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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 8 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, Pons et al. 1989) while they worked at the University of Utah. Since then, the subject continues to be investigated in more than 8 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 (ICCF), 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 (Storms 2007).

The unique process is proposed to involve a reaction between deuterons, resulting in ^{4}He 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 is called transmutation. All of these reactions are thought to occur on or near to 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 D_2O+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.

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 data set 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 (ITER, the planned International Thermonuclear Experimental Reactor in France) or by a laser (NIF, 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.

Table 1
Reactions that result when D+D fusion occurs
Environment:
Hot-Fusion – plasma or high energy
Cold-Fusion – special condensed matter at low energy

:

Reaction	**MeV**	**Hot-fusion Fraction**	**Cold-fusion Fraction**
D+D = ^{4}He + energy	23.8	<1%(gamma-ray)	>99.9%(no gamma-ray)
D+D = Tritium + proton	4.03	50%	rare
D+D = neutron + ^{3}He	3.27	50%	extremely rare

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.

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, Szklarczyk 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 D_2O 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*.

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(Hansen, L. D., Jones et al. 1998; Jones, Hansen et al. 1995) argue that uncertain recombination of the O_2 and D_2 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 D_2 at the cathode and O_2 at the anode that must be recombined back to D_2O 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 and co-workers (1994, 1998) at 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

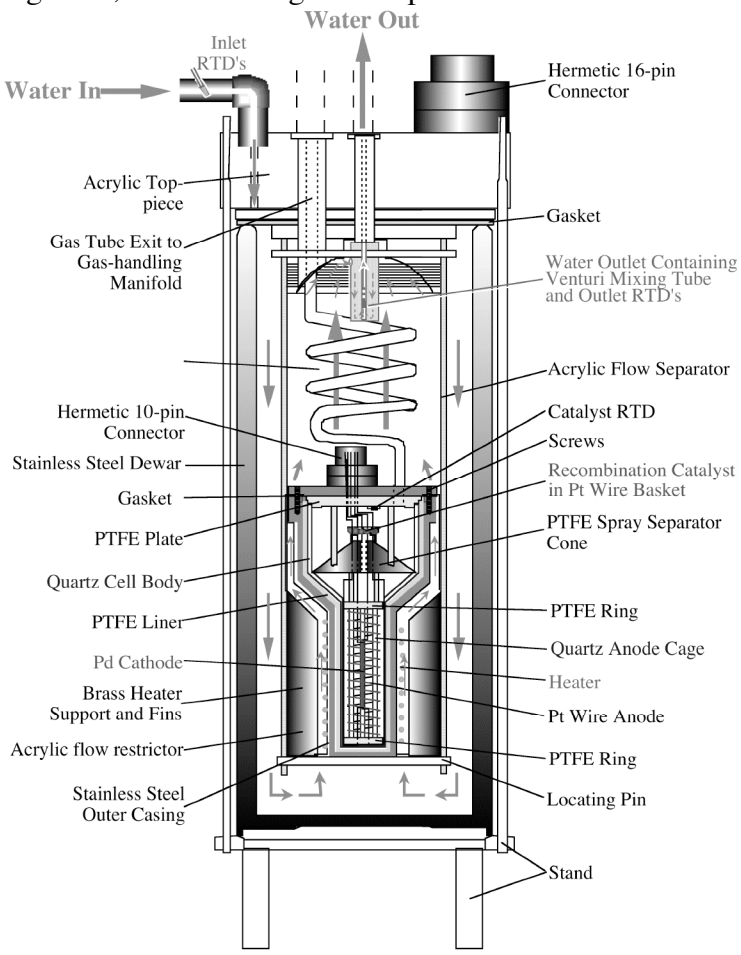

Fig 1. Flow-type calorimeter used by McKubre *et al*. at SRI. The cell was isolated from the atmosphere and contained a recombining catalyst. The average D/Pd ratio was determined by measuring the resistance of the Pd wire cathode. An electric heater kept internal temperature constant and provided a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

through the calorimeter, without making corrections for 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 world-wide 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 expected to contain a variable number of active sites from which the heat originates. Many failures are experienced when no active sites are present;

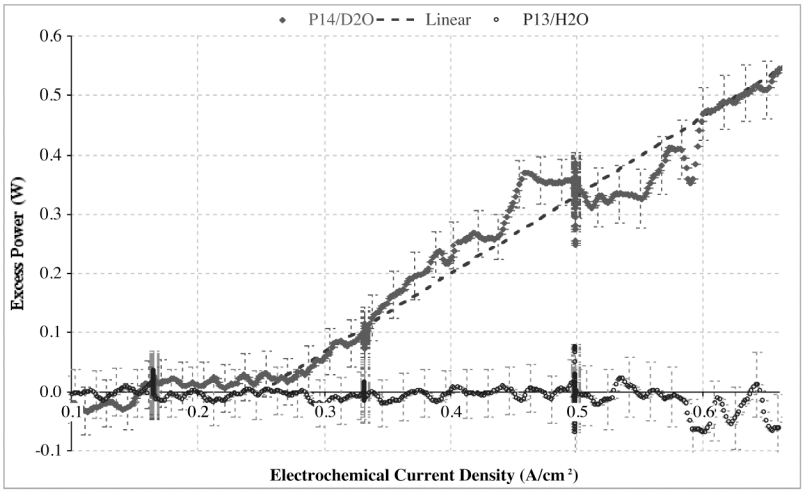

Fig. 2. Effect of current density at the cathode on excess power production. Note the absence of an effect when D_2O is replaced by H_2O. (From: McKubre *et al*.)

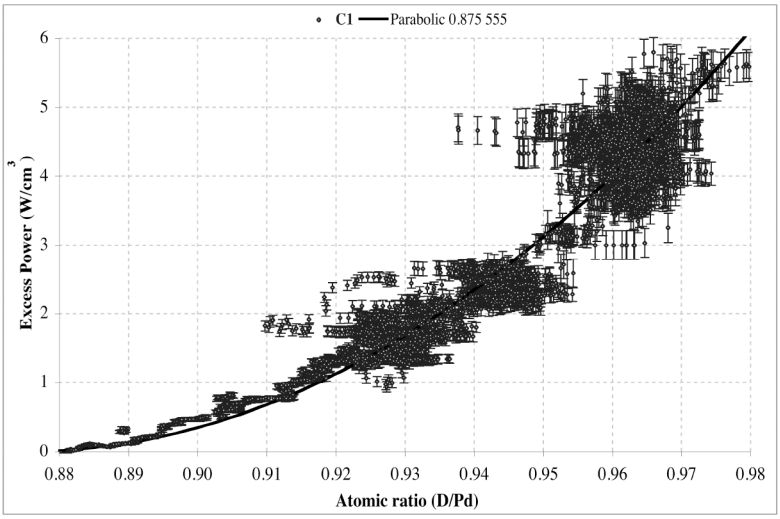

Fig. 3. Relationship between average D/Pd ratio of the cathode and excess power over that applied to the calorimeter. (From: McKubre *et al*.)

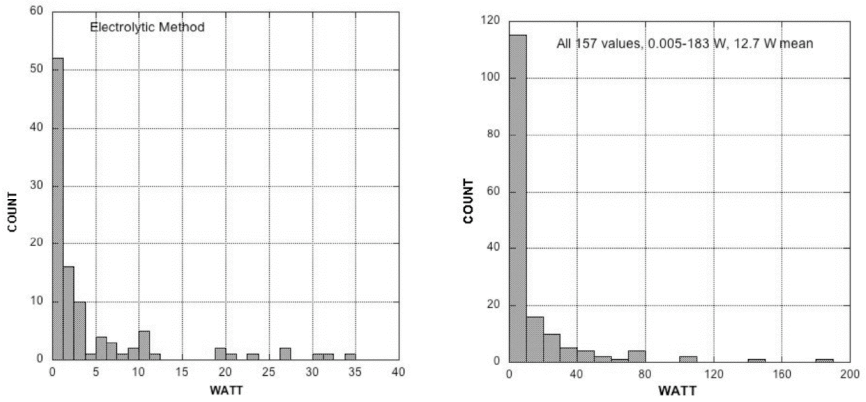

Fig. 4. Histograms of reported abnormal energy using the electrolytic method(left) and 157 values based on all methods (right) using data from 1989 to 2004. Note that occasionally, large amounts of power are generated.(Storms 2007)

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), and the Pyrex container (silicon and boron). As a result, the required nature of the active material, i.e. the nuclear-active environment (NAE), is not known and is produced largely by chance only in certain locations. The characteristically long delay before abnormal 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 $PdD_{0.85}$. These extraordinary and difficult to create conditions partially explain the frequent failure to replicate when using the electrolytic method. A significant effort by Violante and co-workers (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 (1999; 2000) and Case (McKubre et al. 2000) 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 D_2O+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.

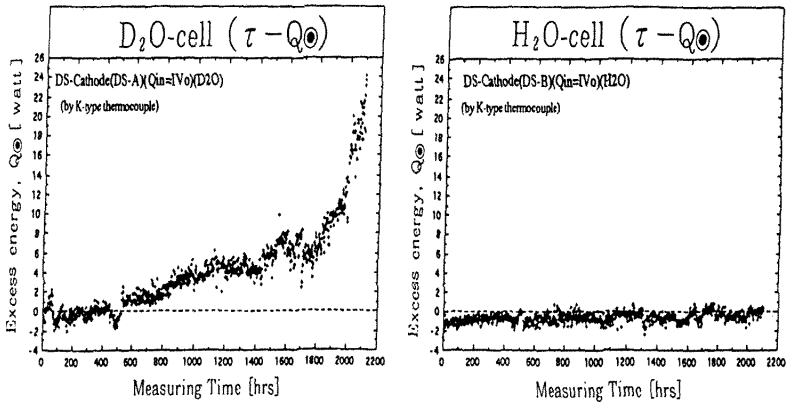

Fig. 5. Heat production as pressure is increased over a period of time in a palladium tube containing palladium-black. A flow calorimeter was used.(Arata and Zhang)

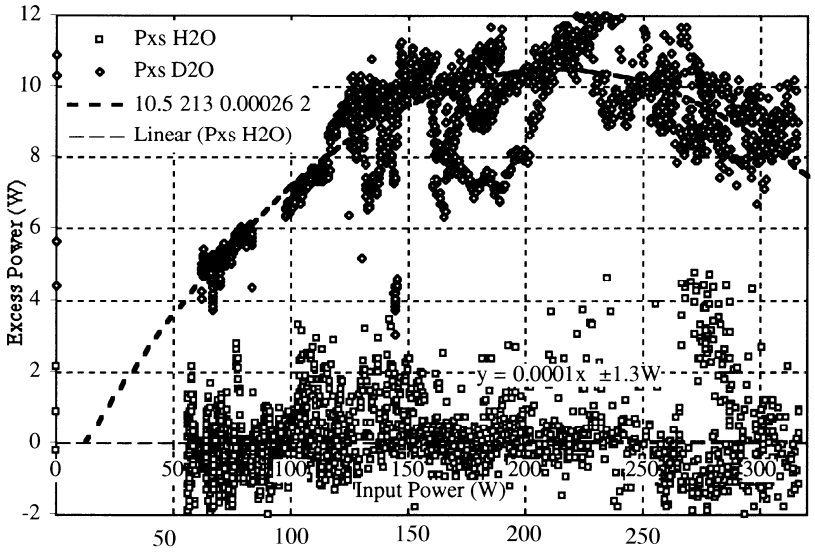

Fig. 6. Replication of Arata-Zhang work by McKubre *et al*. at SRI.

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 Zr+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 the US.

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*. (2000) 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.

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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 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 co-workers at "LUCH" in Russia (Karabut, 2005, 2007; Karabut, Kucherov et al 1991; Savvatimova, Savvatimov 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, Murat et al 2000; Miley, Yang et al 2005; Mizuno, Akimoto et al 1998; Narita, Yamada et al 2005; Storms and Scanlan 2007) Claytor and co-workers(Claytor, Jackson et al 1996; Claytor, Schwab et al 1998; Claytor, Tuggle et al 1992) 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 challenged 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, Lagowski 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

Table 2

Proposed reactions producing helium from materials expected to be present in cold-fusion environments. Involvement of neutrinos and radioactive decay products are ignored.
(H-proton, D-deuteron, T-triton)

Reaction	**MeV/He**	**He atoms/J**
D+D = ^{4}He + energy	23.8	2.6e11
4D = ^{8}Be = 2^{4}He	23.8	2.6e11
D+T = neutron + ^{4}He	17.5	3.6e11
D+^{6}Li = ^{8}Be = 2^{4}He	11.2	5.6e11
H+^{7}Li = ^{8}Be = 2^{4}He	8.4	7.4e11
2H+^{7}Li=^{9}B=2^{4}He+p	8.4	7.4e11
n + ^{7}Li = ^{8}Li = ^{8}Be + beta (13 MeV) = 2^{4}He	13.4	4.7e11
n + ^{6}Li = T + ^{4}He	4.3	14.5e11
Transmutation	3-6? from alpha	

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, 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 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 ^{4}He(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, twelve correlations and four quantitative studies have been reported as described below.

Miles and co-workers(Bush, B. F., Lagowski et al 1991; Miles and Bush 1992; Miles, Bush et al 1994; Miles, Bush et al 1991) 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 (D_2+O_2+D_2O+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; 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 and co-workers(1992) at Texas A & M University (USA) electrolyzed palladium as the cathode in D_2O and occasionally 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 $1.7x10^{11}$ atoms of helium in a piece cut from a location near the cathode surface. Heat production was not measured.

Karabut and co-workers(Karabut, A. B. , Kucherov et al 1992; Savvatimova, I. , Kucherov et al 1994) at LUTCH 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 and co-workers (1992) at universities in Chengdu (China) detected helium in a titanium cathode using a Ga^+ ion source for 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 US 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 $1.2x10^{18}$ 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 $(0.5\pm2.1)x10^{10}$ atoms/sec 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(1995, 1996, 1997, 1999, 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, Oliver et al 2001; McKubre 2003)

Botta and co-workers(Botta, E., Bracco et al 1995; Botta, Bressani et al 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 $(5.3\pm0.7)x10^{18}$ 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 co-workers(Takahashi 1998; Isobe, Uneme et al 2000; Matsunaka, Isobe et al 2002; Uneme et al 2002;) at Osaka University (Japan) measured helium production by electrolysis. Four successful runs gave values between $8.8x10^{14}$ to $7.0x10^{16}$ atoms with a background of about $5x10^{15}$ atoms.

Gozzi and co-workers(Gozzi, Caputo et al 1993; Gozzi, Caputo et al 1993) at Univ. of Rome, La Saptenza (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, Cellucci 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 $1.05x10^{16}$ atoms compared to a background of $0.75x10^{16}$ atoms of helium. The background is from helium initially present in the mass spectrometer.

De Ninno and co-workers(De Ninno, Del Giudice et al 2008; DeNinno, Frattolillo et al 2004) at ENEA-Frascati (Italy) electrolyzed a long thin film of Pd deposited on Al_2O_3. Although only $(8.1\pm0.2)x10^{14}$ 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 twelve 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 twelve 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, Lagowski et al 1991; Miles, Hollins et al 1993), as noted above, a new study by Miles and co-workers (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, Imam et al 2000),

Bush and Lagowski(1998) at Univ. of Texas, while collaborating with Stanford Research International (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 co-workers(McKubre, Tanzella et al 2000; McKubre, Tanzella et al 2000) 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 $(1.9\pm0.8)\times10^{11}$ He/J as listed in Table 3.

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 ^{3}He obtained from tritium decay shows that such trapped helium can be removed from the metal only at temperatures near the melting point.(Abell, Matson 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 deloading 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.

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 (Miles and Bush 1994)	electrolysis	8	1.6e11	0.7e11
Bush (Bush and Lagowski 1998)	electrolysis	3	1.5e11	0.2e11
Miles (Miles, Imam et al 2000)	electrolysis	1	1.0e11	
McKubre (McKubre, Tanzella et al 2000; McKubre, Tanzella et al 2000)	gas loading	13 data points	1.9e11	0.8e11

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 (secondary ion mass spectrometry) 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 palladium (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

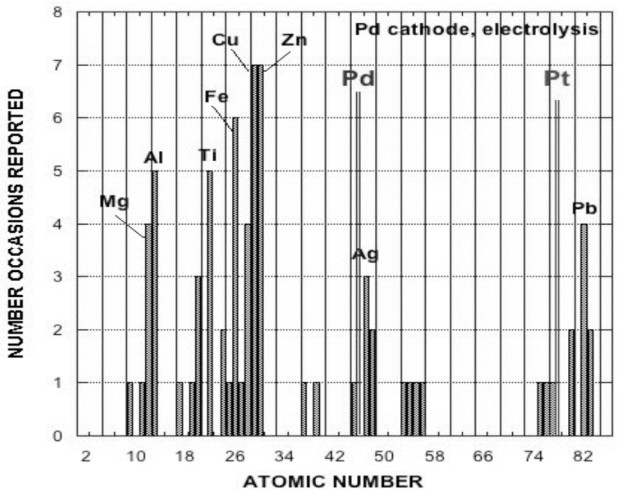

Fig. 7. Histogram showing the number of reports of anomalous elements found on a cathode surface having the plotted atomic number.

noted at Pd and Pt, with the platinum (Pt) being normally transferred to the cathode from the anode. Zinc (Zn) and copper (Cu) are the most common products followed by iron (Fe), titanium (Ti), and aluminum (Al). 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 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 co-workers, Hokkaido Univ., Japan, (Mizuno, Akimoto et al 1998; Mizuno, Ohmori et al 1996) 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 D_2O+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 EDX (energy dispersive X-ray spectrometry), AES (Auger electron spectroscopy), SIMS (secondary ion mass spectrometry) and EPMA (electron probe microanalyser). Figure 8

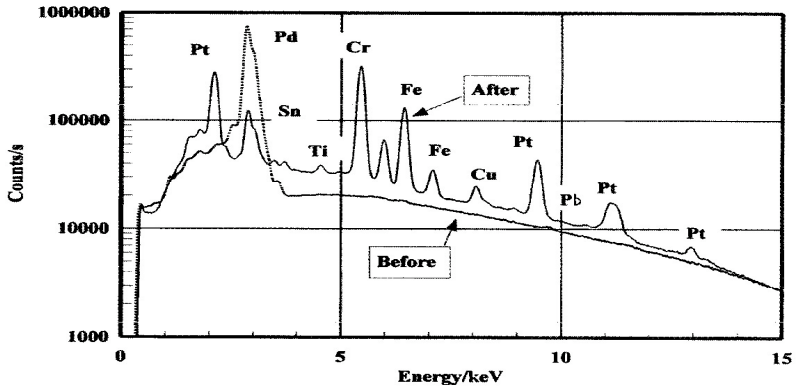

Fig. 8. Result of EDX examination of a cathode before and after discharge.

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 iron (Fe) might come from exposed stainless steel. However, this cannot explain the copper (Cu) and titanium (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 D_2 using applied voltage between 1000 V and 2000 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 co-workers.(Iwamura, Sakano et al 2002; Iwamura, Itoh et al 2002, 2003, 2004, 2005) They passed D_2 through a heated (70°C) sandwich consisting of alternating thin layers of CaO and Pd (Fig. 10). Various elements that were previously

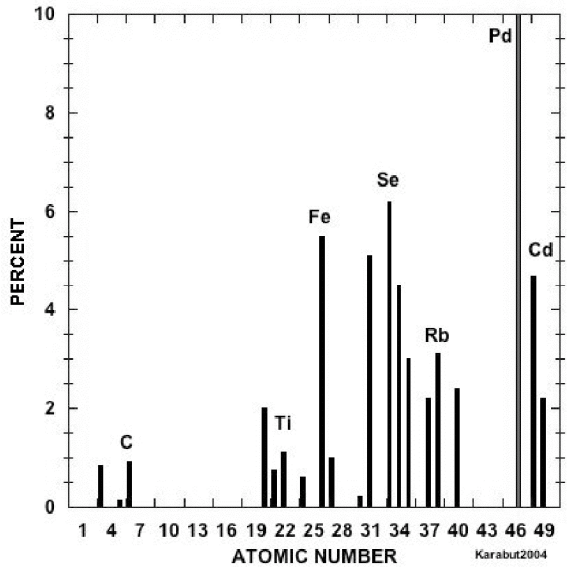

Fig. 9. Elements found on a palladium cathode after gas discharge using 1-2 keV in D_2. (Karabut 2004)

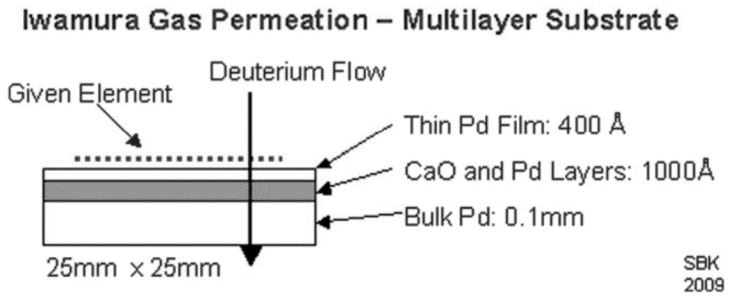

Fig. 10. Simplified drawing (Krivit) of sample used by Iwamura *et al*.

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 (XPS). 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 is a greater flux of deuterium. In contrast, this effect did not occur when CaO was replaced by MgO or when H_2 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 ^{133}Cs on the surface decreased at the rate of about $1.9x10^9$ atoms/sec while the ^{141}Pr 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 watts, 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 and co-workers (Takagashi et al 2005) were able to show conversion of Sr to Mo by diffusing D_2 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 6 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 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, L.C. 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, Kornilova et al 1996; Vysotskii and Kornilova 2003; Vysotskii, Kornilova et al 1996; Vysotskii, Kornilova et al 2001; Vysotskii, Tashyrev et al 2008) carried the work further by making Fe^{57} from Mn^{55} when a collection of bacteria were grown in D_2O. The Fe^{57} 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.

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, Shyam et al 1990; Wolf, Packham 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, Chien et al 1992; Chien, Hodko et al 1992; Chien and Huang 1992) at Texas A&M University (USA) measured a rate of tritium production equal to 10^8 atoms/sec from which power production of $6x10^{-5}$ watts 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, Srinivasan 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~~d, and~~ 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 (gamma-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 co-workers(Mosier-Boss, Szpak et al 2008; Szpak, Mosier-Boss 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

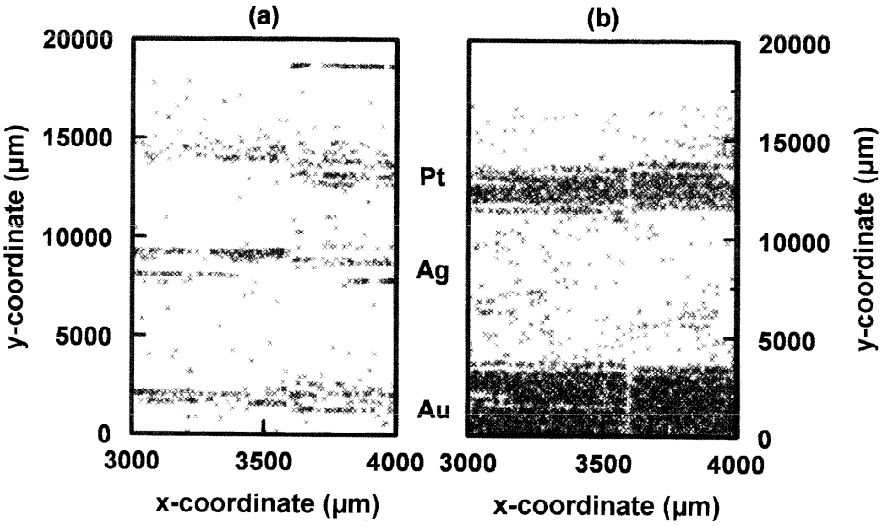

Fig. 11. Front side (a) and back side (b) of CR-39 exposed to an electrolytic cell while palladium is plated on different metal wires. The radiation produced at the silver cathode did not penetrate through the plastic. Note that the images were made by computer analysis of the surface. The front-side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

made pits on the front side and, in two cases, on the back side as well. When the deposit was applied to a silver (Ag) 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 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 are 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 (BEC) 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 2008; Chubb and Chubb 2000; Hagelstein and Chaudhary 2010), 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 Scalan (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

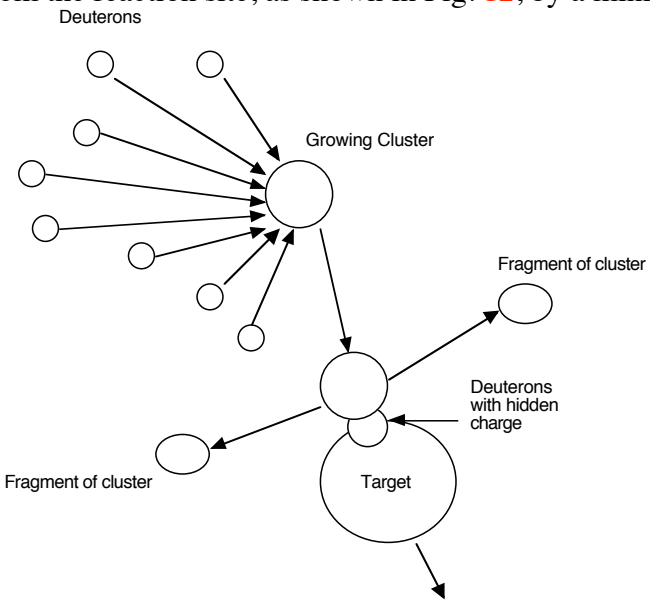

Fig. 12. Growth and destruction of a cluster causing transmutation. The cluster is proposed to grow on the surface of special materials until it contains over 100 deuterons, a few of which enter into nuclear reactions. The many fragments produced by a nuclear reaction between the target and part of the cluster can contain 1 or more deuterons with zero to many missing electrons. The circular shape of the cluster is for illustration proposes only.

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 and Hora (2007) with various co-authors propose the process involves creation of a large nucleus at $^{306}X_{126}$ 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, Andersson et al 2009; Bendkowsky, Butscher 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 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 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 nanosize 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(2005) 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 is 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 *et al.*(1993; 1994) refined the theory to include the following assumptions as paraphased 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, Good et al. 1994) and Rydberg molecules (Bendkowsky, Butscher et al 2009; Holmlid, Hora et al 2009; Wang 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

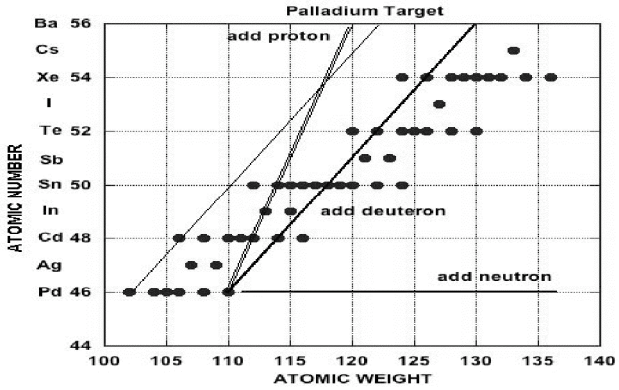

Fig. 13. Relationship between atomic number and atomic weight of stable isotopes between palladium and cesium based on the periodic chart of the elements. (Storms and Scanlan 2010)

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. (Czerski, Huke et al 2004; Huke, Czerski et al 2008; Kasagi 2008; Kasagi, Yuki et al 1998; Lipson, Miley et al 2005; Yuki, Satoh et al 1997) Pure palladium (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, Yuki et al 1998) However, this behavior has

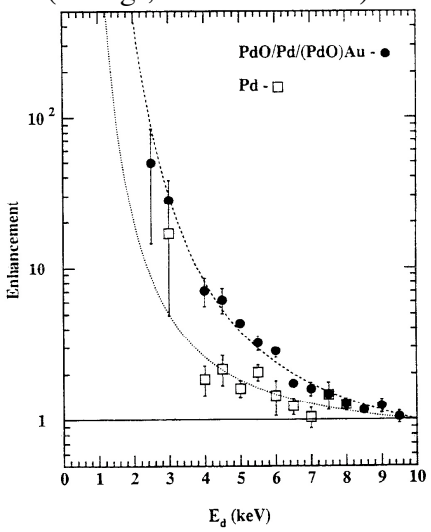

Fig. 14. Enhancement over the free-space hot-fusion rate vs energy of bombarding deuterons. (from: (Kasagi, Yuki et al 1998))

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/sec when one watt 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 co-workers (Claytor, 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 ~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-fusion 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, Khrenov et al 1982), a cluster of electrons called EVO(Shoulders 2006; Shoulders and Shoulders 1996), a new particle with a rest mass of 2 to 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 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 non-living 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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