The Journal of Physical Chemistry

VOLUME 93, NUMBER 12 JUNE 15, 1989

LETTERS

Two Innocent Chemists Look at Cold Fusion

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We propose that the large energy release reported in the experiments of Fleischmann, Pons, and Hawkins may be the consequence of ^2H fusion accelerated through screening by neighboring "heavy electrons" with mass $m^* \cong 10$ electron masses. The presence of the Pd lattice may also accelerate the radiationless relaxation (RR) of the transient excited $^4He^*$, perhaps by an internal-conversion-like process. If RR exceeds the rate of fragmentation of $^4He^*$, this can explain why the bulk of the energy is released as heat rather than via neutron and tritium production. Symmetry considerations show that low-energy fusion can lead to different product channel branching ratios than are observed in high-energy experiments and may allow RR rates to outstrip fragmentation rates. Our analysis also suggests that the rate of $^1H + {}^2H$ fusion may be comparable to or even in excess of that of $^2H + {}^2H$ fusion in the Pd lattice, so that fusion might even be observed in water of natural abundance deuterium content.

I. Overview of the Findings and Introduction to the Model

Recently, Fleischmann, Pons, and Hawkins[1] reported that the prolonged electrochemical charging of a palladium cathode with deuterium, formed by electrolysis of a D_2O solution containing LiOD, leads to the evolution of small amounts of neutrons and tritium together with heat on a scale not easily reconciled with any known chemical reaction. This report has attracted worldwide attention and no little skepticism, although, at this time, there appears to have been piecemeal confirmation[2] of their results in a number of laboratories.

The evolution of tritium and neutrons is consistent with the well-known fusion of deuterium to form an excited helium nucleus $^4He^*$ with 23.85 MeV of excess energy

$$2\,{}^2H \Rightarrow {}^4He^* \tag{1}$$

which, under conditions studied by physicists, decomposes to roughly equal quantities of ^3He and ^3H

$$^4He^* \Rightarrow {}^3He + n + 3.25\text{ MeV} \tag{2}$$

$$^4He^* \Rightarrow {}^3H + {}^1H + 4.03\text{ MeV} \tag{3}$$

The most plausible explanation of the apparent enhanced rate of $^2H + {}^2H$ fusion (by a factor of 10^{53} in these experiments) involves a tunneling phenomenon aided by screening of the Coulombic repulsion between the $^2H^+$ ions by the surrounding electron density[3] in the lattice as discussed further below. The conventional

(1) Fleischmann, M.; Pons, S.; Hawkins, M. *J. Electroanal. Chem.* **1989**, *261*, 301.

(2) At this time, based on news reports and private communication.

(3) A paper by Harrison (Harrison, E. R. *Proc. Phys. Soc., London* **1964**, *84*, 213) deals with the concept of enhanced tunneling due to screening by electrons in the surrounding medium for so-called pycnonuclear reactions. In our picture, the two D^+ nuclei in the presence of the lattice electrons experience an attractive interaction at long range analogous to chemical binding; this attraction is balanced and eventually exceeded by the screened Coulombic repulsion at smaller bond lengths. The screening moves the $E = 0$ turning point inward (this turning point occurs at approximately 0.5 Å in D_2^+) but does not persist much beyond approximately 0.1 Å; from this point inward, the bare Coulombic barrier (plus any centrifugal barrier) pushes the D^+ nuclei apart. The $E = 0$ turning point shifts inward to approximately 0.5 Å$/m^*$ in a model which attributes screening to "heavy electrons" of mass m^* times the true electron mass. Thus, the primary effect of the screening is the reduction of the width of the barrier through which tunneling must occur rather than the height of the barrier.

0022-3654/89/2093-4693$01.50/0

reaction sequence (1–3) produces a predictable amount of heat, based upon that generated in the neutron- and ^{3}H-producing reactions. *The most startling feature of the experimental results of ref 1 is that the actual heat production, measured by simple calorimetry, is 10^7–10^{10} as large as that expected* from the above reaction sequence, given the neutron and tritium counts measured. Clearly, if these experiments are correct, the major path of energy production is something quite different.

At the molecular level with which chemists are familiar, *electronically* excited states of molecules are known to lose their energy by at least three well-recognized paths: (A) dissociation of the molecule by the breaking of chemical bonds; (B) emission of light (fluorescence or phosphorescence); (C) radiationless transfer of energy to surrounding molecules, usually as vibrational energy but sometimes by converting surrounding species to electronically excited or ionized states. Analogues of each of these are known for the decay of excited nuclei. Reactions 2 and 3 clearly parallel path A. The analogue of path B is γ-ray emission; this was not happening in the experiments of ref 1 since it would have carried most of the energy out of the reaction vessel, and the resulting lethal level of radiation would have been detected by radiation monitors in the laboratory. A nuclear analogue of path C is known[4] as internal conversion (IC) in which energy is transferred from the excited $^4He^*$ nucleus by coupling to neighboring electrons (here, of the solid's bands). In the process, the electrons may be ejected as β-radiation, a fraction of whose kinetic energy could eventually produce heat within the palladium electrode:

$$^4He^* \Rightarrow {}^4He + \text{heat } (\leq 24 \text{ MeV}) \qquad (4)$$

Our proposal of a radiationless relaxation (RR) path (perhaps IC), in which energy is transferred to the PdD_x lattice, perhaps mediated through the lattice electrons, is certainly attractive from the point of view of heat and energy production, since it predicts that each fusion event could produce up to 24 MeV of heat, unaccompanied by a large, troublesome neutron flux or by ^{3}H formation. Our proposal predicts a rather copious production of ^{4}He; in a reaction generating 10 W cm^{-3} of excess energy (in the range which has been observed[1]) or some 6.4×10^{13} MeV cm^{-3} s^{-1} of heat, one expects 2.6×10^{12} fusions cm^{-3} s^{-1} if each fusion results in the liberation of 24 MeV of heat.

Pons and Hawkins have informed us[5] that mass spectrometric analysis of evolved gases from a cell operating at 200 mA with an electrode volume of 0.0785 cm^3 and delivering 0.5 W cm^{-3} of excess heat showed a $^4He/D_2$ ratio of 10^{-5} to 10^{-6}, substantially larger than that of a number of blank determinations. With the assumption that each two electrons reduce one D_2O molecule to yield one D_2 molecule in the gas phase (the lattice is saturated at steady state), one predicts that 8×10^{18} D_2 molecules cm^{-3} s^{-1} are liberated. The mass spectroscopy ratio then implies a rate of ^{4}He production of 8×10^{12} to 8×10^{13} atoms of ^{4}He cm^{-3} s^{-1}. The excess energy production of 0.5 W cm^{-3} corresponds to 3.2×10^{12} MeV cm^{-3} s^{-1}. The fact that the ratio of the heat-production and ^{4}He-production rates is (3.2/8–3.2/80) MeV per ^{4}He is evidence in favor of a nuclear process being involved. That the ratio is not 24 MeV is not significant because the mass spectroscopic determination of the $^4He/D_2$ ratio is uncertain to at least this extent. At present, further experimental work is in progress to search for ^{4}He in other cells and to better quantitate the $^4He/D_2$ ratio for these cells.

As far as we know, radiationless relaxation has not previously been observed in deuterium fusion reactions or in the decay of other $^4He^*$ states. Clearly, the question is why might it be occurring in the experiments of ref 1? In the model described here, it is demonstrated that *the same effects which may lead to accelerated fusion (the presence of the lattice electron density as well as the low-energy nature of the process) may also greatly increase the relative rate of radiationless relaxation of the resulting $^4He^*$* to an extent that RR may compete with the usual fragmentations (2) and (3).

(4) A paper by Fowler (Fowler, R. H. *Proc. R. Soc., London* **1930**, *129*, 1) provides one of the earliest accounts on the internal conversion process which now appears in most texts on nuclear physics. Blatt and Weisskopf (Blatt; Weisskopf. *Theoretical Nuclear Physics*; Wiley: New York, 1952; pp 617, 621) give expressions for the rates of internal conversions for states which may or may not also undergo γ-emission.

(5) Pons, S.; Hawkins, M. Private communication to the authors.

II. The Fusion Model

To describe the fusion of two $^2H^+$ nuclei, we use a model much like that outlined in ref 3 and 6. In our approach, the rate R (in fusion events per second per $^2H^+$) is given as a collision frequency f multiplied by a probability of fusion: $R = fP$. The rate can also be expressed as a cross section σ in cm^2 multiplied by a collision speed v in cm s^{-1} and a probability factor P multiplied by the concentration C of $^2H^+$ species: $R = C\sigma vP$. The total fusion rate of the cell, in fusions cm^{-3} s^{-1}, is then computed as either of these rates multiplied by C. It is conventional[3,6] to express σ as $S/(^1/_2\mu v^2)$, where μ is the reduced mass of the colliding nuclei, v is their relative speed, and S is a factor that describes the "size" and fusion efficiency of the nucleus in such collisions; this parametrization is used because experience shows that S is rather weakly dependent on energy. Results of both parametrizations will be presented below to provide some measure of how much the results depend on the particular model.

In characterizing the state of the deuterium in the Pd metal, it is assumed that the mole ratio of $^2H^+$ to Pd is nearly 1:1. In fully saturated Pd, the ratio lies between 0.5 and 1.0; in what follows, a value of 0.7 is assumed, giving a $^2H^+$ density of 4.8×10^{22} $^2H^+$ cm^{-3}. This concentration implies an average spacing between $^2H^+$ ions (if they were uniformly distributed) of 3.4 Å. If the temperature in the Pd lattice ranges from 300 to 1000 K, the mean collisional velocities of the $^2H^+$ pairs would be $(2.7\text{–}5)/\mu^{1/2} \times 10^5$ cm s^{-1}, where μ is the reduced mass, in amu's; the nominal value of $4\mu^{-1/2} \times 10^5$ cm s^{-1} chosen here corresponds to a collision frequency of $f = 1.3\mu^{-1/2} \times 10^{13}$ s^{-1} (for each $^2H^+$) and a collisional kinetic energy $\mu v^2/2 = 8.4 \times 10^{-8}$ MeV.

The fusion probability function P for tunneling through the repulsive Coulombic barrier is taken to be of the form[3] $P = \exp(-2\pi\alpha/\hbar v)$, where the parameter α characterizes the strength of the Coulombic repulsion between the two nuclei. To determine α for the ^2H–^2H interaction, the following procedure is used: (i) The expected[6,8] fusion rate of isolated D_2 of $10^{-63.5}$ s^{-1} is used, in conjunction with a "collision frequency" of 7×10^{13} s^{-1} (the vibrational frequency of D_2 is used in this case instead of the thermal collision frequency) and the corresponding velocity of 7×10^5 cm s^{-1} and a reduced mass μ of 1.0 amu, to determine the value of $\alpha = 2.08 \times 10^{-20}$. (ii) From this "fit", it follows that $P = \exp(-178v/v^*)$, where v^*/v is the ratio of the collision speed in any particular situation and the speed 7×10^5 cm s^{-1} used in determining α. If, alternatively, the fusion rate per $^2H^+$ is parametrized as $CPvS/(^1/_2\mu v^2)$, and the value[3,6] $S = 1.1 \times 10^{-25}$ MeV cm^2 is used with the above vibrational kinetic energies and speeds, one finds that $P = \exp(-170v/v^*)$ is needed to fit the rate of fusion of $10^{-63.5}$.

The first form for P and the collision frequency $f = (\mu^{-1/2})1.3 \times 10^{13}$ cm^{-3} s^{-1} permit the log of the fusion rate R (in s^{-1}) to be written as $\log R = 13.6 - 77(v/v^*)$; if the parametrization based on $R = CvPS/E$ is used, one finds $\log R = 10.6 - 74(v/v^*)$. To achieve a rate of $^4He^*$ formation equal to 2.6×10^{12} cm^{-3} s^{-1} as inferred earlier, given the concentration of $^2H^+$ to be 4.8×10^{22} $^2H^+$ cm^{-3}, requires a fusion rate per $^2H^+$ of $5.4 \times 10^{-11} = 10^{-10.3}$ fusions s^{-1} or a lifetime of 585 years. Using the log of this rate in the above rate expression yields $v^*/v = 3.2$. (It gives $v^*/v = 3.5$ if the model based on $R = CvPS/E$ is used.)

As described on p 218 of ref 3, reduction of the Coulombic potential allows the two D^+ nuclei to approach more closely before reaching their classical turning points. This, in turn, requires tunneling through a shorter distance to reach the region where the strong nuclear forces exist. These effects can be modeled in terms of the "binding" together of the two $^2H^+$ ions due to[6–8] "heavy electrons" in the metal. In this model, the collision energy E of the $^2H^+$ pair is viewed as increased by a factor m^* equal to the ratio of the metal's effective electron mass and the bare electron mass: $E^*/E = m^*$. Considering this increase in energy, which yields a speed ratio $v^*/v = m^{*1/2}$, allows the fusion rate expressions to be extended to treat events taking place in the presence of screening for which

$$\log R = 13.6 - 77(\mu^{1/2}/m^{*1/2}) \tag{5a}$$

or

$$\log R = 10.6 - 74(\mu^{1/2}/m^{*1/2}) \tag{5b}$$

In terms of the model introduced here to interpret cold fusion in deuterium-loaded Pd metal, the rate acceleration required to account for the production of 10 W cm^{-3} requires an effective electron mass of $m^* = 10$ ($m^* = 12.5$ for the second model).

III. Possibilities of Fusion Involving Other Isotopes

These same models can be used to predict the rates of other fusion events that might occur in the Pd system. The estimated rates of fusion in the absence of screening given in ref 6 are used to determine α values for each isotopic reaction in the first model. The S values for the different isotopic reactions are tabulated in ref 6 and 3. The two models predict $^2H + {}^1H$, $^3H + {}^1H$, and $^2H + {}^3H$ fusion rates of $10^{-8.1}$ or $10^{-11.6}$, $10^{-8.9}$ or $10^{-11.7}$, and $10^{-12.4}$ or $10^{-10.6}$ s^{-1}, respectively, in the Pd metal. In each case, the first estimate is a result of the first model ($m^* = 10$) and the second arises from the S-based model ($m^* = 12.5$). Although these rate estimates should be taken as rather uncertain, they suggest that the fusion of $^1H + {}^2H$ ($10^{-8.1}$ or $10^{-11.6}$ s^{-1}) may be important but that $^1H + {}^3H$ and $^2H + {}^3H$ fusion are probably not for D_2O or normal H_2O (because of the low abundance of ^3H). They also suggest that, *in ordinary H_2O, where D_2O occurs at 0.015% in natural abundance, the $^1H + {}^2H$ fusion might take place at appreciable rates* because of the possibly large $^1H + {}^2H$ to $^2H + {}^2H$ rate ratio of $10^{-8.1}$ to $10^{-10.3} = 160$. It also clearly indicates that mixtures of D_2O and H_2O might yield even higher energy production ($^2H + {}^1H \Rightarrow {}^3He + \gamma$ (5.6 MeV)) if the RR process described below (or one like it) were also operative for $^3He^*$. Although the energy per $^2H + {}^1H$ fusion is only 23% of that involved in $^4He^*$ decay, the possible 160-fold increase in fusion rate could yield a much larger energy production rate if the above estimates are accurate. The "ideal" H_2O/D_2O mole fraction can be calculated and depends on the fusion rate ratio and the energy per fusion ratio, as well as the Pd electrode's selectivity for D vs H assimilation. Finally, the m^* dependence of log R expressed in eq 5 suggests that a search be undertaken for materials and/or conditions that permit high ^2H and/or ^1H concentrations to be established and that provide, through the lattice band structure, even larger m^* values; such materials could yield even larger energy production rates.

IV. Branching Ratios and Heat from Radiationless Relaxation

Clearly, the possible production of large amounts of ^4He and heat and the relatively small yield of neutrons and tritium suggest that, in the Pd lattice, the nascent $^4He^*$ nucleus is undergoing

(6) In April of 1989, we received a reprint by S. E. Koonin and M. Nauenberg entitled *Cold Fusion in Molecular Hydrogen* from Professor S. Pons. In this paper, fusion rates for D_2, HD, HT, and DT are estimated and enhanced fusion rates are computed and attributed to "heavy electrons" by using a method which is essentially the same as our S-based method (except for values of the collision energies and velocities used). No mention of internal conversion or any other mechanism for dissipating the $^4He^*$'s excess energy as heat is made in this preprint.

(7) The concept of an effective electron mass is well-established in solid-state physics; it is discussed, for example, in: Davydov, A. S. *Quantum Mechanics*; NEO Press: Ann Arbor, MI, 1966. See also ref 8.

(8) In muon-catalyzed fusion (see, for example: Jackson, J. D. *Phys. Rev.* **1957**, *106*, 330. Van Sichlen, C. DeW; Jones, S. E. *J. Phys. G* **1966**, *12*, 213), the internuclear distances are shortened, potential well depths increased, and turning points moved inward in much the same way as suggested here; the screening caused by the lattice electrons acts much as the muon does, although the fact that only one muon is present per $^2H^+$ pair whereas the $^2H^+$ are surrounded by many electrons may cause the "heavy electrons" and muons to behave differently as far as radiationless relaxation is concerned.

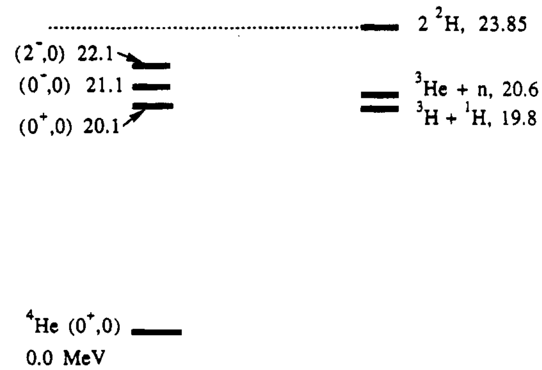

Figure 1. Energy level diagram for ^4He and the two fragment channels $^3H + {}^1H$ and ^3He + n. All energies are in MeV. The symmetry labels refer (ref 9) to angular momentum J, parity +/−, and isospin T: ($J^{+/-}$,T).

relaxation to ground-state ^4He at a rate that is fast compared to fragmentation or γ-emission. Examination of the energy level diagram[9] shown in Figure 1 raises several possibilities: (i) the Pd lattice may accelerate RR of $^4He^*$ to rates that outstrip the rates of fragmentation; (ii) the Pd lattice may slow down the rates of fragmentation; or (iii) the lattice may affect the admixture of excited $^4He^*$ states formed in the initial fusion event in a manner that alters the final branching ratios. These possibilities are examined below.

A. Formation of $^4He^*$ at Low Energy. The low-energy (T = 300–3000 K) and low-angular-momentum fusion of two $^2H^+$ nuclei may preferentially populate the even-parity (0^+,0) state of $^4He^*$ (see Figure 1). For collision energies in this range, it is straightforward to show that the collisional angular momentum is limited to low l values (i.e., $l \leq 3.5$ at 1000 K). Collisions involving $l \geq 1$ will encounter and be stopped by their centrifugal barriers (which are even more repulsive than the Coulombic barrier at short distances) before reaching the tunneling region where fusion can occur. Hence, only $l = 0$ collisions can contribute to low-energy fusion.

For collisions having even 1.0 keV of kinetic energy, for which the turning point is approximately 1.5×10^{-12} cm, collisions with l = 0, 1, and 2 (perhaps even higher l's) all reach near 10^{-12} cm before encountering their Coulombic-plus-centrifugal barriers. Moreover, upon reaching said barriers, tunneling is much more probable than at low energy even when centrifugal contributions are present. Thus, at high energies, both even and odd collisional angular momenta can contribute to the fusion process.

Given that low-energy collisions occur with $l = 0$ (which carries even parity), and noting the even parity of the entrance channel nuclear wave function (both ^2H have their nucleons spin paired to produce spin 1 states with all four nucleons in 1s "orbitals"), low-energy fusion must follow an even-parity route. Conversely, at higher energy, both odd- and even-parity states of $^4He^*$ can be formed (from odd and even l values, respectively). Thus, we speculate that the thermal nature of the ^2H–^2H collisions causes the even-parity (0^+,0) state of $^4He^*$ to be more strongly populated than in higher energy collisions, thereby giving rise to reduced amplitudes in the odd-parity $^4He^*$ states at 21.1 and 22.1 MeV. It is these odd-parity (0^-,0) and (2^-,0) states that fragment to n + ^3He or to $^1H + {}^3H$. At low energies, these states are not appreciably populated, so little neutron or tritium signal is observed. At high energies, collisions populate the odd- and even-parity states; the odd states then fragment quickly to give neutrons and tritium.

Muon-catalyzed fusion is known[11] to yield the conventional products of reactions 2 and 3 even when carried out at liquid hydrogen temperature. However, the process in which the muon-bound mesomolecule ($D\mu D^+$) is formed generates this species overwhelmingly in its $J = 1$ rotational level. Subsequent relaxation to $J = 0$ is very slow because of nuclear spin statistics

(9) Flarman, S.; Meyerhof, W. E. *Nucl. Phys.* **1973**, *A206*, 1.

(10) Dickson, P. E.; Berry, F. J. *Mössbauer Spectroscopy*; Cambridge University Press: Cambridge, 1986.

(11) Bracci, L.; Fiorentini, G. *Phys. Rep.* **1982**, *86*, 169.

constraints (i.e., $^2H-^2H$ can have either even or odd rotational states depending on whether its nuclear spin state is odd or even). Hence, we conjecture that $D\mu D^+$ fusion occurs on the odd-parity channel (because $J = 1$ is predominant) and yields the conventional product branching ratio even at low temperature. For muon-catalyzed fusion, tunneling through the Coulombic-plus-centrifugal barrier is possible even at low temperature because binding by the muon ($m^* = 207$) moves the turning point inward to approximately 2.5×10^{-11} cm.

In summary, low-energy fusion in, for example, a Pd lattice is expected to overwhelmingly produce even-parity products, while high-energy fusion yields the "conventional" product branching. Muon-catalyzed fusion occurs on the odd-parity channel even at low temperatures because of how $D\mu D^+$ is formed.

B. Relaxation of $^4He^*$ to ^4He. Once the $^4He^*$ is formed preferentially in even-parity states, it must then undergo relaxation to produce ground-state ^4He. IC rates scale as the electron density near the nucleus from which they receive energy as do rates of most radiationless transitions that occur via energy transfer from the excited nucleus through the electrons to the lattice. Because this density could be greatly enhanced by the proximity of either Pd electrons or lattice electrons having large "effective masses" (perhaps $m^* \cong 10-12.5$), it is useful to explore the possibility of ^4He formation via IC although it is important to continue to search for other possibilities for quenching the excited even-parity $^4He^*$ nucleus.

In the calculations presented below, we estimate the rate of IC for a process in which a single electron carries away all 24 MeV of energy. We believe that this channel is only one of many that may be operative, so this rate represents a lower bound to what is likely the true RR rate. It is known that IC can eject K-shell, L-shell, and other electrons (see Blatt and Weisskopf[4]) and that more than one electron may be ejected (see Fowler[4]). It may therefore be possible for the excited nucleus to transfer its energy to several electrons, each of which subsequently undergoes thermalizing collisions (although some may escape the lattice and be detected). In the absence of a method for estimating the rate of such many-electron events, we present here the lower bound estimate described above.

The expressions given in eq 5.15 and 5.21 of Blatt and Weisskopf[4] allow absolute rates of internal conversion to be estimated (for example, assuming the conversion of approximately 24 MeV). Using $Z = 2$ for the nascent $^4He^*$ nucleus and scaling the bohr radius a_0 by $1/m^*$ to take account of the accumulation of heavy electrons near the $^4He^*$ nucleus, one obtains a rate of $(2.7-6.7) \times 10^9$ s^{-1} for $m^* = 10-12.5$ (for which the 1s bohr frequency of ^4He heavy electrons is of the order of 10^{17} s^{-1}). Using $m^* = 1$ gives rates in the 10^6-10^7-s^{-1} range. Although the former calculation was carried out using the heavy electron concept, it may be that RR is enhanced instead by high electron density contributed by the neighboring Pd centers (where the density of conventional electrons is even higher than that computed for heavy electrons near $^4He^*$ nuclei and where the inner-shell electrons have bohr frequencies of the order of 10^{19} s^{-1}). It should be noted that these RR energy-transfer rates are in line with isomer shifts in Mössbauer spectroscopy[10] (e.g., an isomer shift of 1 mm s^{-1} corresponds to a frequency shift of 4.8×10^{11} s^{-1} for a 24-MeV photon). Isomer shifts reflect the differential effects on the energies of the ground and excited nuclear states caused by the electron density near the nucleus.

It should be stressed that RR rates need only be considerably faster than the rates of fragmentation to either ^3He + n or ^3H + ^1H for this model to be consistent with the observations. We argue that formation of the odd-parity states of $^4He^*$ that fragment quickly is suppressed at low energies. Moreover, the even-parity $(0^+,0)$ state can not fragment to the odd-parity ^3He + n or ^3H + ^1H products unless the fragments exit with one (or more) unit of collisional angular momentum. Doing so would require these fragments to tunnel outward through their repulsive centrifugal barriers which is certain to slow fragmentation. Clearly, if the $^4He^*$ fragmentation rates are much less than the RR rate, little neutron or tritium signal will be detected. The model put forth here, which attributes qualitative differences between low- and high-energy fusion to parity, is consistent with the observations of ref 1.

V. Summary

In summary, we propose that the high rate of energy production observed by Fleischmann, Pons, and Hawkins[1] may arise from ^2H fusion via a tunneling process facilitated by shielding of the Coulombic repulsion between $^2H^+$ nuclei by neighboring electrons in the PdD_x lattice. We further propose that lattice effects also facilitate the radiationless relaxation of $^4He^*$ (by enhancing RR rates and/or preferentially populating states of $^4He^*$ that fragment slowly), so that the bulk of the energy is detected as heat, with reduced neutron and tritium production. We present a symmetry argument to explain why low-energy branching ratios can be qualitatively different than those observed at high collision energies. These arguments are consistent with muon-catalyzed fusion proceeding via the conventional reactions 2 and 3 even at low temperatures. We further suggest that fusion of ^2H and ^1H is also accelerated and might be an even more rapid process. Finally, we believe that, even if our analysis is incorrect in detail, any model interpreting accelerated low-energy fusion as due to electronic shielding and lattice effects will predict a parallel increase in the rate of radiationless relaxation of the excited nuclei formed and/or a decrease in the effective rate of fragmentation.

Acknowledgment. J.S. thanks Prof. Julian Schwinger for very stimulating and encouraging conversations, Prof. J. D. Jackson for critical guidance, and Prof. Peg Simons for constructive proofreading.

Editorial Comment: The preceding Letter contains new theoretical ideas which the Editors felt should be placed in the public domain, whether or not the experiments cited as evidence of "cold fusion" are valid. For highly debated research, however, the Editors also believe that a summary of favorable and unfavorable comments by the reviewers should accompany the Letter. We note that one reviewer states that "it (is) of the utmost importance to get the data presented in this paper into the public domain as quickly as possible. ...it is a waste of time to quibble about specific mechanism. That can only replace one set of guesses by another set". Other reviewers state that this letter "presents some interesting speculations and discussion, even if the present experiments of Pons and Fleischmann do not involve fusion processes" and is "clearly highly original and of current interest", even if "the proposal cannot explain the heat rate claimed by Fleischmann, Pons and Hawkins, nor the billion-fold too small accompanying radiation".

One reviewer would have preferred that the mass spectrometric data (cited by private communication) "were available on a broader basis, or had been presented and defended at a conference..." This reviewer also argued that "the idea that the excess energy from the decay of $^4He^*$ is turned into heat via internal conversion, or "radiationless relaxation", is not consistent with the reports of Pons and Fleishmann's experiments. At energies of 20 MeV or so, which correspond to betatron energies, electrons in solids convert nearly all their kinetic energy into high energy Bremstrahlung, most of which would escape the electrochemical cell".

Another reviewer cited internal conversion (IC) as "a truly original observation of the authors in this context, but they nevertheless encounter four problems: 1. The "heavy electron" of solid-state physics can neither shield as calculated nor enhance the IC rate. 2. ...the $2.7-6.7 \times 10^9$ deexcitation rate calculated ... is far too slow to compete with particle deexcitation rates... 3.