl Phys* 51:20901–20911
- Narita S, Yamada H et al (2005) Discharge experiment using Pd/CaO/Pd multilayered cathode. *Condensed Matter Nuclear Science, ICCF-12*. World Scientific, Yokohama, pp 188–195
- Notoya R (1994) Alkali-hydrogen cold fusion accompanied by tritium production on nickel. *Trans Fusion Technol* 26(4T):205–208
- Oriani RA, Fisher JC (2004) Nuclear reactions produced in an operating electrolytic cell. 11th International Conference on Cold Fusion. World Scientific, Marseilles, pp 295–303
- Preparata G (1991) Some theories of 'cold' nuclear fusion: a review. *Fusion Technol* 20:82–92
- Preparata G (1993) Cold fusion '93': Some theoretical ideas. Fourth International Conference on Cold Fusion, Lahaina, Maui, Electric Power Research Institute 3412 Hillview Ave, Palo Alto, CA 94304:12–1 to 12–23
- Preparata G (1994) Cold fusion '93': Some theoretical ideas. *Trans Fusion Technol* 26(4T):397–407
- Rabinowitz M (1993) Do the laws of nature and physics agree on what is allowed and forbidden? *21st Century Sci and Technol Spring*, pp 10–17
- Rambaut M (2004) Electrons clusters and magnetic monopoles. 11th International Conference on Cold Fusion, Marseilles, France, World Scientific Co, pp 798–805
- Sankaranarayanan TK, Srinivasan M et al (1996) Investigation of low-level tritium generation in Ni-H₂O electrolytic cells. *Fusion Technol* 30:349
- Savvatimova I, Dash J (2002) Emission registration on films during glow discharge experiments. The 9th International Conference on Cold Fusion, Condensed Matter Nuclear Science, Tsinghua Univ, Beijing, China, Tsinghua Univ Press, pp 312–318
- Savvatimova I, Kucherov Y et al (1994) Cathode material change after deuterium glow discharge experiments. *Trans Fusion Technol* 26(4T):389–394
- Savvatimova I, Savvatimov G et al (2007) Decay in tungsten irradiated by low energy deuterium ions. International Conference on Condensed Matter Nuclear Science, ICCF-13. Tsiolkovsky Moscow Technical University, Sochi, pp 295–308
- Schwarzchild B (2006) Search for magnetic monopoles at Tevatron sets new upper limit on their production. *Physics Today* 59:16
- Shanahan K (2005) Comments on thermal behavior of polarized Pd/D electrodes prepared by co-deposition. *Thermochim Acta* 428:207–212
- Shanahan K (2006) Reply to Comment on papers by K Shanahan that propose to explain anomalous heat generated by cold fusion. *Thermochim Acta* 441:210–214
- Shoulders K (2006) Projectiles from the dark side. *Infin Energy* 12(70):39–40
- Shoulders K, Shoulders S (1996) Observations on the role of charge clusters in nuclear cluster reactions. *J New Energy* 1(3):111–121
- Storms E (1998) Cold fusion revisited. *Infin Energy* 4(21):16–29
- Storms E (2000) Excess power production from platinum cathodes using the Pons-Fleischmann effect. 8th International Conference on Cold Fusion, Lericci (La Spezia), Italy. Italian Physical Society, Bologna, pp 55–61
- Storms E (2004) Calorimetry 101 for cold fusion, www.LENR-CANR.org
- Storms E (2006) Comment on papers by K. Shanahan that propose to explain anomalous heat generated by cold fusion. *Thermochim Acta* 441(2):207–209
- Storms EK (2007) The science of low energy nuclear reaction. World Scientific, Singapore, 312 pages
- Storms EK, Scanlan B (2007) Radiation produced by glow discharge in deuterium. 8th International Workshop on Anomalies in Hydrogen / Deuterium Loaded Metals 2007, Catania, Sicily, pp 297–305 see also: <http://www.iscmns.org/catania07/index.htm>

- Storms EK, Scanlan B (2010) What is real about cold fusion and what explanations are plausible? AIP Symposium Series J Marwan, Am Inst of Phys, in press
- Stringham R (2003) Cavitation and fusion. Tenth International Conference on Cold Fusion. World Scientific, Cambridge, pp 233–246
- Swartz MR, Verner G (2003) Excess heat from low-electrical conducting heavy water spiral-wound Pd/D₂O/Pt and Pd/D₂O-PdCl₂/Pt devices. Tenth International Conference on Cold Fusion. World Scientific, Cambridge, pp 29–44
- Szpak S, Mosier-Boss PA et al (2009) Further evidence of nuclear reactions in the Pd/D lattice: emission of charged articles. *Naturwiss* 94:515
- Takahashi A (1998) Results of experimental studies of excess heat vs nuclear products correlation and conceivable reaction model. The Seventh International Conference on Cold Fusion, Vancouver, Canada, ENECO, Inc, Salt Lake City, UT, pp 378–382
- Takahashi A (2005) Progress in condensed matter nuclear science. Condensed Matter Nuclear Science, ICCF-12. World Scientific, Yokohama, pp 1–25
- Takahashi A, Yabuuchi N (2008) Study on 4D/tetrahedral symmetric condensate condensation motion by non-linear Langevin equation. In: Marwan J, Krivit SB (eds) Low-Energy Nuclear Reactions Sourcebook. American Chemical Society, Washington DC, pp 57–83
- Thompkins P, Byrd C (1993) The secret life of plants. Penguin, New York, 402 pages
- Toimela T (2004) Effective interaction potential in the deuterium plasma and multiple resonance scattering. 11th International Conference on Cold Fusion, Marseilles, France, World Scientific Co, pp 622–634
- Toimela T (2007) Multiple resonance scattering. 8th International Workshop on Anomalies in Hydrogen/Deuterium Loaded Metals, Catania, Sicily, Italy, The International Society for Condensed Matter Science, pp 328–340
- Violante V, Sarto F et al. (2008) Material science on Pd-D system to study the occurrence of excess power. 14th International Conference on Condensed Matter Nuclear Science, Washington, DC, see www.LENR.org
- Vysotskii V, Kornilova AA (2003) Nuclear fusion and transmutation of isotopes in biological systems. Mockba, Ukraine, 302 pages
- Vysotskii V, Kornilova AA et al (1996a) Experimental discovery and investigation of the phenomenon of nuclear transmutation of isotopes in growing biological cultures. *Infin Energy* 2(10):63–66
- Vysotskii VI, Kornilova AA et al (1996b) Experimental discovery of phenomenon of low-energy nuclear transformation of isotopes (Mn⁵⁵=Fe⁵⁷) in growing biological cultures. Sixth International Conference on Cold Fusion, Progress in New Hydrogen Energy, Lake Toya, Hokkaido, Japan, New Energy and Industrial Technology Development Organization. Tokyo Institute of Technology, Tokyo, pp 687–693
- Vysotskii V, Kornilova AA et al (2001) Observation and mass-spectrometry. Study of controlled transmutation of intermediate mass isotopes in growing biological cultures. *Infin Energy* 6 (36):64–68
- Vysotskii V, Tashyrev AB et al (2008) Experimental observation and modeling of Cs-137 isotope deactivation and stable isotope transmutation in biological cells. In: Marwan J, Krivit SB (eds) Low-Energy Nuclear Reactions Sourcebook. American Chemical Society, Washington, DC, pp 295–309
- Wan J, Holmlid L (2002) Rydberg Matter clusters of hydrogen (H₂)N with well-defined kinetic energy release observed by neutral time-of-flight. *Chem Phys* 277:201–210
- Widom A, Larsen L (2006) Ultra low momentum neutron catalyzed nuclear reactions on metallic hydride surfaces. *Eur Phys J C* 46:107 also: arXiv:cond-mat/0505026v1 2 May 2005
- Will F (1997) Hydrogen+oxygen recombination and related heat generation in undivided electrolysis cells. *J Electroanal Chem* 426:177–184
- Wilson RH, Bray JW et al (1992) Analysis of experiments on the calorimetry of LiOD-D₂O electrochemical cells. *J Electroanal Chem* 332:1
- Wolf KL, Packham NJC et al (1990) Neutron emission and the tritium content associated with deuterium-loaded palladium and titanium metals. *J Fusion Energy* 9(2):105–113
- Yuki H, Satoh T et al (1997) D+D reaction in metal at bombarding energies below 5 keV. *J Phys G: Nucl Part Phys* 23:1459–1464
- Zhang QF, Gou QQ et al (1992) The detection of 4-He in Ti-cathode on cold fusion. Third International Conference on Cold Fusion, “Frontiers of Cold Fusion”, Nagoya Japan. Universal Academy Press, Tokyo, pp 531–534