Preface

Low energy nuclear reactions

A quarter century has gone by since Martin Fleischmann and Stanley Pons, two chemistry professors from the University of Utah, USA, made a 'historic' announcement at a press conference in Salt Lake City in March 1989, where they claimed that they had observed sporadic episodes of massive amounts of 'excess heat', over and above what is electrically put into the electrolytic cell. They suggested that in their experiments, the Pd rod which was deployed as cathode got heavily 'loaded' with deuterium (D), thus forming PdD, from the LiOD electrolytic solution during electrolysis. They went on to postulate that the observed large amounts of 'excess heat', which is far beyond the chemical energy available, must be attributed to the occurrence of some sort of nuclear fusion reactions between the deuterons, d, embedded within the Pd metal matrix. This claimed occurrence of fusion reactions at room temperature soon came to be dubbed as 'cold fusion (CF)'.

This announcement initially stunned and shocked the scientific world, but the shock soon gave way to intense skepticism and even anger because a majority of the thousands of researchers the world over who quickly attempted to replicate the experiment, observed neither excess heat nor evidence for any nuclear reactions. In any case, the occurrence of fusion reactions at room temperature defied contemporary understanding of nuclear physics. How can the Coulomb barrier between two positively charged deuterons be overcome at ordinary temperatures to cause a nuclear reaction? Where are the expected neutron and gamma-ray signatures of the well-known d–d nuclear-fusion reaction? The critics argued that the so-called 'excess heat' measured by the experimenters must be due either to erroneous calorimetry or perhaps recombination of deuterium and oxygen within the open test cell. In any case, the physics community had no hesitation in denouncing the claims of 'cold fusion' as utter nonsense and accused Fleischmann and Pons of being incompetent scientists, indeed even as frauds.

Fleischmann and Pons had enjoyed celebrity status for a few weeks, but soon began to be intensely criticized and ridiculed. The highly negative report of the committee appointed by the Energy Research Advisory Board (ERAB) of the US Department of Energy (DOE) headed by Huizenga (University of Rochester), essentially 'killed and buried' cold fusion 'for good' by the end of 1989. It is clear that a majority of mainstream scientists, even in India, have been persuaded to believe that the whole cold fusion episode was a big mistake, a slur on the process of science, and have perhaps dismissed the event as a forgettable 'flash in the pan'.

However, there is more to this fascinating story. A minority group of over 300 researchers, primarily in USA, Italy, Japan, China, Russia, France, and also in India, who had found positive evidence for the occurrence of nuclear reactions in deuterated/hydrided metallic (Pd, Ti, Ni, etc.) lattices, had continued their studies, patiently and painstakingly, although their work was not being taken seriously by their peers. What has transpired is a fascinating global scientific drama played out in the scientific arena. The field has now come to be known as 'condensed matter nuclear science (CMNS)' and the nuclear reactions that occur in deuterated/hydrided metallic lattices are referred to as 'low energy nuclear reactions (LENR)', 'chemically assisted nuclear reactions (CANR)', or sometimes as 'lattice assisted nuclear reactions (LANR)'. Indeed, the CMNS community has its own professional society known as the International Society for Condensed Matter Nuclear Science (www.iscmns.org) and its own peer-reviewed journal, the *Electronic Journal of Condensed Matter Nuclear Science* (http://iscmns.org/CMNS/publications.htm).

To date, a series of 18 international ICCF (International Conference on Cold Fusion) conferences have been held whose proceedings have been published. In Japan, the Japanese Cold Fusion Research Society (http://www.jcfrs.org) organizes annual conferences whose proceedings are uploaded in their website. Russia has been organizing annual conferences under the title 'Russian Conference on Cold Nuclear Transmutation (RCCNT)' for the past 20 years.

In this special section, we have invited many of the stalwarts in the field of LENR to share their main research findings. The goal of the set of papers is to provide an overview of the field from the experts in each area involved. The objective was not to solicit new work(s) that would of course be important for specialists in the field, but to provide, in one place, a scholarly introduction to the various developments, including many of the important references that have been produced over the years. We have allowed the authors of the theory papers to present their models in their own words, rather than having someone else attempt to present them. With the large number of papers in this special section, the authors were requested to limit the lengths of their contributions, relegating details to the references of their prior work and to their online supplementary information. In addition, to indicate the high calibre of those involved in cold fusion research, we have requested the authors to provide a brief summary of their credentials relevant to this work. These bios are uploaded as supplementary files.

We believe that this collection of papers constitutes a major review of the field. The observations over the years confirm the occurrence of not only fusion reactions between the deuterons (d; or protons, p) among themselves, but even between the hydrogenous isotopes and the 'host metal' lattice nuclei. These latter type of reactions have come to be known as LENR transmutation reactions.

As of today there are no experiments being carried out in India in this field even though in 1989, soon after the Fleischmann–Pons announcement, many independent groups at the Bhabha Atomic Research Centre (BARC), Mumbai and a few other institutions like TIFR and IGCAR jumped into the fray and obtained clear confirmation of the nuclear origin of the phenomenon. The early BARC studies are briefly reviewed in a paper in this special section. BARC teams were perhaps the first to publish the fact that tritium yield is a million times larger than neutron output (this 'branching ratio anomaly' was subsequently confirmed by several groups worldwide). Unfortunately, the successful research in CF/LENR was shutdown in BARC in the early 90s, following the release of the highly negative ERAB report mentioned earlier.

Summary of the main findings of the global LENR research

The main findings to emerge from the worldwide research, mostly in Pd–D systems, may be summarized as follows:

(a) McKubre's group at SRI International identified the reasons why most groups failed to replicate the excess heat results of Fleischmann and Pons. By measuring the (D/Pd) loading ratio of the cathode, through a clever online measurement of the resistivity of the Pd rod even while the electrolysis was under way, the SRI group demonstrated that unless and until the loading ratio exceeds a threshold value of about 0.88, no excess heat is observed; and obtaining such high loading ratios needs special expertise in electrochemistry. McKubre has elaborated on this observation in his lead article (p. 495) that immediately follows the Preface.

(b) It is now confirmed that the excess heat observed in Pd–D systems is due primarily to the occurrence of (d–d) fusion reaction forming He^4 (inert helium gas). A paper by Abd Lomax (p. 574) places the importance of the experimental confirmation of the 'heat–helium correlation' in proper perspective. The 23.4 MeV energy released in the He^4 branch of the (d–d) fusion reaction appears to be transmitted directly to the Pd lattice as phonons, photons, or other mechanisms.

(c) The tritium branch of the (d–d) fusion reaction contributes relatively little to heat generation. Neutron production is minimal; it is not clear, even when observed, whether these neutrons are generated directly in a (d–d) reaction or whether such production results from secondary reactions caused by energetic tritons. It is worth pointing out here that the very criticism voiced in the early days, namely the absence of neutrons and gamma rays in the Fleischmann and Pons experiment, turns out to be the main advantage of the cold fusion/LENR phenomenon, making it a clean form of nuclear energy without the accompaniment of radiation.

(d) Yet another important finding that emerged from the early studies was that the nuclear reactions appeared to be mainly occurring on the 'near surface region' of Pd. This finding led to adoption of thin wire and thin film cathodes and eventually to nano powders in order to create maximum surface area. It was Arata (Osaka University), who through deployment of his novel 'double-structured cathode' (Pd black powder packed inside a sealed, thin-walled Pd tube) demonstrated that direct deuterium gas loading of nano powders appears to be a better approach than electrolytic loading of Pd rods and wires. The technique of gas-loaded nano powders has gained popularity mainly because inadvertent surface deposition of unwanted impurities is circumvented in this technique.

(e) It has now become apparent that even on the surface of the host metals, the nuclear reactions seem to be taking place only in selected domains or hot spots. Edmund Storms (p. 531) has elaborated on the importance of the concept of what he calls the 'nuclear active environment (NAE)' for over a decade now. There have been intense discussions and speculations in the CMNS community regarding the nature of the NAE, which seems to hold the key to understanding, controlling and mastering the field. Several authors, besides Storms have addressed this question in this special section.

(f) As already mentioned, yet another puzzling experimental observation has emerged, namely the phenomenon of LENR transmutations, which is the occurrence of nuclear reactions between the loaded hydrogenous isotopes and the host-metal lattice nuclei. A set of four papers (pp. 624–640), beginning with a short review paper, elaborates on the topic of LENR transmutations. In this context the pioneering experiments described by Iwamura *et al*. (Mitsubishi Heavy Industries' R&D laboratories), in this special section deserves special mention. Two other papers, dealing with a sub-topic (namely 'biological transmutations'), discuss the occurrence of nuclear reactions in living entities such as plants, animals and even humans. The topic of biological transmutations first surfaced in the late 60s following the publication of Louis Kervran's book in France. Jean Paul Biberian, who has also authored a recent book on this topic (in French), reviews this subject in his paper. One of the most intriguing outcomes of research in this area with possible practical applications, is the demonstration of transmutation of radioactive waste into stable elements using microbes, described by Vladimir Vysotskii *et al*. in their paper.

Theory

The physics behind the LENR phenomenon is turning out to be more complex than imagined in the beginning.

Seven papers in this special section present the diverse approaches being adopted by theoreticians to try and explain how these lattice enabled or low energy nuclear reactions could possibly be taking place. The following are some of the problems being addressed by the theoreticians:

(i) How is the Coulomb barrier overcome at near room temperature? (ii) The second task is to provide a meaningful explanation for why the fragmentation (energetic particle emission) observed in known (d–d) fusion reactions is not observed? (iii) The third problem is to explain why high-energy gamma rays are not produced, as predicted by known (d–d) fusion reactions, and how the energy from these reactions is transmitted directly to the lattice. Theoretical models must address each of these issues or, at least, not violate them and then proceed to account for all or most of the reported experimental results. (iv) A fourth problem, perhaps the most important and of practical value, is to identify the 'unique structure' (NAE) required for cold fusion to occur and trace where this structure is located within the productive material. Generally, while discussing a theoretical model, a specific known physical mechanism is extended into the lattice or nanometre realm and the consequences are examined with the cold fusion experimental results in mind. Most of the models were initially based on the PdD system and later extended to include the NiH system, as new experimental results became available.

Andrew Meulenberg addresses the first three problems in his paper (p. 499) titled 'extensions to physics'. He shows how, in solving them, one is actually led to an understanding of the phenomenon of cold fusion and then onto new areas of physics and chemistry to be explored at the femtoscale (10^{-15} m range) above the nuclear dimensions.

Akito Takahashi in his paper dealing with cluster fusion theory (p. 514) has taken the strictest 'conventional' path to explain the available cold fusion data by proposing a small 'group' structure within the lattice that, by its collective internal motions, concentrates the electron population between the protons or deuterons. Thus, the Coulomb barrier is eliminated and multiple (e.g. four) nuclei can simultaneously interact and fuse. This process eliminates the known fragmentation products of the (d–d) reaction by going to a multi-step process.

Several authors use interference and overlap characteristics of the proton or deuteron wave functions to calculate fusion probabilities. Vladimir Vysotskii (p. 524) utilizes correlated coherence to determine large enhancements of the fusion probability. Xing Zhong Li (p. 519) presents a model that looks at low-energy proton resonant tunnelling into a ^{6}Li nucleus (through its very large Coulomb barrier), rather than the more common view of the (p–p or d–d) interaction. In addition to this means of producing cold fusion, via transmutation of lithium, he has referenced his extension of this process to nickel.

Ed Storms (p. 531) and K. P. Sinha (p. 516) approach the first and fourth problems from opposite poles, but come to similar conclusions. Storms, from his chemistry background and in-depth study of the cold fusion literature, has concluded that crevices in the PdD lattice are the only possible source of what he has termed NAE. He has also made an assumption (not readily accepted by most physicists, but proposed by Nobel laureate Julian Schwinger in 1991) that much, most, or all of the fusion energy from the (d–d) fusion to the ^{4}He ground state is dissipated before fusion actually occurs. Sinha, from his solid-state and theoretical physics background has proposed and mathematically modelled a system that has electron pairing in the lattice, to overcome the Coulomb barrier problem, and postulates linear defects (including that of the crevice model) to be the source region for cold fusion. He has recognized that hydrogen atoms, in a linear defect with the ability to alter their dominant sub-lattice spacing (unlike the fixed spacing of the host lattice), have a unique property to come much closer together than the host lattice spacing would allow.

Peter Hagelstein (p. 507) elaborates the use of phonon models and is perhaps the most prolific modeller of cold fusion activity. However, he is also the fiercest self-critic. Therefore, he has not yet published what he considers his 'definitive' model. Meulenberg has proposed that a distinction between 'hot' and 'cold' fusion is whether or not the atomic electron(s) are involved (e.g. d–d versus D–D reactions). Hot fusion, in the form of energetic colliding particles or plasmas, is (or can be considered to be) independent of electrons. Cold fusion on the other hand, in its many models, always depends on the presence of bound electrons. Starting with Sinha's model and the anomalous solution to the Dirac equations that predict electron orbitals with Fermi-sized radii, Meulenberg has extended the physics of cold fusion into the femto-regions. The resulting femto-atoms and molecules explain most of the observed cold fusion results (e.g. heat generation, transmutation and low-to-zero radiation) and lead to new areas of both physics and chemistry.

Thus a little over a century after the discovery of the atomic nucleus by Ernst Rutherford, a new chapter seems to have opened up in nuclear science. One cannot but acknowledge that a 'silent revolution in nuclear science' is under way. Every now and then the citadel of science is rocked by the discovery of a new phenomenon that the scientific community at first finds difficult to digest. 'The theory of relativity' and 'quantum physics' were two such paradigm shifts that shook the very foundations of physics in the 20th century, although when first propounded they too had many detractors. The phenomenon of LENR is yet another example of a paradigm shift in science which has not yet been fully comprehended by scientists. This discovery is too important to be neglected by the scientific community.

Application

However, even after two decades of effort by diverse research groups in several countries, no group had come up with a reproducible experiment that any student can replicate (except perhaps the co-deposition technique of the SPAWAR group or the dual laser triggering experiment, described in two of the papers in this special section). One can assign the blame for non-reproducibility of LENR experiments, squarely on the fact that no one has yet understood the nature of the NAE. No one had demonstrated high enough levels of excess heat generation in Pd–D systems that could attract the attention of industry. Many of us who have been watching these developments from day one of the 'cold fusion era' were indeed beginning to get frustrated and impatient.

It is precisely at this juncture that there comes the latest twist in the LENR story. An unknown 'outsider', an engineer–inventor from Italy, Andrea Rossi surprised us all by announcing that he has invented a working, industrial-grade Ni–H LENR reactor. On 14 January 2011, he gave a semi-public demo of the same in the presence of an invited audience and later in the year he followed it up with a demo of a 1 MWth (Megawatt thermal) reactor (composed of over a hundred of the basic 10 KWth modules connected in a series/parallel fashion). Now this 'development' (some would say that, in the absence of a peer reviewed publication, we should treat it merely as an 'unproven' claim) has revived immense worldwide interest in the whole field of LENR. Dozens of websites have cropped up to follow Rossi's Ecat. (One may *Google* search on 'Ecat' to know more.) A recent book titled *An Impossible Invention – The True Story of the Energy Source that could Change the World* by science journalist Mats Lewan chronicles the fascinating story behind the inventor and his Ecat.

We are aware that many of our colleagues in the CMNS community will fault us for bringing into a serious scientific debate any mention of Rossi and his Ecat, as there are no peer-reviewed scientific publications to back his claims. His several patent applications give some information about his device and his blog reveals additional details. His patent applications, however, do not give many crucial details needed to replicate his device. Rossi himself acknowledges that there are some crucial trade secrets that he will not reveal for now. There are a couple of papers uploaded on the Cornell University Library's Archives (http://arxiv.org/ftp/arxiv/papers/1305/1305.3913.pdf) summarizing the reports of so called 'third party tests'.

Presently, there are at least two other private companies who have announced near-commercial products. Two papers by David Nagel (p. 641 and p. 646) discuss the various experiments in the LENR field which have yielded high energy and power gains. Nagel's second paper summarizes the development of Ni–H devices starting from Piantelli's pioneering studies and ending with Rossi's tests and demos. [He also provides, in the online supplementary material, a list of terms used in LENR.]

Status

The field of CF/LENR has thus entered into a different 'ball game'; one with which the academic scientific community, especially in India, is unfamiliar. Let us recognize that almost every product we see in the market today is due to the innovation and R&D efforts of private corporations, be it automobiles, aircraft, TVs, xerox copying machines, internet, smart phones, etc. We in India are not accustomed to venture capitalists taking over an invention and eventually launching it in the marketplace. Analysts have described LENR as an emergent 'disruptive technology' and have predicted that it has the potential to upset the world economic order. Some have described LENR as the 'third route to nuclear energy', beyond fission and thermonuclear fusion.

In any case, all that we are trying to place before the scientific community is that the phenomenon of LENR is real and by all accounts appears to have the potential for practical applications in the not-too-distant future. The continued assertion that 'cold fusion/LENR is unproven' is not justified anymore. It would be unwise to ignore or boycott this field. LENR research deserves the support of Government funding agencies, professional scientific academies and also the private sector. Most importantly we need to encourage the entry of young blood into this field. This however is a challenging task given the stigma attached to the field by those whose sense of 'rightness', pride, academic position, and/or financial interests is at stake.

In this context, we would like to draw the attention of *Current Science* readers to a paper in this special section on the Martin Fleischmann Memorial Project (MFMP, see www.quantumheat.org). The MFMP 'Live Open Science' project was initiated by a few youngsters of the Facebook/Twitter age. Since normal funding agencies have been avoiding LENR, these youngsters decided to appeal to their generation directly through Facebook and organize 'crowd funding' for initiating basic and simple experiments in the field of LENR. See website www.quantumheat.org.

Clearly the LENR field needs similar breakthrough ideas and bold initiatives to break the present impasse.

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