A new look at low-energy nuclear reaction research

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This paper presents a new look at low-energy nuclear reaction research, a field that has developed from one of the most controversial subjects in science, "cold fusion." Early in the history of this controversy, beginning in 1989, a strong polarity existed; many scientists fiercely defended the claim of new physical effects as well as a new process in which like-charged atomic nuclei overcome the Coulomb barrier at normal temperatures and pressures. Many other scientists considered the entire collection of physical observations—along with the hypothesis of a "cold fusion"—entirely a mistake. Twenty years later, some people who had dismissed the field in its entirety are considering the validity of at least some of the reported experimental phenomena. As well, some researchers in the field are wondering whether the underlying phenomena may be not a fusion process but a neutron capture/absorption process. In 2002, a related tabletop form of thermonuclear fusion was discovered in the field of acoustic inertial confinement fusion. We briefly review some of this work, as well.

Cold fusion history

At a press conference on March 23, 1989, organized by the University of Utah, electrochemists Dr Martin Fleischmann and Dr Stanley Pons announced a new room-temperature fusion process (Fig. 1). The University of Utah press release announced the discovery as "Sustained n-fusion at room temperature," but within hours, the media—confused about another field called muon-catalyzed fusion—assigned the term "cold fusion" to the Fleischmann–Pons discovery

For lack of a better understanding for many years following the discovery, the term "cold fusion" remained as a common reference to this work. The historic controversy will always be remembered by the term "cold fusion"; however, scientifically speaking, there are good reasons to leave the term "cold fusion" in the past. We will get to those later.

The field was recognized in 1989 from the work of Fleischmann and Pons: electrolysis experiments using the heavy metal palladium and the hydrogen isotope deuterium. They had begun experimenting at the University of Utah in 1984.

Fleischmann and Pons claimed an electrochemical method of generating nuclear energy, in a way that was previously unrecognized by nuclear physicists.

Their suggestion of creating room-temperature deuterium–deuterium fusion triggered an uproar in the scientific community, particularly among physicists who understood nuclear fusion well.

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The infamous press conference

By all accounts—particularly by Fleischmann and Pons—the press conference was premature. The reasons for the press conference are complex.

Just down the road from the University of Utah, Professor Steven E. Jones at Brigham Young University had been selected in 1988 by Ryszard Gajewski, project director of the Department of Energy's Advanced Energy Projects Division, to review a grant proposal that Fleischmann and Pons had submitted to the Department of Energy.

Gajewski says that his normal protocol would have been to telephone a potential reviewer before sending a proposal to review. At about the same time that Jones would have received the phone call from Gajewski, Jones began work similar to that of Fleischmann and Pons.

After Jones received the proposal in September, he recommended against funding Fleischmann and Pons' Department of Energy proposal, though he later supported the request.

On Dec. 9, 1988, Jones discussed with colleague Jan Rafelski filing a patent—independently of Fleischmann and Pons—for "stimulating nuclear fusion by means of flow of hydrogen isotopes in metal lattice".

On Dec. 10, 1988, in a draft proposal to the Department of Energy, Jones wrote, "We have demonstrated for the first time that nuclear fusion occurs when hydrogen and deuterium are electrolytically loaded into a metallic foil."

On Feb. 23, 1989, after Fleischmann and Pons learned of Jones' research, they, along with administrators from both universities, sought Jones' collaboration for simultaneous publications.

On March 6, 1989, Jones informed Fleischmann and Pons that he was going to announce his work at an American Physical Society meeting scheduled for May 1989. Fleischmann and Pons requested that Jones wait another 18 months, the time Fleischmann and Pons needed to complete their work properly. Jones

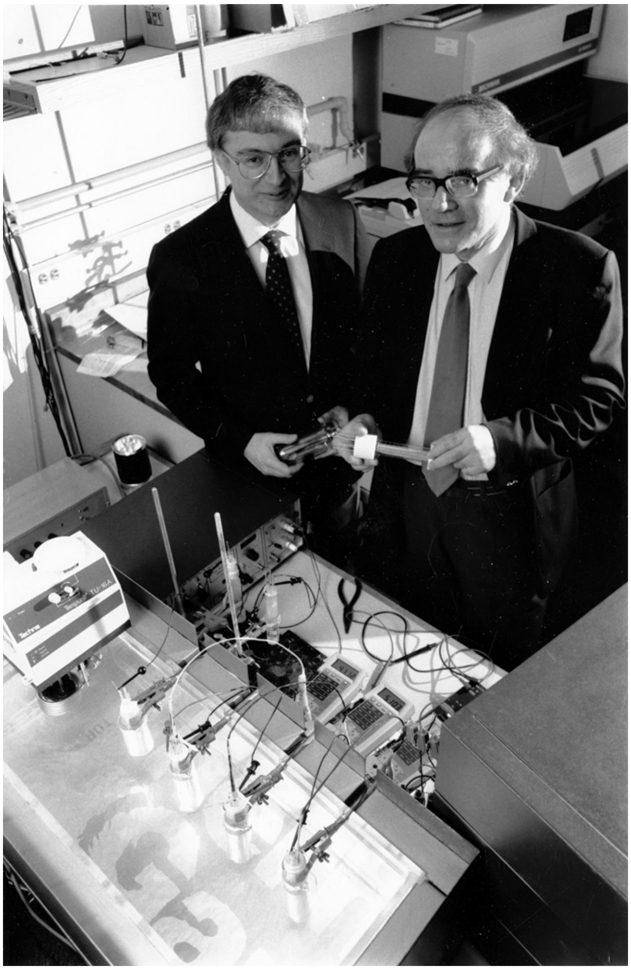

Fig. 1 B. Stanley Pons and Martin Fleischmann (1989) (Image copyright University of Utah).

was unwilling to collaborate, and he advised them that he was going public in May, with or without them.

Feeling their backs against the wall and suspicious that Jones was trying to claim patent and intellectual priority on the fruits of their labor, Fleischmann, Pons, the University of Utah administrators and their attorneys secretly made plans to go public with their claim as soon as possible. When they learned that their paper had been accepted for publication, they hastily scheduled a press conference.

The early challenges

The original Fleischmann–Pons method was and remains difficult to reproduce. If Fleischmann and Pons knew exactly the method and the material to reproduce their claim at the time of their announcement, they were not forthcoming and did not share this information openly with the science community. When many researchers rushed to attempt to replicate Fleischmann and Pons, they failed for numerous reasons. Some of them attempted in vain to get private instruction and information from Fleischmann and Pons, but in that same period, many other researchers began to engage in hostile attacks against Fleischmann and Pons. It was chaos.

Other discoverers and discoveries

Of the few researchers who succeeded very early in getting positive results, most had similar experience with the Pd/D system. Researchers who had experience with metallurgy also had a distinct advantage and had early success.

Fleischmann and Pons were not the only researchers who had observed anomalies in palladium deuterides and hydrides. Once the news of Fleischmann and Pons became public, many researchers around the world—particularly in Russia and Japan—recognized that some of their own earlier work had shown inexplicable behavior. Some of them had mistakenly dismissed the anomalies years earlier as errors or artifacts.

Once the Fleischmann and Pons discovery became publicly known, these other phenomena became more understandable.

Further, since the time immediately following the University of Utah announcement, many other discoveries—some small, some large—have occurred in the field. Some of the discoveries took the form of the search for and observation of key nuclear products, such as tritium and helium-4. Other discoveries took the form of novel LENR methodologies, such as electrolytic co-deposition—which led to a reproducible experiment. Another method was a gas diffusion technique which led to unambiguous evidence of heavy-element transmutations. These are both discussed later in this paper.

The Fleischmann–Pons experiment

Fleischmann and Pons used a standard electrolytic process with a Pt anode and a Pd cathode, and they passed an electrical current through a solution of D_2O and electrolyte. The rest of their design and operating parameters, which can be understood best by reading their papers, were unique and led to their unique results.

Briefly, their design entailed a tall, narrow cell that, through the combination of cell geometry and bubbling action, kept the electrolyte well-mixed and prevented significant thermal gradients. The design used a double-wall vacuum flask to minimize heat conduction out of the cell (Fig. 2).

The first key to a discovery

The first key that Fleischmann and Pons obtained to convince themselves that they had found a way to create nuclear reactions from chemistry was the excess heat produced by the cell. They could see with extremely high confidence that their Pd/D system was producing at least more than 1000 times the amount of heat that could be explained from any previously known chemically induced process.[2]

As the public controversy exploded in the first few weeks of this science controversy, other scientists who were skeptical and some who had failed to replicate Fleischmann and Pons made wild speculations about how Fleischmann and Pons had mismeasured.

Speculating about mistakes, physical or analytical, that Fleischmann and Pons might have made was relatively easy. But few, if any, qualified skeptics entered Fleischmann and Pons' laboratory and personally observed their techniques. Few, if any, qualified skeptics performed forensic analysis on Fleischmann and Pons' data. Those who did confirmed rather than disconfirmed the Fleischmann–Pons excess-heat claim.

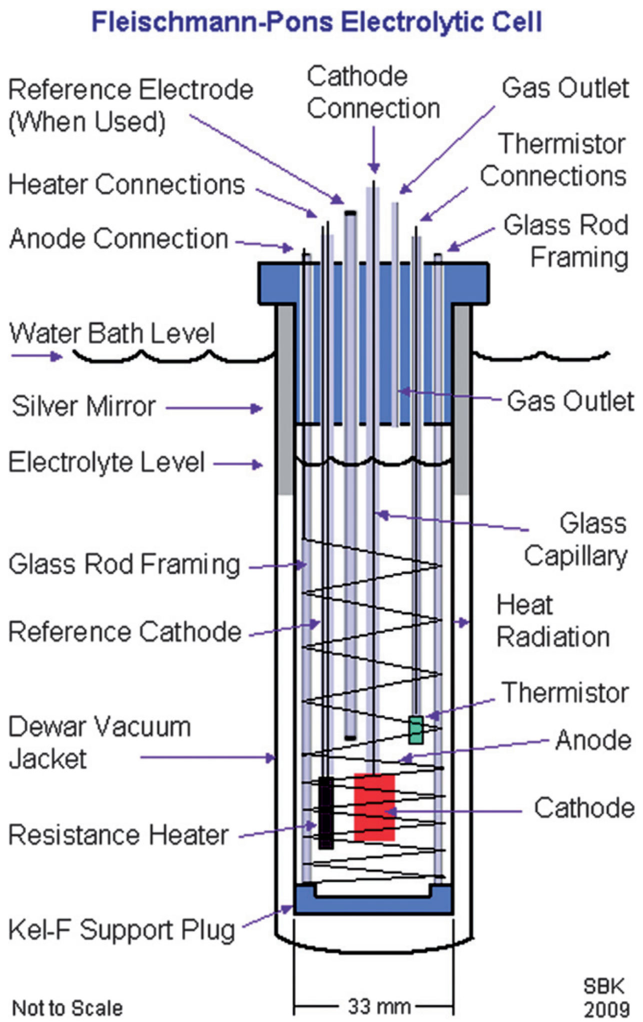

Fig. 2 Fleischmann and Pons electrolytic cell schematic. The platinum anode wire was wound in a helical configuration around glass support rods, surrounding, with a fairly even distribution, the palladium cathode in the center.[1]

The seminal Fleischmann-Pons paper

On April 10, 1989, Fleischmann and Pons published an eight-page "preliminary note" in the *Journal of Electroanalytical Chemistry*. Because of the Jones' circumstances, the paper was rushed, incomplete and contained a clear error about the gamma spectra. This obvious error and the manner in which it changed in early versions of the paper led some nuclear physicists, such as Frank Close, a theoretical particle physicist at the time with Rutherford Appleton Laboratory in Oxfordshire, to speculate that something inappropriate was going on. Fleischmann and Pons acknowledged the gamma spectrum error at an Electrochemical Society meeting in Los Angeles, California, on March 8, 1989.[3]

A year later, in July 1990, Fleischmann and Pons made significant improvements to their "preliminary note" and published a detailed 58-page seminal paper "Calorimetry of the Palladium-Deuterium-Heavy Water System," in the *Journal of Electroanalytical Chemistry*.[2]

In 1992, a group led by Ronald H. Wilson from General Electric challenged the Fleischmann–Pons 1990 paper in the *Journal of Electroanalytical Chemistry* in an apparent attempt to disprove the reported excess heat.[4]

Despite their efforts, they could not. The Wilson group wrote, "While our analysis shows their claims of continuous heat generation to be overstated significantly, we cannot prove that no excess heat has been generated in any experiment."

Despite the analytical confirmation by Wilson, Fleischmann and Pons responded with a defense to the Wilson critique and published a rebuttal in the same issue of the *Journal of Electroanalytical Chemistry.*

When Fleischmann and Pons analyzed the Wilson critique, they found that, based on Wilson's own evaluation, the Fleischmann and Pons cell generated approximately 50% excess heat and amounted to 736 milliwatts, more than 10 times larger than the error levels associated with the data.

Fleischmann and Pons were not reserved in their summary: "[The Wilson group] paper is a series of misconceptions and misrepresentations of previous reports by Fleischmann, Pons and co-workers. [We show] that the conclusions reached by [the Wilson group] lead to gross errors in the prediction of the observed responses of the electrochemical calorimeters described in the original work and that the correct methods of analyses are indeed those we originally described."[5]

To this day, Fleischmann and Pons' often-forgotten seminal paper has not been successfully refuted in the scientific literature, though significant misunderstanding about the subject by some writers and educators perists.

Calorimetry

Although Fleischmann and Pons may have lacked skills with nuclear measurements, they excelled with calorimetry. They custom-built a calorimeter capable of detecting heat to a precision of ±1 milliwatt.

The three main types of calorimeters are isoperibolic, envelope-type, and mass-flow, and each has its advantages and disadvantages. The objective of calorimetry in the context of LENR is to show that conventional electrochemical thermal equilibrium cannot explain the anomalous energy release.

Fleischmann and Pons preferred isoperibolic calorimetry—the measurement of temperature difference between two points—because it produced a fast response and permitted a "positive feedback" effect. That is, heat from the cell tended to amplify the heat enthalpy effect even more.

Other researchers have used flow calorimetry because it requires less-complex mathematics to derive the value of the excess heat enthalpy (Fig. 3).

In the last 20 years but mostly in the first few years of the cold fusion controversy, a lot of discussion has focused on the reality, or lack thereof, of the excess-heat effect. Many skeptics were suspicious that all the electrochemists who were claiming to measure excess heat were incapable of doing so accurately, and the skeptics suggested a variety of arguments. Some were valid; most were not.

A simple review of a "self-heating" event (see below) reported in a 1993 paper by Fleischmann and Pons in *Physics Letters A* demonstrates that anomalous-heat enthalpy can be and has been observed for periods with no input energy, far beyond the quantity of possible stored chemical energy.[1]

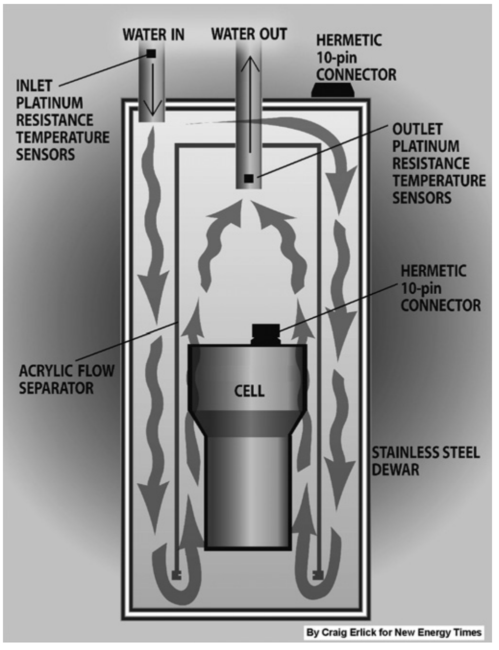

Fig. 3 SRI International-type flow calorimeter.

By 1993, Fleischmann and Pons had developed such control of their experiments, particularly the cathode material, that they had the confidence and ability to set up a row of four cells side by side and initiate anomalous-heat reactions on all four at will.

After about two weeks of applied constant current, the temperature of each cell suddenly, one at a time, without any additional input stimulus, rapidly increased to the boiling point. Within about 30 minutes, most of the electrolyte boiled vigorously and evaporated.

Fleischmann and Pons noted, "Provided satisfactory electrode materials are used, the reproducibility of the experiments is high; following the boiling to dryness and the open-circuiting of the cells, the cells nevertheless remain at high temperature for prolonged periods of time."

Fleischmann and Pons show a detail of the last few hours of the heat enthalpy, which shows that the cell temperature, after boiling dry, remains near 100 °C for three hours. The debate about excess heat, as evidenced by this experiment (among others), is moot: This evidence shows that the cathode is self-heating, with no input power.

The temperature of the cathode appears to have been much warmer than the general cell temperature (Fig. 4); Fleischmann and Pons reported that the "Kel-F supports of the electrodes at the base of the cells melt so that the local temperature must exceed 300 °C."

The entire 28-day run is shown in Fig. 5. Constant current to the cell is supplied at 200 mA through the beginning of the third day, then increased to 500 mA for the duration of the experiment. Cell temperature begins and ends at 20 °C. Cell voltage begins and ends at 0.000. Electrolyte is replenished to the cell approximately once a day, resulting in the slight temporary drops in cell temperature. At around day 16, cell temperature begins to rise rapidly. At around day 17, temperature rises faster until the electrolyte reaches boiling. Fleischmann and Pons performed a time-lapse recording that shows that most of the contents of the four cells boiled and evaporated in about 30 minutes for each cell. Based on a date displayed in the video, it appears that Fleischmann and Pons began the experiment on April 11, 1992.

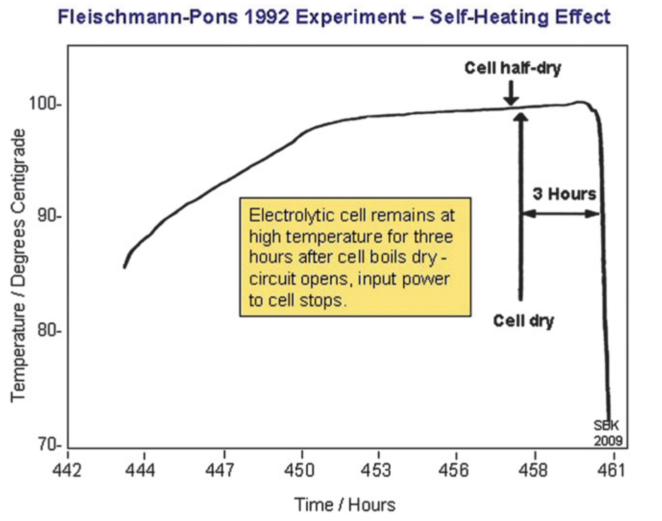

Fig. 4 Fleischmann–Pons 1992 experiment showing self-heating evidence. Image based on Fig. 11 in ref. 1

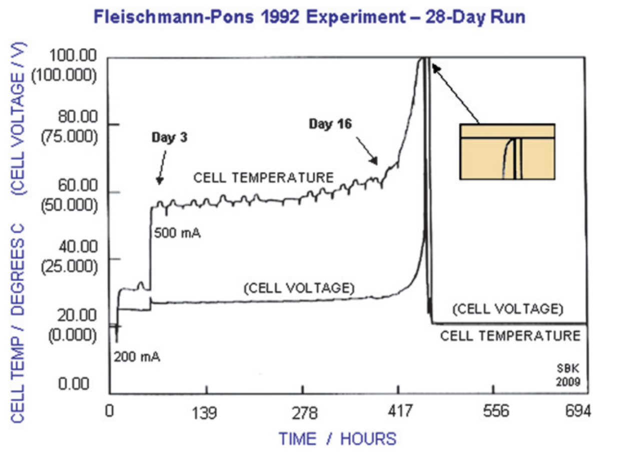

Fig. 5 Fleischmann–Pons 1992 experiment showing full 28 days, terminating in self-heating event. Image based on Fig. 8a in ref. 1.

LENR in the early 20th century

Fleischmann and Pons were not the first to perform low-energy nuclear reaction experiments. In 1922, Gerald L. Wendt and Clarence E. Irion reported the disintegration of tungsten into helium from chemistry experiments.[6]

Four years later, in 1926, Fritz Paneth and Kurt Peters of the University of Berlin experimented with a similar hydrogen-in-palladium experiment. Their paper was published in *Berichte der Deutschen Chemischen Gesellschaft*, *Naturwissenschaften* and *Nature*. Paneth and Peters later retracted their claim but only after intense public criticism.[7]

Fleischmann has mentioned a 1929 paper by another German, Alfred Cöhn, a physics professor at the University of Göttingen, as a source of some of his ideas. Cöhn reported effects with currents running across palladium wires in the presence of hydrogen gas. Fleischmann also has written that Percy Bridgman, professor of physics at Harvard and a Nobel Prize winner who published studies in the 1930s on cold nuclear effects, had a strong influence on his early ideas.

These references provide some examples of related work going on for most of the 20th century.

Twenty years of progress

Despite a few science authorities' predictions of the prompt demise of the field, the field survived long enough to begin to mature.

At least 200 researchers from 13 nations have continued the investigation started by Fleischmann and Pons. The research has been discussed yearly at international conferences. Papers have been published in more than 55 peer-reviewed journals, though not in the highest-profile journals.

The experimental work has been the strongest part of the field for most of these 20 years; not all problems have been solved experimentally, but a vast collection of evidence for nuclear reactions has accumulated.

The attempts to construct theoretical models to explain the observations as a room-temperature deuterium–deuterium fusion process have swayed few skeptics to accept the hypothesis of a "cold fusion." Other nonfusion models, based on neutrons, have been proposed in the last few years. Neutron ideas also were considered in the early 1990s by several researchers, but their ideas never led to successful models at the time.

Variety of experimental methods

LENR experimental research methods have expanded far beyond the conventional electrolysis method used by Fleischmann and Pons. Other researchers used some of these methods as early as 1989; additional methods were introduced later.

The methods include plasma electrolysis, gas plasma (glow discharge), electromigration in solids (proton conductors), biological methods, gas loading into metals, gas diffusion through metals, gas permeation through multilayered substrates, aqueous sonic implantation, ion bombardment, electron bombardment, electrodiffusion (co-deposition) and hydraulic cavitation.

Because the possible products and effects are so vast, it is difficult to say which products and effects are produced by each of the methods; we can say only which products and effects have been searched for and reported.

Researchers typically apply one, two, or perhaps three types of instrumentation to each type of experiment. It becomes increasingly difficult to equip an experiment for a wide variety of data acquisition.

Further, many researchers engage in searches for specific products and effects. In fact, they must maintain a relatively narrow search to keep the parameter space within manageable limits.

Variety of triggering methods

Closely related to the variety of experimental methods is the variety of triggering methods. At least some researchers have known since 1989 that a stimulus is required to initiate the reactions, once the fundamental conditions of the experiment have been established.

A variety of triggers have been used. A favorite of Fleischmann and Pons was a rapid increase in current. Other people have used—sometimes unintentionally—sudden stops and starts in current flow. Ultrasonic stimulus into conventional electrolytic cells has been successful, as have been external electric and magnetic fields. Irradiation with a low-power (30 mW) laser and frequency modulation of the electrolytic input have also worked to trigger the reactions.

Variety of effects and products

Excess heat can be interpreted as an indicator of a nuclear effect, given an anomalously large energy release from a particular reaction relative to its input energy. But excess heat is not, by itself, direct evidence of a nuclear reaction. However, a wide variety of other products and effects—some of them direct evidence of nuclear reactions—have been observed in LENR research.

Direct evidence for nuclear reactions, when found at scientifically significant levels, include helium-4, helium-3, tritium, low fluxes of neutrons, charged particles, transmutations, anomalous isotopic abundances and gamma rays. The list also includes experiments that demonstrate the temporally correlated growth of one element and reduction of another element on palladium substrates.

Another group of effects shows indirect evidence of nuclear reactions. The group includes X-rays, hot spots on cathodes inexplicable by Joule heating, craters, melting and vaporization of cathodes. This group of effects is considered evidence of nuclear reactions because of the relatively low input energies—four watts, for example—to produce these effects, which, considering their experimental environment, are indicative of MeV-scale energetic reactions.

A few examples of these anomalies are provided below.

Tritium—the first nuclear evidence

The first hard evidence to support the claim that Fleischmann and Pons had created a nuclear reaction by chemical means was the discovery of tritium. In addition to being a direct nuclear evidence tritium also has the advantage that it is not nearly as ephemeral as excess heat, which vanishes as soon as it is created.

One of the first teams to witness tritium evolution from a LENR device was that of Padmanabha Krishnagopala Iyengar and Mahadeva Srinivasan at the Bhabha Atomic Research Centre in Trombay, India. They witnessed a burst on 21 April 1989 and reported it to the scientific community in July 1989.

They measured 1.5 μCi ml^{-1} from their cell after the experiment. The value in the stock D_2O before electrolysis was 0.075 nCi ml^{-1}, an increase by a factor of 20 000. This corresponded to total production of 8×10^{15} tritium atoms. They also measured neutron emission from the experiment, and this helped with their confidence that they had observed a genuine nuclear effect. They were perplexed, though, because, while they were searching for a "cold fusion" result, they noticed that the neutron-to-tritium ratio was seven orders of magnitude off from the ratio expected from thermonuclear fusion.

The research effort at BARC was and remains the most massive, multidisciplinary group effort to explore LENR. The experimental results there gave strong evidence of nuclear

Summary of Results From Groups Reporting Tritium and Neutrons in BARC Electrolysis Experiments (1989-1990)

Division	Cathode Material	Geometry	Area Cm^2	Anode	Neutron Yield	Tritium Yield	n / T Ratio
Desalin*	Ti	Rod	104	SS pipe	$3x10^{+7}$	$1.4x10^{+14}$	$2x10^{-7}$
Neut. Phy*	Pd-Ag	Tubes	300	Ni pipe	$4x10^{+7}$	$8x10^{+15}$	$5x10^{-7}$
HWD*	Pd-Ag	Tubes	300	Ni pipe	$9x10^{+7}$	$1.9x10^{+15}$	$5x10^{-7}$
HWD*	Pd-Ag	5 Disks	78	Porous Ni	$5x10^{+4}$	$4x10^{+15}$	$1.2x10^{-9}$
Anal.Ch.@	Pd	Hol. Cyl.	5.9	Pt Mesh	$3x10^{+6}$	$7.2x10^{+13}$	$4x10^{-8}$
ROMg @	Pd	Cube	6.0	Pt Mesh	$1.4x10^{+6}$	$6.7x10^{+11}$	$1.7x10^{-4}$
ROMg @	Pd	Pellet	5.7	Pt Mesh	$3x10^{+6}$	$4x10^{+12}$	$1x10^{-4}$
App.Ch.@	Pd	Ring	18	Pt Mesh	$1.8x10^{+8}$	$1.8x10^{+11}$	$1x10^{-3}$

* = 5M NaOD Electrolyte @ = 0.1M LiOd Electrolyte SBK 2009

Fig. 6 Tritium and neutron results at Bhabha Atomic Research Centre[8]

reactions, and the project stopped a few years later only for lack of courage in the newly appointed top management.

Numerous divisions within BARC were using a variety of exploratory methods to perform the research. Srinivasan concluded that tritium and neutrons were produced simultaneously. He also noted anomalous multiplicity distributions of neutron counts, suggesting that 10% to 20% of total neutrons were attributed to high multiplicity events and that neutrons were often emitted in bursts of tens and hundreds (Fig. 6).

Srinivasan wrote that the first neutron signals were detected in six of 11 cells within the first nine hours, another showed signals after 24 hours, and two more cells showed the first signals only after a couple of weeks. Because of the relatively short "switch-on" time, Srinivasan speculated that high D/Pd loading ratios were not needed for neutron production. He also noted that, on continued electrolysis, all cells stopped yielding neutron signals; he suspected that a poisoning effect began to take place. In later years, researchers who worked with heavy-water systems found that there was a major incompatibility with H_2O in D_2O systems and that the hygroscopic nature of D_2O pulled H_2O from humid environments and killed any LENR effects.

In a talk by Srinivasan at an American Chemical Society meeting in March 2009, he asked the rhetorical question, "Why has no one else observed bunched neutron emission?" His answer was, "No one has looked for it!"

Another reason may be that, in the early 1990s, the LENR field seemed to become preoccupied with proving that LENR was "cold fusion" by trying to prove a definitive and precise correlation between excess heat and nuclear products that matched what would be expected from thermonuclear fusion. Because neither neutron flux nor tritium production even came close to a quantitative correlation for the observed energy output, research interest favored helium and calorimetry studies, instead.[9–11]

Anomalous effects

A variety of anomalous physical effects on the cathodes, such as the melting and vapourization of palladium and tungsten in experiments, have been observed. These effects cannot be the result of Joule heating because the energy inputs are too low.[2,12–14]

Other changes to the cathodes include unusual morphological deformations, craters and "hot spots", (Fig. 7–9).[15]

Helium-4

In the early 1990s, electrochemist Melvin Miles was at the U.S. Navy's China Lake facility, working with analysts Ben Bush and J. Joseph Lagowski at the University of Texas at Austin. While there, Miles observed that He-4 is one of the dominant nuclear products from LENR experiments.

In the following years, several other researchers also measured helium-4 and noted that its evolution was temporally correlated to LENR excess heat production.[18] Some researchers have also

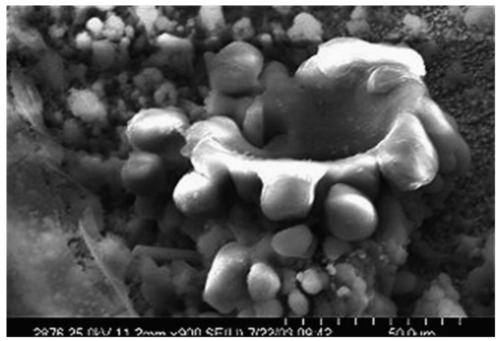

Fig. 7 SEM image of molten Pd on Au foil used as a cathode in a 2003 SPAWAR co-deposition experiment with an external electric field (6000 V). Appears similar to quickly heated molten metal followed by fast cooling from immersion in electrolyte. Photo: Charlie Young.[16]

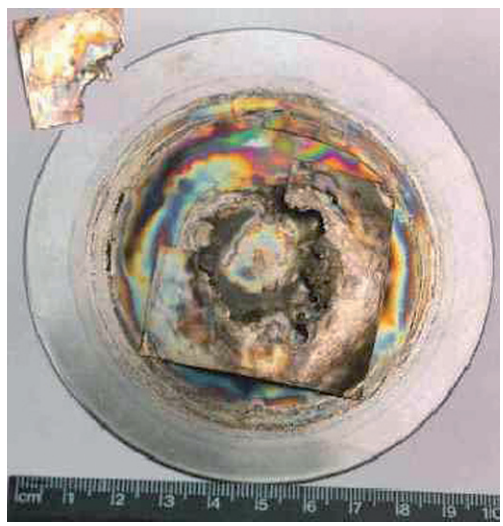

Fig. 8 Two pieces of metal: A 50 × 50 × 0.01 mm Pd foil in front of a 40 mm thick 10 cm stainless steel disk. The pieces were used together by Stringham during a 20-hour acoustic cavitation experiment. The only power applied to the experiment was applied acoustically from a 500 Watt Misonix's 5 cm Ti acoustic horn. The colored pattern on the stainless steel disk is caused by the migration of Pd atoms to the disk. The thin layer of Pd or palladium oxide deposits on the stainless steel disk and the condition of the melted Pd foil indicate very high transient and local temperatures sufficient to vaporize Pd. This experiment was performed around 1994–1995.[11] Photo: R. Stringham.

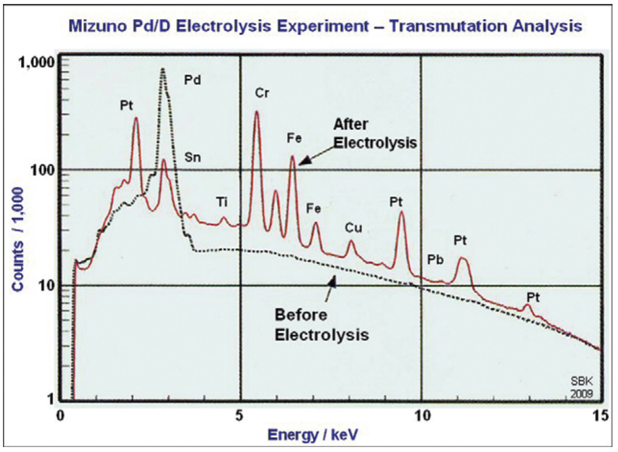

Fig. 9 EDX element analysis of a palladium rod after it produced excess heat during electrolysis. Results from before and after electrolysis are shown. After electrolysis, many elements are observed in the rod.[17]

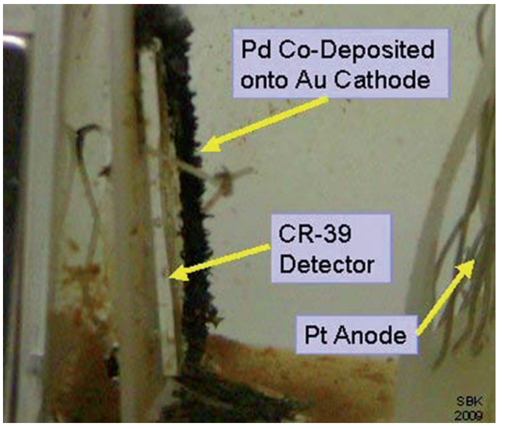

Fig. 10 Pd co-deposited onto cathode wire in SPAWAR LENR experiment. Photo: P. Mosier-Boss.

suggested that helium-4 is the sole nuclear product of LENR reactions, that the measured energy per helium-4 atom produced is precisely 24 MeV and that no other energetic reactions are occurring in LENR systems. Therefore, based on these suggestions, they have asserted that the relationship between helium-4 and excess heat proves the LENR process is a fusion process because the heat and helium-4 mimic the third branch of thermonuclear fusion, though without the gamma. Although a few researchers have accepted the "cold fusion" theory claims of their collaborators, the scientific community has not recognized these claims.

Charged particle and neutron emission

Some researchers, rather than search for the chemical registration of helium emission, search for its energetic signature. They record the emission of charged alpha particles, using solid-state nuclear track detectors, also known as CR-39 track detectors, or observing tracks on X-ray films.[19]

Some of the most significant *in situ* particle detections have been observed in experiments and replications of work originating from the U.S. Navy's Space and Naval Warfare Systems Command Center in San Diego.[20,21]

One unique aspect of the SPAWAR experiment is the co-deposition process, wherein atoms of palladium and deuterium are deposited, atom by atom, onto a host metal (Fig. 10).

In conjunction with the co-deposition process, the SPAWAR researchers use CR-39 detectors to record the emissions of what appear to be charged particles as well as evidence of neutron emission. These detectors permanently record the history of nuclear emissions from the experiments and have shown extremely high track densities and signal-to-noise ratios in these experiments.

The researchers have used the nuclear track detectors both inside the electrolytic cells (wet experiments) and outside the cells, protected by thin membranes (dry experiments).

So far, optical analyses show the visual characteristics nearly identical to those you would expect to see from tracks caused by particle emissions.

Initially, the researchers were looking for evidence of alpha particle emission; however, they also discovered tracks coming through the detectors, which suggested that neutron emissions are causing recoil reactions. For charged particles to traverse through the 1 mm CR-39 plastic, 40 MeV particles would have been required, and apparatus to produce such particles were not present in the SPAWAR environment.

The flux of neutrons they observe is many orders of magnitude lower than would be expected from thermonuclear fusion. This is typical of LENR and has made the detection of neutrons difficult throughout the years. Furthermore, the neutron emissions are bursty and sporadic, and such emissions, when averaged over time, tend to disappear when using electronic detectors. CR-39 has the benefit of being a constantly integrating detector, which helps to reveal sporadic signals over long periods much better.

Lawrence Forsley, of JWK Technologies in Virginia, a collaborator of SPAWAR, used a device (Track Analysis Systems Ltd.) to map the patterns of tracks on CR-39 detectors from experiments. Forsley has shown a direct spatial correlation between the cathode, believed to be the source of the emissions, and tracks on the CR-39 that face toward the cathode and those that face away from the cathode. Given the absence of nearby particle accelerators and the absence of signals from controls, only a proton recoil effect from neutron emissions can explain the phenomenon (Fig. 11).[22]

The SPAWAR group also observed evidence of "triple tracks," reported as evidence of carbon-12 breakup into three alpha particles, assumed to be the result of proton recoil from neutron emission. Replication efforts at SRI International, as well as the University of California at San Diego, also recorded evidence of "triple tracks" (Fig. 12).[23,24]

SRI reported a "neutron count above background suggested in at least three experiments" through the use of a BF_3 ionizing neutron detector that has worked reliably for many years (Fig. 13).

Two of the CR-39 detectors from the SRI International SPAWAR replications were measured and analyzed independently by researchers at the Russian Academy of Sciences. Using a sequential etching method, they reported that "a weak but statistically significant emission of fast neutrons has been

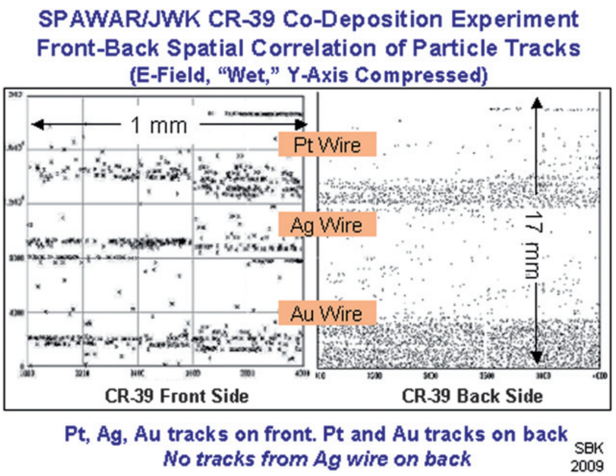

Fig. 11 Front and backside spatial correlation of particle tracks from SPAWAR LENR experiment.

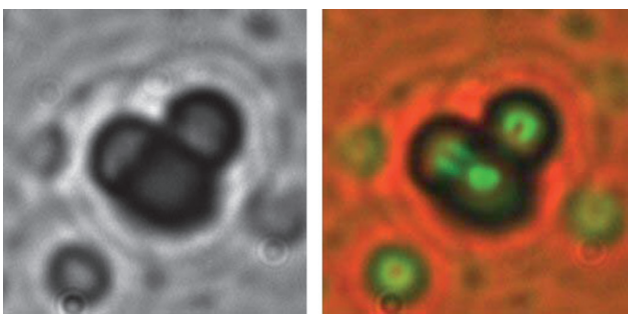

Fig. 12 SRI replication BE010-5 of SPAWAR co-deposition experiment. "Triple track" observed from same experiment that registered neutron signal on BF_3 ionizing neutron detector. Experiment performed by Stanford University student Ben Earle.[25]

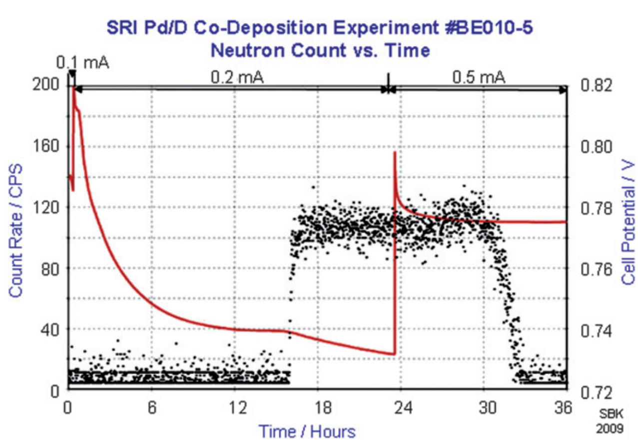

Fig. 13 SRI replication of SPAWAR co-deposition experiment. Neutron signal shows 14× greater than background during a 14-hour burst. Measurement by BF_3 ionizing neutron detector placed about 10 cm from operating cell. Drop in cell potential temporally correlated with onset of neutron signal suggests cell heating. Experiment performed by Stanford University student Ben Earle.[25]

observed in SRI's #7 and #5 runs replicating the SPAWAR Pd-codeposition experiment."

They displayed a plot of track density *vs.* track depth, converted to MeV, which shows a plot that is consistent with neutron emissions from Cf-252.

To rule out concerns about background signals, the researchers compared the sample tracks with tracks from blank CR-39. They concluded that, based on the results of more than 100 similar measurements they had performed with the material, the sample and blank detectors had not been irradiated by neutrons in any airport security facility (Fig. 14).

This method appears to provide the conditions required to create LENR effects repeatably and reproducibly. Many years ago, SPAWAR researchers also reported observing excess heat with the co-deposition method, but their current work has been directed more toward understanding the nuclear characteristics of the phenomena than toward attempts to make hot water.

Iwamura's transmutation experiments

Several rigorous sets of heavy-element LENR transmutation experiments have been performed by Yasuhiro Iwamura at Mitsubishi Heavy Industries. The essential part of the experiment is a multilayered substrate containing layers of palladium and calcium oxide. Atoms from the source element are placed on the surface. Deuterium gas is passed through the substrate. No energy, aside from the flowing deuterium, is applied to the experiment (Fig. 15).

When Iwamura added Cs on the surface of a Pd complex, Pr emerged on the surface while Cs decreased after the Pd complex was subjected to D_2 gas permeation. When Iwamura added Sr to the surface, Mo emerged while the Sr decreased after D_2 gas permeation (Fig. 16).[27]

The Iwamura experiment is one of a variety of LENR experiments that show anomalous heavy-element transmutations as well as anomalous isotopic abundance.

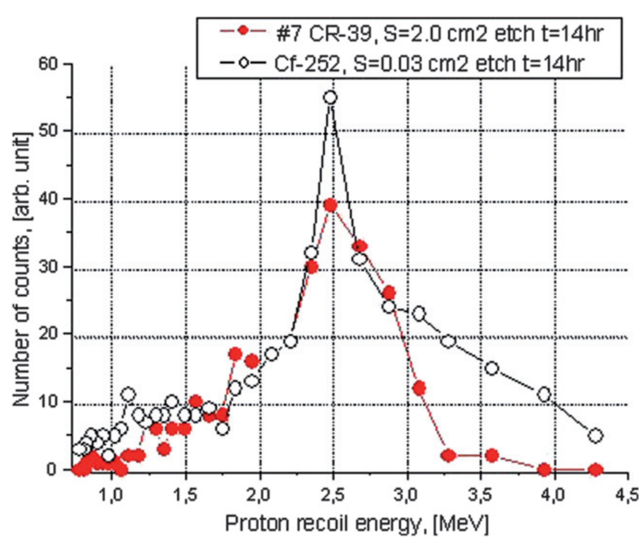

Fig. 14 Russian Academy of Sciences (Lipson and Roussetski) analysis of SRI International replication of SPAWAR co-deposition experiment[26] (Figure copyright ISCMNS).

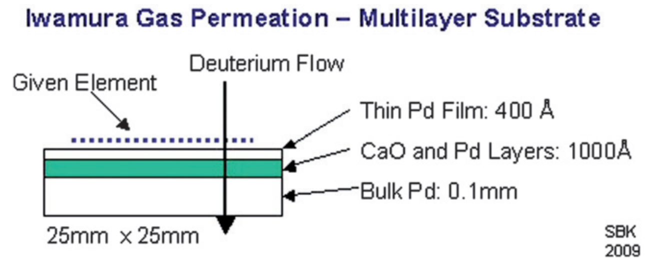

Fig. 15 Iwamura multilayer substrate with source element (for example, Sr) placed on surface. Iwamura has performed the experiment numerous times with a variety of "given elements" placed on the surface of the substrate.

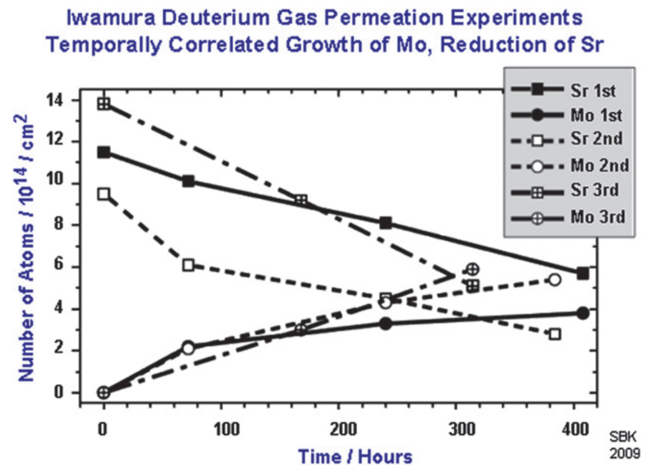

Fig. 16 Three experiments performed by Iwamura and Takehiko Itoh, Mitsubishi Heavy Industries: Increase of Mo and temporally correlated decrease of Sr.[27]

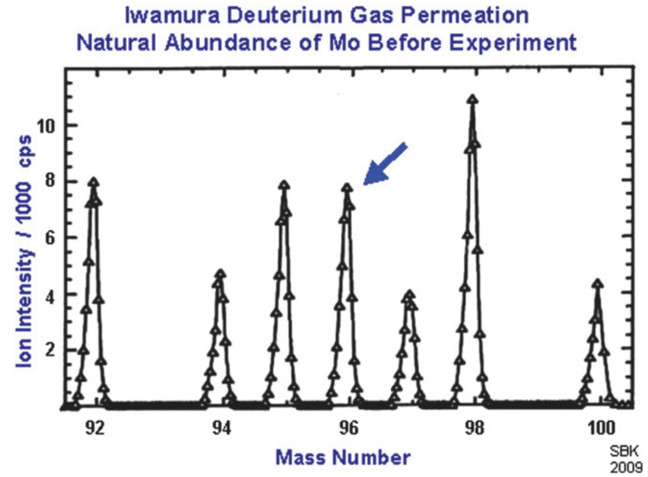

Fig. 17 Iwamura & Itoh, Mitsubishi Heavy Industries experiment. SIMS measurement of natural Mo before performing D2 gas diffusion experiment. Several Mo isotopes are abundant.[27]

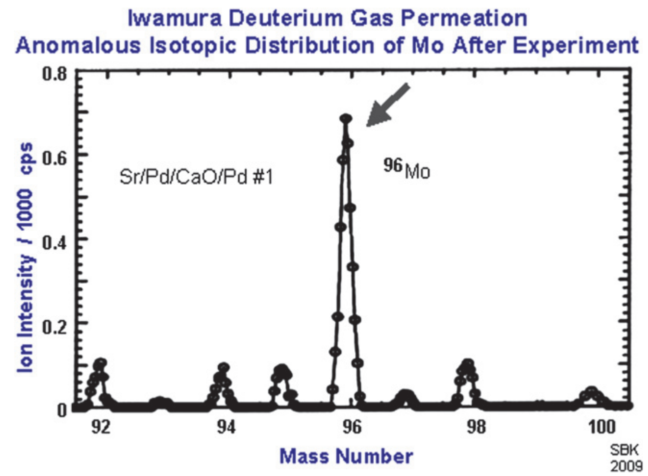

Fig. 18 Iwamura & Itoh, Mitsubishi Heavy Industries gas permeation experiment. SIMS measurement of anomalous isotopic abundances of Mo after performing D2 gas diffusion experiment.[27]

Iwamura reported that the isotopic abundance of the detected Mo was different from the natural abundance. He confirmed the detected Pr by a variety of methods, including TOF-SIMS, XANES, X-ray Fluorescence Spectrometry and ICP-MS (Fig. 17 and 18).

Iwamura and his group performed some analysis *in situ* and later, at the Japanese Spring-8 Synchrotron. They published their research in the *Japanese Journal of Applied Physics* as well as in conference proceedings.[28] A related replication was performed at Osaka University.[29]

Some scientists, particularly LENR researchers who propose a "cold fusion" phenomenon, have expressed skepticism about the transmutation results, suggesting that the new elements are the result of contamination. The same researchers have argued that no other energetic reactions occur in LENR experiments except the direct and exclusive transmutation of deuterium into helium-4.

We are not aware of any published, peer-reviewed critiques of the Iwamura transmutation work that definitively or even remotely disprove it by suggesting an error in laboratory protocol, unreliability of instrumentation, or faulty analysis.

"Contamination" can certainly come from many places, though the registration of the rare element praseodymium in the Iwamura experiment weakens such speculation. Even if the new elements came from "contamination," this speculation does not explain the reduction of the "given elements." Furthermore, the temporally correlated reduction of the "given element" and the growth of the new element show the "contamination" speculation for what it is: misinformation.

A perspective by some researchers who propose the "cold fusion" explanation of LENR is that "transmutation is irrelevant and showing that it occurs is a waste of time." Alternatively, if LENR is not inevitably explained as a "cold fusion" process, then the heavy-element transmutation experiments may indeed shed light on the conversion of deuterium to helium. It, too, may turn out to be a transmutation process: simply, the addition or subtraction of protons, perhaps by way of neutron catalysis.

Some researchers who favor the "cold fusion" explanation speculate that transmutations could be a secondary reaction because of the high energy produced by the fusion reaction D + D > 4He. This logic follows the concept that, if you have "cold fusion," you can make transmutations—if you have "cold fusion."

The speculation that the transmutations are the result of "cold fusion" reactions moves further away from what Nature is saying and closer to a desired human outcome; "cold fusion."

NASA excess-heat experiment

A team at NASA measured excess heat from a gas diffusion experiment in 1989 but, ironically, the researchers didn't recognize their success at the time. They pumped deuterium and hydrogen gas (individually) through a palladium filter.

They were looking for neutrons, because in 1989 many people expected that "cold fusion" was a "colder" form of thermonuclear fusion. The NASA researchers found no significant neutron signal. However, they were perplexed about the "source of the heating which occurs when D_2 and not H_2 is pumped through the Pd."

Without a significant signal of neutron emissions, they incorrectly assumed that their experiment had failed. (NASA now recognizes the significance of this experiment: NASA researcher Marc G. Millis, at the John H. Glenn Research Center at Lewis Field in Cleveland, Ohio, and Dennis M. Bushnell, chief scientist at Langley Research Center in Hampton, Virginia, have developed a newfound interest in LENR.)[30]

Arata-Zhang gas absorption experiment

A more recent LENR method using deuterium or hydrogen gas has also shown evidence of anomalous energy production.[31,32]

Yoshiaki Arata (Osaka University) and Yue Chang Zhang (Shianghai Jiotong University) fed deuterium or hydrogen gas—at pressures reaching 65 atm—into a stainless steel chamber that contained palladium nanopowder samples.

The only source of energy input was the gas pressure. The result was long-lasting anomalous heat production from the cell, as well as the evolution of helium-4. According to Arata, no helium was present in any of the materials before the experiment, and no helium was introduced from the atmosphere.

In 2009, Akira Kitamura's group at Kobe University published a replication of the Arata-Zhang gas absorption experiment. Although they did not report findings of helium-4, they did report anomalously large energy release from both deuterium and hydrogen experiments.[33]

Acoustic inertial confinement fusion (bubble nuclear fusion)

Acoustic inertial confinement fusion is not LENR, but it is closely related because it is another area of nuclear research that, like LENR, can be performed with relatively simple equipment and at or near room temperature. But the local reaction temperature with some of the experiments does get very high.

A chamber is filled with a fluid, and two stimuli react on that chamber. The first stimulus is an ultrasonic acoustic wave that induces cavitation; the second is a "seed" neutron source. The design and construction of the chamber is challenging, and only a few glassblowers at Oak Ridge National laboratory have been successful at making working test chambers. The operation of the experiment is not quite as difficult; it can and has been learned, by students as well as some professionals (Fig. 19).

The acoustic input causes high compression within the chamber, and this leads to a series of rapid bubble growth and collapse. At the collapse, observers see light flashes, a phenomenon known as sonoluminescence (Fig. 20).

AICF has been studied for many years in single-bubble sonoluminescence research, but a group at Oak Ridge National Laboratory, led by nuclear engineer Rusi Taleyarkhan, figured out how to create multibubble sonoluminescence. This discovery

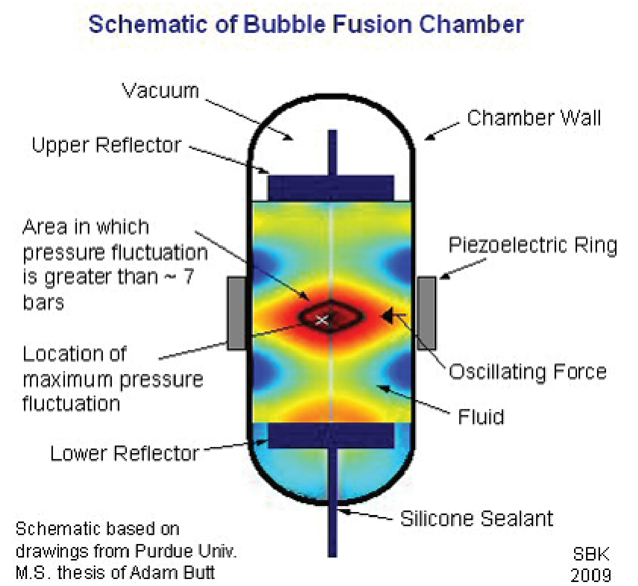

Fig. 19 Schematic of bubble fusion chamber. Regions of high and low acoustic pressure are shown. Based on drawings by Purdue University graduate student Adam Butt.[34]

Fig. 20 Example of high-Q resonance acoustic chamber design developed by Rensselaer Polytechnic Institute (Image courtesy Richard T. Lahey).

led to the pressures and temperatures required to achieve nuclear reactions.

The Taleyarkhan research group at Oak Ridge National Laboratory successfully measured neutrons and tritium in these experiments. No nuclear products are registered in the absence of acoustic cavitation; no nuclear products are registered in the absence of a neutron seed, either. No significant nuclear products are measured in the background (Fig. 21).

Early criticism of the work ignored the fact that statistically significant levels of tritium were being produced. If recognized, that would have, on its own, been sufficient to confirm that a nuclear reaction had occurred. Instead, critics said that the measured neutrons might have been from the pulse neutron generator supplying the seed neutrons.

This critique was based on misinformation because there was a 10-microsecond gap between the signal from the neutron seed and the beginning of the bubble implosion. The researchers were able to gate their neutron detector in such a manner as to isolate the two sets of neutron signals (Fig. 22).

The researchers went further to address lingering concerns about an external neutron seeding source; They developed another method - a self-nucleating method - which removed the question about an ability to discern external seed neutrons from experiment-generated neutrons.[36–38]

The experiment has been replicated, with moderate independence, by the team of Yiban Xu and Adam Butt[39] of Purdue in a laboratory operated by Purdue professor Lefteri Tsoukalas. Ted Forringer of LeTourneau University[40] also replicated the experiment as a guest researcher in Taleyarkhan's lab at Purdue (Fig. 23).

LENR replication successes and challenges

The LENR experiments that have been performed to search for charged particles and neutrons through co-deposition experiments, and experiments performed to search for transmutations through gas permeation through multilayer substrates, have generally been 100% repeatable (by the originators) and reproducible (by replicators). These two methods, and perhaps others, appear to be more conducive to successfully controlling the experimental environment to ensure a positive result. Gas diffusion to produce excess heat has been reported in recent years and seems to be reproducible, but these studies are few.

Alternatively, replication of the excess-heat effect using electrolysis has been more common in the last two decades; it has also appeared to be the most difficult to reproduce consistently.

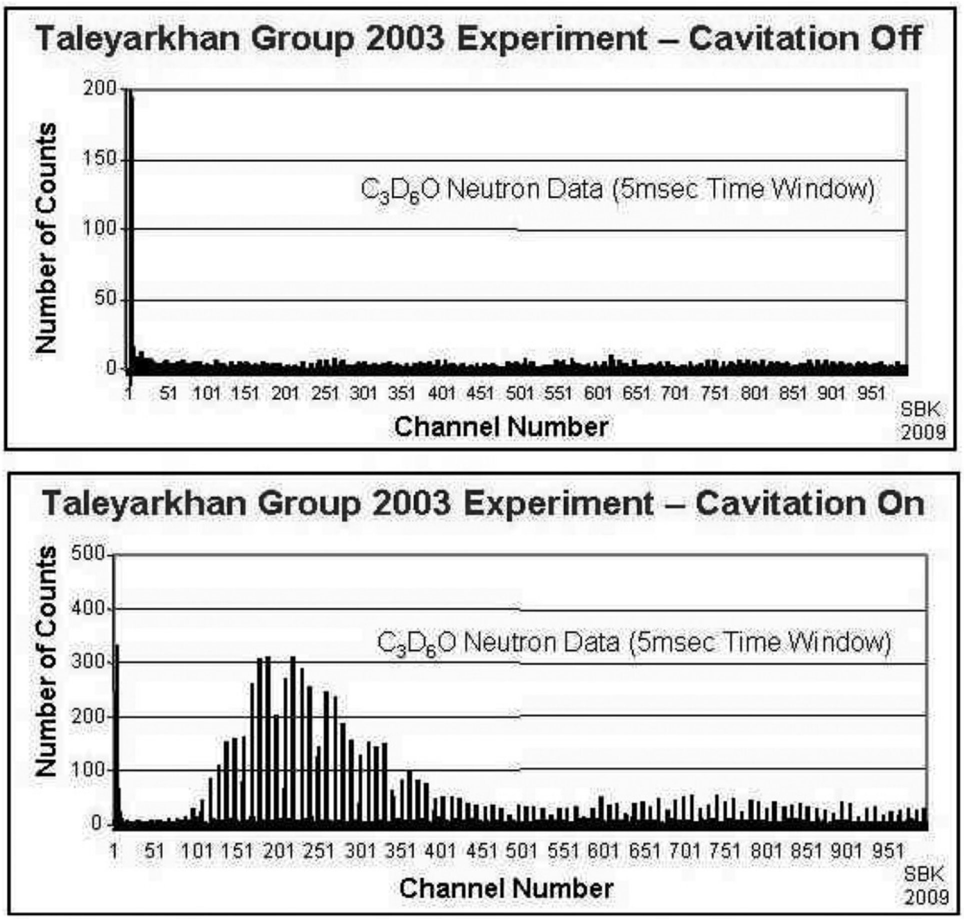

Fig. 21 Statistical analysis is not required to see the dramatic difference between experiments. Both experiments shown above were performed with an external pulse neutron generator. The upper image shows the detected neutron signal with cavitation on. The lower image shows the detected neutron signal with cavitation off.[35]

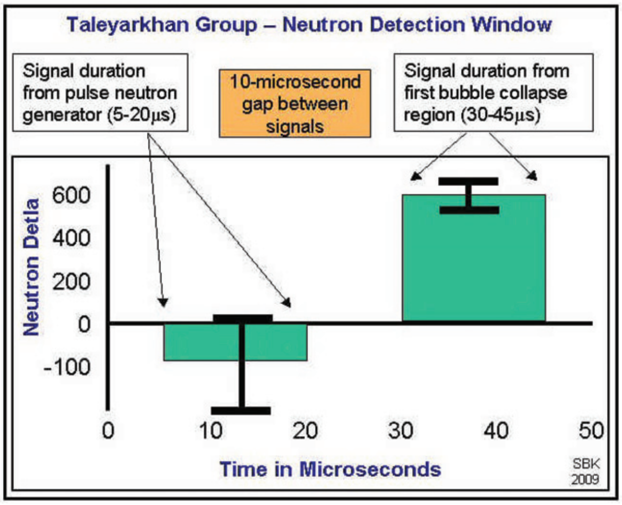

Fig. 22 Time sequence of neutron signals in Taleyarkhan group's bubble fusion experiment. The 10-microsecond gap allowed them to discern neutrons emitted from the pulse neutron generator from the bubble fusion experiment.

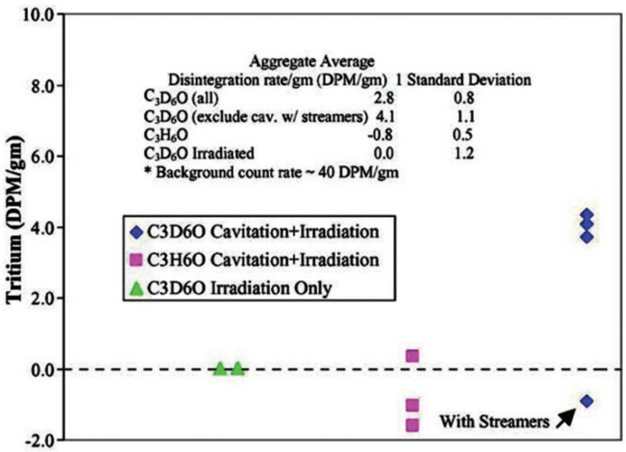

Fig. 23 Three of four experiments showed 4–5 SD signals of tritium from Xu/Butt bubble fusion replication. The fourth experiment displayed "streamers," which indicates that the experiment did not achieve the correct thermohydraulic conditions.[39]

From an experimental (rather than theoretical) point of view, the greatest challenge and mystery in a successful excess-heat experiment is to obtain/fabricate suitable cathode material. Fleischmann and Pons appear to have had the greatest mastery of this during the early 1990s though that knowledge has not transferred to other researchers.

However, researchers have learned which conditions do not lead to excess heat in the conventional electrolytic experiment: an atomic loading of less than D/Pd $= 0.90$, an electrical current density in the cathode less than about 250 mA cm^{-2}, and a state of equilibrium.

A dynamic trigger appears necessary to jolt the cell condition out of equilibrium. Some researchers suggest that inducing some form of disequilibrium imposes a deuterium flux in, on or around the cathode. As mentioned earlier, a variety of triggering methods has been used.

Co-deposition method: a reproducible experiment

Researchers at the U.S. Navy SPAWAR lab in San Diego have developed an experiment that appears to be reproducible on demand. As mentioned previously in this paper, their results have been independently replicated at SRI International, the University of California at San Diego and other labs. Instead of using a traditional palladium cathode, the SPAWAR group electrochemically deposits palladium, simultaneously with deuterium, onto a substrate of nickel, silver, platinum or gold.

The co-deposition electrolysis method achieves the required D/Pd atomic ratio nearly instantly and consistently, thereby circumventing the problem of long wait times to achieve high loading in solid palladium cathodes. Something else about the co-deposition method must make it yield consistently positive results because some LENR researchers who use very thin foils in conventional electrolytic cells can also obtain results within a few hours. Therefore, the co-deposition process does not solve the problem of reproducibility merely by getting the optimal loading ratio quickly; whatever else is occurring is unknown to us.

LENR theories

Two broad categories of theories try to explain low-energy nuclear reaction phenomena. The first category explains LENR phenomena as the result of a process or processes that overcome, reduce, or ignore the Coulomb barrier's electromagnetic repulsion of positively charged nuclei from each other. If successful, these theories would also explain the lack of strong neutron emissions and the lack of strong emission of gamma or X-rays. Together, these three groups of challenges have been known as the three "miracles of cold fusion."

The second category of theories postulates that neutrons play a key role in the addition or subtraction of protons with nuclei. These theories must also explain why no strong nuclear emissions emanate from LENR experiments.

We have contacted many of the researchers who propose theoretical explanations for LENR phenomena. We reviewed with them and sought their input on brief summaries of each of their models. When we did not receive a response from one of the theoreticians, we cited text from his published work.

Yeong Kim

Yeong Kim proposes that a nuclear Bose–Einstein condensation can suppress the Coulomb barrier and explain most LENR phenomena as a fusion process. The theory is based on the concept of nuclear Bose–Einstein condensate state for mobile deuterons trapped in a micro/nanoscale metal grain or particle, which acts as a confinement or trapping potential.[41]

Heinrich Hora and George Miley

Heinrich Hora's theory explains the LENR measurements of Miley's group based on d–d fusion reaction experiments. The reactions are in picometer distance with probabilities of about 100 kiloseconds. The reactions are similar to K-shell nuclear transitions and are based on a reduction of Coulomb repulsion by a screening factor of 14, with preference at interfaces because of the swimming electron layer. This explains the Miley group's measurements of LENR generation of elements up to and beyond gold, with maxima identical to the same element distribution as in the universe. This confirmation of the LENR mechanism leads to a new theory for the well-known magic numbers of nuclei, a similarity of LENR to uranium fission distributions, to the Maruhn-Greiner maxima at fission, and to deuteron clusters in palladium with 2-picometer nuclear distance.[42,43]

Scott Chubb

Scott Chubb initially proposed that cold fusion reactions could occur through an idea involving ion band states that, at the time, appeared to ignore the Coulomb barrier. The underlying concept made use of approximate, quasi-particle ideas, associated with conventional solid-state physics. Beginning in 1997, Chubb developed an important improvement that involves a generalization of the quasi-particle idea that includes time-dependent features and key effects associated with finite size. In the process of formulating this improvement, he generalized the conventional theory associated with energy band theory and quasi-particles by incorporating all of the relevant time-dependent, quantum-mechanical effects associated with the limit where energy band theory applies. In particular, in the limit associated with an ordered solid, many cancellations take place, and the idea that the solid, as a whole, can move rigidly provides an important avenue for justifying conventional energy band theory and forms of reaction that can explain "cold fusion."[44]

Talbot Chubb

Talbot Chubb's theory fits in the category of ion band states. Chubb proposes a metal-catalyzed nuclear fusion theory in which deuterons (pn nuclei) diffusing through a metal encounter 10-nm domains with gem-quality lattice order and adopt the local geometry of the metal electrons.

They form spin-zero deuteron pairs neutralized by spin-zero electron pairs, which have a resonant standing-wave configuration (no Coulomb barrier).Wavelike deuteron pairs change into wavelike helium-4 nuclei with (pn,pn) nuclear geometry. The (pn,pn) helium-4 subsequently decays to (pp,nn) helium-4, which is nuclearly stable. Energy is transferred to bulk metal electrons by multiple electron scatterings (momentum transfers) and/or lattice vibration excitations (phonons).[45]

Xing Zhong Li

Xing Zhong Li proposes a selective resonant tunneling effect, based on conventional quantum mechanics and the weak interaction to explain the three mysteries of room-temperature fusion. His theory is consistent with hot fusion experimental data (d + t, d + d, and d + 3He fusion cross-sections *etc.*), as well, and predicts the anomalous d + d + d fusion reaction, which has been verified in experiments.[46,47]

Akito Takahashi

Akito Takahashi proposes a nonlinear Langevin equation that depicts a tetrahedral symmetric condensate with four deuterons and four electrons. Takahashi proposes this as a seed of four-deuterium fusion with helium-4 products in condensed matter. TSC condenses in about 1.4fs to make 4D fusion; then, the compound nucleus Be-8* breaks up into two helium-4 atoms as a major outgoing channel.[48]

Peter Hagelstein

In a paper Peter Hagelstein wrote, he said that his model is based on "excitation transfer in which global energy is conserved but local energy conservation is violated." In the model, he said, "Two deuterons interact to make 4He, exchanging one or more phonons in the process, with the reaction energy transferred elsewhere. The coupling in this case is weak since the transition is hindered by the presence of a Gamow factor due to coupling through the Coulomb barrier."[49]

Antonella De Ninno

Antonella De Ninno states that deuterons inside the Pd lattice can be viewed as a plasma in condensed matter having a strong electromagnetic coupling with the lattice. Collective phenomena provide the energy required to realize those condensed plasma states.

The basic concept of thermonuclear fusion is to produce extremely high energy densities within very short times in very small volumes. However, solid-state plasmas can be naturally available in nature under suitable circumstances. From this perspective, experiments using deuterium flux or implantation in an appropriate cathode which fulfils the "plasma" condition (that is, over the loading threshold) are just unusual verification of the Oliphant beam fusion.

Collective mechanism can explain the experimentally observed production of 4He. The strong coupling with the electromagnetic field in the lattice and the mismatch between the characteristic times of nuclear reactions and electromagnetic reactions explain the presence of an intense electromagnetic field in the lattice. Its coupling with matter can trigger reactions (giant resonance) which can explain part of the transmutation elements found in the materials.[50]

Krit Prasad Sinha and Andrew Meulenberg

According to Krit Prasad Sinha and Andrew Meulenberg, hydrogen isotopes form a sublattice in the bulk, on the surfaces, and at defects within the lattice of palladium (and other metals). Collective one-dimensional (phononic) motion of these atoms in the lattice(s) is the basis for tightly bound ground-state electron pairs providing super-strong screening of the nuclear Coulomb barrier. During the point of nearest approach in repeated collisions of hydrogen atoms (in pairs: one with electron(s) and one without), the bound electron(s) go deep into the combined nuclear-Coulomb-potential well (without radiating photons) and attain near-MeV energies. The energetic electron(s) remain tightly bound during nuclear penetration of the residual nuclear Coulomb barrier and, on entering the nuclear potential well with both nuclei, temporarily increase(s) the effective nuclear-binding energy. These electrons (before being ejected) reduce the nucleon energies toward or below fragmentation levels, mediate energy transfer from the excited nucleus to the lattice, possibly create neutrons through the pep reaction, and, if paired, allow the "neutralized" nucleus to penetrate neighboring nuclei and result in transmutation. Thus, within known physics, this model can qualitatively explain all experimental results observed in low-energy nuclear reactions.[51]

Vitalii Kirkinskii and Yurii Novikov

Vitalii Kirkinskii and Yurii Novikov performed computer simulations of nuclear fusion in metals at low energies. They based their simulations on two original theoretical models with regard to quantitatively dynamic screening of the ion charges of hydrogen isotopes by electrons of the outer shells of metals near the boundary of their neighboring positions in the crystal structures. According to the authors, calculated rates of nuclear reactions agree within an order of magnitude with the values deduced from experimental data on excess-heat release for palladium deuteride in some processes.[52]

John Fisher

John Fisher proposes that neutron clusters (polyneutrons) containing tens or hundreds of neutrons are tightly bound and are stable against strong decay and that these clusters can react with ordinary nuclei by transferring neutrons to them or accepting neutrons from them. Nuclei that receive neutrons are transmuted by beta decay to many different elements, including helium. Clusters that receive neutrons grow and split in a chain reaction that enables potentially unlimited production of transmutation products and energy.[53]

Allan Widom and Lewis Larsen

Allan Widom and Lewis Larsen propose that, in condensed matter, local breakdown of the Born–Oppenheimer approximation occurs in homogeneous, many-body, collectively oscillating patches of protons, deuterons, or tritons found on surfaces of fully loaded metallic hydrides; Born–Oppenheimer breakdown enables a degree of electromagnetic coupling of surface proton/deuteron/triton oscillations with those of nearby surface plasmon polariton (SPP) electrons. Such coupling between collective oscillations creates local nuclear-strength electric fields in the vicinity of the patches.

SPP electrons bathed in such high fields increase their effective mass, thus becoming heavy electrons. Widom and Larsen propose that heavy SPP electrons can react directly with protons, deuterons, or tritons located in surface patches through an inverse beta decay process that results in simultaneous collective production of one, two, or three neutrons, respectively, and a neutrino.

Collectively produced neutrons are created ultra-cold; that is, they have ultra-low momentum and extremely large quantum mechanical wavelengths and absorption cross-sections compared to "typical" neutrons at thermal energies.

Finally, Widom and Larsen propose that heavy SPP patch electrons are uniquely able to immediately convert almost any locally produced or incident gamma radiation directly into infrared heat energy, thus providing a form of built-in gamma shielding for LENR nuclear reactions.[54,55]

Hideo Kozima

Hideo Kozima uses a phenomenological approach and proposes a "trapped neutron catalyzed fusion" model based on experimental facts, which assumes the existence of quasi-stable thermal neutrons. The neutrons are assumed to be the thermal background neutrons trapped in solids and neutrons bred by nuclear reactions between the trapped neutrons and nuclei in the solids. Once neutrons exist in the sample, the mechanism to produce new nuclides from existing ones in terms of nuclear reactions with the neutrons is conventional and explains the regularity in the mass dependence of the yield of a variety of generated nuclides observed by several researchers. Kozima also tries to explain several features of the "cold fusion" phenomenon using concepts of complexity.[56]

Other ideas

Yuri Bazhutov, working with theoretician Grigoriy Vereshkov, proposes hypothetical particles he calls "Erzions," stable massive hadrons in the cosmic rays, as a theoretical explanation in the framework of the Mirror Model, which could explain all important LENR anomalies.

Another Russian scientist, Fangil Gareev, has invented a hypothetical particle called dinuetroneum, which he says can explain LENR phenomena. The dineutron concept was also introduced in 1992 by Jinqing Yang.

Several researchers (Iwamura, Tadahiko Mizuno and Stan Szpak) have proposed inverse beta decay reactions to explain LENR.

Theory summary

There is no lack of effort to explain LENR. There are also very few comprehensive, qualitative evaluations of LENR theories. One review, however, is worthy of note. In 1994, Fleischmann, Pons and Giuliano Preparata published "Possible Theories of Cold Fusion."[57] The review is about "impossible theories," as well. The authors are boldly critical of some of the LENR theoretical speculations:

"We conclude that all theoretical attempts that concentrate only on few-body interactions, both electromagnetic and nuclear, are probably insufficient to explain such phenomena. On the other hand we find good indications that theories describing collective, coherent interactions among elementary constituents leading to macroscopic quantum-mechanical effects belong to the class of possible theories of those phenomena."

"A further possible way of avoiding the Coulomb repulsion is the proposal that fusion takes place between two particles, one of which is either neutral (a neutron) or seen as neutral by the other particle down to very short distances. We regard these proposals as being impossible unless one is able to show that "on shell" neutrons can be produced from the deuterons in the lattice, or that electrons can stick to deuterons at distances as small as a few hundred fm."

Fleischmann, Pons and Preparata submitted their theory review paper in June 1993. Eight months earlier, in October 1992, the Third International Conference on Cold Fusion took place in Nagoya, Japan. Hagelstein wrote a summary of the conference which included a four-page overview of the theoretical approaches at the time.

In 1992, Hagelstein noted, as we also noted earlier in this paper, a major distinction between theories: "those involving (modified) fusion mechanisms, and those not involving fusion mechanisms."

He concisely summarized the challenges of those in the former group: "Papers considering fusion mechanisms face the two basic problems of (1) arranging to get nuclei close enough together to fuse, and (2) possibly modifying the fusion reaction profiles."

Cyclical patterns have occurred in the views that have attempted to explain LENR. Hagelstein noted that "a number of theorists, including myself, have gone away from fusion reaction mechanisms." He now is a strong advocate of the D + D > 4He "cold fusion" hypothesis. Some recent LENR conferences have also placed a major focus on the D + D > 4He "cold fusion" hypothesis as the fundamental explanation for most LENR phenomena, though this focus, too, may be in flux.

Conclusion

The LENR research is anything but simple. It comprises numerous methodologies, products and effects. Theoretical speculation and interpretation of experiments are diverse. LENR experiments, initiated through chemical and mechanical means, are producing nuclear effects and products. The breadth of the research shows an immensely broad array of phenomenological effects. It is, without a doubt, a new field of science, but it has many mysteries left to solve. The solutions could lead to many applications.

When LENR research was first publicly introduced in 1989 as room-temperature fusion, the hope was that it might be the long-sought-after answer to society's pressing needs for an abundant, clean, sustainable energy source. The fact that the reported energy release occurred without dangerous levels of prompt radiation, long-lived radiation or greenhouse gases seemed too good to be true. As miraculous as these characteristics sounded then and still do today, they are supported by an ever-expanding body of scientific knowledge.

If the remaining secrets of Nature can be unlocked, the likelihood of LENRs becoming a viable source of clean energy is strong. LENR does not represent a mere incremental increase in either energy production or energy efficiency; it represents an exponentially larger potential increase in energy-generation capacity than all fossil fuel solutions.

LENR has the potential to provide unlimited production of electricity for homes, businesses and industry. More important, portable LENR devices could replace liquid fuels for transportation. LENR devices would not have the reliability limitations that exist with wind and solar and would not require the intermediate step of converting wind or solar into stored electrical power.

Acknowledgements

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