COLD "FUSION": THE TRANSMISSION RESONANCE MODEL FITS DATA ON EXCESS HEAT, PREDICTS OPTIMAL TRIGGER POINTS, AND SUGGESTS NUCLEAR REACTION SCENARIOS

COLD FUSION

KEYWORDS: *cold fusion, transmission resonance model, transmission resonance-induced neutron transfer*

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The transmission resonance model (TRM) is combined with some electrochemistry of the cathode surface and found to provide a good fit to new data on excess heat. For the first time, a model for cold fusion not only fits calorimetric data but also predicts optimal trigger points. This suggests that the model is meaningful and that the excess heat phenomenon claimed by Fleischmann and Pons is genuine. A crucial role is suggested for the overpotential and, in particular, for the concentration overpotential, i.e., the hydrogen overvoltage. Self-similar geometry, or scale invariance, i.e., a fractal nature, is revealed by the relative excess power function. Heat bursts are predicted with a scale invariance in time, suggesting a possible link between the TRM and chaos theory. The model describes a near-surface phenomenon with an estimated excess power yield of ~ 1 *kW/cm*^{3} *Pd, as compared to 50 W/cm*^{3} *of reactor core for a good fission reactor. Transmission resonance-induced nuclear transmutation, a new type of nuclear reaction, is strongly suggested with two types emphasized: transmission resonance-induced neutron transfer reactions yielding essentially the same end result as Teller's hypothesized catalytic neutron transfer and a three-body reaction promoted by standing de Broglie waves. The cross section* σ *for the nuclear reaction that is the ultimate source of the excess heat is estimated to satisfy* 10^{-28} *cm*$^2 \lesssim \sigma \lesssim 10^{-18}$ *cm*^{2}*. Suggestions for the anomalous production of heat, particles, and radiation are given. A polarization conjecture leads to a derivation of a branching ratio of* 1.64×10^{-9} *for the deuterium-deuterium reaction in electrolytic cold fusion in favor of tritium over neutrons. The model may account for the Bockris curve, in which a lower level production of tritium mirrors that of excess heat. Heat production without tritium is also accounted for, as well as the possibility of tritium production without heat. Thus, the TRM has a high probability for unifying most, if not all, of the seemingly anomalous effects associated with cold fusion.*

I. INTRODUCTION

Three primary phenomena have been identified and commonly placed under the heading of cold fusion: (a) the low-level neutron emission phenomenon of Menlove et al.,[1] Scaramuzzi et al.,[2] and Mazzoni and Vittori,[3] that is observed when titanium metal shavings or titanium blades are pressurized with deuterium gas; (b) the production of amounts of tritium giving counting rates orders of magnitude above background first reported by Wolf et al.[4] and Bockris et al.,[5] and subsequently verified by Storms and Talcott[6]; and (c) the most exciting phenomenon because of its potential "millennial" portent for mankind, the so-called Fleischmann-Pons effect of measurable excess heat first reported by Fleischmann and Pons[7,8] and subsequently reported by Huggins et al.,[9] Appleby et al.,[10] Scott et al.,[11] and Hutchinson et al.[12] The research of Scott and the subsequent work of Huggins[13] are of particular significance because they were the first confirmations of the excess heat phenomenon involving closed-system microcalorimetry. The thesis of the transmission resonance model (TRM) is that this trinity of phenomena may be unified by the model through their possible association with the phenomenon of transmission resonance, which is a consequence of the wave nature of matter. Should it be shown that cluster-impact fusion[14] (a form of hot fusion in a metal deuteride) is also enhanced by transmission resonance as hypothesized by the author,[15,16] all four phenomena would be unified as examples of transmission resonance-enhanced nuclear reactions in a deuterated matrix (TREND).

The Fleischmann-Pons effect of the production of excess heat is the most interesting phenomenon from the standpoint of potential practical applications, but it also seems the least credible of the three phenomena from the standpoint of conventional physics. The principal part of this paper describes the application of the TRM to account for calorimetric data and to provide a framework for understanding the Fleischmann-Pons effect. Beyond this, the TRM suggests specific nuclear reactions and scenarios capable of explicating the anomalous production of heat, neutrons, tritium, other charged particles, and radiation. (The word "fusion" in the phrase "cold fusion" is used despite the fact that fusion has not been demonstrated to be the nuclear reaction responsible for the excess heat. In fact, it is quite likely that the nuclear reaction leading to excess heat is a new type of nuclear reaction.)

II. REVIEW OF THE TRM

II.A. Basis for the Model

The TRM posits that cold fusion is a phenomenon involving the wave properties of matter. It is assumed that a deuterated matrix (usually a metal deuteride lattice such as palladium in the β phase or titanium in the γ phase) offers a unique environment for diffusing particles such as deuterons. An excellent summary of studies on palladium hydrides and deuterides is that of Wicke and Brodowsky.[17] A treatment of this diffusion employing wave mechanics shows that when a transmission resonance condition is satisfied [when an odd integral multiple of the average quarter wavelengths of the de Broglie waves of the diffusons match the potential well widths of the particles situated in the palladium deuteride (PdD) lattice], essentially 100% transmissivity of these waves may be achieved. This high transmissivity implies that the diffusons can get near enough to the particles in the lattice forming the wells to have a chance of undergoing nuclear reactions. It is the latter that constitute the source of the excess heat.

The basis for the model is as follows:

1. a central assumption of a transmission resonance condition[18] based on a simplification of a recent conjecture by Turner[19-21]

2. Maxwell-Boltzmann (M-B) energy distribution for the diffusons (diffusing particles such as deuterons)

3. effects of phonon exchange between the particles forming the potential wells and the lattice

4. in-principle indistinguishability and boson nature of the deuterons

5. energy shift at or near the cathode surface, which may be equal to the activation overpotential and/or the concentration potential (hydrogen overvoltage).

Turner[19-21] recently conjectured that cold fusion may result when deuterons diffuse through a periodic array of wells formed by the ascending walls of neighboring Coulomb barriers of deuterons occupying interstitial sites within the palladium lattice. Turner points out that conventional quantum mechanics yields a transmission coefficient of unity whenever the resonance condition of

$$\int_0^L k(x)\,dx = \left(n + \frac{1}{2}\right)\pi \tag{1}$$

is satisfied by the wave number of the particle crossing the potential well between the two barriers. The value $k(x)$ is the wave number of a diffuson and L is the well width. Bohm[22] provides an excellent treatment leading to Eq. (1) and indicates when the factor of $n + \frac{1}{2}$ on the right side should be replaced by $n + 1$. If λ is now taken to be the average de Broglie wavelength of a diffuson within the potential well of width L, it is easily seen that Eq. (1) simplifies to the transmission condition[18]

$$(2n + 1)\lambda/4 = L \ , \quad n = 0,1,2,\ldots \ . \tag{2}$$

II.B. Physical Meaning of the Transmission Condition

The transmission condition of Eq. (2) implies that transmission occurs through a barrier-well-barrier (B-W-B) combination whenever an odd quarter number of de Broglie wavelengths of the diffuson fit into the well width L. Consider a de Broglie wave to be incident from left to right upon the B-W-B combination of Fig. 1. The physical meaning of the high transmissivity

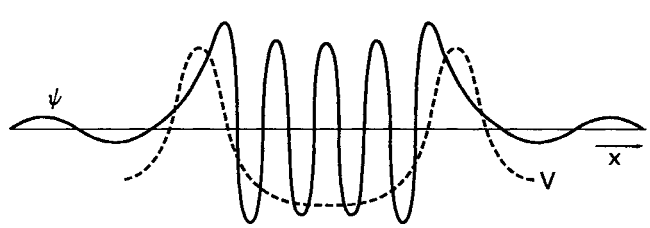

Fig. 1. De Broglie wave incident from left to right on an isolated B-W-B system.

through the combination is that the part of the wave reflected from the front barrier is interfering almost totally destructively with that part of the wave reflected from the rear barrier to yield essentially no reflected wave for the combination. With regard to this situation, Bohm notes[22]: "It is especially interesting that although a single high and thick barrier has a very small transmissivity, two such barriers in a row can be completely transparent for certain wavelengths. This behavior can be understood only in terms of the wavelike aspects of matter. The high transmissivity arises because, for certain wavelengths the reflected waves from inside interfere destructively with those from the outside so that only a transmitted wave remains." The resonance condition also leads to a relatively high wave amplitude inside the well, and Bohm[22] demonstrates that the energy levels associated with Eq. (2) correspond to *metastable states.*

This resonant transmission is assumed to result in a diffuson (e.g., a deuteron) that comes near enough to a particle in the lattice or an interstitial site (e.g., an interstitial deuteron) to give the two particles a large probability of undergoing nuclear fusion compared to the case when the condition of Eq. (2) is not satisfied. Thus, in this model, it is this resonant transmission phenomenon that is invoked to explain a central mystery of cold fusion: How is it possible to give two charged particles, such as two deuterons, a large enough probability of undergoing a nuclear reaction in a metal lattice at room temperature to provide credibility for the purported effects, e.g., the amount of excess heat claimed? (Note that McNally[23] employed the concept of the de Broglie wavelength interaction of very low energy nuclei in 1985.)

An example of such a wave-mechanical phenomenon leading to a startling result accounted for by a high transmissivity associated with a quantum resonance condition is afforded by the Ramsauer effect: Electrons incident upon a noble gas, such as argon, are found not be be scattered if their de Broglie wavelengths satisfy the Eq. (1) condition with the factor $n + \frac{1}{2}$ on the right side replaced by $n + 1$. (See Chap. 12 of Ref. 22 to understand why the wave relation expressing resonance in that case involves a factor of $n + 1$.)

II.C. An Optical Analog for Transmission Resonance

Consider the following optical analog for the transmission resonance phenomenon. Figure 2 shows two 45-deg prisms with an optically flat piece of glass of uniform thickness between them and separated from the prisms by two air gaps, not necessarily of the same width. In this analog, the piece of glass plays the role of the potential well, while the two air gaps play the part of the potential barriers, and the photons in the laser beam are analogs of the diffusons. Recall that if the angle of incidence θ is equal to the critical angle or

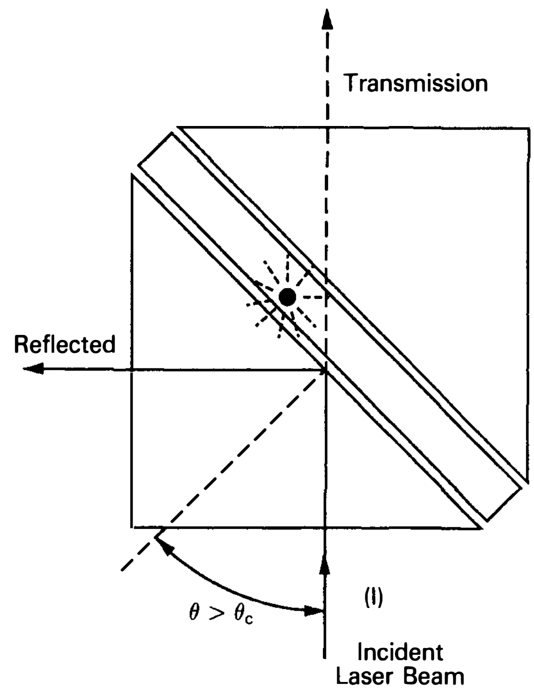

Fig. 2. Experimental setup to demonstrate the optical analog for the transmission resonance phenomenon for an isolated B-W-B system. The air gaps are the analogs of the barriers, while the microscope slide in the center plays the role of the well.

greater, all the incident light is reflected. On the other hand, if the air gaps are on the order of the wavelength of the light, and if, in addition, the wavelength λ satisfies the transmission resonance condition in Eq. (2), i.e., that an odd integral number of wavelengths fits into the plate width, transmission occurs with the reflected intensity becoming small. A variation of this is suggested by Bohm.[22] Let white light in a beam distributed across the face of the first prism replace the laser light. Only those colors satisfying the condition in Eq. (2) for resonant transmission will be transmitted and the transmission will be colored. If, in addition, a flaw is introduced into the interior of the glass plate, the flaw will glow strongly in the colored light, demonstrating the strong buildup of light intensity within the glass plate characteristic of a metastable state.

Another optical analog is afforded by the nonreflective coatings on optical instruments that are designed to minimize reflected light in the visible range. Consequently, such optical instruments have a purple hue indicative of the fact that some light is still being reflected at the long wavelength end of the visible range (red) and some at the short wavelength end (blue). As shown later, the transmission condition in Eq. (2) also has a counterpart in a special case of the Bragg formula for the diffraction of X rays by a crystal.

II.D. A Difficulty (Long Metastable State Lifetimes) and a Way Around That Difficulty

These states are shown (see Ref. 22) to be metastable states; i.e., they are relatively long-lived. The physical picture is one in which de Broglie waves are incident upon the B-W-B system from the left as in Fig. 1. For waves satisfying the transmission resonance condition, that part of the wave reflecting from the front of the first barrier is, to a large extent, canceled out by that part of the wave reflected from the left side of the second barrier. Thus, the wave amplitude builds up in the well. The transmitted part is the tunneling leakage to the right resulting from the huge well amplitude.

If the actual system of physical interest were an isolated B-W-B system, there would be a serious difficulty for this model. For, as Worledge[24] of the Electric Power Research Institute (EPRI) has recently apprised the author, the lifetimes of the metastable states are many, many orders of magnitude too large to have any hope of practical application. Worledge[24] has asked whether the fact that we actually have a chain of B-W-B systems might make a difference here, and the answer is unqualifiedly yes. To see why, it is first necessary to realize that part of the battle has already been won even for an isolated B-W-B system if the transmission resonance condition is realized. Thus, if Eq. (2) is satisfied, there is, with reference to Fig. 1, no net reflected quantum-mechanical flux to the left of the first barrier by virtue of the complete destructive interference in this region between that part of the incident wave reflected from this first barrier and that part reflected from the second barrier. That is, a deuteron has no trouble getting into the well (assuming, of course, that the well has not been changed by the presence of another deuteron already there). It just cannot exit the other side in any reasonable length of time to be of use for a model employing only isolated B-W-B systems. Note, however, that because it has entered the well it has already passed the interstitial deuteron associated with the first barrier, and, therefore, had a chance at a nuclear interaction. However, our real system of physical interest is not the isolated B-W-B system of Fig. 1, but rather the B-W-B-W-B-W-... B-W-B system suggested by Fig. 3. Thus, we now see a solution to our difficulty: Once the deuteron has entered the first well, it can go past the second barrier in the same way by satisfying the transmission resonance condition of Eq. (2) and then through the third, etc. At each barrier through which it is transmitted, it would come close enough to the interstitial deuteron associated with that barrier to undergo a nuclear reaction with it. The only hangup would again occur at the last barrier in the chain. For the same reason the deuteron was unable to get through the second barrier in the B-W-B system in a reasonable time, it would also not be able to get through this last barrier in the chain in any reasonable length of time. As Eagleton[25] points out, however, it could then reflect from that barrier and pass backward along the chain. Thus, the conundrums posed by the author's previously miscalculated lifetimes for the metastable states[15,16] need trouble us no more. It is the periodic chain, rather than the B-W-B system, that is the real physical system of interest in the TRM.

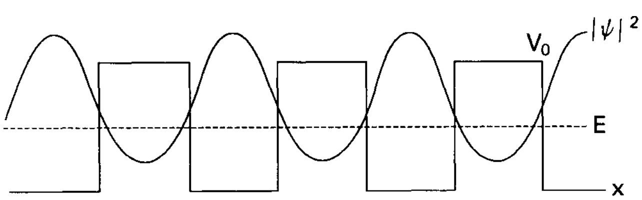

Fig. 3. This B-W-B-W...B system is the actual system of physical interest rather than the single B-W-B system of Fig. 1.

In the case of periodicity such as that associated with the B-W-B-W...-B chain in a crystal, we might expect transmission energy bands for the transmitted diffusons as opposed to the transmission energy lines presented here. It may be that the present transmission energy lines in the TRM are the band edges for transmission resonance bands. We must mention the theoretical work of Chubb and Chubb,[26] who have a transmission band model for deuterons. [Recommended textbooks for the treatment of wave mechanics within a crystalline lattice (periodic potential) are found in Refs. 27, 28, and 29.]

The harshest critics of cold fusion have claimed that cold fusion is done with mirrors. Ironically, if the transmission resonance phenomenon is valid for cold fusion, it is, indeed, achieved with mirrors—lots and lots of them! These are the mirrors of the B-W-B systems reflecting the de Broglie waves to produce a high transmissivity.

II.E. Transmission Resonance Energy Levels

The energies E_n associated with the resonant transmission levels specified by Eq. (2) are readily found by combining the Eq. (2) relation with the kinetic energy relation $E_n = p_n^2/2m$ and the definition of the de Broglie wavelength $\lambda_n = h/p_n$ to form

$$E_n = (2n + 1)^2 h^2/32mL^2 , \qquad (3)$$

with h as Planck's constant and m as the mass of the diffuson. It will be convenient to label these energy levels by the quantities T_n, which have the units of temperature, but are not temperatures, defined by

$$E_n = kT_n , \qquad (4)$$

so that Eqs. (3) and (4) yield

$$T_n = (2n + 1)^2 h^2/32mkL^2 . \qquad (5)$$

Warning! In what follows it is important to realize that ambient temperature will be indicated by T. While the T_n's have the units of temperature, they do not physically have the meaning of temperature. (However, it may be possible to show from the model an important physical significance for the condition in which the ambient temperature bears a simple relation to one of the T_n's. In Ref. 18, neutron bursts in the TRM are associated theoretically with the condition for which the ambient T is such that the peak of the Maxwellian velocity distribution is equal to T_n; i.e., $T = T_n$.)

II.F. Fit of the Model to Data: Level Schemes

In the neutron emission experiments of Menlove et al.[1] involving pressurized D_2 gas and titanium shavings, the temperature of −30°C (243 K) was a signally recurring temperature associated with neutron emission in bursts. It was hypothesized[18] and justified within the context of this model that this temperature corresponds to one of the transmission levels in a sequence of levels specified by Eq. (5) for the case of deuterons diffusing within a titanium deuteride lattice. Substitution of $T_n = 243$ K into Eq. (5) for an as yet unknown integer order n leads to the following generating formula for the possible compatible well widths L_n:

$$L_n = (2n + 1)(0.349 \text{ Å}) \quad . \tag{6a}$$

Corresponding to the respective integers 0, 1, 2, 3, and 4, this relation generates the well widths 0.349, 1.047, 1.75, 2.44, and 3.14 Å. Based on the independent crystalline data of Sidhu et al.[30] for the γ phase of titanium deuteride, a separation of interstitial deuterons is known to be 1.047 Å, in excellent agreement with the generated value of L above corresponding to the order $n = 1$. The value $L = 1.047$ Å is then reinserted into Eq. (5), with the mass m as that of the deuteron as diffuson, to yield the following level scheme for the case of a titanium deuteride lattice with deuterons as the diffusons

$$T_n = (2n + 1)^2(27 \text{ K}) \quad . \tag{6b}$$

This is illustrated in Fig. 4, showing only the first two transmission levels at $T_0 = 27$ K and $T_1 = 243$ K (i.e., −30°C). Higher energy transmission levels are specified by $T_2 = 675$ K (402°C) and $T_3 = 1323$ K (1050°C). It was previously noted[18] that this level scheme is also compatible with the experimental results of Mazzoni and Vittori[3] involving neutron emission in the case of titanium blades pressurized with D_2 gas at high temperatures. This model-fitting procedure was then repeated for the case of electrolytic cold fusion, taking room temperature, i.e., 293.2 K, to be one level in a level scheme for the case of PdD as the lattice and the following respective diffusons: deuterons, ^{6}Li lithons, and ^{7}Li lithons. These other three-level schemes are also illustrated in Fig. 4. For a PdD lattice with deuterons as diffusons, the counterparts of Eqs. (6a) and (6b) are, respectively,

$$L_n = (2n + 1)(0.318 \text{ A}) \tag{7a}$$

and

$$T_n = (2n + 1)^2(3.62 \text{ K}) \quad . \tag{7b}$$

Note that Turner[19–21] also employed room temperature as a significant temperature for the electrolytic case. The dashed lines on either side of the solid levels in Fig. 4 suggest the representative thermal widths to scale for the levels. [The relation for thermal width ΔT_n is given in Eq. (18).] All four cases, along with a comparison of the selected generated well width with the well width obtained from independent crystalline data, are summarized in Table I. Note the excellent agreement of the four comparisons. Finally, it should be indicated that, unlike those pressurized gas neutron emission cases in which there in no applied voltage, the electrolytic experiments usually involve an overpotential; i.e., the potential drop across the double layer in the electrolyte next to the cathode surface. In Sec. V.B, we show that an energy shift at or near the surface of the cathode and possibly related to overpotential can be even more important than the ambient temperature in determining the energy distribution of the diffusons.

II.G. Is a One-Dimensional Model Realistic? Analogy to X-Ray and Neutron Diffraction

There is an analog of the Eq. (2) transmission condition in the case of X-ray diffraction (also, of course, in neutron diffraction). Recall the well-known Bragg law for the diffraction of X rays. For a single crystal of lattice spacing d and X rays of wavelength λ, the n'th order maximum in the diffraction pattern can be found at an angle θ given by[29]

$$2d\sin\theta = n\lambda \quad . \tag{7c}$$

Complementary to this, the reflective minima would be specified by

TABLE I

Comparison of Independently Determined and Theoretical Well Widths Generated by the TRM for the TiD_2 and PdD Lattices for Different Diffusions

Lattice	Diffusion	Well Width from Crystalline Data (Å)	Well Width from Model (Å)
TiD_2	Deuteron	1.047	1.047
PdD	Deuteron	2.85	2.86
PdD	^{6}Li	2.85	2.76
PdD	^{7}Li	2.85	2.89

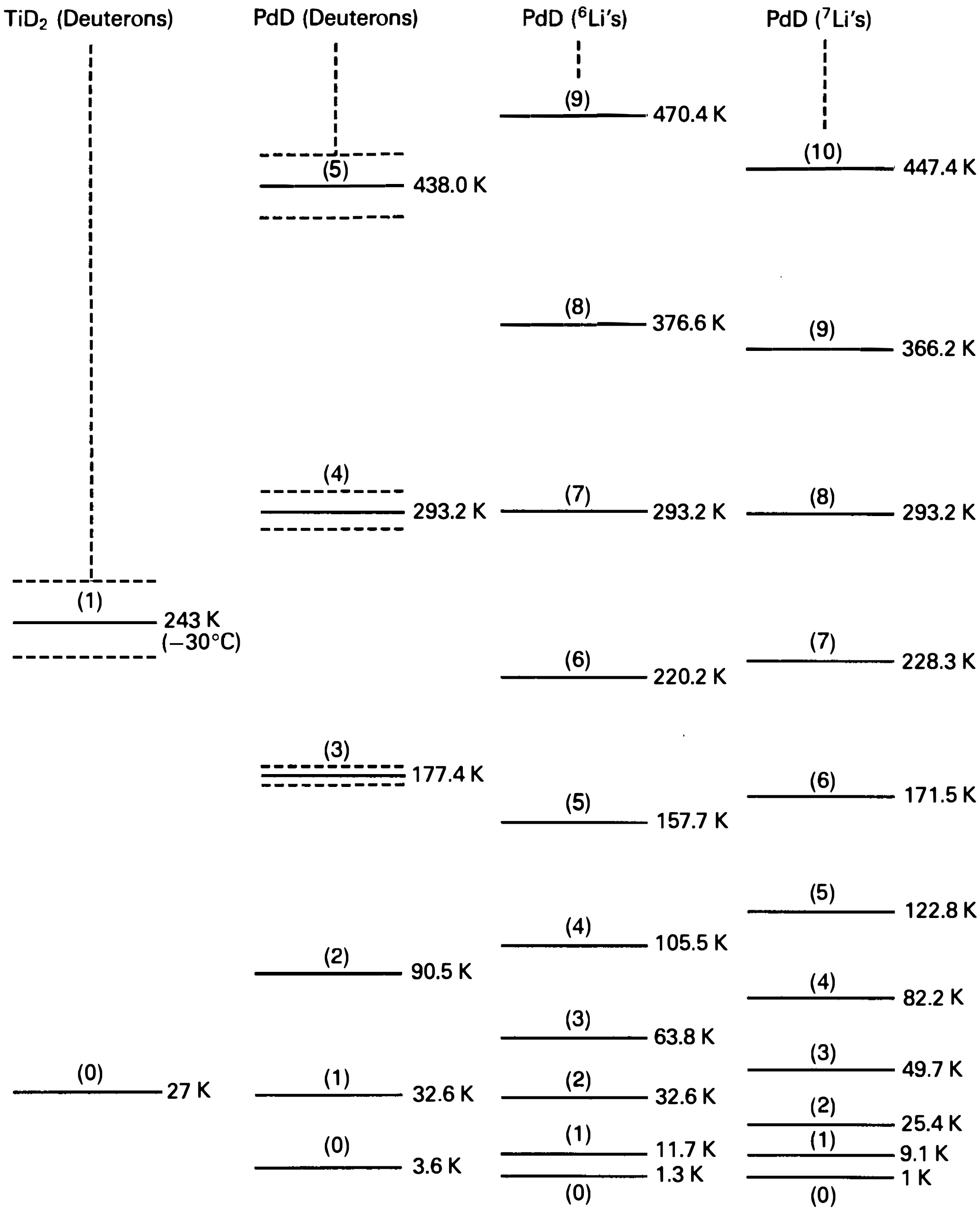

Fig. 4. Energy level schemes based on the transmission condition of Eq. (2) and specified by Eq. (14): $T_n = (2n + 1)^2 T_0$, for two different deuterated lattices, TiD_2 and PdD, and three different diffusons: deuterons, ^6Li, and ^7Li.

$$2d \sin\theta = \left(n + \frac{1}{2}\right)\lambda \ . \tag{7d}$$

For normal incidence, $\theta = 90$ deg, these reflective minima or transmission maxima are given from Eq. (7d) by

$$2d = \left(n + \frac{1}{2}\right)\lambda \ , \tag{7e}$$

which is the same transmission condition we have been employing in Eq. (2).

This analogy to X-ray diffraction emphasizes that the TRM is a one-dimensional model, as opposed to the two-dimensional model inherent in Eqs. (7c) and (7d). Thus, it is reasonable to ask if the TRM is, in fact, a realistic model. Certainly a one-dimensional model would appear to be valid in the case of a plane de Broglie wave incident along the crystal axis of a monocrystalline sample. However, this is not the experimental setup that the TRM must deal with since, in most cases, the samples are polycrystalline. For the X-ray case with a polycrystalline sample, Eqs. (7c) and (7d) are still valid and one recalls the Debye-Scherrer powder pattern. It would seem then that we require at least a two-dimensional model, and preferably a three-dimensional one, to treat the transmission resonance of deuterons for a polycrystalline PdD sample.

Nevertheless, as seen in later sections, the one-dimensional TRM appears remarkable in its ability to correlate calorimetric data on cold fusion. While the reason for its success as a one-dimensional model is not completely clear, the following are possible physical reasons:

1. In PdD with deuterons as diffusons, there may be a tendency for the energy associated with motion at right angles to the interstitial deuteron transmission channels to be dissipated into phonons in the sample.

2. This tendency may perhaps be strengthened as stoichiometric loading is increased because of the wave-mechanical behavior of the deuterons as indistinguishable bosons.

Even though we often appear to be distinguishing diffuson deuterons from the deuterons in interstitial sites forming the B-W-B chains, this is, in principle, impossible. In addition, the symmetrical nature of the wave function for identical bosons makes them tend to behave similarly. Thus, there is a natural tendency to form standing de Broglie waves along the interstitial deuteron transmission channels. These standing waves are associated with motion of the deuterons in both directions along the axis of the deuteron transmission channels. Such a situation would validate the use of a one-dimensional model.

II.H. Many-Body Tunneling as Counterintuitive to the Two-Body Case

Gamow theory has generally been extremely discouraging to the hypothetical prospects for cold fusion. The transmissivity for this two-body tunneling case may be expressed as

$$T = \exp[-\gamma Z_1 Z_2 (m/E)^{1/2}] \ , \tag{8}$$

where

γ = constant

Z = number of protonic charges on the two interacting particles

m = mass of the lighter particle, considered the tunneling particle

E = energy of its approach in a frame where the heavier particle is considered at rest.

Consider two separate hypothetical cases in which all factors are the same except the mass of the tunneling particles. Clearly from Eq. (8), a slight difference in mass is enough to give a tremendous advantage to the less massive particle in terms of transmissivity and thus to the nuclear reaction rate.

Counterintuitive to this would be the many-body case of tunneling associated with transmission resonances within a deuterated metal lattice. Recall that the de Broglie wavelength can also be expressed in terms of the mass and energy of the particle as

$$\lambda = h/(2mE)^{1/2} \ . \tag{9}$$

For equal energies E, the diffuson with the greatest mass has the lowest λ; however, this means that for an equal distribution of energy for two different species of diffusons of masses m and M ($M > m$), the latter is associated with the largest density of transmission resonance levels per unit energy level. This is apparent from Eq. (2) since, at least hypothetically, we can find orders N and n ($n < N$) for the transmission resonance levels for the two species of masses M and m, respectively, such that

$$(2N+1)\lambda_M = (2n+1)\lambda_m = 4L \ . \tag{10}$$

This means that there are more transmission windows for the diffusons of larger mass, giving them an advantage, at least in this respect, in terms of overall reaction cross section. This is clearly exhibited in Fig. 4, where the density of transmission levels is observed to increase for the three cases involving PdD as a matrix as we go from left to right for the successive cases of deuterons and lithons (^{6}Li and ^{7}Li, respectively). It must again be emphasized that this increased opportunity for tunneling in this many-body case is strictly counterintuitive to the two-body case for which slight mass increases, assuming other factors to be the same, radically diminish the chances for a fusion reaction. (A caveat is that we should be comparing particles of roughly equal mobility in the lattice. The two electrons around the lithon make it so much larger than the deuteron that the latter should be compared with a proton, and the ^{6}Li and ^{7}Li lithons should be compared with each other in this many-body tunneling argument.)

An alternative possibility is that transmission resonance involving tunneling through the metal lattice may simply get two nuclear particles close enough together that the two-body Gamow reaction is sufficiently enhanced to yield a cross section leading to detectable energy release within the lattice.

III. MAXWELLIAN VELOCITY DISTRIBUTION

For the diffusons within the electrolyte, it seems eminently reasonable to employ a Maxwellian velocity distribution,[18] although the existence of an overpotential near the surface of the cathode will entail important changes that are detailed in Sec. V.B. Certainly for near-surface reactions, it seems valid to employ this diffuson distribution. For temperature T, the Maxwellian velocity distribution is specified by

$$dN(v)/dv \propto T^{-3/2} v^2 \exp(-mv^2/2kT) \quad . \tag{11}$$

The resonant velocity v_n associated with a transmission level of order n is specified by

$$v_n = h/m\lambda_n \quad , \tag{12}$$

where the de Broglie wavelength λ_n satisfies the transmission condition of Eq. (2). Also, from Eq. (4) we see the v_n is related to the n'th order transmission level by

$$mv_n^2/2 = kT_n \quad . \tag{13}$$

It is clear from Eqs. (5) and (13) that we may express the transmission levels in terms of the zeroth order level T_0 by

$$T_n = (2n+1)^2 T_0 \quad , \tag{14}$$

and the n'th order resonant velocity in terms of the zeroth order velocity by

$$v_n = (2n+1)v_0 \quad . \tag{15}$$

In Fig. 5, two of the curves portray representative Maxwellian velocity distributions for equal numbers of total diffusons and respective ambient temperatures of $T = 293.2$ K and $T = 611.8$ K, with zero overpotential for both cases. The velocities v_n are displayed along the abscissa. The relative number of diffusons with velocities between, e.g., v_1 and v_2, for a particular ambient temperature T is equal to the ratio of the area

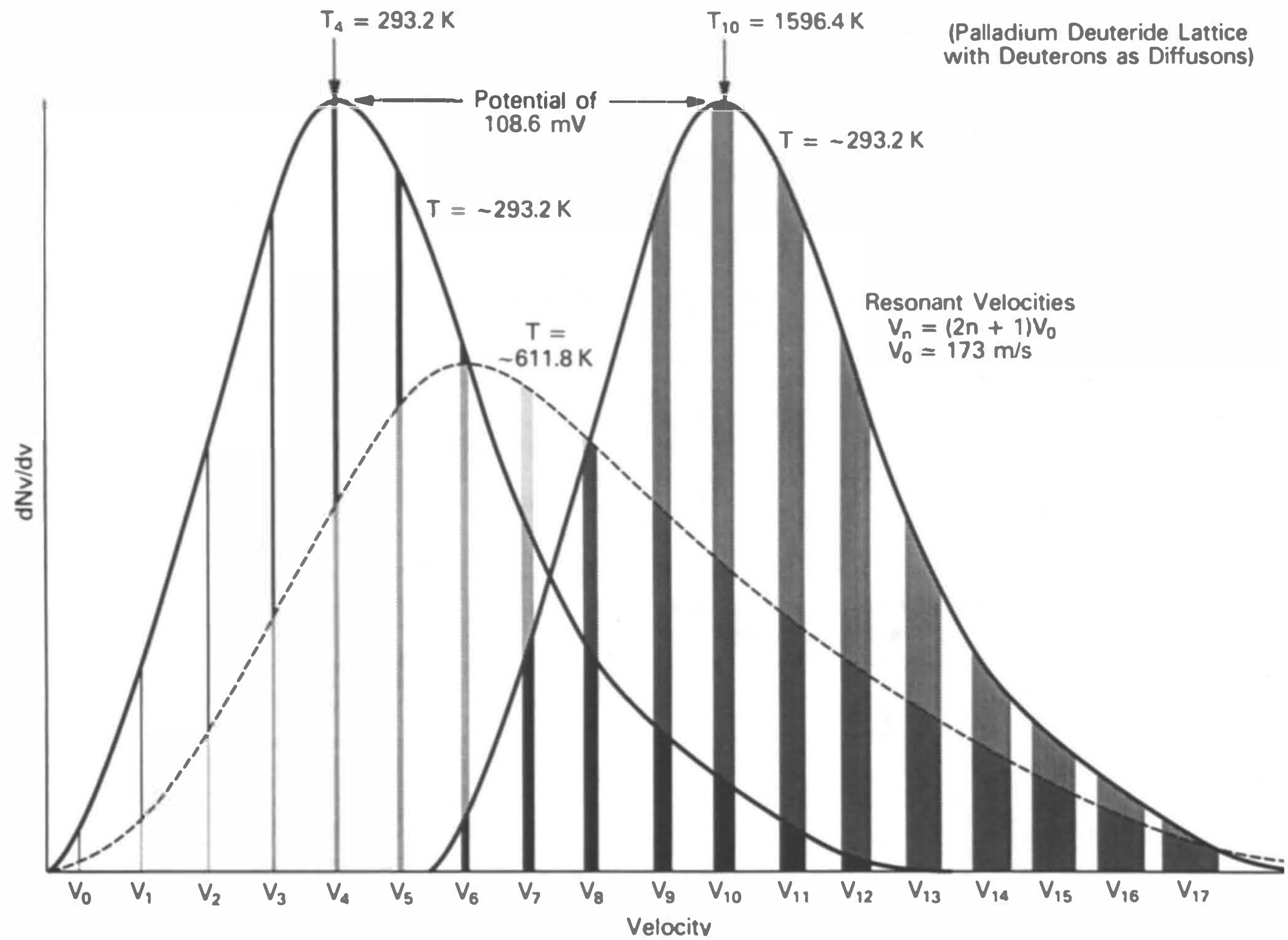

Fig. 5. Maxwellian velocity distributions for temperatures of 293.2, 611.8, and 293.2 K with a velocity shift produced by an overpotential of 108.6 mV. Transmission velocity windows are shaded, but are not to scale. The value v_{16} is the resonant velocity associated with the last usable transmission window for the palladium transmission channel at approximately room temperature.

under the curve between those two values to the area under the total velocity distribution curve for that value of T. Note, however, that the number of diffusons at temperature T corresponding to a particular velocity, e.g., v_n, is zero since the area under the curve at $v = v_n$ is zero. It is the variation in well width L due to thermal vibration that provides candidate diffusons for transmission. Thus, Fig. 5 shows that, because of this thermal width resulting from phonon exchange between the metal lattice and the deuterons, whose Coulomb barriers form the wells, a transmission line centered on v_n extends from $v_n - \Delta v_n/2$ to $v_n + \Delta v_n/2$, resulting in a finite area under the distribution curve corresponding to this range of velocities.

The thermal widths resulting from phonon exchange may be estimated as follows from Eq. (5):

$$\Delta T_n/T_n \simeq 2\Delta L/L \ . \quad (16)$$

The variation in well width ΔL due to thermal vibration may be estimated from the approximation

$$m\omega^2(\Delta L)^2/2 = 2(kT/2) \ . \quad (17)$$

Combining Eqs. (16) and (17) leads to the thermal widths ΔT_n for the transmission levels for deuterons in the TiD_2 matrix:

$$\Delta T_n = [2(2k/m)^{1/2}/\omega L]T_n T^{1/2} \quad (18)$$

$$= (5.8 \times 10^{-3})T_n T^{1/2} \ . \quad (19)$$

[A value of ω of 3×10^{14} from Refs. 31 and 32 has been employed to give the numerical part of Eq. (19).] With regard to phonon effects, note that Schwinger's model[33] for cold fusion employs explicit transfer of energy to the lattice.

IV. PHONON EXCHANGE EFFECTS IN THE TRM

IV.A. A Positive Effect: Thermal Widths of the Transmission Lines

In Sec. III we noted that the number of diffusons corresponding to any particular transmission resonance velocity is zero since the area under a point on the distribution curve is zero. As indicated there, it is the effect of phonon exchange between the wells and the metal lattice (thermal vibrations of the wells) that results in thermal widths (transmission windows) providing candidate diffusons for transmission. For the M-B energy distribution, the same effect provides transmission windows of energy ΔE_n at transmission energies E_n, centered on the latter on the energy axis, and extending from $E_n - \Delta E_n/2$ to $E_n + \Delta E_n/2$. From Eq. (19) we have

$$\Delta E_n = k\Delta T_n = (1.84 \times 10^{-4}\ \text{meV})T_n T^{1/2} \ , \quad (20)$$

where we have modified Eq. (19) for the case of TiD_2 to that for PdD by multiplying by the inverse ratio of the well widths, 1.047/2.85. For $T = 300$ K, Eq. (20) becomes

$$\Delta E_n = (3.18 \times 10^{-3}\ \text{meV})T_n \ , \quad (21)$$

and for $T_n = 300$ K, also,

$$\Delta E_n = 9.54 \times 10^{-1}\ \text{meV} \ . \quad (22)$$

These results would be valid for the deuteron transmission channel of the PdD lattice. For the palladium transmission channel, the results in Eqs. (20), (21), and (22) must each be multiplied by $(M_D/M_{PD})^{1/2} = 0.137$ to take into account the mass dependence of the wells as expressed by Eq. (18). Figure 6 portrays the deuteron and palladium transmission channels in PdD with the former indicated by the longer arrows and the latter indicated by the shorter arrows. (The large circles represent palladium centers while the smaller circles represent interstitial deuterons.) Note that the separation between the centers of two neighboring palladium atoms is the same as that between neighboring interstitial deuterons.

IV.B. A Negative Effect: Maximum Transmission Orders for Palladium and Deuteron Transmission Channels

Just as thermal vibration provides candidates for transmission, the number of those candidates is limited

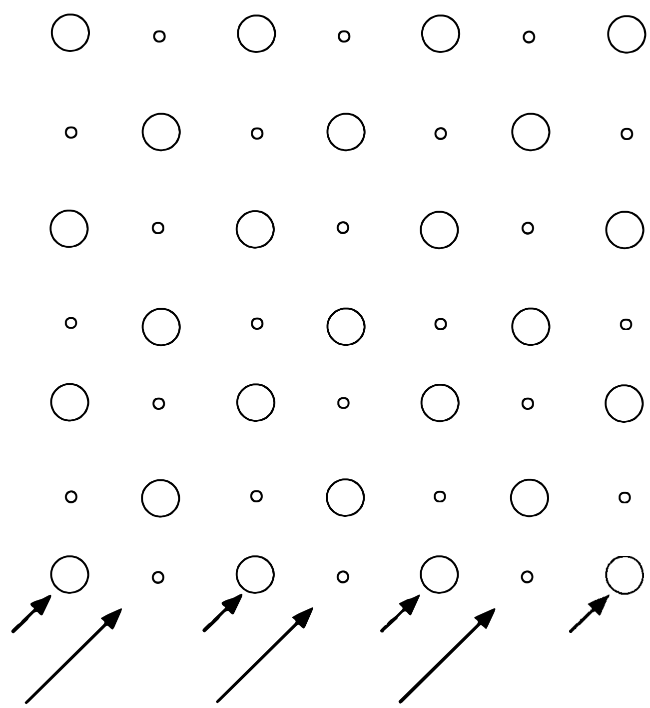

Fig. 6. The palladium transmission channel is indicated by the shorter arrows, the deuteron transmission channel by the longer arrows. Larger circles signify palladium centers; smaller circles indicate interstitial deuterons.

by limiting the transmission order to a maximum value n_{max}. Physically, this is because as the order of transmission increases, the corresponding de Broglie wavelength corresponding to E_n decreases [see Eq. (9)]. Finally, we reach a de Broglie wavelength that is so short that the change in well width due to thermal vibration in a time not small compared to the time of passage of the particle through the well is a large enough fraction of the de Broglie wavelength that the transmission resonance condition of Eq. (2) breaks down. From the fit of the TRM to the data, it appears that this breakdown corresponds to a value of $n_{max} = 16$ for the palladium transmission channel, assuming that the excess heat reaction is associated with this channel. Using this information we can now obtain an estimate for the critical percent $(\Delta L/\lambda)_{crit} \times 100\%$ at which breakdown of the transmission resonance condition occurs. Thus, from Eqs. (2) and (18), it can be shown that

$$n_{max} \simeq 153.9M^{1/2}(\Delta L/\lambda)_{crit} - 0.5 \ . \qquad (23)$$

Substituting $n_{max} = 16$ and $M = 106.4$ for the case of the palladium transmission channel yields

$$(\Delta L/\lambda)_{crit} \times 100\% \simeq 1\% \ . \qquad (24)$$

Equation (24) can serve now as a general criterion for the breakdown of the transmission condition. Substitution of Eq. (24) into Eq. (23) along with $M = 2$ yields $n_{max} = 1.76$ for the deuteron transmission channel. The result suggests that only the $n = 1$ and $n = 0$ order transmission orders contribute to any great extent for the deuteron transmission channel. As might be expected, this transmission order limiting effect is much more severe for the deuteron potential wells because the deuterons have a much lower mass than the palladium atoms.

IV.C. Neutron Emission in Pressurized Gas Experiments (TRM Updated)

Neutron emission in pressurized gas experiments is an important cold fusion phenomenon and was treated previously by the author[15,16,18] on the basis of the TRM. Since the author is planning a future paper containing an updated treatment specific to neutron emission based on the model, a few remarks here will suffice with regard to the possible relationship of the latest experimental results to the TRM.

At the Utah conference, much was made of the fact that there is a "martensitic" phase transition in titanium at approximately 243 K (−30°C) that might account for the now-famous −30°C neutron emission line observed by Menlove et al.[1] Thus, the focus appeared to be on the possibility of fracto-fusion to account for this finding. Since the author[18] had fit his model to the −30°C emission line originally for the case of TiD with deuterons as the diffusons, this consideration was somewhat disappointing. Since the Utah conference, however, data from Zelenskii[34] make it clear that there is probably a whole system of lines for both TiD_2 and a separate one for PdD, both above and below 0°C, that indicate that the TRM is a competitive model to explicate this phenomenon. The data provide additional strong support for the −30°C emission line. Jones[35] points out that data points to the left of the −30°C line indicate the possibility of a lower temperature line that might be associated with the author's predicted neutron emission line at 27 K (−246°C). Since the Zelenskii data appeared, the author has also heard from Jones[36] concerning a preliminary experiment inspired by the author's prediction of a 27 K neutron emission line for the TiD_2 system and conducted at Brigham Young University (BYU) with a Menlove-type detector. According to Jones,[36] the results of an experiment in which warming of the sample from the temperature of liquid ^4He was carried out produced enough counts above the expected background count to make the experiment worth repeating. The emission temperature, while not known precisely, appears, nevertheless, to be far enough below the −30°C line to raise the author's hopes of a connection with the predicted 27 K line on the basis of the TRM.

In Ref. 18, neutron bursts in the TRM are associated theoretically with the peak of the Maxwellian velocity distribution corresponding to a velocity $v = v_n$, so that the ambient temperature T has the value $T_n = E_n/k = mv_n^2/2k$, where the latter equality is seen from Eq. (13).

IV.D. Relative Yield Rate for Neutron Production

For neutron emission experiments of the pressurized gas type, the TRM shows that we may employ the following expression for R, the relative yield rate for neutron production. Note that the units of R are immaterial since it is the ratios of R's that are significant:

$$R = M^{-1/2}PT^{-3/2}\Sigma_n T_n^{3/2}\exp(-T_n/T) \ , \qquad (25)$$

where

M = molecular weight of the diffusons

P = pressure

T = temperature (K)

T_n = energy for the n'th-order transmission line.

An M-B energy distribution has been assumed to give the energy distribution for the diffusons, and the transmission window width dependence on the energy level and the temperature given by the factor of $T_n T^{1/2}$ from Eq. (19) has been employed. In terms of the previous analysis on the effects of phonon exchange, it would be consistent to sum over just $n = 1$ and $n = 0$ in Eq. (25); however, this somewhat simplistic analysis ignored the fact that there will really be a distribution of well amplitudes at any temperature. Based on this, it may be possible to see neutron bursts associated with other higher orders.

V. ELECTROLYTIC COLD FUSION EXPLAINED BY THE TRM

V.A. Section Preview

In this section, we update the model's development by combining the previously developed physics with some electrochemistry of the surface of the cathode to obtain a mathematical expression for P_r, the relative excess power. In addition, P_r is employed to obtain a good fit to new calorimetric data. (This has been sketched previously by the author[15,16] but is here developed in detail.)

The Butler-Volmer formalism of electrochemistry is employed to develop a useful relationship for P_r. The relative excess power formula suggests three basic types of experiments. Two of these types have been performed by the author and his colleague Eagleton[37] at California State Polytechnic University (Cal Poly). In these instances, the model provides a good fit to the data. In fact, the TRM is the first model to provide a fit to calorimetric data of sufficient detail to show significant systematic nonlinear structure in a plot of excess power versus applied current density. When sufficiently detailed calorimetric data are taken, an interesting fine structure emerges. The fact that the model provides a good fit to these data reveals a significant self-consistency. Not only does this encourage confidence in the model in the sense of reflecting a basic correctness, but it also strongly heightens the credibility of the Pons-Fleischmann effect of excess heat production.

The question of how to trigger the excess heat phenomenon has been a relatively long-standing question, and the author[15,16] has previously indicated that the model can successfully address it. The treatment here leaves little doubt that the TRM can predict optimal trigger points. In addition, it appears that the model may predict the phenomenon of heat bursts well known to researchers.

An energy shift, possibly equal to the overpotential, appears to be a crucial element in the model. In this connection, the activation overpotential, the concentration overpotential (or hydrogen overvoltage), and total overpotential are all explored.

The fact that the phenomenon appears to be a near-surface one is encouraging to prospects for scaling up the excess heat phenomenon to provide practical energy-producing devices. While unforeseen difficulties abound in any scaling-up attempt, it is, nevertheless, interesting to employ the naive reactor theory of the model to predict optimal conditions for a cold fusion reactor.

Finally, the basic nature of the mathematical functions involved in the relation for P_r, the relative excess power, is briefly explored. In particular, the projections of these functions from their four-dimensional parameter space into appropriate two-dimensional subspaces exhibit self-similar geometry above a certain lower limit. Above this lower limit, the curves have the same appearance, regardless of the parameter range. This scale invariance suggests the fractal nature of the curves describing cold fusion in the TRM. When extended into the time realm, as suggested by the phenomenon of heat bursts, there is a possible link between the TRM and chaos theory.

V.B. The Relative Excess Power Formula

In Ref. 37, we make clear that, in the experiments described therein, we obtain more energy (in the form of heat) than the total energy put in, where the latter can be thought of as the integration of $(I \times V)\,dt$ (current multiplied by voltage multiplied by dt) over the total time. (The total time is equal to the loading period plus the period of observing excess power.) In no case, though, have we yet obtained more excess heat than the total amount of energy put in. (The excess heat is the total amount of heat output minus the total energy input.) Note, however, that others have recently been able to support the claim of getting more excess energy out than their total energy input. Recently, Liaw and Liebert[38] reported that they have achieved excess heats of 600 to 1200% of the input energy employing an electrolyte of molten salts, including KCl, LiCl, and LiD at temperatures ranging from 350 to 400°C. (As shown later, this increased percentage of excess heat out at elevated temperatures is in agreement with the positive temperature coefficient predicted by the TRM.) In addition, Yang et al.[39] reported achieving excess heat ranging over 100% of the input energy with a more conventional Fleischmann-Pons-type electrolytic setup. In the best case to date at Cal Poly, that of cell 4, an excess power output has been attained that was ~35% higher on average than the input power for a period of ~48 h. The total excess heat in this experiment amounted to ~0.35 MJ, as compared to a total input energy, i.e., $(I \times V)\,dt$ integrated over the total time of ~13 days (loading time + period of observing excess power), of ~2 MJ. Thus, for the entire period of ~13 days, the percentage of excess heat to input energy was ~17.5%. A total of ~2 MJ was input in the form of electrical energy, while a total of ~2.35 MJ was released in the form of heat. Error bars, estimated to be ~10%, are small enough that it is apparent we do not have a device analogous to a chemical storage battery, but are seeing a genuine excess heat effect. In this sense, the terms excess power effect and excess heat effect are applied interchangeably.

In developing a relative excess power formula, it is assumed that the diffuson (e.g., diffusing deuteron) energies are given by the M-B energy distribution. This seems most appropriate for a reaction near the surface.

In this regard, Appleby et al.[40] have found evidence that the heat production reaction, while not exactly on the surface, may be a near-surface reaction occurring in a layer on the order of ~5 μm in depth. To be sure, agreement with data must be the final test for the model. Employing the M-B energy distribution,

$$dN(E) \propto T^{-3/2}E^{1/2}\exp(-E/kT)\,dE \ . \quad (26)$$

Since it makes physical sense that the relative power depends on the incident flux of diffusons i, the applied current density (in milliamps per square centimetre) is introduced as a factor in the expression for relative excess power P_r. In addition, the expression for P_r should include a summation over the areas of the transmission windows. The area of a transmission window is the product of the height and the width. The height is given by dN/dE from Eq. (26) with E replaced by E_n as a reasonable approximation over the width ΔE_n of the window. Note that constant factors are unimportant in the expression for P_r as long as we compare powers for the same type of metal deuteride lattice. Thus, the area of a window centered in energy at E_n and of width ΔE_n is given by $\Delta N(E_n)$ for the distribution function with E_n the transmission resonance energy substituted for E:

Transmission window area

$$= \Delta N(E_n) = (dN/dE)_{E=E_n} \times \Delta E_n \ . \quad (27a)$$

Figures 7 and 8 portray M-B energy distributions showing these narrow transmission windows. Thus, we obtain an approximate relative power factor given by

$$P_r = iT^{-3/2}\Sigma_n E_n^{1/2}\exp(-E_n/kT)\Delta E_n \ , \quad (27b)$$

where T is the temperature describing the diffusons (deuterons), E_n for PdD is given by kT_n with T_n given by Eq. (7b):

$$E_n = kT_n = k(2n+1)^2(3.62\ \text{K}) = (2n+1)^2(3.12 \times 10^{-1})\ \text{meV} \ , \quad (28)$$

and ΔE_n is given from Eq. (20) for our purposes as

$$\Delta E_n \propto T^{1/2}E_n \ . \quad (29)$$

Note again, as in the case of R in Eq. (25) that the units of P_r are immaterial. Thus, it is the ratio of P_r values that are physically meaningful. Substituting these relations in Eq. (27b) yields a preliminary approximate relative power expression for comparing the theoretical excess power on the same sample at different current densities and temperatures:

$$P_r = iT^{-1}\Sigma_n T_n^{1/2}\exp(-T_n/T)(E_n) \ . \quad (30)$$

The qualifier, "preliminary," was employed above because this is not the entire story. Additional information from that branch of electrochemistry known as electrodics, which treats electrified surfaces, must be introduced. A recommended guide for this is the textbook by Bockris and Reddy.[41] We suppose that the deuteron energy is boosted at the surface by an amount $q\eta$ by some mechanism. If η is equal to the activation overpotential, then the deuteron energy is boosted by the amount $q\eta$. Recall that an applied current i (actually, current density) is made to flow because an applied electromotive force (emf) produces a potential drop, the activation overpotential, which upsets the equilibrium. This results in a shift of the M-B energy

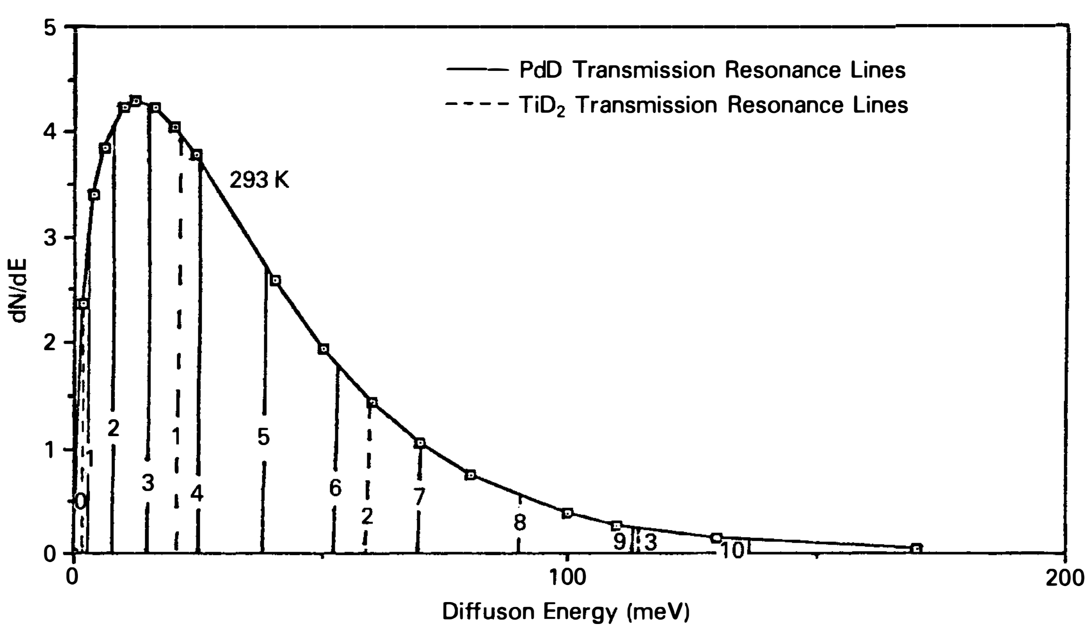

Fig. 7. The M-B energy distribution for $T = 293$ K.

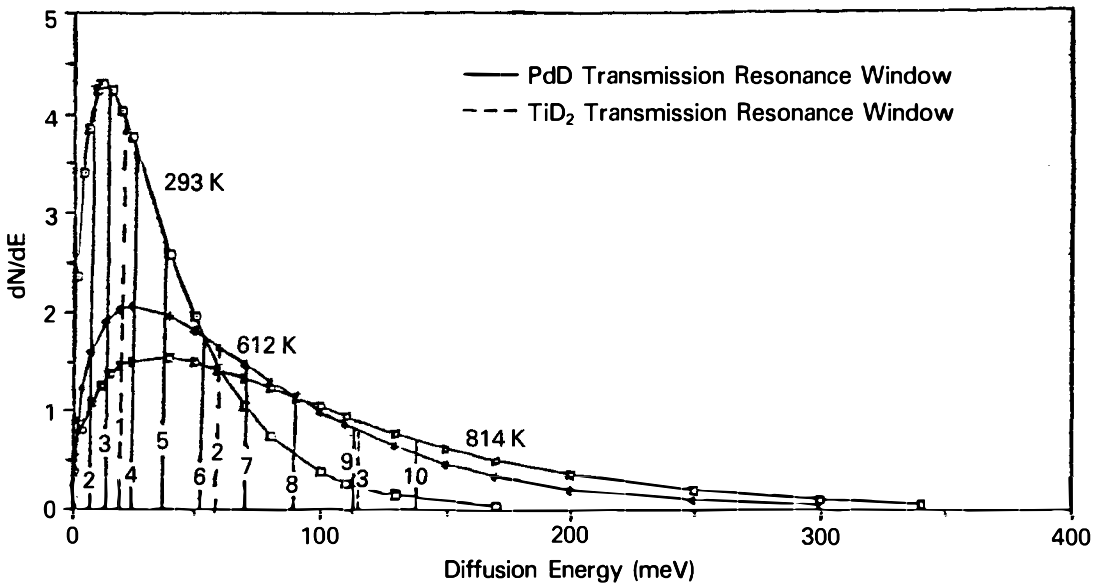

Fig. 8. The M-B energy distributions for the same total numbers of diffusons for temperatures of 293, 612, and 814 K, showing transmission energy windows of different order.

distribution in the direction of higher energies but without any other change such as that in its peak height or shape. This is illustrated in Fig. 5 for the Maxwellian velocity distribution showing the effect of an overpotential, or η, of 108.6 mV. Note one positive effect for the transmission phenomenon: A shift to the right of the velocity distribution brings into play transmission windows of larger width ΔE_n since the latter are proportional to E_n, which provides more diffuson candidates for transmission. To express this rigid translation of the M-B distribution along the energy axis by the positive amount $q\eta$ mathematically, we must guarantee that the function in Eq. (30) has the T_n's each replaced by $(T_n - q\eta/k)$, reflecting the fact that if an original energy kT_3 is considered to be shifted up by the amount $q\eta$, the distribution curve would still be the same height at energy $kT_3 + q\eta$ as it had been at kT_3. Note that the factor E_n at the end of Eq. (30) is not changed because it refers to the energy width of the transmission windows. This leads us to the basic TRM formula for cold fusion, i.e., the relative excess power formula:

$$P_r = iT^{-1}\Sigma_n[T_n - (q/k)\eta]^{1/2}T_n \times \exp\{-[T_n - (q/k)\eta]/T\} \quad , \tag{31}$$

where, for convenience, the factor of Boltzmann's constant has been left out of the E_n term arising from the width of the energy transmission window. For η expressed in millivolts, this can be rewritten in the form

$$P_r = iT^{-1}\Sigma_n(T_n - 11.59\eta)^{1/2}T_n \times \exp[-(T_n - 11.59\eta)/T] \quad . \tag{32}$$

Note again that the units of P_r are immaterial since it is the ratios of these values that are physically meaningful. From this relation we can also see a negative effect of the energy shift. If the energy shift is too far to the right, we have the negative effect for the excess heat phenomenon of shifting the left side of the M-B energy distribution past the highest order usable state, i.e., that for $n = 16$. The minimum overvoltage η_{min} to achieve this is easily shown to be ~340 mV by setting the first term inside the summation in Eq. (31) equal to zero:

$$T_{16} - (q/k)\eta_{min} = 0 \quad , \tag{33a}$$

or

$$\{[(2n+1)^2]_{n=16}\}(3.62\ \mathrm{K}) - 11.59\eta_{min} = 0 \quad ; \tag{33b}$$

therefore,

$$\eta_{min} = 340\ \mathrm{mV} \quad . \tag{34}$$

Basically, Eq. (32) is the mathematical expression of the TRM for electrolytic cold fusion. Equation (32) can be specialized to the case of palladium by substituting the value for T_n given in Eq. (7b). In addition, the summation for the palladium transmission channel will be only over those orders of transmission n from zero to $n_{max} = 16$ (at ~300 K) for which

$$T_n > (q/k)\eta \quad . \tag{35}$$

Thus, we have for this case of greatest present interest, taking η to be expressed in millivolts = 10^{-3} V,

$$P_r = iT^{-1}\Sigma_n\left([(2n+1)^2(3.62) - 11.59\eta]^{1/2}(2n+1)^2 \times \exp\{-[(2n+1)^2(3.62) - 11.59\eta]/T\}\right) \quad . \tag{36}$$

This relation was, however, not employed in this form by the author to fit the calorimetric data or to help guide the experiments conducted at Cal Poly.[37] Rather, the Butler-Volmer formalism of electrodics was used to express this in another form. The relation in Eq. (31) was not previously explicitly expressed by the author, although it is implicit in earlier work.[15,16] (See Chap. 8 of Ref. 41.) Adjacent to the cathode is a transition region often referred to as the double layer. When no applied current is flowing in the cell, the equilibrium current i_0 (actually current density) is flowing in both directions across this transition region. At equilibrium, i_0 may be described accurately by the well-known Nernst equation. Away from equilibrium, however, the Nernst equation ceases to provide an accurate description. The applied current can be related to i_0 and η (taken now as the activation overpotential) by the famous Butler-Volmer equation from electrochemistry. In the high-field approximation valid for the present situation, the Butler-Volmer equation takes the form

$$i = i_0 \exp[(1-\beta)F\eta/RT] \ , \quad (37)$$

where

F = Faraday

R = gas constant

β = so-called symmetry factor.

Taking the natural log of both sides allows us to express the overpotential as

$$\eta = \alpha(kT/q)\ln(i/i_0) \ , \quad (38)$$

where q is the charge on the diffuson (deuteron) and

$$\alpha = (1-\beta)^{-1} \ , \quad (39)$$

which is taken to be 2, resulting from setting β equal to 0.5 as a rough approximation. This gives the following expression for the relative excess power:

$$P_r = iT^{-1}\Sigma_n\big([T_n - 2T\ln(i/i_0)]^{1/2}T_n \times \exp\{-[T_n - 2T\ln(i/i_0)]/kT\}\big) \ . \quad (40)$$

Since the exponent of the natural log of a quantity is the quantity itself, Eq. (40) can be rewritten as

$$P_r = i^3 i_0^{-2} T^{-1}\Sigma_n\{[T_n - 2T\ln(i/i_0)]^{1/2}T_n \times \exp(-T_n/T)\} \ , \quad (41)$$

where P_r depends on the applied current density i through an "i^3 term" in front and a natural log term within the sum. Putting in the expression for T_n and dropping the factor of 3.62 K in the middle factor T_n within the sum leads to the expression for the relative power that was employed to fit to the actual data:

$$P_r = i^3 i_0^{-2} T^{-1}\Sigma_n\{[(2n+1)^2(3.62) - 2T\ln(i/i_0)]^{1/2} \times (2n+1)^2\exp[-(2n+1)^2(3.62)/T)]\} \ , \quad (42)$$

where, again, the sum over states should be taken only over those terms in n, corresponding to the transmission orders from $n = 0$ to $n = 16$, that are positive.

V.C. Crucial Importance of the Overpotential

The TRM suggests that the excess heat effect and probably other aspects are related to a balancing act associated possibly, either directly or indirectly, with the overpotential (or with some other potential drop that rigidly shifts the M-B energy distribution), where the current density comes directly into play as a factor in the total flux of diffusons, and indirectly through its effect on the height of the transmission windows via the effect of the overpotential (or energy shift) to establish the fraction of the incident deuterons that are eligible for transmission. Thus, too small a current density means too few transmission candidates to yield an observable excess heat effect. For a temperature of ~300 K and based on the data of Fig. 10, extrapolation shows that the excess heat effect vanishes at an applied current density of ~70 mA/cm^2. For this current density, the Butler-Volmer relation gives an overvoltage of ~200 mV based on the following relation:

$$\begin{aligned}\eta &= (k/q)2T\ln(i/i_0) \\ &= (0.8625)(600)\ln\left(\frac{60\ \text{mA/cm}^2}{1.47\ \text{mA/cm}^2}\right) \\ &= 0.20\ \text{V} \ . \end{aligned} \quad (43)$$

This shift to higher energies of the M-B energy distribution by 200 meV indicates that not all the transmission order $n = 0$ to $n = 16$ will be contributing. The lowest contributing order will be $n = 12$. Thus, a shift by this amount boosts the point of the distribution curve at $E = 0$ to $E = kT_n$, where n can be calculated from the following:

$$(2n+1)^2 3.62 = (11.59)\eta\ (\text{in mV}) = (11.59)(200) \ , \quad (44a)$$

so

$$n = 12.2 \simeq 12 \ . \quad (44b)$$

V.D. Hydrogen Surface Adsorption as an Additional Key: Activation Overpotential, Concentration Overpotential, and Total Overpotential

It is important to mention an attractive alternative physical interpretation as a postscript since it was not employed by the author at the time of the original fitting of the model to the data presented later in this paper. Until now, the energy shift of the M-B energy distribution that has been considered so crucial for the excess heat phenomenon has been associated with an overpotential that could, more appropriately, be called the activation overpotential and labeled η_a. It is this activation overpotential that upsets the equilibrium in the double layer that was previously crossed by two equal, but opposite, current densities i_0 and $-i_0$ to produce our nonequilibrium current density i.

What may turn out to be just as important, or even much more important, for these considerations is the formation of hydrogen (deuterons in our case) near the cathodic surface in a diffusion layer. Clearly, the existence of such a layer might have a dramatic effect on a near-surface phenomenon. Thus, a concentration overpotential (or hydrogen overvoltage) η_c must be developed to buck out the effects of this charge layer. The theory of the concentration overpotential[41] is somewhat analogous to the Butler-Volmer formalism for the activation potential η_a. Thus, in analogy to the previous equilibrium current density i_0, there is an exchange current density $(i_0)_H$. Recall that the larger i_0, the smaller the value of η_a had to be to establish a desired current density i. Thus, the larger $(i_0)_H$, the smaller the required concentration overpotential to establish a given i when it is the diffusion layer that is the controlling valve, so to speak. Bockris and Reddy[41] show that the relation for η_c is roughly analogous to that for η_a:

$$\eta_c = (kT/q)\ln(c_{x=0}/c_0) \ , \tag{45}$$

where

c_0 = equilibrium concentration of interfacial deuterons

$c_{x=0}$ = new value after the equilibrium has been upset.

This is to be compared with the somewhat analogous relation for η_a in Eq. (38). Note that the ratio $(c_{x=0}/c_0)$ here plays the part of the ratio $(i/i_0)^\alpha$ in the earlier relation of Eq. (38) based on the Butler-Volmer formalism. Thus, it may not be easy to distinguish between these based simply on achieving a good fit to data. If both processes are important, there is a total overpotential

$$\eta = \eta_a + \eta_c \ , \tag{46}$$

and it may be this that should be employed in the relation of Eq. (31). This energy shift situation will have to be sorted out experimentally in future experiments.

How could a hypothetical cold fusion experiment be affected by the concentration overpotential? Figure 9 shows a plot of hydrogen overvoltage, i.e., concentration overpotential due to hydrogen, versus applied current density for different metal surfaces.[43] While curves for palladium are not included in the figure, the platinum curves provide us with important clues since palladium and platinum are chemically so similar. Thus, for a shiny platinum surface, Fig. 9 shows that a much higher maximum overpotential can be achieved than in the case of a platinized surface. In this regard, recall that a large percentage of the anodes employed are platinum, as are the ones used at Cal

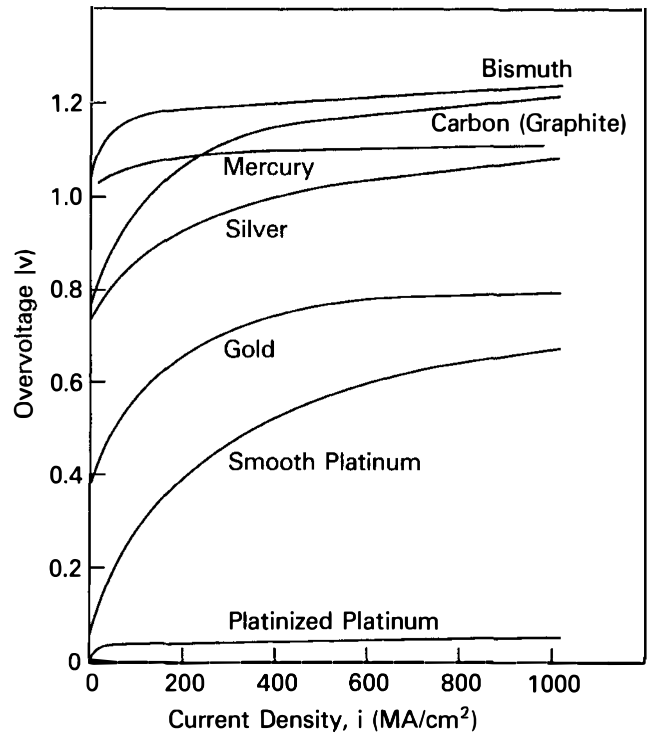

Fig. 9. Concentration overpotential for hydrogen on various metals ($2NH_2SO_4$ at 25°C) versus applied current density.[43]

Poly. As the surface becomes platinized, the maximum overpotential that can be achieved is decreased and the rigid energy translation to higher energies of the M-B energy distribution decreases. The following are examples of exchange current densities $(i_0)_H$ for the hydrogen reaction on different metal surfaces at ~300 K (Ref. 42): platinum (10 mA/cm^2); palladium and rhodium (0.1); tungsten, cobalt, and tantalum (10^{-2}); iron and gold (10^{-3}); nickel, cadmium, and copper (10^{-4}); tin, beryllium, and aluminum (10^{-7}); zinc (10^{-8}); mercury and lead (10^{-10}). The exchange current density here is to η_c as the equilibrium exchange current density i_0 is to η_a. High values of $(i_0)_H$ indicate that the element is a promoter, while low values of $(i_0)_H$ indicate that the material is a poison for our purposes. Thus, platinum is obviously a promoter, while zinc is obviously a poison. From these values, it is clear that the curve for a smooth palladium cathode should lie about midway between the curve for smooth platinum and that for gold. Note that an energy shift of 340 meV, associated with a hydrogen overvoltage of 340 mV, that rigidly translates the M-B energy distribution just past the last usable transmission energy line corresponding to $n = 16$ is associated for a smooth platinum cathode with a current density of only ~130 mA/cm^2. Thus, a smooth palladium cathode with a curve (see Fig. 9) lying about halfway between that for smooth platinum and gold would probably be associated with a current density too low to produce an observable excess heat effect after the η_c value is lowered to include the $n = 16$ level under the curve for the M-B energy distribution. Again, the simplistic physical picture on which this is based is that, once the deuterons are past the diffusion charge layer, this layer acts as part of an electric double layer to provide an acceleration toward the surface of the cathode. The applied emf also comes in since the diffusion layer provides a repulsive electric field that the applied emf must buck out on the anode side of the diffusion layer.

The effect of the hydrogen overvoltage may affect the delay time before excess heat can be observed. Thus, Bockris[44] has asked the author what produces the delay in observing the excess heat effect on the basis of the TRM. As Bockris points out, the time delay from the beginning of charging the palladium cathode with deuterons to the first observance of excess heat is much too long to be governed by the rate of diffusion of the deuterons. Here then is a probable partial answer: It is necessary for a sufficient degree of platinization of the cathode surface to occur to yield a large enough $(i_0)_H$ value such that the rigid energy shift of the M-B energy distribution associated with the concentration overpotential becomes small enough to allow the left side of the curve to overlap with at least the $n = 16$ order energy transmission line. Thus, the leftward shift of the distribution curve must yield a sufficient minimal number of diffusons as transmission candidates via the overlap of the distribution curve with the fixed energy transmission lines in order that an observable excess heat effect occur.

If this interpretation is correct, it would also explain why the excess heat effect phenomenon is observed with only a few metals, i.e., those that absorb deuterons well and those that are, like platinum and palladium, in the transition metal group. Thus, platinum itself should be tried as a possible cathodic material, and there have been sporadic reports that two other transition metals, titanium and zirconium, can be made to exhibit the excess heat phenomenon. However, as one gets further and further away from platinum, palladium, and the other transition metals, the values of $(i_0)_H$ decrease. The consequence of a decreasing $(i_0)_H$ is that the concentration overpotential must correspondingly increase, producing a shift of the M-B energy distribution out of the range of the usable transmission energy windows. For such cases, no excess heat effect will be observed. Of course, if a platinum or palladium anode is employed, it may be possible, with cathodic deposition of this anodic material, to sufficiently platinize the cathode that the effect is produced, assuming that a metal deuteride lattice of sufficiently high stoichiometry can be produced.

If, instead of platinization, the fate of the cathode is to have materials plated out on its surface from either the anode or the electrolyte leading to higher values of $(i_0)_H$, the excess heat effect will never be observed. Thus, based on the TRM, this would be a possible reason why many experiments fail to produce excess heat. Suppose impurities are being deposited on the palladium cathode that produce an energy shift to the right toward higher energies: Once the M-B energy distribution has been shifted to the right of the energy associated with the transmission window for $n = 16$, there are no longer diffuson candidates for transmission and the excess heat effect is destroyed. As already shown, the minimum concentration overvoltage to achieve this is ~340 mV, or an energy of 340 meV corresponding to the transmission energy for the $n = 16$ order.

In cases where the concentration potential dominates the activation potential, Eqs. (45) and (46) show that we may write Eq. (31) in the following form in analogy to Eq. (41):

$$P_r = i(c_{x=0}/c_0) \times T^{-1}\Sigma_n\{[T_n - 2T\ln(c_{x=0}/c_0)^{1/2}]^{1/2} \times T_n \exp[-(T_n/T)]\} \ . \tag{47}$$

Since $(c_{x=0}/c_0)$ plays the role of $(i/i_0)^2$, Eqs. (41) and (47) have essentially the same form. Thus, it is clear that successful modeling attempts employing Eq. (41) do not really allow us to distinguish between these two possibilities if one dominates the other. It is really necessary to have a knowledge of any two of the following experimentally: η, η_a, η_c.

Another possibility for the energy shift, and one that might work in conjunction with the hydrogen diffusion layer associated with the hydrogen overvoltage, is the swimming electron layer in a surface tension model developed by Hora et al.[45]

V.E. Fit of the TRM to Electrolytic Data: Excess Power Versus Current Density

At the Utah Conference, the author[15] presented the following excess power curve (see Fig. 10) based on recent calorimetric data obtained at Cal Poly. Since a companion experimental paper[37] treating important experimental details has been written, it suffices to simply indicate a few of the salient experimental features. The calorimeter is of the steady-flow bath type with thermocouples at the entrance and exit ports of the bath. The cell containing the palladium cathode and platinum anode employs a recombiner, a magnetic stirrer, and two thermocouples. Excess power for each data point is determined as an average of two values determined from the calibration curves for the two respective thermocouples in the cell and their readings. The graph in Fig. 10 shows a plot of excess power versus current density for cell 4 with the data points shown with vertical error bars attached. Except for one exceptionally low lying data point seen to be at ~230 mA/cm^2, the other data points from cell 4 are

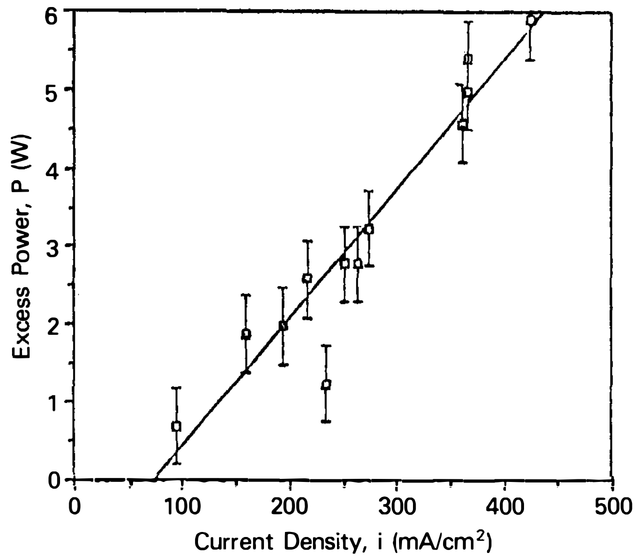

Fig. 10. Plot of excess power versus applied current density showing the initial straightline fit to the data from cell 4. Note the low-lying data point that might easily be ignored as being simply a bad data point.

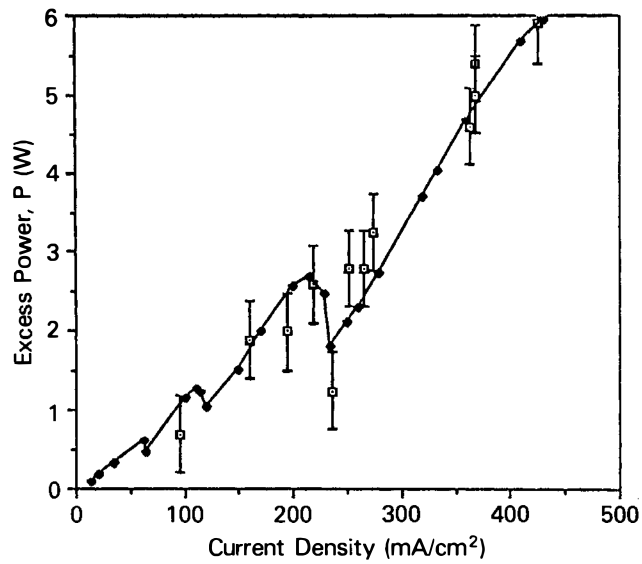

Fig. 12. Plot of absolute excess power versus current density showing the fit of the TRM (solid curve with solid boxes) to the data of cell 4 (error bars).

seen to be fit quite well by a straight line going to zero at ~70 mA/cm^2, in good agreement with other data presented at the conference. There was a considerable temptation to ignore this low-lying data point as relatively meaningless. The data were taken before the expression for relative excess power in Eq. (42) had been derived. Figure 11 shows the model's prediction based on Eq. (42) for a temperature of ~300 K, where the

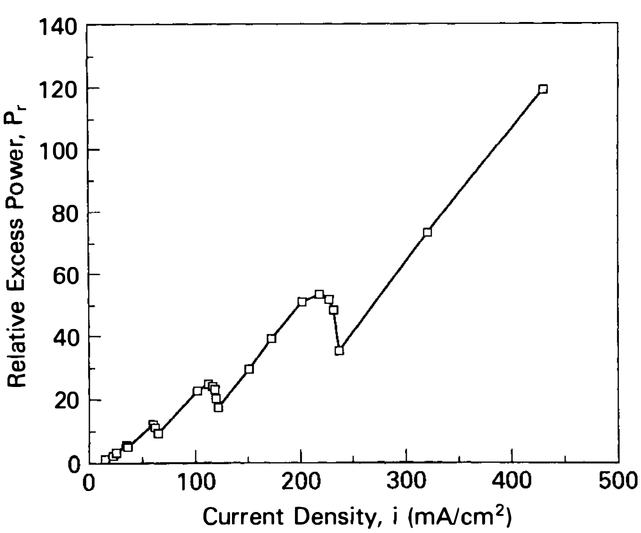

Fig. 11. Theoretical curve of relative excess power (arbitrary units) versus current density predicted by the TRM based on Eq. (42) to fit the data of cell 4. Note the relative minimum at the current density corresponding to the low-lying data point of Fig. 10.

theoretical points are shown as squares. Figure 12 illustrates the fit of the TRM expression in Eq. (42) to the data using $T = 300$ K. A value of $i_0 = 1.47$ mA/cm^2 was found to give the best fit of the relative excess power in Eq. (42) to the data.

Since the values of P_r are only relative excess power values and not absolute ones, it was necessary to find a common conversion factor that would convert the P_r values to absolute excess power values and thus provide the best fit to the actual excess power values found experimentally for the different applied current densities. Rather than give preference to any particular data point, it was decided to simply take the average of the 11 different conversion factors that were calculated to carry the separate P_r values over into the actual experimental excess power values for the 11 respective data points.

The value of n_{max} was taken to be 1000 in fitting the data. This calculation was performed before the limitations on n were explicitly determined. However, there is little problem in employing large values of n_{max} in practice to obtain realistic predictions of the model, provided that one is reasonably far away (in terms of applied current density) from where the excess power curve rolls over and goes to zero. This is because values of T_n that are large compared to T make little contribution because of the negative exponential term in Eq. (42). Thus, the model predicts that a relative minimum should appear on the graph as a cusp at $i =$ ~236 mA/cm^2, and the model point is seen to be vertically within a standard deviation of the low-lying data point shown. The TRM predicts the relative maximum of 2.5 W to be to the left of this at $i =$ ~216 mA/cm^2, in agreement with the data. The TRM also predicts recovery of the excess power value to that of 2.5 W again when the applied current density has reached 278 mA/cm^2, which again agrees well with the data as seen in Fig. 12. In presenting the comparison in Fig. 12 at the Utah conference, the author[15] expressed the opinion that the low-lying data point at 236 mA/cm^2 would turn out to be highly significant despite the lack of additional supporting data that would justify anything other than a straight line.

Since the Utah conference, new theoretical work and experimental work at Cal Poly have made it quite apparent that the low-lying data point was, indeed, prophetic. Thus, work with another cell, cell 5, has provided a much more detailed graph of excess power versus applied current density as shown in Figs. 13, 14, and 15. (Again, the experimental details are available in Ref. 37.) In the case of this second cell, a deliberate search was conducted for the sort of structure in the

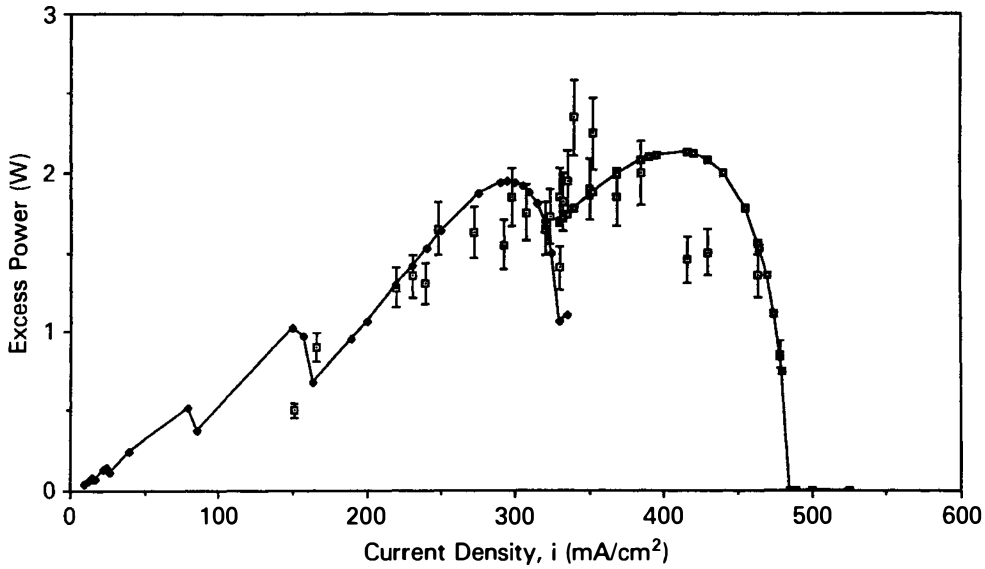

Fig. 13. Plot of excess power versus current density showing the fit of the TRM (solid curve) to the data of cell 5 (error bars). Data points above ~330 mA/cm^2 correspond to an average temperature of 329 K, while those below correspond to an average temperature of 312 K. [TRM employs Eq. (42).]

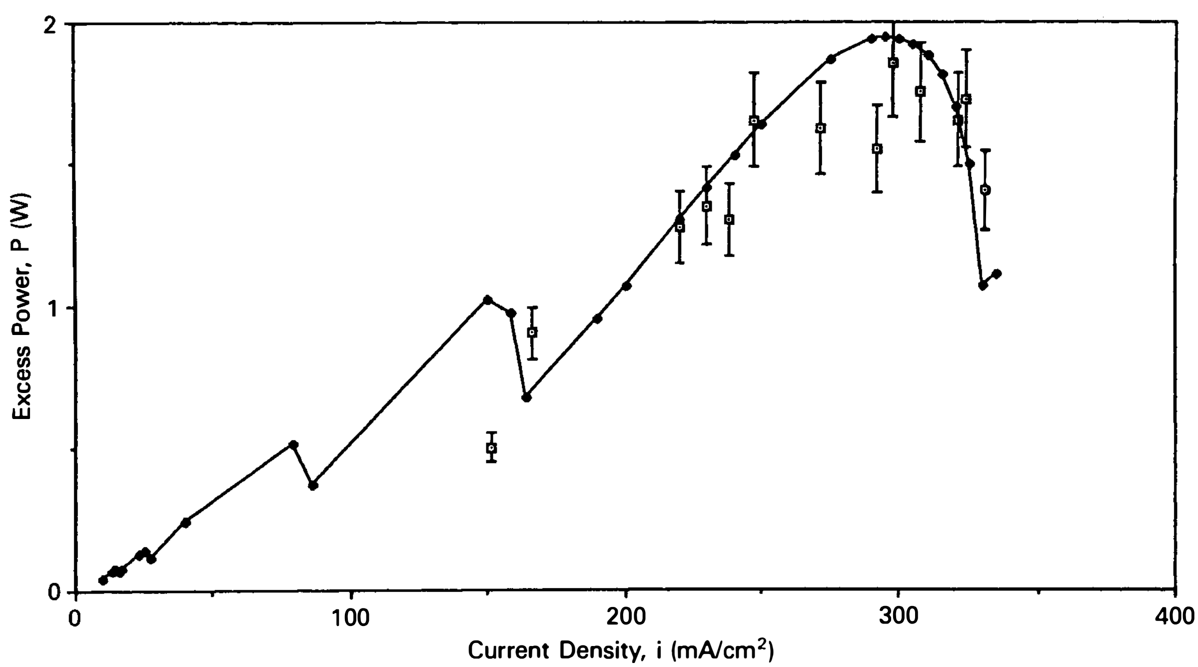

Fig. 14. Expanded view of Fig. 13 of the data and the TRM fit below 330 mA/cm^2.

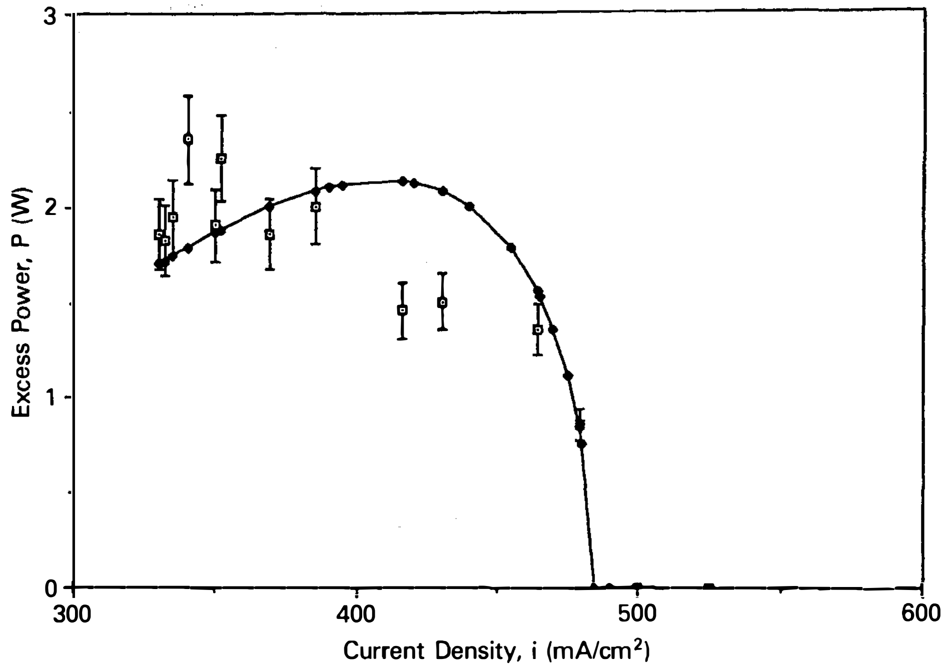

Fig. 15. Expanded view for Fig. 13 of the data and TRM fit above 330 mA/cm^2.

excess power versus current density plot suggested by the TRM and based on Eq. (42). The TRM proved invaluable as a search tool in this regard; however, one glitch should be mentioned. Due to inexperience with the model, it was discovered afterward that the data referring to applied current densities below ~330 mA/cm^2 were associated with an average cell temperature of ~312 K, while those data points having applied current densities above ~330 mA/cm^2 were associated with an average cell temperature of ~329 K. Thus, the model was employed to provide fits to the two groups of data separately. Comparisons of the two fits of the TRM to the respective data are shown in Figs. 14 and 15, with the two segments stitched together in Fig. 13 to provide a comparison of the TRM with the data over the larger range of current densities.

The data referring to an average temperature of ~312 K were best fit by the model employing a value of the adjustable parameter of $i_0 = 1.245$ mA/cm^2. The fit of the TRM to data is shown in Fig. 14. The translation from the relative excess power in Eq. (42) to absolute excess power was carried out as in the case of the 11 data points of Fig. 12. The model predicts a relative minimum cusp to be at ~328 mA/cm^2 with the nearest relative maximum being to the left at 298 mA/cm^2 in excellent agreement with the data of Fig. 14. This dip or relative minimum is to be associated with the energy shift of the M-B energy distribution finally being so great that the $n = 15$ order transmission energy level is exceeded and, thus, no longer operable. To see this, set the first term in the summation in Eq. (42), the expression for the relative excess power, equal to zero for $n = 15$, $T = 312$ K, and $i_0 = 1.245$ mA/cm^2:

$$[(2n + 1)^2_{n=15}]\,(3.62) - 2(312)\ln(i/1.245) = 0 \ . \tag{48}$$

Thus,

$$\ln(i/1.245) = 5.575 \ .$$

So,

$$i = [1.245\exp(5.575)]\ \text{mA/cm}^2 = 328.4\ \text{mA/cm}^2 \tag{49}$$

for the relative minimum, in good agreement with the positions of this cusp shown in Figs. 13 and 14. Also, as seen in Figs. 13 and 14, relative minima are located at ~164 and 87 mA/cm^2, with accompanying peaks at 151 and 80 mA/cm^2, respectively. The experimental error of ~10% associated with the data points in the experiment was too large relative to the changes in excess power involved in going from cusp to crest to make it reasonable to try to trace out these structures at lower current densities.

For the segment of data above ~330 mA/cm^2 and associated with an average temperature of ~329 K, it was found that the TRM gave the best fit to data for $i_0 = 1.210$ mA/cm^2. A comparison of the model to the data is shown in Figs. 13 and 15. The rollover to zero excess power occurs at about $i = 485$ mA/cm^2 and can be seen to arise in the TRM for the same reason as the large dip associated with $n = 15$. Thus, the excess power is going to zero because the energy shift carries the M-B energy distribution beyond the maximum usable transmission energy level specified by $n = 16$. This is how it has been empirically inferred that $n_{max} = 16$ for the palladium transmission channel. This can be seen by setting the first factor within the summation of the expression for the relative excess power in Eq. (42) equal to zero for $T = 329$ K, $i = 485$ mA/cm^2 (current density at which the excess power is extrapolated to go to zero), and $i_0 = 1.210$ mA/cm^2, and solving for n_{max}:

$$(2n + 1)^2_{nmax}(3.62\ \text{K}) - (2)(329\ \text{K}) \times \ln(485\ \text{mA/cm}^2/1.210\ \text{mA/cm}^2) = 0\ . \quad (50)$$

So

$$n_{max} = 15.8\ , \quad (51)$$

suggesting that $n_{max} = 16$ should give the best fit to the data.

The fit of the TRM to this new calorimetric data suggests that the model is on the right track. At the same time, it strengthens the claim that the Fleischmann-Pons effect of excess heat is genuine.

V.F. Fit of the TRM to Data: Excess Power Versus Temperature: Prediction of Optimal Trigger Points

The relation in Eq. (41) for the relative excess power P_r suggests a second type of experiment to test the model. If, instead of holding the temperature fixed in a calorimetric experiment and varying the applied current density, the latter is held constant, the dependence of excess power on temperature alone can be studied. Figure 16 shows a typical plot based on Eq. (42) of relative excess power versus temperature. The variable i_0 has a value of 1.47 mA/cm^2, i is held fixed at 250 mA/cm^2, and n_{max} is taken to be 15. Note that the TRM predicts a rising sawtooth curve until we are near the rollover temperature T_{ro}, which can be predicted in this case by setting the first factor inside the summation of Eq. (42) to zero with $n = 15$, $i = 250$ mA/cm^2, and $i_0 = 1.47$ mA/cm^2:

$$[(2n + 1)^2_{nmax=15}]3.62 - 2T_{ro}\ln(250/1.47) = 0\ , \quad (52)$$

yielding a rollover temperature T_{ro} of

$$T_{ro} = [(961)(3.62\ \text{K})/2\ln(250/1.47)] = 339\ \text{K}\ . \quad (53)$$

Note that this is in agreement with Fig. 16. Of course, if $n_{max} = 1000$, the values of P_r would be reasonably accurate provided the temperature is ~20 K away from the rollover temperature. This is because the negative exponential $\exp(-T_n/T)$ in Eq. (41) produces rapid convergence. This same condition in Eq. (52) gives the locations of the other relative minima if $(T_{min})_n$ is substituted for T_{ro} along with the respective values of n for n_{max}. Thus, in general, the locations of the relative minima in excess power are given by

$$(T_{min})_n = (2n + 1)^2 3.62/2\ln(i/i_0)\ . \quad (54)$$

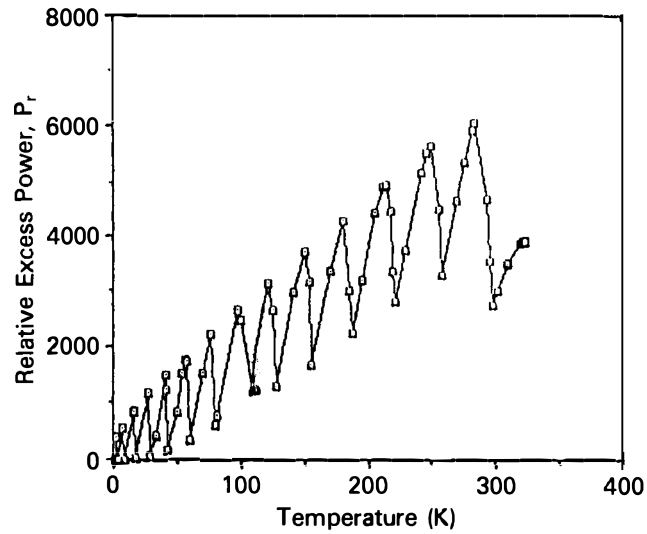

Fig. 16. Typical rising sawtooth curve predicted by the TRM Eq. (42) when relative excess power is plotted versus temperature for constant i and i_0. Beginning of rollover to zero shown just above 300 K due to the limited number of usable transmission orders.

For the case shown in Fig. 16, relative minima corresponding to $n = 14, 13, 12, 11, \ldots, 6$ are located, respectively, at ~296, 257, 220, 186.4, ..., 59.6 K.

The rising sawtooth curve shows that there is usually a positive temperature coefficient for a reactor except in the neighborhood of the rollover. The relatively sharp maxima and minima of this sawtooth structure suggest themselves as possible relative optimal trigger points and antitrigger points, respectively. Although cold fusion research is yet in its infancy, a relatively long-standing question has been how to trigger the phenomenon. Thus, according to the TRM, there are relative maxima in the theoretical excess power curve labeled by n for which there are considerably more candidate diffusons for transmission than at the corresponding relative minima corresponding to n and located at a T value specified by Eq. (54). The physical meaning of these relative minima is the same as that for rollover specified by Eq. (52). Each minimum corresponds to the energy shift $q\eta$ of the M-B energy distribution shifting the latter just beyond the transmission energy window corresponding to that value of n. In between two minima corresponding to $n - 1$ and n, there must be a relative maximum corresponding to n and associated with the fact that the fast-rising M-B energy distribution as a function of E is assuring a relatively optimal contribution of diffuson candidates for transmission associated with the n'th, $(n + 1)$'th, transmission windows. The jaggedness of the curve in Fig. 16 may seem paradoxical when the smoothness of the M-B energy distribution is contemplated. However, it must be remembered that we obtain the candidate diffusons for transmission from narrow transmission windows centered at sharp transmission energies. The number of potential candidates thus depends on two basic aspects: (a) the widths of the energy transmission windows, which depend on temperature T and the energy level; and (b) more crucially, the heights of the transmission windows, given by the respective heights of the M-B energy distribution curve above the windows. Thus, energy shifts associated with changes in η_a (activation overpotential), η_c (concentration overpotential), or $\eta = \eta_a + \eta_c$ (total overpotential) and accomplishing their effect primarily through the negative term in the first term in the summations in Eqs. (31) and (42) can produce rigid shifts of the M-B energy distribution that effect dramatic changes in the relative numbers of candidates for transmission.

This temperature triggering of the excess heat phenomenon predicted by the TRM receives support from an account of an excess heat triggering episode by Scott et al.[11] A cell that had been charged failed to produce observable excess heat at a temperature of ~38°C and a current density of 600 mA/cm^2. With the current density maintained at this value, the temperature of the cell was lowered to 19°C where observable excess heat production was triggered. On the basis of the TRM, this episode can be interpreted with reference to Fig. 17, which shows a plot of relative excess power versus temperature for Scott et al.'s current density of 600 mA/cm^2. (It was found that a value of $i_0 = 1.8$ mA/cm^2 gave the best fit, and n_{max} was taken to be 1000.) Figure 17 indicates that the original cell temperature quoted by Scott et al. of 38°C corresponds to a point on the curve produced by the TRM lying to the right of a relative power minimum at 27°C. Thus, as the temperature of the cell was decreased from 38°C, the cell would initially produce diminishing excess heat, reaching a minimum in excess heat production according to the TRM at a temperature of 27°C. However, a further decrease in temperature, according to the model, would produce an increasing rate of excess heat production, reaching a relative maximum in excess heat production at the peak of the theoretical curve at 19°C.

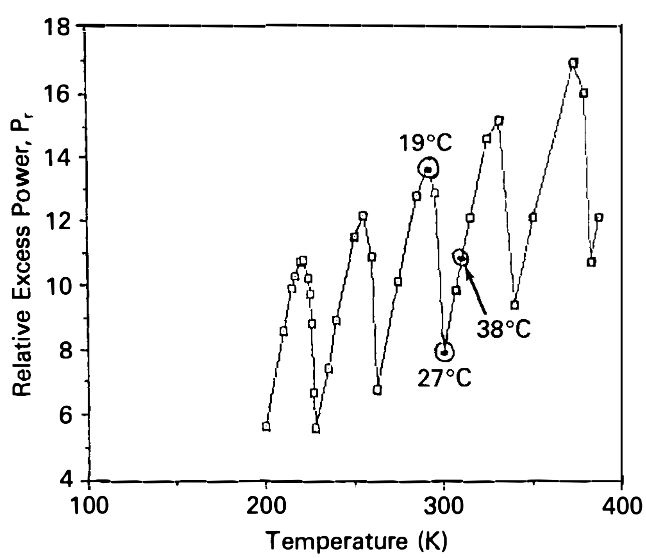

Fig. 17. Fit of the TRM to the conditions of the triggering episode reported by Scott.[11] Cooling down the cell from an initial temperature of ~38°C to a temperature of 19°C triggered observable excess heat.

The author considers this temperature triggering episode reported by Scott et al.[11] to be the first solid piece of empirical evidence in support of the TRM. Moreover, it suggests the correctness of the TRM as opposed to that of other hypothetical models in the following dramatic way. The observance of excess heat was triggered by actually cooling the cell down—and by a relatively small number of degrees. It is difficult to imagine that for either so-called fracto-fusion or some sort of chemical reaction cooling down the cell by a small amount would produce so dramatic an effect. In fact, we would expect that both of these reactions would probably be somewhat diminished by cooling. On the other hand, the subtlety of this effect is readily captured by the sawtooth curve in Fig. 17 with its sharp relative power maxima and minima differing by ~70% and separated by only ~8°C (8 K) (going from 27 to 19°C in Fig. 17). A phase transition such as the freezing of water on cooling can release heat, but it seems highly unlikely that such a phase transition occurred here. Certainly there is no independent evidence of one.

Strong supporting evidence for this temperature triggering effect in support of the TRM has been obtained at Cal Poly.[37] Figure 18 shows the fit of the model to data in a plot of actual excess power versus temperature for a constant applied current density of $i = 252$ mA/cm^2. A best fit to the data was achieved with $i_0 = 1.244$ mA/cm^2. The data were obtained from the same cell (cell 5) that was employed for the data of Figs. 13, 14, and 15. The data and the smooth curve based on the model show a rise in the relative excess power as cooling occurs. An important feature, consistent with Scott et al.'s reported triggering episode and in support of the TRM, is that only ~8°C is involved in the transition from relatively low excess power to relatively high excess power.

The model and the data of this section and Sec. V. E support the following three types of triggering:

1. The first type is pure temperature triggering of excess heat as supported by the data of Scott et al.[11] and the Cal Poly work.[37] If the temperature is at or near a relative minimum, cooling to reach a triggering peak requires the least temperature change for the cell. If the temperature were more than ~10°C higher than that peak, increasing the temperature would be equally

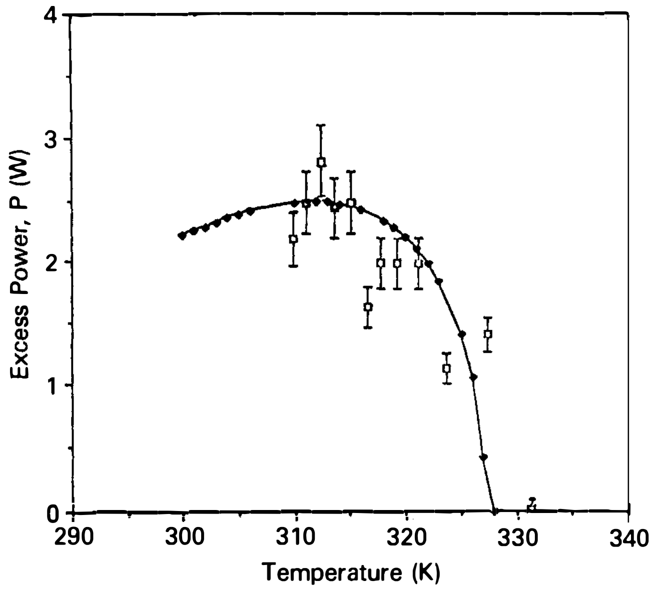

Fig. 18. Temperature triggering experiment at Cal Poly[28] in support of Scott's experiment.[14] Cooling down the cell (cell 5) by only ~8 K doubled the excess power from ~1 to 2 W.

effective, assuming we are away from a rollover region where the power curve goes to zero.

2. The second type is pure current triggering as implied by the TRM and the relative power maxima and minima seen in Figs. 12 and 13. For the experiment of Fig. 13, current triggering might be exemplified by the following hypothetical scenario based on the relative powers predicted by the model. Thus, with reference to Fig. 13, if no excess power had been observed at ~325 mA/cm^2 ($T = 312$ K), a decrease in current density to ~300 mA/cm^2 might have been sufficient to trigger observable excess heat.

3. The third type is combination triggering in which both the temperature and the applied current density are changed. Thus, again with reference to Fig. 14, little or no excess heat might be observed for a temperature of ~312 K and a current density of ~325 mA/cm^2. However, from Fig. 15 we see that observable excess heat might hypothetically be triggered by raising the temperature to 329 K and increasing the current density to 350 mA/cm^2. Note that it is not meant that zero excess heat is being produced at 325 mA/cm^2 for 312 K, but rather that it is being produced at a lower level than at either of the other two triggering points according to the TRM.

In Sec. V.G, we see yet a fourth type of excess heat triggering. One should realize that all four types achieve triggering in the same basic way; i.e., by shifting the M-B energy distribution with respect to the transmission energy windows so as to increase the height of those windows, thereby increasing the percentage of the incident diffusons that are candidates for transmission.

For the case of current triggering, as for that of temperature triggering, it is difficult to see how either fracto-fusion or an alternate model based on chemical effects could lead to an explanation of an effect in which the observable heat is actually enhanced by reducing the applied current! The TRM, however, readily explains this dramatic empirically established phenomenon. Thus, the TRM shows that a drop in current leads to a rigid shift of the M-B energy distribution to lower energies. Then, whenever this shift (associated with decreasing overpotential) to lower energies causes the lower edge of the M-B distribution to shift back to now overlie a transmission window that had been excluded, the relative number of transmission candidates among the incident deuterons is boosted and the excess heat effect enhanced.

For the first time a model to explicate cold fusion allows the prediction of optimal trigger points or search points for achieving excess heat and explains why they occur where they do. The fit of the TRM to data and the rational explanations that it presents encourage the thought that the model has captured a significant portion of the truth. In addition, the Fleischmann-Pons excess heat effect appears to be given a tremendous boost in its claim to legitimacy. Again, however, independent verification will be the key to acceptance of the model.

V.G. Excess Power Versus Overpotential: Prediction of Heat Bursts

Still a third pure type of triggering of excess heat is encompassed by the TRM as seen with relation to Eq. (31). Thus, even if the temperature T were held constant and the applied current density i were held fixed, it would still be possible for the overpotential η to change by virtue of variances in the surface leading to a changing concentration overpotential, η_c, or hydrogen overvoltage (see Fig. 9). This is equivalent in Eq. (42) to holding i and T constant and letting i_0 vary. Thus, in all three types of experiments we let η vary either through i, T, or i_0. When relative excess power P_r is plotted versus η, based on Eq. (31) and taking $T = 300$ K and $i = 200$ mA/cm^2, for $n_{max} = 16$, Fig. 19 results, with the 17 peaks and 17 valleys corresponding to the 17 available orders of transmission, $n = 0$ through $n = 16$. Again, rollover corresponds to $\eta = \sim 340$ mV since for this overpotential the associated rigid energy shift of the M-B energy distribution translates its leftward edge just far enough that the distribution curve no longer overlies the last of the 17 usable transmission windows, i.e., that associated with $n_{max} = 16$.

One does not have to look far to see what this series of peaks and valleys predicted by the TRM might

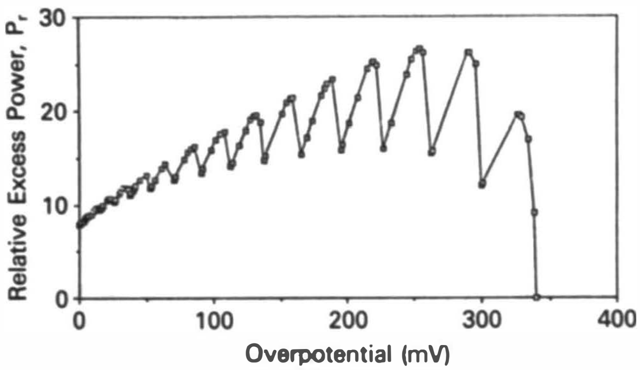

Fig. 19. Theoretical plot of relative excess power versus potential shift (activation or concentration overpotential) based on the TRM with i and T fixed in Eq. (32). Note the 17 hypothetical heat bursts predicted and corresponding to the 17 usable transmission orders $n = 0$ through $n = 16$.

refer to experimentally in cold fusion studies. Many observers have noted the phenomenon of heat bursts occurring over periods of many hours in their experiments when the current density was held approximately constant. Figure 20 shows three hypothetical heat bursts nearest rollover. Depending on the development of the surface of the cathode, one might observe either an ascending or descending series of heat bursts in terms of amplitude of the effect in a particular experiment. Of course, when rollover is approached, the effect would diminish and then vanish as $\eta = 340$ mV is

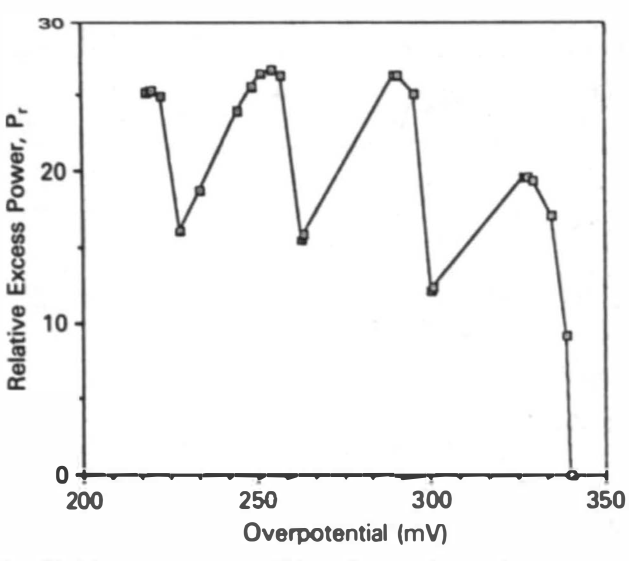

Fig. 20. Three and one-half heat bursts shown in more detail from the right side of Fig. 19 with the rollover to zero seen at ~340 K

reached. Thus, if the cathode is being platinized, perhaps by the deposition of platinum black from the anode so that $(i_0)_H$ is increasing and η_c is decreasing, this should result in a series of heat bursts descending in amplitude. If, on the other hand, deposition on the palladium cathode is leaving impurities associated with lower values of $(i_0)_H$ than the value for palladium and η_c is increasing, a series of heat bursts ascending in amplitude should be observed with the peak amplitude leveling off at a value of $\eta = \sim 250$ mV for the particular values $T = 300$ K and $i = 200$ mA/cm^2 employed in the model calculations. Following this, according to Figs. 19 and 20, would be another burst of about the same amplitude with its peak centered near 275 mV. A last burst of considerably diminished amplitude might be then observed just prior to rollover with its peak centered near $\eta = 325$ mV. After this, to the right of $\eta = 340$ mV, the experiment is over. The M-B energy distribution curve no longer overlies any of the transmission windows corresponding to the 17 usable transmission orders for the palladium transmission channel. The areas of the 17 transmission windows have now all gone to zero by virtue of their heights having all gone to zero: No amount of current (flux of diffusons) will now lead to an excess heat effect.

If changes in concentration overpotential were occurring roughly linearly in time, an ascending burst series would produce bursts of progressively longer duration. This is seen in Fig. 19 where 8 of the bursts are located in the range $100 \lesssim \eta_c \lesssim 340$ mV, while the 9 smaller bursts in the remainder of the complete sequence of 16 are located in the smaller range $0 \lesssim \eta_c \lesssim 100$ mV.

Again, the existence of heat bursts may provide strong evidence in favor of the TRM. The TRM is able to account for a series of such bursts in a very natural way in terms of a changing hydrogen overvoltage leading to shifts of the M-B energy distribution. It is the relation of the distribution curve to the energy transmission windows that controls the fraction of the available flux of deuterons that are candidates for the transmission phenomenon. The energy shift associated with the overpotential again plays a crucial role. *Moral: As the surface of the cathode goes, so goes the experiment!*

V.H. Estimation of Optimal Power: Reactor Considerations

The phenomenon of excess heat production may well be a near-surface effect, probably confined to an active depth near the surface of ~5 μm. The evidence for this is the fact that the TRM as a near-surface model gives a good fit to data, and the fact that Appleby et al.[40] have determined the migration depth of lithium to be ~5 μm for the period of time leading up to observable excess heat activity. If this is the case, it augurs well for the possible scaling-up of the effect.

Thus, if the effect is a bulk effect, then all the world's known reserves of palladium would be required to build one reactor. The fact that we have a surface effect means that relatively small amounts employed in exceedingly thin layers might be efficacious.

The other optimistic consequence of the effect as a near-surface phenomenon can be gauged from the calorimetric data of cell 5. Thus, with reference to Fig. 14, a current density of ~280 mA/cm^2 gave rise to an excess power of ~2 W. Assuming that the active depth is only ~5 μm then leads to an excess power yield per cubic centimetre of palladium given by

$$P_{exc} = 2\ \text{W}/(4\ \text{cm}^2 \times 5 \times 10^{-4}\ \text{cm}) \qquad (55)$$

$$= 1\ \text{kW}/(\text{cm}^3\ \text{of palladium}) \ . \qquad (55)$$

Huggins et al.[9] point out that a standard nuclear fusion reactor yields only ~50 W/cm^3 of reactor core. Indeed, there appears room for optimism here.

It is interesting to see what the TRM might say about the design of an optimal reactor. A computer search was performed employing Eq. (31) for a current density of i = 500 mA/cm^2 to find an optimal reactor in terms of excess power, operating cell temperature T, and overpotential η. Since, however, it was realized that efficiency is also important, a figure of merit was defined as the product of the relative excess power from Eq. (31) multiplied by the factor for thermal efficiency of $(T - 300\ \text{K})/T$, where it has been assumed that the reservoir temperature was at 300 K. Figure 21 shows a plot of figure of merit versus overpotential for the temperatures of 500, 611 (approximately the operating temperature for reactors generating steam), 800, and 1700 K. All roll over and go to zero for an η value of ~340 mV. Note that the curves for the three lower temperatures all have maxima near an η value of ~180 mV. It has been assumed that an i value of 500 mA/cm^2 can be achieved for this η value. Also, the curves have been smoothed out so that the sawtooth nature with its local decreases and relative minima such as appear in Figs. 19 and 20 have been left out. With regard to power, the peak of the 611 K curve corresponds to an excess power of ~4 kW/cm^3 Pd if the palladium is employed in thin layers ~5 μm thick with a backing of a different metal such as nickel. The ratio of excess power to input power would be ~4 in this case. Again, however, it is important to realize that this is a naive reactor theory at this stage, quite ignorant of difficulties that are bound to present themselves in any actual scaling-up attempts. Nevertheless, this naive reactor theory based on palladium sounds a note of genuine optimism. Of course, other metals, perhaps titanium and/or zirconium, and alloys or exotic composites, or designer deuterides may turn out to be important for practical applications.

Recall that accounts in the popular press of attempts to produce a successful hot fusion reactor often refer to these efforts as being in search of the "holy grail" of physics. (Yet another holy grail of physics would be a unified field theory.) The holy grail as a containing vessel seems quite appropriate in the case of hot fusion. It is interesting that, in the most famous of the grail romances, *Parzival*, the grail is actually a sacred stone.[46] Perhaps now we know what that stone was made of . . . .

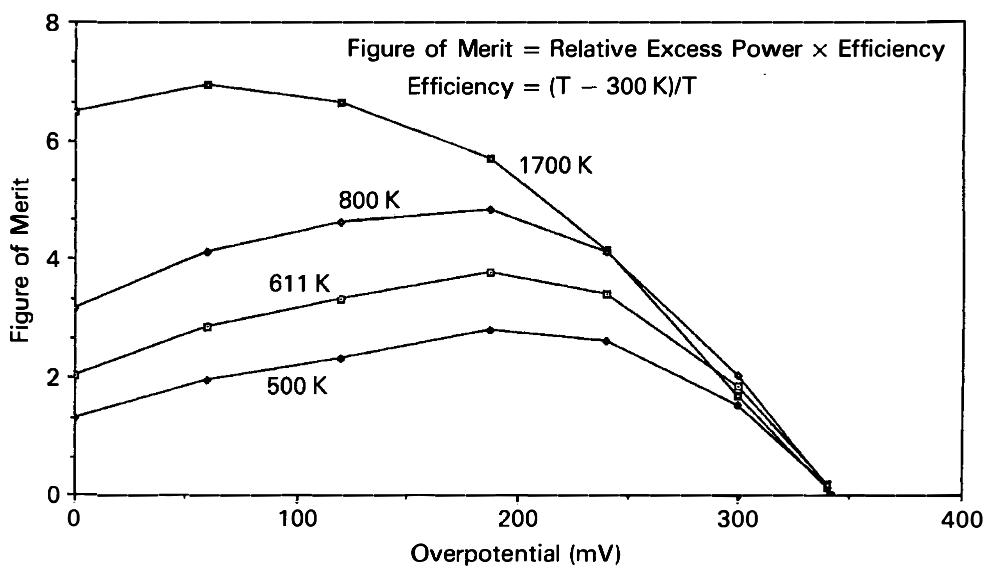

Fig. 21. Optimal reactor theory: plot of a figure of merit versus overpotential for temperatures of 500, 611, 800, and 1700 K, for a fixed current density of 500 mA/cm^2.

V.I. Self-Similar Geometry of the Relative Excess Power Functions: Their Fractal Nature

The sawtooth nature of the curves produced by the TRM from a plot of relative excess power versus temperature (see Figs. 16 and 17) and the cusps in the TRM plots of relative excess power versus current density suggest a fractal nature. Another indication of this fractal nature is that the relative excess power functions associated with Eqs. (31) and (42) when graphed exhibit self-similar geometry or scale invariance. We define relative excess power functions as the expressions for P_r in Eqs. (31) and (42) when the summations are taken over all values of n ranging from zero to infinity. Because of the rapidly converging negative exponentials, such functions are even useful in the model provided we are reasonably far away from the rollover region. This self-similar geometry may be seen by comparing Fig. 22. Thus, a graph of relative excess power versus current density with T and i_0 held fixed looks essentially the same in the three ranges of current density i, 0 to 400, 0 to 800, and 0 to 2000 mA/cm^2, portrayed in these three figures, respectively. As another example, consider Fig. 19 and suppose that the curve were prevented from ever rolling over by taking n_{max} = infinity in the summation. The curve would look the same no matter what range of T we chose to look at. (This is not precisely true since the existence of a lowest state corresponding to $n = 0$ means that the process is truncated in the lower direction. Thus, we coin the term lower limited self-similar geometry to refer to these situations. In fact, all actual objects, such as a minaret cauliflower, actually exhibit lower limited and upper limited self-similar geometry, with the possible exception of the large-scale structure of the universe itself, for rather obvious structural reasons at small and large enough dimensions.) (The author wishes to credit a colloquium at Cal Poly on self-similar geometry presented by Ohrbach,[47] for leading the author to the conjecture of the involvement of self-similar geometry in the mathematical functions important in the TRM.)

Taking this conjecture seriously, Eagleton[48] demonstrated this for the case of the relation in Eq. (42) for P_r plotted versus temperature with i_0 and i held constant. Eagleton was able to show, using $n_{max} = 1000$, that the temperatures corresponding to the relative excess power maxima obey the approximate relation

$$T_{m-1}T_{m+1} \simeq 1.05(T_m)^2 \ . \qquad (56)$$

Note that in each of the three possible sets of curves based on the TRM expression in Eq. (42) (i.e., P_r graphed versus either i, T, or i_0, respectively, with the other two parameters held fixed) the locations P_m of either the relative excess power maxima or the minima, respectively, obey the approximate relation, similar to Eq. (56), of

$$P_{m-1}P_{m+1} \simeq (P_m)^2 \ . \qquad (57)$$

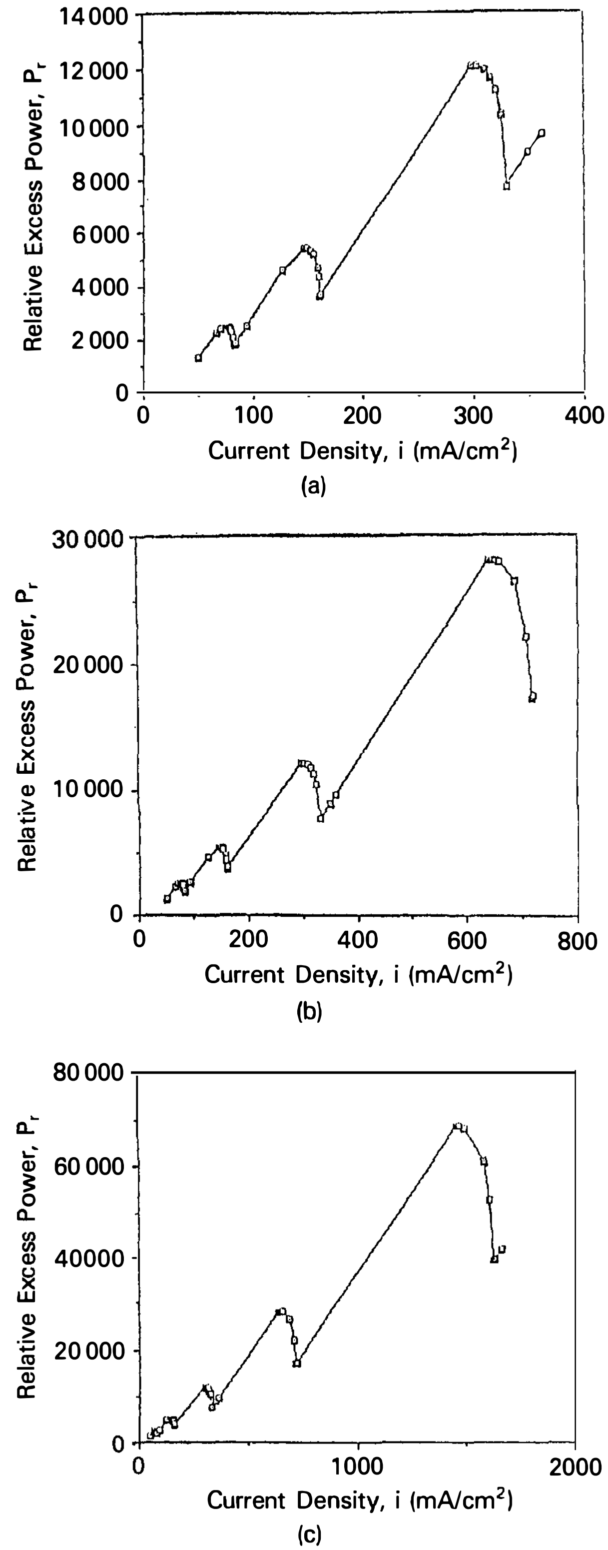

Fig. 22. The self-similar geometry (or scale invariance) of the relative excess power function P_r for cold fusion implying a fractal nature. For these curves, the landscape looks the same regardless of the range examined. (This assumes that the order n is not limited.) Based on Eq. (42), n_{max} was taken to be 1000 for these, and i_0 and T were held constant.

The TRM suggests an approximate scale invariance for the predicted heat bursts when relative excess power is plotted versus hydrogen overvoltage, as seen in Fig. 19. If the change in hydrogen overvoltage is approximately linear in time, this would extend the self-similar geometry to the time dimension. Thus, if η in Eq. (31) changes approximately linearly with time, the resulting scale invariance may link the TRM and cold fusion with chaos theory. Chaos theory describes time-dependent phenomena as seemingly disparate as the dripping of a faucet, the weather, and the beating of a human heart. Scale invariance with regard to time again implies a fractal description, and fractals are the natural descriptive mathematical element of chaos theory.

To conclude this section, it seems appropriate to observe that cold fusion may well turn out to be "fractal," although probably not "fracto"-fusion.

VI. NUCLEAR REACTIONS SUGGESTED BY THE TRM

VI.A. Introduction: Transmission Resonance-Induced Nuclear Transmutation Reactions

Until now, nuclear reactions in general, much less specific nuclear reactions, have hardly entered into the considerations except insofar as the phenomenon of transmission resonance has been hypothesized to allow two particles to get close enough within the lattice to permit a nuclear reaction. In this sense the TRM is reaction aspecific: Its applicability is not tied to a specific nuclear reaction. Ultimately, it is important to know what reaction, or reactions, really are the source of the excess heat. In addition, it is important to be able to explain such anomalies as the small branching ratio for the production of neutrons to protons and the apparent low yield of gamma rays. Thus, it would be helpful if the model could provide guidance in narrowing the list of possibilities, or provide favorite candidates.

The quintessential cold nuclear reactions suggested by the model are labeled transmission resonance-induced nuclear transmutation (TRINT) reactions. A subclass of the TRINT reactions that appears to provide the strongest candidates for the actual reactions involve the cold transfer of a neutron. This subclass is referred to as transmission resonance-induced neutron transfer (trint).

VI.B. The trint Reactions

Due to phonon exchange effects associated with the vibrations of the potential wells, the palladium transmission channel is apparently limited to a maximum transmission order n of 16 (at room temperature), while the deuteron transmission channel is limited to the $n = 0$ and $n = 1$ orders. (Previously,[15,16] we specified these as $n_{max} = 15$ for the palladium transmission channel and $n = 0$ for the deuteron transmission channel.) Two important consequences of this were previously presented.[15,16]

First, the vast majority of deuterium-deuterium (D-D) reactions are associated with the $n = 1$ order of the deuteron transmission channel. For this order, the relative velocity of approach of the deuterons would only be ~519 m/s, corresponding to an energy of only ~3 meV; i.e., 3×10^{-6} keV! Under these circumstances, a large charge distribution polarization effect of the positive charge distributions of the two approaching deuterons is hypothesized. It is this effect that might cause the branching ratio to shift in favor of the tritium-producing reaction over the neutron-producing reaction. (This polarization conjecture is treated at length in Sec. VI.E, where a value is derived for this branching ratio.)

The TRM suggests that the favored cold D-D reaction is a stripping reaction in which one deuteron strips a neutron from the other deuteron to yield a triton and a proton. Thus, this resembles the Oppenheimer-Phillips reaction suggested by Ragheb and Miley,[49] Paolo,[50] and by Bush and Eagleton.[31,32] Since the reaction is also associated with the transmission resonance phenomenon, it is, strictly speaking, a new type of nuclear reaction, a trint reaction. We consider trint reactions to be a possible prototype for cold fusion reactions. They are a special case of that group, TRINT, which includes all the cold nuclear reactions induced via transmission resonance. Note also that the longer wavelengths of the particles at the low energies of the trint reaction could favor an Oppenheimer-Phillips type neutron transfer reaction. (Apparently McNally[23] is to be credited with the original conception of the significance that the longer de Broglie wavelengths might have in the interaction of very low-energy nuclei.)

The second important consequence of the transmission channel limiting effect is that, based on the much larger number of transmission orders [i.e., 17 ($n = 0$ through $n = 16$) as opposed to 2 ($n = 0$ and $n = 1$)], and the fact that the width of a transmission window associated with an order goes directly as T_n, the nuclear reactions of a deuteron with a palladium nucleus in the palladium transmission channel will predominate numerically over the D-D reaction in the deuteron transmission channel.

Recall from the standpoint of the two-body tunneling reaction (Gamow theory) that this would not be reasonable due to the much larger charge on a palladium nucleus than on a deuteron. Again, however, we are reminded that the many-body reaction is counterintuitive to the Gamow case. What matters is whether the transmission resonance condition holds for some of the deuterons relative to the wells formed by the potential curves of neighboring palladium positive centers. Note that the spacings of neighboring palladium atoms will be essentially the same as that of the interstitial deuterons; thus the transmission energy level schemes will be the same.

Again, the velocities of relative approach are posited to be low enough for the transmission orders $n = 0$ through $n = 16$ that polarization effects will overwhelmingly produce a trint reaction in which the palladium nucleus strips a neutron off the deuteron to yield a proton plus a heavier palladium nucleus. The fact that a neutron does not have to face the Coulomb barrier is a tremendous advantage at the low energies of the trint reactions. Indeed, this feature of not having to face the Coulomb barrier is an important consideration recommending the trint reaction as the prototypical cold fusion reaction.

It is this reaction that the TRM suggests as a prime candidate for the excess heat producing reaction. If it is the heat producing reaction then, as was pointed out previously[15,16]: "Because of the fact that the D is a loosely bound nuclear structure, the greater binding energy per nucleon in the heavier Pd nucleus (formed in the trint reaction) as compared to the initial lighter Pd nucleus would be the ultimate source of the energy finally showing up as excess heat."

Two examples of such trint reactions involving the palladium isotopes are

$$D + {}^{105}Pd \rightarrow p(7.35\ MeV) + {}^{106}Pd \tag{58a}$$

and

$$D + {}^{106}Pd \rightarrow p(4.31\ MeV) + {}^{107}Pd\ . \tag{58b}$$

Angular momentum and parity conservation must be ensured by radiation of the appropriate electromagnetic energy or by having the lattice or boson plasma (of deuterons) enter the interaction directly. Since radiation is not detected, there must be some explanation for this. Perhaps the necessary angular momentum, with its associated energy, is given over electromagnetically and directly to the boson plasma of deuterons, and then to the crystalline lattice.

Equation (58a) has been somewhat suggested by the experimental work of Rolison et al.,[51] who have found experimental evidence for a slight enrichment of ^{106}Pd and a corresponding diminution in ^{105}Pd in palladium foils electrolyzed in Li^2SO^4. As mentioned previously,[16] it is not easy to detect the isotope shift of Eq. (58b) either by mass spectroscopy or the beta decay of the ^{107}Pd. One possibility[16] would be to electrolyze the same palladium cathode many times. The cathode should be recast when cracking makes this necessary, but care must be exercised to avoid palladium contamination. It has been estimated that 20 MJ/g of excess heat must be generated for a particular cathode to reach the threshold for detection of ^{107}Pd via the beta decay to ^{107}Ag with a half-life of 7×10^6 yr and a beta energy of 35 keV.

A significant consequence of this trint reaction as the source of the excess heat is that there is no compound nucleus formed in this reaction. Thus, there need be no gamma rays or neutrons emitted in connection with a short-lived excited state of a compound nucleus provided that some other mechanism, such as the boson plasma or crystalline lattice, can also enter the interaction to account for both angular momentum and parity conservation. The protons in both cases would serve very efficiently to carry away the energy! This energy would quickly end up in the lattice as heat because of ionization processes transferring energy from the proton. If these trint reactions are the ultimate source of the excess heat, then a completely new nuclear reaction is involved. (We have, of course, noted the possible similarity to the Oppenheimer-Phillips process. Nevertheless, the association with the transmission resonance phenomenon is important.) This hypothetical trint reaction involving a deuteron on palladium shares common features with both nuclear fission and nuclear fusion but also differs from both. The TRM suggests it as, perhaps, the prime candidates for the source of excess heat.

VI.C. Comparison with Teller's Catalytic Neutron Transfer Hypothesis

Teller[52] has hypothesized the existence of a hitherto unknown neutral particle that would catalyze the transfer of a neutron between two particles such as two deuterons inside a metal at room temperature. This hypothesis, catalytic neutron transfer, has the same end result as the trint reaction just hypothesized, but the latter has the advantage of simplicity. However, should it be discovered that there are variations in the average outputs of excess heat depending on laboratory altitude, shielding depth below the earth's surface, or the solar cycle, this would give additional strength to Teller's suggestion.

VI.D. An Experiment to Convince Physicists

In connection with his hypothesis of catalytic neutron transfer, Teller[52] has suggested employing ^{235}U cathodically in an electrolytic cold fusion experiment since uranium's response to absorbing a neutron is well known. Now, the TRM with its hypothesized trint reactions gives added support to this research suggestion. Thus, if either Teller's hypothesis or the TRM are correct, one should see many more neutrons emitted from a uranium cathode enriched with ^{235}U and loaded with deuterons (cathode immersed in D_2O + LiOD) than from an identically constructed and charged cathode loaded with protons (cathode immersed in H_2O + LiOH). The difference in neutron yields should be dramatic enough to convince physicists that room temperature nuclear reactions are possible inside a metal lattice.

VI.E. Derivation of the D-D Branching Ratio from a Polarization Conjecture

A severe criticism of cold fusion concerns the anomalously low neutron yields reported by different researchers. The anomalous D-D branching ratio has been part of this controversy. According to conventional hot fusion physics, if the standard D-D reaction with its two branches, which ordinarily gives the reaction products (T,p) and $(^3\text{He},n)$ with a one-to-one branching ratio, is involved, why is it that so many more tritons are observed than neutrons when yields of the two species are measured in the same experiment?!

The TRM appears to be able to answer this criticism. Recall that thermal vibrations of the deuteron transmission channel limit it to the $n = 0$ and $n = 1$ orders of transmission, as opposed to the $n = 0$ through $n = 16$ orders available to the palladium transmission channel at room temperature. This means that the stripping reactions (Oppenheimer-Phillips) associated with D-D are occurring in cold fusion experiments at an impressively low energy compared to 1 MeV or even 1 keV. For the $n = 0$ order, Eq. (3) shows that one deuteron approaches an interstitial deuteron with an energy of only about one-third of mega-electron-volt or 0.33×10^{-6} keV! For the $n = 1$ order, Eq. (3) shows that the energy of the approaching deuteron is only about an order of magnitude larger at $\sim 3 \times 10^{-6}$ keV. Thus, the TRM suggests that we are in an extreme polarization regime (with regard to the mutual charge distribution polarizing effects of the approaching deuteronic charges) where the relative velocities of approach of two deuterons within the lattice are absurdly low compared to those typically associated with the asymptotically free environment of a hot plasma. We hypothesize that the electric fields associated with the positive charges on the two deuterons can thus achieve a crucial polarizing effect on the positive charge distributions within the two approaching deuterons leading to an extremely low branching ratio in favor of triton production over that of neutrons. This is part of what is termed the polarization conjecture.

It is suggested that the D-D reaction in a deuterated metal lattice or other material is, in the vast majority of cases, a trint reaction in which a neutron is stripped from one deuteron by the other to yield a triton and a proton. (Again, this is reminiscent of an Oppenheimer-Phillips reaction.) There is a chance that a proton will be stripped from one deuteron by the other to produce an ^{3}He nucleus and a neutron $(^3\text{He},n)$ in a TRINT reaction. We now include the idea of the charge distribution polarization of the two deuterons by each other to arrive at an estimate of the branching ratio in this extreme polarization regime. The derivation is based on the unproven but physically appealing notion of the mutual charge distribution polarization of the two approaching deuterons in these ultralow-energy instances. Thus, the derivation is intended to be heuristic, rather than highly rigorous and a premium is placed on an appeal to physical plausibility and simplicity.

Consider Fig. 23, which shows the hypothetical charge distribution for two approaching deuterons in this extreme polarization regime. We assume that, at some stage where the centers of the two deuterons have reached a crucial separation, the mutual charge distribution polarizing effects of the two positive charge distributions begin to be significant in altering the positive charge distributions relative to their respective deuteronic centers. Figure 23a shows the positive charge uniformly distributed in both deuterons. Assume for the moment that both deuterons are in an s state ($l = 0$), so that they are not rotating relative to each other. We hypothesize that the velocities of approach for the $n = 0$ and $n = 1$ transmission states are so low that charge polarization results in the positive charge centers being located in the back halves of the two approaching deuterons prior to the stripping reaction as shown in Fig. 23b. Since the positive charge distribution is associated with the protonic component of the deuteron, this polarized charge configuration means that the neutronic components of the two respective deuterons see each other "nuclearly," before a neutron and proton "see" each other, and before a proton and a proton see each other.

Thus, overwhelmingly, a nuclear reaction should consist of one of the neutrons being stripped off by the other deuteron, producing a triton and leaving behind a proton. The polarization conjecture, however, brooks one exception to this. If the positive charge distributions of the two deuterons have their centers near the respective leading edges of the two approaching deuterons and on the line connecting the centers of the deuterons, at the time of the crucial separation of the two deuterons at which polarizing effects become important, as shown in Fig. 23c, a reaction is then promoted in which a proton is stripped off, instead of a neutron, leading to an ^{3}He nucleus and leaving behind a neutron. This is because, in this circumstance, the two positive charge distributions push each other directly backward and along the line of the centers of the two deuterons so that the two respective positive charge centers remain in the front halves of the deuterons.

To maximize the stripping away of a proton from its neutron in a deuteron, we also assume that, at the crucial separation of the deuterons and also at the point of stripping, the neutrons are on the far sides of their respective deuterons, as shown in Fig. 23c; thus, the neutrons exert a minimal nuclear attraction on their respective protons. This configuration, with the protons on the leading edges of their respective deuterons and the neutrons on the trailing edges of their respective deuterons, is illustrated schematically in Fig. 23c and is referred to as the "neutron-yielding configuration" (NYC). It is assumed that the NYC is maintained

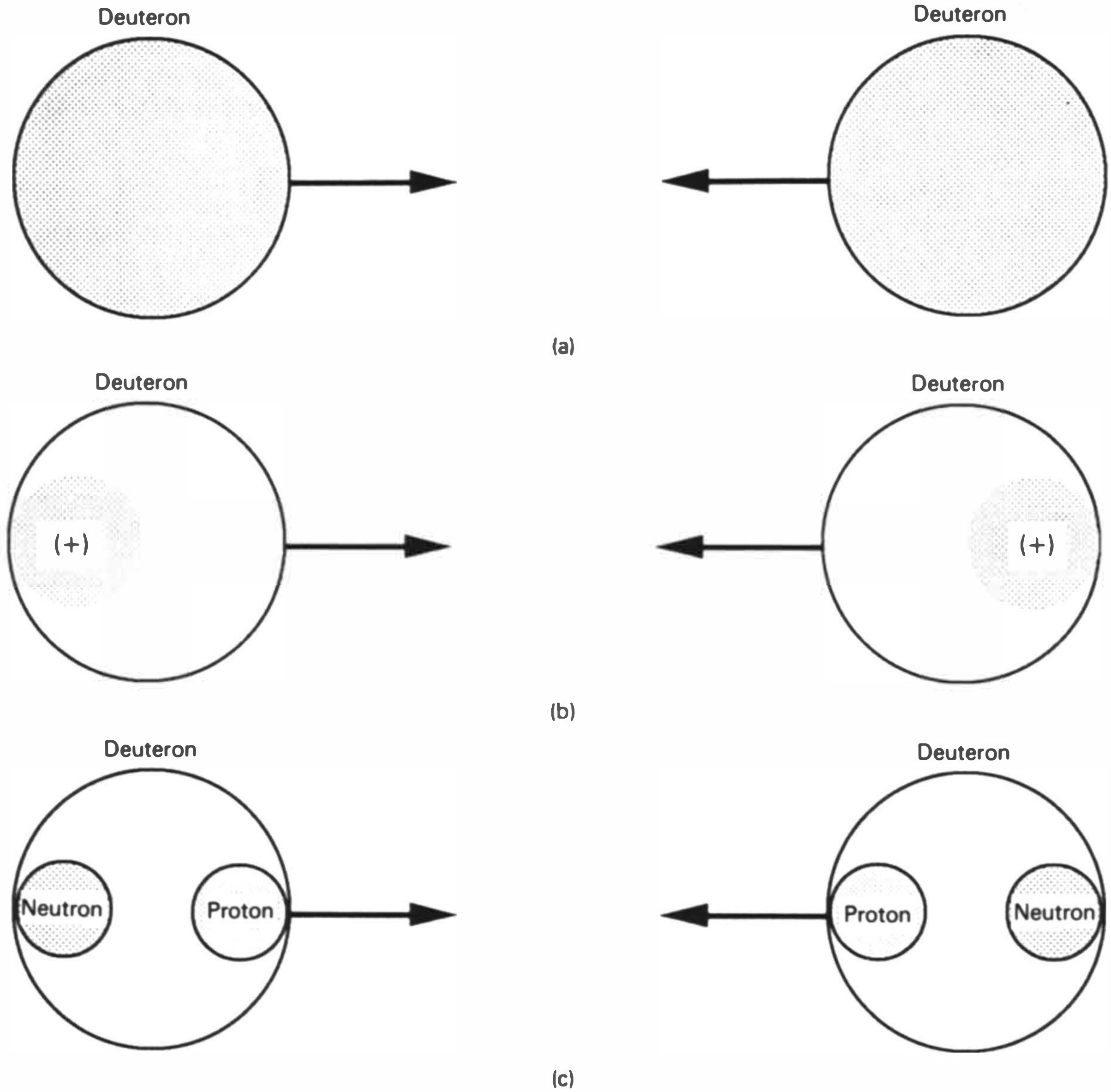

Fig. 23. (a) Approaching deuterons exhibiting as yet no charge distribution polarization (the uniform shading indicates a uniform distribution of positive charge); (b) significant mutual charge distribution polarization has now occurred, leading to a PYC; and (c) the two deuterons exhibiting the NYC, essentially the only configuration leading to D-D neutron production when charge distribution polarization effects are massive, as they should be for the low velocities of approach in the lattice predicted by the TRM.

until the stripping reaction occurs with a deuteron stripping away the proton of the other to yield ^3He plus a neutron.

What then is the probability of realizing this configuration? In calculating this, the deuteron and the proton are treated as spheres with radii R and r, respectively, and the radius of the proton core of the neutron[53] is also taken to be r. The probability $(P_p)_L$ that the proton on the left deuteron in Fig. 23c is in the NYC is given by the ratio of its volume to that of the deuteron:

$$(P_p)_L = (r/R)^3 \ . \tag{59a}$$

The probability that the proton core of the neutron on the left deuteron is in the NYC, independently, is also specified by this. Thus, the probability P_{NYC} that the left deuteron is completely in the NYC is the product of these, assumed to be independent:

$$(P_{\mathrm{NYC}})_L = [(r/R)^3]^2 = (r/R)^6 \ . \tag{59b}$$

The probability that the deuteron on the right side is independently in this same configuration is clearly the same:

$$(P_{\mathrm{NYC}})_R = (r/R)^6 \ . \tag{60}$$

Finally, the probability P_{NYC} that the total NYC exists for both deuterons at the brink of stripping is the product of the two:

$$P_{NYC} = (P_{NYC})_L \, (P_{NYC})_R = [(P_{NYC})_L]^2 = (r/R)^{12} \ . \tag{61}$$

Substituting $r = 0.8 \times 10^{-13}$ cm and R = 4.31×10^{-13} cm (Ref. 53) leads to

$$P_{NYC} = 1.67 \times 10^{-9} \ . \tag{62}$$

This, however, is not yet the branching ratio. It must now be asked what the probability $(P)_{PYC}$ is for the "proton yielding configuration" (PYC) since the branching ratio BR is given by the ratio

$$BR = (P_{NYC})/(P_{PYC}) \ . \tag{63}$$

Clearly, the probability P_1 that any one of the four particles is in the PYC is simply the ratio of that volume of the deuteron, excluding the volume of the particle, to the entire volume of the deuteron.

$$P_1 = (R^3 - r^3)/R^3 = 0.993605 \ . \tag{64}$$

To further illustrate, consider the tossing of four independent coins, each of which represents one of the four particles in the two deuterons. Since the outcome in each case is either H(eads) or T(ails), let us analogize the NYC's being achieved at the point of stripping to the outcome TTTT for the four independent coin tosses. The other 15 possible outcomes for the tossing of the 4 coins all correspond to at least one of the particles not being in the NYC; thus, they all correspond to the PYC. There is one outcome with four H's and no T's, four outcomes with three H's and one T, six outcomes with two H's and two T's, and four outcomes with one H and three T's. This gives us 16 outcomes altogether counting the outcome TTTT representing the NYC. Thus, if H and T each represent a probability of 0.5, assuming an idealized situation, the branching ratio for our problem would be simply 1 to 15. We could represent this schematically by the algorithm

$$\begin{aligned} BR &= (P_{NYC})/(P_{PYC}) \\ &= \{(\tfrac{1}{16})(TTTT)/(\tfrac{1}{16})[(HHHH) \\ &\quad + 4(T)(HHH) + 6(TT)(HH) \\ &\quad + 4(TTT)(H)]\} \ . \end{aligned} \tag{65a}$$

In the present case, T and H, the probabilities for single particles to be in the NYC and the PYC, respectively, are not equal to $\frac{1}{2}$ but are given by $T = (P_p)_L = (r/R)^3$ and $H = P_1 = [1 - (r/R)^3]$. Substituting these values into Eq. (65a), the theoretical expression for the branching ratio becomes

$$\begin{aligned} BR = \big[(r/R)^{12}/([1-(r/R)^3]\ \{[1-(r/R)^3]^3 \\ + 4(r/R)^3[1-(r/R)^3]^2 + 6(r/R)^6[1-(r/R)^3] \\ + 4(r/R)^9\})\big] \ . \end{aligned} \tag{65b}$$

Substituting the numerical values $r = 0.8 \times 10^{-13}$ cm (Ref. 53) and $R = 4.31 \times 10^{-13}$ cm (Ref. 53) into Eq. (67b) yields the following value of the branching ratio for neutron-to-proton (tritium) production from this heuristic derivation:

$$BR \simeq (1.672 \times 10^{-9})/(1.019) \simeq 1.64 \times 10^{-9} \ , \tag{66}$$

which compares rather well with the most recent best experimental value[54] for this branching ratio of

$$(BR)_{exp} = 2 \times 10^{-9} \ . \tag{67}$$

Note that the theoretical BR based on the polarization conjecture is expected to be lower than the experimental result since, in reality, the centers of the protons for the NYC should be able to range slightly around the line of centers of the approaching deuterons, and the protons should not need to have their centers exactly r away from the edges of their respective deuterons to yield a neutron in the reaction.

Worledge[55] pointed to the fact that there is a d state ($l = 2$) component of the deuteron wave function along with the s state ($l = 0$). Thus, a certain portion of the deuterons, 2 to 8% according to DeBenedetti,[53] are spinning about their centers. If this were true in the trint reactions under consideration, the branching ratio would be many orders of magnitude larger than that in Eq. (66), and in extremely poor agreement with the experimental one in Eq. (67). To deal with this criticism, we must include in the polarization conjecture that the d state is somehow inoperative in these trint reactions. There are several possible physical reasons for this. One possibility is simply that the torques associated with these fields stop the rotation of the approaching deuterons. Note that the protonic charge relative to the deuteron might be likened in a first approximation to a combination of an electric dipole, with the negative end at the deuteronic center, and a positive monopole at the deuteronic center. A second possibility is that the charge distributions can adjust to the polarizing fields at close distances with response times that are short compared to the period of revolution. Finally, we really do not know what percentage contribution the states with angular momentum of the deuteron make to the exchange reactions at higher energies. Perhaps the percentage is low enough to be compatible with Eq. (65b) for the trint reaction.

In the spirit of the polarization conjecture, it is anticipated that the branching ratio is a function of the relative energy of approach. This is not a new idea, but is worth reemphasizing in the context of the polarization conjecture. The branching ratio would be expected to vary depending on the energy distribution of the reactants because of the mutual charge distribution polarizing effects of the deuteronic charge distributions of the two approaching deuterons. The theoretical expression [Eq. (65b)] derived would be expected to be an approximation to the actual limiting expression that should be valid for the ultralow energies of the trint reactions. Thus, as the energy of the reaction is increased, the branching ratio should eventually attain the high-energy approximation of 1:1 well known to plasma physicists.

That the derived branching ratio based on simple probability and an appealing physical argument is in such good agreement with the experimental result suggests that the derivation and result are more than a mere curiosity. Again, the derivation is not intended to be rigorous; it is intended to be a plausibility argument based on the polarization conjecture. It is included because the low energies of approach derived from the TRM suggest the plausibility of trint reactions with such charge distribution polarization effects. It is an intriguing result, and theoretical work is now in progress to rigorously prove or disprove the scenario presented here.

According to Bockris,[56] the value in Eq. (67) is a best value, with the experimental values actually ranging as high as $\sim 10^{-3}$ and as low as $\sim 10^{-10}$. It may be that this range reflects the different energy ranges involved in the different types of experiments or differing opportunities for tritium to be freed from the sample. Note that more recent experiments of a different variety conducted by Clayter[57] at somewhat higher energies yield a best value branching ratio of $\sim 3 \times 10^{-9}$.

VI.F. The TRM's Suggestion for the D-T Puzzle

Another trenchant criticism of cold "fusion" research concerns the well-known neutron-producing deuterium-tritium (D-T) reaction

$$D + T \rightarrow {}^4He\ (3.5\ MeV) + n\ (14.1\ MeV) \ . \quad (68)$$

Thus, critics contend, even if one could possibly account for the low branching ratio of neutrons to tritons, there should be plenty of tritons to interact with the deuterons. Accordingly, this should yield an observable neutron flux via the reaction above. Section VII shows that observable tritium production is rather unusual in the case of electrolytic cold fusion based on the TRM. Thus, the TRM indicates under what conditions observable excess heat and observable tritium should be produced simultaneously in electrolytic cold fusion. However, it also shows that, ordinarily, excess heat is seen without observable tritium in an electrolytic experiment. Nevertheless, the reaction in Eq. (68) is examined within the context of the TRM assuming that readily observable tritium is being produced.

Inside the lattice, the tritons produced in D-D reactions, for example, should quickly lose their kinetic energy to the lattice via ionization processes. This means that the D-T reaction in Eq. (68) would need be a cold nuclear reaction. The polarization conjecture, which was successful in predicting the branching ratio for the D-D reaction at ultralow energies, vastly favors the exchange of a neutron (i.e., a trint reaction) over that of a proton for the D-T reaction. However, since a neutron exchange (Oppenheimer-Phillips reaction) from the deuteron to the triton would yield an unstable hydrogen with three neutrons and one proton, the most likely trint reaction is one in which the deuteron strips a neutron from the triton to produce a simple exchange of identities. Thus, from the perspective of the TRM, the D-T puzzle is solved because the reaction in Eq. (68) would be very rare in the environment of cold fusion.

VI.G. Three-Body TRINT Reactions

The ideal physical situation for the TRM to be valid may be that of a standing wave of deuterons within the palladium lattice. The reason for this is the in-principle indistinguishability of these bosons and the fact that we have made a somewhat artificial division of the deuterons into interstitial particles and diffusons. Because of this indistinguishability, a wave traveling in only one direction is essentially composed only of diffusons and thus does not provide the encounters for nuclear reactions provided by a standing matter wave associated with particles moving in both directions and stationary particles, which can represent particles vibrating about interstitial equilibrium positions. We anticipate that the favored reaction based on symmetry, both spatial and wave mechanical, would be a three-body reaction (D + D + D) in which two deuterons as diffusons approach an interstitial deuteron from opposite directions. Ordinarily, as in the case of a hot plasma, the chance of a three-body reaction as opposed to a two-body reaction is miniscule. However, because of the different environment and the possibility of a standing de Broglie wave, the situation could be very different within a lattice. Since the relative speeds of approach are rather small on the basis of the TRM, we anticipate significant polarization effects produced via the interactions of the protons in the deuterons. Thus, an Oppenheimer-Phillips process coupled with this polarization effect would be expected to lead to the production of tritons and ${}^3He$ nuclei with equal kinetic energies of ~ 4.77 MeV, as opposed to the 1.01-MeV tritons and 0.82-MeV ${}^3He$ nuclei of the two-body D-D reaction. If the latter reaction is rare compared to the D + D + D reaction, it could also help to explain the anomalously low yields of neutrons associated with cold fusion. The author is grateful to Worledge[58] for asking me whether the TRM has anything to say about such reactions. (According to Worledge,[58] such three-body reactions may explain some results achieved by Cecil of the Colorado School of Mines and Hubler of the Naval Research Laboratory.) The D-D reaction, when it does occur, would also involve low relative speeds of approach of the particles so that charge distribution polarization effects could lead to the observed branching ratio of $\sim 2 \times 10^{-9}$ as already shown. Takahashi[59] recently published studies of three-body cold fusion reactions.

The three-body deuteron reaction could also result in the fusing of the deuterons to produce ^{6}Li, as suggested by Cecil.[60] Since some experimenters have seen an increase in ^{6}Li concentration,[61] this reaction poses a possible explanation. The latter would be stopped quickly within the lattice, but the lack of observable electromagnetic radiation would have to be explained.

Recall now the earlier treatment of the limitations on the spatial coherence of the de Broglie wave of a diffuson introduced by phonon exchange (vibration of the potential wells) and that it has much more effect in the deuteron channel for transmission resonance than in the palladium channel since the greater mass of the palladium centers means less amplitude of vibration of their potential wells than for those of the interstitial deuterons. If, at ~300 K, the palladium channel can sustain the spatial coherence of the de Broglie waves for the diffusions to a maximum order of transmission of $\sim n_{max} = 16$, the deuteron channel for transmission offered by the interstitial deuterons would correspondingly sustain only $n_{max} = 1$. Thus, it might be anticipated that the ultimate source of the energy associated with excess heat is associated with the palladium channel. In direct analogy to the earlier D + D + D reaction associated with a wave-mechanical standing wave in which two deuterons converge in opposite directions on an interstitial deuteron, a natural reaction for this channel favored by these considerations from the TRM would be a reaction in which the two deuterons converge on a palladium nucleus from opposite directions to produce a cadmium nucleus in an excited state. Since the latter is hooked into the lattice, a reasonable deexcitation reaction might involve the emission of two alpha particles (^{4}He) in opposite directions and the creation of phonons in the lattice. In the former case, the final state of the positive center would be a ruthenium nucleus. This type of reaction, a three-body TRINT reaction, stands a remote chance of being the ultimate source of the excess heat associated with cold fusion. However, we must still consider the possibility of the emission of gamma rays and neutrons associated with compound nucleus formation.

The inability of researchers to detect ^{4}He thus far seems to argue against the specific TRINT reaction involving the emission of two alpha particles and leading to the production of ruthenium. As pointed out at the Utah conference, there is a possibility that ^{4}He has escaped from the cathode via cracks near the surface. This would especially be the case if the excess heat process is one occurring relatively near the surface. Thus, a case against ^{4}He, or a reaction involving the production of ^{3}He, has not really been established experimentally.

Two additional three-body reactions deserving mention as possible energy sources involve two deuterons converging on either a substitutional ^{6}Li or a ^{7}Li to give, respectively, an excited ^{5}B^{10} nucleus and an excited ^{5}B^{11} nucleus. A nod should perhaps be given here to the ^{7}Li reaction since there is more of it, and researchers have reported the apparent increase of ^{6}Li concentrations in their cells. Of course, both reactions might be possible.

Hutchinson[43] has reported achieving excess power employing 97% pure ^{6}Li in the electrolyte. A two-body candidate reaction is the deuteron on a substitutional ^{6}Li to give the metastable state ^{4}Be^8, which decays into two alpha particles and probably emits some phonons as well. Again, why are no gamma rays observed? Another possible reaction within the palladium channel would be two deuterons fusing with a palladium nucleus (e.g., 106) to give an excited ^{110}Cd nucleus, which then deexcites by emitting two ^{6}Li nuclei and leaving a ^{98}Mo nucleus. This could result in excess heat and an increased ^{6}Li concentration.

The majority of the possible three-body TRINT sequences within the periodic table involve (spin 0, parity +) nuclear states. It is interesting to note that there are unsubstantiated reports of the Fleischmann-Pons effect having been achieved with titanium, zirconium, and uranium. In addition, there has been a claim of having achieved the effect with platinum. From the standpoint of the TRM and the three-body TRINT, all of this would be understandable. The fact that palladium works so well electrolytically compared to titanium, for example, would probably be due to the greater number of transmission resonance levels available to diffusons in the case of the former and the fact that the palladium nuclei are more massive than the titanium nuclei, thus allowing a larger maximum transmission order n_{max} via the palladium channel than via the titanium channel.

If the TRINT reaction is involved with the production of excess heat, it might be susceptible to a strong magnetic field. Thus, in the vast majority of these reactions, and all reactions involving transitions between (spin 0, parity +) nuclear states, the spins of the two deuterons converging on the middle particle in the three-body reaction are antiparallel. Thus, if a strong applied magnetic field could align these spins, it could quench the heat-producing reaction. This would have a better chance as the temperature is lowered, and it may be speculated that such an effect, if it can be demonstrated, might someday be employed to help control this phenomenon in a practical device.

It may be that, in addition to a near-surface excess heat effect, there is also a bulk excess heat effect. If the latter also exists under certain conditions, then it is possible that the three-body TRINT and three-body trint reactions are more appropriate for that case.

Finally, it might be possible to have a TRINT reaction in the form of a double trint reaction. In this case, two neutron exchange reactions would occur at the same time, abetted by the standing de Broglie wave scenario:

$$D + {}^{104}Pd + D \rightarrow p + {}^{106}Pd + p \quad (69a)$$

and

$$D + {}^{105}Pd + D \rightarrow p + {}^{107}Pd + p \ . \quad (69b)$$

In each of these reactions, a neutron is stripped from each of the two deuterons at the same time by the palladium nucleus, leaving two protons and a heavier palladium nucleus. This reaction would probably be favored over the three-body trint reaction in which two deuterons are absorbed by a palladium nucleus because a Coulomb barrier does not have to be contended with in the case of a neutron exchange. However, it seems that reactions (69a) and (69b) would probably also be less likely than reactions (58a) and (58b), which only involve a single neutron exchange. The kinetic energies of the resultant protons in reaction (69a) would be ~6.05 MeV, while those in reaction (69b) would have kinetic energies of ~5.77 MeV. While the possibility of these reactions would be miniscule in an ordinary hot plasma, as for any three-body reaction, the situation could be quite different in the lattice environment for cold fusion, where a standing de Broglie wave could come into play along with the boson nature of the deuterons and their indistinguishability.

VI.H. Additional Role of the Deuterons

Deuterons play crucial roles as the principal components of the nuclear fuel plugging up interstitial sites into which candidate diffusons would otherwise fall, and providing the deuteron transmission channel for transmission resonance. In addition, they should be very effective as moderators, helping to slow down deuterons that are moving too rapidly to be candidates for transmission resonance. Work is now proceeding to assess the importance of this for the TRM and to explicitly incorporate this effect into the mathematical description via the interplay of the energy states of the interstitial deuterons with the transmission resonance levels of the diffusons and incorporating the phonon description of the lattice vibrations.

VI.I. Roles for Lithium and Sodium

Possible nuclear reactions involving ^6Li and ^7Li have been indicated. Storms[62] and Marshall[63] have suggested that lithium, in addition to its role in the electrolyte, may play an important role in achieving a relatively high stoichiometry for the deuterons and in helping to stabilize this. It may achieve this through the formation of a hydride with the palladium. (Note that, where PdD is indicated elsewhere in the paper, the stoichiometry can vary and a true chemical compound is not indicated.) Sodium was employed successfully by Iyengar et al.[64] and should perform much the same role as lithium because of a similar chemistry with regard to the idea of Storms and Marshall. However, tritium rather than heat was reported by Iyengar.[64] If heat cannot be produced in experiments involving sodium, this strongly suggests lithium as a nuclear fuel associated with the excess heat phenomenon. The potential role of lithium in this regard is treated later in this paper. The importance of lithium is also suggested by the fact that the excess heat phenomenon seems to be a near-surface effect limited to ~5 to 10 μm; this is the approximate depth reached by the diffusing lithium when observable excess heat appears according to Appleby et al.[40]

VI.J. Anomalous Production of Particles and Radiation: Role of the Boson Plasma: Is the Boson Plasma a Quantum Fluid?

Since trint reactions do not involve the formation of a compound nucleus, the usual gamma rays and energetic neutrons that would ordinarily be associated with the deexcitation of such compound nuclei pose no problem. In this regard, no special reaction with the lattice or boson plasma (of deuterons) appears to be required if the trint reactions are the only ones involved. Nevertheless, the existence of charged particles, such as protons or tritons with mega-electron-volt range energies, as reaction products creates difficulties. For example, it might be expected that, as the result of the bremsstrahlung process or the deexcitation following Coulomb excitation by these charged particles, X rays would be produced and that penetration of this hard radiation through the electrolyte and the cell walls would yield a detectable radiation flux outside the electrolytic cell. Thus, it is reasonable to ask whether the boson plasma might have properties that would enable it to trap most of such radiation with the energy ending up as heat in the lattice.

Can the boson plasma of deuterons be regarded as a quantum fluid that might have the desired properties of being able to amply absorb radiation? Kittel[65] gives the following mathematical criterion for deciding whether a fluid is a quantum fluid or a classical one:

$$\begin{aligned} \exp(-u/kT) = (0.026M^3/2T^{5/2})/P \\ \gg 1, \text{ fluid is classical} \\ \ll 1, \text{ fluid is a quantum fluid} \\ \simeq 1, \text{ fluid may be a quantum fluid} \ , \end{aligned} \quad (70a)$$

where

u = chemical potential

M = molecular weight (amu)

T = temperature (K)

P = pressure (atm).

Kittel[65] points out that air at standard temperature and pressure (STP) gives an $\exp(-u/kT)$ of $\sim 10^6$ and is clearly a classical fluid according to the criterion. At the other extreme, he points to the electrons in a metal for which the value at 300 K is $\sim 10^{-4}$, making this clearly a quantum fluid. In between these two cases is ^{4}He gas at 4 K and 1 atm for which the value of Eq. (70a) is ~7.5. Thus, the latter is not safely classical. Applying Eq. (70a) to our boson plasma of deuterons with $T = 300$ K and $P = 1$ atm, we obtain a value of

$$\exp(-u/kT) \simeq 1.2 \times 10^6 \ , \qquad (70b)$$

so that the boson plasma at first appears to be safely a classical fluid. However, this judgment may be too hasty. Fleischmann and Pons[7] have suggested that the high overpotentials achieved during electrolysis enhance the fugacity to the extent that the deuteron pressure may be $>10^{20}$ atm. We note that 10^5 atm for the case of the boson plasma of deuterons would be enough to change the value in Eq. (70a) to

$$\exp(-u/kT) \simeq 1.2 \ , \qquad (71)$$

which is below the value for ^{4}He at 1 atm and 4 K. Thus, it seems that we may well be dealing with a quantum fluid.

The energy differences between the various energy states of this quantum fluid are negligible so that there is no trouble in its absorbing energy, unlike the case of liquid ^{4}He < 4 K at 1 atm. Another major distinction exists between our quantum fluid and, for example, ^{4}He: Due to the periodicity of the crystalline environment, the wave function itself must have the same periodicity as the crystallite. (Recall Floquet's theorem.) Bush and Eagleton[31,32] emphasized the importance of this periodicity in connection with cold fusion. The behavior of the boson plasma must, itself, be periodic in space. And, unlike the case of superfluid ^{4}He, the boson plasma inside the sample is not coherent over an entire crystallite. Rather, it is periodically coherent with the spatial periodicity of the crystal. Thus, rather than having the equivalent of just one coherent particle (all the particles behaving as one particle) as in the case of ^{4}He we have the equivalent of a vast incoherent collection of interpenetrating coherent fluids in the crystal. This guarantees that energy absorbed is not coherently reradiated to reach the region outside the crystal: The incoherence of the different coherent groups ensures that the energy will soon reach the lattice in the form of heat. The consequence of the periodicity is that, for example, if the bosons near the center of the 11th and 22nd interstitial site are oscillating in unison, they are also mutually in unison with those near the centers of the 33rd, 44th, and 55th interstitial sites. It is as though we have a large collection of different intracoherent superfluids in the lattice box. (Chubb and Chubb[26] also pointed to this nature of the boson plasma and have aptly termed this fluid a Bose-Bloch condensate.) A startling consequence of this nature is that any energy given to the boson plasma must be quickly shared among all the particular members of one of the superfluids. It is apparent that the boson plasma may be able to absorb much more energy than would be accorded to it classically based on its mediocre plasma frequency. Thus, it seems quite possible that X rays and gamma rays created within the cathode will simply be absorbed by this boson plasma with the energy quickly being dissipated in the form of lattice vibrations.

An experiment to test the absorptive properties of the boson plasma has been suggested by the author.[66] The absorptive properties of the boson plasma can be tested by comparing the opacity of a thin film of palladium or titanium to X rays or gamma rays when the film is unloaded and, also, when it is loaded with deuterons. This experiment would be easiest to perform with titanium since it holds onto the deuterons at room temperature. In the case of PdD, a cold finger could be used to ensure that the deuterons remain in the film for a long enough time. A marked decrease in the intensity reaching the detector after deuteration of the sample has been achieved would be evidence for the absorptive nature of the boson plasma of deuterons. It would also be important to examine the change in the reflective properties of the film for the radiations employed.

VI.K. Might Ordinary Hydrogen Give Excess Heat on the Basis of the TRM? Consideration of the Role of Lithium in the Energy Process

Bockris[67] recently asked the author what the TRM would predict if light water were substituted for heavy water. At that time, the author was aware of no positive results for the excess heat effect in electrolytic experiments employing light water and indeed knew of a number of experimental cases, e.g., that of Appleby et al.,[10] where the substitution of light water for heavy water, or LiOH for LiOD, had quenched the excess heat effect. Thus, the answer[68] was rather defensive. For example, the lower mass of the proton as compared with that of a deuteron might decrease the maximum transmission resonance order involved. Also, if the trint reaction is a key reaction, protons have no associated neutrons to exchange, unlike the deuterons. Moreover, the lack of positive results with protons might rule out the three-body TRINT reactions as important since it would be difficult to see why protons should not work as well as deuterons for those reactions. The three-body trint reactions would still be an option, however. Yensen[69] brought to the author's attention the claim of Matsumoto[70] of the observation of neutron emission with 0.1 to 0.6 ^{6}LiOH electrolyte in light water, but no excess heat. In view of this claim, it is interesting to reconsider the possibility of employing protons on the basis of the TRM. As we shall see, this may also provide an important clue for determining the heavy water reactions.

A priori, there is no reason why an excess heat effect with protons instead of deuterons should be dismissed on the basis of the TRM if the nuclear reactions are similar. The TRM should guarantee that, when their de Broglie wavelengths satisfy the transmission resonance condition, protons should be transmitted in the palladium transmission channel and in a proton transmission channel in essentially the same way as deuterons are transmitted within their respective transmission channels, giving the protons a chance to interact nuclearly with particles forming the barriers. Assuming Matsumoto's claim is valid, the reactions cannot be of the trint type since protons, unlike deuterons, have no neutron to exchange. They could, however, include the three-body TRINT reactions. At this stage, we can only guess that the nuclear cross sections for these reactions might be smaller for the case of protons substituted for deuterons. Also, a fusion reaction of two protons might be possible:

$$p + p \rightarrow \mathrm{D} + e^{+} + \eta\ (0.26\ \mathrm{MeV})\ , \qquad (72)$$

where the neutrino carries away 0.26 MeV of the energy leaving 1.18 MeV. This is the proton counterpart of the D-D fusion reaction

$$\mathrm{D} + \mathrm{D} \rightarrow {}^{4}\mathrm{He} + (= 24\ \mathrm{MeV})\ . \qquad (73)$$

Thus, if reactions (73) and (72) are actually occurring counterparts taking place in the cold fusion environment, then based strictly on the energies released, the excess heat yield for light water would be only ~7.7% of that for heavy water. This would lead to strong quenching of the excess heat effect when heavy water is replaced with light water, which is known to be true experimentally.

A likely reaction for the excess heat effect might seem to be the following:

$$p + {}^{6}\mathrm{Li} \rightarrow {}^{4}\mathrm{He}\ (1.7\ \mathrm{MeV}) + {}^{3}\mathrm{He}\ (2.3\ \mathrm{MeV})\ . \qquad (74)$$

With the possibility that there might have been some contamination of the electrolyte with ^{7}LiOH, the exothermal branch of p-^{7}Li should also be considered:

$$p + {}^{7}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + 17.3\ \mathrm{MeV}\ . \qquad (75)$$

Hutchinson[43] reported achieving excess heat by employing 97% pure ^{6}Li in the electrolyte. In addition, Bockris[71] points out that the time delay at the onset of the excess heat reaction is much greater, in agreement with the relatively slow migration inward of the large lithons ^{6}Li and ^{7}Li nuclei each with a complement of two electrons than with the much more rapid inward diffusion of the deuterons (or protons in the case of a light water reaction). Thus, it may be in the transmission resonance phenomenon that ^{6}Li is an important reactant with the deuteron counterpart of the reaction in Eq. (74) being a reaction previously indicated[18] as a prime candidate for the excess energy reaction:

$$\mathrm{D} + {}^{6}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + 22.4\ \mathrm{MeV}\ . \qquad (76a)$$

Storms[72] has apprised the author that recent work by his group indicates lithium most likely enters the palladium lattice substitutionally, as opposed to interstitially. Thus, as in the case of the trint reaction of deuteron on palladium, the palladium transmission channel would most likely be involved for the TRINT reactions (74), (75), and (76a) involving lithium.

Finally, we must get back to the question of why, assuming there may be an excess heat effect with protons, should that effect be considerably reduced compared to that for the deuterons? First, a comparison of reactions (74) and (76a) shows a (22.4 MeV/(1.7 MeV + 2.3 MeV) = 5.6 factor advantage for the energy yield alone in favor of the heat effect with the deuterons. This would lead to a sufficient reduction in the excess heat effect in the majority of experiments to make it appear that the effect had been completely quenched in the case of a substitution of protons for deuterons. In addition, there may be an advantage in cross section for the deuteron reaction (76a) over the proton reaction (74). Kettani and Hoyaux[73] state that reaction (76a) has a cross section of $\sim 2 \times 10^{-27}\ \mathrm{cm}^2$ at 150 keV, while reaction (74) has a lower cross section of $10^{-28}\ \mathrm{cm}^2$ at 300 keV. The difference could also be primarily due to the lower velocity value associated with the 150 keV energy. At the much lower energies of the TRINT reactions, cross-section considerations might give reaction (76a) even more of an advantage over reaction (74). We must be prepared for the possibility that the basic nature of reactions (74) and (76a) may differ from their high-energy counterparts. At high energy, an intermediate nucleus is formed in both cases. At the low energies for the $n = 0$ and $n = 1$ transmission orders on the basis of the TRM, or even at the relatively low energies associated with the palladium transmission channel, the reaction may exhibit very strong charge polarization effects such as those already hypothesized on the basis of the TRM. The result might be that, since ^{4}He is a tightly bound structure nuclearly, both cases might involve strong charge polarization effects producing a reaction via an exchange of a deuteron from the ^{6}Li nucleus to the deuteron or proton.

A factor in favor of the heat effect for protons is that the transmission windows have a width going directly as T_n and inversely as mass$^{1/2}$. Moreover, the height of the window goes as $[T_n \exp(-T_n/T)]$, where T_n goes as (mass)$^{-1}$. However, this advantage would be outweighed by the fact that the $n = 0$ and $n = 1$ orders are effective at 300 K for the deuteron transmission channel, while only the $n = 0$ order is available to the proton transmission channel because of thermal vibrations. This gives another factor of 6.1 to the advantage of the heat reaction involving the deuterons, so that the total advantage based on the TRM and from the assumed energy yields is a factor of $6.1 \times 5.6 = 34$, if the energy is coming from reactions associated with the deuteron and proton transmission channels, respectively. (There may be an additional advantage to the deuteron reaction based on cross-section comparisons, but we currently cannot assess this.) If the lithium reactions occur in the palladium transmission channel as inferred from the suggestion of Storms[72] that lithium enters the palladium lattice substitutionally, we can only claim the $\frac{1}{5.6}$ factor (i.e., 18%) as an upper limit for the advantage of deuterons over protons. On this basis, the TRM shows that there is a large excess heat reaction advantage in using deuterons over protons. It is clear now why the substitution of H_2O for D_2O and LiOH for LiOD would quench the heat reaction. An 82% reduction in the reaction rate would, in most cases, make it seem as though the excess heat producing reaction had been completely quenched.

Finally, because of the involvement of the Coulomb barrier with all these reactions from Eqs. (72) through (76a), it seems that the following trint reaction in which a ^{6}Li nucleus strips a neutron from a deuteron might have the best chance in the cold fusion environment:

$$D + {}^6\text{Li} \rightarrow p + {}^7\text{Li} \ , \tag{76b}$$

where the proton should have a kinetic energy of ~4.35 MeV. Now, as in the case of the trint reactions (58a) and (58b), there can be no proton counterpart of reaction (76b) since it has no neutron to give up. Also, the reverse reactions, in which the proton strips away a neutron from the heavier particle, are energetically unfavorable. Thus, if a trint reaction fuels the excess heat effect in the case of heavy water, there would be no light water counterpart to produce measurable excess heat.

VI.L. Estimation of Upper and Lower Limits for the Nuclear Cross Section

As previously indicated, the TRM gives no direct nuclear information. However, utilizing the experimental results on excess power, it is possible to employ the TRM semiempirically to place upper and lower limits on the nuclear cross section for the reaction ultimately responsible for the excess heat.

An upper limit for the nuclear cross section can be obtained employing a conventional statistical treatment. Thus, the absolute excess power can be written as

$$P = N_{inc} f_{TR} n \tau \sigma E_1 \ , \tag{77}$$

where

$$N_{inc} \simeq (iA/q) \times 10^{-3} \tag{78}$$

= approximate number of deuterons incident on the cathode surface per second

i = applied current density

A = cathode surface area

q = charge on a deuteron

f_{TR} = fraction of the incident deuterons in the available energy transmission windows

n = number of palladium nuclei as targets per unit volume

τ = depth of the active volume of the cathode

σ = cross section for the nuclear reaction

E_1 = energy release in one nuclear reaction.

An expression for f_{TR} is given by

$$f_{TR} = (BP_r/i) \ , \tag{79}$$

where P_r is the expression for excess power from Eq. (42), and B is a constant made up of (a) constants from the M-B energy distribution giving the height of an energy transmission window and (b) constants from the width of an energy transmission window $k\Delta T_n$ from Eq. (18). The full expression for the M-B energy distribution can be written as

$$dN/dE = (2N/\pi^{1/2})(kT)^{-3/2} E^{1/2} \exp(-E/kT) \ , \tag{80}$$

where N represents the number of deuterons incident per unit time and is given in Eq. (78). From Eqs. (18), (42), (79), and (80), the constant B can be written as

$$B = (4/\omega)(k/m)^{1/2}(M_D/M)^{1/2} L^{-1} \ , \tag{81}$$

where M_D/M is the ratio of the mass of a deuteron to that of the species associated with the wells in the particular transmission channel being considered. Thus, for the case of the palladium transmission channel,

$$B \simeq 2.1 \times 10^{-4} \ . \tag{82}$$

The other values to be employed are

$$n = (6.82 \times 10^{28}/\text{m}^3)S \ , \tag{83}$$

where S is the stoichiometry, equal to one in the case of the palladium transmission channel. Of course, if lithium becomes the other component of the nuclear fuel and enters the lattice substitutionally, S could be considerably lower. The value $\tau = 5 \times 10^{-6}$ m is an educated guess based on the migration depth of lithium found by Appleby et al.[40] Finally, we take $E_1 = 10^7 q$ (joules). These values are now substituted back into Eq. (77) and data from cell 5 (see Fig. 13) on excess power are employed to estimate a value for σ.

For an applied current density of $i = 250$ mA/cm^2 at $T = 312$ K, Fig. 13 indicates that the excess power was ~1.5 W. The area A of the palladium cathode = 4×10^{-4} m^2 and the computer gave a P_r value of ~2.2×10^4. Substituting these quantities into the expression for P in Eq. (77) and setting it equal to 1.5 W yields

$$\sigma \simeq 0.2 \times 10^{-21}\ \text{m}^2 \quad (84)$$

$$\simeq 2 \times 10^{-18}\ \text{cm}^2\ . \quad (85)$$

Equation (85) is a naive upper limit for σ since it does not take into account that, in the TRM, a deuteron satisfying the transmission condition would most likely be able to move rather rapidly along a periodic chain of barriers and wells and, therefore, have many more opportunities for nuclear reactions than are allowed in Eq. (77). If, in fact, a diffuson is allowed the chance of reflecting at the end of such a chain and passing along the chain in the reverse direction, a different expression is obtained for absolute excess power P'. This alternative expression to Eq. (77) allows the semiempirical determination of a lower limit for σ:

$$P' \simeq [(iA/q) \times 10^{-3}] f_{TR} N_{BS} P_{B1} E_1\ , \quad (86)$$

where

i = applied current density

A = surface area of the cathode

q = charge on a single deuteron

f_{TR} = fraction of the incident deuterons in the energy transmission windows in Eq. (77)

N_{BS} = number of barriers passed per second

P_{B1} = probability of a reaction per barrier that is passed

E_1 = energy release in a single nuclear reaction, and also the same as in Eq. (77).

The cross section σ is related to P_{B1} by the reaction

$$P_{B1} = \sigma / L^2\ , \quad (87)$$

where L is the lattice spacing and is taken to be $\sim 2.85 \times 10^{-10}$ m for PdD. As in Eq. (77), f_{TR} should be taken to be $\sim 5 \times 10^{-4}$. For the state $n = 15$, which gives a slight overestimation, but a lower value for σ, the factor N_{BS} has a maximum value of

$$N_{BS} = (5363 \times 1\ \text{s})/(2.85 \times 10^{-10})\ , \quad (88)$$

where the first term in the numerator is the velocity for the transmission order $n = 15$, and the denominator is the approximate distance between consecutive barriers. (Here we assume a situation in which the transmitted deuterons are reflected back at the end of a chain of wells and barriers.) Substituting these back into P' in Eq. (86) and employing the same data as for the previous calculation of the upper limit from Eq. (77) yields

$$P_{B1} = 4.3 \times 10^{-12} \quad (89)$$

and, from Eq. (87),

$$\sigma \simeq 3.5 \times 10^{-28}\ \text{cm}^2\ , \quad (90)$$

as a lower limit for the cross section. Based on Eqs. (85) and (90), we anticipate that the actual cross section σ for the nuclear reaction that is ultimately the source of the excess heat satisfies

$$10^{-28}\ \text{cm}^2 \lesssim \sigma \lesssim 10^{-18}\ \text{cm}^2\ . \quad (91)$$

VII. THE TRM'S SUGGESTIONS FOR THE TRITIUM PUZZLE

VII.A. Introduction: Crucial Role of the Overpotential

A number of research groups, most notably those at Texas A&M University,[4,5] Los Alamos National Laboratory[6] (LANL), and Bhabha Atomic Research Centre,[64] have reported the production of tritium. While tritium production has been reported for cases with and without the detection of observable excess heat, excess heat production without observable tritium being produced seems to be the usual result for most groups. (At Cal Poly, for example, no measurable tritium has accompanied the production of excess heat.[37]) A completely successful model should be able to account for all three cases. That the TRM appears to be capable of this is additional indication that it is on the right track.

All considerations are based on the relative power relations, Eqs. (31) and (42). The role of the overpotential, or surface energy shift of the M-B energy distribution, is again paramount. Based on Eq. (42), the TRM predicts tritium production at low overpotential below ~2.8 mV, with another possibility at high overpotential above ~1 kV. The region of overpotential (activation overpotential, hydrogen overvoltage, or potential shift) between these values is referred to as the "tritium desert," where relatively little tritium should be produced.

Finally, the Bockris curve[74] showing the mirroring of heat production by tritium production, but at a level for the latter too low to account for the excess heat observed, might be accounted for by the TRM, at least at low overpotential.

VII.B. Heat Production Without Tritium via the TRM

Only the $n = 0$ and $n = 1$ transmission orders are available to the deuteron transmission channel associated with the production of tritons, protons, neutrons, and ^{3}He nuclei. If the overpotential η is too high in Eq. (31), the M-B energy distribution is shifted too far to the right with no overlap of the energy windows corresponding to $n = 0$ and $n = 1$. Under these circumstances, only the palladium transmission channel is operative, and only heat is produced. (Recall that one possible explanation for the excess heat reaction is the trint reaction in which a D-Pd reaction leads to a neutron being stripped away from the deuteron by the palladium nucleus.) The lower threshold value for η such that heat is observed, but not tritium, is given by the following condition based on the relative excess power relation, Eq. (42):

$$T_1 - (q/k)\eta_{lt} = 0 \ . \tag{92}$$

Thus,

$$\eta_{lt} = (k/q)T_1 = 2.8 \text{ mV} \ . \tag{93}$$

Above an overpotential of ~2.8 mV, observable excess heat may be produced but relatively little tritium.

At the other end of the scale, too high an overpotential will shift the M-B distribution past the $n = 16$ transmission order energy window, shutting down the palladium transmission channel (excess heat reaction). According to Eq. (34), the upper threshold overpotential value for this is 340 mV. Above an overpotential of ~340 mV, the palladium transmission channel is essentially shut down, and excess heat production is quenched. This subregion of potential in the tritium desert is termed the "tritium-heat desert."

VII.C. Tritium Production at Low Overpotential on the TRM: The Bockris Curve

Suppose the fate of a particular cathode is platinization with a consequent lowering of the overpotential (see Fig. 9). If the value of η falls below the threshold value of ~2.8 mV calculated in Sec. VII.B, the $n = 1$ transmission order of the deuteron transmission channel is activated and tritium production begins. Figure 24, based on Eq. (42), shows a plot of the percentage rate of tritium production to excess heat production versus overpotential. Note that, to the left of the tritium desert, at an overpotential of ~2.8 mV, this curve reflecting the tritium production rate rises very steeply, in agreement with experimental observation.[75] Figure 25 focuses on a magnified view of the percent production rate extending over the narrower range of overpotential from 2.800 to 2.811 mV at the edge of the tritium desert. At an overpotential of ~2.8105, the percent rate of tritium production is ~0.1% of the heat production. It appears that the TRM might account for the Bockris curve[74] in which the tritium production rate mirrors that of excess heat but is only about one-thousandth of the latter. In addition, Bockris[74] found that the initial production of tritium lags behind that of heat by ~5 days, possibly because sufficient platinization of the cathode surface to reach the threshold value of ~2.8 mV required about this amount of time.

It was indicated earlier that, for an i_0 value of 1.47 mA/cm^2, excess heat production would probably not be measurable below an overpotential of ~200 mV, so it might be asked how we could be to the left of the tritium desert at 2.8 mV and still be seeing measurable excess heat production. The answer is found in the platinization of the cathode indicated by Fig. 9: Platinization can lead to a large enough value of i_0, or $(i_c)_H$ in connection with the concentration overpotential, that a high enough value of i can be reached even though we are yet at a relatively small value of overpotential η.

Various cathodes could produce widely differing amounts of tritium depending on the different overpotentials involved. In this regard, we note the wide variation in the concentration of tritium produced in

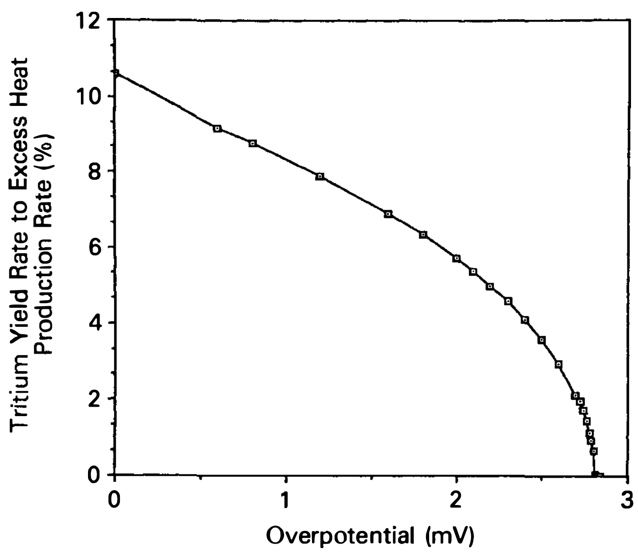

Fig. 24. Theoretical percent tritium yield rate normalized to the rate of excess heat production and graphed versus overpotential at constant temperature and current density, and based on the TRM in Eq. (32). To the right of ~2.8 mV lies the tritium desert where relatively little tritium should be produced.

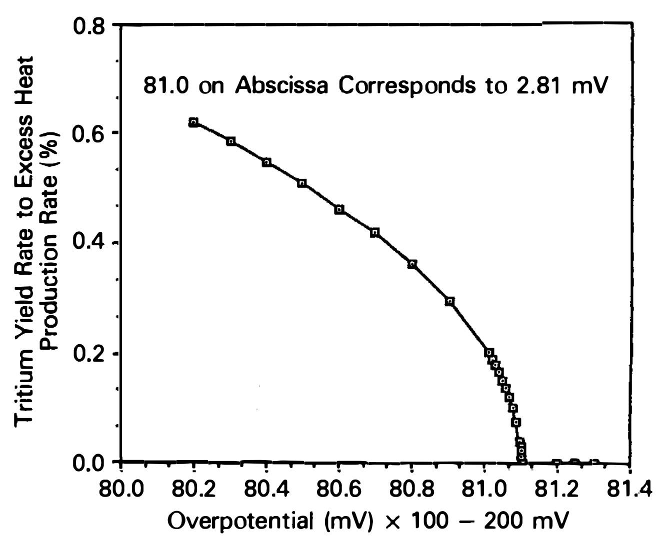

Fig. 25. A more detailed look at the right side of Fig. 24. If the hypothetical experiment remained at an overpotential of ~2.8105 mV, the Bockris production ratio of ~1% tritium to heat would be satisfied.

different electrolytic cells in experiments conducted by a particular group and also the wide variation between the average concentration of tritium produced by different groups. Such wide variations in tritium yields can be readily accounted for on the TRM. Note from Fig. 24 that the percentage rate of tritium production normalized to that for excess heat varies from ~10.3% at zero overpotential to 0% at the beginning of the tritium desert at an overpotential of ~2.8 mV. An end to tritium production for a particular cathode could result from the deposition of materials on the cathode that now drive its overpotential above ~2.8 mV and drive the energy associated with that overpotential into the tritium desert. Note, also, that the erratic behavior reflected by the fact that a few lucky cells might be producing tritium, while most cells do not, can be accounted for because these other cells have their overpotentials (or hydrogen overvoltages) located in the tritium desert.

It is important, according to the TRM, in a particular experiment searching for tritium, to be able to measure the hydrogen overvoltage or other potential shift near or at the surface of the cathode. It appears that the development of a technology providing control of this overpotential could offer the interesting prospect of a cold fusion reactor that is extremely clean, i.e., nearly tritium free. Of course, a tritium reactor could also be designed based on overpotential considerations that might produce needed tritium as well as heat.

The low branching ratio of $\sim 2 \times 10^{-9}$ favoring tritons over neutrons for the D-D reaction was derived from a polarization conjecture based on the low relative velocities of approach of deuterons in the $n = 1$ and $n = 0$ states. The cold fusion reaction is an ultralow-energy reaction in a lattice and, most likely, a trint reaction.

VII.D. Tritium Production at High Overpotential: The Dendrite Hypothesis

The fate of a particular cathode can be the reverse of platinization, so that a buildup of impurities on the cathode surface raises the overpotential rather than lowering it. The M-B energy distribution is shifted to higher energies driving the experiment deeper into the tritium desert. After the transmission window associated with $n = 16$ is passed, the experiment has entered a region of energy values in the deuteron distribution space containing transmission windows that are all of too high an order, i.e., $n > 16$, for the production of either heat or tritium according to the TRM. This portion of the tritium desert was earlier referred to as the tritium-heat desert.

It might be asked, however, whether this desert is infinite, or whether it is possible to cross it and again realize transmission resonance-induced nuclear reactions. This may be possible provided we can reach high enough energies that the time of passage of a deuteron through a well in one of the transmission channels is small compared to the period of vibration of that well. For this situation, the vibration of the well is effectively too slow to vitiate the transmission resonance condition in Eq. (2) during the passage of the deuteron through the well. Since the well vibrations are unlikely to be coherent, there will be a greater time delay than usual because the particle can only pass through the next barrier when the transmission resonance condition is reached again by the well beyond that barrier.

It is fairly easy to show that this other edge of the desert occurs for deuterons at an energy of ~1 keV. How might such energies be reached in an ordinary electrolytic experiment? This brings us to the dendrite hypothesis promoted most notably by Bockris.[76] According to Bockris, such dendritic growths on the cathode surface can lead to high fields and, intermittently, potential drops between the dendritic tips and the cathode surface on the order of 20 kV. In essence, there is a form of hot fusion occurring at the surface, just as fracto-fusion is hypothesized to be hot fusion associated with high electric fields occurring in connection with cracks in the palladium. Bockris[76] has been very clever in supporting this hypothesis with calculations, showing that the 5-day delay in the appearance of tritium compared to excess heat might be accounted for on the basis of the time necessary for dendrite growth to reach a crucial stage.

Other researchers have questioned whether energies of 20 keV for deuterons could be achieved, although Bockris claims this need be only an intermittent effect. The small branching ratio highly favoring the triton branch of the D-D reaction over the neutron branch would presumably be caused by polarization effects associated with the strong fields. A more serious difficulty has seemed in the past to be that tritium is often found when there are no dendritic growths observed on the cathodic surface. However, the TRM offers help here since tritium production occurring below the tritium desert at low overpotential would not be associated with dendritic growths. If TREND (Refs. 15 and 16) is occurring here, this might enhance the effect of the dendrites on the other side of the tritium heat desert so that lower fields with potential drops of ~1 kV might suffice. For potential drops one order of magnitude higher than this, the dendrite mechanism requires no help from the TRM since a mechanism for hot fusion would be realized. Conceivably this could result in the production of tritium without measurable excess heat. The dendrite hypothesis should not be rejected simply because tritium production is sometimes observed in the absence of dendrites. The TRM predicts separate energy shift regimes (or hydrogen overvoltage regimes) for the production of tritium without dendrites and, quite possibly, with dendrites. It should be mentioned here that a competing model for tritium production at the surface is the surface tension model of Hora et al.[45]

A final note on dendritic tritium production: The branching ratio might be quite different in this higher energy regime of tritium production (10^{-3} perhaps?) than it is to the left of the tritium desert, where dendrites are not involved.

VII.E. Postscript: Tritium via Contamination or "Tampering"?

Claims of tritium production via contamination and/or tampering (spiking) have arisen; therefore, it seems important at least briefly to address this, and to do so especially insofar as the TRM might have a bearing.

Consider first the very legitimate claim of tritium contamination raised by Wolf.[77] Wolf recently discovered tritium contamination in virgin palladium to the extent that he feels that his original claims of tritium production via cold fusion are vitiated. Wolf[78] has told the author that he now believes that neutron emission and the production of excess heat are more reliable indicators that cold fusion may exist. Wolf[77] also points out that a number of the research groups claiming tritium production obtained their palladium from the same source that he did, which is also disturbing. Nevertheless, the large amounts of tritium claimed by Bockris et al. and by other groups, some using a different supplier, appear too large, according to Worledge,[79] to be accounted for by Wolf's thesis of spot contamination. Storms[80] points out that the pattern of tritium production has been essentially the same with cells that have produced tritium, as opposed to the random sort of pattern of behavior that random spot contamination would reveal.

In a recent experiment, Storms[81] obtained an interesting result that appears to undermine the spot contamination hypothesis. A palladium sample was run cathodically in tritiated light water to allow a significant uptake of tritium. When the cathode was removed from the tritiated light water and run cathodically in uncontaminated light water, no tritium was observed to exit the palladium cathode, even after 100 h of continuous running in the uncontaminated light water. While it is necessary to repeat this experiment with deuterium present to see if that would somehow release some of the tritium to contaminate the electrolyte, it seems unlikely that the result would differ from that of light water. And, as Storms[81] points out, Wolf had to dissolve his palladium sample in an acid solution to free the contaminating tritium.

In addition to this very legitimate issue raised by Wolf, there has lately arisen, unfortunately, an issue of a somewhat sinister nature. Since the production of tritium has appeared to be the strongest pillar of cold fusion, it is not surprising that some critics, perhaps even those with a possible stake in cold fusion's demise, would attack this apparently strongest link forged in the cold fusion chain at what they might feel is its own most vulnerable point. Thus, a recent article,[82] without making specific accusations, suggests, on the basis of circumstantial evidence at best, the possibility of the spiking of tritium within the Bockris group. In view of this incredibly unfair attack, the following comments appear in order:

1. Claims of tritium production by Bockris et al. have inevitably been accompanied by a disclaimer indicating the sporadic nature of the process. Tritium production by a cell chosen at random has been the exception rather than the rule, as they have discovered. The TRM fully supports this idea of the accidental production of tritium; i.e., the TRM indicates that tritium is to be expected only under relatively unusual conditions. In the absence of the recipe provided by the TRM and assuming this viewpoint to be correct, electrolytic tritium production appears to be an accident. In fact, the erratic behavior with regard to tritium production around the world appears to provide additional support for the TRM.

2. Despite claims of erratic behavior in terms of seeing tritium, those who see it, and who have also been able to make assays in essentially real time, report that the initial rate of production seems to rise rapidly in time. Again, this is supported by the TRM (see Figs. 24 and 25).

3. Other groups around the world have reported tritium that could not be the result of spot contamination. Are we to believe that there is an international spiking team at work?

4. While experimentally determined branching ratios range from 10^{-3} to $\sim 10^{-10}$, according to Bockris[83] most values seem to lie in the range from 10^{-8} to 10^{-10}. The international spiking team also must include specialists working in the area of neutron spiking as well, to be sure to make the branching ratio appear acceptable.

5. Light water found in samples of electrolyte saved from cells in which tritium was found to have been produced by the Bockris group is not *prima facie* evidence of spiking. Hydrogen exchange is a distinct possibility in these situations. Eagleton[84] points out that even the containers in which the electrolyte was stored should be checked for the possibility of hydrogen exchange.

6. Finally, it should be pointed out that an experiment was conducted by the Storms group[80] to test whether spiking would leave a signature that would allow researchers to distinguish such a situation from that of the legitimate cold fusion process. Such a signature was, indeed, discovered. Spiking does not produce any tritium in the gas phase in the cell, as opposed

to the electrolytic process. On the basis of this, and combined with the known history of the production by some cells of tritium at Texas A&M, Storms[80] has concluded that spiking could not account for all of the tritium discovered by the Bockris group. And, because of the pattern of production and the large amount discovered, it is very unlikely that the contamination hypothesis could do duty here.

Neither the contamination hypothesis nor the innuendo, nor the combination of these two, suffice to conjure away cold fusion tritium.

VIII. CONCLUSION

The ability of the TRM to fit relatively complex calorimetric data and to predict trigger points for the excess heat effect strongly suggests that the model is meaningful. At the same time, it provides significant support for the notion that the Fleischmann-Pons excess heat phenomenon is genuine. While wholesale acceptance of the model will, necessarily, depend on independent corroboration of the model, the TRM appears to provide a basic breakthrough in cold fusion research. Hopefully, the experiments suggested here will be conducted by other research groups, who will scrutinize the model in its ability to guide their own experiments and to ultimately fit the data obtained.

It appears that the TRM, with the addition of the TRINT reactions, can unify the seemingly disparate prime trinity of neutron emission, tritium production, and excess heat production in a metal deuteride lattice at room temperature. However, no new basic physics has really been employed. If the TRM is correct, we are probably seeing the most dramatic of the consequences of the wave properties of matter – a scientific vista that is absolutely breathtaking in its scope. Indeed, the almost Byzantine series of scientific developments strewing sheer confusion in their wake with combinations of enigmas leaves little doubt that we are seeing a basic Kuhnian paradigm shift, with implications for all branches of the physical sciences and beyond. The promise of the TRM for an emergent collective paradigm may well be the following: On the one hand, this new collective paradigm seems likely to include the dream of the physicist Steve Jones in having a significance for such scientific issues as seemingly disparate as geothermal energy (very likely), the radiation of Jupiter (likely), and the solar neutrino problem (possibly). On the other hand, it captures mankind's hopes in its potential for fulfilling the dream of the electrochemists Martin Fleischmann and Stanley Pons for the development of a relatively inexpensive, safe, nonpolluting, and essentially inexhaustible supply of energy for mankind. Certainly much work must now be done to demonstrate new science and the basic correctness of the TRM.

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