REFORMULATION OF THE COLD FUSION PROBLEM: HETEROGENEOUS NUCLEATION - A LIKELY CAUSE OF THE IRREPRODUCIBILITY AND INTERMITTENCY OF COLD FUSION OBSERVATIONS

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ABSTRACT

The Irreproducibility and intermittency of the observed cold nuclear fusion effects is linked to the known difficulties affecting the observation of homogeneous nucleation of D_2 bubbles on the surface of the cathode in the electrolysis of D_2O. In general some nucleation centers are present, allowing for heterogeneous nucleation of D_2 bubbles at the Pd, Ti or Zr cathode, long before the chemical potential of D in the cathode reaches the levels necessary for cold fusion. By carefully eliminating the impurities and surface defects which can act as nucleation centers, one can create homogeneous nucleation conditions which correspond to higher values of the cathodic D chemical potential, provided the cathode is completely covered by the electrolyte, or extremely large currents are applied to the cell. A decrease of the surface tension due to tensio-active impurities in the electrolyte must also be avoided. A well-known collective lattice effect is the increased effective mass of the electrons which can lead to increased D-D nuclear fusion rates and to enhanced multiphonon generation amplitudes, i.e., to non-radiative dissipation of the reaction energy. At the very low center-of-mass energies of the order of 1eV encountered in this form of the fusion reaction we expect a breakdown of the charge-invariance of inter-nucleonic forces which can lead to a strong preference of the tritium channel over the He^3 fusion channel.

INTRODUCTION

The observation of excess heat production in the electrolysis of D_2O by Pons and Fleischman [1] as well as other indications of electrolytic cold fusion [2,3] have met with many negative reactions, because few people were able to reproduce the initial results. Even the few "lucky" experiments which produced excess heat and/or neutrons and/or tritium proved in general to be very unreliable, with an intermittent character. Indeed, most experiments yielded negative results, causing most workers to doubt the correctness of the initial claims, while the few positive results could not be reproduced at will. In fact, electrolytic cells, inactive for several weeks, suddenly could turn active, putting out excess energies in the MJ range which cannot be explained in the absence of nuclear reactions. After an arbitrary time period which could last from minutes to weeks, an active cell would suddenly become inactive to the outmost frustration of the "lucky" experimentalists. It appears that the reaction is switched on and off by factors beyond control. This situation reminds us of the most frustrating experiments known from the studies of homogeneous nucleation of new phases in condensed matter physics and in the related fields of cloud physics, metallurgy of alloys, and surface phenomena.

It is well-known that in the absence of any impurities which could act as nucleation centers, a liquid can be cooled far below the melting point, or a vapor can be pushed to supersaturations of the order of 40% or higher, right to the homogeneous nucleation limit. This limit appears when the rate of spontaneous germ creation approaches unity. A germ is defined as a spontaneous aggregate of molecules which is large enough to continue growing on its own, in spite of the large surface energy required to separate the new phase. Under normal atmospheric conditions condensation occurs already at supersaturations of 1-3%, due to the ubiquity of condensation centers which waives the large supersaturation requirement needed to produce a condensation germ homogeneously. In the case of supercooled liquids, or of supersaturated solutions, it is again the omnipresence of solid mesoscopic impurities acting with various degrees of efficiency as nucleation centers, which causes heterogeneously nucleated phase transitions at various supersaturation levels, all considerably lower than the homogeneous supersaturation limit. Even the most meticulous purification attempts were not able to insure the reproducible homogeneous nucleation conditions except for a few "lucky" cases, in which no qualifying impurities must have been present. Finally, in spite of the frustrating and uncontrollable randomness of the experimental results, a consensus about the homogeneous nucleation limit emerged in reasonable agreement with the elementary theory [4], and in better agreement with more advanced molecular models [5].

The present paper considers the nucleation of D_2 bubbles at the surface of a deuterium absorbing cathode in the electrolysis of D_2O and evaluates the corresponding homogeneous nucleation barrier. If impurities and defects can be controlled to inhibit heterogeneous nucleation, a considerable

increase in the achievable D chemical potential, roughly equal to the homogeneous nucleation barrier, can be realized, as we show in the following section. This increased chemical potential could switch on the fusion reaction and could therefore explain the difference between the active and inactive states of an electrolytic fusion cell. Based on this reformulation and new understanding of the intermittent and irreproducible character of cold fusion, we make some recommendations concerning the cathode geometry and configuration.

In the subsequent section a brief discussion of the increased electronic effective masses in deuterium absorbing metals is presented. An estimate of the average electronic mass observed in specific heat measurements performed on these metals yields about 3 times the free electron mass, while hydrogen rejecting metals do not show a sizable increase of the thermal effective mass. The thermal effective mass measured at low temperatures in the so called heavy fermion compounds is much larger than the free electron mass, up to 1000 times. The enhanced electronic mass is a collective lattice effect related to Bragg reflection on a large number of crystalline planes which can strongly bind together a pair of deuterons, can bring them close enough for nuclear fusion and can cause large multiphonon emission amplitudes which help carry away the reaction energy.

Finally we discuss the breakdown of the charge invariance in the low-energy interaction between nucleons as a possible cause of the preference of the tritium channel in the D-D reaction.

NUCLEATION LIMIT TO CATHODIC D LOADING

If all trivial routes of deuterium loss have been eliminated in the electrolysis of D_2O, the increase $\Delta\mu$ in the electro-chemical potential μ of D in the cathode will be limited by the surface tension barrier for homogeneous nucleation of D_2 bubbles at the interface between the cathode and the electrolyte.

In principle, a small gas bubble, i.e., a germ of the gas phase which appears at the interface, would be bound on one side by the cathode with surface tension σ_{cd} and on the other side by the electrolyte with surface tension σ_{wd}. The effective surface tension would then be $(2\sigma_{cw}-\sigma_{wd}-\sigma_{cd})/2$. Here σ_{cw} is the surface tension at the cathode to electrolyte interface. However, since $\sigma_{cw}>\sigma_{wd}$ and $\sigma_{cw}>\sigma_{cd}$, a thin film of electrolyte will creep in between the gas and the electrode at a certain point in the nucleation process, creating a barrier, which hinders the further growth of the germ, strongly depressing the nucleation rate and enhancing the effective nucleation energy barrier ΔF_g, while replacing the effective surface tension with σ_{wd}. The homogeneous nucleation energy barrier [6] for a D_2 germ of area Ω_g is $\Delta F_g = \sigma_{wd}/3$.

The nucleation rate J of germs is given by

$$J = c_{D2}w_D\Omega_gZexp[-\Delta F_g/kT], \qquad (1)$$

where

$$Z=[\Delta F_g/3\pi kTg^2]^{1/2}$$

$$= (2v/\Omega_g) (\sigma/kT)^{1/2} \qquad (2)$$

is a Zeldovich correction factor. In Eq.(2) g is the number of D_2 molecules in a germ corresponding to the maximum of ΔF_g, w_D is the flux density of incoming D_2 molecules at the interface, and c_{D2} is the concentration of D_2 molecules in the electrolyte. The value of ΔF_g for which the nucleation rate is J=1 bubble/cm^{3}s will be taken as the effective achievable potential.

The rate w_D at which D_2 molecules reach the germ is the rate by which they scale the energy barrier from the adsorbed state on the cathode surface to the germ, plus the rate by which they reach the germ from the electrolyte. The latter will be neglected, because the concentration of D_2 in the electrolyte will not exceed the saturation concentration at 1 atm very much. The rate is therefore given by the absolute reaction rate theory [7,8].

$$w_D = (N_ckT/h)exp(-\Delta F_a/kT), \qquad (3)$$

where h is Planck's constant and N_c is the number of deuterium molecules present in the absorbed state on the cathode in contact with the unit area of the germ. the rate thus becomes

$$J =$$

$$c_{D2}(N_ckT/h)exp(\Delta F_a/kT)\Omega_gZexp(\Delta F_g/kT)=$$

$$c_{D2}(N_ckT/h)exp[(\Delta F_a+\Delta F_g)/kT]2v(\sigma/kT)^{1/2} \qquad (4)$$

Nucleation takes place when the free energy difference ΔF_g is sufficiently large, so that the nucleation rate J becomes of the order of the unity. Setting J=1 we can find the free energy threshold

$$(\Delta F_a + \Delta F_g)/kT$$

$$= \ln[c_{D_2}(N_c kT/h) \, 2v \, (\sigma/kT)^{1/2}] \quad (5)$$

$$= \ln\{10^{17} cm^{-3}(10^{15} \, cm^{-2} 4 \, 10^{-14} erg$$

$$/6 \, 10^{-27} erg \, s)7 \, 10^{20} cm^3$$

$$[(150 erg/cm^2)/4 \, 10^{14} erg]^{1/2}\}$$

$$= \ln[6 \, 10^{32}] = 75.6;$$

$$\Delta_0\mu = \Delta F_a + \Delta F_g = 1.9 \text{ eV}. \quad (6)$$

Thus, to move from the adsorbed state on the electrode surface to the gas phase by creating a small D_2 bubble, deuterium molecules must overcome a potential barrier $\Delta_0\mu$ of about 1.9 eV. The activation energy ΔF_a can be found in the literature [9] and is 0.7 eV for a pair of D atoms. Therefore, we obtain for the homogeneous nucleation barrier ΔF_g=1.9 eV - 0.7 eV = 1.2 eV. Provided no nucleation centers which would induce heterogeneous nucleation are present on the cathode-electrolyte interface, this means that through electrolysis the effective electrochemical potential of D_2 at the cathode surface and in the bulk of the cathode can be raised 1.2 eV above the level applicable in the absence of the homogeneous nucleation barrier, i.e., above the level achievable at low electrolytic currents, when the cathode is not completely immersed in the electrolyte, so that the deuterium can slowly diffuse through the electrode and escape into the atmosphere. Even in the presence of nucleation centers at the surface of the cathode, there will be a small effective (heterogeneous) nucleation barrier present, which we consider negligible.

It is interesting to calculate the D_2 gas pressure increase over a standard D_2 pressure of p_o=1 atm at the dry cathode surface, which would correspond to the same ΔF_g=1.2 eV increase in the electrochemical potential. Setting ΔF_g=$kT\ln(p/p_o)$, which implies ideal gas behavior, we get p=$p_o e^{48}$ = 10^{20} atm, because p_o =0.1 atm. for D_2. This is an extremely high D_2 gas pressure. It also provides a general idea of the pressure which would have to be present above the dry part of the electrode protruding out of the electrolyte during electrolysis, in order to stop the slow loss of D_2.

The first trivial route of D escape is thus the heterogeneous nucleation of D_2 bubbles at the cathode surface. Unfortunately, this route has not been blocked in general so far. Only a few lucky experiments may have avoided heterogeneous nucleation. Even in these lucky experiments, once homogeneous nucleation sets in, the nucleation process will be induced by the now-existing bubbles which act as nuclei, and tends to become gradually heterogeneous, which corresponds to lower $\Delta\mu$ values. This impairs the reproducibility of the achieved $\Delta\mu$ and of $\Delta\mu$-dependent results of any nature, leading to an intermittent operation at best, or to an activity in the form of bursts, and would let us understand claims of sporadic heat generation by cold fusion, limited to time periods in which no nucleation centers happened to be present, periods marked also by an increased voltage drop at the cathode surface.

The second trivial route of D escape is the above-mentioned emergence of electrodes from the electrolyte, which leads to current-dependent, somewhat lower, achievable $\Delta\mu$ values, limited by the diffusion rate of D through the cathode. The third difficulty, also connected to the second escape route, is caused by the electric connection wires. To avoid the emergence of parts of the cathode from the electrolyte, the electric connection must be done under the electrolyte surface.

The electrode geometry suggested here is thus characterized by the presence of a cylindrical protrusion of the electrode material, electrolytically covered with a sufficiently thick *layer of metal* which most strongly *rejects* the hydrogen isotopes, e.g, Cr, Ni, Cu, Ag, Au, Mo, W, Co, Pt, Mg, Cd, Zn, Al. This layer carries the electric connection soldered at the far end of the cylindrical protrusion. On top of this layer of metal, and on the connecting wires, there should be an electrically insulating layer of chemically inert plastic or paint which keeps the electrolyte from making contact with any conductor other than the electrode material.

After this description of the electrode geometry, it is useful to clarify the terms used in the description. *Strong D-rejection* by a metal means a large negative difference $2d_\alpha$-d_g between the energy $2d_\alpha$ released when two isolated deuterium atoms are brought from infinity into the bulk of the metal in the α-phase on one hand, and the dissociation energy d_g of an isolated D_2 molecule on the other hand. The solubility decreases on cooling in this case. The α-phase describes deuterium in metals at low atomic fractions (<0.1 in Pd at room temperature). In *D-absorbing metals* ($2d_\alpha$-d_g>0, such as in Sc, Y, Er, Tu, Lu, La, Ti, Zr, Hf, V, Nb, Ta, Pd, and some additional rare earths and actinides) the solubility of D increases on cooling, and at higher atomic D-fractions, various phase transitions from the α-phase to other phases are observed.

Finally, a physical example may help in nailing down the main concept of deuterium

cramming with the help of the homogeneous nucleation barrier for bubbles at the surface of the electrode, which is the primary notion developed in this section in the context of cold electrolytic nuclear fusion. Consider a carbonated soft drink or beer poured into a glass. After the foam at the surface has dissipated, it becomes very easy to notice that bubble formation continues at a low rate for a long time from a few points on the bottom of the glass and on the walls, which are the active nucleation centers. This is heterogeneous nucleation, and is observed as strands of rising bubbles, coming from each of the nucleation centers. Through special surface treatment which eliminates impurities and defects from the surface of the glass, we can reduce the number of these centers. By removing a large regular Quartz crystal at the top from an even larger crystal in vacuum, we can imagine getting closer to the ideal case of a container with perfectly clean and homogeneous crystalline surfaces presenting no nucleation centers at all. In this ideal Gedanken-experiment case, a relatively large supersaturation is needed before CO_2 bubbles are formed on the walls, this time by what we call homogeneous nucleation, because no point on the bottom or on the walls of this ideal container or "glass" is different from any other point, or offers a lower nucleation barrier (except, perhaps, for the corners). Our homogeneous nucleation is still heterogeneous with respect to the whole volume of the liquid, because the points on the surface present a lower nucleation barrier than points in the volume of the impurity-free liquid, but we do not take this into account here either.

A real quartz beaker will have a few nucleation points even if it is monocrystalline, e.g. where dislocation lines reach the otherwise perfect surfaces. Due to random migration of thermally activated impurities to and from the surface along the dislocation lines, a process which is well known in many crystals, we can witness the intermittent activation and deactivation of nucleation centers. If only a few potential nucleation center points are present, sometimes the surface may remain with no active centers for certain time periods. A similar process is likely to be present at the surface of experimental electrolytic cold fusion devices, and we suggest here that it causes large fluctuations of the chemical potential in the cathode material, which result in the observed erratic intermittent activation and deactivation of the cold nuclear fusion reaction in the fusion cells. This would qualitatively explain the observed intermittency of tritium- and excess heat- production in the cells, as a restriction to periods with no deuterium bubble nucleation centers left, centers that would offer a low or negligible nucleation barrier. The randomness would be caused by the migration of impurities and defects to and from the cathode surface.

QUALITATIVE INTERPRETATION OF COLD FUSION IN TERMS OF HEAVY FERMIONS, PREFERENTIAL NEUTRON TUNNELING AND MULTIPLE GENERATION OF PHONONS

Due to their interaction with the periodic potential of the rigid crystal lattice, as well as due to interactions with phonons, and with other electrons, the electrons in the cathode acquire new dynamical properties which can be described by a larger effective mass. This larger effective mass of the electrons in certain states, in turn, could allow them to bind together deuterons in pairs much tighter than the normal-mass electrons. The electrons in states characterized by very large effective masses are quasi-particles called heavy fermions. We suggest here that heavy-fermion effects could also lead to increased fusion rates compared to the extremely low rates expected, e.g., in D_2. This heavy-fermion-fusion effect would bear some similarity to cold fusion catalysed by muons, although in this case the applicable effective mass may not be quite so large as the mass of the muon ($m_\mu = 207 m_e$), and although the fusion rate may be only slightly enhanced everywhere in the crystal where pairs of deuterons appear. The presence of heavy fermions in metals has been established experimentally through electronic low-temperature specific heat measurements and through the De Haas van Alphen effect. We shall first provide below a general discussion, and then a qualitative illustration of the plausibility of our suggestion, followed by an examination of the corresponding low-energy nuclear reaction.

The heat capacity of metals contains contributions from phonons ($\sim T^3$) and from electrons ($= \gamma T$). At low temperatures, the electronic contribution becomes dominant. By looking at the known experimental data (see Table I), we find that the values of the *electronic specific heat coefficient* γ are of the order of 1 mJ/(mol K^2) for most D-rejecting metals, an order of magnitude higher (10 mJ/molK^2) for most D-absorbing metals (9.42 mJ/mol K^2 for Pd), and two or three orders of magnitude higher at low temperatures in some inter-metallic compounds discovered after 1974, known as heavy fermion compounds, and containing ions with f-electrons, such as $CeAl_3$, $CeCu_2Si_2$, $CeCu_6$, UBe_{13}, UPt_3, UCd_{11}, U_2Zn_{17}, $NpBe_{13}$, $CePb_3$, $CeSn_3$ with up to $m_{th} \approx 1000$ m.

Table I

Electronic specific heat coefficients in mJ/K²mol

1. D-Rejecting metals: $2d-d_g < 0$

Mg	Cr	Mo	W	Fe	Co	Ni	Pt	Cu	Ag	Au	Zn	Cd	Al
1.3	1.4	2	1.3	4.98	4.73	7.01	6.8	0.7	0.65	0.73	0.64	0.69	1.35

Average: 2.45 mJ/K²mol, corresponding to $m_{th} \approx m$

2. D-Absorbing: $2d-d_g > 0$

Pd	Se	Ti	V	Y	Zr	Nb	La	Hf	Ta
9.42	10.7	3.35	9.26	10.2	2.8	7.79	10	2.16	5.9

Average: 7.16 mJ/K²mol, corresponding to $m_{th} \approx 2.92\ m$

It is well known that the electronic heat capacity of metals is given only by the active electrons within an energy interval kT of the Fermi surface; their concentration is of the order of nT/T_F, where $T_F = \varepsilon_F/k = \hbar^2 k^2_F/2m_{th}k$ is the Fermi temperature, ε_F the Fermi energy, $k_F = (2\pi^2 n)^{1/3}$ the Fermi wave vector, m_{th} the thermal effective mass of the electrons, and n the electronic concentration, all in the approximation of a spherical Fermi surface. In the free electron model, the molar heat capacity contribution of the electrons is thus of the order of $3RT/T_F$ (more precisely $\pi^2 RT/2T_F = \gamma T$), where R=Nk is the ideal gas constant, and γ is identified as $\gamma = \pi^2 R/2T_F = \pi^2 R m_{th}k/\hbar^2 k_F^2$. The large values of γ thus correspond to large values of the effective mass m_{th} of the electrons in these metals, or in a more appropriate formulation, to the large dynamical mass of the single-particle elementary excitations. The ratio of the thermal effective mass to the free electron mass is thus $m_{th}/m = \gamma_{exp}/\gamma_{free\ electron}$. For Pd this ratio is difficult to evaluate, since in metallic Pd the 4d band is not completely filled, about 0.36 holes being present; the Fermi surface includes therefore also sections (containing 0.36 electrons) located in the 5s band, and is very different from the simple spherical (free electron) example considered above. Nevertheless, the measured electronic specific heat coefficient of Pd would indicate a thermal effective mass of about $m_{th} = 4\ m$ in the Fermi sphere model, based on $k_F = (3\pi^2 n)^{1/3}$ and n=0.36(6.8 10^{22} cm⁻³) for metallic Pd.

The stoichiometric hydride PdD has a NaCl structure and is more relevant for our problem, since electrolytically loaded Pd electrodes will be close to this Pd/D ratio, and will try to exceed stoichiometry by as much as possible. However, for PdD we also expect at least $m_{th} = 3m$, from a comparison of the measured and calculated electronic specific heats by Switendick [10].

The increased effective mass will cause both a (roughly m/m_{th} times) lower distance between deuterons wherever pairing occurs, and a (roughly m/m_{th} times) larger pair binding energy, making the statistical occurrence of pairs energetically affordable and much more likely. Indeed, by introducing the notations $(m_{th}/m_D)^{1/2} = \rho$ and $m_{th}m_D e^4/\hbar^2(m_{th}+m_D) = U$, we obtain [11] the deuteron pair binding energy

$$W = [-0.0697 - 0.06681(\pi/4 - \arctan \rho)^2 - 0.16736(\pi/4 - \arctan \rho)^4]U. \quad (7)$$

The corresponding separation of the deuterons of a pair is about 0.25 Å, for $m_{th}=3$. For this reduced internuclear distance one can calculate [3] a fusion rate of about 10^{-20} s⁻¹ per deuteron pair.

Palladium is known [12,9] for its very high diffusion coefficient for all hydrogen isotopes; it increases with the isotopic mass and it increases exponentially with temperature. Although most of the diffusion is thermally activated, there is also a relatively large tunneling matrix element which had been underestimated earlier by Kehr [13] with a Bloch/Mathieu functions approach. More realistic calculations performed by Sugimoto and Fukai [14] yield 0.1 meV for D in Pd. An additional correction factor was introduced by Kondo [15], taking into account also the interactions with conduction electrons. As a result, in Pd super-diffusion can occur in certain circumstances with very high effective diffusion coefficients, leading to almost instantaneous deuteron motion under certain circumstances. With almost 100% occupation of the octahedric lattice positions, deuteron diffusion can only proceed through occasional double occupancy of these sites. These occasional D_2 pairs are the ones we refer to everywhwhere in this paper. Deuteron diffusion involves to a certain extent delocalization of the deuterons in Wannier states, which implies more than single-occupancy in PdD. We conclude that for the observation of cold fusion in the metallic lattice two conditions must be satisfied. First D loading must have reached a state close to stoiciometry (PdD or TiD_2, e.g.), at least in certain regions. Second, considerable D motion must be present, leading to a large macroscopic probability of double occupancy, with a fraction of mutiply-occupied sites not smaller than about 0.01. In this situation the deuteron pairs will be bound by electrons described in terms of nonlocalized but weakly overlapping electronic states, including also f-states with very high effective mass values. The large effective mass leads to the close approach between deuterons, of about 0.25 Å, mentioned above as being conducive to a nuclear fusion rate of the order of $10^{-20}/s$.

Finally, the (m/m_{th} times) reduced size of the electronic states which cause the deuteron-deuteron binding, will allow the states to fit even better into the octahedric positions of the fcc palladium lattice. It is also likely that heavy fermion effects from the lowered, initially empty, 4f states participating in the deuteron pair binding, play a certain role in the stronger deuteron pair binding in the Pd lattice, as well as in rare earth intermetallic compounds such as $CeAl_3$, $CeCu_2Si_2$, $CeCu_6$, UBe_{13}, UPt_3, UCd_{11}, U_2Zn_{17}, $NpBe_{13}$, $CePb_3$, $CeSn_3$, which are therefore suggested here as most promising replacements of Pd for cold fusion purposes.

Preferential tunneling of neutrons. The single-nucleon tunneling attempt frequency between the deuterons of a deuteron pair separated by 0.25 Å in the Pd cathode is very large, but the nuclear potential barrier transparence is extremely low, both for neutrons and for protons at room temperature, in spite of the aerated structure of the deuterons, of their d-state component, and of their low 2.2 MeV binding energy. At the very low energies in the center of mass (CM) system of the deuterons of such a pair, small differences caused between the slow tunneling rates of protons and neutrons by the electromagnetic interaction get to be amplified in the presence of resonance effects by the small barrier transmission factor. Therefore, the reaction rates in the $_2He^3 + _0n^1$ channel can be depressed many orders of magnitude with respect to the $_1H^3 + _1H^1$ channel which is based on neutron tunneling. This "piezonuclear" fusion process is quite different from the usual reaction mechanisms involving nucleon stripping processes, or formation of a compound nucleus. These usual reaction mechanisms require more than 1 KeV in the CM system for an observable fusion rate, and are applicable when DD collisions are produced through the acceleration of deuterons, or by raising the temperature to thermonuclear levels.

To describe these considerations in more detail, we note that the D-D reaction rate can be written in a first approximation as the product of a barrier penetration factor T_b and an intrinsic nuclear reaction rate Γ_n

$$\Gamma = T_b\Gamma_n \qquad (8)$$

In this approximation the deuterons are considered as point particles tunneling through the Coulomb barrier. The point particle model is reasonable as long as the distance between the two tunneling deuterons exceeds a value of the order of 100 fm = 10^{-11}cm. For shorter distances, the polarization of the deuterons can no longer be neglegted, due to the strong electric field present, and the point particle description breaks down. It is therefore convenient to write the barrier penetration factor as a product of two penetration factors, and to replace the second factor by an expression which also allows for individual tunneling of the nucleons which make up the deuteron. The reaction rate can then be written in the form

$$\Gamma = T_{b1}(\alpha T_{b2}\Gamma_n + \beta T_{bN}\Gamma_N + \beta T_{bP}\Gamma_P), \qquad (9)$$

where T_{b2} is the Coulomb barrier tranparence to deuterons on the last 100 fm, and similarly T_{bN} and T_{bP} are the combined nuclear and Coulomb transparence factors on the last 100 fm for neutrons and protons, respectively. Due to the absence of the Coulomb repulsion for neutrons, $T_{bN} >> T_{bP}$. The coefficients α and β indicate the

probabilities for survival and for desintegration of the deuteron. At very low energies of the relative motion of the two deuterons in the CM system we expect β to be much larger than α, so that finally $\beta T_{bN}\Gamma_N \gg \alpha T_{b2}\Gamma_n$, in spite of $T_{bN} \ll T_{b2}$. Indeed, in the limit of very low CM energies the probability β of disintegration of the deuteron on the last 100 fm interval becomes very large, and may lead to the dominance of the tritium channel of reaction. This may explain the extremely low branching rates observed for the He^3 channel in cold fusion experiments. Our simplistic approach highlights the distance of 100 fm arbitrarily in order to provide a clear picture. However, a more realistic calculation will replace Eq.(9) through a more complicated relation which superposes many expressions similar to Eq.(8), with different partitions of the barrier, i.e., with all possible distances replacing our choice of 100 fm.

Finally, the large effective masses of electrons, obtained, e.g, with the help of d&f-electron tight-binding and LDA calculations are instrumental in bringing the D nuclei close together in delocalized states, and since the large electronic masses arise from delocalized coherent Bragg reflection on the whole lattice, they should also allow for the delocalized multiphonon processes which carry away most of the large nuclear reaction energy.

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