ISOTOPIC MASS SHIFTS IN CATHODICALLY-DRIVEN PALLADIUM VIA NEUTRON TRANSFER SUGGESTED BY A TRANSMISSION RESONANCE MODEL TO EXPLICATE ENHANCED FUSION PHENOMENA (HOT AND COLD) WITHIN A DEUTERATED MATRIX

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Abstract: The transmission resonance model previously presented by the author [3] to explicate cold fusion phenomena is now extended to treat the full range of enhanced fusion phenomena, from "hot" to "cold", within a deuterated matrix. Such seemingly disparate effects as low-level neutron emission, tritium production, the Pons-Fleischmann effect (i.e.,excess heat production in electrolytic cold fusion) [1],[2], and "cluster-impact" fusion (i.e., hot fusion within a lattice), may share a commonality as enhanced fusion phenomena resulting from the resonant transmission of de Broglie waves within a deuterated matrix. A new phenomenon is suggested as a possible source of excess heat; "transmission resonance-induced neutron transfer" (t.r.i.n.t.), which, in its effect, is essentially equivalent to Teller's hypothesized "catalytic neutron transfer" [4], and gives added support to a research suggestion of Teller [4]. An expression is given for relative excess power in the electrolytic case in terms of temperature and current density, and is suggestive when applied to new data on excess power. A postscript in this section indicates an apparent breakthrough for the model. The relative excess power expression is incorporated into a relation to give absolute excess power. When combined with the data it is found that the cross-section for the nuclear process that is the ultimate source of the excess power is on the order of 10^{-24} cm^2; viz., one barn.

INTRODUCTION

The transmission resonance model as applied strictly to cold fusion will first be updated and summarized in order to provide a framework for its generalization to predict enhanced fusion phenomena, hot and cold, in a deuterated matrix; e.g., palladium deuteride or titanium deuteride. The generalized model suggests that neutron emission (such as that observed in experiments employing pressurized deuterium gas and titanium shavings), electrolytic cold fusion, tritium production, and "cluster-impact" fusion (hot fusion) may all be examples of such enhanced fusion phenomena within a deuterated matrix. The model suggests a new phenomenon, "transmission resonance-induced neutron transfer" (t.r.i.n.t.), as a possible source of excess heat which, in its effect, is essentially equivalent to Teller's hypothesized "catalytic neutron transfer"[4]. A research proposal of Teller's [4] thus receives additional support from the transmission resonance model. A relative excess power expression is introduced for electrolytic cold fusion and compared to new data. A postscript in this section indicates that the model has achieved a breakthrough. An absolute excess power relation for electrolytic cold fusion is introduced and employed to derive a nuclear cross-section for the nuclear reaction that is the ultimate source of the excess heat.

THE TRANSMISSION RESONANCE MODEL (TRM) FOR COLD FUSION

Model Basis

The central assumption of the model is a transmission resonance condition for the de Broglie waves associated with diffusons, e.g. diffusing deuterons (hereafter: D's), within a deuterated matrix (usually a metal deuteride lattice) that is a simplification of a recent conjecture by L. Turner of L.A.N.L. [5],[6]. Combined with this central assumption are an energy distribution for the diffusons (taken as a Maxwell-Boltzmann distribution at the surface of the sample), and the effects of "phonon exchange" between the interstitial D's in the matrix and the matrix; e.g., a palladium lattice. Finally, the boson nature of the D's is invoked at several stages.

Transmission Resonance Condition

Turner [5],[6] has recently suggested that cold fusion may involve transmission resonances for D's diffusing through a periodic array of wells formed by the "ascending walls of neighboring Coulomb barriers" of interstitial D's within the Pd lattice. He points out that "conventional quantum mechanics yields a transmission coefficient of unity whenever the resonance condition of

$$\int_0^L k(x)dx = (n + 1)\pi \qquad (1)$$

is satisfied by the wavenumber of the particle crossing the potential well between the two barriers." [k(x) in (1) is the wavenumber of the diffusing particle, and L is the well width. [An excellent treatment leading to (1), and indicating when the term on the righthand side should be replaced by (n + 1) is provided in Chap. 12 of Bohm's Quantum Theory 7].] If λ is now taken to be the average de Broglie wavelength within the potential well, it is easily seen that (1) is simplified to

$$(2n + 1)\lambda/4 = L, \quad n = 0, 1, 2, \qquad (2)$$

(If the well were reasonably flat, λ would be essentially constant within it.)

Physical Meaning

Based upon the condition expressed by (2), we will assume that transmission occurs through a barrier-well-barrier combination whenever an odd quarter number of de Broglie wavelengths of the diffuson fit into the well width L. If we consider a de Broglie wave incident from left to right upon the barrier-well-barrier combination, then the physical meaning of the high transmissivity through the combination is as follows: That part of the wave reflected from the second barrier is interfering almost totally destructively with that part of the wave reflected from the first barrier to yield essentially zero reflected wave for the combination. (See Fig. 1, below.) With regard to this situation Bohm 7] notes: "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 amplitude of the wave inside the well, and Bohm [7] demonstrates that the energy levels associated with (2) correspond to metastable states.

It is of course this resonant transmission that is assumed to result in a diffuson (e.g., a D) getting close enough to a relatively fixed particle within the lattice to give the two particles a large probability of undergoing a nuclear reaction compared to the case when the condition (2) is not satisfied. Thus, in this model it is this resonant transmission phenomenon that is invoked to explain the central mystery of cold fusion; viz., how is it possible to have two charged particles, such as two deuterons, have a large enough probability to undergo 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.

As an example of a well-known wave-mechanical phenomenon involving a high transmissivity associated with a quantum resonance condition we need only to recall the Ramsauer effect: Electrons incident upon a noble gas, such as argon, are found not to be scattered if their de Broglie wavelengths satisfy condition (1) with the factor (n + 1/2) on the righthand side replaced by (n + 1). [See Bohm's Quantum

Theory [7], Chap. 12, to understand why the wave relation expressing resonance here is altered from that of (1).]

Metastable States: Lifetimes and the Effect of Coherence

The physical picture that emerges is one in which the lack of a reflected de Broglie wave causes the amplitude of the wave to become relatively large inside the well as it bounces back and forth between he barriers as shown qualitatively in Fig 1. It is the "leakage" of this large amplitude wave through the barrier on the far side that leads to a wave of amplitude low compared to that in the well, but of comparable amplitude to the wave incident upon the first barrier. Thus, transmissivity is essentially 100%.

Since the transmission resonance condition is also the condition for a "metastable state"; i.e., a relatively long-lived state, the question arises as to whether there are states with short enough lifetimes to allow them to be associated with the the excess power phenomenon. Elsewhere [8] we show that, without bringing in considerations involving the coherence of the bosons, the lifetimes of the first four metastable states corresponding to orders n = 0, 1, 2, and 3 are, respectively, 0.76×10^{-10} s, 1.36×10^{-8} s, 4.4×10^{-6} s and 1.7×10^{-3} s. Thus, all four states have short enough lifetimes to be operable in an excess heat scenario based upon the transmission resonance model (hereafter: TRM). The next three states, i.e. n = 4, 5, and 6 have lifetimes that make them interesting candidates for the "heat bursts" reported by some observers: Respectively, they are 0.7 s, 3.1×10^2 s (approximately 5 min.), and 1.4×10^5 s (approximately 39 hours). (The n=7 state, however, already has a lifetime of about 2 years.)

If considerations of coherence are employed for the bosons (the D's), however, it is possible to show [8] that, depending upon the effective "coherence volume", a number of higher order states can be brought into play: The basic idea, here, is that for the coherent case, when one particle makes the transition through the second barrier they essentially all do. So, it becomes a question of figuring out how long one would have to wait to see one particle emerge for the case in which the wavefunction is considered to be appropriately enhanced and the number of parallel, but interdependent-via-coherence, " transmission experiments" is vastly increased. In essence, then, coherence produces a totally new situation that we might liken to a large number of "phase-locked" de Broglie wave lasers operating over the coherence volume. For a coherence volume equal to 1% of the active region the new lifetimes corresponding, respectively, to metastable states of order n =15, 16, 17, 18, and 19, would be 2ms, 0.1 s, 51 s, 2.5×10^3 s (0.7 hrs), and 1.4×10^7s (162 days). So states of order n = 0 through n = 15 would here be available for what is observed to be the "steady" production of excess heat. And, again, the longer-lived of these might conceivably account for "heat bursts". Of course it is clear that even the "steady-state" production of excess heat has a "burst" nature if one looks on a small enough time scale. In this context we note that Huggins [9] has remarked that the production of

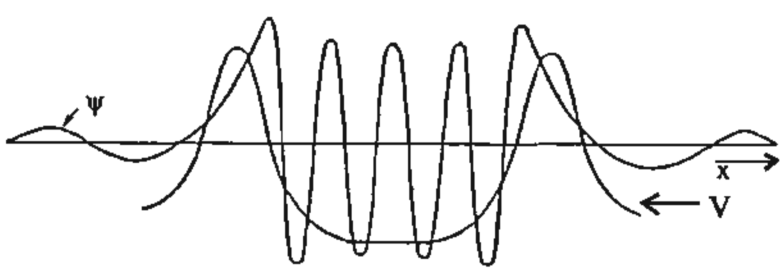

Fig. 1. Barrier-Well-Barrier Combination with de Broglie Wave Incident from Left.

excess heat is essentially a "non-equilibrium phenomenon", as opposed to a steady-state phenomenon.

The symmetry of the boson wavefunctions with the additional strict requirements of periodicity imposed by the periodicity of the crystalline lattice (Floquet's theorem) appear capable of producing the sort of coherence for the bosons (D's), which make them behave in a given coherence region almost as a single particle. It is this collective behavior that would presumably be responsible, for example, for "neutron bursts" and for "heat bursts". (In this regard we note that Bush and Eagleton [10] have previously emphasized the importance of the boson nature of the D's combined with the periodicity of the crystalline lattice. More recently this has also been stressed by S.R. Chubb and T.A. Chubb [11] of N.R.L. .)

The harshest critics of cold fusion have claimed that " it is done with mirrors." It is a wry observation that, if the picture presented here involving metastable states with the reflections of de Broglie waves is correct, it is indeed done with mirrors. Lots of them! This would, in fact, be how nature accomplishes the feat of "cold fusion".

An Optical Analogue For Transmission Resonance

It is possible to give a rather nice optical analogue for the transmission resonance phenomenon which we have taken as explaining the central mystery of cold fusion. With reference to Fig.2, two forty-five degree prisms have between them an optically flat piece of glass 9e.g., a microscope slide) of uniform thickness separated from the prisms by two air gaps on the order of a wavelength in thickness, but not necessarily of the same width. In this analogue, 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 analogues of the diffusons. Recall that, if the angle of incidence θ is equal to the critical angle θ_c or greater, all of the incident light, (I), is reflected, (R). On the other hand, if, in addition, the wavelength λ satisfies the transmission resonance condition (2), that an odd integral number of wavelengths fit into the plate width, transmission occurs as indicated by (T), with the reflected intensity becoming small. A variation of this is suggested by Bohm[7]: Let white light in a beam distributed across the face of the first prism replace the laser light. Only those colors satisfying the condition (2) for resonant transmission will be transmitted and (T) 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 in addition the strong buildup of light intensity within the glass plate characteristic of a metastable state.

Transmission Level Energies

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

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

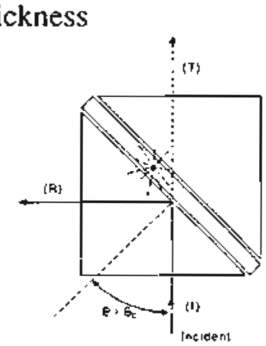

Fig.2. Optical Analogue for Transmission Resonance.

with h as Planck's constant and m as the mass of the diffuson. It will turn out to be convenient, and also, as will be shown, physically meaningful, to label these energy levels by the temperatures T_n, where we define the T_n by

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

so that (3) and (4) yield

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

Warning!: In what follows it is important to realize that the ambient temperature will be indicated by T, and not T_n. We will soon show from the model, however, an important physical significance for the condition $T = T_n$.

Many-Body Tunneling as Counterintuitive to the Two-Body Case

Two-body tunneling reaction theory has generally been extremely discouraging to the hypothetical prospects for cold fusion. The transmissivity for the two-body, or Gamow, case may be expressed by

$$T = \exp[-\gamma Z_1 Z_2 (m/E)^{1/2}], \qquad (6)$$

where γ is a constant, the Z's refer to the number of protonic charges on the two interacting particles, m is the mass of the lighter particle considered the tunneling particle, and E is the energy of its approach in a frame where the heavier particle is considered at rest. Thus, consider two separate hypothetical cases in which all factors are the same except the mass of the tunneling particles. Clearly, from (6), a slight increase in mass is enough to give a tremendous advantage to the less massive particle in terms of transmissivity, and thus the nuclear reaction rate.

Counterintuitive to this, on the other hand, is 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,

$$\lambda = h/(2mE)^{1/2}. \qquad (7)$$

Thus, for equal energies E, the diffuson with the greatest mass will have 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 will be associated with the largest density of transmission resonance levels per unit energy. This is apparent from (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

$$(2N + 1)\lambda_M = (2n + 1)\lambda_m = 4L, \qquad (8)$$

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 the number of candidates available for nuclear reactions. This is clearly exhibited in Fig. 3, where the density of transmission levels is observed to increase for the three cases involving palladium deuteride as a matrix as we go from left to right for the successive cases of deuterons, and lithons (Li^6 and Li^7, 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 nuclear reaction.

Fit of the Model to Data: Level Schemes

In the neutron emission experiments of Menlove, Jones, et al. [12] involving pressurized D_2 gas and titanium shavings the temperature of -30C (243K) was observed to be a recurring temperature associated with neutron emission in bursts. It was, thus, hypothesized within the context of this model by the author [3] that this temperature corresponds to one of the transmission levels in a sequence of levels specified by equation (5) for the case of deuterons diffusing within a titanium deuteride lattice. (The physical rationale for this hypothesis is presented in a later section:) Substitution of $T_n = 243K$ into (5) for an as yet unknown integer order n leads to the following generating formula for the possible compatible well widths, L_n:

$$L_n = (2n + 1)(0.349A) \qquad (9)$$

Corresponding to the respective integers 0,1, 2, 3, 4, etc. this relation generates the well widths 0.349A,
0.047A, 1.75A, 2.44A, 3.14A, etc. Based upon the independent crystalline data of Sidhu et al.[13] for the γ phase of titanium deuteride, a separation of interstitial deuterons is known to be 1.047A in excellent agreement with the generated value of L above corresponding to the order n = 1. The value L = 1.047A is then reinserted into equation (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:

$$T_n = (2n + 1)^2(27K). \qquad (10)$$

This is portrayed in Fig. 3 showing only the first two transmission levels at $T_o = 27K$ and $T_1 = 243K$ (i.e., -30C). Higher energy transmission levels are specified by $T_2 = 675K$ (402C), $T_3 = 1323K$ (1050C), etc. It has previously been noted that this level scheme is also compatible with the experimental results of Mazzoni and Vittori [14] involving neutron emission in the case of titanium blades pressurized with D_2 gas at high temperatures. Since there was no neutron emission data for the case of PdD, the model fitting procedure was then repeated for the case of electrolytic cold fusion taking room temperature, i.e. 293.2K, to be one level in a level scheme for the case of palladium deuteride as the lattice and the following respective diffusons: Deuterons (D), Li^6 lithons , and Li^7 lithons. The optimism for employing this result was based on the success of Pons and Fleischmann [1] at room temperature. (In this respect, it should be noted that Turner [5],[6] also employed room temperature as a significant one for the electrolytic case.) These other three level schemes are also portrayed in Fig.3. The dashed lines on either side of the solid levels in Fig.3 indicate representative thermal widths for the levels. [The relation for thermal width, ΔT_n , is given in equation (12).] 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 the Table on the next page. Note from that Table that the poorest agreement of the four comparisons is still to within three percent. Finally, it should be indicated, however, that ,

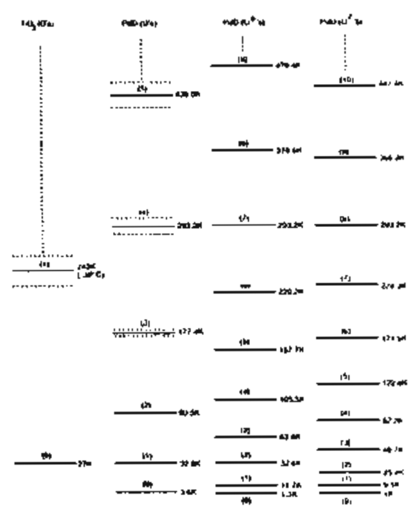

Fig.3. Transmission Resonance Energy Level Schemes.

Lattice	Diffuson	Well Width from Crystalline Data		Well Width from Model
TiD_2	d	1.047A	vs.	1.047A
PdD	d	2.85A	vs.	2.86A
PdD	Li^6	2.85A	vs.	2.76A
PdD	Li^7	2.85A	vs.	2.89A

TABLE of Well Widths

unlike those pressurized gas neutron emission cases in which there is 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, that is just as important as the ambient temperature in determining the energy distribution of the diffusons. The new developments in the model involving overpotential will be treated in a later section.

MAXWELL VELOCITY DISTRIBUTION AND THE EFFECTS OF PHONON EXCHANGE

A Maxwell velocity distribution is assumed for the diffusing D's. However, it is important to realize that for sharp values of the resonant velocities v_n corresponding to the de Broglie wavelengths for the various transmission orders n there are no candidate diffusons, corresponding to the fact that the area under a point on the distribution curve is zero. Candidates for transmission exist because of the the spread in well widths produced by phonon exchange between the interstitial deuterons and the metal lattice. Thus, Fig. 4 portrays three different velocity distributions overlying transmission resonance "windows": For the nth order resonance the window is centered upon v_n and lies between $v_n - \Delta v_n/2$ and $v_n + \Delta v_n/2$. The areas underneath the distribution curve lying within the windows provide relative measures of the number of candidate diffusons for transmission associated with the respective transmission orders at the temperature T. (The portrayal is not to scale. In addition, it should be noted that the widths of the transmission windows increase with the temperature T.) For PdD it is relatively easy to show that

$$\Delta v_n = 0.2(T_n T)^{1/2} \text{ m/s.} \qquad (11)$$

Thus, for n=0, for which the velocity v_o = 173m/s, Δv_o = 7m/s. We have previously shown that ΔT_n for TiD_2 is given by,

$$\Delta T_n = (4.1 \times 10^{-3})\, T_n T^{1/2}. \qquad (12)$$

Since this formula has been shown elsewhere [3] to scale inversely as the well width, the width of the energy window for a Maxwell-Boltzmann energy distribution not shown) for the nth order transmission resonance energy is given by approximately

$$\Delta E_n = k\Delta T_n = (1.3 \times 10^{-7})(T_n T^{1/2}) \text{ eV.} \qquad (13)$$

Thus, for the n=4 transmission resonance level the energy window is centered on E_4 = 25meV, while ΔE_4, the width of the energy transmission window is approximately 0.7meV around room temperature.

A second effect of phonon exchange, in addition to providing transmission candidates among the diffusons, is a negative one: It limits the maximum order of the transmission resonance that can contribute transmission candidates. Thus, as the order n increases, the de Broglie wavelength decreases as seen from (2). When the variation in the well width due to phonon exchange is no longer small compared to the de Broglie wavelength of the diffuson (and the period of well vibration is comparable to, or less than, the time of passage of a particle through the well) the resonance condition (2) can no longer be said to be obeyed: Transmis-

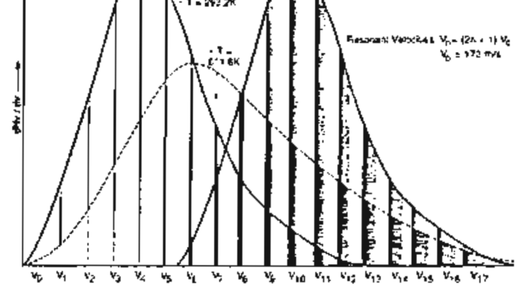

Fig.4. Maxwell Velocity Distributions for Diffusons showing Transmission Resonance Windows.

sion resonance no longer occurs for states above n_{max}. For the wells formed by neighboring Pd atoms we show elsewhere [8] that n_{max} = 16 at room temperature. However, for wells formed by neighboring D's in interstitial sites the situation is far more severe: Here, the corresponding n_{max} = 0, due to the fact that the variation in well width associated with thermal vibration scales inversely as the square root of the mass of the particles forming the wells as we have previously shown [3]. (Note that the Pd-channel well widths are essentially the same as for the D-channel.) (I am grateful to David Worledge of E.P.R.I. for asking me how thermal vibration might affect my model [15].) The fact that the Pd-channel for resonant transmission is thus far more robust than the D-channel within PdD will be shown to have profound ramifications.

Finally, we note that we have previously shown [3] that the peak of the Maxwell velocity distribution is centered at vn when the temperature T is equal to Tn. Thus, neutron bursts associated with the Tn level might be seen to occur upon warming of the sample when the temperature has reached that value of T such that the peak is associated with vn. However, we note that the envelope of the distribution also includes other values of vn. so it isn't clear what would prevent them from contributing. Perhaps, however, since small numbers of neutrons are observed, it is predominantly those associated with the peak that are numerous enough to be observable. In that regard it should be noted that neutron production will be associated in a later section with the D-channel, which will restrict the neutron numbers even more severely, as just discussed.

THE TRM APPLIED TO ELECTROLYTIC COLD FUSION

A Formula for Relative Excess Power

We will employ a Maxwell-Boltzmann energy distribution for the diffusons. While this might seem most appropriate for a reaction near the surface of the cathode it should be noted that most researchers, e.g., the Appleby group of Texas A&M [16], have found evidence for an excess heat reaction occurring within about 5 microns or so of the cathode surface. Thus, the relative heights of the transmission resonance windows are governed by the Maxwell-Boltzmann "envelope" for the temperature T and energy E expressed by

$$\Delta N(E) \propto T^{-3/2}E^{1/2}\exp(-E/kT)\Delta E. \qquad (14)$$

A particular transmission resonance window of order n will thus make a relative contribution to the candidate pool for nuclear reactions expressed by (14) with E replaced by E_n. The candidate number is also proportional to the current density i in the case of a given sample. Then, since it has been shown elsewhere [3] that

$$\Delta E_n \propto T^{1/2}T_{n,} \qquad (15)$$

it might seem that an appropriate expression for relative power for the purpose of comparing the theoretical excess power from the same sample at different current densities and temperatures would be given by

$$P_r = iT^{-1}\Sigma_n E_n^{1/2}\exp(-E_n/T)\,(T_n). \qquad (16)$$

However, this would ignore the fact that, at the surface, there is an additional energy gained by the diffusons associated with the overpotential, η, of $q\eta$, where q is the charge on the diffuson. Since the net effect is to add this energy to the diffusons, the Maxwell velocity distribution or the Maxwell-Boltzmann energy distribution is shifted to the right without a change in shape. This rightward shift without a change in shape is expressed mathematically by subtracting $q\eta$ from E in the two places where it occurs in (14), so that (16) is transformed as follows:

$$P_r = iT^{-1}\Sigma_n (E_n - q\eta)^{1/2}\exp[-(E_n - q\eta)/kT]\,(Tn) \qquad (17)$$

We present the details of the incorporation of the the formalism of the Butler-Volmer equation from electrochemistry elsewhere [8]. Finally, employing $E_n = kT_n$, and throwing away a factor of $k^{1/2}$, (17) is transformed into the following relation, which we take as defining the relative excess power, P_r:

$$P_r = i^3 i_o^{-2} T^{-1} \Sigma_n \{ [T_n - 2T\ln(i/i_o)]^{1/2} T_n \exp(-T_n/T) \}, \qquad (18)$$

where i_o is the "equilibrium current density" when no net current flows to the cathode and serves as the adjustable parameter in this model. The sum is only over those values of n from 0 to about 15 for which the quantity $T_n - 2T\ln(i/i_o)$ is positive. (Recall that the upper limit upon n enters because of the fact that thermal changes in the well width have become comparable to the de Broglie wavelength of the particle for periods of vibration comparable to, or shorter than, the time of passage of the particle across the well.) We now investigate to see whether the expression in (18) is meaningful, by comparing it to new calorimetric data obtained by Eagleton and Bush [17] of Cal Poly, Pomona.

Comparison with Data

Fig. 5 is a plot of excess of power versus current density for T = 300K. The data is from Eagleton and Bush [17], where the experiment is described in thorough detail. However, a few details may be of interest here: The calorimeter is of a steady-flow design and the flow rate is periodically checked. The entrance and exit ports of the bath in which the electrolytic cell resides have thermocouples to monitor their temperatures. Two thermocouples inside the cell are employed to obtain temperature readings near the cathode. Separate calibration curves for each of these in-cell thermocouples are rectilinear, as one would expect. A value of excess power is guaged from a thermocouple reading and the corresponding calibration curve. The two values are then averaged to provide the experimental excess power that appears in Fig. 5 . The system is fast-mixed since a magnetic stirrer is employed. In addition the cell is closed and a recombiner is used. The cathode was gently loaded for about two and one half weeks at a charging current density of about 70mA/cm². The total integrated input power from the beginning of charging until the end of the experiment; i.e., until the end of the excess power output, was approximately 2.0MJ, while the total integrated excess power output for the approximately 36 hours of excess power production was about 0.35MJ. However, during that final 36 hours of the experiment, i.e. that period in which excess power could be observed, the excess power was rather spectacular, being, on average, about 30% of the input power associated with the applied current. Nevertheless, we refer to "excess power" rather than "excess heat" since the 0.35MJ obtained was less than the applied energy of 2.0MJ. (In this connection, however, it should be noted that other researchers, e.g. Pons and Fleischmann [1] and Huggins [18], have observed excess heat. Moreover, the excess heat is on the order of megajoules per mole of material, rather than kilojoules per mole of material, with the thousandfold difference clearly indicative of a <u>nuclear source</u> for the excess energy as opposed

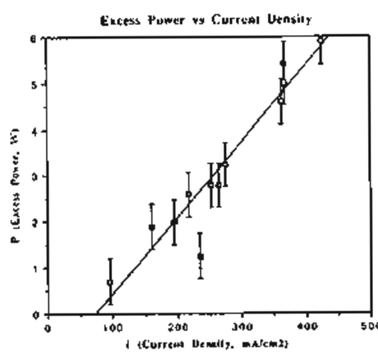

Fig.5. Experimental Excess Power versus Current Density.

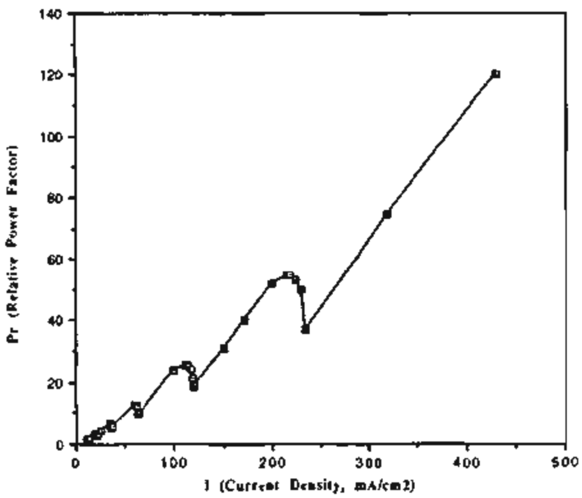

Fig.6. Relative Power versus Current Density on tne Transmission Resonance Model

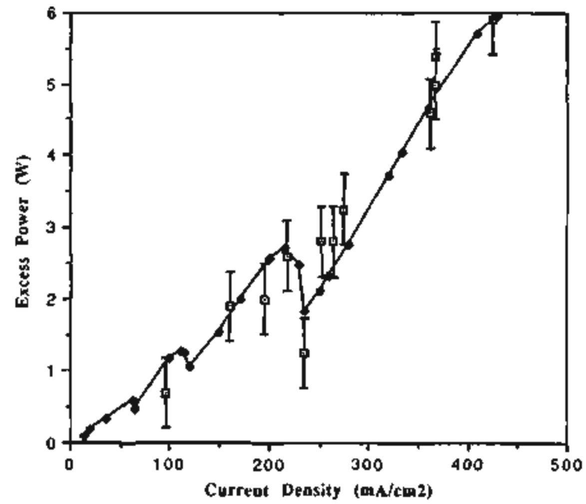

Fig.7. Comparison of Transmission Resonance Model to Data of Fig.5.

to a chemical source.)

The data of Fig. 5 appears to be quite typical. In particular, with the exception of the low-lying data point at 235mA/cm² it seems to indicate a linear relation between excess power and the applied current density over the range of values shown.. Another typical feature is that the effect apparently is no longer observable when the applied current

density is lowered to a value (found by extrapolation here) of about 60mA/cm² . Fig 6 shows a plot based upon the TRM: The relation for relative excess power in (18) was employed to plot theoretical excess power versus applied current density for T = 300K. The values of T_n for the transmission resonance levels of PdD are taken from (10) with the 27K for TiD2 replaced by the 3.62K appropriate for PdD with D's as diffusons. . A value for the adjustable parameter of i_o = 1.47mA/cm² was shown to give the best fit to the data. This is displayed in Fig.7 with the curve based upon the model shown as a solid line with dark squares showing the theoretical points entered in the Cricket graph. Note that a relative minimum of the theoretical curve, a sort of "cusp", corresponds to the low-lying data point at 235mA/cm². In my presentation at the Cold Fusion Symposium I indicated that, while this was rather "flimsy" evidence for the model , nevertheless, I would stick my neck out by indicating that I felt it would turn out to be prophetic. [**Postscript:** Since the First Annual Cold Fusion Symposium at the end of March we (Bush and Eagleton) have obtained additional important evidence of the sort of fine structure seen in the model curve of Fig.6 and Fig.7. This will be made available in references [8] and [17]. Thus, the model with its ability to relate relative excess power to applied current density and temperature near the surface of the electrode according to the formula in (18) appears to be quite meaningful. In addition, the fact that in these post-Symposium studies there is finally a reasonable physical model providing a good fit to data on excess heat appears to provide an enormous boost to the credibility of the Pons-Fleischmann effect, itself. In a word it seems that the transmission resonance model has achieved a genuine breakthrough in the study of "cold fusion". Implicit in this model, which now combines physics and electrochemistry, is an extremely important role for the overpotential. To be sure, acceptance of the TRM will depend upon independent confirmation of our results by other researchers.]

TRANSMISSION RESONANCE-INDUCED NEUTRON TRANSFER (t.r.i.n.t.)

Excess Heat Source in "Cold Fusion"

It has already been observed that the phonon exchange effect associated with vibration of the potential wells limits the Pd-channel for transmission resonance to an order n of about 15, but limits the D-channel to only about n=o, due to the greater amplitude of well vibration for the far less massive deuteron wells. Two effects arise from this: First of all, the vast majority of D-on-D reactions would occur in the n=o state, which means that the relative velocity of approach of the two D's would be only about 173m/s corresponding to an energy of only about 3×10^{-4}eV! Under this circumstance we would anticipate a large polarization effect due to the two protons residing on the D's. This should lead to a stripping process, or Oppenheimer-Phillips type process, in which this massive polarization effect favors the exchange of a neutron to yield a T (triton) plus p (proton) as opposed to the exchange of a p to yield an He^3 nucleus plus a neutron. Thus, the TRM may be able to account for the "anomalous" branching ratio on the order of 10^8 favoring the production of tritium over neutrons that several observers have noted.

The second effect is that the nuclear reaction of a D with a Pd nucleus will be a far more common occurrence than will be a D+D reaction in the D-channel. (From the standpoint of the Gamow reaction this would not be reasonable, due to the much larger charge on a Pd nucleus than on a D. Again, however, the many-body tunneling reaction implicit in the transmission resonance phenomenon is counterintuitive to the Gamow case: All that counts is whether the transmission resonance condition holds for the wells formed by the potential curves of neighboring Pd nuclei.) (Remember that the spacings of neighboring Pd's will be essentially the same as that of neighboring D's.) Employing the above reaction as a prototype we again suppose that polarization effects due to the positive charges in the two particles (D and Pd) vastly favor the transfer of a neutron to the Pd nucleus from the D leaving a heavier isotope of Pd and a proton. We will refer to this reaction as a "transmission resonance-induced neutron transfer" ("t.r.i.n.t."), or by the acronym trint (reaction). (D+D to give T + p is a special case of a trint reaction.) (The greater velocities of approach for the higher order states would be compensated for in terms of this polarization process by the larger positive charge on the Pd nucleus.) Because of the fact that the D is a loosely bound nuclear structure, the greater binding energy per nucleon in the heavier Pd nucleus would be the ultimate source of the energy finally showing up as excess heat.

Based upon spin considerations the only acceptable trint reactions for the Pd isotopes are,

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

and,

$$D + Pd^{106} \rightarrow p(4.31MeV) + Pd^{107},$$

where Pd^{107} β-decays with a half-life of 7×10^6 years (35keV β) to Ag^{107}, which,in turn, decays with a halflife of 42s by emitting a 93keV gamma ray. It will not be easy to demonstrate the existence of these isotope shifts based upon either mass spectroscopy or the β-decay of Pd^{107}. The best bet would, perhaps, be to run the same cathode over and over again to enhance the isotopic shift in the Pd metal. It has been estimated that a 5 gram Pd cathode would have to produce about 100MJ of excess heat, assuming the validity of trint, before the β-decay of the Pd^{107} would be detectable. (When rerun, the surface of the cathode should be made clean again. If cracking due to the D's gets too severe it may also be necessary to recast the Pd cathode being careful to avoid other Pd contamination.)

Similarity to Teller's Hypothesized "Catalytic Neutron Transfer"

Teller [4] has hypothesized a reaction, "catalytic neutron transfer", in which a hitherto unknown neutral particle would catalyze the transfer of a neutron between, for example, two D's. In essence the trint reaction hypothesized above has the same end result as Teller's hypothesized reaction, but requires no unknown particle as a catalyst.

An Experiment to Convince Physicists

Teller has suggested (4) in connection with his hypothesized "catalytic neutron transfer" reaction that U^{235} be employed cathodically in an electrolytic cold fusion experiment because "uranium's response to absorbing a neutron is well-known." The TRM with the hypothesized trint reaction also suggests trying this experiment: Thus, one uranium cathode enriched with U^{235} and loaded with D's from a heavy water electrolyte should emit many more neutrons than should an essentially identical uranium cathode loaded with protons via an electrolyte made from ordinary water. The contrast in neutron emission should be impressive enough to convince those physicists who need to see particle emission in order to believe that a nuclear reaction is occurring at room temperature inside a metal lattice.

APPLICATION TO 'HOT' NUCLEAR PHENOMENA WITHIN A DEUTERATED MATRIX (T.R.E.N.D.)

Introduction

Phonon exchange implies that transmission resonance states above about order n=15 will not make a contribution for a lattice temperature around 300K for the Pd-channel. However, at high enough velocities for which the transit time through a barrier-well-barrier system becomes short compared to the period of vibration of the well width due to thermal effects it may again be possible to see the effects of transmission resonance. Thus, we might anticipate reaction yields for such cases that would be larger than Gamow theory based on a two-body reaction at those energies predicts. This condition is met near the lower end of the range at which the elegant "cluster-impact" fusion experiments of Beuhler,Friedlander, and Friedman [19] have been carried out; viz. at around 1keV per deuteron of the heavy water clusters used as projectiles upon a TiD_2 target.

"Cluster-Impact" Fusion

Beuhler has, in fact, indicated [20] that the calculated theoretical yields for "cluster-impact" fusion are "highly unflattering" for their experiment. It seems highly likely that their actual experimental yields of protons, tritons, and He^3 nuclei are in fact higher than conventional nuclear physics would predict because a sizeable fraction of the reactions that result in particle transfer between a "diffusing" D and either a D or a Ti nucleus in the TiD_2 lattice are examples of "transmission resonance-enhanced nuclear phenomena", or "TREND.": In this case, particles would, via transmission resonance within the lattice, get much closer together in this environment than in the asymptotically-free environment of a hot plasma. Note that the D-channels would now be competitive with the Ti-channels since the well widths are virtually "frozen " during the transit time of a D. Neutrons as reaction by-products are apparently not yet being studied by them. However, based upon the ratios of T's and p's to He^3's the branching ratio appears to be 1:1. This is what we would anticipate based upon the much larger relative velocity of approach of the particles at these higher energies: The polarization effect associated with the positive charges on the two particles which has time to be important for the Oppenheimer-Phillips type process in the case of low relative velocity of approach now has no time to produce a noticeable effect. One mystery, however, is this: If the Ti-channels are competitive with the D-channels with regard to this effect, it appears that Beuhler et al. should be seeing a branching ratio of in favor of proton-triton production over that of

He^3. In addition, the protons from the Ti-channel reactions would have energies ranging from about 6MeV to about 9.3MeV, making them rather difficult to confuse with the 3 MeV protons from the D-on-D reaction. The answer to this may be that the wider range of well widths (larger amplitude of vibration) for the D-wells give this channel a large advantage over the Ti-channel. That is, there is a larger number of possibilities in the D-channel case all of which are essentially equally likely in the transition resonance "lottery" at these energies. The result would be relatively few Oppenheimer-Phillips type reactions involving the Ti-channel with negligible chance of seeing Ti-isotope ratio shifts except in the case of a target that is employed over and over with relatively large currents.

An experiment that might show whether transmission resonance is effective here involves employing a single TiD_2 crystal as a target: If transmission resonance is involved, changing the orientation of the crystal axis relative to the beam direction should produce variations in the yields. Such an effect would be evidence in support of TREND. Of course, due to the "splattering" nature of the water "droplets", perhaps the more random the target the better. In this regard it should be indicated that, in addition to obtaining good results with polycrystalline TiD_2 targets, Beuhler et al. [20] have also had excellent results with more "random" targets such as polydeuteroethylene in which ordinary hydrogen atoms have been replaced by deuterium atoms. Here again there is a large range of well widths available for TREND. An indication of this "randomness effect" might also be obtained by employing a sintered TiD_2 target to attempt to see an enhancement of yield over that for their usual polycrystalline targets.

THE TRM AND THE TRITIUM PUZZLE

Introduction

Some researchers, the most prominent being Bockris [21] of Texas A&M, have suggested that tritium is produced on the surface of the cathode in association with the growth of "dendrites". According to this argument the dendrites would produce enormous fields, e.g. 10^5V/cm, near their tips which would accelerate D's onto their surfaces to plough into other D's. It is further argued that the polarizations produced by these fields would shift the branching ratio strongly away from the neutron branch towards the tritium branch of the D+D reaction. Potential drops on the order of 20kV have been hypothesized, so that such a reaction would, in actuality, be a "hot" nuclear reaction. Thus, the reaction would have a lot in common with the "fracto-fusion" reaction hypothesized in connection with observations of low-level neutron production by Jones, Menlove, and others. Bockris [22] has recently been very clever in apparently correlating dendrite growth times with the appearance of tritium in the electrolyte. However, this dendrite hypothesis appears to face two difficulties: Most researchers grant the existence of the high fields, but cannot see these as being extensive enough to give anywhere near the potential drops required for the scheme to operate. (Bockris claims that these high potential drops are attained intermittently.) A more telling difficulty, however, is the fact that tritium production is sometimes observed in the absence of dendrites. It is this observation which, notwithstanding the ingenuity of the dendrite hypothesis, renders it difficult to accept.

The Role of Lithium

Whether or not lithium, either Li^6 or Li^7, plays a major role in tritium production is not clear. What suggests that it does not is that tritium has been observed for both relatively pure Li^6-component electrolytes and relatively pure Li^7-component electrolytes. In addition Iyengar et al. [23] have reported tritium production in the case of electrolytic cold fusion where sodium was used in place of lithium. Also, excess heat production has been observed [16] for both relatively pure Li^6 and Li^7 cases.

Thus, the role of lithium is not clear. Appleby's group at Texas A&M [16] has, however, established that both Li^6 and Li^7 are found to about a depth of 5 microns in those cathodes evidencing excess heat when they employ the naturally-occurring ratio in their electrolyte. So,there may then be an important role for the lithium since the heat reaction appears to involve this sort of active depth. One possibility, suggested previously by the author [3] is that of a heat producing reaction

$$D + Li^6 \rightarrow He^4 + He^4$$

However, we would have to suppose that there is still enough Li^6 contaminant in the relatively-pure Li^7 electrolyte to still produce observable excess heat. Also, if this is a transmission resonance reaction it would seem likely that the D's are the diffusons rather than the Li^6's. The depth of Li^6 penetration would then reflect the extent of the Li^6 participation in the lattice and/or as interstitials for enough reactions with diffusons (D's) to occur for observable excess heat production.

Another role for lithium has been suggested by Storms [24] of L.A.N.L. and, independently, by Marshall [25]. Hydrogen dissolves well in both palladium and lithium. Perhaps the combination is even more effective. Maybe a lithide compound of Pd is formed, for example, which promotes the absorption of hydrogen. In this scenario the lithium simply helps to achieve a high enough loading of the D's to make the reaction go in this region. It may also aid the process of filling interstitial sites by occupying those interstitial sites that the D's do not occupy. Presumably, sodium might play the same sort of role.

Explaining the Bockris Curve

Bockris [26] has presented a curve for excess heat production which is mirrored by a lower-level curve for the production of tritium, although with an initial lag behind excess heat production of about five days. In this connection it is interesting that the TRM, if limited to the first four metastable states (n=0,1,2,3) for heat production (Pd-channel) (except for bursts of heat as described earlier) and the first state (n=0) (D-channel) for tritium appears able to account for the situation described by the two-component Bockris curve: Thus, in this TRM scenario, initially the overpotential shifts the energy distribution so far to the right that none of three shorter-lived metastable states are operative. However, as the electrode is "platinized" via cathodic deposition, the overpotential decreases, and the energy shift of the D's that we have associated with it decreases so that first the n=3 state is brought into play as the curve shifts leftward followed by the n=2 state etc. Thus, excess heat is now being observed, but tritium will not be produced in observable amounts until the leftward shift of the envelope via the decreasing overpotential allows it to overlap the n=0 state. In this connection, the P_r value (See ( ).) for the n=0 state (i.e. P_r evaluated for just n=0) is about 0.1% of that for the sum of the P_r values for the states n=0,1,2,3 (i.e. P_r evaluated with the sum over the first four states), which is in agreement with Bockris' estimate of the percentage correlation between the production of "excess heat" and tritium production.

CALCULATION OF A NUCLEAR CROSS-SECTION

We show elsewhere [8], that the relative excess power factor can be incorporated into the following expression for absolute excess power:

$$P = \{8k/qL(\pi m\omega^2)^{1/2}]A(\rho/M)N_o f N_c E_1 \tau\sigma i^3 i_o^{-2} T^{-1}\} \bullet \bullet \Sigma_n\{[(2n+1)^2 T_o - 2T\ln(i/i_o)]^{1/2} \bullet \bullet (2n+1)^2 T_o \exp(-T_n/T)\}, \quad (19)$$

where q is the charge on a D, L is the well width (meters), m is the mass of a D, ω is the angular frequency of vibration (average) for the interstitial D's, A is the surface area of the cathode, ρ is the density of the palladium , M is the grammolecular weight of Pd, N_o is Avogadro's number, f is the "sticking factor" (i.e. the number of D's that enter the surface for each electron passing in the current), N_C is the number of singly-charged positive particles in a Coulomb of charge, E_1 is the energy released in a single nuclear reaction (taken here to be about 5MeV), τ is the depth of the active region (taken to be about 5 microns), and σ is the nuclear cross-section. To estimate σ we employ the data of Fig.7 taking P to be 2W for an applied current density of $i=250 mA/cm^2$ and $i_o = 1.47 mA/cm^2$. The relative power factor from the computer program was 4,280. The result is,

$$\sigma = (2.8/f) \times 10^{-26} cm^2. \qquad (20)$$

Thus, if the sticking factor is on the order of 3/100, the cross-section for the nuclear reaction would be on the order 10^{-24} cm^2, viz., a barn, which seems not unreasonable.

CONCLUSION

The transmission resonance model appears to account for the Pons-Fleischmann effect of excess heat production: The model gives an excellent fit to data, strengthening the likelihood that it is correct, and boosting the credibility of the effect, itself. Nevertheless, the results indicated must be confirmed by other researchers. That the TRM stands a good chance,also, of explicating both the phenomena of low-level neutron production and the higher-level production of tritium is very apparent, though there is much work remaining to be done in order to sort this out.

Finally, if the the model is correct it appears that there is little new physics involved. Rather, the Pons-Fleischmann effect is, quite simply stated, the most startling of the consequences of the wave nature of matter discovered thus far.

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