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Research Article

Evidence from LENR Experiments for Bursts of Heat, Sound, EM Radiation and Particles and for Micro-explosions

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Abstract

We examined published evidence for power production by LENR, which occurred too fast to be captured by calorimeters. That evidence includes observations of craters in materials, measurements of sound emission, recordings of radio-frequency, infrared and X-ray emissions, measurements of neutrons and charged particles and micro-explosions. The energy emission times, some below 1 ms, are tabulated.

Keywords: Energy bursts, Low energy nuclear reactions, Micro-explosions, Power bursts

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1. Introduction

The energy released in low energy nuclear reactions (LENR) experiments and generators is unavoidably pulsatile on the scale of atoms. This is because some amount of energy is released during each LENR event at some point in time and space. If there are many LENRs occurring simultaneously, the power production on mesoscopic and macroscopic levels can occur in bursts. Or, if there are numerous LENRs occurring sequentially, the power production can have an apparently continuous and smooth time history. So, there are four basic modes of uncontrolled energy release: (a) a constant rate (ignoring shot noise), (b) a slowly varying (pseudo-steady) rate, (c) bursts of various durations and magnitudes, and (d) a mix of the more-or-less steady output plus the occurrence of some bursts.

The time scale over which energy is released in LENR experiments and anticipated products is important for both scientific and practical reasons. The basic mechanisms for the occurrence of LENR are still not understood. Hence, fast energy releases might help in understanding what is happening at a fundamental level. For example, are energy

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releases, which require the near-simultaneous occurrence of numerous LENR, the result of many uncorrelated events, or are they due to some type of a fast cascade of reactions, essentially a chain reaction? This is a very basic question.

The practical importance of temporal variations in LENR power production seems clear. Comparisons with the release of chemical energy are instructive. There are some chemical heat production situations that are more-or-less steady, such as the burning of coal, oil or gas in a boiler. Others are pulsed, but tightly controlled. Explosions of petrol vapors in automobile engines at rates of hundreds of Hz are a common example. At this early stage in commercialization of LENR power generators, it is unclear what power production profiles will be employed for the many possible applications of the new sources. However, it is clear that both reproducible behavior and adequate control will be needed. Hence, the time histories of heat production in LENR experiments are directly relevant to later applications.

There are four different classes of evidence for the occurrence and characteristics of LENR, some of which are relevant to the question of fast energy releases. The first is production of heat that cannot be explained by chemistry. Because of the long time constants of calorimeters, most thermal measurements cannot resolve LENR energy releases that occur in fast bursts However, there are some other rapid thermal phenomena, such as crater production and infrared emission, which require nuclear events for their explanation. The second kind of evidence is the residue of nuclear reactions, that is, the nuclear ash left from transmutation reactions. Here again, data from transmutations cannot provide evidence of bursts of energy production because the sensitive chemical analysis methods needed to quantify nuclear ash can only be used after an experiment. That is, localization in time cannot be detected, but localization in space can be discerned by post-run scanning spectroscopy of materials. Measurements of energetic particles and hard electromagnetic radiation, which cannot be due to chemistry, are the third foundation for LENR. In this case, it is possible to see bursts of energetic quanta, so that something can be learned about the time history of the occurrence of LENR. The fourth class of information on LENR includes acoustic emission. Bursts of sound from LENR experiments have been measured, and will be discussed below.

In this paper, we examine the available evidence that illuminates the short-time history of the energy production by LENR and, for some cases, the spatial distribution of power production. Fast thermal events, including characteristics of craters left in cathode surfaces and the emission of infrared radiation from cathodes during electrolysis, are surveyed.

The characteristics of pulsed sound emission, electromagnetic radiation and fast particles from LENR experiments are studied. The goal of this review is to compare the temporal extent of bursts from LENR experiments that are measured in these various ways.

Section 2 discusses evidence for energy releases, both slow and fast. Sound emission is the subject of Section 3. Temporal measurements of electromagnetic radiation in the radio-frequency, infrared and X-ray regions are reviewed in Section 4. Section 5 deals with neutron and fast ion measurements. References to papers discussing micro-explosions are in Section 6. A summary and discussion of evidence for the relatively fast measured phenomena constitutes Section 7.

2. Energy Releases

Much of the experimental literature on LENR includes measurements of energy going into and out of experimental electrochemical and other cells, and the excess energy, gotten as the difference between output and input energies. The calorimeters used for such measurements are diverse in type and specific design. They can be remarkably sensitive, with the ability to measure powers to less than a milliwatt in some cases. However, even that remarkable threshold is too high to capture events involving relatively small numbers of reactions and associated energy releases or emissions.

The thermal masses, and associated time constants, of calorimeters are such that it is not possible to temporally resolve events that occur on the time scale of one minute or less. This is simply understandable by considering how long it takes for a cup of hot coffee to cool to room temperature. Water has a high thermal capacity, and loss of its

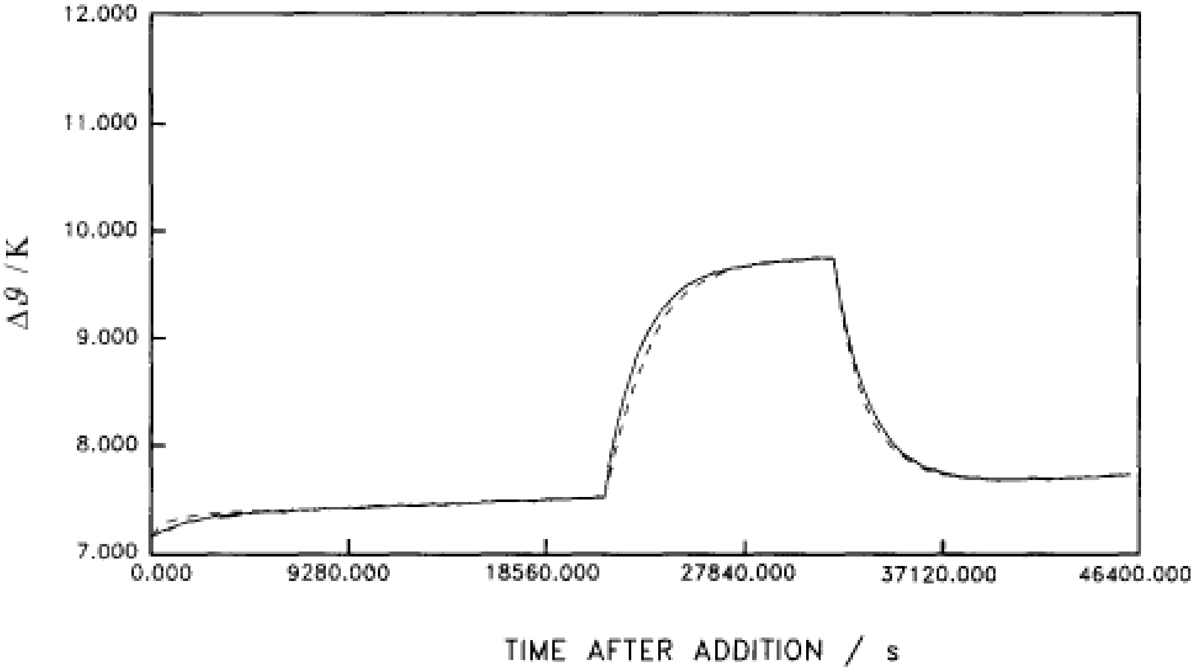

Figure 1. Cell temperature (K) vs time for about 12.5 h showing the response to application and removal of a heater pulse [1]. The horizontal bar shows the time between tick marks on the horizontal axis. See text for discussion in details.

thermal energy by conduction, convection and radiation takes times on the scale of minutes for volumes such as those within calorimeters.

Many LENR calorimeters have time constants on the scale of hours. Figure 1 is from a very important 1990 publication by Fleischmann, Pons and three colleagues [1]. It shows the time history of temperature in one of their isoperibolic calorimeters before, during and after the application of a heater pulse. The figure contains two curves, the solid experimental line and the fit using their equations for behavior of the calorimeter. The close similarity shows that, early in the field, Fleischmann and Pons understood the quantitative behavior of their instrumentation very well.

Even though calorimeters are too slow to capture energy emission events on time scales fast enough for mechanistic understanding and practical utilization, many LENR experiments have evidenced burst-mode behavior. Figure 2 is one example [2]. It shows bursts of energy as measured by a sealed Seebeck envelope calorimeter with a recombination catalyst. The overshoot after each burst is ascribed to the possible loss (leakage) from the cell of the gases produced during bursts. Such leakage would reduce the energy recovered from recombination and give apparent negative excess power for a period of time. The main point here is that LENR experiments often produce bursts of energy of a few hours duration. The pulses occur at seemingly random times, with highly variable amplitudes. However, the authors found that a plot of the number of pulses with specific excess powers (<0.5 W) had a $1/f$ character, where f is the frequency of occurrence. Such behavior is seen in many natural and man-made situations. It has been attributed to "self organized criticality" [3]. Whether or not the $1/f$ behavior seen in these experiments reveals anything about the creation of nuclear active regions, or the dynamics within such regions, remains to be explored.

There is one phenomenon widely observed after LENR experiments, which indicates fast thermal energy releases.

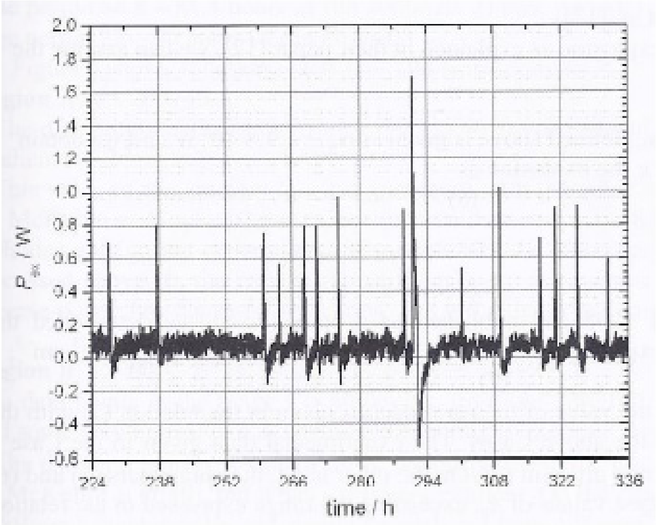

Figure 2. Excess power for 112 h of a 14-day experiment showing bursts of emitted energy [2].

It does not involve the use of inevitably slow calorimeters. And, it can be employed to set a limit on the duration of an energy emission event. The phenomenon is the production of small craters on the surfaces of cathodes used in electrochemical LENR experiments.

Craters have been observed for a very wide variety of materials and conditions in LENR experiments. Figure 3 gives a sampling of craters from co-deposition experiments (top three images) and super-wave experiments (bottom

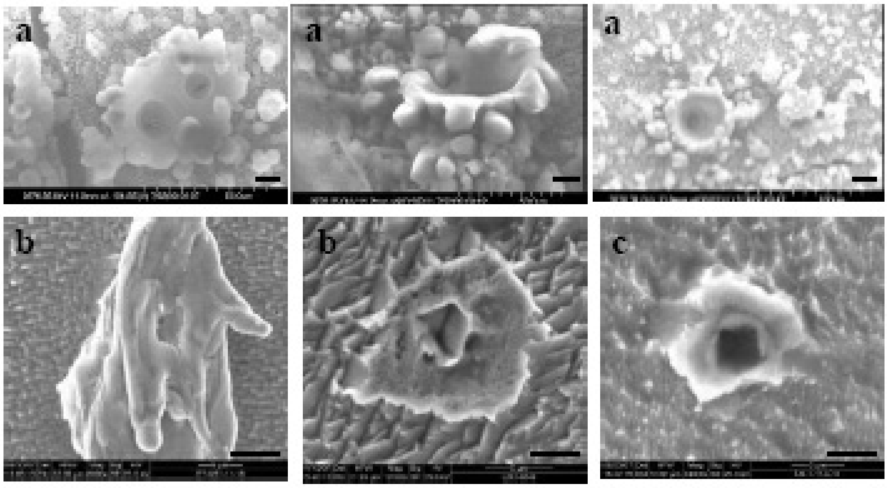

Figure 3. Scanning electron micrographs of craters in cathodes from LENR experiments. (a) shows craters from co-deposition experiments with 10 μbar [4]. (b) [5] and (c) [6] are from super-wave experiments with 2 μbar.

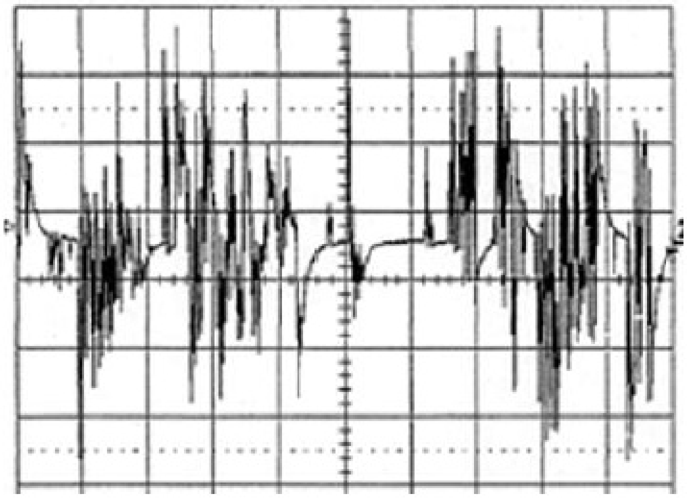

Figure 4. Record of sound emission from a LENR experiment [10]. Time is horizontal (200 ms/div) and voltage is vertical (5 V/div).

three images). The rounded character of parts of most of these and many other crater images indicates that melting probably occurred during production of the craters. A study of LENR micro-craters showed that they have diameters generally in the 1–100 μm range [7]. Two methods were used to estimate the energies needed to produce such craters. They were in reasonable agreement, and showed that the energies necessary to make the observed craters fall in the range from 1 nJ (1 μm craters) to 1 mJ (100 μm craters). However, neither that study nor any other has reported on estimates of the time for crater formation. Those times could be computed using modern thermal analysis software [8,9]. Such computations should be straightforward and would be valuable.

3. Sound Emission

A rapid release of energy, sufficient to form a crater, would also result in the emission of sound, possibly a click. For this reason, as well as to exploit all avenues for the experimental study of LENR, measurements of sound from active cells could be important.

There seems to be only one study that included measurements of sound from a LENR experiment. The scientists at the US Navy SPAWAR Laboratory co-deposited Pd and D on the surface of a piezoelectric transducer [10]. This enabled them to efficiently pick up and record the sounds emitted within the cell. Figure 4 shows one of the resultant oscilloscope records. It contains apparently random spikes with widely varying peak height and time of occurrence.

It should be worthwhile to do the same kind of analysis of such acoustic data as was done for the heat bursts seen in Fig. 2. It might also be possible to correlate the number of craters observed by post-run microscopy with the number of sound bursts measured in the same experiment. Such a correlation, and statistical analyses of both the crater and sound data, could establish a quantitative relationship between the craters and sound. Finally, spectroscopy of the sound emission is possible using very fast modern digitization hardware and methods. The spectrum of individual bursts of sound might be instructive.

4. Electromagnetic Radiation

Emission of electromagnetic radiation, like sound emission, occurs on a fast time scale. Hence, it is potentially valuable for understanding the mechanisms active in LENR energy releases. Many experimenters in the field have sought to measure radiation within several regions of the EM spectrum. Emission for short periods has been recorded in the radio-frequency, infrared and X-ray ranges. Samples of such data are given below.

Afonichev performed experiments in which deuterium-saturated Ti samples were deformed during measurements of neutron and radio-frequency (RF) emission [11]. At ICCF-10 in 2003, he showed time traces over about half an hour that exhibited what look like random bursts of neutron emission during deformation, but not when the deformation was interrupted. There were three systems measuring the RF emission at the same times. His paper states that the RF emission "had a sporadic character; the same character was noted when detecting neutrons."

More recently, Dominguez and ten colleagues sought to measure RF emissions during electrochemical LENR experiments [12]. They performed over 300 runs, many with a spectrum analyzer in place to search for RF emission. In one run, they observed two episodes of excess heat, both of about two hours duration. Each heat burst was accompanied by RF signals near 400 MHz. There is clearly a need for more attempts to listen for RF signals from LENR experiments.

Infrared (IR) radiation from LENR experiments was measured with a camera sensitive to such long wavelength radiation [13]. Figure 5 shows one frame from the video record. The temperature range for the image is from 29 to 49°C. It is seen that some small spots of the image are white, so they have temperatures near 49°C, that is, about 2°C higher than the region in which they occur (the red area). These temperatures imply energy releases on the scale of nuclear values. The video shows that the small spots turn on and off as time progresses. It is as if there are very local releases of energy at different point of the cathode at different times. Presumably, the relatively hot, red-colored region covering most of the viewed area of the cathode was heated by such bursts or by conduction from locations of earlier bursts. It is highly desirable to make more IR measurements and to thoroughly analyze them spatially and temporally. Spectral measurements of IR emission from LENR experiments should also be made.

X-ray (XR) emission from LENR experiments is especially interesting because, unlike RF or IR photon energies, the energy in a single XR photon is much greater than chemical energies. There have been many measurements of XR emission from LENR experiments with mixed success. But, some of the observations are very noteworthy. Karabut

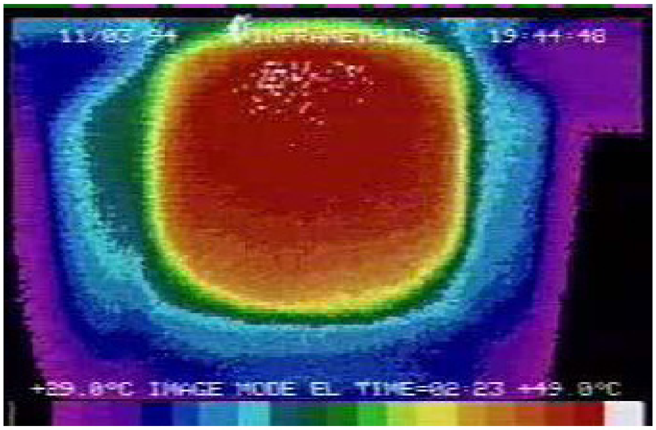

Figure 5. Image recorded by an infrared camera viewing the cathode in a co-deposition experiment [13].

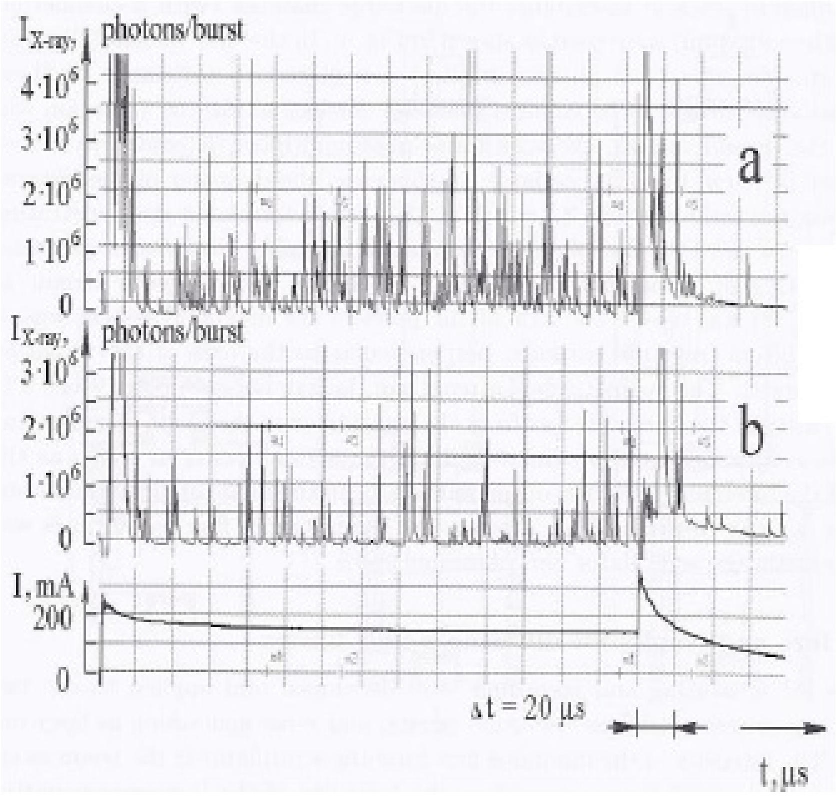

Figure 6. Two time traces of X-ray emission, as measured by a Photo Multiplier Tube viewing a scintillator covered with a Be foil to exclude light. The grid lines on the horizontal time axis are 20 μs wide, as indicated. The current history for the glow discharge is shown at the bottom [15].

has been performing glow discharge LENR experiment for over 20 years. He measured the spectral, spatial and temporal characteristics of such emissions with "100% reproducibility" [14].

Karabut found that the emitted X-rays are in the 0.6–10 keV region. They are collimated, which is truly remarkable. Figure 6 shows one of the many time histories, which Karabut and his colleagues have published [15]. It is not possible to fully resolve the time variations of the fastest pulses. However, they appear to have full widths at their half maxima of about 10% of the grid line spacing, that is, about 2 μs. Here again, as with the slow heat pulses (Fig. 2) and the sound emission (Fig. 4), both the appearance times and the magnitudes of the pulses appear to be quite random. However, a detailed analysis of those two parameters and their relationship ought to be done.

We sought to locate published gamma ray data from LENR experiments, which showed rapid time variations. However, there is relatively little gamma ray data and it is almost always time integrated because of low count rates. Fast gamma ray data would be of great interest.

It is possible to instrument various LENR experiments to simultaneously record electromagnetic radiation is several spectral regions. Potential time correlation of such measurements would be valuable.

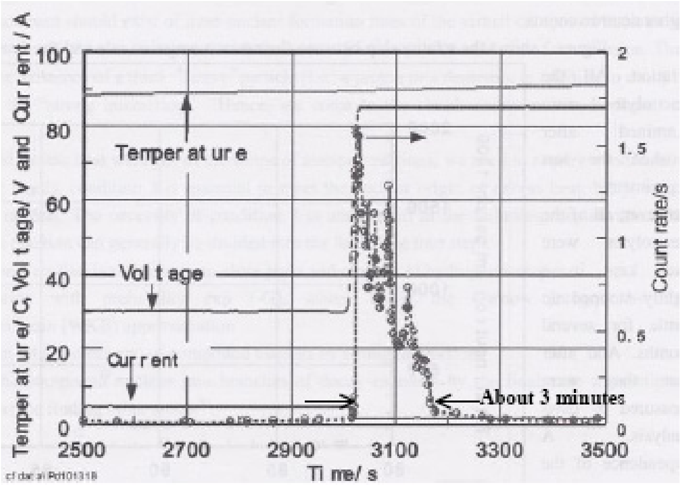

Figure 7. Time variation of neutron count rate (*right axis*) [16]. The burst of neutrons was triggered by change in the voltage (*left axis*).

5. Particle Emissions

As with emission of EM radiation, particle emissions occur individually on very fast atomic time scales. So, measurements of the time histories of the emission of neutrons and ions might also be instructive. We begin with two kinds of neutron data. The first is direct measurements of time variations. The second involves measurements of neutron multiplicities.

There are neutron detectors able to capture the variations in neutron signals with time resolutions well below 1 s. Hence, it is possible to record fast neutron emissions from LENR experiments. Figure 7 is one example of neutron emission that varies in times as short as about 10 s [16]. It might be difficult to obtain neutron time variation data for much shorter times because of relatively low count rates.

The overall history of neutron measurements from LENR experiments is a complex story. Many attempts were made to record evidence of neutron emissions, some of them in underground laboratories with low cosmic ray background and others with veto detectors over the experiments. Very generally, it has proven difficult to obtain neutron data. The time trace in Fig. 7 was one of the exceptions, until recently. Remarkably, there were three papers at ICCF-17, which reported high neutron count rates.

Jiang et al. [17] performed a complex and careful set of experiments and obtained strong neutron data. They employed samples of uranium deuteride and D-loaded Ti, and cycled the experiment. The materials were surrounded by 88 ^{3}He neutron detection tubes in a polyethylene moderator. Bursts of neutrons were measured in a short time window. Up to 2800 neutrons were observed in a 64 μs interval for D-loaded Ti.

Prelas and Lukosi reported on neutron emission from Ti in deuterium gas that was thermally shocked from liquid nitrogen temperature to 100°C [18]. These researchers used a pair of ^{3}He detectors. Two million neutrons were recorded in 5 min. It remains to be learned if the D-loaded Ti common to both the Jiang et al and Prelas–Lukosi experiments reported at ICCF-17 was key to such intense neutron production, or if the protocols used (cycling and thermal shocking) caused the large measured intensities.

Yuri Bazhutov et al. measured radiation emission from a variety of materials loaded with mixtures of hydrogen and deuterium gases [19]. The samples included $LaNi_5$, Ni and Be. Neutrons were recorded using one ^{3}He tube. Pulses of neutrons exceeding 100 per minute were observed for short periods for $LaNi_5$ and Ni samples. For some runs, roughly one-half million neutrons were registered in about 1 h.

The equipments for the measurements of neutrons discussed so far in this section were qualitatively similar. That is, pulses from neutron detectors were recorded as a function of time for the duration of an experiment. A different approach to obtaining data on the simultaneous, or very nearly simultaneous, emission of neutrons was taken by researchers at the Bhabha Atomic Research Center (BARC) very early in the field [20]. That approach produced some qualitatively different results.

It is possible to distinguish between single neutron emission events and multiple neutron emission events by carrying out a frequency analysis of the neutron pulse train issuing from a thermal neutron detector embedded inside a hydrogenous moderator. A cluster of fast neutrons incident simultaneously on such a detector assembly will get temporally resolved due to the statistical nature of the neutron slowing down process in the moderator. The resultant time spread is typically of the order of 100 μs. For statistical analysis, the neutron counts in 10 ms time bins were recorded to yield a frequency spectrum of counts. It was concluded that over 20% of the neutrons generated in Pd–D_2O electrolytic cells and gas loaded TiD samples could be due to multiple neutron events wherein 20 to about 400 neutrons were possibly released in each “burst”.

Besides neutrons, it is also possible to measure energetic ions from LENR experiments. This has been attempted much less frequently than neutron measurements, because the ranges of ions in solids and even gases, are relatively short. However, attempts to measure ions have still resulted in worthwhile data. Figure 8 shows the count rate obtained from a D-loaded Ti foil subjected to 400 mA DC current [21]. It can be seen that temporal variations on the time scale of a few minutes were recorded. Particle energies up to more than 10 MeV were obtained. It is not known specifically which particles produced these data. The authors speculated that they may be tritons, ^{3}He or possibly alpha particles.

There are some other ion measurements, but without time resolution. As in the case of gamma rays, ion count rates are low, making it difficult to obtain good time histories showing fine temporal structure. However, more attempts to

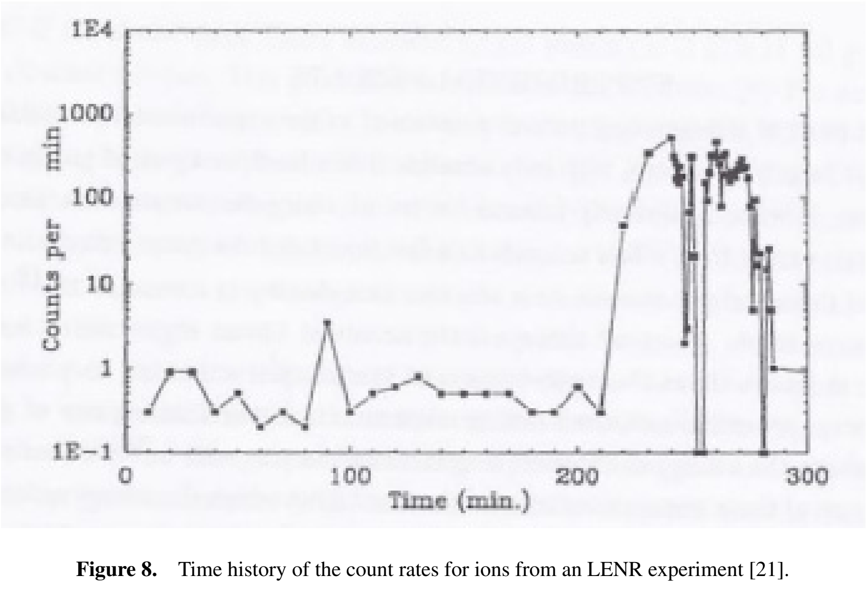

Figure 8. Time history of the count rates for ions from an LENR experiment [21].

measure ions might be made from gas loading experiments by use of differential pumping, a common practice in mass spectrometers.

6. Micro- and Macro-explosions

The papers noted above deal with measurements of phenomena in LENR experiments that occur too fast, or involve too little energy, to be captured by calorimeters. They have caused some scientists dealing with such data to speculate on the occurrence of small explosions on or in materials within LENR experiments. The earliest such surmise was based on the neutron multiplicity data measured at BARC and discussed in the last section. Piecing together all the BARC findings, it was concluded that micro-nuclear explosions are probably occurring, wherein 10^8–10^{10}tritons are generated in a sharp highly localized event. It was speculated that neutrons arise from secondary reactions involving the interaction of energetic tritons with deuterons in the lattice. A recent discussion of the early BARC data, and whether it is the signature of micro-nuclear explosions, is available [22].

The authors of several other papers were lead to contemplate small explosions as the source of what they and others measured [23–29]. The last of these papers is especially interesting. At ICCF-17, Biberian reported on his experimental attempts to understand an explosion that happened in his laboratory with an open cell [25,28]. Thrice, he triggered purposeful explosions using a mixture of hydrogen and oxygen, but the test cell was not damaged. Biberian concluded "It is therefore possible that in this case the explosion was of nuclear origin: some kind of a chain reaction." The recent study of the energies required to form small craters on the surfaces of electrolytic LENR materials was already noted [7]. The micro-craters are prima facie evidence for small explosions on or near the surface of LENR cathodes.

The most notable macroscopic event was described in a paper by Fleischmann and Pons in 1989 [30]. They were conducting an electrolytic LENR experiment in which the cathode was a cube of Pd 1 cm on a side. During a weekend, the experiment suffered a thermal runaway, which lead to the following statement in their paper. We have to report here that under the conditions of the last experiment, even using D_2O alone, a substantial portion of the cathode fused (melting point 1554°C), part of it vaporized, and the cell and contents and a part of the fume cupboard housing the experiment were destroyed." After burning through the table, the event left a hole in the concrete floor about 3 inches deep and 8 inches wide [31].

7. Summary and Discussion

A compilation of the various measurements, which show time variations faster than a calorimeter can respond, is given in Table 1. The order is the same as discussed above. The last column gives the authors' views of what should be done for each type of observable. Straightforward simulations should give limits on the times for crater formation. The annotations "More Work" mean both additional measurements and sophisticated data analysis would be valuable. Actually, the need for initial or better data analysis applies to all of the entities. There are X-ray detectors with sub-

Table 1. The shortest reported times and further work needed for the indicated measurements from LENR experiments.

Observations	Shortest time	Needs
Craters	$\ll 1$ s	Simulations
Sound	About 20 ms	More work
RF emission	A few seconds	More work
Infrared emission	$\ll 1$ s	Spectroscopy
X-ray emission	About 2 μs	Fast detectors
Neutrons	$< 64\mu$s	More work
Energetic ions	About few min.	New designs

nanosecond response times that should be used. The outstanding neutron apparatus of Jiang et al. should be used for more measurements. New experiment designs to capture ions with little attenuation are both possible and needed.

The overall message from the tabulation is that some processes happen in LENR experiments on the time scale of microseconds.

Bursts, such as studied in this review, will probably be of most use scientifically. That is, they serve to guide and constrain theories about the mechanisms that lead to LENR. This may be most true for the fastest energy releases, which set limits on the durations of energy release events. Fast recordings might turn out to have something to say about the difference between near-simultaneous reactions and cascaded (chain) reactions. However, it is also likely that bursts of power that occur over much longer times, including those resolvable with calorimetry, will be important. The use of LENR generators for myriad applications will be influenced by large variations on longer time scales. It is already clear that the ultimate disposition (as heat, sound, radiation, etc.) of the energy released from nuclear binding energies will be significant, at least scientifically, and probably practically. Such energy branching ratios are needed.

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