Can Established Physical Principles Explain Solid-State Fusion?

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ABSTRACT

This report examines, in the light of new evidence, whether low energy nuclear fusion can possibly conform to fundamental laws of physics. The new evidence examined here may explain two cited deficiencies, the lack of a sufficient deuteron coupling mechanism and the lack of certain nuclear by-products. The concept that heavy electrons (fermions, pseudo-particles) are able to screen deuterons may have been dismissed too early. In this paper we show that heavy electrons may cause a high degree of localization, a central effect that is needed in the screening process. Many heavy electron (heavy fermion) materials exist, and in many of these, an increase in electron localization on lattice sites has already been seen directly. The lack of nuclear by-products may in fact be explained by a physically reasonable interaction between four deuterons in which only easily absorbed alpha particles and low energy gammas are produced.

1. INTRODUCTION

The many positive reports of success in recent low energy nuclear reaction (LENR) processes lead one to wonder if there isn't a possible, perhaps unexplored, set of physical or chemical electrolysis principles by which they may be explained. In this paper a set of possibilities is put forward in hopes that experiments will be performed to answer this question. These possibilities consist of the application of heavy pseudo-particles to provide the detailed localization and inertia needed for effective Coulomb screening, and multiple deuteron interactions in which only easily absorbed alpha particles and gammas are produced [1].

The critical view of research in the LENR area is based mainly on the lack of an established screening mechanism, and the lack of observed nuclear by-products, making it hard to reconcile the purported observations with well established physical principles. This situation has continued to the present time in spite of the publication of numerous reports of positive experimental results, with correlated improvements in reproducibility.

Two prominent expositions are those of Leggett and Baym [2] and Koonin and Nauenberg [3]. Each of these is mainly concerned with the lack of a strong coupling method rather than the lack of fusion by-products. A possible method out of this difficulty is addressed in Section 2. In Section 2.1 it is argued that high effective-mass in some cases allows a localization of the pseudo-particles on lattice sites. An operative question is on how fine a spatial scale these heavy mass effects occur. Section 3 discusses the crystalline geometries. Section 4 uses the

results of the previous sections to propose a possible fusion mechanism. The other question, about possible explanations for the absence of fusion by-products, will be addressed in Section 5.

2. POSSIBLE SOLID-STATE MECHANISM TO PROVIDE STRONG COUPLING

It is common knowledge that muon induced fusion has been produced in the hydrogen molecule. The muon, a particle similar to the electron but having a mass 207 times larger, when substituted for an electron in a hydrogen molecule, causes hydrogen isotopic nuclei to come closer to each other (by about 200 times). This is well understood by modern physical principles. The result is a much increased rate at which the nuclei fuse. This increased rate is so much larger than for the normal hydrogen molecule, that the method has been extensively investigated for use in fusion energy production. The muon exists for too short a time to produce enough fusions for a practical application.

Koonin and Nauenberg [3] give details showing that putative electrons with an extra mass can increase the rate of fusion of the nuclei in molecular hydrogen. An electron with five times as much mass could generate fusions at the level reported by Steven Jones, et al. [4], and a mass ten times heavier might generate fusions at a rate in line with the original Pons and Fleishman [5] reports.

Is it possible that deuteron fusion may be enhanced by use of heavy electron materials? If so the enhancement would need to be caused by a more effective negative electron screening of the deuterons' positive charges. The critical question in this regard is whether the action of these pseudo-particles is at all similar to that of heavy electrons on the fine spatial scales required. There are many indications that it is. For many solid state phenomena, such as the de Haas-van Alphen effect (DHVA) [6], experiments show them performing like individual but heavier electrons. Luttinger, in discussing the DHVA effect in a system of interacting pseudo-particles states that his result "… is exactly what one computes on a single-particle basis, except that the true single-particle excitation energies must be used,…[6] " Other phenomena that have been explained using a single-particle description of heavy fermions include electronic heat capacity, Pauli spin susceptibility, Landau diamagnetic susceptibility, and electrical resistance and mobility. It is possible that only experiment will tell the smallest (finest) spatial extent of these effects.

Heavy mass also implies the existence of an inertial effect, and this means that its negative charge could resist being pushed or accelerated out of locations such as between two or more deuterons. This is important since it implies that the heavy-electron has a smaller wavelength in any given energy state than single electrons in a simple tight binding model.

Palladium, platinum, nickel, and cobalt, as tabulated by Kittel [7], are materials with a very high electron effective-mass. Today's interest in heavy fermion materials, on the other hand, arises largely from the fact that many high-temperature superconductors (copper oxides) belong to this class. It may be of interest in this regard that hydrogen doped palladium is a superconductor, with an increasing critical temperature with hydrogen loading. Along with

having superconducting phases these materials often exhibit ferromagnetic and anti-ferromagnetic phases [8, 9]. Heavy fermion properties continue in the so-called normal phase that occurs above the superconducting critical temperatures.

Heavy-electron materials include, but are not limited to palladium, platinum, nickel, cobalt, niobium, tantalum, vanadium, titanium, tungsten, yttrium, and zirconium atoms. Heavy-electron materials may be other than the transition metals. These include $CeCu_2Si_2$, UBe_{13}, UPt_3, URu_2Si_2, UPd_2Al_3, UNi_2Al_3, $CeCu_2Ge_2$, $CeRh_2Si_2$, $CePd_2Si_2$, $CeIn_3$, and many others. To our knowledge, prior to this report this type of material has never been considered for low temperature fusion when embedded with deuterons. An additional fusion possibility occurs when one of the high temperature superconducting materials is substituted for one of the transition metals. These materials include the doped lanthanide copper oxides, the yttrium-barium-copper oxides, those with the generic composition $RBa_2Cu_3O_{7-x}$ in which R stands for yttrium or one of the lanthanide rare earths, and many others in this copper oxide family.

The suggestion is made here for the first time that low temperature fusion might be expected to occur in any of these heavy electron systems if they contain absorbed deuterons. A more reproducible effect may occur. An interesting experiment should be performed by embedding deuterons in these materials and investigating possible fusions at low temperatures. At these temperatures the fermion heavy mass effect is well demonstrated for many of them.

Koonin and Nauenberg point out that effective-mass "should not be associated with any physical excitation in a solid material, as only the bare electron is relevant at the short length scales that are important here." The Energy Research Panel Advisory Board investigating early fusion reports stated that "…this phenomenon is described as… involving strong correlation near the Fermi surface. As such, heavy fermions extend over many lattice sites. …. only short-wavelength 'bare' electron excitations are relevant for screening…" [10].This statement is correct for the classical effective-mass concept. It omits consideration of many materials with very heavy effective masses caused by other strong interactions. Could it be that these authors have inadvertently given away a major advantage of the solid state medium by not expanding the scope of what they mean by effective-mass? Heavy electrons correspond to pseudo-particle peaks in an energy spectrum, and in addition they may be broadly spread in wavelength. This spreading is particularly significant if the pseudo-particle resides on or near the Brillouin zone boundary. Based on elementary Fourier analysis the pseudo-particle spatial distribution is concentrated in smaller regions when the wave number distributions have these broadened properties.

It is because pseudo-particle phenomena are coherent (highly correlated) over macroscopic volumes that the concept of pseudo-particle mass in these heavy fermion materials may be important. Here, 'spatial bandwidth' refers to the width of the band of wave numbers near the peak energy of the pseudo-particle [12]. A Fourier expansion in terms of these wave numbers can produce a periodic but apparent unit-cell-localized result as is easily demonstrated**.** Also Fourier expansion in terms of a band of wave numbers concentrated around one-half this wave-number**,** $\pi/(2a)$ with a equal to the square-lattice spacing, may produce unit cell localized results that occur on every second unit cell, etc.

The higher the mass of a particle (or pseudo-particle) the greater is our ability to localize it, and vice versa [13]. In the following paragraphs this relationship will be used to point to the fact that high effective-mass pseudo-particles can imply high localization of electrons (and charge stiffness) on the atomic lattice sites. This in turn will be used to argue that the effect of the heavy-electrons in a palladium lattice doped with deuterons may be to provide a much more effective screening effect between deuterons.

2.1. HIGH PSEUDO-PARTICLE MASS AND LOCALIZABILITY

Pseudo-particles may acquire the effect of an additional mass through mutual interactions in a many-body system [7, 14, 15]. Consider a many–body system with a Hamiltonian

$$H = H_0 + H_1, \tag{1}$$

where H_0 and H_1 are the free particle and interaction Hamiltonians respectively. If the free particle Green's function G_0 (based on H_0) is known, the many-body Green's function may in principle be found by solving the Dyson equation

$$G = G_0 + G_0 \Sigma G, \tag{2}$$

in which $\Sigma = \Sigma_1 + \Sigma_2 + \Sigma_3 + ...$ is known as the "irreducible self-energy part" or "the mass operator" [14, 16]. It is the expression for the contributions to the mass of a quasi-particle generated in the system due to inter-particle and lattice interactions. The expression for Σ is a sum of progressively larger (but weaker) stages of the interaction. After "mass renormalization" the Green's function is commonly expressed in the frequency-wave number (k, ω) domain as

$$G(k, \omega) = [\omega - e_k - \Sigma(k, \omega)]^{-1}, \tag{3}$$

in which Σ is in general a complex number. e_k is the peak energy in a band at wavenumber k. The corresponding spectral function is

$$A(k, -i\omega) \equiv -\frac{1}{\pi} \mathrm{Im}(G(k, \omega)) \tag{4}$$

$$= -\frac{1}{\pi} \left[\frac{\lambda}{(\omega - e_k - \Sigma_r)^2 + \lambda^2} \right],$$

where $\Sigma_r = \mathrm{Re}(\Sigma(k, \omega))$, and $\lambda = \mathrm{Im}(\Sigma(k, \omega))$ are the real and imaginary parts of Σ.

The spectrum is a Lorentzian density if λ, the imaginary part of Σ controlling the lifetime of the pseudo-particle, is independent of energy. If e_k and k are to be good (stable) quantum numbers the imaginary part must be small and the particle lifetime long. The real part of Σ is the contribution to the pseudo-particle's effective-mass in addition to that that an electron has

in, for example, a single electron tight binding approximation [7, 14]. Since the target crystal lattices are mostly cubic, the spectrum may be treated as being isotropic.

An extremum of the spectral function occurs where $E_k \equiv \omega(k) = e_k + \Sigma_r$. For a particular direction in wavenumber space the point at which the extremum occurs will be denoted $k = k_0$. For an isotropic environment the effective-mass [14, 17] evaluated for the pseudo-particle representing the spectral peak, has the definition

$$\frac{1}{m^*} = \left.\frac{\partial^2 E_k}{\partial k^2}\right|_{\substack{\omega=\omega(k_0) \\ k=k_0, e_k=e_{k_0}}} . \tag{5}$$

When the expression for the energy is expanded about this peak it becomes

$$E_k = E_{k_0} + \frac{1}{2}\left(k - k_0\right)^2 / m^* + ..., \tag{6}$$

and if this expression is substituted in the spectral function there results

$$A(k, -i\omega)\,|_{k\approx k_0} = -\frac{\lambda}{\pi}\left|\left[\left(\frac{\left(k-k_0\right)^2}{2m^*}\right) + ... + i\lambda\right]\right|^{-2} , \tag{7}$$

which, for small λ, is the transfer function of a linear system having a peak whose wave number mean-squared bandwidth is proportional to m^*, and this in turn corresponds to an impulse response that is highly peaked spatially with appropriate periodicity and with a mean-squared spatial width at lattice sites proportional to $1/m^*$ [16]. The Fourier transform of a narrow spectral band extends periodically and is seen to have a spatial resolution inversely proportional to the band's wave-number bandwidth. Thus a narrow spectral (energy) bandwidth implies a broad correlation in space, but not necessarily a long wavelength if its wave number contributions are near a zone boundary.

Thus far the objective of this section has been to show that a spectral line corresponding to heavy-electrons or pseudo-particles, though defined over long ranges, is spatially periodic and is locally concentrated within any one or two spatial periods, if its k_0 is near (or a significant way toward) the zone boundary, and if it has a large enough wave-number spread. Alternatively, if k_0 is located half way to the boundary the localization, while still concentrated, may occur at alternate unit cells, etc. Unless the pseudo-particle represents a moving charge density wave, the charge will be concentrated on atomic lattice sites. This implies concentration near the positive hydrogen nuclei. This is particularly true if the heavy-electronic system conforms to a model similar to the Hubbard model, for which (two) electrons being confined on a site, in a lattice with more than one electron per site, is a basic part of the model.

The Hubbard model [18, 19], along with the Kondo model, is commonly used to explain heavy-fermion systems. A characteristic is a configuration of atoms with near-half filled 4d or 5d-shells forming a narrow band interacting with atomic sites. The narrowness of the d-band, along with the interactions, implies a high degree of correlation among the electrons. To explain certain behavior, the Hubbard model contrasts this implied delocalized band motion with the effect of a tight-binding model in which excess d-electrons (or holes) are allowed to spend a proportionately large amount of time in the vicinity of the lattice sites. The Hubbard Hamiltonian may be written in the following form

$$H = -t\sum_{i,i',\sigma} c^{+}_{i,\sigma} c_{i',\sigma} + U\sum_{i} n_{i_\uparrow} n_{i_\downarrow} . \qquad (8)$$

Here the sum over σ means a sum over up and down spins, $c^{+}_{i,\sigma}$ is a creation operator for an electron with spin σ at lattice site i, and $c_{i',\sigma}$ is the corresponding annihilation operator at site i'. If an electron is created at i and another is annihilated at i', one says that the electron has hopped from one site to the other. It is generally found that a physically verifiable model may be achieved even when these hopping transitions are restricted to adjacent lattice sites. This is called hybridization between states on neighboring sites. The second sum is over number operators: $n_{i_\uparrow}$, for example, is the number of electrons with up-spin at site i, etc. As usual, $n_{i_\uparrow} \equiv c^{+}_{i_\uparrow} c_{i_\uparrow}$, and $n_{i_\downarrow} \equiv c^{+}_{i_\downarrow} c_{i_\downarrow}$. Each of the terms in the second sum corresponds to two electrons interacting at the same site. t and U are coefficients that determine the relative contributions of the two terms. From the point of view of wanting charges concentrated at lattice sites for the purpose of screening hydrogen nuclei a large value of U is desirable, but hopping may also be allowed in order to transfer the charges between the transition metal atoms and the hydrogen nuclei and so-forth.

In this section it has been recalled that palladium, and the other metals that have been involved in LENR are members of the class of heavy-electron metals, and it has been demonstrated that this implies, in some metals, a high degree of localizability of the electrons on atomic lattice sites. Thus it is possible to question the claim that there is no conceivable strong coupling between the metal lattice, the electrons, and the embedded hydrogen nuclei. It is possible to argue to the contrary. But the electrons need to screen the positive charges, and the screening effect must be large enough, and must be accompanied by localization of electronic charge at lattice sites. That such a screening effect is large enough has not been proved here. But it has been shown that there that it is reasonable to look for a large effect that localizes charge at lattice sites with attributes of heavy mass. This indicates that a high level of screening by this mechanism may indeed be available.

It has been argued that the heavy nature of pseudo-particles in certain materials can enhance localization of electronic charge on lattice sites. It is appropriate at this point to recall that charge concentration on lattice sites has recently been directly observed on surfaces of high temperature superconductor classes of materials [8, 10].

3. GEOMETRIC STRUCTURES

Before estimating the feasibility of multiple nuclei interactions, it is appropriate to review the crystal geometries that are involved [20, 21]. Henceforth, when the term deuteron is used it will represent any of the three hydrogen isotopic nuclei. Fig. 1 shows an arrangement of palladium atoms and deuterons in a planar configuration that occurs when the 4-d transition metals are highly doped with absorbed deuterons. Palladium is used here as an example of metals that have been used in claims of successful low temperature fusion experiments. It may be of interest to point out the similarity of these planar configurations to the arrangements of copper and oxygen atoms in planes occurring in the copper oxide high temperature superconductors [22]. In the copper-oxygen configuration, there is a plane where the copper atoms occupy the locations of the palladium shown here and the oxygen atoms occupy the locations of the deuterons. The statement of the similarity may imply that the configuration is common to a complete class of heavy electron (high effective-mass) materials. Subsequent figures show how these planar arrangements appear in three types of crystalline unit cells.

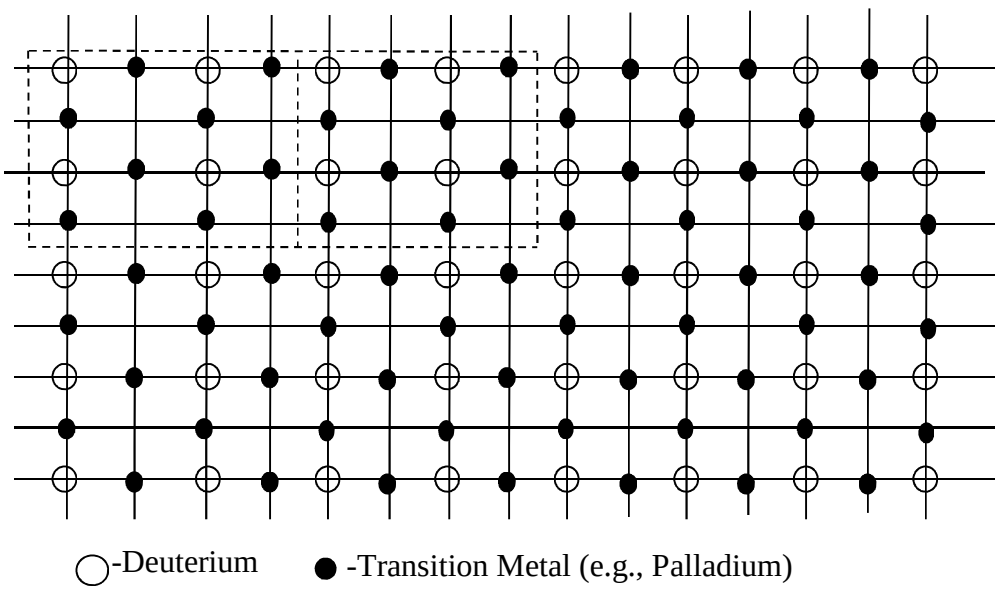

Figure 1. Two-Dimensional Arrangement of Transition Metal and Deuterium in a Disposition Similar to That in the Active Planes of Typical High-Temperature Superconductors.

Fig. 2A shows an atomic arrangement of deuterons in a body centered cubic (bcc) lattice, where the deuterons, with a slight effort, may be seen to be residing on planes. These are planes on which convergence of the deuterons (shown in Fig. 4) may be induced. Fig. 2B shows an atomic arrangement of deuterons in a face centered cubic (fcc) lattice, where the deuterons also reside on planes on which convergence of the deuterons may be induced.

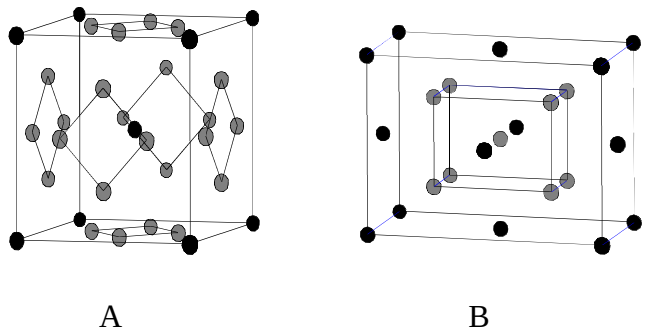

Figure 2. Atomic Arrangements of Hydrogen in a bcc Lattice, Left, and an fcc Lattice, Right. These are Arrangements with Tetrahedral Symmetry.

Fig. 3A shows an octahedron enveloping a deuteron indicating an arrangement in which deuterons have this octahedral coordination. Fig. 3B shows a planar square sub-lattice in the case where deuterons have octahedral coordination. Fig. 3C shows a tetrahedron with a deuteron on each vertex, the center of which may be the locus of convergence of the deuterons.

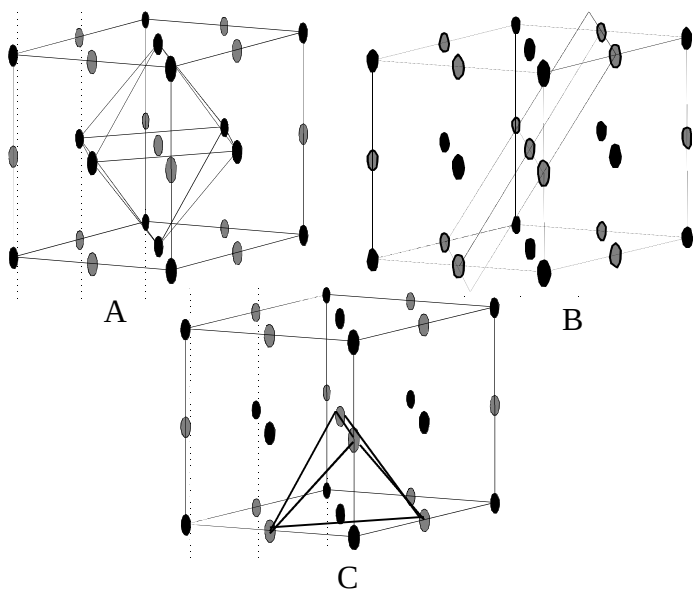

Figure 3. In Lower Concentrations, Hydrogen is in Sites with Octahedral Symmetry in an fcc Lattice. An Octahedron Enveloping a Hydrogen Nucleus is Seen on the Left. A Plane Square Sub-Lattice Containing the Octahedral Hydrogen Nuclei is Indicated on the Right. A Tetrahedron with a Hydrogen Nucleus on Each Vertex is Shown Below.

This last sort of convergence to the center of a tetrahedron is similar to that proposed by A. Takahashi [1, 23] in his electron quasi-particle expansion theory (EQPET). His theory involves the convergence of deuterons (along with certain electrons) toward the centers of the tetrahedrons with convergence being due to “transient Bose-type condensation (TBC) of

deuteron cluster at PdD_x lattice focal points" [23]. This is not required in the mechanism proposed in this report.

4. A MODEL FOR LATTICE, ELECTRON AND DEUTERON INTERACTION

In order to motivate the investigation of whether nuclear reactions could possibly be explained using basic principles, a general concept illustrated in Fig. 4, is introduced. The figure shows a two-dimensional lattice excitation, or motion, with deuterons converging toward one another as a part of general lattice vibration modes, with the arrows being reversed after a 180 degree phase change. The figure is an adaptation of Fig.1 in which lattice motions of the deuterons have been generally indicated. At a time corresponding to a half period later the deuterons have reversed directions. This motion is a part of high wavenumber lattice excitations that are an integral part of an ambient (optical and longitudinal) phonon spectrum. The corresponding wave numbers in the plane are substantially near a Brillouin zone boundary ($k = \left[\frac{\pi}{2a}, \frac{\pi}{a}\right]$ with a equal to the spacing of the square lattice.) Motions of the lattice host atoms (solid circles) are not indicated since they may assume different forms for different lattice normal modes. This particular mode for the vibration of the deuterons is not the only dynamic mode that may be important to the process described here, but it is one which may produce results that are consistent with recent measurements of surface charge ordering [8, 9].

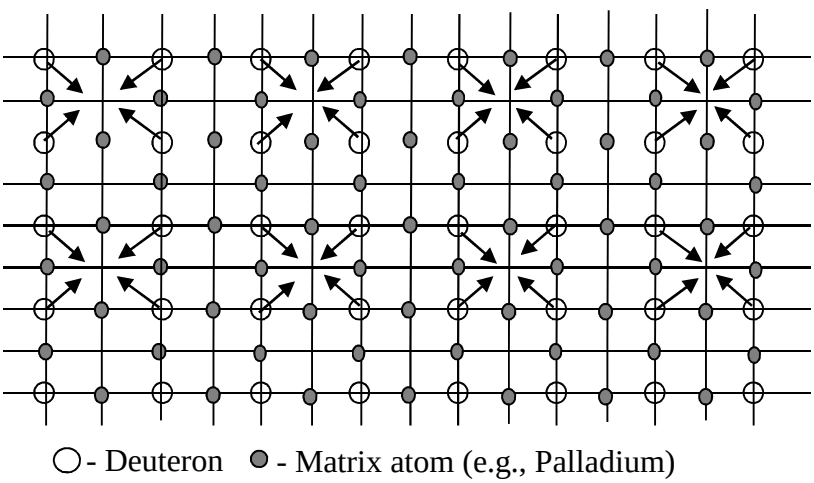

Figure 4. Two-Dimensional Lattice Excitation, with Hydrogen Nuclei Converging as a Part of General Lattice Vibration Modes That are Enhanced by Heavy Electron Screening.

The concept is as follows. The system is chosen to consist of a transition metal in the heavy-electron class in which deuterons are embedded. The extent of loading of the deuterons is stoichometric (Pd_xD, x=2 or less.) An electron model such as the Hubbard model applies. This implies that electronic charge is localized to a large extent on the positive ions, i.e., the metal ions and the deuterons. This charge localization is a result of the heavy-mass-pseudo-particle many-body phenomenon. Because negative charge screens the positive charges of the

deuterons, their interaction is affected and enhanced by this concentrated cloud of negative charge. The Born-Oppenheimer approximation applies only insofar as the positive ions have much greater mass than the electrons, meaning that their displacements are slow variables in the many-body system. The electronic structure however is strongly affected (slaved) by their motions. The closer any number of deuterons is grouped, the greater is the mean positive charge in their vicinity and, in response, the localized negative charge is greater.

The electronic response is not without inertial effects because of its heavy mass, and this offers the possibility of a resonance of sorts with the motion of the deuterons. A set of deuteron motions tending to a common point, as in Fig. 4, induces a screening effect such that the lattice vibration force constants for these motions are greatly reduced. The amount of reduction is greatest on the two-dimensional Brillouin zone-boundaries of the lattice planes containing these vibrating deuteron modes. This is because these are the wavelengths at which the greatest spatial convergence occurs. Being on or near the Brillouin zone boundary, these modes possess phase velocities in the two-dimensional Brillouin zone that are near zero. Considering the use being made here of comparisons to the copper oxides, the two-dimensional, instead of three-dimensional, nature of these lattice excitations, along with their wavenumber dependence, conforms to experimental observations on the "importance of the momentum anisotropy in determining the complex properties of the cuprates….[9]."

The variation of lattice force constants with wavenumber, due to the screening effect, along with their dependence on the wave amplitude, is an indicator of non-linear interactions. A model that fits this type of non-linear wave phenomena, describing the normal modes (phonons), with need for only minor alteration, has already been worked out. It is presented in [24] as one possible derivation of the non-linear Schrödinger equation (NSE). An outline is presented here.

Assume the wave equation $L(\partial_t, \Delta)u = 0$ applies, where L is an operator with constant coefficients. For small amplitudes any non-linear terms may be neglected in which case the solution has a form $u = \varepsilon\psi e^{i(k\cdot x - \omega t)}$, where k and ω are related by the dispersion relation $L(-i\omega, k)u = 0$. ε represents a small number. The non-linearity is introduced by requiring a specific, but alternate, dispersion relation and introducing this dispersion relation in place of the linear one in the form,

$$\omega(i\partial_t, -i\Delta)\psi e^{i(k\cdot x - \omega t)} = 0. \tag{9}$$

For the new dispersion relation the function ψ is constrained to be modulated in space and time in a specified fashion. Without belaboring the point, after expanding the desired dispersion relation about the linear one, the function ψ is found to first-order to be required to satisfy the (NSE)

$$i\frac{\partial\psi}{\partial\tau} + \frac{1}{m_a}\nabla^2\psi + \left[\frac{1}{2}qx^2 + \gamma\left|\psi\right|^2\right]\psi = 0, \tag{10}$$

where the mass at the lattice sites m_a has been replaced by half m_e and q is the vibration force constant for this mode. The parameter γ is proportional to the first order term in the expansion of the non-linear dispersion relation in terms of its dependence on the wave amplitude-squared. This is precisely what is useful in the present context. The parameter γ must be made a function of wavenumber matching the physics expected near the two-dimensional Brillouin zone boundaries as discussed above. Especially it must correspond to a lowering of the mode energy $\hbar\omega$, per phonon, on this boundary (a reciprocal effect of the electron screening). This corresponds to an increase in the occupancy of these deuteron many-body oscillator states.

The conceptual model is based on a coupling between the Hubbard model for the electronic motion and the non-linear Schrödinger -type equation describing the lattice interaction. The coupling is evidenced in the two parameters: U of the Hubbard model and γ of the NSE. An examination of the possibility of resonance phenomena being induced by this type of coupling is planned. It is anticipated that mode locking and mode competition phenomena will exist, and these may lead to highly correlated, large amplitude, deuteron motions.

An effect known as a Peierls instability occurs on a zone boundary when the d-band is not filled and the Fermi level E_f falls within the band as described in [25]. A periodic spatial distortion may happen to induce a lower energy state than that that occurs for the undistorted lattice. The distortions produced by the motions indicated in Fig. 4 are of just this sort. They have a periodicity twice that of the lattice, inducing a spatially periodic lattice distortion. This opens an additional possibility of a time-periodic Peierls instability at the frequency of these vibration modes.

5. MULTIPLE DEUTERON NUCLEAR REACTIONS WITH NO UNACCOUNTED BY-PRODUCTS ARE A POSSIBILITY

Typical experiments in nuclear physics involve a high energy projectile (perhaps a deuteron) directed onto a stationary target (possibly also a deuteron). Also by pointing two high energy beams at one another, particles may be made to interact. In either scenario, the interaction between more than two particles is improbable. The probability of having more than two in the same small volume at the same instant is just too small (unless of course they are already in a common nucleus). In a metallic, crystalline environment the situation is different. Many-body interactions are common and varied.

What is missing in the many-body environment is the high energy provided by particle accelerators, but to compensate for this, electrons are present and they may participate in a role similar to that of a catalyst (by screening positive charge). No such catalyst is present in the normal nuclear physics experiment. These are reasons that it is safe to say that when multiple free deuterons are brought together in the presence of electrons, the detailed physics involved is not completely understood. There is room for new physics but physics that is still based on familiar concepts.

The following discussion of fusion products, being expected but not observed, is based on a fundamental supposition. The reason that proton, neutron, and gamma ray by-products are

expected in D-D reactions is that when energy is released and converted to kinetic energy there must be something for the helium isotope to react against in order to conserve momentum. There is no feasible physical mechanism for it to react directly against the lattice mass itself, often cited as a difficulty for a description of low temperature fusion. But when four deuterons are brought together, whether all of them are involved in the final reaction product or not, there are many alternative methods of sharing energy and conserving momentum. The reaction is expected to involve production of a range of lower energy gammas. The reactions that produce higher atomic masses are improbable compared to those producing one or two helium nuclei. A helium nucleus (alpha particle) is one of the most stable (magic number) nuclei in existence. In the event two helium nuclei are produced they may conserve momentum by reacting one against the other, rather than ejecting smaller sized particles. In the event a single helium nucleus is produced it may react against and share energy with the remaining deuterons.

This is an appropriate juncture to address an important point made by Leggett and Baym [2] to the effect that as two deuterons approach one another the local electron configuration should approach that of a helium atom. This concept is also found in Baym [26]. They argue that helium doesn't have a binding affinity to the metal and as a consequence the deuterons are energetically less likely to converge. If the convergence is that of four deuterons then the same argument says that the electron configuration approaches that of a beryllium atom instead, for which a binding affinity to the host metal is probably more likely.

In this report the possibility of an explanation for the lack of fusion by-products, insofar as multiple deuterons are involved, is similar to that in Takahashi's EQPET theory [23]. In this paper the source of screening would be the heavy-electron character of the materials involved, along with a non-linear enhancement of the screening effect in a layered structure of deuterons distributed in parallel planes. Enhancement would be due to heavy-electron interaction with very short wavelength phonons that are on or near the edge of the planar Brillouin zone. The planes are formed from deuterons on tetrahedral and octahedral sites. Similarly, thicker planes are formed by deuterons on octahedral sites.

It should also be emphasized that although four deuterons may be involved not all of them need to be changed in the nuclear reaction. The dominant expected output is a helium nucleus, and for this the need for other deuterons nearby for momentum conservation may itself be viewed as a type of catalytic phenomenon.

Alpha particles are well known to be easily absorbed in air and much more so in water. A 1 Mev alpha particle is absorbed in less than one centimeter of air. A good explanation why nuclear products haven't been found in abundance in earlier experiments might be that they were absorbed in the electrolysis medium prior to detection. The expectations were for neutrons, protons and gammas. The lack of neutrons or protons observed could actually be a strong confirmation of the arguments herein in the sense that it implies that if any nuclear process occurs it must necessarily involve the production of alphas since others have been eliminated. When alpha particles are absorbed they become helium atoms. If helium atoms are produced where they didn't exist before, there has to have been a nuclear reaction of some sort.

Miles, Bush, Ostrom and Lagowski [26] performed an electrolysis experiment in which the amount of helium produced was measured along with the amount of excess heat. They were able to closely correlate the helium and heat production under the assumption that deuterons fused to form alpha particles with the well known amounts of energy release. This is a strong confirmation of alpha particle production in a multiple deuteron process.

6. LACK OF EXPERIMENTAL REPRODUCIBILITY AND POSSIBLE REMEDIES

The fusion mechanism proposed in this paper would be difficult to initiate. In establishing motivation for the fusion mechanism, various analogies have been drawn between crystal planes of deuterons in the transition metal hydrides and the copper-oxide planes in high temperature superconductors. The transition metal hydrides have a much greater symmetry than the copper-oxides in that there are three or more sets of parallel planes of deuterons in their lattices. There is a need to break this greater symmetry if the desired vibration mode is to be established. Interactions in layered sets of a single one of these planes are what are desirable.

The difficulty in establishing these conditions may well be a source of the difficulty in reproducing these effects. Factors expected to influence the establishment of proper symmetry conditions are crystal shape, orientation, and electrical and thermal fluxes. A promising method for reducing the symmetry is the application of an intense magnetic field perpendicular to one of the planes. As an example, the de Hass-van Alphen effect couples with the electron charge distribution at the requisite length scale, and this in turn couples to the interaction of the electrons and the lattice**.** This effect offers an opportunity to initiate the low temperature fusion process. The remedy for lack of reproducibility is a proper understanding of the physics and the development of any method for setting the two-dimensional process in motion. More details are spelled out in a provisional patent based on this paper.

7. DISCUSSION

This report has not attempted to calculate possible fusion rates. Such calculations are available. The most quoted calculations are those presented in Koonin and Nauenberg [3], where they state "A mass enhancement of $m^* \approx 5m_e$ would be required to bring the cold fusion rates into the range claimed by ref. 7……An enhancement of $m^* \approx 10m_e$ is required by the results of ref.6". References 6 and 7 are to the papers by Fleischmann, Pons, and Hawkins [5], and Jones, et al. [4] respectively. The symbol m^* used here is not the same as the symbol used elsewhere in this report. Here it denotes the mass of a putative electron that is 5 or 10 times the physical electron's mass (similar to the way the muon weighs 207 times as much as the physical electron).

The fact, as quoted by Kittel [7], that palladium has a high effective-mass, $27m_e$ platinum has an effective mass $m^* \approx 13m_e$, nickel, $28m_e$, and many of the transition metals are members of this class may be more than a coincidence.

It is being argued that, while heavy electrons are long range phenomena, their effect is periodic and a significant localization effect may occur within a unit-cell. In this sense a process may have a periodic local effect even if it is itself a long range phenomenon. This is true if the pseudo-particle is long lived, and has sufficient bandwidth in wave-number space substantially near a Brillouin boundary. All that is required is this large spatial bandwidth, e.g. the width of the wave number spectrum around a pseudo-particle peak. That charge concentrations actually occur in heavy electron materials has been demonstrated in many experiments recently by direct observation [8, 9]. These recent measurements are, in particular, indicative of pseudo-particles (resonances) near approximately one-half of the way to the zone boundary.

There have been authors who advocate effective-mass as a contributor two low temperature fusion. Parmenter and Lamb [29] made calculations based on an electron screening approach using a modified Thomas, Fermi, Mott (TFM) equation. Their effective-mass varied with wavenumber, but in a way opposite to that described above. T. Tajima, et al. [30], have found a very large screening effect in their candidate process. An interesting result with regard to screening is that of Hora, et al.[31], who note that the fusion rate changes by five orders of magnitude if the screening factor changes by only a few percent. They also note that D-D and D-T fusion reactions are “rather exceptional as the cross sections are up to several barns and the nuclei react at distances 50 or more times the nuclear diameters.” The implication for multiple deuteron interactions of an expanded strong nuclear range is apparent, especially if the deuterons are well screened.

A notable lack in this report has been any specification of electron configurations expected near the confluence of deuterons on a common site. An investigation of electronic states that are compatible with the 4d and 5d atomic electron configurations and that are most effective for bonding and screening is planned. The complexity involved in the hydrides is expected to be as large if not larger than for the copper-oxides. It is possible that when the transition metal hydride is doped or otherwise has an excess of electrons, more than one for each metal and deuteron site, bonding of the types described by Sachdev [32] based on Anderson’s resonating valence bond idea [33] occurs between the deuterons.

8. CONCLUSIONS

In summary, two major reasons that have been used for rejecting the possibility of low temperature fusions have been addressed in this report. A significant counter-possibility has been produced for each of them. It has been postulated that low temperature fusion may not be barred by any basic principles of physics as has been suggested. Based on this paper, if LENR is barred at all, it is likely due to inadequate strength of the heavy-fermion screening effect that has been discussed here.

APPENDIX: EFFECTIVE-MASS AND THE WIGNER LATTICE

The term ‘effective-mass’ is somewhat ambiguous. It has been used since the quantum theory of metals was first described. If one uses the term effective to mean that effective-mass acts as the mass of an electron different from that of the natural electron, then it appears that one

should include what has recently been described as heavy electrons or heavy fermions in the terminology. In this appendix effective-mass refers to the effect of a heavier mass whatever its cause. The historical effective-mass appears to be a correlated motion effect of a single electron moving in a periodic field, whereas the appearance of heavier electronic effective-mass may be due to correlations with other electrons and the lattice.

One example of electron-electron interactions is found in a Wigner lattice, which is discussed next. This is significant since it has been observed that effective-mass in systems conforming to two-dimensional Wigner lattices can range above 150 electron masses [34].

A description of a Wigner crystal may be found in Philips [35]. As the Wigner-Seitz radius r_s is expanded above one atomic unit an electron gas tends to form an ordered array A Wigner lattice (or crystal) is the name given to a pseudo-equilibrium state involving electrons or holes in which the electrons or holes find that their lowest energy state in a body-centered-cubic (or similar) configuration where the renormalized forces are balanced against each other. Such a state may be stable when situated against a positive lattice background. The configuration is commonly employed in explanations of the Mott transition. It is a good indicator of the tension existing between the delocalized band states and the localized atomic states, in a model such as the Anderson or Hubbard models. The Wigner crystal has been implicated in recent charge-order investigations [34]. In the description below it is used to illustrate the fact that the vibrations induced in the Wigner array of confined electrons produce their greatest charge concentrations on the spatial scale that is conducive to the screening effect described in the main body of this report.

In the model, as a charge moves away from its stable position it influences charges nearby and thus produces a correlation. The precise form of the screened potential between two electrons or holes embedded in a Wigner crystal in metal lattice is not known. Here, with negligible loss of generality, it is assumed to have the Coulomb form. Only nearest neighbor interactions on a cubic lattice will be considered for simplicity. The Hamiltonian operator may be expressed in the form

$$\sum_n \left[-\frac{\hbar^2}{2m}\nabla_n^2 + V(r_n) + \frac{\frac{1}{2}e^2}{4\pi\varepsilon_0}\sum_{[n]}\frac{1}{\left|r_n - r_{[n]}\right|} \right] \tag{A.1}$$

$$\cong \sum_n \left[-\frac{\hbar^2}{2m}\nabla_n^2 + V(r_n - R_n) - \frac{1}{2}K\sum_{[n]}\left|r_n - r_{[n]}\right|^2 \right]$$

where the first sum is over electrons that are each assigned to positively charged lattice locations, r_n, $n = 1,...,N$, and the second sum is over the nearest neighbors to this location. $V(r_n - R_n)$ is the positive potential about the nth lattice site. The summation over [n] is the summation over the nearest neighbors that are interacting with the n^{th} electron. The factor of $\frac{1}{2}$ is to prevent potentials from being counted twice. Otherwise the notation is standard. The total wave function is a sum over permutations of the solutions of the joint Schroedinger equation

with odd permutations weighted by -1. No more than one electron is in any spin-orbit state, thus satisfying the exclusion principle.

In the second expression for the Hamiltonian the inter-electron Coulomb potentials have been expanded about the electron equilibrium positions $|r_n - r_{n-1}| = a$ where a is the nearest neighbor distance in the cubic lattice. The last term in the Hamiltonian has combined the inter-electron coupling into an effective constant $K/2$. The actual coupling constant in a real crystal is the result of a complex renormalization process involving electron screening. The inter-electron interaction will be treated as dominating the electronic correlation. The result is that for small deviations from equilibrium the appropriate Hamiltonian is given by

$$H = H_0 + H_1, \tag{A.2}$$

where $H_1 = \sum_n V(r_n - R_n)$ is treated as a perturbation.

This form of the equation would result from any inter-electron coupling as long as the first term in the potential's expansion in the displacement from equilibrium is quadratic. R_n is the location to which the nth electron is attracted. In this case, H_0 is the Hamiltonian of a lattice of electrons with harmonic nearest neighbor interactions. What is significant here is that this result tells us that, for the simple case of a one-dimensional lattice, the dispersion relation induced in the oscillators has the form

$$\omega_l = (K/m)^{1/2} \sin(k_l a/2) = (K \sin^2(k_l a/2)/m)^{1/2}. \tag{A.3}$$

It is important to note that this form implies that the largest effective electronic coupling constant occurs where $k_l = \pi/a$, e.g., on the Brillouin zone boundary. In two dimensions the loci for the largest coupling parameters are the wave number domain lines $\pm k_{l,x} \pm k_{l,y} = \pi/a$. If the electrons are acting with an increased mass, the effective mass may be substituted in this expression, and it will act to decrease the energy in each mode. The increase in effective inter-electron coupling in this simple model occurs at locations where it is beneficial for the low temperature fusion mechanism discussed in the main body. It is also at these wave numbers that the deuterons are most strongly interacting and it is to be expected that the screening by the electrons will act in concert. The electrons act to screen the deuterons and vice versa. As mentioned above, it has been observed that effective-mass in systems conforming to two-dimensional Wigner lattices can range above 150 electron masses [34].

Locking of the Wigner lattice on atomic lattice sites for this model is provided by the perturbing term in the full Hamiltonian. As the Wigner lattice vibrates, its individual components are induced to remain near the lattice sites. But because the positive potentials at the sites are finite, and in the case where there are excess electrons or holes, motion between sites will occur. At greater energies the electron states merge into the band states and a Hubbard-like model ensues. Quantum mechanically this is described in terms of transition probabilities or, equivalently, by means of a hopping effect. It may also be described as hybridization between band states and atomic states.

ACKNOWLEDGMENT

The author is grateful to Dr. D.R. Word, Dr. P.S. Lowell, Dr. F. Meserole and Prof. J.J. Lagowski, University of Texas, Austin, for helpful comments, suggestions and help in initiating experiments. He is grateful to Dr. Edmund Storms for comments, experimental advice and hospitality. He appreciates Dr. H.R. Byerly's reading of the manuscript and providing useful advice. He appreciates stimulating correspondence with Prof. A. Takahashi whose EPQET theory appears similar and complementary in many aspects.

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