OPPOSITION AND SUPPORT FOR COLD FUSION

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ABSTRACT

Situations analogous to the present situation in Cold Fusion (CF) have previously occurred in science. Conventional theory appears so diametrically opposed to the possibility of CF that little room is left for commonality in the theoretical realm. Bifurcation persists because there is still only a sparse experimental meeting ground between the two camps. Experiment should and will be the final arbiter. Nevertheless, a theoretical existence proof i.e. a proof of principle would go far in putting to rest reservations and doubts regarding the reality of CF. Our goal is to see if reasonable answers to the opposition can be given in support of CF.

I. THE CHALLENGE

John Huizenga[1] challenged Cold Fusion (CF) with his three Miracles. In doing so he has made a good, honest, and strong case against CF. Let us explore whether his negative points can be objectively answered with an equally strong case in support of CF. Is there an historical precedent for such a demarcation from the conventional view? What is the basis for the conventional view? What alternative paradigms or models are there? First let's look at his objections.

A. Fusion Rate Miracle

The conventionally expected fusion rate at T = 300K is $< 3 \times 10^{-64}$ fusions/sec-dd for r = 0.74 Å as in D_2. Huizenga[1] allows only for r ≥ 1.7 Å in Pd with a considerably smaller fusion rate than in D_2. Sun & Tomanek[2] show that r = 0.94 Å is possible. To account for calorimetiric power levels, $\sim 10^{-22}$ fusions/sec-dd are needed. For r = 0.74 Å, this is 10^{55} higher than expected! To account for the Jones[3] rate, $\sim 10^{-22}$ fusions/sec-dd are needed. This is 10^{42} higher than expected for r = 0.74 Å. So even the modest Jones level appears considerably too high.

B. Branching Ratio Miracle

The n & t channels occur about equally with a slightly higher frequency for the t branch. Conventionally t/n ~1. This nearly equal branching ratio is the result of the charge independence of the nuclear force. The $^4He + \gamma$ channel[4] has only a branching ratio $P \sim 10^{-7}$ because of the small ratio of the electromagnetic to the nuclear force. $d + d \rightarrow {}^4He + e^+ + e^-$ has only $P \sim 10^{-9}$.[4] So this reaction is not likely to account for the absense of high energy γ's in Cold Fusion (CF), and when the e^+ annihilates with a lattice e^-, two 0.5 Mev γ's are emitted. The Problem with CF is that t/n ~10^4 to 10^8 and no high energy γ's have ever been observed. Here are the fusion reactions in question.

$$d + d \rightarrow {}^3He(0.817\ MeV) + n(2.452\ MeV), \quad Q = 3.269\ MeV, \quad P \approx 0.5 \tag{1}$$

$$d + d \rightarrow p(3.025\ MeV) + t(1.008\ MeV), \quad Q = 4.033\ MeV, \quad P \approx 0.5 \tag{2}$$

$$d + d \rightarrow {}^4He(7.6\ keV) + \gamma(23.7\ MeV), \quad Q = 23.8\ MeV, \quad P \sim 10^{-7} \tag{3}$$

C. No Nuclear Products Miracle

Huizenga[1] argues that no nuclear products (ash) whatsoever have been validly observed in CF. He feels that the lack of high energy γ detection invalidates any presumed ^4He detection. The production of 1 MeV tritium from the $d + d \rightarrow p(3.025\ MeV) + t(1.008\ MeV)$ reaction implies that there must be a secondary reaction even if the t energy is somehow degraded by dE/dx or otherwise to the ~ 50 keV range.

$$d + t \rightarrow {}^4He(3.52\ MeV) + n\ (14.07\ MeV). \tag{4}$$

Unfortunately, these 14 MeV neutrons have never been detected.

II. HISTORICAL PRECEDENT

The scientific milieu of our time with Grand Unified Theories and Theories of Everything leads us to think that we have final answers to the mysteries of nature. This has not always been the case in the history of humankind, but neither is it a singular view.

A. Napoleonic and Victorian Theories

Perhaps the earliest period with similarly pretentious scientific views was in the early 1800's in France. The chief architect, of what Heilbron[5] calls the Napoleonic Model, was the Marquis de Laplace. The chief ingredients of this theory were fluids. They were the capital feature since every distinct force was supposed to have as its carrier at least one such fluid. There was a postive and negative fluid for electricity; austral and boreal fluids for magnetism. Caloric was the fluid for ordinary heat. Radiant heat was another fluid. The Napoleonic theorists deemed that they had tied together all of *astronomy and microphysics. They thought they* really understood their fluids; the very large; the very small; and their union. In fact they really didn't know what their fluids were, and in some cases as in the case of Caloric (ordinary heat) the fluid didn't even exist. This theory didn't long survive Napoleon.

In the late 1800's, in Great Britain, Lord Kelvin (Wm.Thompson) was the Chief Architect of what Heilbron[5] calls the Victorian Model. Its chief Ingredients were discrete particles in the ubiquitous, continuous ether. It had many notable successes such as Maxwell's equations and theory of gases, as well as some unheralded ones. For example, Joseph Larmor[6] [better known for his theory of charged particle precession] created a theory of ether knots. He had knotted rings of opposite helicity that he called negative & positive electrons. For him atoms were the rotation of symmetric rings of opposite electrons. His ideas date from the 1890's --before the discovery of the electron and long before the nuclear atom, and were not readily accepted at the time. Despite its many successes, the Victorian theory with its absolute space and time, together with mechanical analogs for the machinery of the ether, was felled by the Energists and Relativity.

Our grand and all encompassing theories today may fare no better than that of the Napoleonic and Victorian theories. These theories produced quantitative results; agreed to some degree with experiment; and enjoyed a wide consensus among scientists of the day. The Defenders of the Scientific Faith considered these theories to be fundamental, universal, and immutable. Though they had many good points, to a large extent both of these theories have long since been abandoned. One might think that these theories were ill-fated because they go back so far in time. Let us examine more recent theories to see such a fate for contemporary paradigms.

B.Superconductivity and High Temperature Superconductivity

Onnes discovery of superconductivity in 1911 falls into the realm of something that was totally unexpected by the laws of physics.[7] Not long before the 1957 BCS theory of superconductivity, Felix Bloch the founder of solid state theory jokingly said that the only theorem about superconductivity which can be proved is that any theory of superconductivity is refutable. By this he meant that superconductivity appears theoretically impossible because the energy of the current carrying state is higher than the ground state. The Meissner effect, the exclusion of a magnetic field *from the bulk of a superconductor*, was not discovered until 1933, some 22 years after the discovery of superconductivity. In that 22 year period the scientific community thought the field would be trapped as predicted by Maxwell's equations. It was then thought that the magnetic field could not be trapped, until Rabinowitz et al[8] demonstrated that it could be.

Although there were many spurious observations of high temperature superconductivity (HTSC) prior to its discovery in 1986, almost the entire scientific community thought that HTSC was impossible. For the last 37 years it has been thought by the scientific community that it is impossible to calculate transition temperatures without knowing the electron pairing interaction and its strength. Yet the transition temperatures for a wide range of superconductors has been accurately calculated[9,10] without knowledge of the pairing interaction and its strength.

C. Superfluidity

Although theory agrees reasonably well with the superfluid transition temperature T_c of 2.17 K for ^{4}He, it has done rather poorly for the T_c of ^{3}He.[11] By analogy with the BCS theory for superconductivity, in 1959-60 top theoreticians throughout the world predicted $T_c \sim 0.1$ K for ^{3}He. When the experimentalists couldn't find ^{3}He superfluidity down to ~ 0.01 K, the theoreticians sharpened up their calculations and predicted $T_c \sim 10^{-6}$ to 10^{-9} K. In 1972, the experimentalists[11]

Osheroff, Richardson, and Lee found $T_C = 2.6$ mK, which can be closely calculated by the Rabinowitz interaction-free approach used for HTSC.[10, 12]

D. Solar Neutrino Problem

The standard solar model helped to predict the abundance of the elements in the universe and in all types of stars including the sun. Although it worked extremely well and the scientific community was thoroughly satisfied with it, Davis ran an experiment that would help to verify predictions of the model in terms of the neutrino flux. After running an experiment from 1968 to 1986, the neutrino flux was found to be 2 to 3 times lower than predicted. This large inconsistency has continued even with recent experiments. We were drawn to the solar neutrino problem in the hope that insight into this hot fusion paradox might also help us understand CF. We think our findings help to solve this problem.[13-15] However, it has not led to insight into CF.

III. THEORETICAL ISSUES

A. Introduction

Theoretical demonstration of CF "permissibility in principle" would provide an important psychological factor for putting the reported phenomenon into a framework which might lead to its general acceptance. A trustworthy hypothesis would be invaluable if it could correlate observations, make predictions, and stimulate experiments. Theory needs to explain why the calorimetric excess energy is $\sim 10^5$ times higher than the fusion tritium energy which is $\sim 10^8$ times higher than the neutron energy. Experimentally it may be possible to distinguish between cold fusion and hot fusion on an atomic scale (which is the basis of some CF models) by temperature and kinematic broadening and shift-ing of the characteristic fusion product lines.[16] High loading claims (d/Pd > 0.7) must be considered with caution as in some cases this may simply be due to the filling of voids and cracks that are created as the host lattice is forced to expand.

Calculating tunneling probabilities for the Coulomb barrier between two d's, and their sensitivity to shielding can quickly make us aware of one basis for the conventional pessimistic view, followed by optimism with respect to CF. In the context of α-emission, Gamow in 1928 first derived the tunneling (transmission) probability $G = e^{-2\Gamma}$ (Gamow factor) through the mutual Coulomb barrier of two particles of charges Z_1e and Z_2e, when the center of mass (CM) energy E is much less than the barrier height, in esu

$$\Gamma = \frac{1}{\hbar}\left(\pi Z_1 Z_2 e^2\right)\sqrt{\frac{\mu}{2E}} \tag{5}$$

where $\mu = m_1 m_2/(m_1 + m_2)$ is their reduced mass, and $\hbar$ is (1/2π)Planck's constant. For two d's taking E ~ (1/40) eV for illustration, $G \sim 10^{-2730}$; and in free space the classical distance of closest approach would be ~580 Å. G is extemely small yielding pessimism about CF, but also illustrating that electron shielding of the barrier cannot be neglected at low E.

There are many models for shielding (screening potential) in a solid which lead to roughly similar results. Rabinowitz[17-20] developed a model of a spherical shell of radius R of negative charge surrounding each d as the simplest conceptionally as well as computationally since it results in only a shifted Coulomb potential ,

$$V = e^2[(1/r) - (1/R)], \quad r_n \le r \le R, \tag{6}$$

where r_n is the nuclear well radius. $G' = e^{-2g}$, where

$$g = \frac{\pi e^2}{\hbar}\left[\frac{\mu R}{2(ER + e^2)}\right]^{1/2} \tag{7}$$

For E ~ (1/40) eV and R = 1Å, $G' \sim 10^{-114}$, picking up ~2616 orders of magnitude which illustrates one basis for optimism about CF. In the limit as $R \to \infty$, $g \to \Gamma$, yielding the unshielded case for $Z_1 = Z_2 = 1$ here, and in general. A model of a uniform cloud of electrons as well as use of the Maxwell-Boltzmann (MB) deuteron velocity distribution[21,22] would give a significantly higher tunneling and fusion rate but still not enough to account for CF.

B. Response to Foremost Theoretical Challenge

Leggett and Baym (L&B) presented the foremost theoretical challenge to CF by calculat-ing a maximum upper limit of $\lambda = 3 \times 10^{-47}$/(sec-dd) for the fusion rate in a lattice.[23,24] It is important to bear in mind that the Leggett and Baym argument is an equilibrium argument, and that CF is not necessarily an equilibrium process. Interestingly, R.H. Parmenter and the Nobel Laureate Willis E. Lamb (P&L) do not invoke non-equilibrium in responding to L&B. In their 1st paper[25] they calculate a fusion rate $\lambda = 2 \times 10^{-30}$/(sec-dd), exceeding the L&B limit by 10^{17}. They attribute this to the potential well of the trapping site in the lattice that holds the 2 d's. This was neglected by L & B. They get the L & B limit when the harmonic oscillator potential is disregarded, and only the screening at large distances is kept.

In the 2nd P&L paper,[26] the L&B limit is further circumvented by means of a larger effective mass for the conduction elections at wave numbers ≤ the inverse Debye screening length, though they agree that the free electron mass should be used at much larger wave numbers. Their analysis leads to the usual free electron mass for electrons that are close to the deuterons, but finds that at large distances the electrons behave as if they have a larger effective mass ~ 2.6 times the free mass. This increases the fusion rate another factor of 10^7 over the L&B limit for a total factor of 10^{24} allowing them to account for the Jones level of fusion.

The P&L results are controversial. The unfavorable milieu for supportive publications is indicated by their comment,[26] "The calculations reported here may be viewed by some as a vain attempt on the part of the authors 'to revive a dead horse,' in view of the recent outpouring of negative publicity concerning cold fusion and the sometimes vicious attacks on its proponents." For them, the low n levels "can be explained without invoking any physics more esoteric than that of screening of positive charges by conduction electrons."

IV. THEORETICAL MODELS

Analyzing CF theoretical models is like shooting at a moving target. Some of these models may already be abandoned as new models are created. Nevertheless shortcomings will be presented so that models do not resurface unchallenged. Space limitations only permit looking at a small number of models briefly. We will look at a much larger number of models in depth in a critical review.[27] The main problem in CF is overcoming the Coulomb barrier. We shall present at least one model in each category to show how this problem is dealt with.

A. Barrier Circumvention

1. Transmission Resonance (TR)

The presence of only one barrier leads to a very low transmission probability (coefficient) through it. However anti-intuitively, quantum mechanics allows high probability transit for the one-dimensional problem of particle passage through two (or a periodic sequence) of potential energy barriers for certain discrete values of energy (e.g. at which an odd number of quarter wavelengths fit into the well width). This quantum mechanical effect occurs as a result of destructive interference of waves reflected from multiple barriers as lucidly analyzed by Bohm,[28] and is called transmission resonance (TR). TR was suggested by Turner[29] for CF, though he apparently did not pursue it further. The idea was further developed by Bush.[30]

Critique: There is a basic defect in the TR model. Contrary to Turner, Bush, and Jandel,[31] we feel that Bohm's one-dimensional TR model is not applicable to d's in a lattice, as a given d must also get through the nuclear well of another d. Bohm's model applies to electrons, as they do not have a nuclear interaction. Following Bohm, Jandel has presented his objectons to Bush's TR model of CF, but not to the relevance of the model itself.

The TR model of CF has a number of inconsistencies beginning with its basic premise. Although the transmission coefficient can be high (but as we shall show not necessarily in the CF realm), fusion rates can still be extremely low. The build-up of the wave function between the barriers near resonance is a very slow process with time scales ~ the time for alpha decay . As Bohm points out, the process is similar to the building up of an intense standing wave in a resonant cavity --be it acoustic or electromagnetic.

The seriousness of the filling time problem can easily be seen quantitatively. For a system of two barriers, with each described by the potential V(x), the transmission probability (coefficient) as obtained from the WKB approximation is:

$$P' \approx [\ 1 + 4G^{-4} \sin^2\{(\pi - J)/2\}]^{-1}, \qquad (8)$$

where G = exp(-J) is the Gamow factor given in Sec. 3.1.

Let us consider two d's approaching each other through two barriers at room temperature, with E = kT = 1/40 eV. Taking into account screening of the Coulomb potential barriers, $G \sim 10^{-100}$ as shown in Sec. 3.1. If the system is far from the resonant energy E_{res}, $P' \sim G^4 \sim 10^{-400}$. This corresponds to a small fraction of ~ $(G^2)(G^2)$ of the incident d's tunneling through two barriers. At resonance $J = \pi$, and equation (8) gives a unity tunneling probability, i.e. P' =1 for any G. The resonance is related to the existence of a metastable state whose lifetime is $\Delta t \sim \hbar / \Delta E$, where the half-width $\Delta E = E - E_{res}$ for P' = 1/2. Bohm shows that the lifetime is

$$\Delta t = t_t G^{-2}\ , \qquad (9)$$

where t_t is the classical transit time to cross the well and return. For a well width of ~ 1Å = 10^{-8} cm, and a velocity ~ 2 x 10^5 cm/sec, $t_t \sim 10^{-13}$ sec.Thus at resonance, $\Delta t \sim 10^{-13}$ sec $(10^{200}) = 10^{187}$sec. The age of the universe is small in comparison, being only ~15 x 10^9 years = 4.7 x 10^{17} sec. Of course shorter times are possible as E gets further from resonance, but the combination of lifetime and tunneling probability does not appear capable of accounting for CF.

2. Lattice Induced Nuclear Chemistry (LINC)

The main theme of a series of papers by Chubb and Chubb[32,33] relates to the wave nature of boson particles in a solid. They feel that just as electrons are better described as waves in a solid, deuterons should not be described as particles when they are inside a solid lattice. The position of these authors is, "Overlap of the wave functions necessary to initiate the reaction is ensured by algebraic properties of a many-particle wave function, but not by tunneling which is the basis of conventional nuclear physics." The basic predictions of the LINC model are a high rate of fusion in a lattice, dominance of the production of ^{4}He, and heat release without observable fast nuclear products.

Critique: The authors' premise identifying overlap of the d wave function with fusion in a lattice is erroneous. This is because their wave function is derived from a Hamiltonian which neglects the d-d interaction, and does not minimize the full Hamiltonian of the d system. Their excess energy is due to a neglect of dd Coulomb repulsion, which if included gives a tremendously smaller fusion rate. Furthermore, the factor corresponding to the Astrophysical Function is neglected, i.e. the probability that nucleons will stay in the nuclear well after tunneling into it. Thus their model calculates a higher p-p fusion rate than d-d because this factor is neglected.

B. Barrier Reduction

1. Superradiance (SR)

Bressani et al,[34] and Preparata[35,36,37,38] propose that the key to understanding CF lies in superemissive dynamics -- superradiance (SR) -- in a solid. According to these authors, this means that the components of elementary atomic systems to some extent lose their individuality and become part of a kind of collective plasma. This plasma is a medium of charged particles vibrating about their equilibrium positions with plasma frequencies $\omega_p = e\sqrt{n'/m\varepsilon}$, where e and m are the charge and mass of the particles, n' is their number density, and ε is the permittivity of the medium. They have an instability in the quantum electrodynamic (QED) ground state (independent zero-point oscillations). Their minimal energy state is a superradiant one in which all the plasma particles oscillate in phase with the electromagnetic field that is excited coherently from the perturbative ground state of QED. They assert that SR provides a very strong effective screening of the Coulomb dd potential by the electron plasma in Pd.

SR was first presented by Dicke,[39] though his work is not referenced in any of these papers. It is rather strange that Preparata claims to credit Dicke in his lectures, but does not bother to do so in his published papers on cold fusion.[34-39] Neither is credit given to previous work for the shifted Coulomb potential which Preparata borrows freely. The shifted Coulomb potential was developed by Rabinowitz[17-20,40] to facilitate an accurate approximate calculation of shielding effects on tunneling which could be done with ease analytically without the need for laborious computer calculations. A screening model of a spherical shell of radius R of negative charge e surrounding each deuteron is the simplest conceptionally as well as computationally since it results in only a shifted Coulomb potential. In mks units this is

$$V = (e^2/4\pi\varepsilon)[(1/r) - (1/R)], \quad r_n \le r \le R, \tag{10}$$

where r_n is the nuclear well radius, and ε is the permittivity. This may be interpreted as the first order expansion of the exponentially shielded potential

$$V = (e^2/4\pi\varepsilon)\exp[-r/R]\,. \tag{11}$$

Preparata[37] in his eq. (15) writes

$$V(r) \cong \frac{\alpha}{r_o} - V_o \quad (V_o \cong 100\text{ eV}) \tag{12}$$

where he is at the classical turning point r_o, and for any other point r_o becomes r. In mks units, $V_o = (e^2/4\pi\varepsilon R)$, and $\alpha = (e^2/4\pi\varepsilon)$. With these substitutions, one can see that eqs. (10) and (12) are identical.

The use of superradiance (SR) may be considered a highly imaginative attempt at reformulating old established theoretical field concepts with possibly new twists. However, this work contradicts quantum mechanics in its overestimates of superscreening to achieve cold fusion (CF). Coherence is the key to understanding SR. If we have N particles radiating incoherently, then the total power radiated is the sum of the individual powers. For particles radiating coherently (in phase) in a small enough volume that the phase coherence is not lost from one end to another, then the total electric field E_t is the sum of the electric fields in each of the radiated waves. The total radiated power $\propto E_t^2$. For example, in simple terms, if the individual radiated power is P for each particle, then $P_{incoherent} = NP$, and $P_{coherent} \sim N^2P$.

Critique: Preparata[37] makes a number of numeric errors. His value of r_n= 20 fm is too large for the deuteron-deuteron (d-d) nuclear attraction radius. Blatt and Weisskopf, (*Theoretical Nuclear Physics* p. 506) list 1.1 fm as the d-d radius. Kaplan (*Nuclear Physics* p. 520) lists 2 fm as the d-d radius. Perhaps Preparata meant to use 2 fm rather than 20 fm. With r_n=2 fm, D_T = 3.12 x 10^{-43}, which is smaller than his value of 10^{-40} by a factor of 320. However, using his value of r_n=20 fm, yields a tunneling probability of D_T = 7.8 x 10^{-42}, significantly smaller than the value of 10^{-40} he gets from his eq. (16).

For the convenience of those who would like to check these numbers, Preparata's eq. (16) is

$$D_T^{1/2} \cong \exp\left\{-(2\mu\alpha r_o)^{1/2}\left[\frac{\pi}{2} - 2\left(\frac{r_n}{r_o}\right)^{1/2}\right]\right\}, \quad (13)$$

where Preparata has set $\hbar$ = 1. Squaring this equation and substituting for α,

$$D_T \cong \exp\frac{-2r_o}{\hbar}\left\{(2\mu V_o)^{1/2}\left[\frac{\pi}{2} - 2\left(\frac{r_n}{r_o}\right)^{1/2}\right]\right\}, \quad (14)$$

where in mks units V_0 = 100eV = 1.60 x 10^{-17} J, r_0 =1.44 x10^{-11} m, m =1.67x10^{-27} kg, and $\hbar$ = 1.05 x10^{-34} J-sec.

With r_n< 8 fm, D_T < 1.39 x 10^{-42}, which differs from his value of 10^{-40} by a factor of >72. Consequently, his claim of achieving the Jones level of CF is not supported. His disparity with experiment[37] increases considerably more than this factor of 10^2 since as we will show, this model has too much shielding. Thus at the top of his[37] p.88 rather than "an enhancement of some 30 orders of magnitude over the tunneling amplitude for molecular deuterium", the resulting number is many orders of magnitude less.

His eq.(26) is crucially important,[37] but appears overly simple which suggests either algebraic errors or equivalently inappropriate computational approximations. This can be fully judged if and when he presents a thorough derivation. It is not derived in detail in any of his papers. Its reliability is thus questionable. For the complex Feynman diagram (Fig. 5) it is not clear what approximations are made for the coupling constants and vertex functions.

In the course of their screening estimate,[37] an assertion is made that Z electrons orbiting in phase about a Pd nucleus look like a sphere of radius δ defined by the dispersion of the plasma oscillations

$$\delta = \left[\frac{\hbar}{2m_e\omega_p}\right]^{1/2} \approx \frac{6.7\text{x}10^{-9}}{Z^{1/4}}\text{cm}. \quad (15)$$

Due to electron oscillations, they assume a d may be covered by a cloud of Z electrons. According to these authors, the screening potential of these electrons takes the form

$$V_{screen} \equiv V_s \approx -\frac{Ze^2r^2}{2\delta^3} \text{ for } r \leq \delta. \quad (16)$$

$$\text{At } r = r_0 = \delta(2/Z)^{1/2}, \; V_s + V_d = 0 \quad (17)$$

since V_d= e^2/δ at r = δ. With this abnormally large amount of screening the tunneling probability P' = G^2 is exceedingly high especially for E_d ~ 0.

To understand this anomalous result, note that δ is close to the characteristic dimension of a Thomas-Fermi atom of atomic number Z,

$$R_{TF} = \frac{0.885\hbar^2}{me^2Z^{1/3}} = 4.5\text{x}10^{-9}\text{cm}/Z^{1/3}. \quad (18)$$

Consequently, the arrangement of Z electrons inside the region r ≤ r_0 ~ R_{TF} is possible only in the Coulomb potential Ze/r of a nucleus of charge Z, but not in the field of a singly charged d. One of the conceptual errors of this model is having Z electrons take part in steady state screening of the d's Coulomb field. Solids would collapse if such close equilibrium screening were possible.

Preparata[36] violates the laws of physics in trying to ensure a large enough time for the existence of a large charge density on the sides of a crack in terms of his superemissive (superradiance) model for the solid to avoid rapid charge leakage. This is an application of his SR conjecture to Fracto-acceleration, since he has the cracks filled with coherent radiation generated in the solid by plasma oscillations of the nuclei. This is due to an exaggerated overestimate of the amplitude of the plasma oscillations as a free parameter.[27] In addition, according to his scheme highly energetic electrons ~ 100 keV should be emitted from such a process. These electrons have never been detected.

2. Lattice Vibrations (LV)

Perhaps the most notable theoretical support for CF comes from the Nobel Laureate Julian

Schwinger[41,42,43] who contends d's encounter a relatively narrow Coulomb barrier allowing them to fuse into ^3He in a highly deuterated lattice. He cites Einstein (1907) as pointing out "that the initial phase of a novel investigation can be hindered by an excess of realism". According to Schwinger the effective potential of the d+d and also p+d interactions are modified due to averaging related to their zero-point oscillations in a solid lattice. In simpler words, the coupled harmonic motion of particles is supposed to lead to a reduction of the Coulomb barrier for fusion. When calculating this effect, one replaces the coordinate **r** in the Coulomb potential e/r by **r** + δ**r**, where the operator addition δ**r** corresponds to d oscillations and has a conventional expansion in terms of phonon degrees of freedom

$$\delta \mathbf{r} = \sum_q \sqrt{\hbar/2m_d\omega_q N}\,(\mathbf{a}_q e^{-i\omega_q t} + \mathbf{a}_q^{+} e^{i\omega_q t}) \,. \quad (19)$$

Here $\mathbf{a}_q$ is the boson operator for phonon production with q momentum; N is the number of d's, $\hbar\omega_q$ is the energy of the q th phonon. When averaged to first approximation in the ground state, the effective potential of interaction for a slowly moving proton with a phonon oscillated d is

$$\langle 0|V(\mathbf{r}+\delta\mathbf{r}|0\rangle \sim e^2/r \text{ for } r >> \Lambda, \text{ and } e^2/\Lambda \text{ for } r << \Lambda. \quad (20)$$

Where $\Lambda = \sqrt{\frac{\hbar}{2m_d}\left\langle\frac{1}{\omega_q}\right\rangle}$, and $\left\langle\frac{1}{\omega_q}\right\rangle$ is an average in terms of phonon modes. For $\langle 1/(\hbar\omega_q)\rangle \sim 1/(0.1\text{eV})$, we obtain $\Lambda \sim 10^{-9}$ cm. In the next approximation

$$\delta V \approx -[\nabla V(r)]^2 \sum_q \left[\frac{1}{2m_d N}\left\langle\frac{1}{\omega_q^2}\right\rangle\right] \quad (21)$$

Assuming $\left\langle\frac{1}{\omega_q^2}\right\rangle \approx \left\langle\frac{1}{\omega_q}\right\rangle^2$ and considering that $2\Lambda \sim 10^3\hbar^2/(m_d e^2)$, Schwinger finds that

$$\delta V = -\frac{e^2}{r}\left(\frac{10\,\Lambda}{r}\right)^3 . \quad (22)$$

This expression is valid for r >> Λ. For r > 10 Λ, eq. (22) gives a rather marked decrease of the Coulomb potential, e^2/r. Schwinger concludes from this that a substantial suppression of the Coulomb barrier may be possible at the expense of lattice vibrations (LV).

Critique: We have great respect for Schwinger, yet our analysis indicates that there is a limit to what the phonons can do, and that there is not a sufficiently strong effect from LV. To us, Schwinger's LV approach appears applicable only for δV <<V. Accordingly, this implies a small relative correction to the repulsive Coulomb potential rather than the large one he finds. As we showed in Section 2, modest decreases in the width of the Coulomb barrier can have enormous increases in the tunneling probability P' (the more so the lower P' is to begin with). However, the LV decrease in V goes further than seems warranted, and gives too large of an increase in P'. In going from the d+d reaction[41] to the p+d reaction,[42,43] the 23.8 MeV γ is avoided and only a 5.5 MeV γ has to be absorbed directly by the lattice. There are also two minor issues that may need resolution for the d+d case. 1) The competing decay channels d+d→ t+p and d+d → ^3He+n normally occur in times ~ 10^{-22}sec. The maximum frequency of the phonons ~ 10^{13}/sec implies a phonon emission time ~ 10^{-13}sec. It is not obvious *a'priori* that these decay channels will not depopulate the d+d scattering state faster than the phonon emission. 2) Schwinger[43] suggests that his model can produce t production rates ~ 10^3/sec -10^{10}/sec. It is not obvious that even with dE/dx energy degradation of ~ MeV t due to electron and ion interactions, that the reaction

$$d + t \rightarrow {}^4He(3.52\text{ MeV}) + n\ (14.07\text{ MeV}) \quad (23)$$

cannot take place in measurable quantities. Reaction (23) has not been observed in CF. This issue also applies to other models and experiments which have a large t production. Detailed cal-culatons by Szalewicz et al[44] and Petrillo et al[45] of the effects of d oscillations in a lattice agree with us. Crawford[46] is even more pessimistic, claiming that "properly treating deuteron motions would lead to smaller calculated p-d fusion than if phonons were neglected."

C. Barrier Ascent

1. Interface Acceleration (IA)

In 1989, Rabinowitz and Worledge[18,20] suggested the following interface acceleration (IA) model based upon an observation of dendrites on electrolytic cathodes.[47] Asperities (sharp micro-scopic whiskers) grow on electrolytic cathodes, as a way of relieving internal and external stresses in a variety of settings.[48] Field enhancement at the tip of the whisker ~height/(tip radius), together with the already present high double-layer electric field, can lead to very high local electric fields ~ 10^7 V/cm even though the macroscopic field is very low.[49] A high current density of electrons can be field emitted from a whisker and ionize some D's.

They pointed out[18,20] that if a small number of d's become entrained with the high current density of electrons, the d's would attain the same velocity v as the electrons -- just as a log in a river attains the velocity of the current in the river. The ratio of the energy of the d's to the energy of the electrons would be the same as their mass ratio

$$\frac{\frac{1}{2}m_d v^2}{\frac{1}{2}m_e v^2} = \frac{m_d}{m_e} = 3670. \qquad (24)$$

Even though the potential difference in a D_2O bubble is only a small fraction of the voltage applied to the cell, they pointed out possible non-equilibrium mechanisms for producing larger transient voltages. Thus for an electron energy ~ 10 eV, the d energy could be as high as 37 keV. Some consequences of the IA model for CF are discussed by Kim.[21,22]

In the context of CF experiments produced by gas discharges, IA may be a possible explanation. The experiments of Karabut, Kucherov and Savvatimova[50] do have an incubation period which could be related to whisker growth. Furthermore, low pressure gas discharges are unstable leading to arcing with high L dI/dt voltages. Entrainment of d ions could lead to microscopic hot fusion, and resulting neutrons could cause transmutation of elements. Predictions of the IA model are:

1) Fusion rates at the Jones level and higher.
2) Sporadic character and burst-like nature of the process as whiskers are damaged.
3) Incubation period related to the growth of whiskers.
4) Poor reproducibility of the data related to the irregular behavior of the whisker growth process, and of the occurrence of non-equilibrium discharge conditions.

Critique: Although whiskers can grow due to stress during temperature cycling and rapid phase transitons in Ti, there is no applied electric field in the cycling experiments. Perhaps electron acceleration with entrainment of the d's could be related to field enhancement by whiskers of fracture produced electric fields. The IA model applies more clearly to electrolytic and gas discharge experiments. The same serious criticism that applies to other acceleration models applies to IA that the branching ratio, and rates for the different reactions should be the same as for hot fusion, but appears not to be so.

4.4 Exotic Chemistry

A number of models assume the existence of an exotic chemical system whose occurrence either precedes nuclear synthesis or makes it quite unnecessary. Such systems are assumed to be engendered by electromagnetic or nuclear interactions. The similarity of these postulated models is in their tight binding of electrons in atoms and/or molecules.

Critique: None of these models appears correct. They do not avoid the nuclear ash problem as the tight orbits would lead to apprecialble fusion rates. A simple demonstration of proper spectral lines would constitute proof in all these models, but this has not been done. Detail- ed analysis on all these models can be found in refs.51 and 52. Let's look at some here.

Maly and Va'vra[53] solve the relativistic Dirac equation for the hydrogen atom and get an electron orbit of ~ 500 keV binding energy, and radius r ~ 5 fm. There is a serious error in their analysis. At the nuclear surface, $r = r_n \neq 0$, which implies both the regular and irregular solutions are simultaneously allowed for $r \geq r_n$. The general solution is a linear combination of both for $r \geq r_n$ making the irregular solution nearly negligible compared to the regular solution. They erroneously assumed that the general solution can be given by just the irregular solution, independent of the regular solution. Their electron orbit radius of ~ 5 fm is 50 times smaller than muonic orbits of 250 fm . If such tight D atoms existed, upon collison, they should produce fusion at a much higher rate than muon catalyzed fusion.

Barut,[54] Gryzinsky,[55] and Vigier[56] propose a Superbound H_2^+ or D_2^+ with ~ 50 keV binding energy, and r ~ 40 fm for H_2^+ with r ~ 20 fm for D_2^+. Their analysis is predicated on the electron being exactly between the 2 d's which implies that the system is unstable. The tightness of the orbit violates the Uncertainty Principle if the potential is only Coulombic. Their non-relativistic analysis is warranted for H isotopes. However, a non-stationary electron requires a relativistic treatment. Perhaps a full relativistic calculation including spin-spin and spin-orbit coupling may save this model; but this has not been presented as yet. Their electron orbits ~ 20 fm, are 13 times smaller than the 250 fm muonic orbits and upon collison would produce fusion at a much higher rate than muon catalyzed fusion.

V. CONCLUSION

In spite of considerable efforts, no theoretical formulation of CF has succeeded in quantitatively or even qualitatively describing the reported experimental results. Those models claiming to have solved this enigma appear far from having accomplished this goal. Not all of the models are testable. It is imperative that a theory be testable, if it is to be considered a physical theory. The mechanism for anomalous effects in deuterated metals is still unknown.

The issues raised by Huizenga[1] have not yet been fully answered. The most important miracle to answer is Miracle 3: Where are the Nuclear Products? The exotic chemistry solutions are appealing because they completely eliminate this miracle. However, we have not seen a convincing one yet. Miracles 1 and 2 also need to be answered. However, too many historical exceptions weaken Huizenga's attempt to discredit Cold Fusion by reliance on disagreement with conventional fusion theory. Nevertheless, it is important to understand why the tunneling coefficient is so exceptionally high, why the branching ratio is so far from unity, why the secondary reaction d + t is not occurring, and why high energy γ's have not been observed.

Reproducibility of CF claims by an independent qualified laboratory should be given the highest priority to firmly establish the credibility of CF. However, lack of reproducibility is not a just reason for branding CF a "pathological science." Many valid fields of scientific inquiry such as weather, catalysis, regular and ball lightning, earthquakes, and solar storms are not well understood and are far from reproducible. The example of the semiconductor field may be a source of optimism. In 1931, the great physicist Wolfgang Pauli[57] said, "I don't like this solid state physics...though I initiated it. ...One shouldn't work on semiconductors, that is a filthy mess; who knows whether they really exist." Not withstanding this pessimistic view, the semiconductor field became a great success once the important variables were understood and controlled.

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