



Research Article

# LENR Excess Heat may not be Entirely from Nuclear Reactions

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## Abstract

Some theories of the mechanisms active in producing Lattice Enabled (or Low Energy) Nuclear Reactions (LENR) predict the formation of compact objects with binding energies and sizes intermediate between those of atoms and nuclei. The existence of compact objects remains unproven. But, if such objects exist and are formed during what are now called LENR experiments, they might release substantial energy without any nuclear reactions. Because of the small size of hypothetical compact objects, it is thought that the protons or deuterons at their centers might subsequently participate in nuclear reactions, producing more energy, transmutation products or energetic quanta. Such a two-step sequence could explain the relatively low production rates of nuclear reaction products, and also difficulties in correlating excess heat with the amounts of such products.

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## 1. Introduction

During heavy-water electrochemical experiments in the mid-1980s, Fleischmann and Pons found that more thermal energy came out of their experiments with Pd cathodes than was put in electrically. The excess heat was greater than could be explained by any chemical reactions. Hence, they postulated that the excess energy was due to unexpected nuclear reactions. It is now well established experimentally that the amount of excess heat measured in many experiments greatly exceeds what can be attributed to chemistry [1]. For this reason, and also because of numerous reports of nuclear reaction products and energetic radiations, it is widely believed that excess heat is due primarily, and maybe exclusively, to nuclear reactions. Hence, the field is now usually called Low Energy *Nuclear* Reactions (LENR). We prefer the more precise terminology Lattice Enabled Nuclear Reactions.

Given the envisioned simultaneous generation of heat and products from nuclear reactions, it is reasonable to expect them to be related quantitatively. The best linking of heat with nuclear products is the correlation of the

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produced excess energy with quantities of helium-4. That relationship was discovered by Miles in 1993 [2], reviewed by Bressani in 1998 [3] and Miles in 2003 [4], and well demonstrated in the work of McKubre and his colleagues in 2000 [5]. Fits to their measured amounts of heat and helium gave roughly 32 MeV per reaction, close to the gamma ray energy occasionally emitted during conventional fusion of two deuterons to form  $^4\text{He}$ . Despite all the work, the heat–He relationship remains contentious. Other quantitative correlations between excess heat and nuclear products are desirable, but might be difficult to obtain for the reasons discussed below.

Our focus is the alternative scenario for production of excess heat and observation of low levels of nuclear reaction products and radiations. It is far from new, but has received relatively little attention. Several theorists have postulated the formation of “compact objects” with sizes and energies between those of atoms and nuclei. If such objects do form, they could account for some or all of the measured excess heat without the requirement that nuclear reactions occur.

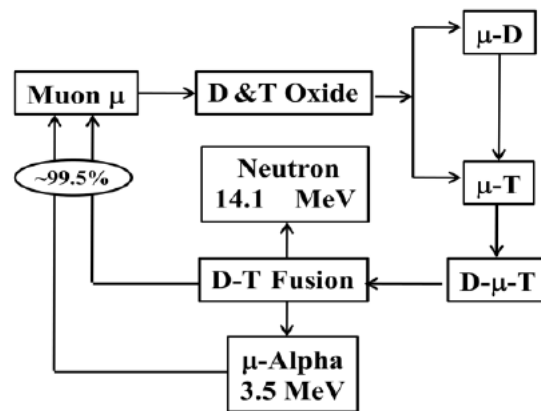
Nuclear reactions might follow the formation of the compact objects because of their small sizes, similar to how nuclear reactions occur in muon-catalyzed fusion. The presence of a heavier muon in place of a lighter electron results in atoms and molecules with much smaller sizes than usual. This brings nuclei into closer-than-normal proximity and greatly increases conventional fusion probabilities. The process is summarized in the next section. The third section reviews the compact object theories of by Mills, Maly and Vavra, Dufour, Heffner, Mayer and Reitz, and Meulenberg and Sinha. Based on these theories, the possibility that not all of the excess heat in LENR experiments is due to nuclear processes is examined in the fourth section. The last section considers possibilities for experimental discovery of compact objects.

## 2. Muon-Catalyzed Fusion

This process provides a model for the formation and nuclear reactions of compact objects, which is experimentally and theoretically well established. The possibility of using negative muons to promote fusion of hydrogen isotopes was published first in 1950 [6]. The fundamental notion is due to the muon being 207 times heavier than the electron. Replacement of an electron with a muon in an atomic or molecular orbital will result in the new orbital being about 207 times smaller than originally. The radius of a hydrogen atom, with a muon in place of the normal electron, is 285 fm [7]. The small size is due to the inverse scaling of orbital radii with mass. This applies to atoms and binary molecular ions with nuclei of protons (P), deuterons (D) and tritons (T). In a D–e–T molecule, the two nuclei are separated by about 100 pm. In a muonated D– $\mu$ –T molecule, they approach each other more closely during even low-temperature molecular vibrations due to their initially smaller spacing. This increases the probability of their tunneling through the Coulomb barrier and fusing. That is, the tunneling probabilities and associated nuclear reaction rates are greatly increased (catalyzed). The fusion probability is highest if the two nuclei are a deuteron and triton, although D–D fusion can also be muon-catalyzed.

The sequence of steps during muon-catalyzed fusion is indicated in Fig. 1. The cycle starts with introduction of a muon into a mixture of heavy water ( $\text{D}_2\text{O}$ ) and tritiated (generally TDO) water, which is often frozen for experimental convenience. The muons can displace electrons in D or T atoms, leading to formation of the D– $\mu$ –T molecule, the nuclei of which quickly fuse. The fusion produces 17.6 MeV of energy, which is carried off by the two particles that are produced, a fast neutron and an alpha particle. The muon can be liberated and start another cycle, or can stick to the outgoing alpha particle 1% of the time. If the latter happens, the muon and alpha particle will separate about one third of the time, freeing the muon for another cycle.

There are a few practical problems with muon-catalyzed fusion for production of energy. The first is that an accelerator is needed to produce the muons in the first place, usually by the production and decay of pions. That process is very energy consumptive due to the need to use a high-energy particle accelerator to make the pions. Second, the muon has a very short lifetime of 2.2  $\mu\text{s}$ . And, some of the muons are lost by staying with the liberated alpha particles. As many as 150 fusion reactions have been observed, on average, from one muon, although theoretical estimates are



**Figure 1.** Simplified schematic of the cycle in which muons form compact molecules of D and T in heavy and tritiated water, and then fuse, liberating both energy and most of the muons.

almost twice that value [6,8]. Muon-catalyzed fusion is a factor of about five short of energetic breakeven. The cost of tritium is another factor.

The existence of compact atoms and molecules involving muons enhances interest in the possibility that other compact objects might play a role in LENR. Theories about the formation and characteristics of such new compact objects constitute the next section.

### 3. Compact Object Theories

Like smaller nuclei and larger atoms, the compact objects envisioned by different LENR theoreticians have characteristics that can be described and quantified. The most important characteristics deal with energies, sizes and lifetimes. The formation energies for compact objects are clearly of great interest in a field that hopes to produce energy generators. And, there is the open question about excitation energies in addition to the ground-state binding energy for any specific compact object.

The sizes of such objects will, like the sizes of nuclei and atoms, be only approximate due to the distributed character of wave functions. However, just as nuclei have overall sizes on the scale of femtometers, and atoms have sizes on the scale of tenths of nanometers, it is possible to define the size of various theoretical compact objects. Orbital diameters can suffice for that purpose.

It might be that, once formed, the compact objects are stable like atoms, and not subject to spontaneous or other decay processes, like many radioactive nuclei. However, it is also possible that these envisioned objects are not stable. The basic question of the stability of hypothetical compact objects is unresolved. Maybe, if they exist, they have escaped attention because they are not stable. No estimates of their lifetimes are available.

The reader of theories dealing with particular visions of compact objects might be incredulous that, after decades of increasingly sophisticated experimental research, such objects have remained undiscovered. However, the situation is not unprecedented. In astronomy and cosmology, the existence of two entities, dark matter and dark energy, has been invoked to rationalize the observed dynamics of the overall universe. However, neither dark matter nor dark energy has been directly detected to date.

In the rest of this section, we will provide brief overviews of the several theories of compact objects with references to the detailed papers and postings by their authors. The ideas vary widely in their development, with some having

virtually no elaboration and others including specific values for binding energies and orbital radii. Their common characteristic is having binding energies greater than those known for H or D atoms or molecules, and sizes that are substantially smaller than those that are well known both experimentally and theoretically for atoms and molecules which contain H isotopes.

Late in the 1980s, Randell Mills postulated the existence of a deeply bound form of hydrogen, which he called the hydrino [9]. The least binding energy, and hence the energy that might be released during formation of the entity, was thought to be 41 eV. More tightly bound levels were postulated to have higher binding energies. If such tightly bound energy levels existed, they should be evidenced in spectra and, possibly, in electron scattering experiments. The spectral evidence for the hypothetical levels is not compelling [10]. And, the scattering experiments do not seem to have been done. Hence, the existence of Mills' envisioned deeply bound energy levels in hydrogen is still an open question.

There were two papers by Maly and Vavra on compact objects in the 1990s, stimulated by reports of cold fusion [11]. They dealt with "deep Dirac levels" in various atoms. Those levels are solutions of the Dirac equation, the relativistic analog of the Schrodinger equation in Quantum Mechanics. The papers give energies and charge distributions for compact objects. The binding energies fall in the range of 300–500 keV and the orbital radii are on the scale of femtometers. The authors of the papers considered experiments to test for the existence of these levels. They pointed to calorimetric evidence from LENR experiments as indirect evidence of the levels they computed.

In the mid-1990s, Dufour proposed the existence of bound states that result from equilibrium between the attractive electrostatic force and the repulsive electro-weak force [12]. He termed the entities Hydrex and Deutex, depending on whether a proton or deuteron was involved. The radii of various energy levels of the Hydrex were computed to be in the range of 1.78–3.47 fm. Their binding energies varied widely from about 393 keV for the lowest ( $n = 1$ ) quantum level to 36 keV for  $n = 20$  and beyond to small energies for higher quantum numbers. Dufour envisioned the Hydrex as a composite with oscillatory behavior between a proton with a very close electron and a neutron–neutrino pair.

Another theory on compact objects called "deflation fusion" was posted on the internet in 2007 and published during the next year by Heffner [13]. He considered oscillatory electron dynamics, where initially the electron wave functions are dispersed widely over atomic volumes (Bohr radius = 5.3 nm), causing nuclei to mutually repel. The electrons then return to regions closer to the nuclei, screening their repulsion during motion toward an (instantaneous) equilibrium state. For this brief state, it is possible that the nuclei approach close enough (<picometers?) so that the nuclear wave functions can overlap. This releases energy in the form of infrared and visible radiation from fusion-excited molecular electronic, vibrational or rotational states.

In the "deflation fusion" picture, a close-approach electron is envisioned to have a finite, but very short-lived (attosec) probability, to be "captured" in the neighborhood of, or actually within a nucleus at distance scales as short as fractional femtometers (fm or fermis). The electron capture amounts to wave function collapse and a charge neutral "compact object" formed may be viewed as a completely screening atom. Or, the situation may be thought of as "catalytic", because the deflated H atom may penetrate a nearby nuclear Coulomb barrier via short distance tunneling.

Heffner wrote of weakly bound pairs of electrons in the same state with opposed spins. In his concept, the existence of these electron pairs increases the probability of creation of a "deflated paired state". In that state, the two electrons have wavelengths sufficiently small to exist "in the nucleus." This was offered as the explanation of the occurrence of "cold fusion" [14].

In 2011, Mayer and Reitz published an article entitled "Electromagnetic Composites on the Compton Scale" [15]. They postulated a small three-body entity, called a tresino. Such particles would consist of a central proton or deuteron, plus two orbital electrons with anti-aligned spins. The compact size of the tresino makes the electron spin-spin interaction stronger than in the negative H ion, which is composed of the same three particles. Computations based on a simple Schrodinger equation gave 3.7 keV for the binding energy for a tresino and 386 fm for the orbital radius of the two electrons. Note that this is much smaller than both the Bohr radius in ordinary atoms (52.9 pm) and the 100 pm

D–T separation in ordinary D–e–T molecules. However, for D– $\mu$ –T, the nuclear separation is about 100/207 pm, or 483 fm, leading to muon-catalyzed fusion.

If tresinos do form, their subsequent reactions with nearby nuclei might have a relatively high probability. Mayer and Reitz hypothesized how tresinos can induce nuclear reactions due to their compact sizes, much as happens in muon-catalyzed fusion. More specifically, a negatively-charged deuteron tresino would be attracted electrostatically to another deuteron. The small size of tresinos could lead to the close approach of the two deuteron nuclei, resulting in a neutron transfer reaction and the production of tritium [16].

Assuming that tresinos can form, the Mayer and Reitz argued that they might explain two major current scientific riddles, the heating of the earth in geology [16] and dark matter in astronomy [17]. Finally, the two authors applied the concept of the composite particle to explain aspects of LENR. The heat observed in calorimetric experiments could be attributed to tresino formation. Note that the tresino formation mechanism does not require nuclear reactions for the production of energy. Tritium formation is reportedly due to tresino-caused neutron transfer reactions in highly loaded Pd, that is, Pd with a high ratio of the concentration of protons or deuterons to the Pd atom concentration.

Meulenberg and Sinha have also addressed the mechanism of LENR by consideration of compact objects. Their approach also involves a short term composite of two electrons and either a proton or deuteron, along with a bare proton or deuteron [18]. Their mechanism is the formation of such an object, followed by D–D fusion. That is, the approach necessarily involves nuclear reactions. They envision that the non-uniform lattices in heavily loaded Pd involve localized and high-frequency phonon modes. Those vibrations produce dynamic electrostatic fields that interact strongly with electrons in the materials. The resultant “potential inversion” causes the formation of “lochons”, that is, local-charged-boson–electron pairs, giving deuterons compact screening and a net negative charge. That removes the coulomb barrier, leading to the D<sup>+</sup>–D<sup>–</sup> fusion.

In a recent paper [19], Meulenberg summarized the related work by Naudts [20], who arrived at a total orbital energy of the rest mass of the electron times the fine structure constant, specifically, 511 keV/137 = 3.7 keV and a radius of about 390 fm. These values are essentially identical to those for tresino formation. Meulenberg considered an interpretation of Naudts’s results to be closer to those predicted by Maly and Vavre, who used the Dirac equations, since they are specific to fermions (such as electrons) [21].

Recently, in response to reports of high LENR powers from the Ni–H system, Dufour hypothesized the existence of a new composite system, which he terms the Hypole[22]. He envisions a Ni nucleus about 1.9 pm from a proton, with an electron orbiting the combination. Both the proton and electron are within the electron shells of the Ni atom. Dufour gives the Hypole formation energy as 10.5 keV. Because of the picometer separation of the Ni nucleus and proton, Dufour applies the new term “pico-chemistry” to LENR reactions that follow formation of Hypoles.

The compact object theories just surveyed are all essentially concepts with some supporting computations. It is natural to ask why such compact objects have not been observed previously. The answer might be that very special conditions are needed for their formation in observable numbers. For example, Mayer and Reitz envision spin alignment of the two electrons in a tresino. Having two spin-aligned electrons simultaneously near each other and either a proton or deuteron is required for tresino formation. That might be a very rare circumstance because of chemical and thermal effects. This is offered as a potential reason that such composite particles have not been observed before.

#### 4. Implications

It is simple to compute the implications of the formation of compact objects, and possible, but not assured subsequent nuclear reactions. If formation of compact objects is indeed the initial step in the production of excess heat, the total amount of excess energy  $E_T$  depends on the number  $N_C$  of reactions that form compact objects, the energy  $E_C$  released per formation of a compact object, the fraction  $f_N$  of the compact object formation reactions that lead to subsequent

nuclear reactions, and the energy  $E_N$  released per nuclear reaction:

$$E_T = N_C(E_C + \sum f_N E_N). \quad (1)$$

The summation is over the number of subsequent distinct exothermic nuclear reactions. The values of  $f_N$  can range from zero (no secondary nuclear reactions) to unity (when a particular nuclear reaction follows each compact object formation event). Importantly, the energies  $E_C$  are thought to be mostly in the keV range, while the energies  $E_N$  are generally in the MeV range.

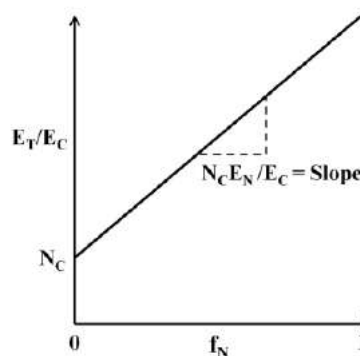
The fraction of the excess heat due to nuclear reactions, namely  $(N_C \sum f_N E_N / E_T)$ , can be as low as zero or as high as nearly unity. The energy gain  $(E_T / E_{\text{INPUT}})$  will be determined by the values of the parameters, almost all of which are currently unknown. Note that, if there were no secondary nuclear reactions, there would be no production of radioactive products.

Figure 2 is a conceptual plot of Eq. (1), divided through by  $E_C$ , for the case that there is only one possible subsequent nuclear reaction.  $N_C$  is large. And, some of the compact object theories, indicate that the ratio of  $E_N / E_C$  is on the order of one thousand. Hence, a plot such as the one in Fig. 2 would be very steep. This shows the great sensitivity of the total excess energy to the probability  $f_N$  of nuclear reactions following the formation of a compact object.

The additional complexity just described makes the correlation of overall excess heat with the amount of nuclear products difficult to quantify and, possibly, much more widely variable. This is because excess energy from LENR experiments and generators might be initially, and maybe largely, due to formation of compact object without any or with only some nuclear reactions, as in Eq. (1). Any nuclear reactions that do occur, and their manifestations (reaction products or energetic particles) would depend on the lifetime of the compact objects, their diffusion rates and their probability of reacting with nearby substrate or impurity nuclei. Note that the availability and spatial distribution of impurity nuclei can vary widely, especially due to defects in the host material.

We defined  $f_N$  as the ratio of nuclear reactions to the formations of compact objects. Hence, the number of nuclear reactions is  $N_C f_N$ . If one transmuted element formed or energetic particle were emitted for each nuclear reaction, then the correlation between total excess heat and measures of elements or particles would be as follows:

$$(E_T / N_C f_N) = (E_C / f_N) + E_N. \quad (2)$$



**Figure 2.** Schematic of Eq.(1) rearranged to exhibit the dependence on  $f_N$  of the excess energy normalized to the formation energy of a compact object.

Again, we assumed only one type of nuclear reactions for simplicity. This shows that the relationship between excess heat and the number of transmuted atoms depends inversely on the value of  $f_N$ . For low values of  $f_N$ , the amount of excess heat would be relatively low, but the ratio of heat to number of transmutions ( $E_T/N_C f_N$ ) could be relatively high. If  $f_N$  increased toward unity, the ratio of heat to transmutation products would be determined by the energy released by each nuclear reaction. This is the situation envisioned in the absence of the formation of compact objects, that is, if the only heat producing reactions were nuclear. Figure 3 addresses the correlation between the total excess energy and some manifestation of nuclear reactions, such as the concentration of transmutation products or the number of emitted energetic particles.

If compact objects did form and were followed by some nuclear reaction in each case, it would be difficult to know that the compact objects actually formed. This is due to the large ratio of  $E_N/E_C$ . Examination of the case of  $f_N = 1$  makes this point. For this situation, the energy given by Eq. (1) becomes the following for  $f_N = 1$  and  $N_C = N_N$ , the number of nuclear reactions:

$$E_T = N_N(E_C + E_N). \quad (3)$$

The large ratio of  $E_N/E_C$  makes it possible to ignore  $E_C$  relative to  $E_N$ . Similarly, Eq. (2) collapses as follows:

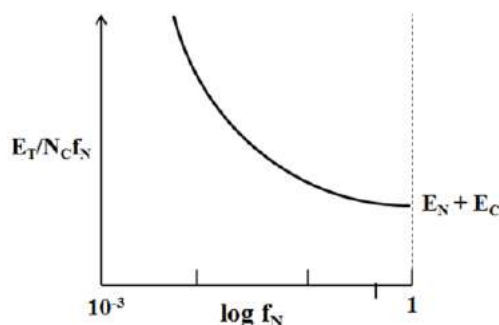
$$(E_T/N_N) = E_N. \quad (4)$$

Both Eqs. (3) and (4) are what would be expected if all the excess energy were due to nuclear reactions, that is, there were no formation of compact objects. But, the equations hold to a good approximation even with the formation of compact objects, if each is followed by a nuclear reaction, since  $E_C/E_N$  is small.

Storms has postulated the existence of a “nuclear active environment” of still unknown composition and structure in which LENR occur [23]. If the initial reactions are not nuclear, but are instead the exothermic formation of a compact objects, a nuclear active environment is not a requirement. However, in that case, it is still undoubtedly necessary to have a particular combination of material (composition and structure) and ambient (sonic, magnetic or other fields) conditions favorable to the formation of compact objects.

## 5. Discussion

The theories about the formation and implications of compact objects may be significant to understanding LENR. Observations of large excess energies, not explicable by chemistry, might not require the occurrence of nuclear reactions. However, the numerous measurements of nuclear products and of emitted energetic particles certainly do require nuclear reactions for their explanation.



**Figure 3.** Schematic of the ratio of excess energy to the number of nuclear reactions as a function of the probability of secondary nuclear reactions.

It can be asked if there is any hope of inferring the formation of compact objects from total excess energies and some measures of nuclear reactions. Doing that would seem to require control of the values of  $f_N$  in order to plot graphs such as those shown schematically in Figs. 2 and 3. That might be possible if samples of alternating monolayers of different materials could be made, possibly by Atomic Layer Epitaxy. If compact objects formed in only one of the two types of layers, the probability of reactions with nuclei in the other very close layer of material would depend on the geometry and atomic makeup of the second layer. The production of samples, and the constraint of compact object formation to only one of the layers, would both be very challenging experimentally.

If it is either very difficult or impossible to use excess energy and nuclear reaction products to infer the existence of compact objects, there might be other, more direct means of proving their existence. It seems that spectroscopic searches for energy levels predicated by the compact object theories might be fruitful. Such experiments can be done in two ways. The first is the use of Electron Energy Loss Spectroscopy. That is done in transmission electron microscopes, where the beam can be limited to probing a very small volume. A sophisticated sample stage would be required for that approach. The second technique would be to use ultraviolet, X-ray or gamma ray absorption to search for spectral features at the predicated binding energies. Such experiments would best be done using synchrotron radiation, at least for the ultraviolet and X-ray spectral ranges. Success with either of these techniques would hinge on the number of compact objects in the volume of a sample being probed, that is, on their production rates and lifetimes integrated over the experiment duration.

Proving the existence of compact objects and assessing their relevance to LENR are two separate and important steps. If those two features are established, then further theoretical work will be required to quantitatively relate measured LENR rates to basic parameters. The overall rates of heat production and appearance of new elements or energetic particles would depend critically on the  $f_N$  parameters. It would be very desirable to obtain theoretical values for such fractions. Doing that would require tunneling calculations given initial separations and thermal vibration amplitudes for various combinations of compact objects and other nuclei. Those computations are possible with current tools.

If the fundamental mechanisms and probabilities for formation of compact objects were available, the overall dynamics for production of heat, nuclear reaction products and energetic particles could be computed. Such calculations would require three-dimensional and time-dependent simulations of the overall flow of matter and energy on or within the solids that support the formation of compact objects.

Before the advent of theories of compact object formation, only chemical and nuclear energies were considered during analysis of LENR experiments. If compact objects are proven to exist, and if they are involved in what are now called LENR experiments, then their characteristics must also be considered to understand the energetics and dynamics of “LENR” experiments.

Resolution of this question about the source of excess heat will probably not come from any clear yes-or-no experiments. It is conceivable that, under some conditions, all of the excess energy is indeed due to nuclear reactions and, under other conditions, little of it is nuclear. Intermediate situations could also exist. Much additional quantitative experimental and theoretical work will be necessary to determine what actually happens for various conditions.

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Helpful correspondences with Frederick Mayer and Andrew Meulenberg are recalled with pleasure. Useful comments from the reviewer were welcome.

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