Chapter 1

Low Energy Nuclear Reactions: The Emergence of Condensed Matter Nuclear Science

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Introduction

It is helpful to begin with an introduction of relevant terminology. Low energy nuclear reactions (LENR) is the chosen term to describe the observations in the field of condensed matter nuclear science (CMNS).

Initially, the media labeled the field "cold fusion." However, that is a less-than-optimal name for this research. One of the primary reasons is that the term cold fusion implies that these reactions were just a "colder" form of conventional thermonuclear reactions, which they are not. This has resulted in significant confusion. As well, other nonfusion reactions have been clearly observed in addition to the possible fusion reaction.

The field is in its 19th year. It was introduced in 1989 by Martin Fleischmann and Stanley Pons at the University of Utah. The field evolved from their research, which used an electrolysis experiment with the elements palladium and deuterium.

Fleischmann and Pons' first significant experiment occurred in the spring of 1985, when they informally reported that, overnight, an experimental cell had exhibited significant anomalous behavior that included the melting and partial vaporization of the palladium cube used for their cathode. They also informally reported the partial destruction of their lab bench, a small hole in the concrete floor and damage to the fume hood.

The two electrochemists worked as quietly as possible for several years and, after using up their own research funds, applied to the Department of Energy for a grant. This led to the eventual public disclosure of their work at a press conference on March 23, 1989.

Fleischmann and Pons discovered an electrochemical method of generating nuclear energy, in the form of heat, in a way that was previously unrecognized by nuclear physicists. Much drama and unscientific reaction followed the

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announcement and the unexpectedness of their claim. The claim flew in the face of hot fusion research, which had yet to demonstrate a commercially viable product, and thus triggered no small amount of disbelief and hostility.

To the surprise of many people, the research in the field has shown consistently positive, coherent sets of results. Progress has been slow, but the research shows considerable promise.

Low energy nuclear reaction research composes a new field of science. It does not belong exclusively to chemistry, physics, or any other previous scientific discipline. Much is known about the science, but many significant facts remain unknown.

Two general groups of reactions exist in the field. In addition to the heat-producing reaction discovered by Fleischmann and Pons, the field encompasses a set of experiments that demonstrate transmutation with heavy elements that are not all fusion reactions. This is another reason for referring to the field as low energy nuclear reactions rather than cold fusion.

The LENR term does not imply that the potential energy output is low; rather, it distinguishes the research from high-energy nuclear physics, which involves either the use of high temperatures or energetic devices such as particle accelerators and magnetic confinement fusion machines.

The First Department of Energy Cold Fusion Review

An early significant milestone in the history of LENR occurred in the first year of what was then called cold fusion. The president of the United States in 1989, George H.W. Bush, sought the guidance of Glenn T. Seaborg, a Nobel prize winner in chemistry and former chairman of the Atomic Energy Commission, to counsel the White House on the highly public matter of cold fusion.

Seaborg was convinced that the whole idea was entirely wrong. Nevertheless, he recommended that Bush form a committee to review the idea. He predicted that the committee would decide that the idea was not a valid form of science and not a worthwhile application of government funding.

Bush followed Seaborg's advice, and through the Energy Resources Advisory Board, an investigative panel was formed. John Huizenga, a professor of chemistry and physics at the University of Rochester, a major government-funded hot fusion research facility, was selected to lead the panel. Huizenga, later wrote in his book *Cold Fusion: The Scientific Fiasco of the Century* that cold fusion was entirely a mistake.

Not surprisingly, six months later, the panel concluded that cold fusion did not produce fusion products in the expected quantities and proportion. Therefore, the panel said, the experimental results reported by Fleischmann and Pons were entirely mistaken.

The members of the panel either failed to recognize or failed to communicate the possibility that some other novel nuclear process may have been at work.

Public Confusion

During the confusion about cold fusion in the following years, many people lost sight of the developing science.

The first significant milestone occurred in July 1990 with the publication of Fleischmann and Pons' seminal paper, "Calorimetry of the Palladium- Deuterium-Heavy Water System," in the *Journal of Electroanalytical Chemistry* (*1*).

They reported very strong results: Nineteen runs registered positive excess heat, with an average of 586 milliwatts. Fourteen control runs showed negative excess heat, averaging -1.3 milliwatts. Their detection limit was 1 milliwatt, and their signal over background ratio was 450-1. (Fleischmann and Pons provided an explanation for the slight negative readings in their paper.)

Later that year, University of Minnesota professor Richard Oriani published the first corroboration of Fleischmann and Pons' excess heat claim in the December 1990 issue of *Fusion Technology* (*2*).

A common public perception is that the Fleischmann-Pons claims were disproved because others failed to replicate their experiment. This is a gross misunderstanding that not only presents a lesson to historians and observers of this subject but provides insight to future explorers in other fields of science. As the example of the cold fusion episode shows, failure to replicate does not equal disproof of a claim.

The key question to consider is whether critics found an explicit error of protocol, procedure, or analysis in the Fleischmann-Pons work. With the exception of flawed gamma/neutron data, which was a minor component of their laboratory evidence, the Fleischmann-Pons 1990 paper and that of Oriani were never refuted successfully in the formal, scientific literature.

In July 1992, the Wilson group from General Electric did its best to find fault with the Fleischmann-Pons 1990 *Journal of Electroanalytical Chemistry* paper; however, the group failed to disprove it. In fact, the effort effectively, and likely unintentionally, provided a third-party confirmatory analysis. Wilson concluded that the Fleischmann and Pons cell generated 40 percent excess heat, amounting to 736 milliwatts, more than 10 times the error level associated with the data.

Excess Heat

Excess heat is the fundamental observation and claim of Fleischmann and Pons. In electrochemistry, when a researcher applies a certain amount of electrical energy to an electrolytic cell, he or she expects a commensurate amount of heat to come out of the cell based on Joule heating.

Fleischmann and Pons found that, in their cold fusion cell, more heat was coming out of their experiment – on the order of 1,000 times more – than could be explained by normal chemistry.

Calorimetry

Part of the challenge of this field has always been the acceptance of the phenomenon of excess heat. Calorimetry was a relatively obscure art, and the levels of heat in these experiments were, and still are, typically registering in the milliwatt range, though occasional experiments have registered in the tens of watts. Experiments performed at such low power require the utmost care and precision with the instrumentation and data analysis. These issues gave rise to much skepticism and doubt in the early period of this history.

However, many researchers responded to the distrust that many critics had with Fleischmann and Pons' isoperibolic calorimetry and initiated experiments using far simpler methods. Isoperibolic calorimetry is not intrinsically complex, however, it becomes so when a mixture of radiative, conductive, and convective heat flows must be accounted for.

One alternative method which became popular in the early 1990s is the use of the Seebeck-type enclosure. This method uses a fully enclosed thermally insulated container in which an experiment is placed. Many thermocouples are embedded within the walls of the enclosure, and they measure temperature both within the container and outside it. These data are collected and used to determine the heat generated from the experiment.

Another method uses mass-flow calorimetry (Figure 1). These systems are practically more difficult but they have the advantage of being much easier to calibrate and errors are easier to recognize. In this method, the experiment is fully enclosed within a chamber, and a recirculating fluid surrounds this chamber or uses a closely contacting heat exchanger to extract heat. The temperature of the fluid is measured when it enters the chamber as well as when it exits the chamber. The difference in the temperatures along with the flow rate can be used to accurately calculate the heat coming from the reaction.

One disadvantage of the mass-flow calorimeter system is that it has the effect of cooling an experiment. Researchers have found that, when an experiment starts to generate heat, the heating effect, if allowed, provides positive feedback and amplifies heat generation from the reaction.

LENR Materials

Deuterium, in the form of heavy water, as well as palladium, as used by Fleischmann and Pons in 1989, still appear to be the essential materials used in most LENR research.

However, many experiments also have been performed with deuterium gas and palladium, as well as with normal water and nickel and, occasionally, other metals, too. An important question remains unresolved: To what extent is palladium consumed in the reactions, if at all?

What is Known

Many facts are now understood about these reactions, and several other essential mysteries remain. Somewhere on the order of five hundred researchers from a dozen nations have been active in the field, most since it began. Three thousand papers exist on the subject, a third of them in peer-reviewed journals. Together, they represent many thousands of experiments.

The dominant byproducts of the palladium-deuterium experiments are excess energy, in the form of heat, and helium-4. LENR reactions contrast with conventional nuclear fusion, in which helium-4 is the least dominant byproduct, which, when observed in conventional nuclear fusion is always accompanied by gamma radiation. LENR reactions do not produce gamma radiation at anywhere near the levels seen in conventional nuclear fusion.

Half a dozen independent reports show a very close correlation between the excess heat and the evolution of helium-4 (*3-7*). This correlation matches the energy that would be expected as a release from the fusion of two deuterons. Remaining discrepancies between the expected amount of helium-4 and the observed amount are accounted for by the expected absorption of helium into the palladium in the experiments.

On very rare occasions and in low but statistically significant proportions, tritium and helium-3 (thought to be decay from tritium) have been observed in LENR experiments. Tritium has been measured both in the gas phase and in the electrode.

Required Threshold Parameters for Excess Heat

Michael McKubre of SRI International was one of the first to identify three essential parameters that, when obtained, produce excess heat reactions repeatedly. By far the most significant of these is the ratio between deuterium and palladium atoms within a cathode. This is also called the loading ratio.

In general, a minimum deuterium to palladium loading ratio of 0.90 is required to achieve the excess heat effect. Loading ratios lower than 0.90 sometimes produce the excess heat effect, but it becomes increasingly unlikely below this threshold. A 1-1 ratio, along with the other required parameters, appears to yield consistently excess heat.

In most, but not all cases, many days, if not weeks, were required before researchers could get bulk palladium loaded to these levels. This long wait was one of the crucial facts that appeared to be unknown to most of the people involved in early replication attempts, and a major culprit for most early failures to replicate. In most of these failed attempts, people did not even bother to measure the loading. In addition, they were doing their electrochemistry in such a way that they would never have obtained the required loading. More recently,

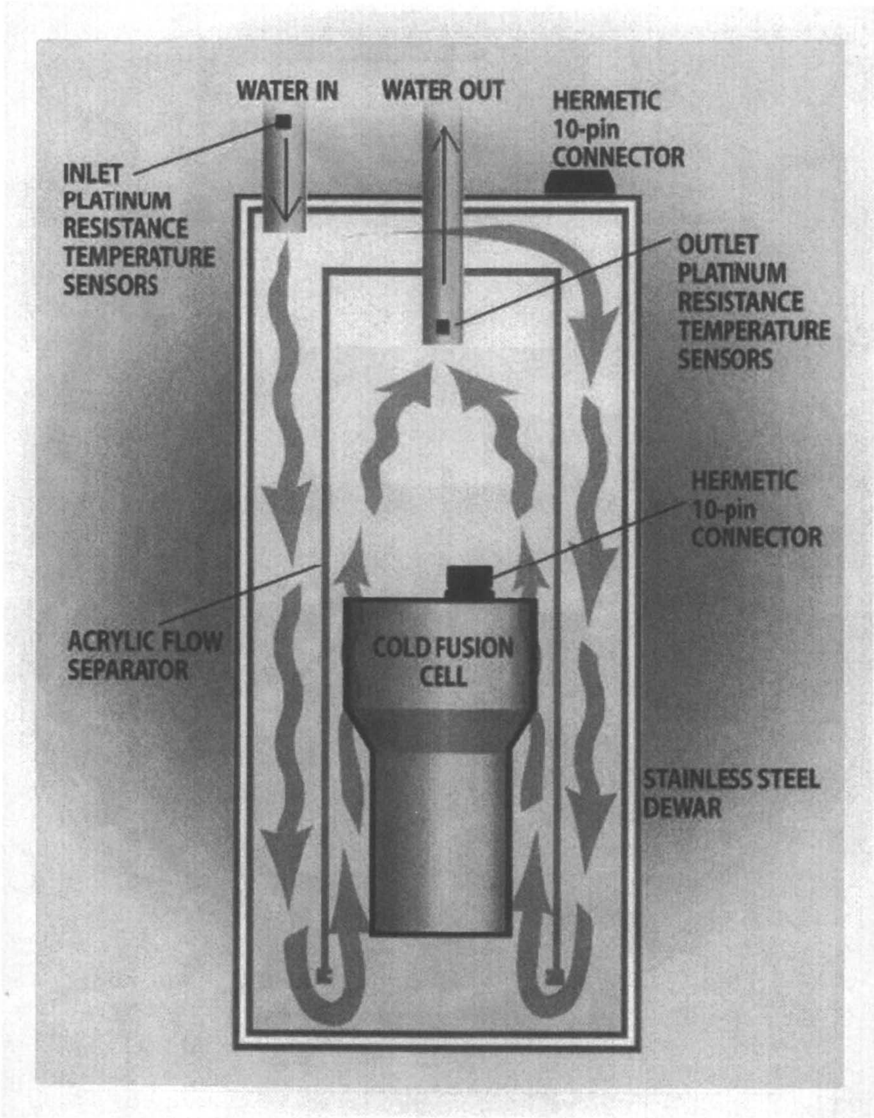

Figure 1. SRI-International Type Mass-Flow Calorimeter

researchers have found ways to obtain the required loading quite early, without the long wait.

The second threshold requirement is a relatively high current density through the cathode surface, a minimum of 250 mA/cm2. However, this parameter varies somewhat based on cathode size and geometry.

The third requirement calls for some sort of a dynamic trigger, a stimulus which will cause the electrochemical cell to enter a state of disequilibrium. For example, Fleischmann and Pons' dramatic 1985 reaction occurred after the current was increased abruptly from 0.75 amperes to 1.5 amperes. Additional known triggers that others have used are the application of temperature changes, low-power (30 mW) laser excitation, external electrical fields, and external magnetic fields.

Power and Energy Release

Numerous energy-releasing reactions have been reported, though reproducibility is inconsistent. Several of the recorded reactions have indicated relatively large capacities for power and energy release.

One of the earliest was in 1992, when Akito Takahashi of Osaka University observed 130 watts of excess heat. Edmund Storms attempted and successfully reproduced the experiment using some of the same palladium used by Takahashi.

The potential energy density of LENR experiments is difficult to predict because the mechanism is so far from being sufficiently understood. However, some attempts have been made to quantify the volumetric energy density relative to the volume of the palladium cathode. These estimates indicate that LENR might have a very high energy density, even higher than that of the uranium fuel rods used in fission reactors.

Fleischmann and Pons (*8*) and Giuliano Preparata (*9*) published papers showing volumetric power densities in the range of 10^4 and 10^5 watts/cm^3 based on single and nonreproduced experiments. More conservative estimates from McKubre suggest that the maximum rates presently being observed are in the range of 10^3 to 10^4 watts/cm^3. The estimate may even be conservative because the fuel consumed is believed to be deuterium, not palladium.

Excess Heat after Boil-Offs

Several rare excess heat reactions have been reported in which the reactions appear to reach some kind of critical point and run autonomously, long after the input current is turned off or disconnected.

Many of these reports are anecdotal, and none has been repeatable. Only a few have been precisely instrumented and observed because the reactions have come as a surprise.

In 1992, Fleischmann and Pons did not replenish the electrolyte in a cell and allowed it to run dry. When the electrolytic circuit was broken as a result of the absence of the electrolyte, the cell continued to give off excess heat for three hours. A Kel-F plastic support melted, indicating temperatures above 300°C (*8*). Fleischmann and Pons videotaped this experiment.

At an MIT symposium in the early 1990s, Lawrence Forsley of JWK Technologies Inc. reported on a cell in which the electrolytic current was turned off momentarily. The cell had been running at 80°C, at equilibrium, for one day. After the abrupt power interruption, the cell temperature shot up to 125°C, cracked a plastic insulator, and boiled off all the electrolyte – at a power input far below that required for Joule heating.

In the early 1990s, Tadahiko Mizuno of Hokkaido University reported the boil-off of a cell initially running 24 watts of input power that, in its last eight days with current turned off, boiled more than 15 liters of water. Mizuno had placed the cell in a bucket of water after disconnecting it from the power supply. According to Mizuno's calculations, during the time the cell was turned off, it evaporated enough water to account for 8.2 x 107 joules of energy (*10*).

Other researchers to report excess heat after boil-offs are Giuliano Mengoli of the Instituto di Polarografia and Melvin Miles of the U.S. Navy's China Lake Weapons Center.

A recent boil-off event occurred in a U.S. military laboratory in the spring of 2007. However, the researchers have decided not to report it publicly; instead, they are struggling to find how to make it repeatable.

Low Energy Nuclear Transmutation Reactions

Transmutation of heavy elements has been observed in LENR experiments as early as 1990, largely through the work of John O'Mara Bockris at Texas A&M University.

A significant body of work in transmutations has been reported by George Miley, director of the Fusion Studies Laboratory at the University of Illinois, Urbana, and former editor of the American Nuclear Society's journal *Fusion Technology*.

In 2003, he performed a survey, "Review of Transmutation Reactions in Solids"(*11*). He reported LENR transmutation evidence obtained by 15 independent laboratories. Three general combinations of reactions have been described: fusion of various light elements, fusion of light elements with heavy elements, and fission of heavier elements. The resultant elements are often reported as anomalous isotopic ratios, adding support to the hypothesis that such elements are created by LENRs (*12*).

A rigorous set of LENR transmutation experiments has been performed by Yasuhiro Iwamura et al. at Mitsubishi Heavy Industries in Japan. These experiments cause deuterium gas to pass through a multilayered substrate containing palladium and calcium oxide. On the front side of the substrate, atoms from the new element are found in place of the elements initially deposited there.

Iwamura et al. have reported three groups of transmutation reactions: cesium into praseodymium, barium into samarium, and strontium into molybdenum (*13-16*).

Normal Water Reactions

The role of normal water, sometimes inaccurately called light water, is perplexing as it applies to LENR research. Many researchers within the field are skeptical of light-water excess heat claims. In typical heavy-water experiments, introduction of light water to a cell containing some heavy water will poison and halt the excess heat effect. However, some researchers have been investigating anomalous reactions with normal water and nickel and reporting excess heat.

One such group was that of physicist S. Focardi, which published an experiment in *Il Nuovo Cimento* (then the journal of the Italian Physical Society) that produced an average excess heat of 18 watts for 319 days with an integrated energy of 600 MJ (*17*). One author of that paper, Francesco Piantelli, reported later that the introduction of deuterium into their nickel-hydrogen experiment terminated the excess heat effect.

It is possible that the introduction of deuterium into hydrogen experiments as well as the introduction of hydrogen into deuterium experiments may poison the experiments.

Nuclear Evidence

LENR experiments produce various forms of nuclear radiation. Types of prompt radiations detected include x-ray (*18, 19*), gamma ray (*20*), and energetic particles (ions and electrons) (*21, 22*). All of these radiations are emitted at very low intensities so they are difficult to measure in LENR experiments. Furthermore, most x-rays and energetic particles rarely travel outside of a LENR experiment so, typically, a detector for them must be located inside the experimental vessel.

Some of the most significant in-situ particle detection has 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, California (*23*).

Pamela Mosier-Boss, Stanislaw Szpak, and Frank Gordon developed such a method using solid-state nuclear track detectors, also known as CR-39 plastic track detectors, and the co-deposition LENR method.

Other researchers have detected helium-4 and helium-3 (*3-7, 18*) and tritium in other experiments (*24-26*).

A variety of anomalous physical effects on the cathodes has been observed, such as the melting and vaporization of palladium in experiments. None of these effects can be the result of Joule heating, because the energy inputs are too low (*1, 4, 27*). Other changes to the cathodes include unusual morphological deformations (*28*), craters (*10, 28*), and "hot spots" (*29*).

Environmental Issues

As was known from very early in the history of LENR research, all of the observed reactions appear to lack significant high-energy neutron and gamma ray emissions. As a result, this new science shows promise as the possible basis for new types of nuclear power systems that do not need complex containment or disposal systems.

Low levels of radiation are found in at least some of these reactions, but this radiation is usually absorbed directly and promptly within the experiments. Consequently, they offer hope of practical applications that do not pose major health hazards or compromise the environment.

In addition to the lack of high-energy radiation, the experiments do not appear to produce any greenhouse gases or long-lived radioactive decay emissions.

Numerous LENR Methods

Fleischmann and Pons' original method used electrolysis of heavy water, a method which has been used worldwide many times to achieve excess heat.

However, a wide variety of methods has been reported to produce both excess heat and anomalous nuclear products. These include other variations of electrolysis, pressurized deuterium gas, gas-electric field discharge, gas diffusion, plasma electrolysis, ion bombardment, acoustic and mechanically induced cavitation, nanostructured or finely divided palladium, and even biological mechanisms.

No Lack of Theories

The proposed theories for the anomalous effects are numerous and therefore, unfortunately, pose great difficulty for someone trying to develop a coherent understanding of the underlying mechanisms.

Most of the LENR theories incorporate the idea that fusion and/or fission processes are primarily responsible for the observed experimental results. These theories invoke the strong interaction as the underlying physical mechanism.

An alternative approach proposed by Allan Widom and Lewis Larsen of Lattice Energy LLC, which is considered with great skepticism by many researchers within the field, tries to understand and predict LENR phenomena by postulating the creation of extremely cold neutrons that facilitate low energy nuclear reactions. This theory, unlike other LENR theories, uses the weak interaction and does not need to explain how to overcome the Coulomb barrier repulsion problem because neutrons have no charge.

Concluding Remarks

The challenge presented by Fleischmann and Pons was unexpected and surprising, to say the least, for most nuclear experts of the day. Most researchers who initially attempted this difficult work gave up within six weeks of its introduction. Only a few careful, persistent researchers had early success. Their firsthand experience gave them the confidence to trust what they saw in their own labs.

However, during the 1989 Department of Energy cold fusion review, only one member of the panel was willing to entertain the validity of the discovery. Dr. Norman Ramsey, Nobel laureate and professor of physics at Harvard University, was selected as co-chair of the panel, though the historical record (*30*) suggests that this title granted him little authority or influence. To see that his dissenting view was included, he had to threaten to resign from the panel unless the following preamble was included in the Department of Energy report: "Ordinarily, new scientific discoveries are claimed to be consistent and reproducible; as a result, if the experiments are not complicated, the discovery can usually be confirmed or disproved in a few months. The claims of cold fusion, however, are unusual in that even the strongest proponents of cold fusion assert that the experiments, for unknown reasons, are not consistent and reproducible at the present time. However, even a single short but valid cold fusion period would be revolutionary."

Thanks to the work of Fleischmann and Pons, and those who followed them, a complex and important chapter in scientific history is evolving for all the world to witness.

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