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COLD FUSION '93: Some theoretical ideas *

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Abstract

The status of the theoretical research on the Cold Fusion phenomenology of the Fleischmann-Pons system is reviewed within the framework of coherent QED. A particular emphasis is put on the description of the possible complex phenomena that occur at the Pd-catode during the electrolysis of heavy water

I. INTRODUCTION

In spite of the heavy charges of being pathological science, the "scientific fiasco of the century" and "too hot to handle", Cold Fusion has managed to survive for the fourth year, an I come to the enchanted island of Maui to draw a balance of the past years of struggles and achievements. For struggles there were many, and even serious ones but, as it has been amply shown at this Conference, they have not been in the way of a slow but steady progress towards first to establish the reality and the modalities of the phenomena announced by Fleischmann and Pons [1], and second to appreciate the deep implications of these phenomena for our understanding of condensed matter and the physical laws that are at work in it.

The consequences of the ongoing "quiet revolution" of Cold Fusion today appear still limited to the devoted activity of a (relatively) small scientific community, that is pursuing with determination a research, which is surrounded by an almost universal and often rabid hostility; however there are some signs that we may be very close to an epochal change, whose outcome is still beclouded, but its *grandeur* in shaping new scenarios in both science and society can hardly be doubted.

This talk is about the application to the Cold Fusion (CF) phenomena of the Fleischmann-Pons type (heavy water electrolysis with a Pd-cathode) of a set of new ideas

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about the working of Quantum Electro Dynamics (QED) in the deep recesses of Condensed Matter [2]. The general attitude toward such ideas is still far from enthusiastic, but I am confident that the reality of CF phenomena will finally prove their being indispensable also for a deep, general understanding of many other poorly understood behaviours of condensed matter systems, including life itself.

II. PROBLEMS AND FRAMEWORK

As I have already mentioned, this talk will uniquely concern the Fleischmann-Pons (FP) system, i.e. the Pd/D system at high concentration $x = \frac{D}{Pd}$. From all that has been so far established, the problems one must solve are of two kinds:

(α) The QED dynamics of D's in the host Pd-lattice, which leads to the following explicit questions:

(α_1) Why and how does the process

$$D_2|_{gas} \rightarrow D + D|_{lattice} \tag{II.1}$$

proceed?

(α_2) why and how, in the lattice

$$D|_{lattice} \rightarrow D^+ + e^-, \tag{II.2}$$

D^+ and e^- enjoying a different, independent dynamics?

(α_3) why is D^+ so mobile at high x?

(α_4) what are the problems of Pd/d? [1]

(α_5) what happens during electrochemical loading?

(α_6) why one observes "Heat after death"? [2]

and

(β) the mechanisms of CF in the highly loaded Pd/D system, which leads to the further explicit questions:

(β_1) how can one overcome the Coulomb barrier?:

(β_2) which is the main DD-fusion dynamics?:

(β_3) can we understand rarer processes: n,T,X-rays...?

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[1] see Fleischmann's talk, these Proceedings

[2] see Pons' talk, these Proceedings

In the following I shall attempt to answer all the above questions within the theoretical framework of QED-coherence in condensed matter (QEDCM) [2] that fully recognizes the essential rôle played by the electrodynamical interactions in determining the structure and the properties of the innumerable systems of Condensed Matter. On the other hand one must stress that in the generally accepted condensed matter physics (GACMP) such interactions are totally disregarded, based on a number of faulty arguments that P. W. Anderson [3] borrowed, unwarrantedly [4], from laser physics. When such misgivings are removed and the correct QED dynamics is recognized, GACMP, which is (almost) universally adopted in the theoretical analysis of physical systems such as the one which forms the object of our analysis, is found severely hampered.

According to the correct QEDCM one may look at condensed matter as comprising a set of **plasmas**, i.e. ensembles of identical charges of charge e and mass m, oscillating around their equilibrium positions with a typical frequency, the plasma frequency ω_p

$$\omega_p = \kappa\omega_0 \qquad \omega_0 = \frac{e}{(m)^{1/2}}(\frac{N}{V})^{1/2} \tag{II.3}$$

κ being a factor $O(1)$, representing the deviation of the particular plasma from the ideal one, whose plasma frequency is ω_0.

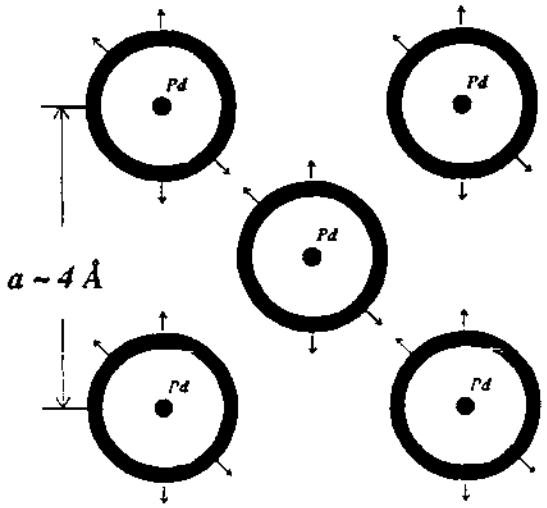

FIG. 1. The electronic d-shells of Pd as seen slicing the lattice along the (1,0,0)-plane.

Let us analyze in detail the plasmas of the Pd/D system that are relevant for Cold Fusion:

(γ_1) the plasma of the d-electrons [5].

We can visualize this plasma (see Fig. 1) as consisting of charged shells of charge $n_d e$ ($n_d = 10$ for Pd) of radius $r_d = 1$Å and thickness a fraction of one Ångstrom, which at this time we need not specify precisely. In order to estimate the deviation of the plasma

frequency of the d-sheil ω_{ed} from the ideal value $\omega_{ed}^{(0)} = \frac{e}{(m_e)^{1/2}}(\frac{n_d N}{V})^{1/2}$, we remark [6] that the neutralizing charge of the plasma is not homogeneously distributed in space, but is rather concentrated over the atomic volume. A simple geometrical argument yields

$$\omega_{ed} = (\frac{6}{\pi})^{1/2}\omega_{ed}^{(0)} = 1.38\ \omega_{ed}^{(0)} \simeq 41.5eV, \tag{II.4}$$

a rather high value. As for the maximum oscillation amplitude $\xi_d \simeq 0.5\mathring{A}$ appears as a reasonable estimate. [2]

(γ_2) the plasma of delocalized s-electrons

These electrons are those which enter the lattice to neutralize the absorbed D^+'s. These electrons will be essentially delocalized, however, due to the Pauli principle and Coulomb repulsion. The volume to them V_a available to them (see Fig. 2) will be just ($\frac{N}{V}$ is the Pd density; $\frac{N}{V} \simeq 6.3 \cdot 10^{22} cm^{-3}$)

$$V_a = V[1 - \frac{N}{V}V_{Pd}] = \lambda_a V, \tag{II.5}$$

V_{Pd} being the volume effectively occupied by the Pd-atom and its oscillating d-shell.

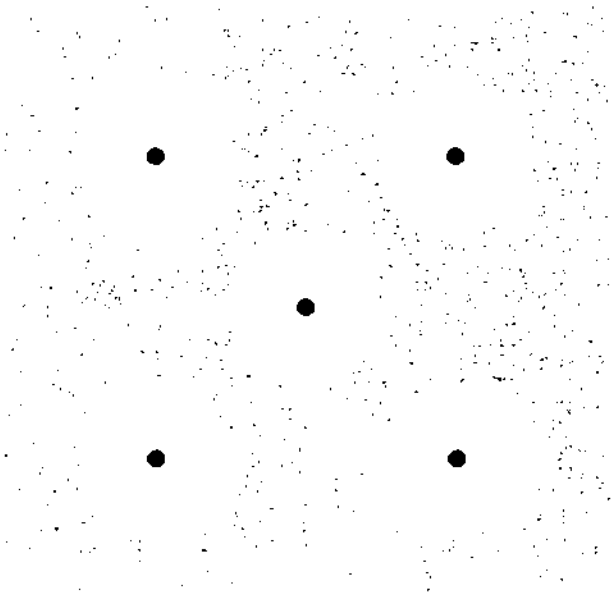

FIG. 2. The region occupied by the s-electrons that enter the lattice together with the positive D-ions.

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[2] A "real" calculation of ξ_d requires a careful consideration of the (short-range) interaction of the d-shell with the Pd-core.

Note that setting $R_{Pd} \simeq 1.3\mathring{A}$ we obtain $\lambda_a \simeq 0.42$, i.e. about 40% of the metal volume can be occupied by the s-electrons. The parameter λ_a plays an important role in the energetics of the s-electrons' plasma for their plasma frequency is just

$$\omega_{se} = \frac{e}{(m_e)^{1/2}}(\frac{N}{V})^{1/2}\frac{x^{1/2}}{\lambda_a^{1/2}}, \tag{II.6}$$

and the effective coupling [6] g, which controls the gap of the coherent plasma is given by

$$g = (\frac{2\pi}{3})^{1/2}, \tag{II.7}$$

while the gap itself is given by:

$$\delta = -\frac{(g^2 - g_c^2)}{2g^2 g_c^2}\omega_{se}, \tag{II.8}$$

$g_c \simeq (\frac{16}{27})^{1/2}$ being the critical coupling constant. The "superradiant" gain is in part balanced by the "Pauli energy" (N is the number of Pd-atoms)

$$\frac{E_{Pauli}}{Nx} = \frac{3}{10}\frac{(3\pi^2)^{3/2}}{m_e}(\frac{N}{V})^{2/3}\frac{1}{\lambda_a^{2/3}}x^{2/3}, \tag{II.9}$$

arising from the filling of the electron states in the available volume. Putting (II.8) and (II.9) together we may write for the chemical potential

$$\mu_{se} = \epsilon_p x^{2/3} - \epsilon_s x^{1/2}, \tag{II.10}$$

where for $\lambda_a = 0.45$, one computes

$$\epsilon_p = 6.45eV, \quad \epsilon_s = 4.61eV. \tag{II.11}$$

The interest of the Eq. (II.10) lies in the fact that for very small x and for $\lambda_a \simeq 0.4$ the negative term arising from QED coherence predominates over the positive Pauli-term, while for larger values of x μ_{se} becomes positive. In Fig. 3 μ_{se} is plotted for $\lambda_a = 0.425$, which appears experimentally favoured (see later).

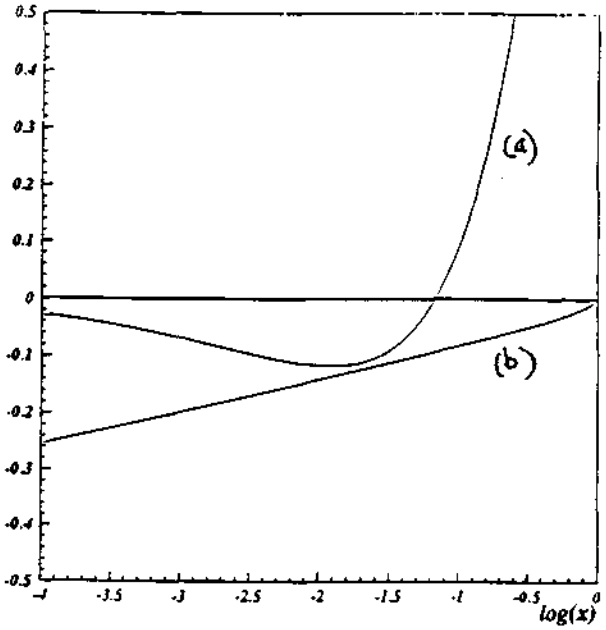

FIG. 3. The chemical potentials $\mu_{,e}$ (a), compared with μ_{CE} (see Eq. (III.5)) as a function of x.

(γ_3) The plasmas of D^+'s in the octahedral sites

We shall now analyze the conditions for and the energetics of the coherent plasma of deuterons that enter the lattice and get localized in the octahedral sites (Fig. 4). The basic quantities that characterize a coherent plasma are [6] the plasma frequency and the coupling constant. As for the plasma frequency we write:

$$\omega_{D\beta} = \bar{\omega}_{D\beta}(x + x_0)^{1/2} \tag{II.12}$$

where

$$\omega_{D\beta} = \frac{e}{(m_D)^{1/2}}(\frac{N}{V})^{1/2}\frac{1}{\lambda_a} = \frac{0.15}{\lambda_a^{1/2}}eV, \tag{II.13}$$

is the renormalized plasma frequency for $x \simeq 1$, and $x_0 \simeq 0.05$ reproduces the measured value at very low x-values. Note that for larger x-values (II.12) yields the expected $x^{1/2}$-behaviour of a pure (renormalized) plasma oscillation.

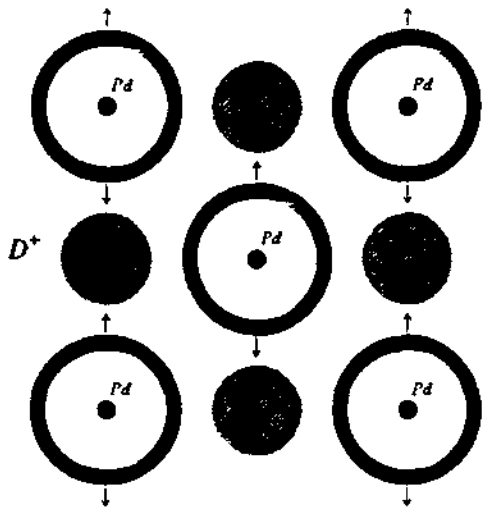

FIG. 4. The octahedral sites in the (1,0,0)-plane of the Pd lattice.

The coupling constant g_β can be written ($V_{D\beta} = \frac{4}{3}\pi\xi_{D\beta}^3$)

$$g_\beta = (\frac{2\pi}{3})^{1/2}\lambda_a^{1/2}(\frac{x}{x_0+x})^{1/2}[1-(\frac{N}{V})V_{D\beta}\frac{x}{\lambda_a}], \qquad \text{(II.14)}$$

where the last factor is particularly noteworthy, originating from the screening of the D^+-charge smeared in the oscillation volume V_D ($\xi_{D\beta}$ is the maximum oscillation amplitude of the D^+'s in the octahedral sites); $\xi_{D\beta} \simeq 0.5\mathring{A}$, but its precise value depends on the careful evaluation of the interaction of the s-electrons with both the d-shell and the D^+-ions. The chemical potential $\mu_{D\beta}$ for $\lambda_a = 0.425\mathring{A}$ and $\xi_{D\beta} \simeq 0.6\mathring{A}$ summed with the s-electrons' chemical potential μ_{se} [Eq. (II.10)] is plotted in Fig. 5.

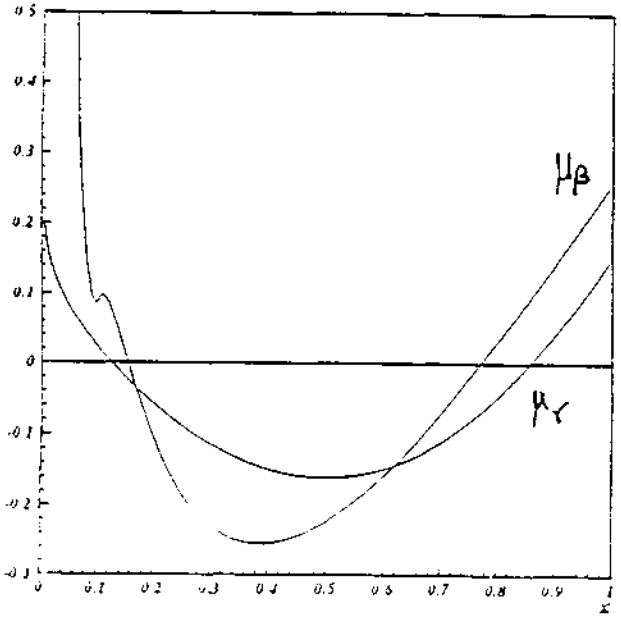

FIG. 5. The chemical potential μ_β of the β-phase octahedral sites, compared with μ_γ of the γ-phase tetrahedral sites, as a function of x.

(γ_4) The plasma of D^+'s in the tetrahedral sites

Besides the octahedral sites the plasma of D^+'s can occupy the thin disks that encompass two tetrahedral sites, as depicted in Fig. 6. Differently from the octahedral sites, the tetrahedral sites present to the D^+'s a barrier, whose height can be computed as follows: in the direction $\vec{n}$ of Fig. 6 a repulsive force is exerted by the Pd-ion, of effective charge $Z_{eff} \simeq 10$ at a distance $y_0 \simeq 1.4\mathring{A}$. Note in fact that the electrons of the d-shell oscillate past the equilibrium distance y_0 thus embedding the D^+'s in a static "cloud" of negative charge, whose screening of the D^+-Coulomb barrier will prove essential for the Cold Fusion phenomena [7] (see Section IV). A simple electrostatic calculation yields for the potential of these repulsive forces ($\alpha = \frac{1}{137}$ is the fine-structure constant)

$$V_{rep} \simeq \frac{2Z_{eff}\alpha}{y_0}(1 + \frac{y^2}{y_0^2}), \tag{II.15}$$

whose associated harmonic oscillator frequency ω_{rep} can be calculated from

$$\frac{1}{2}m_d\omega_{rep}^2 = \frac{2Z_{eff}\alpha}{y_0^3}, \tag{II.16}$$

to yield

$$\omega_{rep} = (\frac{4Z_{eff}\alpha}{m_D y_0^3})^{1/2} \simeq 0.65eV. \tag{II.17}$$

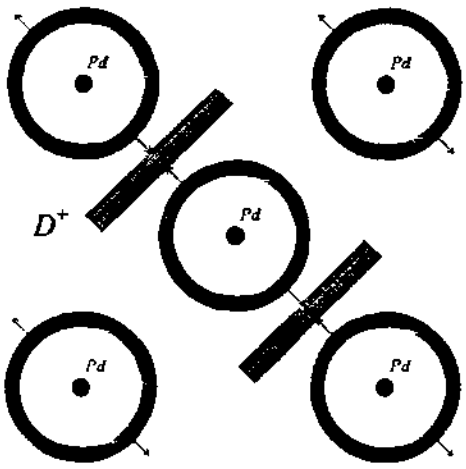

FIG. 6. The thin disks of the tetrahedral sites in the section along the (1.0.0)-plane of the lattice.

Thus the barrier to the access of the D^+'s to the tetrahedral sites is nothing but the zero-point energy of the harmonic oscillator in the $\vec{n}$-direction, i.e. $\frac{\omega_{rep}}{2} \simeq 0.33eV$. We can also estimate the thickness $\Delta = 2t$ of the "tetrahedral disk" from the relation

$$\frac{1}{2}m\omega_{rep}^2 t^2 = \frac{\omega_{rep}}{2}; \tag{II.18}$$

corresponding to the classical turning point. Thus we get

$$\Delta = \frac{2}{(m_D\omega_{rep})^{1/2}} \simeq 0.12\mathring{A}. \tag{II.19}$$

The coupling constant g_γ of this plasma can be written

$$g_\gamma = (\frac{2\pi}{3})^{1/2}\lambda_a^{1/2}[1 - (\frac{N}{V})\frac{\pi}{\lambda_a}\xi_{D\gamma}^2 x\Delta]\frac{e_{eff}}{e}, \tag{II.20}$$

where the only new element (note that the term in square brackets arises from the screening of the s-electrons. $\xi_{D\gamma} \simeq 1\mathring{A}$ is the maximum amplitude of the plasma oscillations of D^+'s in the tetrahedral disk) is the effective charge e_{eff} of the D^+'s embedded in the d-electrons' "cloud". In order to estimate $e_{eff} = e - \Delta e$, Δe is computed geometrically by first evaluating the overlap of a d-shell of thickness $\delta \simeq 0.1\mathring{A}$ and radius $r_d \simeq 1\mathring{A}$ and constant density $\rho = \frac{10e}{4\pi r_d^2 \delta}$, with the "tetrahedral disk" of thickness Δ and radius $\xi_{D\gamma} \simeq 1\mathring{A}$. One obtains $\frac{e_{eff}}{e} \simeq 0.9$ By using for the chemical potential the formula

$$\mu_{D\gamma} \simeq -\frac{e^2 x}{\lambda_a}(\frac{N}{V})\xi_{D\gamma}^2 2\sqrt{3}(g_\gamma - g_c), \tag{II.21}$$

that can be derived from the theory of coherent plasmas of maximum amplitude $\xi_{D\gamma}$ and $g_\gamma \simeq g_c = (\frac{16}{27})^{1/2}$. for $\lambda_a = 0.425$. $\xi_{D\gamma} = 1\mathring{A}$ we obtain for the total chemical potential μ_gamma the curve plotted in Fig. 6.

I am now going to use these theoretical tools and ideas to answer the questions I have formulated at the beginning of this Section. But before doing this I would like to enphasize the still rather semiquantitative nature of the theory so far developed. nevertheless for the purpose of <u>understanding</u> the nature of the phenomena occurring in the Fleischmann-Pons system. as we shall see. this theory turns out to be perfectly adequate <u>and</u> essentially indispensable.

III. THE PD/D SYSTEM

I shall now try and answer all questions of type (α) posed in the preceding Section. The framework is QEDCM and some preliminary work in this direction can be found in Ref. [5].

Let's take up the first questions which. for convenience. I shall repeat here:

(α_1) Why and how does the process

$$D_2|_{gas} \stackrel{?}{\rightarrow} D + D|_{lattice} \tag{III.1}$$

proceed?

(α_2) why and how in the lattice

$$D|_{lattice} \rightarrow D^+ + e^-, \tag{III.2}$$

D^+ and e^- enjoying different, independent dynamics?

We must envisage the dynamics of D_2 absorption in the lattice as comprising three steps (see Fig. 7). Step (i), in which the D_2-molecule is brought in contact with the Pd-surface: this step is fully governed by the chemical potential of the D_2-gas which can be written (we use the natural units $\hbar = c = k_B = 1$)

$$\mu_{D_2} = -\frac{T}{2}[19.3 + \frac{3}{4}\log\frac{T}{T_0} - \log\frac{p}{p_0}], \tag{III.3}$$

where $T_0 = 300K$ and $p_0 = 1$ Atm. Please note that this formula is the standard result for the perfect gas of a diatomic molecule. Step (ii) describes the interaction of the D_2-molecule with the Pd-surface. as emphasized in [5] in the QEDCM framework the most important process in this step is by far the interaction with the evanescent coherent electromagnetic field, associated with the various plasmas that we have discussed in the previous Section. As a result the D_2-molecules, immersed in strong coherent fields, have a good chance to tunnel through the electrostatic barrier (about $30eV$ high!) undergoing the dissociation process

$$D_2 \rightarrow 2D^+ + 2e^-, \tag{III.4}$$

with no energy expenditure. This is what Quantum Mechanics in presence of a strong coherent e.m. field predicts [6], and if you think this hard to believe you should give a harder look at the Debye-Hückel theory of electrolytic dissociation in water. You certainly do not believe that the macroscopic. static dielectric constant of water can be responsible for the overcoming of barriers several eV's high.

Finally in step (iii) the "shattered" D_2-molecule enters the lattice with its D^+- and e^--components subject to independent dynamics. This much for question (α_1) and (α_2).

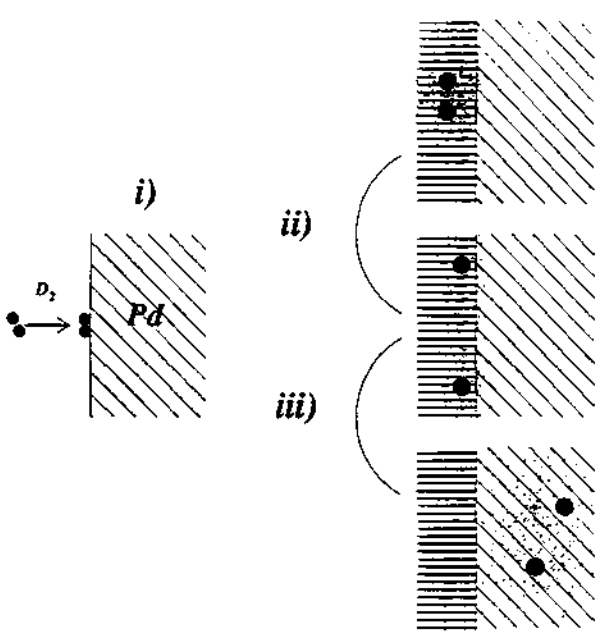

FIG. 7. The three steps of D_2 absorption by the Pd-lattice.

By following through the independent dynamical evolutions of D^+'s and e^-'s we can now answer two more questions:

(α_3) why is D^+ so mobile at high x?;

(α_4) what are the phases of Pd/D?.

For, as we have seen in the preceeding Section the e^-'s access a coherent plasma state whose chemical potential μ_{se} [Eq. (II.10)] is plotted in Fig. 3. For very low x, as we have also seen in the preceeding Section, the D^+'s that must occupy the octahedral sites (for, in order to occupy the "tetrahedral disk", they must overcome the barrier $\frac{\omega_{rep}}{2}$, see Eq. (II.17) and the following discussion) find themselves in a disordered state, with a chemical potential only determined by the configurational entropy of the system, i.e.

$$\mu_{CE} = -T[\log\frac{1-x}{2} - \frac{1}{x}\log(1-x)]. \tag{III.5}$$

This phase of the Pd/D system whose chemical potential is

$$\mu_\alpha = \mu_{se} + \mu_{CE}, \tag{III.6}$$

is the well known α-phase, and is in thermodynamical equilibrium with the gas when

$$\mu_{D_2} = \mu_\alpha. \tag{III.7}$$

It is clear from the behaviour of μ_{D_2} and μ_α as a function of T, p and x, that the α-phase can be stable only for very low x ($x \leq 0.1$); and this is just what is experimentally observed (see Fig. 8). On increasing p and decreasing T, i.e. on decreasing the absolute value of the negative chemical potential μ_{D_2}, a new phase at higher x can be accessed where the D^+ are in the "octahedral plasma".

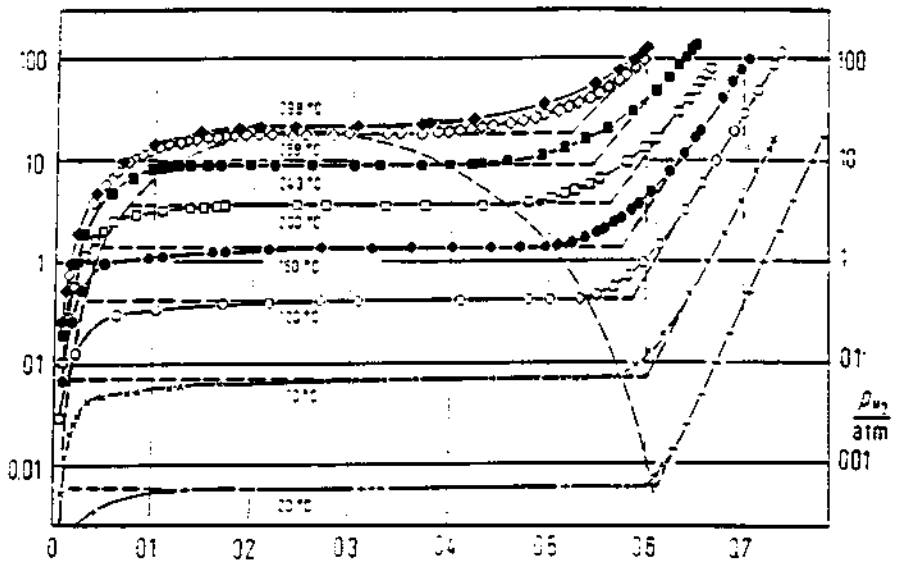

FIG. 8. The $p - x$ phase plane for the Pd/H system.

The chemical potential of this new phase, the well known β phase, is accordingly

$$\mu_\beta = \mu_{es} + \mu_{D\beta}, \tag{III.8}$$

while if the D^+'s are in the "tetrahedral disk" one gets the chemical potential

$$\mu_\gamma = \mu_{es} + \mu_{D\gamma}. \tag{III.9}$$

I have plotted both potentials in Fig. 5, which is remarkable for more than one reason. First it shows that at appropriate values of the thermodynamical variables there is indeed a first order phase transition to a high x-state which has first the features of the β-phase and then, for smaller absolute values of μ_{D_2} at $x = x^* \simeq 0.7$ it undergoes a second-order phase transition to the new phase that we can naturally call the γ phase.

I should remind you that the evidence of this new phase was actually predicted [8] on the grounds that Cold Fusion cannot take place in the β-phase, for

(i) the D^+'s are too far away;

(ii) only the tetrahedral sites can accomodate more than one D^+;

(iii) only in the tetrahedral sites the d-electrons can effectively screen Coulomb repulsion.

Is there any direct evidence? It is a fortunate coincidence that in the summer of 1993 a very nice work was published by a Padova group [9] that seems to support the theoretical evidence. The measurement of the diffusion coefficient of D's in Pd at different concentrations, which can be represented as:

$$D = \sigma x \frac{\partial \mu}{\partial x}, \tag{III.10}$$

where σ is the Einstein mobility, yields the experimental behaviour a fit of which is reported in points in Fig. 9, which clearly suggests a discontinuity around $x^* = 0.7$. As shown in Fleischmann's talk, by a simple parametrisation of the diffusion coefficients of D in both the $\beta-$ and the $\gamma-$phases one can get a good quantitative understanding of recent experiments carried out at IMRA-Europe. We may thus conclude that the γ-phase is a reality and that the QEDCM approach passes here a difficult and important test.

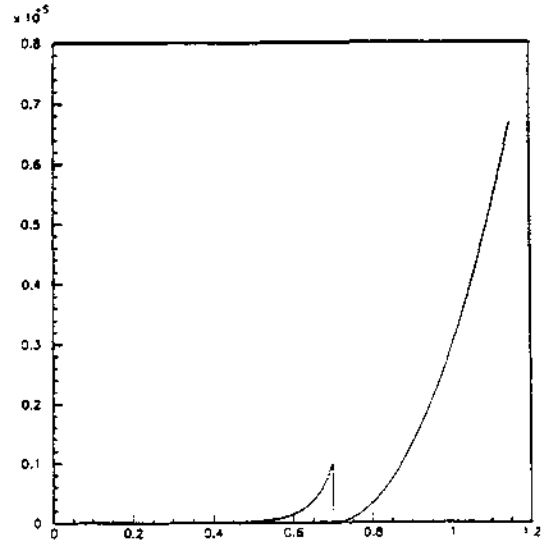

FIG. 9. The measured diffusion coefficients (Ref. [[8]]) for different values of H/Pd and different electrolytes.

We may now come to the last two questions:

(α_5) what happens during electrochemical loading?;

(α_6) why one observes "heat after death"?

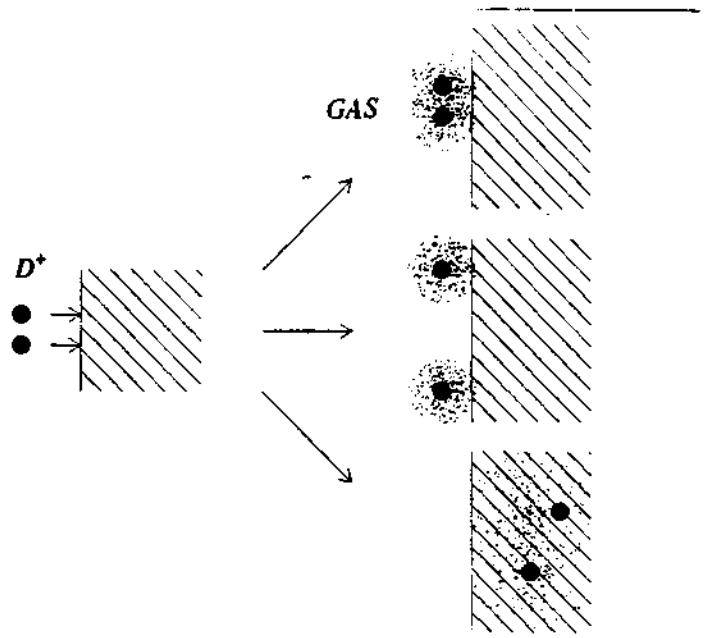

FIG. 10. The different fates of D^+'s arriving at the Pd-cathode.

The fact that through prolonged electrolysis one could drive the system off the thermodynamical equilibrium (the β-phase), to high values of x, was known to M. Fleischmann since a long time and most likely lies at the basis of the FP's "fantasy" that perhaps high loadings could induce two deuterons to fuse inside the Pd-lattice. However, as far as I can make out from the extant literature, how can this happen is still a mystery. Let us see whether and how the new ideas of QEDCM can lift the veil. It should be clear that the electrolysis device is nothing but a means to deploy a definite number of D^+'s per second (the electrolysis current) at the surface of the Pd-cathode. Once on the surface any two D^+'s (see Fig. 10) can do one of three things:

1. by diffusing on the surface they get within a molecular range (at distance $d \leq 1\mathring{A}$), and they combine with the ingoing electrons (that the electrolysis lends to the cathode) according to the process

$$2D^+ + 2e^- \rightarrow D_2. \tag{III.11}$$

The D_2-molecule thus formed will bubble out into the surrounding atmosphere. One can estimate that in order for the process (III.11) not to exhaust the incoming D^+-current i (in Ampère units) for the surface diffusion coefficient D_s one must have:

$$D_s < i\ 10^{-9}\ cm^2/sec. \tag{III.12}$$

a very low value that, most likely, can only be achieved through the deposition of some kind of "muck" on the Pd-cathode surface. Such small D_s's as required by (III.12) can also conceivably be obtained through some smart "poisoning" of the Pd-surface. In any case this appears as the most tricky aspect of the FP-system, one that can discriminate between successful and unsuccessful loadings and therefore determine the degree of reproducibility of FP Cold Fusion phenomena.

2. the D^+'s stay on the surface becoming members, together with the neutralizing electrons, of a double layer whose chemical potential shall be denoted by μ_s;

3. the D^+'s enter, (almost) independent of their neutralizing electrons, the Pd-lattice and load it at a bulk-chemical potential μ_B.

Little reflection is needed to convince ourselves that in order for processes (1) and (3) to lead to high x-values two very strange phenomena must occur:

(i) a negative surface-chemical potential μ_s must arise at high x;

(ii) the bulk chemical potential

$$\mu_B = \mu_\gamma + e\Phi_{ec} \tag{III.13}$$

due to a new electrochemical component $e\Phi_{ec}$ must also become negative at high x, differently from the predicted behaviour of μ_γ reported in Fig. 5.

It is remarkable that in QEDCM one can explain both phenomena in terms of the ponderomotive forces that the different evanescent coherent e.m. fields on the Pd-surface exert upon the charged particles: e^- and D^+. Taking the z-axis normal to the Pd-surface, directed in the outward direction, the evanescent e.m. field can be written

$$\vec{A} = \vec{A}(0)\cos\omega_r t e^{-\omega_0 z} \tag{III.14}$$

where ω_r is the renormalized frequency and $\omega_0 = \frac{2\pi}{\lambda}$ ($\lambda \simeq 10^{-4}$ cm for the D^+ plasmas) is the original frequency of the coherent process ($\omega_0 > \omega_r$). The static ponderomotive potential acting on the charged particle of charge e and mass m is

$$V_{pm} = e\left\langle \frac{\vec{A}(0)^2}{2m} \right\rangle = e\frac{|\vec{A}(0)|^2}{4m}e^{-2\omega_0 z}. \tag{III.15}$$

For the D^+-plasma in the "tetrahedral disks" one estimates a ponderomotive electric field for the electrons

$$E_{pm} = -\frac{\partial V_{pm}}{\partial z} \simeq 2.4 \cdot 10^8 V/cm \cdot x^{3/2}, \tag{III.16}$$

$4 \cdot 10^4$ times larger than for D^+'s. Please note the x-behaviour of (III.16). Giving the potential V_e that binds the electrons to the Pd-surface the simple harmonic representation:

$$V_e = -V_0[1 - \frac{z^2}{z_0^2}], \tag{III.17}$$

where V_0 is the work function and $z_0 \simeq 1\text{Å}$ (a typical atomic dimension), for the width $\bar{z}$ of the double layer one gets

$$\bar{z} = \frac{z_0^2}{2V_0}E_{pm} \simeq 2.4 \cdot 10^{-9}x^{3/2}cm, \tag{III.18}$$

where for the work function V_0 we have taken $5eV$, a reasonable value.

It can be ascertained without much ado that the formation of the double layer has two main consequences:

(i) it induces a negative surface chemical potential

$$\mu_{pm} = -V_0(\frac{\bar{z}}{z_0})^2 = -Ax^3, \tag{III.19}$$

with $A \simeq 0.3eV$, according to the previous estimates;

(ii) it induces a bulk electrochemical potential

$$e\Phi_{ec} = -B\lambda x^{3/2}, \tag{III.20}$$

where $B \simeq 5.5eV$, again from the previous estimates.

One of the most remarkable features of these consequences in their strong dependence on x, we shall now see that this may explain completely the strange phenomena alluded to above.

Indeed , we can write the thermodynamical equilibrium equation for the electrolysis:

$$\mu_s = \mu_{Pd}, \tag{III.21}$$

where the surface chemical potential is

$$\mu_s = \mu_{pm} - \frac{T}{T_0}[0.0875 + 0.025 \log \frac{1}{\lambda} + 0.025 \log \frac{T}{T_0}]eV, \tag{III.22}$$

where the second term ($T_0 = 300K$) stems from the chemical potential of the surface D^+ modeled as a two-dimensional perfect gas; as for the bulk chemical potential one may write:

$$\mu_{Pd} = \mu_\gamma + e\Phi_{ec}, \tag{III.23}$$

where the γ-phase chemical potential can be represented (at least for x not much bigger than 1) as

$$\mu_\gamma \simeq (-0.14 + 5.2(x - x^*)^3)eV, \tag{III.24}$$

where, as usual, $x^* \simeq 0.7$.

Solving Eq. (III.21) for $\lambda = \lambda(x)$ one obtains the curves reported in Fig. 11.

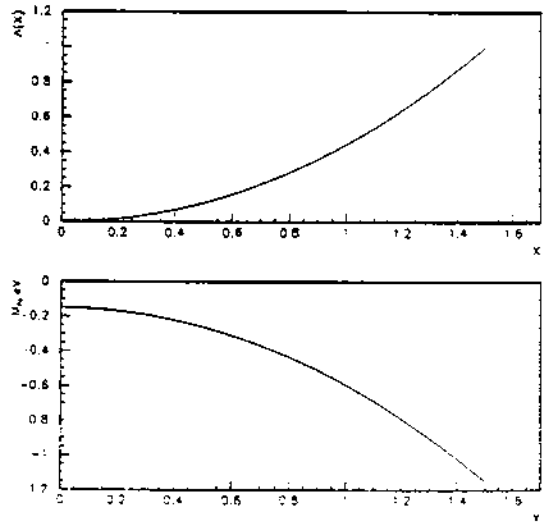

FIG. 11. The behaviour of $\lambda(x)$ and $\mu_\gamma(x)$ from Eqs. (3.19)-(3.22).

Thus it is clear that to achieve high x, fundamental for significant Cold Fusion rates, one must be able to achieve high values of the surface covering λ, and the electrolysis protocol must be optimized to obtain high values of λ.

Also, the events of "heat after death" presented at this Conference by S. Pons, [1] can be readily understood in the framework just presented.

IV. COLD FUSION

On the theoretical understanding of the mechanisms of Cold Fusion proper there has not been much progress since last year [5], and as a matter of fact there has been very little progress since the initial theoretical work [7]. Indeed the phenomenology is still basically the one outlined in the original Cold Fusion paper [7], and the new facts (light water electrolysis, nuclear transmutation, etc.) are still too vague and uncertain to warrant a serious theoretical effort to put them in the proper perspective at this time. Thus in this Section I will limit myself to reiterate known answers to the traditional questions of Cold fusion *à la* Fleischmann-Pons. As reminded in Section II the first question is:

(β_1) how can one overcome the Coulomb barrier?

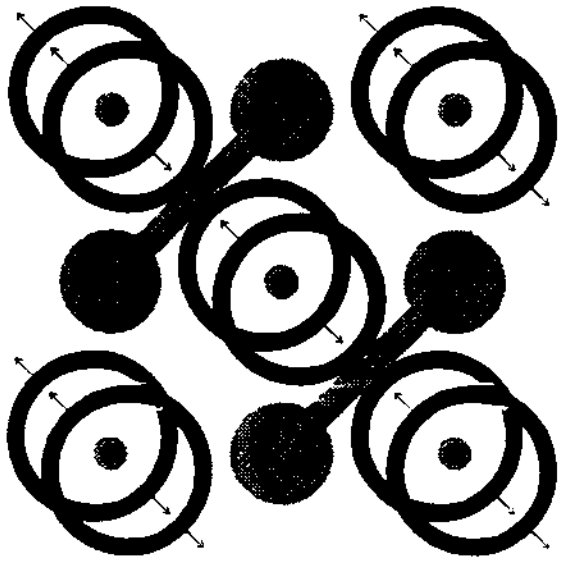

FIG. 12. The oscillating d-shells "fill" the tetrahedral "disks" with a static negative charge.

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[1] See Pons' talk at this Conference

The answer is (since 1989 [7]) given pictorially in Fig. 12, which implies that, due to large plasma oscillations of the d-elections' shell, in the disk-like tetrahedral region (where the γ-phase D^+'s are located) a high density negative charge condenses statically giving rise to a screening potential V_0 whose profile is reported in Fig. 13. For $x > 1$ (naturally within a single coherence domain of the γ-phase), for below this threshold no D^+ will stably occupy a tetrahedral site that is already occupied, the Gamow amplitude for D-D fusion is given by

$$\eta_G \sim \exp -(2\mu)^{1/2} \int_{r_N}^{r_0} dr' [V(r') - E]^{1/2}, \tag{IV.1}$$

where r_0 is the classical turning point (for which $V(r_0) = E$), r_N is a typical nuclear distance $r_N \leq 10$ F (10^{-12} cm), μ is the reduced mass ($\mu = \frac{m_D}{2}$) and the screened potential $V(r)$ is given by:

$$V(r) = V_0 + \frac{\alpha}{r}. \tag{IV.2}$$

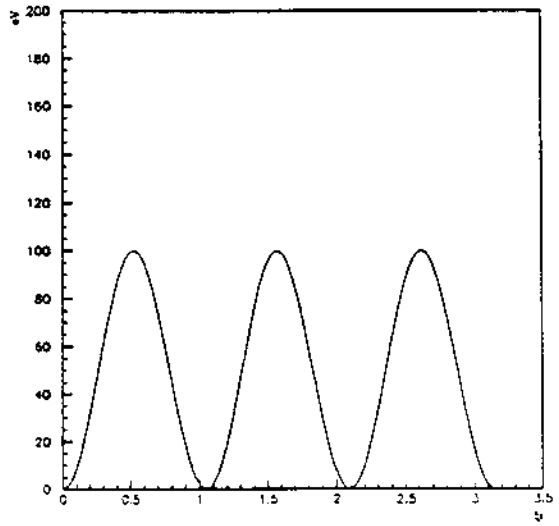

FIG. 13. The electrostatic potential as seen by the D^+'s along the tetrahedral disks.

Note that for $V_0 \simeq -85\ eV$ and $E \simeq 0$ (cold fusion), one obtains $r_0 \simeq 0.16\mathring{A}$ much smaller than the average distance of the D_2-molecule. $r_{D_2} \simeq 0.75\mathring{A}$. This is enough to increase the infinitesimal $\eta_G(D_2) \simeq 10^{-51}$ to $\eta_G(Pd) \simeq 10^{-22\pm1}$ for two D^+'s in the tetrahedral disk.

Thus we may conclude that Coulomb screening is well understood, and that it leads to fusion rates of "Jones' type", about ten orders of magnitudes lower than required by the excess heat observed by Fleischmann and Pons. Indeed for "incoherent fusion" one gets:

$$\Gamma_{INC} = |\eta_G|^2 \Gamma_{NUCL} \simeq 10(x-1)\ fusions/sec\ cm^3. \tag{IV.3}$$

if one takes for $\Gamma_{NUCL} \simeq 1 MeV$, a typical nuclear rate. This, then, leads us to the other question:

(β_2) which is the main DD-fusion dynamics?

We should recall that D^+'s that pack the Pd-lattice are in strong coherent e.m. fields. For instance the coherent field associated to the plasma oscillations to the Pd-ions (i.e. the Pd-atoms, deprived of the electronic d-shell, according to QEDCM follow their own quantum plasma dynamics) can be written

$$\vec{A}^{(N)} = a_N \vec{u} \cos \omega_r t, \tag{IV.4}$$

where one estimates $a_N \simeq 3.2 \cdot 10^6$eV and $\omega_r \simeq 0.1eV$. In such field the process:

$$D_e D_\gamma \rightarrow Nuclear\ State, \tag{IV.5}$$

(where D_e is the excess ($x > 1$) deuteron, D_γ is the γ-phase deuteron, and *Nuclear State* (NS) denotes any of the accessible nuclear states) is governed by the interaction Hamiltonian:

$$H_{INT} = e \int_{\vec{x}} \vec{A}^{(N)}(\vec{x}, t) \vec{J}(\vec{x}, t), \tag{IV.6}$$

where the e.m. current operator can be represented as:

$$\vec{J}(\vec{x}, t) = \int_{\vec{\xi}} \Psi^\dagger_{NS}(\vec{x}, \vec{\xi}; t) \vec{J} \Psi_D(\vec{x}, \vec{\xi}; t) \eta_{D_e}(\vec{x}, \vec{\xi}; t). \tag{IV.7}$$

Here $\Psi^\dagger_{NS}(\vec{x}, \vec{\xi}; t)$ is the quantum wave-field describing the plasma oscillations of the (doubly charged) NS, of amplitude $\vec{\xi}$ around the equilibrium position $\vec{x}$, $\Psi_D(\vec{x}, \vec{\xi}; t)$ the quantum field of the D^+ in the γ-phase, and $\eta_{D_e}(\vec{x}, \vec{\xi}; t)$ the wave field of the excess D^+. Diagrammatically the interaction Hamiltonian is given in Fig. 14.

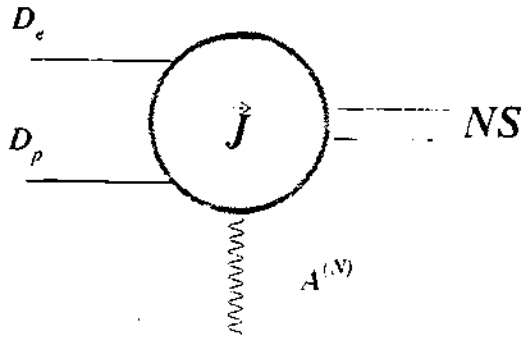

FIG. 14. Diagram for the interaction Hamiltonian [Eqs. (IV.6)-(IV.7)].

The e.m. current J_k, appearing in (IV.7), has the expression:

$$J_k(t) = \langle NS(t)|j_k|D_e D_p\rangle = \eta_G \langle NS(t)|j_k|NS(t)\rangle, \tag{IV.8}$$

where $|NS(t)\rangle$ obeys the Schrödinger equation:

$$i\frac{\partial}{\partial t}|NS(t)\rangle = (H_N + e\vec{A}^{(N)}\cdot\vec{j})|NS(t)\rangle, \tag{IV.9}$$

H_N is the nuclear Hamiltonian and j_k is the nuclear current operator. We simplify the problem by restricting the nuclear states to the three states reported in Fig. 15. Writing

$$|NS(t)\rangle = c_0(t)e^{-i\omega_0 t}|0\rangle + c_1(t)e^{-i\omega_1 t}|1\rangle + c_2(t)e^{-i\omega_2 t}|2\rangle, \tag{IV.10}$$

with $c_0(0) = 1$ and $c_1(0) = c_2(0) = 0$, the Shrödinger equation (IV.9) yields the following result:

$$\begin{aligned} c_0(t) &\simeq 1, \\ c_1(t) &= \frac{eq_N V_{01}}{\omega_0-\omega_1}(e^{-i(\omega_0-\omega_1)t}-1), \\ c_2(t) &= \frac{e^2 q_N^2 V_{01}V_{12}}{2(\omega_0-\omega_1)(\omega_1-\omega_2)}(e^{-i(\omega_0-\omega_1)t}-1)(e^{-i(\omega_1-\omega_2)t}-1), \end{aligned} \tag{IV.11}$$

where we have set

$$\begin{aligned} V_{01} &= \langle 1|\vec{j}\vec{u}|0\rangle \\ V_{12} &= \langle 2|\vec{j}\vec{u}|1\rangle \end{aligned} \tag{IV.12}$$

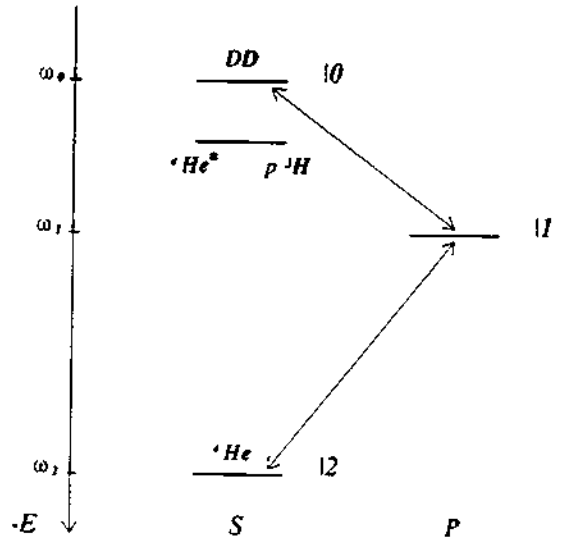

FIG. 15. The level diagram for the states in the dynamical evolution described by (IV.9) Also reported is Schwinger's-$^4He^*$ state.

We must now compute the transition amplitude over the time $T = \frac{2\pi}{\omega_r}$ (ω_r is the renormalized frequency of the Pd-plasma oscillations), which has been estimated [6] as the time needed for the collective plasma excitation to relax their excess energy to the lattice, that will finally appear as heat. One has

$$A(D_eD_p \to NS,T) = -i\int_0^T dt'(NS|H_{INT}|D_eD_p) \simeq -iT_{\eta_G}\frac{2e^2a_N^2}{\omega_0-\omega_1}|V_{01}|^2N_{CD}, \quad \text{(IV.13)}$$

where the factor $N_{CD} \simeq 10^{12}$ – the number of deuterons in a coherence domain of the plasma of deuterons – is especially noteworthy. From (IV.13) we compute the rate

$$R(D_eD_p \to NS,T) \simeq \frac{|A(D_eD_p \to NS,T)|^2}{T} = \quad \text{(IV.14)}$$

$$= |\eta_G|^2\frac{4e^4a_N^2}{(\omega_0-\omega_1)^2}|V_{01}|^2\frac{2\pi}{\omega_r}N_{CD}^2. \quad \text{(IV.15)}$$

In order to evaluate the average energy that the fusion process "dumps" onto the lattice, we first notice that under the action of the e.m. field $\vec{A}^{(N)}$ the nuclear state $|NS\rangle$ will very rapidly go to the ground state consisting of a coherent state ^{4}He which will progressively decay into α-particles that migrate out of the lattice.

We have now all elements to estimate the power W_{CD} that in each coherence domain is produced by the fusion of the excess $(x-1)N_{CD}$ deuterons with the deuterons of the γ-phase. We obviously have:

$$W_{CD} = (x-1)N_{CD}R(D_eD_p \to NS)|\omega_{DD}-\omega_{^4He}| \simeq 10|V_{01}|^4(x-1)Watt/CD \quad \text{(IV.16)}$$

where we have set $|\omega_{DD}-\omega_1| \simeq 10$ MeV. By the further estimates $|V_{01}| \simeq 10^{-2}$ and $(x-1) \simeq 10^{-1}$ we get the very rough evaluation

$$W_{CD} \simeq 10^{-8}Watt/CD \quad \text{(IV.17)}$$

and, considering that in one cm^3 there are $\frac{1}{(2\cdot10^{-4})^3}$ CD's, we obtain:

$$W \simeq 1.25kW/cm^3. \quad \text{(IV.18)}$$

a very large power, of the magnitude reached by Fleischmann and Pons.

As for the final question

(β_3) can we understand rarer processes: n,T,X-rays...?

We note that there can be other fusion routes which may become important in regions where the e.m. field amplitudes a_N are smaller (for instance at the boundary of CD's or around dislocation, plasma vortices etc.). Indeed the transition route (see Fig. 15) $DD \to P \to state \to ^4$He is in general more complicated including the excited ^{4}He-state lying 3.8 MeV below the DD-state [2]. Where a_N is weakened the dominant e.m. energy

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[2] As enphasized by Schwinger [10] this state will be able to decay into the pT- but not into the n^3He-channel.

producing process, that leads to the ground state ^{4}He, may find some competition from a pure nuclear process such as

$$^4He^* \rightarrow pT, \tag{IV.19}$$

which would explain the anomalous ratio

$$\frac{n}{T} \simeq 10^{-6}. \tag{IV.20}$$

But, how about strange nuclear products that have been announced in the literature, such as:

- high energy neutrons
- Pd X-ray lines
- High energy charged particles
- nuclear transmutation
- ... ?

A possible explanation could be worked out along the following line: as we have seen the main fusion rate is the coherent process

$$D_eD_p \rightarrow^4 He + \delta a^{(N)}, \tag{IV.21}$$

whereby a coherent wave of ^{4}He is produced along with an excited state of the coherent e.m. field $\vec{A}^{(N)}$ (of amplitude $a^{(N)} + \delta a^{(N)}$). This excited state will most probably relax its excess energy to the lattice in the form of heat, however over "nuclear times" ($T_N \simeq \frac{2\pi}{\omega_N} \simeq 10^{-6} \div 10^{-7}\frac{2\pi}{\omega_r}$) and with a branching ratio of order $\frac{T_N}{T}$ the excited field may induce all kind of "coherent" photonuclear reactions, including the photodissociation of deuterons and the successive capture of the neutrons by the Pd-nuclei. This would then provide a realistic physical realization of the neutron transfer mechanisms that have been considered and studied by P. Hagelstein. [1]

But, of course, a decent understanding of these complex issues requires much more theory and experiment!

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[1] P. Hagelstein, contribution at this Conference

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