COLD FUSION: WHAT DO THE LAWS OF NATURE ALLOW AND FORBID?

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1. INTRODUCTION

This talk will not be a summary of the theoretical contributions to this Conference: I think that the individual papers that this book collects can give a much better representation of the work that is now going on in the field than I can possibly attempt to give in a short talk. As a partial excuse I may quote a recent review article of mine[1], where I try to discuss the most significant theories of cold fusion, and the fact that nothing much new has happened in the last few months. Nor will I discuss cold fusion in the non-equilibrium conditions prevailing in Titanium[2], fracto-emission[3] and 'lukewarm' fusion[4].

I shall rather try to examine first the strange facts of hydrogen incorporation into Palladium, and then I shall discuss the phenomena of cold fusion in relation to those facts. In the light of the known experimental data I will then discuss the general features of what we might call 'possible' and 'impossible' theories of cold fusion, somehow drawing a demarcation line between which theoretical ideas can and cannot explain those observations, given the well established and accepted general laws of condensed matter (Quantum Electro Dynamics, QED) and nuclear physics (Quantum Chromo Dynamics, QCD).

My discussion will follow quite closely a paper recently completed in collaboration with M. Fleischmann and S. Pons[5].

2. FACTS

As Martin Fleischmann and Stanley Pons have explained us time and again they were induced to undertake a work «... that was initiated on the strength of a calculation that no moderately intelligent graduate student, let alone experienced electrochemists, ought to take seriously... »[6] by their being puzzled by the odd behaviour of Hydrogen - and its isotopes - when inserted in a host metal lattice, like Palladium. Let me try to briefly list and describe the strange facts that captured the imagination of our friends.

- **High concentration of Hydrogen in Pd**

When a piece of Pd is put in an atmosphere of gaseous Hydrogen at normal pressure it soakes a large quantity of the gas spontaneously and exothermally up to a ratio

$$x = \frac{H}{Pd} \simeq 0.6 .$$

In order to get much higher x one needs very large pressures; in any case with accessible pressures one cannot reach from gaseous Hydrogen the apparently relevant 'threshold' x=1 (see later)[7].

- **High Hydrogen mobility**

The anomalously high mobility of Hydrogen in Pd, in particular its being accelerated by electric fields shows that Hydrogen and its isotopes (D and T) in Pd exist in their nuclear (not atomic) state, immersed in a very dense plasma of d-electrons[8]. And the natural question is: why highly compressed Hydrogen does not form?

- **High H/D separation factor at equilibrium**

In equilibrium conditions H and D exhibit a high separation factor, completely consistent with a statistical mechanics model based on delocalized classical oscillators showing high affinity for Pd.

In order to appreciate the latter statement let us consider two possible Born-Haber cycles (Fig. 1) for molecular Hydrogen to penetrate into Pd.

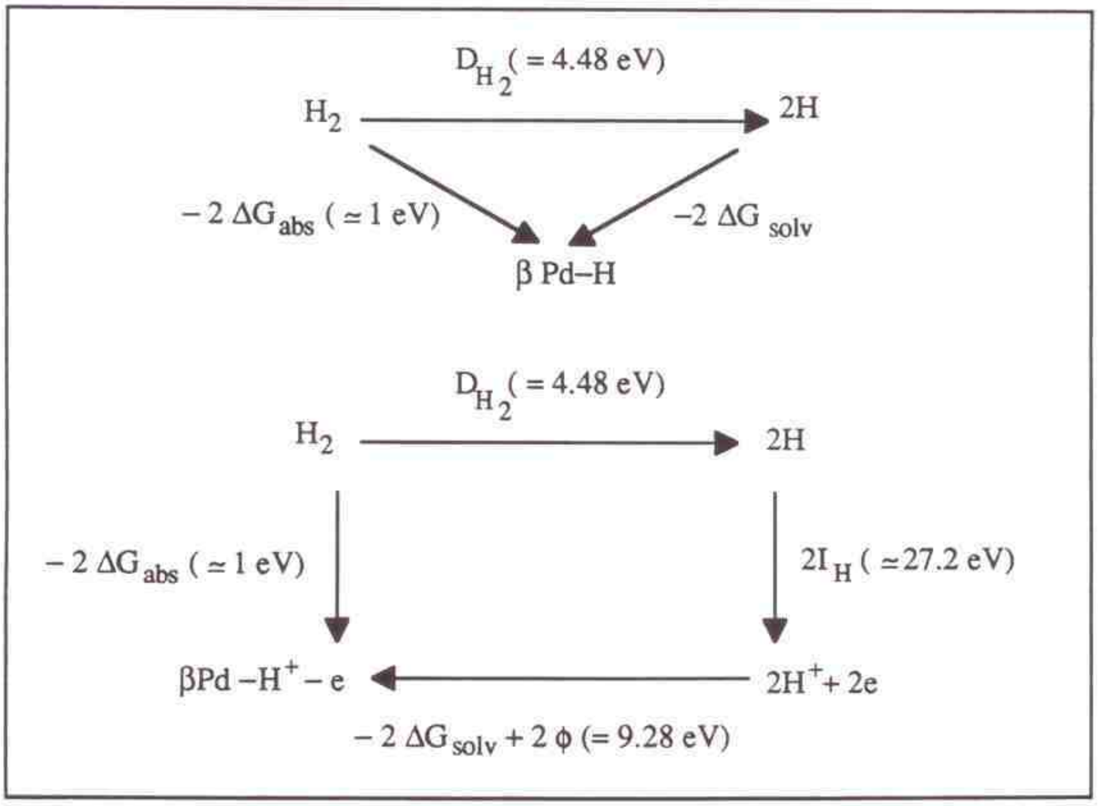

FIG. 1 - Two possible Born-Haber cycles for β Pd-H.

One sees that one obtains solvation potentials of Hydrogen in Pd of the order of several eV's, a most noteworthy physical phenomenon.

– Large diffusion coefficients - Inverse isotope effect

Transport measurements show that the diffusion coefficients D of Hydrogen in Palladium are of the order of 10^{-7} cm^2 sec^{-1} - a very large value - and are ordered as[9]

$$D_D > D_H > D_T. \quad (1)$$

The inversion of the diffusion coefficients of D and T, that runs contrary to what one would have expected from their masses, is a kind of 'inverse isotope effect', which is also observed for the critical temperatures of the superconducting Pd - hydrides ($T_D > T_H$)[10].

– High chemical potential of dissolved Hydrogen

All these facts can be assembled to build the 'Scenario' reported in Table I.

TABLE I - Scenario from the facts of Hydrogen in Palladium.

FACTS	DEDUCTIONS
High concentration - Ionized species	Large electrostatic fields to 'undo' molecular and atomic H; 'deep' electrostatic potential holes
High affinity - high separation factors	Highly delocalized wave-functions, 'shallow' potential holes
Large diffusion coefficients	'Shallow' holes
Inverse isotope effect	Bosons (D) have a configuration space different from fermions (H,T)
High chemical potentials	Formation of large proton clusters

Let us now turn our attention to the facts of Cold Fusion (CF) as we have learned them in the last two years.

• Sporadicity, variability, metallurgical factors

The phenomenology that has accumulated so far shows that the 'irreproducibility' of the CF phenomena is most likely tied to the large number of relevant parameters and even to path-dependences in the space of parameters.

• Low T-levels, $n/_T \ll 1$, absence of γ-rays and secondary n's

The nuclear physics of CF has been since the beginning[11] (March 1989) a tremendous puzzle, why the outgoing channels are not $^3T + {}^1H$ and $^3He +$ in 1 : 1 proportion, like it happens in the vacuum? Indeed this dramatic discrepancy has convinced the majority of physicists that CF phenomena must be a bogus.

- **Bursts in T, n production**

  Are they due to non-equilibrium conditions?[12]

- **High energy T, n and protons**[13]

  Unconventional nuclear physics?

- **Soft X-rays**

  As shown by Szpak's [14] and Miles' [15] dental films.

- **^{4}He unaccompanied by high energy γ rays**

  As shown by the beautiful experiments of Melvin Miles and collaborators[15].

- **Excess enthalpy production far above that corresponding to T + n production**

  In particular the new results of Fleischmann and Pons[16], that have been corroborated by Wilford Hansen's independent analysis[17], indicate powers of kW/cm^3.

The scenario that originates from assembling these facts together is reported in Table II.

TABLE II - Scenario from the facts of CF phenomena in Pd.

FACTS	DEDUCTIONS
Sporadicity, Variability, Path-dependence	Delicate conditions, thresholds
Low T-levels, $^n/_T \ll 1$, no γ's	Asymptotic Freedom (AF)badly violated inside lattice
Bursts in T, n production	Strange non-equilibrium conditions - Special domains
High energy T, n and p	AF is violated - DDD fusion?
^{4}He and no γ's	AF is violated - e.m. coupling to electron plasmas
Excess enthalpy	AF is violated

3. - POSSIBLE AND IMPOSSIBLE THEORIES

We shall now try to bring the 'facts' and the scenarios of the preceding Section to bear upon the key question of this talk, namely which of the the proposed theories are possible, and which among them, on the other hand, are impossible. But before going into the specifics, it is important to set down a clear demarcation between possible and impossible theories, which might run as follows:

Any ' possible' theory must explain the new phenomena (facts), without 'unexplaining' the old.

To this we may add the corollary: the old theory (ies) which does not explain the new phenomena cannot be used against the new theory in the realm where the old theory 'worked'.

Or, said differently, the 'successes' of the old theory cannot be taken as evidence that there is no need of different explanations of those successes.

3a - Hydrogen and its Isotopes in Pd

According to the scenario of Table I inside and at the surface of Pd there must exist very strong electrostatic fields.We realize at once that these fields must be able to polarize the Hydrogen molecule so strongly as to break it into its elementary components - p, d, T and electrons -, thus piercing through an energy barrier which is as high as $\simeq$ 30 eV. The 'deep potential holes' that are created by such fields, however, cannot have gradients that exceed ~ 70eV / 0.5 Å, for otherwise ^{4}He would also exist in the form of an α-particle, and this is contradicted by observations. This fact nicely disposes of the arguments, embodied in the Baym-Leggett Theorem[18], that were made against CF. Indeed, in the Pd lattice the observed behaviour of ^{4}He is completely different from that of pairs of D's, contrary to the 'reasonable' assumptions of Ref. [18].

From the very existence of the β-phase the number of 'deep holes' (with electric fields 30 eV / Å $< |\vec{E}| <$140 eV / Å) must exceed $x_\beta = 0.6$, and the well known difficulty of charging the Pd electrodes above $x \simeq 1$ makes it plausible that the number of such holes equals just the number of Pd-nuclei. Here, however, a severe difficulty shows up: how can we reconcile the existence of such 'deep holes' with the fact that Hydrogen is delocalized? The oddity of this fact puts all the generally accepted theories, based on two-body electrostatic forces between matter constituents, in the category of IMPOSSIBLE THEORIES.

Also the magnitudes and the inverted ordering ($D_D+ > D_H + > D_T+$) of diffusion constants speak against the usual theories, for they appear to require the existence of collective bosonic/fermionic states for the Hydrogen 'plasma'.

We may thus draw a fundamental demarcation between POSSIBLE AND IMPOSSIBLE THEORIES of Hydrogen in Pd in their allowance for collective many-body phenomena.

In models invoking explicity the existence of collective phenomena[1,19] the 'deep holes' that must form in roughly 1 : 1 proportion originate from coherent plasma oscillations of d-electrons. The difficult problem of 'delocalization' can be solved by imagining that the collective dynamics makes the Hydrogen state deep in the potential wells unstable. This can only happen if there are interactions other than electrostatic which provide the necessary negative interaction energy that allows the Hydrogen to occupy highly excited (delocalized) states in the potential well.

The only theoretical proposal, known to me, that achieves just that is the simplified model of plasma that is discussed in Ref. [20]. According to this model, as long as the charged particle of a plasma moves in a harmonic potential, its coupling to the e.m. quantum modes with the frequency $\omega = \omega_p$ (ω_p is the plasma frequency) will lift it up indefinitely, its excitation stopping when strong non-harmonicities appear.

This means that the Hydrogen nuclei will go to band states of the deep (~ 100 eV) potential that are highly delocalized, and in such circumstances all other properties discussed in the preceding Section appear to find a natural explanation.

3b - Nuclear Fusion Processes in Pd

As discussed in Ref. [1] the difficult problems that must be dealt with by any theory of these phenomena are two:

(i) How can the Coulomb barrier be penetrated at such large rates?
(ii) How can the process avoid the restrictions posed by 'Asymptotic Freedom' (AF)?

As for problem (i), all simple evaluations of 'tunnelling' probabilities lead to estimates that are 50-60 orders of magnitude much too small! Regarding problem (ii) one must notice that, even if the former severe difficulty could be resolved, there remains the even more severe difficulty that fusion in the lattice does not proceed experimentally in the same way as in hot-fusion processes.

In particular, the discoveries of high excess enthalpy uncorrelated to T-production and of the large $T/_n$ ratio imply that the lattice must play a fundamental role and, consequently, AF, with its implications of independence of nuclear processes from lattice dynamics, must be violated in a fundamental way. Besides a deep reason for the violation of AF, a good theory should also give some explanation of variability, dependence on x, bursts in T and n and generation of high energy n, p and T.

Getting now to the proposed theories of the penetration of the Coulomb barrier, I note that a simple application of the Gamow-formula (which contains essentially all the 'juice' of the problem of the penetration of the Coulomb barrier) requires the existence of a screening potential of about 100 eV, just in order to enhance the naive estimates of fusion rates by the 50 orders of magnitude necessary to account for the relatively rare neutron emission processes.

All POSSIBLE theories must thus include at least a semiquantitative explanation and estimate of screening potentials of such size. IMPOSSIBLE are those theories which do not consider explicitly this problem[22].

Among IMPOSSIBLE theories, I note those which try to avoid the barrier either by having 'off-shell' neutrons to initiate the fusion process[1], or 'on-shell' neutrons that originate from an incoherent exchange of energy with the lattice[23]. Equally IMPOSSIBLE is to have tight De bound states up to 300 F (Hydrons)[24], which appear in clear conflict with known phenomenology.

On the other hand the superradiant plasmas considered in Ref. [20] do provide for such screening in a natural way[25].

The necessary violation of AF puts all theories based on the usual, electrostatic view of condensed matter interactions among the IMPOSSIBLE theories. For in a lattice governed by short-range forces no room for such striking phenomenon can be found: indeed, with such forces there is absolutely no way in which the space-times of a lattice (10^{-8} cm and 10^{-15} sec) can influence the space-times of a fusion process (10^{-12} cm, 10^{-21} sec). I note in passing that similar mismatches occur in the physics of the Mössbauer effect, putting this well known phenomenon in the category of natural mysteries - at least within the conventioned picture of condensed matter[26]. POSSIBLE theories of CF must take due account of these odd collective phenomena, which the theory of superradiant plasmas explains naturally.

Recall, in fact, that the theoretical analysis based on superradiant behaviour[19] explicitly violates AF and provides estimates of the rates of ^4He (plus excess heat), T and n-production in reasonable agreement with known phenomenology. In particular, the production of ^4He unaccompanied by γ-rays demands a very fast ($\sim 10^{-21}$ sec) energy transfer to the lattice electrons (which then will release it away in various ways: heat, ultraviolet light, x-rays...). Without a macroscopic quantum behaviour the impossibility of any theoretical description is clearly seen by computing the velocity υ of such transfer from the site of fusion (somewhere inside the lattice) to the nearest atom (~ 3 Å away), one has

$$\upsilon = \frac{3\text{Å}}{10^{-21}\ \text{sec}} \simeq 10^3\ c\ !$$

Remember the EPR paradox? Something like it seems to be occurring here[27].

Getting now to the sporadicity of some CF phenomena I would like to note that the theory which invokes the existence of heavy charged particle showering the earth from outer space[28], though a logical possibility, appears rather unlikely. On the other hand the existence of a threshold at $x \simeq 1$, as discussed in Ref. [29], seems a more likely explanation. Furthermore lattice defects, dislocations etc. interfering with the basic electron cooling mechanism responsible for the production of γ-less ^4He[1,19], might naturally explain T-production. It is clear, however, that along these lines a lot of work needs to be done.

4 - CONCLUSIONS AND OUTLOOK

I would like to end this talk with a few 'lapidary' statements, that try to capture the essence of my analysis.

- CF exists, its phenomenology is diverse but coherent, and reproduced by many different groups in different conditions.
- No previously known law of nature (QED and QCD) appear to be violated by CF phenomena.
- Deductions from these laws of nature, based on the generally accepted notion of AF, belong to the class of IMPOSSIBLE THEORIES.
- The key ingredient to construct POSSIBLE THEORIES is

  MACROSCOPIC QUANTUM MECHANICS (Macro QM)

  which originates from Quantum Field Theory (QFT) as applied to complex systems.

Let me note that a demarcation is seen to be emerging between simple (micro QM) and complex (Macro QM) systems and of their theoretical description. It appears that a powerful, detailed, correct theory of CF must be constructed along the lines of a macroscopic Quantum Mechanics, induced by long-range electromagnetic (radiative) interactions[20], i.e. according to QFT of Superradiance.

I hope that the next few years will see a lot of work along these lines. CF will then be looked upon not only as a magnificent gift to energy-hungry mankind, but as an essential window to the deep and subtle behaviours of condensed matter, which have remained hidden for such a long time.

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