Research Article

Observation of Macroscopic Current and Thermal Anomalies, at High Temperature, by Hetero-structures in Thin and Long Constantan Wires Under H\textsubscript{2} Gas

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Abstract

Since 2011, we introduced into LENR field, the use of a Constantan (Cnst) alloy to absorb/adsorb proper amounts of H\textsubscript{2} or D\textsubscript{2} and to generate thermal anomalies even at low temperatures (>200\degree C). We developed a reactor with a core of sub-micrometric layered Cnst wires that produced measurable excess power (almost reproducible). Subsequently, we used fiberglass sheaths as electrical insulation and found out that this material actually improves reactor performance. In the most recent configuration, we studied the effects of adding Fe nanolayers to the Cnst wires and of including several small knots along their extension, actions that resulted in a larger excess power that grew with increasing wire temperature. We detected a new electric effect: the generation of spontaneous voltage between the ends of a floating wire in the reactor. We performed tests to study results in agreement with Inverse Rydberg Matter model by L. Holmlid.

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1. Constantan alloys as H$_2$-Dissociation Catalyzers

Our investigations concerning the ability of metals such as palladium (Pd) and nickel (Ni) to absorb D$_2$ and H$_2$, and to generate anomalous heat at high temperatures, gained new momentum following the introduction of Constantan alloys to LENR research in 2011.

Our original idea was to create a low-cost material able to replace the very expensive (and mechanically weak) palladium in LENR experiments. We focused our interest on the family of copper-nickel Constantan alloys as materials that fit our purposes because of their ability to dissociate molecular hydrogen [1]. In particular, we selected a low-cost commercial material called ISOTAN44, with atomic composition Cu$_{55}$Ni$_{44}$Mn$_1$ (Isabellenhütte Heusler, Germany). Together with a high H$_2$-diffusion coefficient at high temperature, this material offers good mechanical resistance against the aging effects of the thermal cycles and H$_2$ absorption/desorption. Moreover, it has very large values of (calculated) catalytic power with respect to hydrogen dissociation, as shown in Table 1.

We demonstrated experimentally that Constantan at nano-/micrometric size and at low temperatures ($T > 120^\circ$C, in comparison with about 2000$^\circ$C for tungsten) is able to catalyze the dissociation reaction H$_2$ → 2H and absorb/adsorb atomic hydrogen even inside the bulk of the lattice, as well as at the surface. The demonstration was reported in Ref. [1], chapter IV, points 18 and 19, as follows: 18) To get deloading we put the cell under a dynamic vacuum and increased the temperatures. 19) After several hours, we got the original starting value of $R/R_0 = 1$, meaning that the test was fully successful. The fact that H$_2$ decreases the resistivity of Constantan was first reported in Ref. [2].

<table>
<thead>
<tr>
<th>Table 1. Catalytic power of different metals and alloys with respect to the reaction H$_2$ → 2H, computed in Density Functional Theory [20].</th>
<th>$\Delta E$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni0.3750 – Cu0.6250</td>
<td>+3.16</td>
</tr>
<tr>
<td>Ni0.6250 – Cu0.3750</td>
<td>+2.86</td>
</tr>
<tr>
<td>Ni0.8125 – Cu0.1875</td>
<td>+2.10</td>
</tr>
<tr>
<td>Ni</td>
<td>+1.74</td>
</tr>
<tr>
<td>Ni0.1825 – Cu0.8175</td>
<td>+1.57</td>
</tr>
<tr>
<td>Ag0.8125 – Pd0.1875</td>
<td>+0.57</td>
</tr>
<tr>
<td>Ag0.625 – Pd0.375</td>
<td>+0.51</td>
</tr>
<tr>
<td>Ag0.1875 – Pd0.8125</td>
<td>+0.51</td>
</tr>
<tr>
<td>Pd</td>
<td>+0.42</td>
</tr>
<tr>
<td>Cu</td>
<td>−1.11</td>
</tr>
<tr>
<td>Ag</td>
<td>−1.42</td>
</tr>
</tbody>
</table>

In our experiment we employed Constantan wires of length 100 cm and diameter 0.1–0.2 mm (Fig. 1). To increase their effective surface available for catalytic processes, wires were subjected to specific thermal/electric treatments that created sub-micrometric and multilayered structures at the surface and deeper in the bulk (Fig. 2). The sub-micrometric structures were simply created by oxidation, with a threshold temperature of 600$^\circ$C in free air. Such structures are somewhat similar to hetero-structures. The treatment includes electric high peak power pulses (20 kVA/g of material) with a rise time $T_r < 1\mu$s, corresponding to a current density $J > 50$ kA/cm$^2$, even neglecting skin effects. Such pulses induce extremely fast thermal treatments (warming→cooling) and shock waves. A rough evaluation by fast photo-camera of the color of light emitted from the wire revealed a surface temperature even larger than 1000$^\circ$C in some tests. At the end of the process we observed glassy materials formed on the wire surface.
This treatment produces sub-micrometric geometries, a sort of chaotic mixture of Ni, NiO, Cu, CuO, Ni\textsubscript{x}Cu\textsubscript{y}O\textsubscript{z}, reducing/avoiding, at the same time, the usual deleterious self-sintering processes due to high temperatures. SEM observations revealed that the wires so treated had a large number (up to 700 in some samples) of multilayered structures with thickness of 20–100 nm.

The number of layers was roughly characterized by preliminary experiments using 10, 20, 50 and 100 pulses, by SEM and “oblique” cross section of the wire. Among other parameters, we observed that the distance between layers decreases with an increase in the number of pulses. Sadly, the original documents (papers and CD) of this preliminary testing, located in another laboratory, were destroyed by a “third party” in February 2015, together with other materials and documents.

Our treatment was inspired by the Melt Spinning and Quenching metallurgical process, extensively used by Prof. Yoshiaki Arata and his collaborators (Osaka and Tohoku Universities, Japan) to produce nanomaterials (palladium, or Pd\textsubscript{x}Ni\textsubscript{y}, both dispersed into a matrix of ZrO\textsubscript{2} at 65(%) concentration) for his Solid State Fusion devices under
interaction with D$_2$/H$_2$ at 150–300°C, pressurized up to 60 atm [3]. In the quenching process their cooling rate was over 100,000 K/s. The important feature of Arata’s technique was this “ultra-fast quenching” which yields glassy-like materials. Arata used fast rotating Cu disk where the mixture of palladium (35%) and zirconium (65%) was dropped in a melted state (about 1600°C). Instead of using this kind of disk, we employed ultra-fast powerful electric pulses with fall time <1 $\mu$s. We needed only cooling from about 900°C down to 650°C. With very long and thin wires it is easy to perform this in a short time, just by natural cooling, because of the dependence of emitted power as $T^4$ (in Kelvin), i.e. the Stefan–Boltzmann law.

2. First Generation Experiments: the Introduction of Constantan wires

The dissipation reactor we designed to test the new generation Constantan wires consisted of mica sheets (of the type used in electrical heating elements) supported on a central stainless steel (SS) tube ensuring electrical insulation, on which two wires, one active (the surface-modified constantan wire) and the other inert (Ni–Cr control wire), arranged in parallel and helicoidally wound. Because the Ni–Cr wire is intrinsically stable against oxidation or other stresses, it was used to heat the reactor itself (via “indirect” resistive heating, i.e. by radiation and conduction by gas). The core of the reactor was contained inside a borosilicate Schott Duran glass tube with a wall thickness of 3 mm. Temperatures at the external glass wall and inside the reactor were detected by means of several Type K, SS-screened, MgO insulated, thermocouples (diameter 1.5 mm) [1].

Calibrations were made in noble gases (helium, argon) with different power levels applied to the inert wire. The first test was conducted in an atmosphere of H$_2$/Ar mixture in the ratio 75/25 at 7 bar of total pressure. The power input was 48 W. Figure 3 shows the behavior of the measured quantities over time. The green color line represents the temperature of the external borosilicate wall, while red shows the temperature close to the mica inside the reactor. The key monitor parameter is the ratio $R/R_0$ between the resistance of the wire at a given temperature $T$ and at room temperature.

![Figure 3](image-url)
temperature $T_0$. For Constantan, this ratio, because of hydrogen interaction, decreases with increasing temperature and time. In the blue line we indicate $R/R_0$ for the inert (Ni–Cr) wire and in the orange line $R/R_0$ for the active (Constantan) wire. Recall that one of the key characteristics of Constantan is its normally excellent resistivity stability ($\pm 1\%$) from $-75$ up to $500^\circ$C.

We observed that when the temperature inside the reactor reached $120^\circ$C, the $R/R_0$ of the active wire fell to 0.92 in about 2500 s and to 0.88 in 100,000 s. Correlated with this decrease in resistance, we also observed an increase in excess output power of the reactor. Coinciding with this, all temperatures in the reactor increased. The external glass temperature increased from about $140^\circ$C to $150^\circ$C; the SS tube temperature from $168^\circ$C to $190^\circ$C, and the gas temperature (close to the mica) from $170^\circ$C to $195^\circ$C (Fig. 4). These variations are unrelated to changes in room temperature. Instead, room temperature instabilities somehow helped the anomalous heat generation, perhaps by introducing non-equilibrium conditions. In fact, after a long time, room temperature went back to its initial value, while heat production continued to increase.

During several tests performed in Frascati with mainly Agilent instrumentation (in addition to many ancillary home-made instruments), the excess power ranged between 2 and 12 W (reaching 12 W a few times) at the reference input power value of 48 W. When excess heat was produced, it was typically in the range of 5–10 W. We found no difference in operating the reactor at constant current and constant voltage. Most of the time it was in the constant current regime.

After the National Instruments Annual Meeting (NI-Week, August 2012, Austin, TX, USA), the reactor at Frascati Laboratories, Italy, was disassembled, shipped and reassembled in the USA where it was operated in a public demo for three days. During this event, we observed the highest values of maximum excess power for this experimental set-up: about 21 W with indirect heating (power applied on the inert wire) and about 25 W with direct heating of the active wire with input power of 48 W. Just after NI Week, the reactor was again shipped to South Korea for our participation at the ICCF17 conference at Daejeon. Even there, after overcoming difficulties with the new strict safety rules and conditions of air travel from USA (no gas apart from air inside and no vacuum or pressure conditions allowed), the reactor functioned normally with reasonably reproducible results: 5–15 W of anomalous excess heat with 50 W of electric input power. The values seen were lower than in the test performed during NI-Week. Moreover, for safety reasons, the reactor was operated for most of the time in Constant Voltage regime, both at NI-Week and ICCF17.

After returning to Frascati and performing several cross checks, we realized that the new NI system (the hardware and software set-up since August 2012) in our hands had underestimated the value of electric input power in the regime of Constant Voltage by 11.11% in the range of input power of 40–60 W, i.e. that used in the experiments. Considering this unexpected problem, the real values of AHE power would change to: 8–20 W at Ni-Week, 0–10 W at the ICCF17 Conference (assuming similar hardware arrangements).

We note that all the data were and are fully correct in the constant current regime. The reported lower values are however closer both to our starting values in Frascati and to the results of the subsequent experiments performed by the Martin Fleischmann Memorial Project group which used a batch of Constantan wire with a different starting composition from the old pre-1970s batch we used in the first series of experiments. See Section 3 for further details.

Regarding the overall better performance during NI-Week, in the absence of any systematic study, we can only suspect a positive effect from an accident that happened during the preparation of the set-up: some vapor of silicon oil from the rotary pump went inside the reactor chamber. We did try to remove the possible residual deposits by heating the wires. Anyway, we feel that such an accident was a further strong indication of the catalytic origin of the AHE effect, at least with our materials and operating parameters.
3. Second Generation Experiments: the Addition of Glass

The successive series of experiments exhibited unsatisfactory overall reproducibility. Using SEM/EDS/ICPMS analyses, we found out that the first batches of raw material we used in our experiments, which were produced before 1970, had a composition different from those we used later. Analyses revealed iron contamination in the order of 1000–5000 ppm, and locally up to 10,000 ppm.

Because of a severe budget cut in late 2013, we were forced to redesign and reschedule our experiments with the purpose to study again more deeply some of the most interesting effects obtained in the past and, if possible, to increase the AHE.

In the new experimental set-up we modified the geometrical arrangement of the wires inside the reactor [4]. We used three wires instead of two: a 500-layer Constantan wire, a 2-layer Constantan wire and a platinum wire for control and monitoring purposes. They were inserted inside fiberglass sheaths (\(L = 100\) cm, \(\Phi_{\text{ext}} = 1\) mm, produced by SIGI–Favier, Italy–France Company). Each fiber was porous, of 5 \(\mu\)m mean diameter, and closely braided together. The braid was then twisted around the central SS support that was likewise covered with a fiberglass sleeve with internal diameter of 12 mm. As before, the core was inserted into the thick-wall borosilicate glass tube previously used.

Since February 2013, all the sheaths were embedded in a Sr(NO\(_3\))\(_2\) diluted solution and further decomposed in SrO by thermal treatment. Strontium is a material with a low work function for electron emission (\(W = 2.59\) eV), similar to the calcium oxide used by Yasuhiro Iwamura at Mitsubishi Heavy Industries Laboratories (Yokohama, Japan) since 1999. Electron emitter materials are empirically recognized to have “beneficial effects” on LENR reaction. We have studied the effects of calcium, barium, strontium and magnesium in electrolytic environment, since about 1995. Iwamura, independently, adopted CaO in his famous transmutation device (2002, JJAP) by flowing deuterium gas. Moreover, he showed that MgO is not effective, similarly to our electrolytic experiments (barium worked best, but it is toxic).

We calculated the emitted power using Stefan–Boltzmann law (emission proportional to \(T^4\), in Kelvin) for the

![Figure 4](image_url)  
**Figure 4.** Temperature of the external glass wall (red), the internal SS tube (blue), the internal mica support (orange) and the ambient (green) as a function of time.
radiated energy from the glass wall and Newton’s law (proportional to temperature) for the energy dissipated by convection.

During the tests several uncontrolled and unexpected phenomena occurred – including spontaneous overheating that damaged the 500-layer wire – making the results unclear. Therefore, we decided that the only way to clarify the role of the fiberglass in the process was to add a larger amount of glass. Even the SS-tube, where the glass-covered wires were twisted around, was inserted inside two more glass hoses.

To calculate excess heat, we decided that tests carried out with a smaller amount of glass would be considered the threshold, i.e. the blank test. Even with such a conservative constraint, the comparison between the two experiments showed that glass has intrinsic co-effects in the generation of anomalous heat. In Fig. 5 we compare the temperatures at the external wall and at the internal SS-tube in the two cases of a small and a large amount of glass. We note that, under the same conditions of pressure and input power, the temperature in the second case is clearly larger than the corresponding values for the experiments with lower glass content in the reactor.

4. Effect of Fiberglass on Hydrogen Storage

The experiments we carried out clarified that the borosilicate fiberglass (type E) we used as electrical insulator plays a role in the generation of excess heat. We signal out the mechanism responsible for this in the adsorption property of (borosilicate) glass, which was observed by Prof. Irving Langmuir since 1920 during his studies on hydrogen dissociation at high temperatures by Tungsten (W) wires (>2000$^\circ$C, at H$_2$ low pressures). The hydrogen atoms,

![Figure 5. Data comparison between tests conducted with a small and a large amount of glass in the reactor. In red we display external glass temperature, in blue internal SS tube temperature after subtracting ambient temperature. Under the same conditions, temperature is higher when more glass is employed.](image-url)
produced by the dissociation of molecular hydrogen by means of the catalytic action of our sub-micrometric structured Constantan wires on the reaction (at quite low temperatures, about 200°C), are largely adsorbed onto the surface of the micrometric glass fibers, forming a thin film. Moreover, according to one of our colleagues (Cesare Lorenzetti, private communication), a long-time expert in Fischer–Tropsch type catalysts, the oxides (in the specific case made by iron, potassium, strontium, boron) “locked” inside glassy materials (like fiberglass) are quite stable for long time (months) even in reducing environments and at high temperatures. The stability effect against the “evaporation” of light elements (like potassium) is further enhanced by manganese (present, in the type of Constantan that we used, at 1% concentration).

Langmuir measured the density of hydrogen atoms adsorbed onto the surface of a glass bulb (presumably of type borosilicate) kept at low temperature (about 90 K). The density is of the order of 10^{15} atoms/cm^2. In his experiments, the dissociation was obtained through a hot tungsten filament in H_2 atmosphere and the fraction of dissociated molecules depended on pressure and temperature: the lower the pressure and higher the temperature, the larger the fraction [5,6].

In our experiments the effective surface of each small sheath is larger than 1 m^2. The total surface of the used fibers could be larger than 50 m^2, corresponding at about 10^{20} – 10^{21} adsorbed atoms according to Langmuir’s measurement. The hydrogen atoms concentrated onto the glass surface by adsorption are much closer to each other than the hydrogen atoms moving in the bulb as a gas, increasing so their probability of recombination in the molecular form. This reaction is largely exothermic with the release of 4.52 eV to the environment.

Moreover, the recombination time is in the time regime of so-called femtochemistry (some-several 10^{-15} s). The experimental demonstration that several chemical reactions have extremely short reaction time (10^{-12} – 10^{-15} s) has been performed since 1980 by Prof. Ahmed H. Zewail using ultra-short laser pulses [7]. Obviously, with such short times, the peak power of recombination is extremely large, 10^{12} – 10^{13} times larger than the mean power at steady-state conditions.

With this new equipment configuration, the net effect of the introduction of glass in the reactor is the increase of the rate of the chemical reaction of hydrogen recombination. Therefore, the adsorption property of glass appears to be a co-factor in the generation of heat excess, in addition to the main unknown LENR process of non-chemical origin. We note that nearly all of the chemical reactions produce at most 4.5 eV of energy. In our experiment, the effect lasted for several weeks and its integrated value is very much higher than the product of chemical energy times the amount of material involved. We also suppose that adsorption may enhance absorption of atomic hydrogen in the Constantan lattice, supporting in this way the main LENR process of heat generation. Actually, the possibility that the presence of a hydrogen film closely surrounding the wire favors the diffusion of atomic hydrogen inside the metal should not be excluded. In conclusion, further investigation aimed at clarifying the effects and role of glass in such phenomena is necessary.

5. The Hypothesis of Energy Localization

In 1954 Enrico Fermi and his coworkers J. Pasta and S. Ulam with the help of M. Tsingou performed, at LANL-USA, the numerical simulation of a discrete nonlinear system using the computer MANIAC I [8]. The dynamic system they studied consisted of 64 one-dimensional oscillators coupled to the nearest-neighbors by nonlinear force terms. Fermi’s expectation was that the excitation energy associated with a normal node would be distributed along all the normal modes after a sufficiently long time interval; that is to say, the system would have evolved toward a state of energy equipartition. Surprisingly, energy remained localized to few modes and showed a sort of periodicity, returning most of it to its initial mode.

Dr. Brian Ahern (previously at DARPA, USA) has recently revisited the Fermi–Pasta–Ulam problem/paradox, proposing it as a candidate to explain some of the complex phenomena occurring in LENR experiments [9]. While in
most solids the atoms reside in parabolic potential wells and therefore undergo simple harmonic motion, generally at high frequency and low amplitude, the atoms of some materials are subject to a non-parabolic potential corresponding to nonlinear force terms. This leads to nonlinear vibrational modes of large amplitude and low frequency. Hence, Ahern proposes that energy localization may take place in structures with a small number of atoms. Both properties – a relatively small number of atoms and nonlinear coupling – are possessed by nanoparticles of size 3–12 nm. This is the “right” dimension suggested by Y. Arata; experimentally reconfirmed by Takahashi–Kitamura, Univ. Osaka, Kobe, Japan, in experiments of LENR by interaction of D$_2$ and nanoparticles at high temperatures. In nanoparticles, a large fraction of atoms is located at the surface and is subject to nonlinear binding forces with the internal atoms.

The transition to the new regime would be triggered by a pulse of energy that the cluster can receive from thermo-mechanical oscillations of the surrounding medium, or from electrical pulses, even by radiations. As a consequence, a very small number of atoms in the cluster acquire a significantly greater amount of energy than they would in conditions of thermal equilibrium. Locally, the large oscillations manifest as hot regions. This is closely similar to the phenomenon of oscillons in granular media [10]. We note that, in our experimental conditions (i.e. especially the effect of glass fiber sheaths), the local pulse of energy could be provided by the H + H $\rightarrow$ H$_2$ recombination reaction.

Energy localization could clarify the catalysis processes, usually associated to the lowering of the activation energy of a reaction. In this scenario, a few excited atoms, corresponding to a locally hot region, make their energy available for the activation of chemical reactions that could take place only at higher temperatures if the cluster was absent. Ahern sustains that energy localization could also explain the initiation of LENR reactions in H$_2$/D$_2$ saturated nanosstructures. As a consequence, energy localization circumvents the second law of thermodynamics, since nanoparticles act as Maxwell’s demons able to convert part of their thermal energy into valuable chemical energy potential.

The violation of the second law is apparent, because it is not applicable to ensembles with a small number of particles. We quote Maxwell’s words [11]: “The truth of the second law is . . . a statistical, not a mathematical, truth, for it depends on the fact that the bodies we deal with consist of millions of molecules . . . Hence the second law of thermodynamics is continually being violated and that to a considerable extent, in any sufficiently small group of molecules belonging to a real body.” Violations of the second law at nanoscales have also been observed experimentally as occasional short-time (less than 2 s) fluctuations around the thermal equilibrium state [12,13].

The catalytic action of nanostructures at the surface of our surface-modified Constantan wires can partially explain the thermal anomalies we found in our experiments, as they enhance H$_2$ dissociation even at temperatures $T \ll 800^\circ$C. If further confirmed, the energy localization would be the mechanism for coordinating the normal thermal motion of particles in nanometric regions of matter into localized high-energy oscillations.

6. Spontaneous Voltage Generation

In our experimental set-up, we can control only two wires at the same time. For this reason one of the Constantan wires is not connected to the Data Acquisition System (PIXIe, NI) and left unconnected (“floating”). However, we measure periodically its resistance by means of a high sensitivity multimeter (Fluke 187) to evaluate the amount of adsorbed hydrogen. When the wire is heated in the presence of hydrogen, its resistance ratio can decrease up to 0.7. Anyway, from what we know from “open literature”, any systematic study on the relationship between the amount of hydrogen absorbed and the decrease of constant resistance is not available. We have just qualitative data about the correlation of the two quantities.

On June 25, 2014, we noted, just by chance, that the floating Constantan wire generated by itself a macroscopic voltage of the order of hundreds of microvolts that resulted as a function of many parameters: temperature, type of gas, pressure, resistance ratio. The highest measured values were about 1400 $\mu$V for the voltage and 120 $\mu$A for the current with duration of only few hours, while stable outputs were about half. We note that the spontaneous tension cannot be ascribed to the usual Seebeck effect, because we considered only one single wire and not a junction of two

In previous experiments we discovered that iron contamination in the wires had a positive influence in terms of stability and excess power of the reaction. Hence, we decided to develop a procedure to add iron of nanometric sizes to the surface of Constantan wires and even some microns deep into the bulk during our thermal/electric treatments for the preparation of the nanolayers. From a chemical point of view, iron is characterized by a solubility of hydrogen
into the lattice that increases largely with temperature: in 100 g of material, from 0.37 cm$^3$ at 400°C to 7 cm$^3$ at about 1000°C. To fully exploit this property of iron, the reactor had to reach higher temperatures than we previously obtained. For this reason, we added another sheath over the usual borosilicate glass one, made of alumina (Al$_2$O$_3$), with a higher melting temperature ($T_{\text{max}} = 1200°C$). Figure 6 shows a complete schematic of the reactor and in Fig. 7 we show a photograph of it, taken during the execution of some of the experiments we conducted. To increase wire temperature at constant input power, we used a mixture of H$_2$ with low thermal conductivity noble gases (argon, xenon). The effectiveness of such mixtures was verified by comparing the corresponding excess heat results.

With the new preparation procedure, fully developed at INFN-LNF, we produced 20–40 iron thin layers, similar to multiple hetero-structures, at the wire surface. Moreover, we introduced further non-equilibrium conditions in the wire by making several (up to 20) knots with hole diameter 0.3–2 mm. These knots represent local geometrical variations of the path of the current flowing in the wire and are crossed by the lines of the magnetic field they generate. Because of the large currents (up to 2.3 A) we inject in the wire, they become the locus of large thermal non-homogeneities. The tests we carried out with all different combinations of elements (wire with/without iron/knots) showed that the new configuration (iron plus knots) offers measurable advantages in terms of hydrogen absorption and AHE amount.

As usual, we calculated very conservative estimations of the excess power, using as a blank the corresponding result obtained with the configuration with no iron in the wire. The best result (with Xe/H$_2$ mixture) was 15 W against an input power of 100 W. The local temperature of the wire was estimated, through the platinum wire, at around 800°C. In Fig. 8, we show the results of the tests carried out in hydrogen atmosphere. $T_{\text{ext}} - T_{\text{amb}}$ is plotted as a function of the input power in the case of standard Constantan wire (blue) and Fe-added Constantan wire (red). In green we indicate the excess power of the configuration with iron compared to that without it. Clearly, excess power increases with temperature. This behavior was confirmed by the experiments with Xe/H$_2$ atmosphere, where larger wire temperatures were reached (Fig. 9). Wire temperature was estimated through SS-support temperature measured by the thermocouples (Fig. 10). For comparison, while at an input power of 90 W, excess power is about 7.5 W in a pure H$_2$ atmosphere, this raises up to 15 W in a gas mixture.

We also verified the presence of a spontaneous voltage in the non-powered wire in the reactor. In wires having several knots with hole diameter smaller than 1 mm and filled with iron at nanometric size, we observed in gas mixture atmosphere currents up to 150 μA and voltages up to 1900 μV, stable over long times. We compared current generation for different wires with the same number of knots and measured values about 2.2 times larger with the addition of iron. In particular, we ascertained that the local presence of iron in knots was extremely important for maximizing the effect.

8. Discussion on the Indetermination of Temperature Measurements

With regard to the thermometric experiments and the relative indeterminate results, we used three different approaches/typologies/analyses:

(A) Experiments performed in 2012–2013, i.e. the so-called first series.

(B) Experiments performed during 2014, in which we studied in some detail the effect of fiberglass addition, as presented at MIT March 21–23, 2014 Colloquium on Cold Fusion effects.

(C) Experiments concerning the effect of iron addition together with a wire geometry with several knots (main results at ICCF19, April 2015.

First of all, we note that the AHE are considered real by us if, and only if, there are simultaneous increases of both the internal and external temperatures of the reactor, at a given constant input power used as reference. For the experiments of type A we adopted the approach of performing calibrations in inert gases, mainly helium or argon before H$_2$ addition. Helium has a thermal conductivity similar to H$_2$. Argon has about seven times lower thermal conductivity than H$_2$. 

Figure 8. Tests performed in H\textsubscript{2} atmosphere for the configurations with knots with (red) and without (blue) iron addition. The difference of power between the two configurations is displayed in green.

The improvement of the overall performance using a low thermal conductivity gas, i.e. increasing the wire temperature at constant input power, was discovered by us after 2010, employing both palladium and/or nickel wires. At that time we used flow-calorimetry and the effects were no longer in doubt. The main drawback was the low response time of the system: meaning we could do only two tests per day at most. With isoperibolic-type measurements we can do up to 5–6 experiments/day.

Figure 9. Tests performed in gas mixture atmosphere of Xe (1.4 bar) and H\textsubscript{2} (1.7 bar). The meaning of the colored curves is the same of Fig. 8.
Because we used a mixture of H\textsubscript{2} and argon in the actual experiments (as opposed to the control experiments), we carried out the same procedure for He/Ar mixtures. Furthermore, in the old experiments, we realized that one of the reference “good working points” was at an electric input power of 48 W. As a consequence, the results made public are mainly at the input power of 48 W (plus a few tests at 50 W). All the work performed at different input powers were not shown or discussed in public, and was only used for internal discussions in the working group.

The main disadvantage of this approach is the large indetermination, usually quantified in $\pm 1$ W and in some specific conditions up to $\pm 2$ W. The typical excess power when the system showed “useful” effects was in the range of 5–10 W during the test performed at Frascati Laboratories using the Agilent DAQ. In conclusion, the detected excess power, even in the worst situation, is real beyond any doubt.

As regards to the experiments of type B, they were actually a comparison of two different experiments. The two were at the same power level of 50 W, but with varying pressure of H\textsubscript{2} inside the chamber, from 3.8 down to 0.5 bar at low glass content and from 2.7 down to 0.1 bar for a large amount of glass. This was accomplished by dismantling the internal set up in order to add additional glass fibers. In this case the comparison is more difficult. Anyway, the difference on both the external (about 16°C, from 149 to 165°C) and highest internal temperatures (over 50°C, from 270 to 320°C) at 0.5 bar of pressure, is so large that one can hardly infer that the results are meaningless or invalid. In short, adopting for the calculation of the true effective area of the reactor just a value of length = 10 cm, diameter = 4 cm and for the (convective) Newton component a value of 15, we conservatively assumed that the experiment with a low amount of glass is the blank, i.e. equal to the input power of 50 W. In such conditions, the excess power of the configuration with large amount of glass seems to reach a value as large as 11.7 W.

In conclusion, even supposing a margin of error of $\pm 3$ W, the effect seems to be real. About the experiment of type C, the comparison is performed in a very conservative way. We have two Constantan wires, with the same length and diameter, both with several knots, where the only difference is the addition of at most a few milligrams of iron inside the knots of the “active” wire. Iron is added through a very dilute solution of Fe(NO\textsubscript{3})\textsubscript{2} in HNO\textsubscript{3} (at about 5% concentration), 18 times, for 14 knots. In such a way iron is deposited in sub-micrometric layers. After such

Figure 10. Tests performed in gas mixture atmosphere of xenon (1.4 bar) and H\textsubscript{2} (1.7 bar). The temperature of the SS internal support is showed in red. The difference in power between the configuration with iron and without iron is in blue.
treatments, the knots show strong ferromagnetic behaviors. Each wire is put inside the usual glass sheath and again inserted in an Al₂O₃ sheath (T\text{max} = 1200°C). The sheaths are twisted around each other about every 2 cm. Moreover, they are inserted in another, more large diameter sheath. In such a geometrical configuration it is very difficult that temperature differences arise because of some geometric effect: only internally generated energy can be their source. For such kind of set-up power indetermination can be easily kept at less than 1 W.

9. Conclusions

The observation of single-wire spontaneous voltage generation in our experiment, in addition to achieving the aim of increasing AHE (using iron in the most recent specific case), represents one of the unexpected results of our recent research activity. The phenomenon shows itself as the generation of a voltage between the extremities of the non-powered wire in the reactor. The effect was first revealed serendipitously in the second-generation reactor with a large amount of glass. Furthermore, the successive addition of iron nanolayers and small knots in the wire (third generation reactor) increased and stabilized the magnitude of the generated voltage (up to 1900 V) and current (up to 150 A).

As concerns the anomalous heat production, iron has a beneficial effect because of its solubility of H₂ in the lattice largely increasing with temperature, while the knots are meant to create further non-equilibrium conditions inside the reactor. With such new wire features, we obtained larger excess power. From our observations and experiences we deduce that anomalous heat excess and spontaneous voltage generation are somehow related to the following conditions, or at least to some of them:

- Temperature as large as possible, obviously avoiding material sintering.
- Large hydrogen absorption/adsorption by means of catalytic materials, i.e. nanomaterials.
- Hydrogen flux as large as possible from regions at high concentration to regions at lower concentration.
- Presence of elements with hydrogen concentration increasing with temperature, such as iron.
- Presence of non-equilibrium conditions as large as possible: this is the main condition for getting any type of thermal or electrical anomaly.

We highlight that wires with good performances in terms of excess heat showed remarkable values of spontaneous voltage. One key aspect to be clarified is the role of strontium (Sr) in the generation of the spontaneous voltage. Supposing that the effect is due to some motion of electrons from the powered-wire toward the non-powered one, i.e. a thermionic emission or a process similar to it, an electron-emitting material like strontium (due to its low work function) might give a large contribution to it. Unfortunately, we performed no measurement of wire voltage for the old set-up with no strontium deposited on the glass sheaths, therefore, targeted tests are needed. Regarding iron, we found out that the fiberglass sheaths (SIGI Inc.) that we used may contain measurable amounts of iron (<2%) and iron oxide (<1%). Hence, a certain amount of iron was already present in the second-generation experiments. In this article we have also formulated some hypotheses about the mechanisms leading to thermal excesses in our experiments. We have focused on H₂ → 2H → H₂ reactions, individuating three combined processes:

- The catalytic properties of Constantan help molecular hydrogen dissociation.
- The hydrogen produced is partly adsorbed at fiberglass surface. Adsorption favors hydrogen recombination (an exothermic chemical reaction) but could also promote hydrogen absorption into the metallic lattice.
- If demonstrated, energy localization at nanoscales would enhance H₂ dissociation by converting thermal mechanical energy into a valuable chemical energy potential.

The next step of our activity is aimed at investigating in detail spontaneous voltage generation and possibly identify its nature and the variables that are related to this anomalous effect as well as to get its maximization. As concerns the better performance of the reactor after the accident with vapors of silicon oil, we think it is somehow related to the
recent “Breakdown of Richardson’s law . . .” found in the electron emission from heated carbon nanotubes [14]. In this study, the authors measured an emission density at large temperature (1800–2000 K) more than one order of magnitude higher than that expected with the normal thermionic emission at macroscopic levels. We hypothesize that the heating of the wires in presence of silicon oil vapor may have led to the formation of meta-stable carbon nanostructures at the surface, acting as enhancers of the anomalous effects produced in our reactor. Further inspired by the experimental design of such an important paper, we observe that the pointed shape of the nanotube is also found in some of the nanostructures present at the surface of our Constantan wires after the thermal/electric treatments. As a consequence of the supplied power or even of the energy localization mechanism if real, hot pointed-shaped nanostructures could be also responsible for an electron emission whose current manifests even at temperatures (averaged on macroscopic extensions of the wire, as measured by the thermocouples) lower than 600°C, the threshold of the known thermionic emission (i.e. Richardson law). We note that also in Iwamura’s experiments, the anomalous effects, specifically in the case of “transmutations”, disappear if the size of the nanoparticles is too large or the Low Work Function material used (CaO) is changed to another with higher values of Work Function (MgO) [15].

Addendum

After the ICCF19 Conference, in May 2015, we became aware that Prof. Leif Holmlid (Göteborg University, Sweden) suggested the use of nanosized iron, as a cofactor in its deuterium catalyzer (the so-called “hydrogen transfer catalyst”), to increase the amount of the so-called, ultra-dense Rydberg matter in its specific reactor by Inertial Confinement Fusion (ICF) processes. He aimed, and demonstrated experimentally possible by high quality and sophisticated charge particle measurements, to produce very large excess power (energy gain over 1000) just using Deuterium gas (made ultra-dense by an appropriate catalyst, based on Fe–K) as initial fuel and a table-top laser as stimulator for the fusion processes. His main ideas are summarized in the recent patent application EP 2680271A1 [16].

Moreover, Prof. Friedwardt Winterberg (Germany–USA, Nevada Univ., USA), the well-known expert in ICF at the international level, suggested the use of a magnetic field to increase the amount of Rydberg matter in Holmlid’s experiments [17]. We observe that our knots (carrying a sufficiently large current), filled with iron and/or iron oxides at nanosize, can represent a simple/first step, experimental set-up, to match some of these requirements. We guess that the ultra-short time of recombination reaction with a range of hundreds of femtoseconds could help the stimulation of LENR effects (extremely high peak power), especially in our set-up where we have at the same time:

- Sub-micrometric structured Constantan (large production of hydrogen);
- Large amount of fiber glass where to “store” and recombine hydrogen;
- Large electron emission as a consequence of the use of low work function materials and of the increased field emission due to the low dimensionality (the trigger of the system).

In the final analysis, we conclude that in some tests where we used pure D₂ and/or Xe/D₂ mixtures (ratio 10/1) at mild pressures, we observed a certain increase of gamma radiation by a NaI(Tl) gamma detector (model LB125 by Berthold), in the energy range of 25–2000 keV. This increase happened mainly during the fluctuations of operating temperatures of the system, i.e. increasing or decreasing input power. The effect lasted for several hundreds of seconds. Again, this effect appears to be due to non-equilibrium conditions. The first detection of this phenomenon occurred on June 2012; it was reported in a meeting on LENR held at the Italian Parliament (July 2, 2012) and shortly after that discussed at both the NI Meeting and at the ICCF17 Conference (Daejeon, South Korea) in August 2012.

Considering the fact that such effects happened mainly using D₂, we suppose that even in our experimental set-up there are places where Rydberg Matter, as described by Leif Holmlid, might produce a low intensity signal in our experiment during non-equilibrium conditions. Further systematic work has been planned in the next experiments to explore this possibility.
Finally, some of the authors of this report, considering the experimental evidence that in several LENR experiments (performed worldwide since 1989) there is no consistency between the AHE detected and the usual nuclear particles emitted, have the feeling that some LENR are related, in some aspects, to the so-called Dark Matter (which is theoretically or experimentally necessary to explain the universe, although its existence has not yet been clearly demonstrated) and emission of new type/exotic particles like the WIMP (Weakly Interacting Massive Particles). Even studies devoted to explain the large discrepancies in observations involving heat and helium released from the earth – such as the finding that heat measured when compared to helium too large by a factor of 20 – indicate the existence of new types of particles and related reactions [18].

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References
[15] Y. Iwamura, S. Tsuruga and T. Itoh, Deuterium permeation induced transmutation experiments using nano-


Research Article

Off-mass-shell Particles and LENR

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Abstract

A recent and somewhat radical theoretical explanation for LENR is reviewed. It is based on variable mass theories of relativistic quantum mechanics that date back to the 1930s in works by Fock and Stueckelberg, and up to the present by many others. It explains a large number of observed anomalous effects in LENR by positing that nuclear rest-masses can vary in “nuclear active environments” in condensed matter settings. The varying masses modify the kinematic constraints of the nuclear reactions. It also offers a mechanism for enhancing electron screening and-or quantum tunneling rates, for allowing for resonant tunneling, and for modified radioactive decay rates by mass changes in the decaying isotopes.

Keywords: Horwitz-Piron, LENR, Nuclear anomalies, Stueckelberg, Variable mass

1. Introduction

There are a large number of experiments that cannot be explained easily or at all by conventional nuclear physics theory. These include most experiments from the LENR community along with a number of others concerning radioactive decay rates and other anomalous phenomena ([7,8] and references therein). Physicists have largely disengaged from this subject, although many study it secretly late at night, the problem being frustration over how these experimental results can possibly be true. If one reads enough of the experimental literature though, one begins to ask the mirror question - How can these experiments all be wrong? I found myself on this path and tried about a dozen ideas to explain and reconcile this dilemma over a number of years. Slowly, I felt cornered into the theory presented here, and in previous papers [7,8]. My conclusion was, and still is, that the only way the experiments can be explained is if the nuclear rest masses of particles are somehow varying in those “nuclear active environments” where the reactions are occurring. But how could that be? Aren’t the rest masses fixed? Having been trained in theoretical particle physics, I knew that in relativistic quantum field theory, like the standard model of particle physics, the masses inside of Feynman diagrams – the “virtual particles” – can and do vary from their rest masses [50,49]. These particles are also called “off the mass shell” in the vernacular of particle physics for this reason. Actually, the standard model makes a very interesting prediction in this regard. It predicts that all interacting particles have some probability of being off the mass shell all of the time, even if the inter-particle interactions are very weak (just not exactly zero for all time).

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This conclusion follows from the fact that Feynman integrals, the building blocks of perturbative solutions to quantum fields, involve integrations over the masses of particles in loops and in the interior portions of the diagrams, and since all particles in our universe have been interacting with other particles since the beginning of time and will continue to interact, they are always at least slightly virtual. In order to explain LENR, quite large off-shell deviations are required, often in the MeV range. These have never been directly observed, or expected. Thus this must be viewed as a highly speculative idea. I’ve proposed this theory because I see no other way to explain the experiments of LENR. I want the reader to understand this, and that I am not claiming that mass variation is in any way proven. I shall make arguments in favor of it, but proving that nature works this way will depend on future experiments.

Off-mass-shell behavior is an inherently relativistic effect. Usually it’s associated with high velocity motion. In ordinary matter at near to room temperature we expect that the velocities of the particles to be non-relativistic, since otherwise the matter would not be stable. The usual relativistic correction factor of \( \gamma = 1 / \sqrt{1 - v^2/c^2} \) can be safely set to 1. Nevertheless, we consider the possibility that the rest masses can deviate from their usual values in some special systems. Inside of a Feynman diagram, consider a virtual particle with a 4-momentum \( P^\mu \). The velocity of the virtual particle (if it is timelike) can be taken to be \( |\mathbf{v}| = c \sqrt{P_0^2 - \mathbf{P}^2} / \sqrt{P_0^2} \) (I use the time-like metric signature here \((+,−,−,−)\)). So it is possible for a virtual particle to have a slow velocity, but still go off the mass shell, since all values for \( P^\mu \) are integrated over in the Feynman integral. Even though the motions of all the massive particles in a solid might be non-relativistic, we must still use a relativistic theory to examine this off-shell behavior. The laws of physics in a local Lorentz frame are Lorentz covariant to a high degree of accuracy (if we ignore curvature of space-time locally and gravity effects). The non-relativistic limit of the laws of physics, resulting in Galilean invariance, is only an approximation to this. So we should use a Lorentz-covariant theory, like the standard model of particle physics or quantum electrodynamics (QED), to study this sort of phenomenon. The problem is that this is very hard to do. We would prefer to use a relativistic wave mechanical theory, like Schrödinger’s non-relativistic equation, to describe it instead. But the standard relativistic versions of wave mechanics, like the Dirac equation, Klein–Gordon equation, Proca equation, Rarita–Schwinger equation, etc. are all unacceptable as many body quantum theories because either their energy is not bounded from below, or they have negative probability states, or both. The modern view among particle physicists is that only a quantum field theory description is possible, and a wave mechanical particle description does not exist. Due to the complexity of the perturbation theory for the standard model in a solid, there exists no rigorous bound on how far the virtual masses can wander off-shell. Thus we are venturing into terra incognita, but I feel that the experiments require us to pursue this theoretical possibility.

The difficulties with developing a relativistic wave mechanics can be understood very easily. Relativity theory says that space and time are coordinates in a 4-dimensional manifold, and that they mix linearly under Lorentz transformations. So space and time are the same in some sense. But in quantum mechanics, time is a c-number parameter that precisely orders the evolution of causal history and events and therefore commutes with all the operators of the Hilbert space of quantum states, whereas the positions of quantum particles become non-commuting operators. So in quantum mechanics, time is very different from position. These two different requirements on the time variable produce lots of problems for relativistic quantum mechanics. The time variable is overloaded. This problem was recognized early on in the development of quantum theory, and a solution was proposed in the 1930s independently by Fock and Stueckelberg [13,47,46]. We discuss these theories more below.

2. The Time–energy Uncertainty Relation and Variable Mass

Some physicists might ask the following question.

In a solid, where the velocity of the particles are non-relativistic, the energy of a particle is simply given by \( E \approx mc^2 \). But we expect an energy-time uncertainty relation of the form \( \Delta E \Delta t \approx \hbar \), and therefore (taking \( c = 1 \)
\[ \Delta m \Delta t \approx \hbar. \text{ If the particle is stable, so it is lifetime is infinite, then we can take } \Delta t \text{ to be } \infty \text{ and consequently why is not } \Delta m \approx 0, \text{ i.e. on the mass shell?} \]

Therefore, they expect weakly interacting particles to be always on the mass shell. This argument is reinforced by the fact that most of the time when we measure a particle’s mass in condensed matter It is on the mass shell. I believe that the experimental evidence in LENR suggests that in very rare and special nuclear active environments, the masses are varying unexpectedly, and so let’s examine the theoretical basis for this Heisenberg uncertainty argument a bit deeper.

First of all, the Heisenberg uncertainty relation deals with the uncertainty for \( E \), it says nothing about the expectation value \( \langle E \rangle \)

\[
\Delta E = \sqrt{\langle (E - \langle E \rangle)^2 \rangle},
\]

(1)

Second of all, the Heisenberg uncertainty relation is an inequality, and so for energy and time it would be

\[
\Delta E \Delta t \geq \hbar/2
\]

(2)

and therefore, if \( \Delta t = \infty \) all we can say is that \( \Delta E \geq 0 \), which is not a very significant result.

Third, the origin of the Heisenberg uncertainty is the canonical quantization rule \( [p, q] = -i\hbar \), but time \( t \) in conventional quantum mechanics is a c-number which commutes with all the operators in the Hilbert space of states. Therefore the commutator \( [E, t] = 0 \). So how could there be a time-energy uncertainty relation? This unresolved question has occupied many articles over the years, a partial list being [5,3,6,9,26,43,36].

Finally, there is no acceptable relativistic wave mechanical theory, and so we can’t even define a Hamiltonian or position operators covariantly for a many-body system.

Consequently, I conclude that the Heisenberg uncertainty principle argument against variable masses in a condensed matter setting are not conclusive or even relevant. We expect the nuclear active environment to be a non-equilibrium mixed-state quantum open system with complex morphology, unknown catalytic processes, and possibly with external electromagnetic fields, and proton, deuteron, and electron currents flowing in the material. In other words, it is basically a perfect storm of complexity about which it is very difficult to say anything with rigor and confidence. One thing we can say for sure though, and that is that the energy–momentum tensor density is conserved, since this is a property of the standard model, or any other relativistic model we might consider. Consequently, even though the mass of a particular particle may change, this does not mean that energy is not conserved. Just as in the Feynman diagrams of relativistic perturbation theory where the particles are off shell, the total energy and momentum are always exactly conserved.

3. Fock–Stueckelberg Covariant Wave Mechanics

The idea of Fock and Stueckelberg was to add a second time variable and make the space five dimensional (for a single particle) [13,47,46]. Sometimes these are called historical-time or proper-time models. The theory was utilized by Feynman, Schwinger, and Nambu [11,41,34]. For example, Feynman used it to carry out his path integration approach to quantum mechanics for the Klein–Gordon equation [11]. This is the simplest example of a historical time theory.

The usual Klein–Gordon equation is

\[
(i\partial - A)^\mu (i\partial - A)_\mu \Psi = -M^2 \Psi,
\]

(3)

where \( M \) is the particle’s rest mass, and where \( A \) is the vector potential for an external classical electromagnetic field. The conserved current is \( j_\mu = i[\phi^* \partial_\mu \phi - \phi \partial_\mu \phi^*] \), but \( j_0 \) takes on both positive and negative values, and so it cannot
be taken to be a probability current. Moreover, a localizable Schrödinger type position operator cannot be defined for this equation in the sense of Newton and Wigner [35]. The idea is to add a second invariant time $\tau$, and consider the modified Klein–Gordon equation

$$i \frac{\partial \varphi(x, \tau)}{\partial \tau} = \frac{1}{2} (i \nabla - A)_{\mu} (i \nabla - A)^{\mu} \varphi(x, \tau), \quad \text{where } x = \{x^0, x^1, x^2, x^3\}. \quad (4)$$

It is very similar to the time dependent Schrödinger equation, but with the “historical time” $\tau$ replacing the usual time variable $t$, and with the four coordinates of space-time $x^\mu$ replacing the usual three coordinates of space. Because of this, it is quite easy to formulate the path integral method for this system by following the same steps as used for the Schrödinger equation. Feynman points out that if $A^\mu$ does not depend on $\tau$, then separable solutions exist so that $\varphi(x, \tau) = \Psi(x) \exp(i \frac{1}{2} M^2 \tau)$ and $\psi$ is the solution to the usual Klein-Gordon equation. Equations of this type were first studied by Fock and Stueckelberg. The path integral solution includes all paths in space-time connecting two space-time points and parametrized by $\tau$, with no restrictions on the path, so that off-mass-shell paths are included in the path integral solutions. This reflects the fact that Feynman diagrams contain virtual particles which are not on the mass shell. Horwitz and Piron [19–23] extended the theory to multiple particles. This theory is no longer simply a reformulation of the standard quantum mechanics. It is now different, and in particular the off-shell behavior is much more prevalent. In the quantum version of this theory, the on-mass-shell state vectors are not complete in the whole quantum Hilbert space. Rather, off shell states are also required for completeness.

Another approach that has been taken is to develop a 5-dimensional generalization of QED, called pre-Maxwell theory, for which the Feynman diagram rules have been worked out and applied to various scattering processes [29,28].

So the assumption is that in the “nuclear active environments” of LENR, a variable mass theory such as one of these has become an effective theory for the solid state behavior. Perhaps this assumption can be derived from just the standard model of particle physics, exploiting its off-shell virtual particle qualities, but in the meantime we can take a phenomenological approach and try and deduce what experimental conditions seem to lead to off-shell behavior in LENR. More discussions along these lines were presented in [7,8].


The standard model is believed by most physicists to describe all phenomenon observed in nature except for gravity [37,50]. Thus all of nuclear and condensed matter physics are believed to be derivable from the standard model. For example, the neutron–proton mass difference has recently been accurately calculated, and agrees with the measured value, by using lattice QCD plus QED [2].

The first question then is, are there any theorems that would rule out the possibility of large mass variations? The usual arguments based on the Heisenberg uncertainty relations, as we have seen above, are not conclusive on this point. There is the equivalence theorem in field theory which states that changing field variables will change off-shell Green’s functions while leaving the S-matrix invariant [10,48]. But this does not prove that in condensed matter which is undergoing some arbitrary complex non-equilibrium process, that large excursions off the mass shell cannot occur and contribute significantly to the resulting probability amplitudes for different reactions. I have not found any theorem that rigorously limits off-shell mass excursions of this type in condensed matter that would be relevant.

In quantum electrodynamics, charged particles do not have a simple fixed mass due to the interaction with infrared photons as in [16,4,33] and references therein. Charged particles continually interact with massless infrared photons, and therefore cannot be assigned fixed masses. The charged particle surrounded by its cloud of infrared photons is called an infraparticle. This infrared problem poses an interesting and as yet unsolved challenge to QED and the standard model. When you consider these results in the framework of an interacting, non-equilibrium condensed matter system, it seems quite plausible that in some special circumstances a large mass variation for charged particles
may be possible. Perhaps, in some approximation, the Fock–Stueckelberg models might describe such an interacting
intraparticle.

We can say for certain that the Fock–Stueckelberg type of models are compatible with the basic principles of
relativity and quantum mechanics, and that they do allow for large mass variation. It is conceivable that in some special
circumstances in a solid, the matter there might be better described by them rather than by the usual Schrödinger
theory. What environmental conditions are required to bring about such a state of matter? I do not know, but the
experiments of LENR shed some light on it. The nuclear active environments tend to occur near the metallic surface,
in non-equilibrium situations, possibly in cracks or crevices, and in the presence of fluxes of deuterium, hydrogen, and
electrons through the metal. External stimulation with electrical, optical, or other stimuli of the metal often helps, as
do catalytic elements.

5. Enhanced Tunneling Rates Caused by Increased Electron Masses

In the Born–Oppenheimer approximation for molecules and solids, the size scale is determined by the inverse of the
electron mass [7]. Therefore, an electron mass increase will reduce the inter-nuclear distance, and greatly enhance
quantum tunneling and fusion rates. This is a form of electron screening. The enhancement of deuterium fusion in a D₂
molecule was rigorously quantified by Koonin and Nauenberger [27], where it was shown that a mass of ten
electron masses was necessary to explain the reaction rates measured by Fleischmann and Pons, and a mass of five
electron masses was needed to explain Jones’ results. With simply a large electron mass, one cannot explain the
discrepancy in the branching ratio, but with a simultaneous reduction in the deuterium mass, one can explain that as
well, and in this case the electron mass increase factor can be much smaller than 10 since the resonant tunneling effect
greatly enhances the fusion rate [7]. An electron mass increase factor of 5 is sufficient to explain the results of Jones,
and this could be adequate, when combined with resonant tunneling, to explain the excess heat experiments that have
been observed [7].

Another form of tunneling which might have been observed in some experiments is neutron transfer. In a test of
the commercial E-Cat reactor [30] it was reported that the fuel consisting of powder containing nickel and lithium
in their natural isotopic ratios, was modified by the reaction and that the ash consisted mainly of lithium-6, most of
the lithium-7 having apparently lost a neutron, and the only isotope observed in the ash of nickel was nickel-62, the
heaviest stable isotope. So apparently the neutrons from lithium-7 had been transferred to nickel isotopes. Neutron
tunneling has been proposed as an explanation for this [15]. If electron masses were to increase in a molecule binding
together lithium and nickel atoms, then the tunneling rate could increase by many orders of magnitude. Therefore, this
neutron transfer mechanism seems quite plausible as a candidate for explaining these results provided that masses can
vary in this way. I take this experimental result as quite tentative though.

6. Some Anomalous Nuclear Reactions that can be Interpreted as Allowed by Mass Variation

Most of the nuclear anomalies that have been observed in LENR experiments and elsewhere cannot be explained by
conventional nuclear physics. I believe that they can all be interpreted as being enabled by variable mass behavior. So,
here is a partial list of various effects and how they can be explained. I do not claim that these experimental claims
are all correct. I do think that there is some non-zero probability in the Bayesian sense that any of these experiments
might be true though, and since they are persistently reported in the literature I have tried to explain them.

(1) Deuterium fusion d + d → α. This reaction was studied in detail in [7]. It takes place between two neighboring
deuteron in a palladium lattice. The electron mass must increase for at least one electron which is binding
the two deuterium particles together, and the deuteron masses must subsequently decrease. When the two
deuteron, imagined as continuously going off-shell in [7], reach a combined mass which is very close to the
mass of an alpha particle, a resonant tunneling effect can be expected to occur, and this gives the observed behavior of Pons and Fleischmann. Fusion is enabled by mass-tuned quantum tunneling in this picture, but only excess heat is produced.

(2) In the Widom–Larsen theory [51] it is argued that protons and “heavy” electrons can react to form a neutron and a neutrino $e + p \rightarrow n + \nu_e$ at near room temperatures, because the electron’s rest mass has increased. The neutron activation caused by the presence of these neutrons then can produce nuclear reactions. The general variable mass theory contains this Widom–Larsen effect as a special case. We allow masses for all charged particles to decrease as well as increase, unlike Widom–Larsen, and this leads to many more reactions being possible.

(3) Oppenheimer–Phillips processes whereby a deuteron gives up a neutron to a metal nucleus through quantum tunneling. This effect has been advocated by Passell [38]. Enhanced electron screening is required for the cross sections of these reactions to be large enough to account for observed effects. Increased electron mass would provide such a mechanism.

(4) Neutron transfer involving two deuterons $d + d \rightarrow p + t$. This reaction would be made possible by an increased electron mass which would increase the electron’s screening ability, along with possibly a variation in the deuteron mass to allow for resonant tunneling of the neutron when the summed mass of the two deuterons were to equal the sum of the on-shell masses of the proton and tritium. This reaction could help explain why there is much more tritium observed in Fleischmann–Pons type experiments than neutrons [45].

(5) The ‘Reifenschweiler effect’ [40] is the observation that the beta-decay rate of tritium (half-life 12.5 years) is reduced reversibly by about 25–30% when the isotope is adsorbed into 15 nm titanium-clusters in a temperature window between 160–275°C. Remarkably at 360°C the original radioactivity reappears. First discovered circa 1960/1962 at Philips Research, Eindhoven. The reported decay rate reduction can be explained if the tritium mass and consequently the kinematic phase space for the decay were reduced [8]. Since the $Q$ for tritium decay is about 18.6 keV, if the mass of the tritium drops by this amount, its decay rate would go to zero.

(6) Other radioactive decay effects that might indicate mass variation [8]. Radioactive isotopes implanted into metals at low temperature $\sim 12$ K show variations of decay rates in some cases, which could be due to enhanced electron screening, which in turn could be due to mass variation [31,32,14]. These results have not been completely reproducible so far, and the theory proposed based on conventional electron screening has been criticized. It is another controversial LENR phenomena.

(7) Time varying radioactive decay rates may indicate mass variation [8]. Experiments show decay rates varying with time for a number of isotopes. Frequency analysis has shown annual, diurnal, and approximate monthly variations [12]. Once again, these results are controversial. It has been suggested that solar neutrinos might be the cause of this decay-rate variation.

(8) With varying particle masses, transmutations can in theory at least occur in a number of ways in nuclear active environments. Enhanced electron screening caused by electron mass increases can modify alpha decays, beta decays, and electron capture rates. Mass changes of nuclei can change reaction rates or make reactions possible which would normally be forbidden. Resonant fusion of hydrogen or deuterium with other nuclei, resonant fusion of alpha particles and other nuclei, and even fission of heavier nuclei might occur after a mass change. Also, there is the possibility of neutron creation and subsequent capture as in the Widom–Larsen theory, or neutron stripping or hopping reactions, leading to many possible transmutations. In short a world of possibilities exist, and a managerie of transmutations have already been observed experimentally in LENR [44,45]. The number of transmutations observed in LENR are so large, that many scientists have concluded
that it is proof that the experiments must be wrong. But maybe not, given the multitude of processes made possible by variable masses.

More details may be found in [7,8].

7. Suggestions for Experiments to Test the Variable Mass Idea

If radioactive nuclei are placed into the nuclear active environments, their decay rates should change if their masses change, and this might be observable by monitoring the real-time radiation during an experiment. Probably gas loading experiments would be the easiest ones to monitor in this way, and some imaging capability would be desirable because the nuclear active environments tend to be very localized on the surface of the metal. Tritium is an excellent candidate to serve as a tracer element to reveal mass variations of hydrogen isotopes. Tritium can be added to deuterium or hydrogen in LENR experiments. The tritium in the nuclear active volumes should experience a mass change like deuterium if the variable mass theory is correct. This should be detectable as a change in the tritium decay rate in those zones while they remain in a nuclear active state. Other radioactive isotopes might be tried as well. A replication of the Reifenschweiler experiments would be very desirable too.

8. Implications for other Theories of LENR

The possibility of variable mass does not rule out any of the other prevalent theories of LENR, but actually can provide a mechanism for them to be valid. For example, the Widom-Larsen effect is enabled by the type of variable mass behavior we are contemplating here. Also, the collective interaction of the lattice with the nucleus as proposed by Hagelstein [17,18], Preparata [39], and Schwinger [42] could be understood as mediated by mass variation over an extended time leading up to the nuclear reaction. The lattice could slowly take up or give up energy to the nuclear environment as the masses of some of its particles changed prior to a nuclear reaction. There are a number of theories which rely on the existence of small atoms which can be understood if electrons can increase their mass. A theory due to Kim proposes a Bose–Einstein mechanism [25], and the existence of such a state of matter might be enabled by resonant tunneling as in [7] where deuterium resonant tunneling was enabled by mass reduction of the deuterium particles.

9. Choices for Physics

As I see it, physics should re-engage in a serious way with this subject. Here are the choices facing mainstream physics: (1) Dismiss the experimental claims and the entire field of LENR (more than 1500 international research papers); (2) Do nothing, but wait and see what happens next; (3) Continue to try and explain the claims with existing theories after 24 years of failed effort; or (4) Develop a new theory, based on relativistic quantum mechanics, that modifies existing theory and explains the experiments. Obviously I prefer the fourth choice.

Much of modern physics has separated from close laboratory experimental feedback. Fields like quantum gravity, string theory, interpretations of quantum mechanics, emergent theories of gravity, etc. are examples. Here, with LENR, we have a large discrepancy between theory and experiment which may require a fundamental modification of our theories for nuclear physics and condensed matter, and we also have lots of laboratory feedback to aid us.

If off-mass-shell quantum mechanics is needed in order to understand LENR results, then our understanding of quantum mechanics will be affected at a fundamental level. The standard on-shell wave equations would have to be considered then as approximations to more general off-shell theories. The standard relativistic wave equations (Klein–Gordon, Dirac, Proca, etc.) all have problems with a localized position operator, or negative energies, or negative probabilities. Thus, modern physics regards quantum fields as preeminent over wave mechanics. But a resurgence
of the Fock–Stueckelberg theories could change this, and make wave mechanics prominent once again. The practical implications if LENR is real are obviously potentially enormous. Only the re-engagement of the physics community will allow the full promise of this technology to be realized. The downside monetary risk of coming up dry seems insignificant compared to the potential benefits both to mankind and to fundamental physics. What gambler would not take this bet? Even if all the experiments in LENR turn out to be wrong, physics could still benefit if by examining this issue we can learn to engineer the control of rest masses. This would then open doors to finding new ways to make LENR devices and provide a powerful tool in chemistry and condensed matter physics.

10. Conclusion

We have listed here some of the anomalous LENR reactions which have not been explained by conventional nuclear physics. If nuclear rest masses can vary in special nuclear active environments, then all of these reactions can be allowed with the right mass variation.

After surveying the literature on mass variation in relativistic physics, the historical time models pioneered by Fock and Stueckelberg are prominent. The modern refinements of this theory especially by Horwitz and co-workers stand out as the most likely candidate theories around which to construct a model for LENR. The task before us is to try and quantify what physical effects cause a nuclear active environment to come into existence.

The theories for mass variation are not yet complete. In particular, we do not have a theory which interpolates between theories in which the rest mass is quite freely variable, like for instance pre-Maxwell theory, and ones that have fixed mass, like conventional QED or the standard model applied to few particle systems. I have in mind a new phenomenological parameter that would depend on position inside a material and control how easy or hard it is for particles to drift off the mass shell. In ordinary matter or in vacuum, this parameter would make deviation from standard rest masses exceedingly small, but in the nuclear active environments it would allow significant deviation of mass from the expected value.

Many of the objections to LENR experimental claims in the past were based on the fact that neutrons and tritium were not observed in experiments involving deuterated palladium in the proper amounts, energies, and ratios as deuterium fusion would require [1,24]. If masses of electrons and deuterons can vary, then this not a valid justification for rejecting these results out of hand. So, if one is to rule out a theory like this one, the change in the ratios of tritium to neutrons or their energies cannot be used to dismiss experiments. Rather, they might be viewed as experimental evidence in support of variable masses.

Much of modern physics has separated from close laboratory experimental feedback. Fields like quantum gravity, string theory, interpretations of quantum mechanics, emergent theories of gravity, etc. are examples. Here, with LENR and related anomalies, we have a large discrepancy which may be resolved by a fundamental modification of our theories for nuclear physics and condensed matter, and we also have lots of laboratory feedback to aid us. It seems that physicists ought to re-examine this subject in the light of these new developments, and determine with certainty whether or not the nuclear anomalies are real.

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References


Quantum Tunneling in Breather ‘Nano-colliders’

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Abstract

In many crystals with sufficient anharmonicity, special kinds of lattice vibrations, namely, discrete breathers (DBs) can be excited either thermally or by external triggering, in which the amplitude of atomic oscillations greatly exceeds that of harmonic oscillations (phonons). Coherency and persistence of large atomic oscillations in DBs may have drastic effect on quantum tunneling due to correlation effects discovered by Schrödinger and Robertson in 1930. These effects have been applied recently to the tunneling problem by Vysotskii et al., who demonstrated a giant increase of sub-barrier transparency during the increase of the correlation coefficient at special high-frequency periodic action on the quantum system. In the present paper, it is argued that DBs present the most natural and efficient way to produce correlation effects due to time-periodic modulation of the potential well width (or the Coulomb barrier width) and hence to act as breather ‘nano-colliders’ (BNC) triggering low energy nuclear reactions (LENR) in solids. The tunneling probability for deuterium (D–D) fusion in ‘gap DBs’ formed in metal deuterides is shown to increase with increasing numbers of oscillations by ~190 orders of magnitude, resulting in the observed LENR rate at extremely low concentrations of DBs. Possible ways of engineering the nuclear active environment based on the present concept are discussed.

Keywords: Correlation effects, Discrete breathers, Low energy nuclear reactions, Nuclear active sites

1. Introduction

The problem of tunneling through the Coulomb potential barrier during the interaction of charged particles is the key to modern nuclear physics, especially in connection with low energy nuclear reactions (LENR) observed in solids [1–4].

The tunneling (a.k.a. transmission) coefficient (TC) first derived by Gamow (1928) for a pure Coulomb barrier is the Gamow factor, given by

\[
G \approx \exp \left\{ -\frac{2\pi \hbar}{\mu} \int_{r_1}^{r_2} \frac{dr}{r} \sqrt{\frac{2\mu}{V(r) - E}} \right\},
\]

where \(2\pi \hbar\) is the Planck constant, \(E\) is the nucleus CM energy, \(\mu\) is the reduced mass, \(r_1, r_2\) are the two classical turning points for the potential barrier, which for the D–D reaction are given simply by \(\mu = m_D/2\), \(V(r) = e^2/r\).

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For two D’s at room temperature with thermal energies of $E \sim 0.025$ eV, one has $G \sim 10^{-2760}$, which explains the pessimism about LENR and shows the need for some special conditions arising in solids under typical LENR conditions (D$_2$O electrolysis [1–3], E-cat [4], etc.), which help to overcome the Coulomb potential.

Corrections to the cross section of fusion due to the screening effect of atomic electrons result in the so-called “screening potential”, which acts as additional energy of collision at the center of mass [5]. The screening potential was measured by the yields of protons or neutrons emitted in the D(d, p)T or D(d, n)${}^3$He reactions induced by bombardment of D-implanted solid targets with deuterons accelerated to kinetic energies of several keV, equivalent to heating up to $\sim 10^7$ K [6]. However, even the maximum screening potentials found in Pt (675 eV), PdO (600 eV) and Pd (310 eV) are far too weak to explain LENR observed at the temperatures of these experiments, which are below the melting point of solids (in the E-cat) or boiling point of liquids (with electrolysis). Besides, the absence of significant radiation under typical LENR conditions indicates that other reactions should take place, based on interactions between ‘slow’ particles, which may be qualitatively different from the interactions between accelerated ones.

The most promising and universal mechanism of the stimulation of nuclear reactions running at low energy is connected with the formation of coherent correlated states of interacting particle, which ensures the high probability of the nuclear reactions under conditions, where the ordinary tunnel effect is negligible. These states minimize a more general uncertainty relation (UR) than Heisenberg UR usually considered in quantum mechanics, namely, Schrödinger–Robertson UR [7,8], which takes into account correlations between coordinate and momentum operators. Correlation effects have been applied to the tunneling problem by Dodonov et al. [9] and more recently by Vysotskii et al. [10–13] who demonstrated a giant increase of sub-barrier transparency (up to hundreds of orders of magnitude!) during the increase of correlation coefficient at special high-frequency periodic action on quantum system.

In this paper, we argue that such an action can be most naturally and effectively realized due to time-periodic modulation of the width of potential wells for atoms oscillating in the vicinity of discrete breathers (DBs). DBs are spatially localized large-amplitude vibrational modes in lattices that exhibit strong anharmonicity [14–23]. Due to the crystal anharmonicity, the frequency of atomic oscillations increase or decrease with increasing amplitude so that the DB frequency lies outside the phonon frequency band, which explains the weak DB coupling with phonons and, consequently, their robustness at elevated temperatures. DBs can be excited either thermally or by external driving, as was observed experimentally [17,18] and modelled in various physical systems [19–24].

Studies of DBs in three-dimensional crystals by means of molecular dynamics simulations using realistic interatomic potentials include ionic crystals with NaCl structure [16,19,20], diatomic A$_3$B crystals [21], graphene [22], semiconductors [23] and metals [24,25]. DBs in biopolymers such as protein clusters have been studied using the coarse-grained nonlinear network model [26].

Presently the interest of researchers has shifted to the study of the catalytic impact of DBs on the reaction rates in solids and on the biological functions of biopolymers [26,27]. The excitation of DBs in solids have been shown to result in a drastic amplification of the reaction rates in their vicinity. Two cases considered up to now include chemical reactions [27–30] and LENR [31]. In the former case, the amplification mechanism is based on modification of the classical Kramers escape rate from a potential well due to a periodic modulation of the well depth (or the reaction barrier height), which is an archetype model for chemical reactions since 1940 [27].

In the latter case, the so-called gap DBs, which can arise in diatomic crystals such as metal hydrides/deuterides (e.g. palladium deuteride, PdD), have been argued to be the LENR catalysts [31]. The large mass difference between H or D and the metal atoms provides a gap in the phonon spectrum, in which DBs can be excited in the H/D sub-lattice resulting in time-periodic closing of adjacent H/D atoms, which should enhance their fusion probability. The main problem with this mechanism was that unrealistically small separation between atoms ($\sim 0.01$ Å) must be attained in order to increase TC (Eq. (1)) by $\sim 100$ orders of magnitude required for a noticeable LENR rate at the best choice of parameters. However, this estimate did not take into account correlations between coordinate and momentum operators arising in a DB due to the
cooperative nature of its dynamics. This problem is addressed in the present paper.

This paper is organized as follows. In Section 2, formation of coherent correlated states (CCS) under time-periodic action on a particle in the parabolic potential is reviewed [11–13]. In Section 3, this model is applied to the evaluation of the TC for the atoms oscillating in the vicinity of DBs and of the corresponding increase of their fusion rate. In Section 4, based on the rate theory of DB excitation under D_2O electrolysis and on the modified TC for D–D fusion in the PdD lattice, the fusion energy production rate is evaluated as a function of temperature, electric current and material parameters and compared with experimental data. The results are summarized in Section 5.

2. Formation of Correlated States in Non-stationary Potential Well

2.1. Schrödinger–Robertson UR and TC

The tunneling effect for nuclear particles is closely related to the uncertainty relation (UR), which determines the limits of the applicability of the classical and quantum descriptions of the same object. It appears that the well-known and widely used Heisenberg UR is a special case of a more general inequality, discovered independently by Schrödinger [7] and Robertson [8], which can be written in the following form [9]

$$\sigma_x \sigma_p \geq \frac{\hbar^2}{4(1 - r^2)}, \quad \sigma_x = \left\langle \left( x - \langle x \rangle \right)^2 \right\rangle, \quad \sigma_p = \left\langle \left( p - \langle p \rangle \right)^2 \right\rangle,$$

$$r = \sqrt{\sigma_x \sigma_p}, \quad \sigma_{xp} = \frac{\langle \hat{x} \hat{p} + \hat{p} \hat{x} \rangle}{2} - \langle x \rangle \langle p \rangle$$

where

$$G_{r \neq 0} \approx \exp \left\{ -\frac{2}{h_{\text{ef}}} \int_{r_1}^{r_2} \frac{dr}{r} \sqrt{2 \mu \left( V(r) - E \right)} \right\} = (G_{r=0})^{1 - r^2}. \quad (5)$$

This approximation is within an order of magnitude of the result of the exact calculation of the potential barrier transparency using rigorous quantum-mechanical methods [10–13]. From Eq. (5), it follows that when a strongly correlated state with \( |r| \to 1 \) is formed, the product of the variances of the particle coordinate and momentum increases indefinitely, and the barrier becomes ‘transparent’: \( G_{|r|=1} \to 1 \) even if \( E \ll V_{\text{max}} \).
Although the substitution $\hbar \rightarrow \hbar_{\text{ef}}$ is not quite correct, it clearly demonstrates the high efficiency of using coherent correlated states in solving applied tunneling-related problems in the case of a high potential barrier and a low particle energy $E \ll V_{\text{max}}$, which is typical for LENR.

CCS can be formed in various quantum systems. The most natural way to form such state is to place a particle in a non-stationary potential well.

2.2. Formation of CCS under time-periodic oscillation of harmonic potential well

A model system considered by Vysotskii et al. [11–13], for the evaluation of the correlation coefficient, is a particle with the mass $M$, coordinate $x(t)$ and momentum $p(t)$ in a non-stationary parabolic potential well (i.e. non-stationary harmonic oscillator),

$$V(x, t) = M (x(t))^2 (\omega(t))^2 / 2$$

for which a change of the eigen frequency $\omega(t)$ was shown to result in an increase of $|r(t)|$. Several scenarios of time evolution $\omega(t)$ have been investigated [11–13], including its monotonic decrease or periodic modulation. The latter regime can be provided, e.g. at a constant well depth $V_{\text{max}}$ and the potential well width $L(t)$ that changes periodically resulting in a time-periodic modulation of the eigen frequency as follows:

$$L(t) = L_0 \left(1 + g_\Omega \cos \Omega t\right), \quad L_0 = \sqrt{8V_{\text{max}} / M\omega_0^2},$$

where $L_0$ and $\omega_0$ are the initial parameters of the well before the action of correlated forces, $g_\Omega$ and $\Omega$ are the modulation amplitude and frequency, respectively.

![Figure 1](image-url)  

**Figure 1.** Sketch of the time-periodic parabolic potential $V(x, t)$ at different moments of time corresponding to the initial (solid black), minimal (dash red) and maximal (dot blue) well width. Probability density $|\psi(x, r)|^2$ for the particle localization in the well and in the sub-barrier region is shown schematically for uncorrelated state $r = 0$ (solid black) and for strongly correlated state $r = 0.98$ at the times of the maximal coordinate dispersion (dash green) [10]. $x_0 = \sqrt{\hbar / M\omega_0}$ is the half-width of the particle localization in the unperturbed well.
Figure 2. (a) Tunneling coefficient increase with increasing number of the well modulation cycles, \( n = \omega_0 t / 2\pi \), evaluated by Eq. (8) for the correlation coefficient amplitude increasing as shown in (b) at \( \Omega \approx 2\omega_0 \), \( g_{\Omega} = 0 \). D–D equilibrium spacing in a D\(_2\) molecule (\( L_0 = 0.74 \) Å) and in the PdD crystal (\( L_0 = 2.9 \) Å).

Figure 1 shows that the probability density \( |\psi (x, r)|^2 \) for the particle localization in the time-periodic well is very narrow for uncorrelated state \( r = 0 \) (solid black), while it spreads significantly into the sub-barrier region for the strongly correlated state \( |r|_{max} \rightarrow 1 \) at the times of the maximal coordinate dispersion (dash green) [10].

From a detailed analysis [11–13] it follows that the process of formation of strongly correlated coherent state with \( |r|_{max} \rightarrow 1 \) in response to the action of limited periodic modulation (Eq. (10)) is possible only at any of two conditions: (i) \( \Omega = \omega_0 \) (resonant formation) or (ii) \( \Omega \) is close to \( 2\omega_0 \) (parametric formation): \( |\Omega - 2\omega_0| \leq g_{\Omega}\omega_0 \).

Figure 2 shows the evolution of the correlation coefficient in time under the action of the harmonic perturbation with a parametric frequency \( \Omega = 2\omega_0 \) at \( g_{\Omega} = 0.1 \). The correlation coefficient oscillates with time but its amplitude \( |r|_{max} \) increases monotonically with the number of modulation cycles, \( n = \omega_0 t / 2\pi \), resulting in a giant increase of the tunneling coefficient, as demonstrated in Fig. 3, which shows the TC evaluated by Eq. (8) that takes into account both the electron screening [31] and the correlation effects [13]:

\[
G^* (L, r) = \exp \left\{ \frac{2\pi e^2}{\hbar\epsilon (r)} \sqrt{\frac{\mu}{2 (E + e^2 / L)}} \right\},
\]

where \( L \) is the minimum equilibrium spacing between D atoms determined by electron screening, \( E \) is their kinetic energy (\( \sim eV/40 \) at room temperature) \( \ll \) screening energy \( \sim e^2 / L \). One can see that the difference in electron screening and the corresponding initial D–D distances in a D\(_2\) molecule (\( L_0 = 0.74 \) Å) and in the PdD crystal (\( L_0 = 2.9 \) Å) leads to a huge tunneling difference in the initial (uncorrelated) state, in which TC is negligible in both cases. However, with increasing number of modulation cycles, the correlation coefficient amplitude increases according to Fig. 2 resulting in a giant increase of TC up to \( \sim 1 \) in dozens of cycles for parametric formation \( \Omega \approx 2\omega_0 \), which does not require an exact coincidence of the frequencies [13].

The most important and non-trivial practical question now is: how to realize such a periodic action at the atomic scale? Modulation of the frequency of the optical phonon modes via excitation of the surface electron plasmons by a terahertz laser suggested in [13] as a driving force for the CCS formation is very questionable [31], and it does not explain LENR observed in the absence of laser driving. In Section 3, we will consider a new mechanism based on the large-amplitude time-periodic oscillations of atoms naturally occurring in discrete breathers.

In order to develop a mechanism for DB-based LENR in metal hydrides/deuterides (e.g. PdD or NiH), let us consider their crystal structure in more detail. At ambient conditions, Ni/Pd hydrides/deuterides crystallize in FCC structure with the space group of the Rock-salt structure, which is called Fm3m in Hermann–Mauguin notation [32,33].

Molecular dynamic (MD) simulations have revealed that diatomic crystals with Morse interatomic interactions typically demonstrate soft type of anharmonicity [19], which means that DB’s frequency decreases with increasing amplitude, and one can expect to find the so-called gap DBs with a frequency within the phonon gap of the crystal. The large mass difference between H or D and the metal atoms is expected to provide a wide gap in phonon spectrum (Fig. 3), in which DBs can be excited, e.g. by thermal fluctuations at elevated temperatures, as demonstrated by Kistanov and Dmitriev [20] for the different weight ratios and temperatures. The density of phonon states (DOS) of the NaCl-type crystal for the weight ratio \( m/M = 0.1 \) at temperatures ranging from 0 to 620 K is shown in Fig. 3 (a)–(d).

Figure 3 (e) shows that DOS for PdD and PdH measured experimentally are qualitatively similar to DOS calculated for the NaCl-type crystal. First-principle calculations [33] point out that phonon spectra in PdD and PdH are strongly renormalized by anharmonicity. The appearance of two additional broad peaks in the DOS of NaCl at elevated temperatures (starting from \( T = 310 \) K) can be seen in Fig. 3 (c), (d). One of them is in the gap of the phonon spectrum, while another one lies above the phonon spectrum. The appearance of the peak in the gap of the phonon spectrum can be associated with the spontaneous excitation of gap DBs at sufficiently high temperatures, when nonlinear terms in the expansion of interatomic forces near the equilibrium atomic sites acquire a noticeable role. As the temperature increases, the lifetime and concentration of gap DBs in the light atom sub-lattice increase [21]. The dynamic structure of gap DBs has been revealed in [19] where they have been excited simply by shifting one light atom or two neighboring light atoms from their equilibrium positions while all other atoms were initially at their lattice positions and had zero initial velocities.

There are two main peculiarities of DBs related to the formation of coherent correlated states, namely, oscillations of atoms comprising a DB are (i) time-periodic and (ii) coherent, i.e. they have different amplitudes but the same or

Figure 3. DOS of the NaCl-type crystal for the weight ratio \( m/M = 0.1 \) at temperatures \( T = (a) 0, \) (b) 155, (c) 310, and (d) 620 K. (e) DOS for PdD and PdH crystals based on the force constants [33] fitted to the experimental results for PdD\(_{0.63}\) assuming that the forces in PdD and PdD\(_{0.63}\) were identical. Reproduced from [20,33] Copyright by APS.
commensurate frequency. In the extreme case of DB localized at one light atom, it oscillates with a large amplitude, \( A \) in the anharmonic potential well, which determines its frequency \( \Omega \) as follows [19]

\[
\Omega (A) = \sqrt{\alpha + \frac{3}{4} \beta A^2}, \quad \alpha = \frac{2\gamma_1}{m}, \quad \beta = \frac{2\gamma_2}{m}, \quad \gamma_1 (A) = R_1 A + S_1, \quad \gamma_2 (A) = R_2 A + S_2, \tag{9}
\]

where \( \alpha \) determines the quasi-harmonic eigenfrequency of the potential well, and \( \beta \) describes its anharmonicity. Both of them depend on the DB amplitude, since it changes the force constants \( \gamma_{1,2} \) of the potential. \( \beta \) is positive, which corresponds to hard type of non-linearity with frequency increasing with \( A \). However, the central atom oscillating with large amplitude shifts positions of neighboring atoms so that \( \alpha \) decreases with \( A \) resulting in the observed decrease of \( \Omega (A) \) [19].

Let us apply this model to a DB in the PdD lattice, dispersion curves of which [33] are shown in Fig. 3(e). Figure 4(a) shows DB\( \langle 110 \rangle \) frequency \( \Omega \) and eigen frequencies of (quasi-harmonic) potential wells for neighboring D atoms, \( \omega_0 \) as functions of the DB amplitude, evaluated with the force constants assumed to fit dispersion curves of PdD\( _{0.63} \) (Fig. 3(e)):

\[
\omega_0 (A) = \sqrt{\frac{2\gamma_1 (A)}{m}}, \quad \gamma_1 (A) = R_1 A + S_1, \tag{10}
\]

\[
R_1 = -0.026 \text{ eV/Å}^3, \quad S_1 = 0.008 \text{ eV/Å}^2, \quad R_2 = -0.017 \text{ eV/Å}^5, \quad S_2 = 0.035 \text{ eV/Å}^4. \tag{11}
\]

The frequency of the optic modes at the zone center (~9 THz), which determines the maximum DB frequency, is low in comparison with other hydrides, thus implying a weak nearest-neighbor Pd–D force constant in PdD\( _{0.63} \) [33].

Figure 4. DOS of the NaCl-type crystal for the weight ratio \( m/M = 0.1 \) at temperatures \( T = (a) 0, (b) 155, (c) 310, \) and (d) 620 K. (e) DOS for PdD and PdH crystals based on the force constants [33] fitted to the experimental results for PdD\( _{0.63} \) assuming that the forces in PdD and PdD\( _{0.63} \) were identical. Reproduced from [20,33] Copyright by APS.
Figure 4(b) shows $\Omega$($A$) and $\omega_0$($A$) evaluated with the force constants fitted to raise the lower optic phonon edge for stoichiometric PdD up to 22 THz and to broaden the phonon gap accordingly:

$$R_1 = -0.143 \text{ eV}/\text{Å}^3, \quad S_1 = 0.048 \text{ eV}/\text{Å}^2, \quad R_2 = -0.013 \text{ eV}/\text{Å}^5, \quad S_2 = 0.143 \text{ eV}/\text{Å}^4.$$ (12)

In the PdD$_{0.63}$ case (Fig. 4(a)), increase of the DB amplitude up to 0.274 Å leads to the excitation in neighboring wells of the harmonic with the frequency $\sim$ 3.3 THz equal to half of the main DB frequency ($\sim$6.6 THz), which interacts with acoustic phonons below the gap and makes the DB unstable, similar to the NaCl case for $m/M > 0.2$ [19].

In the PdD case (Fig. 4(b)), increase of the DB amplitude up to the critical value $A_{cr} \approx 0.292$ Å leads to the excitation in neighboring wells of the harmonic with the frequency $\sim$ 7.5 THz equal to half of the main DB frequency ($\sim$15 THz), which lies above the upper acoustic phonon edge and does not interact with phonons. Such DBs are stable, and they lead to the parametric formation of CCS of deuterons in the neighboring quasi-harmonic potential wells subjected to time-periodic modulation of their eigenfrequencies $\omega_0$($A_{cr}$) $\approx$ 7.5 THz by the DB frequency $\Omega(A_{cr}) \approx 15$ THz. As a result of such modulation, D–D fusion is expected to occur in several dozens of DB cycles (Fig. 2(a)) since the modulation amplitude

$$g_\Omega \approx A_{cr}/\left(a_{\text{PdD}}\sqrt{2}/2\right) \approx 0.1.$$ Three main resonances of excess energy released under joint action of two low-power laser beams with variable heat frequency ranging from 3 to 24 THz at $\sim$ 8 ± 1 THz, 15 ± 1 THz and 21 ± 1 THz [34] correlate in our model with the DB-induced harmonic frequency, $\omega_0$($A_{cr}$) $\approx$7.5 THz, DB parametric frequency $\Omega(A_{cr}) \approx$15 THz and DB initial frequency, 21 THz, respectively.

4. LENR Rate under Heavy Water Electrolysis

The DB excitation occurs by thermal fluctuations and by external driving displacing atoms from equilibrium positions. The rate of thermal excitation of DBs having energy $E$ is given by the Arrhenius law [27,31]

$$K^\text{th}_{\text{DB}}(E) = \omega_{\text{DB}}k^\text{th}_{\text{DB}} \exp\left(-\frac{E}{k_B T}\right),$$ (13)

where $k_B$ is the Boltzmann constant, $T$ is the temperature, and $\omega_{\text{DB}} \approx \Omega(0)$ is the attempt frequency that should be close to the edge of the phonon band, from which DBs are excited. In the case of gap DBs under consideration, it is about 21 THz (Fig. 4(b)), $k^\text{th}_{\text{DB}}$ is the efficiency coefficient for the excitation of DBs with parameter fitting parametric resonance conditions.

External driving of the DB excitation can be provided by knocking of surface atoms out of equilibrium position by energetic ions or molecules under non-equilibrium deposition of deuterium under electrolysis. This produces focusing collisions and moving DBs (a.k.a. quodons) that can transfer vibration energy in the crystal bulk [25]. The amplitude of the quasi-periodic energy deviation of atoms along the quodon pathway, $V_{ex}$, can reach almost 1 eV with the excitation time, $\tau_{ex}$, of about 10 oscillation periods, which results in the amplification of the DB generation rate proportional to the electric current density $J$ [31]:

$$K^J_{\text{DB}}(E) = K^\text{th}_{\text{DB}}(E) \left(1 + \left(\frac{V_{ex}}{k_B T}\right)\omega_{ex}\tau_{ex}\right), \quad \omega_{ex}(F_q) = F_q b^2 \frac{3l_q}{R_p}, \quad F_q = \frac{J}{2e},$$ (14)

where $\omega_{ex}$ is the mean number of excitations per atom per second caused by the flux of quodons, e is the electron charge, $b$ is the atomic spacing. The product $F_q b^2$ is the frequency of the excitations per atom within the layer of a thickness $l_q$ equal to the quodon propagation range, while the ratio $3l_q/R_p$ is the geometrical factor that corresponds to the relative number of atoms within the quodon range in a PdD particle of a radius $R_p$. The coefficient of proportionality
between \( F_\Omega \) and the electron flux \( J/e \) assumes that each electrolytic reaction that involves a pair of electrons releases a vibrational energy of \( \sim 1 \) eV, which is sufficient for generation of one quodon with energy \( V_{ex} < 1 \) eV.

Multiplying the DB generation rate (14) by the tunneling probability in a DB, \( G^* (L, r)(8) \) and integrating over DB energies one obtains the D–D fusion rate per PdD unit cell:

\[
FuR = \frac{1}{\Delta E} \int_{E_{DB}^* - \Delta E}^{E_{DB}^* + \Delta E} K^j_D (E) G^* (r) \, dE
\]

that dramatically depends on the correlation coefficient, \( r \), which, in its turn, strongly depends on the DB amplitude \( \sim DB \) energy and the number of DB cycles before decay, \( n_{DB} \).

Only a small fraction of DBs can form CCS in their vicinity and act as effective breather nano-colliders (BNC). They must have some particular energies, \( E_{DB}^* \pm \Delta E \), in order to cause the parametric resonance producing CCS. If \( \Delta E \ll k_B T \) Eq. (15) is reduced to

\[
FuR \approx 2K^j_D (E_{DB}^*) G^* (r (E_{DB}^*, n_{DB})) \rightarrow_{n_{DB} > n_{DB}^*} K^j_D (E_{DB}^*), \quad G^* (r (E_{DB}^*, n_{DB}^*)) \approx \frac{1}{2}
\]

where the number of DB cycles required to make the Coulomb barrier ‘transparent’, \( n_{DB}^* \approx 100 \) at \( g_\Omega = 0.1 \).

We consider the following reaction [2]: \( D + D \rightarrow ^4\text{He} + 23.8 \) MeV \( (\text{lattice}) \), which is based on the experimentally observed production of excess heat correlated with production of “nuclear ash”, i.e. \( ^4\text{He} \) [2,3]. Multiplying the DB-induced fusion rate (16) by the energy \( E_{DB} \rightarrow ^4\text{He} = 23.8 \) MeV, produced in D–D fusion one obtains the excess energy production rate per atom, \( P_{D–D} \) as a function of temperature and electric current: \( P_{D–D} (T, J) = K^j_D (E_{DB}^*, T, J) E_{D–D} \).

Usually, the output power density is measured per unite surface of a macroscopic cell, \( P_{D–D} \), as a function of the electric current density at a fixed temperature and at temperature increasing with \( J \), as illustrated in Fig. 5. This is given by the product of \( P_{D–D} \), the number of atoms per unit volume, \( 1/\upsilon_{PdD} \) being the atomic volume of PdD) and the ratio of the cell volume to the cell surface:

\[
P_{D–D} (T, J) = P_{D–D} (T, J) \frac{L_S}{L_{PdD}},
\]

where \( L_S \) is the cell size, if cubic, or thickness, in case of a plate.

Figure 5 shows the LENR output power density DBs as a function of electric current density and temperature evaluated by Eq. (17) assuming material parameters listed in Table 1. Comparison with experimental data shows that the present model describes quantitatively the observed linear dependence of \( P_{D–D}^{S} \) on the current density at a constant temperature as well as the deviation from the linear dependence, if temperature increases with increasing electric current density. Thermally activated nature of the reactions leading to LENR has been noted for quite a long time [3], and the activation energy was estimated in some cases to be \( \sim 0.65 \) eV. The present model not only explains these observations, but also reveals that the underlying physics is a consequence of the synergy between thermally activated and externally driven mechanisms of the DB excitation in deuterated palladium.

5. Conclusions and Outlook

The main message of this paper is that DBs present the most efficient way to produce CCS due to time-periodic modulation of the potential well width (or the Coulomb barrier width) and hence to act as BNC triggering LENR in solids. The BNC concept proposed in a previous work [31] did not take into account correlation effects, and hence, unrealistically small separation between atoms (\( \sim 0.01 \) Å) would have to be attained in order to enhance the LENR rate up to a noticeable level. Figure 2 demonstrates effect of CCS in the BNC model manifested by a number of DB
cycles required to produce experimentally observed LENR rate $\sim 1$ W/cm$^2$. It can be seen that in the modified model, the DB lifetime plays a much more important role than the tunneling D–D spacing, and that DB amplitude of several fractions of an angstrom is sufficient to produce the required effect, if CCS parametric conditions are met.

The present model describes the observed linear dependence of the excess power output on the current density under heavy water electrolysis at a constant temperature, as well as its exponential increase with increasing temperature, which can be the basic LENR mechanism in the hot CAT-type installations.

Table 1. Material parameters used for the plot in Fig. 5.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>D–D spacing in PdD, $b$ (Å)</td>
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<td>DB parametric amplitude, $A_d$ (Å)</td>
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<tr>
<td>DB parametric freq, $\Omega (A_{cr})$ (THz)</td>
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<tr>
<td>Harmonic frequency $\omega_0 (A_{cr})$ (THz)</td>
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<tr>
<td>DB lifetime, $\tau_{DB}^\ast = \tau_{DB}^\ast/\omega_{DB} (s)$</td>
<td>$6 \times 10^{-12}$</td>
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<tr>
<td>DB excitation efficiency, $k_{ef} DB$ (eV)</td>
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<tr>
<td>Quodon excitation energy $V_{ex}$ (eV)</td>
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</tr>
<tr>
<td>Quodon excitation time, $\tau_{ex} (s)$</td>
<td>$6 \times 10^{-13}$</td>
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<tr>
<td>Quodon range, $l_q = 10b$ (nm)</td>
<td>2.9</td>
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<tr>
<td>Cathode size/thickness (mm)</td>
<td>5</td>
</tr>
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</table>
The proposed mechanism of CCS formation near the gap DBs requires a sufficiently broad phonon gap that is not observed below the critical D loading $\sim 0.83$ examined so far. Our hypothesis is that mechanical stresses arising in a fine powder of PdD$_x$ above the critical loading $x > 0.83$ can make the phonon band similar to that shown in Fig. 4(b), thus switching on the DB-induced formation of CCS. Further investigations of DOS and DBs in the extreme conditions of LENR are required.

An alternative mechanism of the DB-induced CCS formation may involve high frequency (hard type) DBs, manifested by the peak above the phonon spectrum in NaCl type crystals. Atomic modeling of DBs of various types in metal hydrides/deuterides is an important outstanding problem since it may offer ways of engineering the nuclear active environment.

Acknowledgements

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References

Research Article

Final Report on Calorimetry-based Excess Heat Trials using Celani Treated NiCuMn (Constantan) Wires

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Abstract

Sensitive mass flow calorimetry was used in a series of tests to evaluate eight treated NiCuMn (Constantan) wires in a gas loading cell. The goal of this testing was to reproduce and confirm the production of excess heat when using an experimental setup similar to that demonstrated in 2013 by Dr. Francesco Celani at National Instrument’s NI week and ICCF 17. Six of the eight Constantan wires used in the SKINR tests were provided by Dr. Celani and the remaining two were obtained from Mathieu Valat. Initial tests in the series closely followed the set-up, operation, and heating protocols used by Dr. Celani with a significantly modified stainless test cell to enable the use of mass flow calorimetry. Later tests used the same modified test cell but added additional heating protocols using pulsed or highly modulated electric currents (SuperWaves) to enhance hydrogen loading and create additional thermal gradients within the Constantan wires. No excess heat was observed in a calorimeter of a sensitivity $<10$ mW when running either the initial or later test protocols during $\sim$ 200 days of testing.

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Keywords: Calorimetry, Gas loading, Hydrogen, Micro-nano surface, Nickel, Nickel hydride

1. Introduction

In 2005 Baranowski and Filipek summarized 45 years of Nickel Hydride history and prospective [1]. Although palladium hydride was discovered by Graham in 1866 [2], it took almost 100 years to prove experimentally that nickel is also a hydride forming metal [3–4]. The limited penetration depth at room temperature and the fast kinetics of hydrogen desorption at normal conditions defines the Ni–H interactions [3–5]. Experiments of charging nickel of different layer thicknesses (from few micro-meters to more than 100 $\mu$m) deposited on copper wires, demonstrated that hydrogen is mainly located near the wire. These experiments showed clearly that hydrogen penetrates only about 30 $\mu$m into the bulk, below the surface [6].

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Baranowski and Filipek [1] showed that the d-band of nickel is at least partially filled by the electrons from hydrogen during hydrogenation. Similarly, as in the Pd–H system, this filling of the d-band vacancy has radical consequences for electronic and magnetic properties of the hydride formed. For example, this results in a strong decrease of the electrical resistance, due to the reduction of the electron scattering at the d-band vacancy or/and to a decrease of the electron–phonon coupling.

On the right-hand side of Fig. 1, as shown by Baranowski [1], the relative electrical resistance ratio of a nickel sample as a function of gaseous hydrogen pressure at 25°C is presented. Before the hydride phase starts to form – that is below 6 kbar of gaseous hydrogen – the electrical resistance ratio rises a few percent above the initial value, due to the uptake of some hydrogen in the range of the α-phase; the dissolved hydrogen forms new scattering centers for the conduction electrons. As soon as the hydride phase is formed, the resistivity is reduced by more than 20%, becoming more metallic than in the hydrogen-free nickel. Even more radical are the changes of the magnetic properties of nickel. The ferromagnetism is lost, when going over to the hydride phase. In further electrochemical studies the electrode potential of the nickel cathode was measured as a function of the atomic ratio H/Ni of the nickel layer involved. The figure on the left presents such an example. The electrode potential measured was that of the cathode, taking the normal hydrogen electrode as reference. Clearly, three-phase regions are evident, α-phase for H/Ni atomic ratio ranging from 0 to below 0.1, the mixed α + β phase (plateau region) for H/Ni ratios up to about 0.6 and the β-phase region, in which a small change in H/Ni ratio is accompanied by steep change of electrode potential.

Starting in February 2011, Celani [7] studied the feasibility of new Nickel based alloys that are able to absorb Hydrogen (H₂) and/or Deuterium (D₂) and that have, in principle a possibility to generate anomalous heat effects at temperatures > 100°C. Reports by Focardi and Piantelli [8], Miley 1996 [9] and, claims by A. Rossi and (later on) by Defkalion Company led Celani to investigate the family of NiCu alloys under high temperature H₂ gas loading. Due to theoretical considerations in a paper on catalysis (not related to LENR studies) by Romanowski et al. [10], Celani decided to explore the “large family” of CONSTANTAN alloys.

In the selection of materials, the figure of merit was the ability to decompose H₂ into H. A Constantan alloy (Ni₃₇Cu₆₃), among the materials studied, has the highest decomposition value (i.e. 3.2 eV); in comparison, pure Ni and Pd have values of 1.74 and 0.42 eV, respectively. Even if the alloy composition is changed to Ni₆₂Cu₃₈, the decomposition value remains almost constant (2.86 eV).
Therefore Celani focused on a commercial (low cost) material, called ISOTAN44, with an alloy composition Cu$_{55}$Ni$_{44}$Mn$_1$, developed many years ago by Isabellenhutte Heusler, GmbH, KG-Germany. The ISOTAN 44 was selected according to the following, overall, considerations: high diffusion coefficient, low cost, good mechanical properties, high decomposition values-catalytic power ($\Delta E$, in eV) and the ability to produce nano-micro structures on the wire’s surface.

In NI week and ICCF17 Celani presented a working borosilicate Schott Duran glass cell with ISOTAN 44 wire wound on a MICA core which according to Celani’s reports shows anomalous heat with a high reproducibility rate for the whole duration of the conferences. That experiment attracted the interest of SKINR which was committed to conduct an accurate calorimetric replication experiments with Celani’s treated wires.

2. SKINR Test Cell and Experimental Facility

The experimental cell, as seen in Figs. 2(a)–(e) and 3, is made of a T-shaped stainless steel pressure chamber having inner diameter of 70 mm and a total length of 126 mm. Two horizontal opening of 40 mm in diameter are sealed with stainless steel flanges pressed by brass threaded nuts, against Viton O-rings. The two stainless steel flanges are supporting the inner centered ceramic (LAVA) wire holder which is riding on a stainless steel water cooled inner core. A vertical stainless steel opening is sealed with stainless steel CF multipin connector flange (Figs. 2(d) and 3). Two pins are used for measuring the ISOTAN 44 resistance when the ISOTAN wire is heated indirectly by the Nickel Chrome wire, and two pins are for delivering input electric power. In case of direct heating of the ISOTAN wire, its resistance is calculated by dividing the measured voltage by the current. Two remaining pins are for measuring the ISOTAN 44 wire temperature. All wires are connected to the pins using gold plated cylindrical 1 mm sliding...
connectors. Cooling water flows along a spiral rectangular duct specially formed in the stainless steel core (Figs. 2(a) and 3). Heat transfers radially by convection and by radiation from the hot wires to the LAVA holder and by conduction to the stainless steel water-cooled core, which allows for accurate mass flow calorimetry. The LAVA ceramic wire’s holder as seen in Fig. 2(b) has six longitudinal legs to support wires hanged freely in Hydrogen atmosphere. The legs are grooved with two nested spirals to separate the active wire from the heater wire. MICA coated glass tape are put on the face of each grooved leg to allow for further thermal barrier. The wire holder wound with treated ISOTAN 44 wire and with a 32 AWG Nickel Chrome heater wire. A PT100 RTD ceramic sheath is placed within the wires. The core assembly prior to insertion into the stainless steel chamber is shown in Fig. 2(a) and (b).

The assembled cell and the experimental facility are presented in Figs. 2(c)–(e) and 3. Figure 2(c) shows the experimental facility connected to a gas manifold containing Hydrogen, Deuterium, Argon, and Helium. Each gas can be used either separately or as a component of mixtures. Some of the experiments have been conducted with pure Hydrogen and some with Hydrogen–Argon mixture at different mixture rates to allow higher wire temperatures. The gas supply system has a mechanical pressure regulator to control the gas pressure accurately. The facility is equipped with turbine vacuum pump, so that the cell as well as the gas tubing can be evacuated down to $10^{-6}$ Torr before switching to a different gas or mixture, or for wire de-loading under vacuum. The cooling treated water flow rate is

Figure 3. Experimental facility.
controlled by a Porter Mass Flow Controller as shown in Fig. 3. Cooling water before entering the cell passes through stainless steel heat exchanger immersed in water control bath, in order to stabilize the water inlet temperature to the set point within ±0.01°C, as shown in Fig. 3. National Instruments, in-house developed, LabVIEW data acquisition
program is used. The program allows to measure and store the cell body temperature using TC, wire, and ambient temperatures, the water inlet and outlet temperatures are measured by RTD PT-100 temperature elements. RTD PT-100 temperature elements used in experiments have an accuracy better than ±0.1% and with sensitivity of 0.001°C as well as the wire resistance, the water mass flow rate, the cell pressure and the electrical input parameters. The

Figure 5. Cross section and surface images before and after exposure to H₂ of two layer wire.
Before exposure

<table>
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<tr>
<th>Element</th>
<th>C%</th>
<th>O%</th>
<th>Si%</th>
<th>Al%</th>
<th>Mg%</th>
<th>Ca%</th>
<th>Fe%</th>
<th>Ni%</th>
<th>Cu%</th>
<th>Mn%</th>
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After exposure

<table>
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<td>Fe%</td>
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</tr>
<tr>
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<td>0.82</td>
<td>0.30</td>
<td>0.03</td>
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Figure 6. EDX analysis before and after exposure to H₂ of two-layer wire.

The cell is energized by Kepco amplifier BOP 50-8D, which can be operated in a constant current or voltage mode. The amplifier is remotely controlled by the LabVIEW wave generator which is capable of generating DC, AC, positive and negative pulses as well as highly modulated waves (known as SuperWaves). The data acquisition system samples the temperatures, pressure and mass flow at a rate of 0.5 Hz (slow data). Simultaneously, pairs of current (I) and voltage
(V) and \( I \times V \) at a rate of 50 kHz are being sampled (fast data). \( I \) and \( V \) and \( I \times V \) are stored on a buffer memory and then they are averaged and stored in a hard drive. Averaged input power calculated as \( P_{in} = I \times V \) is compared with the output power being calculated as \( P_{out} = mC_p(T_{out} - T_{in}) \). If the difference between \( P_{out} \) and \( P_{in} \) is positive, then there is excess heat (\( P_x \)). The power gain is also calculated as \( \text{COP} = (P_{out} - P_{in}) / P_{in} \). Energies are calculated by integrating \( P_{in} \), \( P_{out} \) and \( P_x \) over time and are presented as \( E_{in} \), \( E_{out} \) and \( E_x \).

Figure 2(d) shows the assembled

Figure 7. Wire number 280912A: 480-layer wire – initial loading.
insulated cell exposed on its upper side, in which one can identify the brass tightening nuts as well as the conflate flange with the multi-pin connector’s plug. Also the gas intake/vacuum tubing and the gas vent through a needle valve can be seen. The thermally insulated cell, tubing and wiring are shown in Fig. 2(e). Figure 3 describes the water mass flow calorimeter having an accuracy of $\pm 1\%$ with sensitivity better than 10 mW. The mass flow calorimeter’s

Figure 8. Pulsed power cycling – wire number 280912A: 480-layer wire 480-layer wire – initial loading.
Figure 9. Cross section and surface images of 480-layer wire before and after exposure to H₂.
effectiveness varies from 95% to 90%, due to imperfect thermal insulation.

3. Results

3.1. Wire number 270912B: 2-layer wire experiment (Fig. 4)

The wire treating procedure was not disclosed to SKINR, but it is believed that the number of layers indicates the number of cycles of wire oxidation at elevated temperatures under air atmosphere.

Experiment was conducted under the following conditions: 25% Hydrogen /75% Argon atmosphere, DC current stepped to 2.1 A, electrical input power stepped up to 67 W and kept constant while gas pressure lowered in steps from 6 to 1.1 bar in order to increase the wire temperature. The initial wire resistance was 15.01 Ω. Constantan (ISOTAN 44) wire was heated indirectly by the 32 AWG Nickel Chrome wire up to a temperature of about 300°C. It can be seen from the $R/R_0$ vs. pressure graph in the introduction that the electrical resistance increases in $\alpha$-phase and decreases after transition from $\alpha$-phase to $\alpha + \beta$ and to $\beta$-phase. In this experiment a resistance increase of up to 15.7 Ω ($R/R_0 = 104\%$) was observed probably because the wire remained in $\alpha$-phase region at a low hydrogen

<table>
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<tr>
<th>Element</th>
<th>Wt%</th>
<th>Wt% error</th>
<th>Atom%</th>
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</table>

Figure 10. Cross section of 480-layer wire (number 280912A) before experiment.
Figure 11. Pulsed power and SuperWaves cycling for the 650-layer wire (number 270912C).
loading of less than 10% H/Ni atomic ratio on average. It is believed that H/Ni ratio is higher near the surface and even higher in the nano-structures developed on the surface. No excess heat was observed \((P_{\text{out}} < P_{\text{in}})\). Experimental results with 300 L wire are similar to those with 10 L wire and therefore were not presented. The wire resistance is slightly increased, which is again an indication of relatively low loading, presumably in \(\alpha\)-phase, which refers to atomic loading ratio (H/Ni) of less than 10%. No excess heat was observed.

Figure 12. Pulsed power cycling for the 650-layer wire (number 270912C).
Figure 5 shows clearly that the treated wire (number 270912B) with two layers has a higher modified surface before exposure than that after exposure to H\textsubscript{2}. It seems that the exposed wire oxides undergo reduction in the H\textsubscript{2} atmosphere.

Figure 13. SuperWaves cycling for the 650-layer wire (number 270912C).