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Research Article

Ultra-High Density Deuteron-cluster Electrode for Low-energy Nuclear Reactions

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Abstract

This paper reviews new and previous theoretical and experimental studies of the possibility of nuclear events in clusters created in multilayer thin film electrodes, including the correlation between excess heat, transmutations, and the cluster theory that predicts it. As a result of this added understanding of cluster reactions, a new class of electrodes is under study. These electrodes are designed to enhance cluster formation and subsequent reactions. Two approaches are under development. The first employs improved loading–unloading techniques, intended to obtain a higher volumetric density of sites favoring cluster formation. The second is designed to achieve Rydberg Matters. Various methods of exciting (triggering) cluster reactions are also discussed. Based on these insights, the design of Low-energy Nuclear Reaction (LENR) power cells is proposed. While still in the research stage, this approach promises ultimate development of "green" nuclear powered "batteries" offering remarkable energy densities well beyond present technology.

Keywords: Deuterium cluster, Electrolysis, Glow discharge, Laser triggering, Low-energy nuclear reaction, Rydberg matter

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1. Introduction

Recent research has developed a technique for imbedding ultra-high density deuterium "clusters" (50–100 atoms per cluster) in various metals and its compound such as Palladium (Pd), and Iron oxide (Fe) [1]. Experiments have shown that in Pd these condensed matter state clusters approach metallic conditions, exhibiting super-conducting properties while, in crystal defects of iron oxide, cluster states with deuterium densities of up to 10^{29} per cm^3 have been achieved [2] as shown from measurements of the emission of 630 eV deuterium ions during laser irradiation. This supports the hypothesis that these clusters are in an inverted Rydberg state.

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The discovery of these clusters potentially has a revolutionary impact on Low-energy Nuclear Reactions (LENRs), which rely on excitation and reaction of the dense deuterium at room temperature without added compression as done in hot fusion. Although our previous research at the University of Illinois at Urbana-Champaign (UIUC) has recorded a net power through either electrical charging or deuteron ion-beam irradiating of deuterium loaded thin film electrodes, the power output was too low to be utilized for a practical power supply application. Work described here is now focussed on increasing the volumetric density of cluster sites in the electrodes to boost the net power output. There is strong evidence that this approach, if successful, will finally enable a useful LENR power cell.

In this article we first review the previous studies of ultra high density deuterium clusters, including early thin film electrodes for LENR at UIUC, then address recent studies of increasing the cluster densities in various electrode materials. Several ways of triggering cluster LENRs will also be discussed. It is proposed that these developments provide a "path" to the development of practical LENR power cells.

2. Early Thin Film Electronde for LENR at UIUC-Cluster Implications

Our initial studies of LENRs involved thin films coated on a flat alumina substrate as illustrated conceptually in Fig. 1. In this design, a double-layer Pd/Ni thin film, at 8000 Å and 1000 Å, respectively, sputtered on ceramic Al_2O_3 substrate [3], was used as a cathode. The design forces an electrical current flow parallel to the thin film surface so that a high current density and high proton flow rate are obtained simultaneously with a high deuterium density [3]. By using this electrode, the excess heat evolution during electrolysis runs was detected by a high sensitivity open-type calorimeter in a fixed temperature of 28.0 ± 0.05°C [4]. Smooth Pt sheets were used as cathodes in "Reference" runs, since Pt does not produce excess heat in light water electrolysis [5]. In these experiments, ca. 20% excess heat was measured. In typical cases the excesses heat evolution from the cathode at $I = 200$ mA continues for ∼15 days.

The excess heat measured is correlated with the observation of reactions causing nuclear transmutations, attributed to proton–metal initiated reactions [6]. Such a correlation for these LENR transmutation reactions are equivalent, in principle, to the correlation of He-4 with excess heat that is reported for heavy water–Pd experiments where a D–D reaction is postulated. Interestingly, a recent study by Widom and Larsen claims that their theoretical transmutation calculations reasonably well match these results (see Fig. 3 in [7]). The situation where heavy water is used instead of light water, as reported in some other LENR studies (see [8]), is less clear but again appears to involve proton–metal reactions. In that case, p-metal reactions could occur simultaneously with D–D reactions. More study is needed to resolve all of the possible reactions involved in this important regime.

In order to obtain further proof of nuclear reactions in the thin-film cathodes [9], the detection of nuclear radiation accompanying the electrochemical loading of those cathodes is desirable. Although we have observed time-integrated rates of MeV proton and alpha emission during these electrolysis runs [10], time dependent emission rate measurements

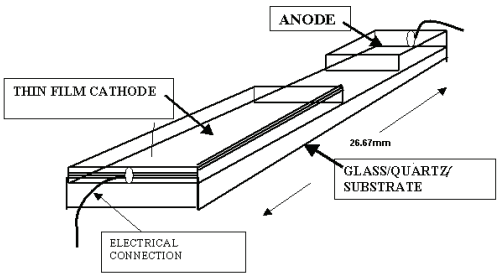

Figure 1. Recent work uses a unique integrated thin film plate-type electrode.

would be highly desirable to understand the reaction correlations Unfortunately, it is hard to apply electronic SSB and X-ray detectors directly to the cathode during an electrolysis experiment since the emission rates are low compared to background interference. Thus, the technique using non-electronic detectors (CR-39 and thermal luminescence detector (TLD)) was employed to allow in-situ measurement of energetic charged particles and X-rays during the electrochemical loading of the flat-plate Pd-thin film cathodes. The total counts of tracks from protons and alphas after subtraction of background counts are statistically significant. In the control experiment with CR-39 detector attached to the thin film NiO_x (obtained by annealing of Alumina/Ni(4000A) sample in air atmosphere), where despite of the high voltage applied (U ~10.0 V), the electrolysis current in the cell was very low (I ~1.0 mA), and no tracks with $d < 7.8$ μm were detected whereas, in the active electrode runs, numerous tracks with $d > 7.8$ μm are clearly visible.

In summary, the observation of MeV particle emissions, combined with the transmutations and excess heat measurements, provide extremely strong evidence for nuclear reactions occurring in the thin films during electrolysis. These results, combined with recent observations of localized ultra-high density deuterium clusters in electrodes of this type have led us to consider the new "cluster" approach to power producing LENR power cells described here.

3. Ultra-High Density Deuterium-cluster Formation and Reaction Theory

3.1. Deuterium-cluster formation in palladium foils

In 1999, Nellis pointed out that it should be possible to form solid metallic hydrogen from H atoms since hydrogen may be considered to be the lightest alkali metal [11]. Recently, we achieved ultra-high-density metallic-like hydrogen and deuterium states through electrochemically loading-unloading H/D into a thin metal film, such as palladium (Pd) [1,12]. During the repeated loading-unloading process, the metal lattice expands significantly to form dislocation defects (Fig. 2). The diameter of the dislocation defects is around two burgers vector, while their length depends on the dimensions of the palladium film. The dislocation defects inside the metal form a potential trap for deuterium which then collects there to form ultra-high density clusters. The existence of ultra-high density H/D clusters in the palladium foil has been demonstrated through several different types of experimental methods [1,12]. Briefly, temperature programmed desorption (TPD) measurements suggest that the local loading ratio of hydrogen ([H]/[Pd]) within the dislocation loops is 1.8. Both a direct resistance measurement and measurements using a super-conducting quantum interference device (SQUID) indicate an H-loaded sample exhibits type-II superconductivity. These results suggest that hydrogen (or deuterium) inside the dislocation loop in a condensed metal-like state has an ultrahigh density.

3.2. Cluster reaction theory

Independently from the last year's results on clusters, the generation of deuterium clusters in a Bose–Einstein state has been fundamental to the explanation of the reaction product distribution observed in the earlier transmutation

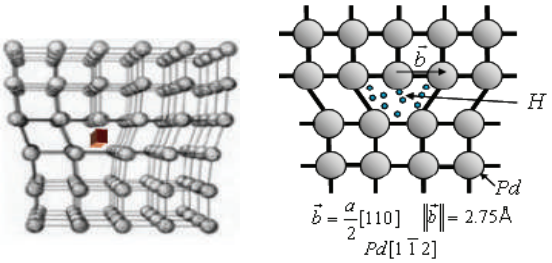

Figure 2. Scheme of edge dislocation loops in Pd containing condensed H/D.

experiments [13,14] as summarized in [15]. The state of the deuterium clusters with about 2 pm nuclear distance in a Bose–Einstein condensation was shown [14,15] as the way that the transmutation product distributions could be generated by the reaction of a palladium nucleus with a cluster of 156 deuterons [15] ([16] see Eq. (10)). An essential point is that the deuterons have a Maxwell distribution in the palladium and profit from their Coulomb screening factor 14 [17] within the background of the conduction electrons. Then, the deuterons can move within the metal and within the interior of the inner electron clouds of the palladium atoms like neutral particles, comparable to neutrons within distances d of about 2 pm. The deuteron charge, i.e. Columbic repulsion, only occurs over shorter distances, allowing strong tunneling and reactions in the cluster.

The 2-pm nuclear distance is sufficient for nuclear reactions (see Fig. 1 of [16]) to occur within times of kilo- to mega-seconds (ks to Ms) as evident from inverse beta decay. The Bose–Einstein state prevents any localization between the deuterons within the 10 pm diameter cluster, such that the reaction with all 156 deuterons could happen as soon as the cluster surface reaches a 2-pm distance from a neighboring palladium nucleus. A screening factor of 14 was derived earlier [16] from an evaluation of reliable D–D reaction experiments in palladium [18] and measured later in a very sophisticated way directly in palladium [19,20]. The reason for the "clinging or clustering together" of the screened deuterons is discussed in [16] and assumed to be a type of molecular force possibly due the Casimir effect, which assumes a significant value at the very short 2 pm distance.

Prior to realizing the connection of the clustering mechanism of deuterium to the UIUC transmutation experiments, the formation of high density states in defects was of strong interest at UIUC. This leads to the experiments noted earlier where localization of 100 or more deuterium atoms within the small defect volume was measured from SQUID responses implying superconducting properties of this new localized state when a large number of crystal voids (Schottky defects) are artificially generated [1,12,21].

Another approach to clusters in void-defects of solids was the discovery of cluster states with ultra-high deuterium densities of up to 10^{29} per cm^3 in near-surface crystal defects of iron oxide. This was found [22] from measurements of the emission of 630 eV deuterium ions during laser irradiation with the conclusion that these clusters are in an inverted Rydberg state. It may be assumed that the clusters in these surface defects are related to the ones we have described relative to the defects formed by loading–unloading methods [1]. One difference is that the latter is located in the interior of the palladium, though they may be associated with the dislocation "anchor" at the film interfaces. In addition to the present interest in LENR, we have shown that these clusters in solids with very high deuterium densities is also of interest for experiments with high temperature nuclear fusion where they are compressed to cause high reaction rates using laser compression [23,24].

The reaction of the deuterium clusters was initially proposed to proceed via a compound nucleus by Miley 1997 [25] and was compared with various exothermal compound nuclear reactions [26,27]. The minimum of the element distribution was shown to resemble the fission reaction of uranium [15,16] and in addition [13,14] even showed a small local maximum as predicted by the Maruhn–Greiner theory where the compound nucleus is an excited state (unexcited uranium does not produce the small local maximum as well known from measurements [15,16]). The reaction of a deuterium cluster with 156 deuterons may then result in

$$^{108}\mathrm{Pd}_{46} + 156\,\mathrm{D} =^{306} \mathrm{X}_{126} + 38\,^{3}\mathrm{He}_2 + E, \tag{1}$$

where E is the energy release. The mass per nucleon expressed in proton masses in X is derived to be 1.004946 (ignoring the minor contribution associated with E). This compares favorably with the value of uranium 1.0001868 or with the very low value for iron 0.9988376.

A key point is that [15] the precise measurement of the element distribution has the local Maruhn–Greiner maximum at 155, not at the nucleon number 153 predicted by a classical extrapolation of magic numbers. However, the nucleus X with 126 protons and 180 neutrons represents a double magic number case where all well known magic numbers up to 126 agree with the derivation from the LENR measurements [15] giving the new number 180 [28]. This alternative

theory of the magic numbers based on these LENR measurements leads to a 3^n ($n = 1, 2, 3, ...$) relation for a nuclear shell model. This allows resolution of a long standing issue in quark structure which could not distinguish between magic numbers of 184 vs. 180 [28].

3.3. Rydberg matter formation in surface defects of iron oxide

The relationship between the deuterium clusters observed in the UIUC experiments [1] and the surface states shown to be inverted Rydberg Matter (RM) [22] is important and now under study. This will be briefly described here. The generation of Rydberg matter in the universe as interstellar clusters has been discussed over recent years. These are molecular structures where the electrons are in orbital states with a quantum number $m = 1$ or higher. It is difficult to produce these states in the laboratory because the atoms needed for joining to a molecule require an energetic excitation much higher than the molecular binding energy. However, the statistics in interstellar space does permit this. Such RM clusters in space cannot be detected by spectroscopic methods but may be dark matter which is only measured by gravitation. Indeed, this may be the dark matter predicted to have some concentration inside and near the discs of galaxies.

A special method was developed by Holmlid et al. [22] to use the catalytic property at the surface of ion oxide. In voids of the crystal defects it is possible that hydrogen or deuterium atoms obtain a $m = 1$ excitation, leading to a RM molecular compound. It is calculated [22] that the proton distance of 74 pm in a H–H molecule with covalent binding is changes into a distance

$$d = 150\,\mathrm{pm} \tag{2}$$

in the RM state. This state is a metallic modification of hydrogen H(1) where the number one expresses the $m = 1$ state [29]. Its generation by a low-pressure catalytic process was first obtained through clever use of iron oxide [30].

The inverted RM is using an inversion of the role of the electron and proton to form a hydrogen atom. The normal atom is based on the electric field of a central proton and the electron is attracted by this field. In Bohr's model, the electron is considered in a point mechanical treatment as rotating with an angular momentum p at a radius r such that the quantum relation

$$rp + nh/(2\pi) = n\hbar \quad (n = 1, 2, 3, \ldots) \tag{3}$$

is fulfilled. This rotation is not true in the ground state for $n = 1$ because the electron would then emit energy by radiation. This problem was solved by Schrodinger's quantum mechanics where the electron orbiting is possible only for $n = 2$ and higher. The merit of both models should not be ignored. The transition of a rotating electron from a higher to lower orbit described the radiation emission to arrive at the measured times of about 10^{-8} s spontaneous emission. This was possible in the quantum mechanical description only by Dirac's introduction of the quantization of the electromagnetic field energy density (second quantization).

A quantum mechanical extension of Bohr's model is possible in the following way for exclusion of his orbiting problem for $n = 1$. The electric field energy gained by an electron when falling into the proton depends on the distance r and can be compared with the Fermi–Dirac energy for squeezing the electron into a sphere of radius r. The difference of the exponents of the energies arrives at a radius where both energies are the same. This is just the value [31].

$$r_\mathrm{B} = \hbar^2/(me^2) \tag{4}$$

of the Bohr radius where m is the rest mass and e the electric charge of an electron ([31] see Section 2.3). Using this model, the measured polarization shift of spectral lines in plasma (Inglis–Teller effect) for hydrogen can be theoretically explained [32] with higher accuracy than by the earlier derived model by Griem.

The inverted hydrogen atom occurs when an electron produces the central electric field and the proton (or deuteron) falls into the electron until a radius is reached where the electric field energy gained is equal to the increase of the

Fermi–Dirac quantum energy. The radius is then different from the normal case by the square root of the ratio of the mass of the proton p or deuteron D, see the equations between 2.16 and 2.17 of [32].

For the distance d, Eq. (2), in Rydberg cluster, the distance d^* in the inverted deuterium RM cluster D(-1) is then expressed with the deuteron mass m_D

$$d^* = (m/m_D)^{1/2} d. \tag{5}$$

Remarkably, this value is 2.5 pm as was initially calculated [22] from the orbital motion within the clusters.

The direct experimental proof of this distance was obtained from measurements using laser irradiation of the catalytic produced D(-1) clusters [22]. The mechanism is described in Fig. 3. Photons from a laser beam irradiate the cluster and photo-electrically removing electrons at binding centers for the deuterons in the inverted RM. The remaining deuterons are then to repel each other by Coulomb repulsion causing a Columbic Explosion (CE) and are subsequently emitted into the vacuum above the iron oxide. Time of flight (TOF) measurements show energies of 630 eV. This corresponds to an initial distance of the deuterons in the cluster of

$$d^*_{\text{exp}} = 2.3\,\text{pm}. \tag{6}$$

In Section 4.3, a quantum theoretical explanation of the laser produced electron emission process is given, fitting the parameters obtained in this experiment. The small discrepancy between Eq. (5) and (6) may be a way to analyze some properties of the inverted Rydberg state of D(-1). The threshold of the laser intensity is found to be close to

$$I_{\text{thre}} = 10^{10}\,\text{W/cm}^2 \tag{7}$$

for a wave length of 565 pm. It should be noted that this experiment did not work with H(1) and H(-1) RM at the low intensities (7). This indicates that the D(-1) clusters are in a Bose–Einstein condensation state which is not normally possible with protons as fermions while deuterons are bosons. As suggested by Kim [33], at the densities involved pseudo bosons may form allowing condensation. While the density of the deuterons in the clusters of the inverted RM state of (D-1) based on the measured deuteron distance (6) corresponds to a value of about 10^{29} cm^{-3}, somewhat higher than estimated for our volumetric cluster, the two still may be related.

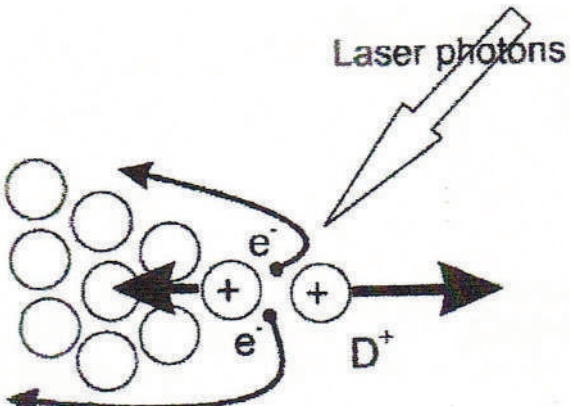

Figure 3. A pictorial representation of the Coulomb repulsion of deuterons in the cluster after removal of electrons by laser produced virtual quivering. Two electrons are excited into higher localized non-shielding orbital states by the laser pulse [2] leaving the remaining deuterons to be accelerated to the time-of-flight measured 630 eV energy by Coulomb forces, as Coulomb explosion CE.

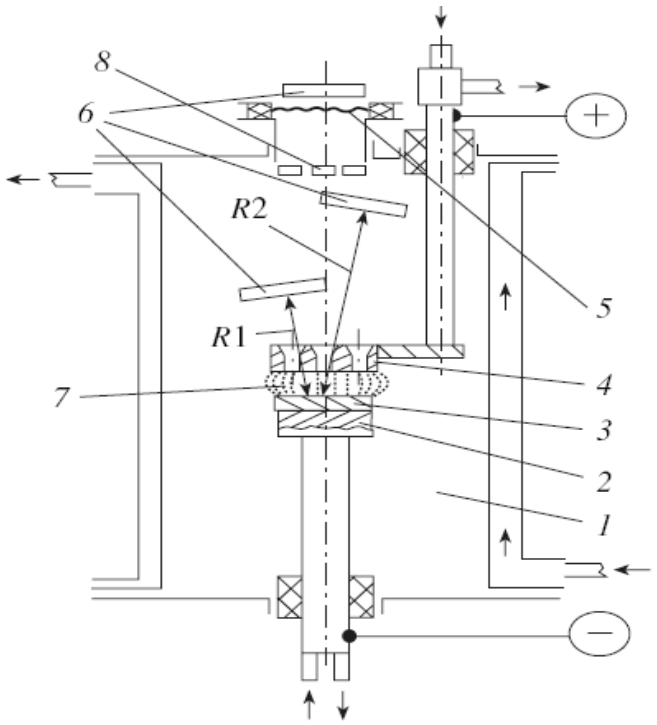

Figure 4. Schematic diagram of the glow discharge setup: (1) vacuum chamber; (2) cathode holder; (3) cathode; (4) anode; (5) Be window; (6) CR-39 detectors; (7) glow discharge region; (8) thermoluminescent detectors (TLDs) with 15- to 300-μm-thick Be filters. (b) Schematic diagram of the experiments with open cathode: (view A) TLDs with Be filters of different thickness; (1) cathode; (2) anode; (3) Be filters; (4) TLDs or pinhole camera; (5) metal holder of detectors; (6) 15- to 300-μm-thick Be filters. [35]

4. Excitation Methods for Cluster LENR

4.1. Electrolysis

LENR first gained attention in 1989 when Pons and Fleischmann reported that nuclear fusion was produced during electrolysis of heavy water on a palladium (Pd) electrode. They reported excess heat production of a magnitude of which the only possible sources were thought to be nuclear processes. They further reported measuring small amounts of nuclear reaction byproducts, including neutrons and tritium. These reports raised hopes of a cheap and abundant source of energy. Since then, the experimental results from various research groups, have shown support of the inital Pons and Fleischmann's measurement.

4.2. Glow discharge experiments

An alternative possibility for studying the D–D reaction yield is offered by the experiments with a high-current pulsed discharge in deuterium. The results of previous experiments [34] showed that pulsed glow discharge makes it possible to obtain ions with the energies within 0.8–2.5 keV and current densities within 300–600 mA/cm^2 at a deuterium pressure of 1–10 Torr.

The current density used for the bombardment of the cathode (target) surface in glow discharge is three orders of

magnitude higher than those using accelerators. Preliminary estimates show that high-current bombardment of the cathode with deuterium ions in a high current glow discharge can provide detection of the D–D reaction products even at $E \leq 1$ keV for exposures not exceeding several tens of hours (not possible with normal accelerator-target reaction measurements due to the current limitations of ion accelerators). This low-energy cross section data is relatively unexplored. However, it is not only vital information for LENRs, but also for fusion in astrophysical objects.

Figure 4 shows a schematic diagram of the experimental setup and the arrangement of detectors. Using this setup, intense directional X-ray emission has been observed from metal targets (Pd and Ti) in a pulsed high current (100–400 mA) and low-voltage (1.0–2.0 keV) deuterium/hydrogen glow charge. X-ray measurements showed an intense ($I_x = 10^{13} - 10^{14}$s^{-1}-cm^{-2}) soft X-ray emission (with a mean energy of quantum $E_x = 1.2$–1.5 keV) directly from the Pd or Ti cathode. The X-ray yield is strongly dependent on a deuterium diffusivity in the surface layer of the cathode, and the emission can be associated with enhanced electron screening effects at metal surfaces and interfaces and a coherent oscillation of this screening layer.

4.3. Low-energy laser excitation of RM matter

Low-energy laser excitation may be another way of exciting LENR reactions in RM mater. This requires development of efficient methods for coupling the laser photon energy with the inverted RM state of D(-1) clusters in order to remove electrons, and cause the D-atom in the cluster to fuse. The mechanisms to explain removal of the electrons by the laser field from the inverted surface RM state of D(-1) clusters, Fig. 1, is explained from the oscillation of the electron in an electromagnetic field (quiver motion at laser irradiation) in combination with a quantum relation to obtain a correspondence principle for the electromagnetic interaction [36].

A free electron in space, e.g. in a plasma, quivers in a laser field with the amplitude E of the laser field having a maximum elongation

$$r = eE/(m\omega^2) \tag{8}$$

with a maximum momentum $p = mv$ from the quiver velocity v

$$p = mv = eE/\omega, \tag{9}$$

where ω is the radian frequency of the laser. Indeed, free electrons in a vacuum perform the quiver motion as detected also from Thomson scattering where oscillation energy of the electrons

$$\varepsilon_{\text{osc}} = (eE/\omega)^2/(2m). \tag{10}$$

is the quiver energy.

A basic difference between this analysis and classical point mechanical motion in vacuum occurs when it is bound in an unexcited hydrogen atom or any bound state including the Rydberg state. If the laser field has a sufficiently high intensity $I > I_i$ above the ionization threshold I_i in vacuum, the electron will be ionized and then follow the quiver motion where I_i is defined by the ionization energy ε_i. At lower intensities photon interaction of the laser light can occur quantum-electro-dynamically with the electron in the hydrogen atom by resonance for energy levels given by energy eight-values of the quantum states of the electron within the bound atom. At these lower intensities one cannot describe the electron interaction with the photons in the point-mechanical classical way as quiver motion. Nevertheless, the correspondence to the quiver motion might be considered as a virtual oscillation (with all caution not to overstress this description until it is studied further). It is therefore interesting to see when the product of the length of the quiver motion, r of Eq. (8), with the momentum $p = mv$, Eq. (9) reaches the value of Planck's constant h

$$rmv = \hbar = h/(2\pi). \tag{11}$$

This quantum relation permits substitution of the laser field E of the quiver velocity v in Eq. (9) with the quiver energy (10) to arrive at

$$\varepsilon_{\mathrm{osc}} = \hbar^2/(2mr^2). \tag{12}$$

For low-laser intensities, this can be considered as a "virtual" quiver motion of the electron which is fundamentally different from the quantum states of the electron when bound in the atom. Based on this virtual description, it is interesting to see what happens if r assumes the value of the Bohr radius, Eq. (4). This arrives at a value of a "Bohr"-quiver oscillation energy

$$\varepsilon_{\mathrm{B,osc}} = me^4/(2\hbar^2) = \alpha^2 mc^2/2 = 13.6\,\mathrm{eV};\ \alpha = e^2/(\hbar c) \tag{13}$$

using the vacuum speed of light c and the fine structure constant a. This is just the ionization energy of hydrogen. It is worth noting that this value is simply expressed by the fine structure constant α and the electron rest energy mc^2. It is remarkable that this ionization energy for hydrogen marks a border line between the classical and the quantum mechanical state now expressed by the quiver motion, i.e. by the virtual electron oscillation.

The state of the inverted Rydberg cluster D(-1) [22] with distance d^* of 2.3 pm between the deuterons (as measured from the 630 eV energy of the emitted deuterons with the TOF mass spectrometer) is a rather complicated quantum state for the electrons and deuterons. In fact, it is the state of the electron of an unexcited hydrogen atom. Using the radius $r^* = d^*/2 = 1.15$ pm as a first approximation in the inverted Rydberg deuterium cluster in the same way as the Bohr radius (4) was used for hydrogen, we arrive at a virtual oscillation energy for the electron for "ionization" from the bound state in the inverted Rydberg state cluster.

$$\varepsilon_{\mathrm{DD,osc}} = \varepsilon_{\mathrm{B,osc}}(m_{\mathrm{e}}/m_{\mathrm{D}})[d/(2r_{\mathrm{B}})]^2. \tag{14}$$

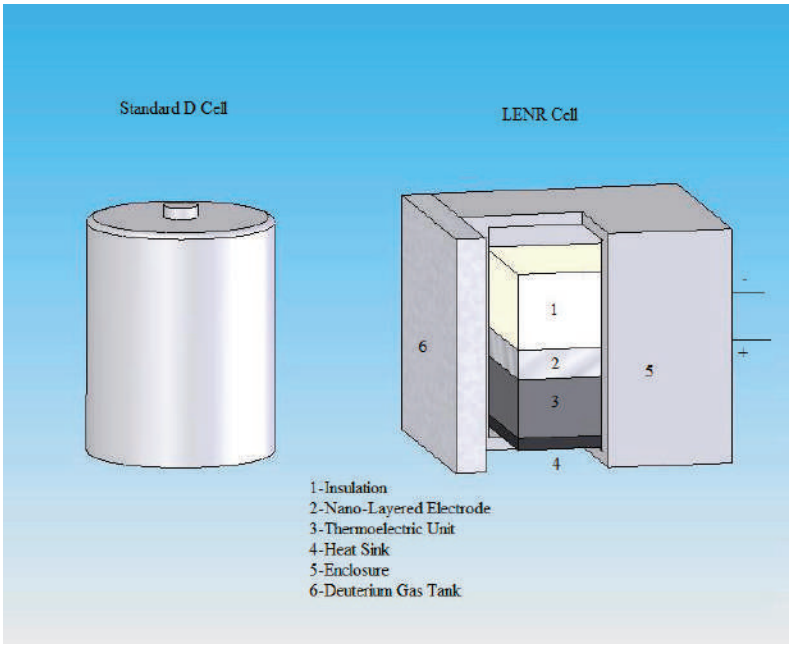

Figure 5. Small LENR battery – design based on present experimental data base.

The laser intensity for producing a quiver energy $\varepsilon_{B,osc}$ for the boron ionization Eq. (14) at the wave length 565 pm is 2.298×10^{14} W/cm^2 resulting with the same ratios as Eqs. (13) and (14) to arrive at a laser intensity

$$I^* = 3.1 \times 10^{10}\,\mathrm{W/cm^2}. \tag{15}$$

This is close to the measured threshold in the experiment. We assumed an ad hoc distance d^* for the inverted D-clusters in these calculations in order to work with the radius $r^* = d^*/2$ according to Fig. 1. The correct value may be somewhat different, leading to a slightly different threshold I^*. When very precise measurements of the threshold intensity are at hand, the more precise elongation of the virtual quivering in the D (-1) cluster could be calculated and may give more important information about the inverted Rydberg state of the D-clusters which definitely will not be a "clumping" together of spheres of the kind illustrated schematically in Fig. 1, but with much more complicated structures. This result and the corresponding theory also provide exciting new insights to the correspondence principle of electromagnetic interactions [36].

It is very important to realize that the measured [22] $d^* = 2.3$ pm value is lower than the initially expected theoretical value. This shows qualitatively that the radius of an inverted deuterium atom is larger than for an inverted Rydberg state of free deuterium. This confirms the implied overlap between the cluster members with neighboring states within the D (-1) state under the assumption of a cubic deuteron lattice structure in the cluster. The degree of overlap can be defined quantitatively from this type of analysis and should be carefully studied when more precise measurements are obtained.

The very low emission energy of the electron in D(-1) is understandable from the comparison of the model described in Fig. 1 where the binding is much weaker than in a hydrogen atom, cf. the model in Section 2.3 of [31]. Compared to the very long time of the resonance transition of electrons in atoms, the virtual-quiver-model ionization process is indeed extremely fast, roughly in the femto-second range. The electric field amplitude of the laser of 10^{10} W/cm^2 is 2.7×10^6 V/cm in good consistence to a laser driven field emission process. The laser intensity threshold near 10^{10} W/cm^2 for removing the electrons in the inverted Rydberg state for the subsequent 630-eV Coulomb explosion of the deuterons arrives at the virtual electron oscillation energy in full analogy to the ionization of hydrogen. This represents a characteristic of the correspondence principle of electromagnetic interaction [36]. It is a further example of the different mechanisms when transitioning from the classical to the quantum mechanical range as first noted when explaining the Schwarz–Hora effect [37,38].

5. A Potential Power Cell Using Gas Loading

While these clusters have extremely local high density, the low fractional volume of the clusters (which is where the LENRs would occur) limits total reactions over the electrode to low levels. The development of materials with abundant nano- or micro-structures may solve this problem, allowing a high volumetric density of cluster sites, i.e. a high cluster "packing fraction". The idea is that the dislocation loops mainly form at the near surface of the material. Nano- or micro-structures feature with large surface area, thus providing more room for dislocation formation. If high volumetric densities of cluster sites can be created via methods outlined earlier, a high reaction rate per cc should result in a competitive power cell at small size. We term the electrode designed to achieve a "massive cluster electrode" (MCE) for controlled cluster reactions.

To avoid use of expensive materials, the power unit may ultimately use different structures. Dislocations can also form in materials other than Pd such as Nickel with direct hydrogen charge [39]. It is encouraging that higher hydrogen loading at dislocation cores than in the bulk material has been reported. Hydrogen interactions at dislocations in Silicon have been extensively studied [40], but no work has yet been done to investigate application of LENRs. As the understanding of the technology of H/D condensation in the defects of solid materials continues to grow, development of a family of possible host materials is only a matter of time.

Based on the prior excess heat measurements described earlier, local power densities exceeding a kW/cm^3 are possible, promising very high energy density power units. Since the radiation emitted (protons, alphas, and X-rays) are not very penetrating (do not escape the cell structure) and no long lived radioactive reaction products are observed, LENR power units would be a remarkable "green" nuclear technology. A sketch of a small Dcell equivalent LENR battery is shown in Fig. 5.

The cell shown has a deuterium gas "fuel" tank attached. Gas loading is used rather than electrolysis for compactness. Heat flow is directed to the outer casing through a thermoelectric element using an insulation and heat sink design. Modular sections connected in series allow a 1.5 V output at 0.1 A. This type of battery must be used in devices where natural convection air cooling or other heat flow dissipates heat from the battery casing. The battery run time is determined by the amount of deuterium stored. Refilling of the depleted tank is done by pump down and gas injection through a filtered line connected to a "filling station". The unit shown is designed for 1000 A h per gas fill. The main technological step needed before construction of this battery is to finish development of the nano-layered electrode structure described earlier.

6. Conclusion

While LENR D-cluster studies are still in the research stage, there is mounting evidence that this technology may lead to a very attractive "green" power unit. If so, small self-powered battery-like units could be constructed with very high energy densities, well beyond present 1000 W-h/kg battery technology. Power densities would also be formidable. This revolutionary development would drastically impact the distributed mobile power industry. Much more R&D is needed, however, to achieve this vision, not only will this allow a radical new energy technology, but it will develop a whole new science related to these unique cluster states in metals. Preliminary experimental studies with the Bose–Einstein condensed ultra-high density deuteron clusters have been performed at the LANL TRIDENT Petawatt Laser with the goal of generating high energy (MeV) deuteron beams from the embedded deuterium clusters [41]. Such ultra-intense laser interactions provide important insight into the cluster states present in the targets (equivalent to the electrodes when used for LENR). This work, while not directly LENRs, uses the condensed mater cluster aspect to enhance Inertial Confinement Fusion (ICF) and ultimately has a similar goal of producing fusion energy without emission of radioactive radiation [42–44].

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