

Research Article

Dynamics in Pd–H(D) Systems

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Abstract

PdH(D) shows many peculiar aspects which make it unique both for solid state and for LENR physics. Its most surprising characteristic is that it behaves like a stable dense plasma consisting of H(D) nuclei which can be well explained on the basis of an appropriate many-body model.

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1. Introduction

The Pd/H(D) system is historically the first that had attracted research activities [1] because it represents one of the most transparent and instructive models for a metal–hydrogen system. Palladium hydride shows many interesting features, most of them not explained yet.

Perhaps the most intriguing conundrum is the effective charge of hydrogen inside the lattice and whether it can migrate under the action of an electric field. It has been shown by Alfred Cöhn [2] that the dissolved hydrogen get ionized when it enters into the lattice and settle in its equilibrium position in ionic form. Ionization may actually occur just at the surface of the crystal and ions reach their equilibrium positions later on [3].

Moreover, the Pd–H system exhibits a complex phase diagram: at room temperature and pressure hydrogen is in a gas like situation within the Pd lattice when $H/Pd \leq 0.02$ (α -phase); increasing the loading a new phase, named β -phase, emerges coexisting with the α -phase; in the β -phase hydrogen is confined in the octahedral sites of the Pd lattice. When $H/Pd \sim 0.6$, the β -phase extends to the whole lattice.

In Fig. 1, it is shown the Pd lattice where Pd atoms occupy the fcc (face centered cubic) positions. Two equilibrium positions are allowed to the solute atoms: the octahedral position along the minimum distance between Pd atoms, and the tetrahedral position at the center of a tetrahedron having four Pd atoms at its vertex. The octahedral sites correspond to the minimum energy position of the empty Pd lattice, however, increasing the loading, the energy bands of PdH undergo a severe modification.

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Experimental evidence [4] shows that a new phase in which hydrogen migrates from octahedral to tetrahedral positions in the lattice exists. In fact, the volume expansion due to hydrogen absorption shows that, when $H/Pd \sim 0.8$, the rate $\Delta V/V$ changes pointing towards a different occupation of hydrogen in the lattice.

Evidence for a structural and electronic phase transition, we will call it $\beta \rightarrow \beta'$ in the next, is also provided by measuring the number of charge carriers in the Pd–H system [5] which undergoes an unexpected change when $H/Pd \geq 0.83$. It has been found that each hydrogen entering the Pd lattice in the β -phase contributes with about 0.75 electrons to the conduction band, whereas for $x = H/Pd$ exceeding a threshold each hydrogen contributes with more than four electrons to the conduction band; since the hydrogen has only one electron on its own it must persuade more than three Pd electrons to jump into the higher energy band, so that the hydrogen that enters the lattice causes a local reshuffling of the Pd electronic bands.

The electrical resistivity $\rho(x)$ of the Pd–H system as a function of x shows an increase of the carrier and/or mobility over a certain threshold [6] too. In the coexistent $\alpha - \beta$ region, $\rho(x)$ increases almost linearly with the hydrogen content up to the value where the $\beta - \beta'$ transition occurs: then it decreases quite sharply reaching the value ρ_0 of the pure Pd metal.

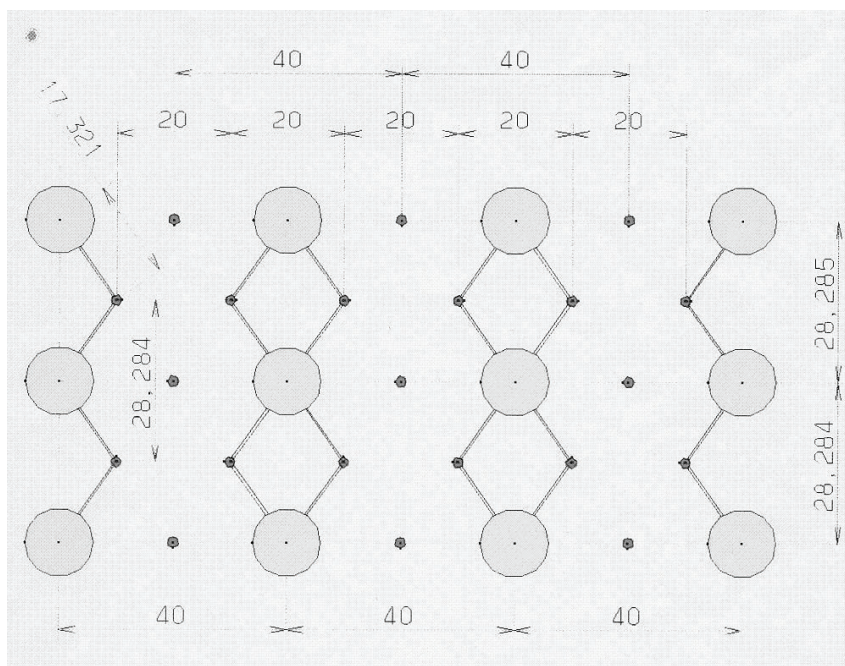


Figure 1. Palladium lattice. The big spheres are Pd atoms, their distance was set equal to 4 Å; the octahedral sites lie on the same plane just in between two Pd atoms; the tetrahedral sites are positioned on a different plane at a relative distance of 2.828 Å.

2. Hydrogen Kinetics in Palladium

In spite of such a puzzling picture, the understanding of hydrogen dynamics inside the solid state lattice is a very important task both for theoretical physical chemistry, for applications in the fields of hydrogen fuel cycle and for LENR researches. As mentioned above, the most interesting state of the Pd/H system starts at a specific loading threshold which is not easy to obtain. During the isothermal loading process, the solute gradient inside the metal suffers from a thermodynamic force influenced by all the fields that can affect the free energy of the solute.

The diffusion flux is described by the general equation:

$$J = -M \cdot c \cdot \text{grad } \mu,$$

where c is the hydrogen concentration, M the mobility related to D , the diffusion coefficient, by the Einstein relation and μ is the chemical potential. The stress induced by the hydrogen diffusive flux causes an inhomogeneous distribution of the solute. Kandasamy [7] showed that a suitable strain can stop the diffusion of hydrogen caused by the concentration gradient, in fact the previous equation is modified as follows:

$$J = -D \left(\nabla c - \frac{c \bar{V}}{RT} \nabla \sigma \right),$$

where $\bar{V}$ is the molar volume of hydrogen in the metal and σ the stress field.

It is well known that during the loading expanded β areas grow near the α areas. In this region of coexistence very strong deformation fields are generated at the border between the two phases, due to the different lattice parameters. This process is highly irreversible because of the energy dissipation involved in the generation of dislocations. Calculations performed for a cylindrical Pd cathode show that the maximum shear stress is obtained on the surface at the beginning of the diffusion process. This means that the loading is abruptly limited to a thin slab underneath the surface, as a consequence, the loading path is very important to determine the final concentration profile inside the metal [8].

The coexistence phase allows the strain gradient to grow and introduces into the system a stress energy which can prevent any further intake of hydrogen, however, an appropriate path on p - c - T diagram can skip the coexistence region and improve the loading [9]. In Fig. 2, it is shown the comparison between two loading procedures: (a) electrolysis of LiOH solution using Pd wire; (b) the Pd wire has been pre loaded at high (>34 bar) pressure and (>270°C) temperature and then used as a cathode in LiOH electrolysis with the same parameters as in the former case. Above the point $P = 34$ bar and $T = 270^\circ\text{C}$ which is the critical point on the p - c - T diagram, the co-existence phase does not exist anymore. The results clearly show that the loading ratio is 20% higher than usual.

A further increase of the concentration can be reached if the stress is allowed to relax with suitable loading procedure both in gas phase and in electrolysis [10]. Figure 3 shows that switching the current level between two values improves the loading ratio because the stress field is allowed to relax during the low-current phase.

The experimental data show that the self-induced strain field arising from very steep concentration gradients is responsible for the well-known difficulty in obtaining reproducible high loading samples. In addition, possible damages induced by the loading process itself can modify the material during the experiment in an unpredictable way, resulting in poor reproducibility of the loading procedure.

3. Influence of Microstructure on Loading

To facilitate the loading avoiding the growth of an excessive strain it can be useful to prepare a material with intrinsic characteristics such as to minimize the gradients in the solute concentration. Since the hydrogen diffusion coefficient is orders of magnitude higher in the grain boundaries than in bulk, the diffusive process takes place in two steps: firstly, hydrogen is included in the grain boundaries where the diffusivity is higher, in a second step it diffuses inside the grain.

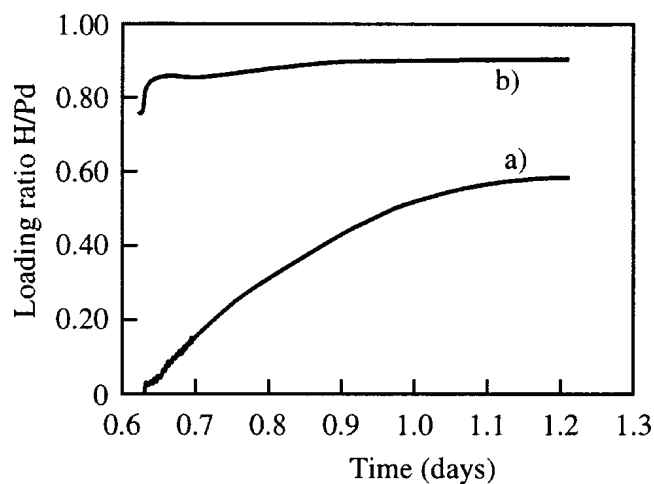


Figure 2. Concentration behavior vs time. (a) Pd sheet charged in electrolysis, $I = 10$ mA, (b) Pd sheet pre charged in H_2 gas and then in electrolysis with $I = 10$ mA.

The grain boundaries act as a source of hydrogen for the bulk where the actual diffusive process takes place. Thus the presence of a suitable network of grain boundaries enhances the kinetics and reduces the chemical potential gradient increasing the loading on the whole. The same mechanism works on thin films where the reduced dimensionality limits the growth of high stress fields, and the strains accumulated inside the film can be relaxed toward the substrate. The thin

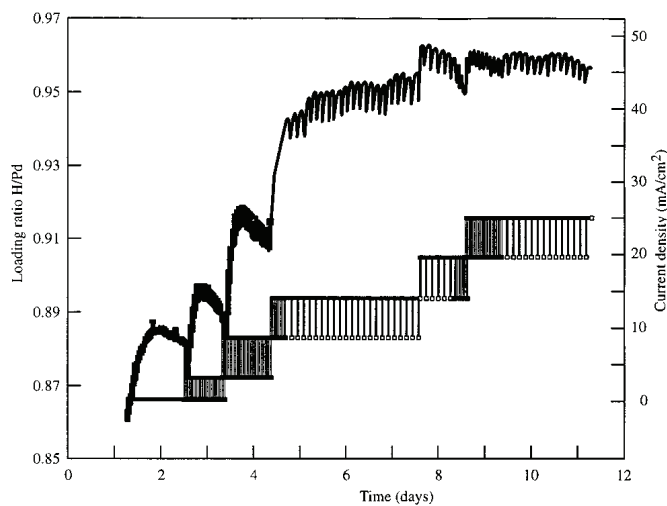


Figure 3. A further increase of the concentration value is obtained that allows the lattice to relax the stored stress fields temporarily decreasing the electrochemical action on the electrode surface: changing the electrolytic current between two values instead of using only the high level improves the loading.

film loading is complicated by the expansion of the lattice. In Pd, $\Delta l/l$ can reach 10%, under this condition the films loose their adhesion on the substrate and delamination occurs. In case several loading–unloading cycles are required the situation is even more difficult to be faced. Several “tricks” can be used to improve the adhesion to the substrate choosing appropriate buffer layers made out of several different layers in order to absorb part of the mechanical stress generated by the loading process.

Thermo-mechanical treatments and in particular cold working followed by baking can be used to modify the grain size in Pd samples. Grain size dimension can be changed both with the mechanical machining and with the thermal treatment, and it is possible, fixing one parameter, to obtain curves as those in Fig. 4 which shows a maximum of the loading ratio versus the grain size. Such a behavior implies that two different factors enhance the hydrogen diffusion into the lattice: smaller grain size reduces the strength of the stress field since the boundary network acts as fast hydrogen transporter through the sample; on the other hand the softening of the mechanical properties induced by larger grain size activates the stress relief mechanism based on plastic deformations. The combination of the two mechanisms enhances both diffusivity through short circuit path and stress relaxation by plastic deformations. Concentrations larger than 0.95 H/Pd and 0.90 D/Pd have been obtained in electrolytic loading of samples with about 50 μm grain size [11].

4. PD/H Systems in H Plasmas

It is known that an electric field causes the changes of Pd surface reactivity and, as a consequence, an increase of the stoichiometry of Pd/H can be measured. Di Pascasio et al. [12] studied the possibility to increase the hydrogen loading in a metallic material, Pd in particular, in presence of a hydrogen plasma. They found that the hydrogen confinement in Pd can be increased by exposing it to cold H plasma without changing any other parameter. The term “cold plasma” is used for plasmas having a low concentration of ions ($\sim 10^6 \text{m}^{-3}$) in thermal equilibrium within the environment. Due to the low concentration of electrons the heat transfer is controlled by the neutral species. They concluded that a new thermodynamic condition is achieved in presence of a plasma, in particular, the thermodynamic condition of H inside

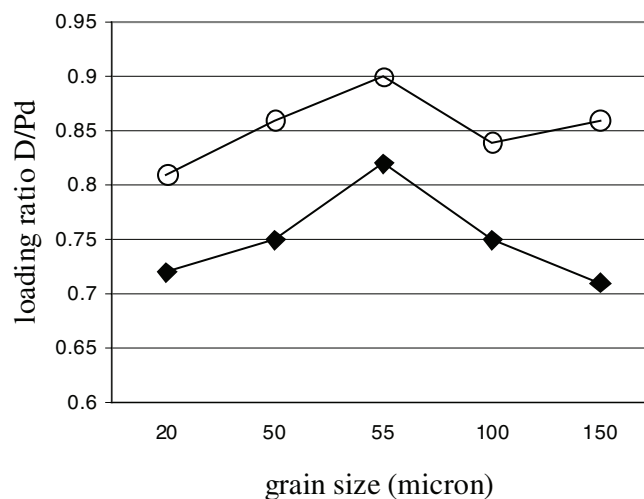


Figure 4. Loading ratio D/Pd vs. grain size. The two series refer to different values of reduction by cold rolling. Open circles: reduction rate = 1/5; black diamonds: reduction rate = 1/7. The annealing temperature was 900°C for both. Samples were loaded in electrolysis with a current density $i = 25 \text{ mA/cm}^2$.

Pd is affected by the presence of an external electric field even if the material characteristics are still that of a metal. Even Tomaszewska and Stepie [13] found that in presence of an external electric field Pd–H bonds seem to become stronger or, in a different view, the existence of an electric field decreases the activation energy required for hydrogen diffusion into the subsurface. More recently, an international team of researchers has developed a process using an electric field which can significantly improve hydrogen storage and release in/from materials [14].

In these reports, they came to the conclusion that, in a cold plasma, hydrogen inside the Pd lattice undergoes a transformation which affects the state, the number and the transport properties of both electrons and H ions.

A very interesting demonstration of external plasma effect on the loading of H in Pd can be observed inducing a corona discharge between two plane electrodes like those usually operating in electrolysis. The working electrode, a Pd coating 2 μm thick on a Si wafer, was grounded and a positive voltage was applied to the counter Pt bulk electrode. Both electrodes had a planar geometry with a 25.35 mm area, the gap between the electrodes was 4 mm. At the beginning of the experiment, the gap was filled with LiOH solution, the applied potential was kept well below the breakthrough voltage and the ordinary H loading occurred. As soon as the loading reached the threshold of the $\beta \rightarrow \beta'$ transition (see above), the solution was removed, the change of the electronic density on the Pd–H surface increased the number of secondary electrons involved and a negative corona discharge was formed. H^+ ions were accelerated with a high kinetic energy toward the working electrodes and impinged on Si trespassing the Pd coating. Removing the electrode from its housing and observing the surface with an optical microscope, a grid made out of very peculiar scratches was observed (Fig. 5a). The strange morphology of the scratches is quite hard to understand because it is perhaps the heritage of the polishing procedure of the Si wafer from which the electrode substrate was obtained. The same experiment carried out using a deposition of Pd on Vycor glass shows pits randomly distributed (Fig. 5b). A possible explanation is that tiny defects on the surface, although non visible before the discharge, have been amplified by the presence of the very high gradients of the electric field around the pins which, in turn, accelerate the ions within the limit of the plasma area. Inside the area delimited by two parallel scratches a very high temperature was reached by the Si (Fig. 5c) which appeared to be fused and resolidified. Cubic shapes with a pipe in the middle suggesting a re-crystallization process from the fused state can be seen (Fig. 5d) using the SEM analysis. The accelerated H^+ ions knocks with a very high energy on the surface producing very deep damages. Profilometry shows scratches as deep as 5 μm at the border of the structures shown in Fig. 5.

Besides the visual inspection of the sample, the Pd on Si cathodes were subjected to Rutherford Backscattering Spectroscopy (RBS) used for compositional thin film analysis (less than 1 μm) and to Elastic Recoil Detection Analysis (ERDA) which is an efficient technique for high resolution depth profiling of light elements, especially for detection of hydrogen depth profile. In Fig. 6 (a–c) the RBS analysis results are shown compared to simulations in order to get a quantitative evaluation. Figure 6a shows the comparison between a reference (not used in the experiment) sample of Pd on Si and the behavior expected for a 9000 Å thick Pd film; this is just to calibrate the instrument, 9000 Å is the bulk limit for the instrument. Figure 6b shows that, after the experiment described above, the Pd film was almost completely removed from the Si surface: the analysis fits the result obtained simulating a 40 Å thick film made out of a mixture of the metals used in the experimental set up; a bigger amount of Pd, about 300 Å thick film, was found on the back side of the Si wafer that was 1 mm thick (see Fig. 6c). ERDA analysis, in Fig. 6d, shows the hydrogen content in a 6000 Å depth (the analyzed depth depends on the energy of the beam): signal below channel 200 accounts for the H_2 content in a 6000 Å layer beneath the surface whereas the peaks around channel 200 show the hydrogen adsorbed on the surface. An amount of hydrogen four times greater than in the reference was found on the surface exposed to the plasma, however, a much higher value was found on the backside surface. The small amount of hydrogen found inside the sample after the discharge can be ascribed to the very high reactivity of H^+ ions which react with other species and are subtracted to the analysis.

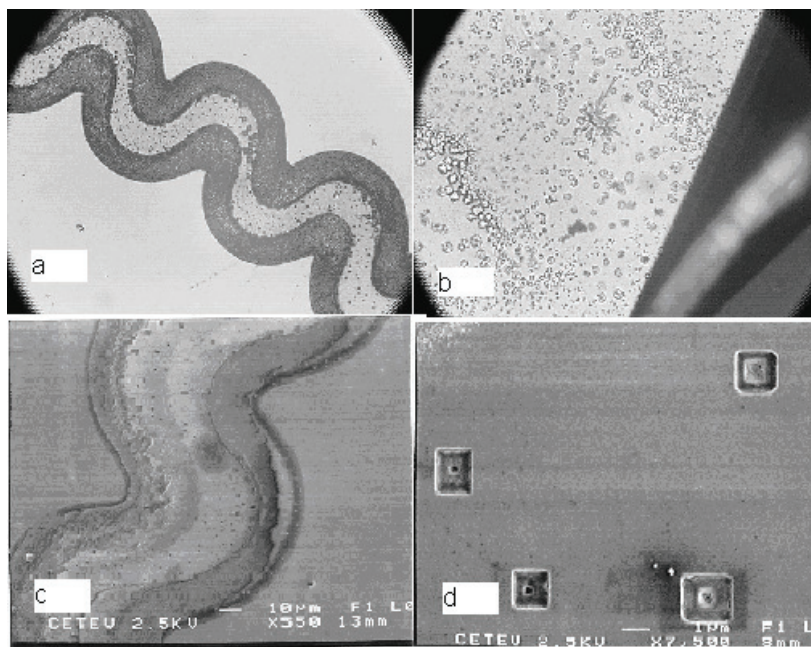


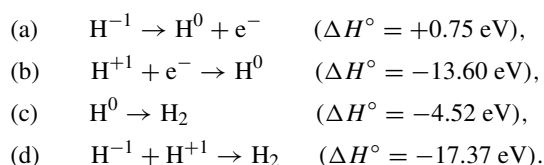
Figure 5. (a) Optical microscope image of a Pd on Si cathode exposed to negative corona discharge, (b) same as above but on Vycor glass substrate, (c) and (d) SEM images of the sample shown in (a) with different magnifications.

5. A Conceptual Discontinuity

Another surprising feature of the PdH system is the very high diffusion coefficient (about $10^{-7} \text{ cm}^2 \text{ s}^{-1}$ for hydrogen in the α -phase) and the fact that the diffusion coefficients for deuterium, hydrogen and tritium are in the order $D_{\text{D}^+} > D_{\text{H}^+} > D_{\text{T}^+}$ different from what can be expected on the basis of a simple classical model of diffusion. Moreover, Dandapani and Fleischmann [15] reported a very high equilibrium H/D separation factor for H and D dissolution into Pd cathodes at high negative over potentials. They interpreted this fact in a way that the species behave like classical oscillators in the lattice, in other words, they are virtually unbounded. Since the delocalization depends on the occupancy by the protons of highly excited states, the above stated properties of deuterons inside Pd lattice: high diffusion coefficient, inverse isotopic effect, large oscillation in the lattice, implies that many-body interactions must come into play and supply the energy required to raise the H^+ to such excited states.

Even the analysis of the Born–Haber cycle for H in Pd requires some hypothesis “ad hoc”.

The rational chemical design of high-efficiency hydrogen Storage Metals (HSM) has to take into account the large difference between H^+ and H^- ions :



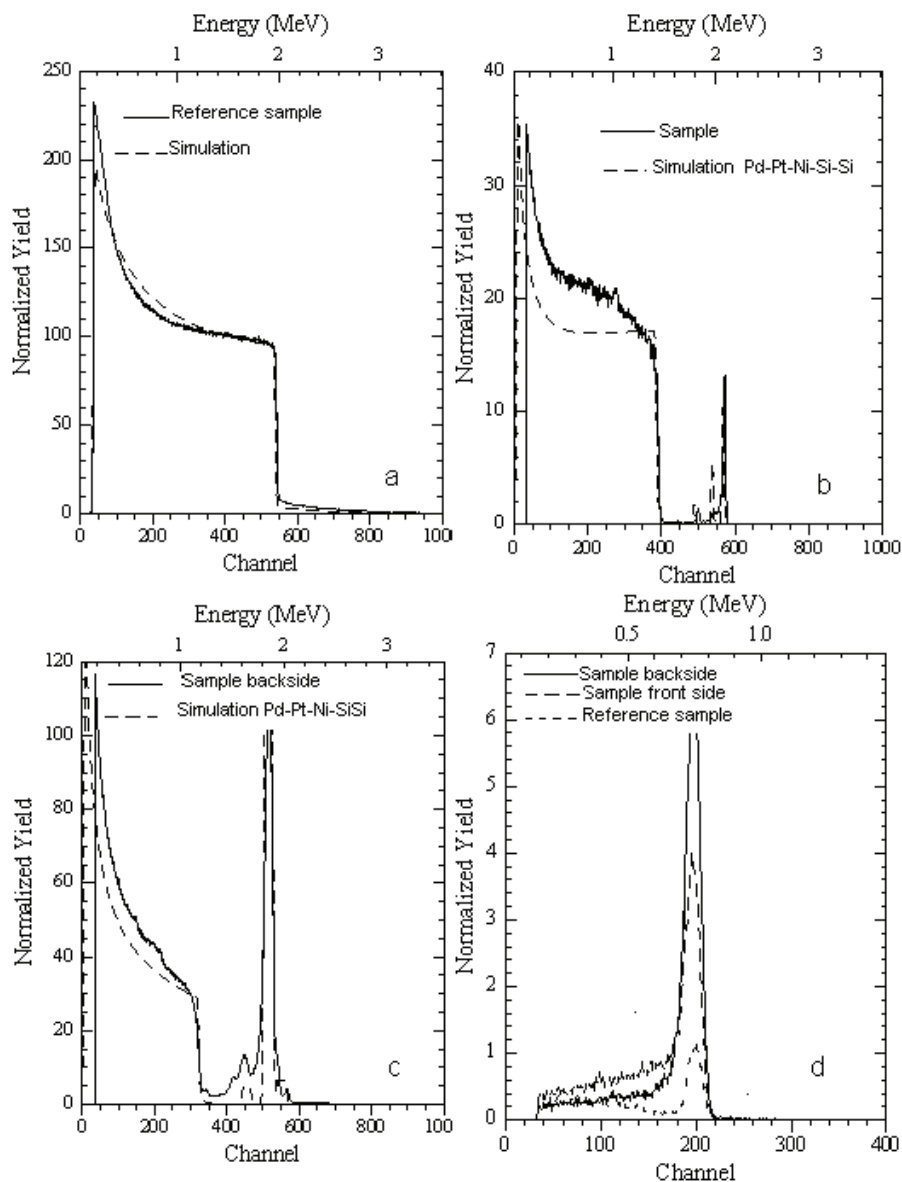
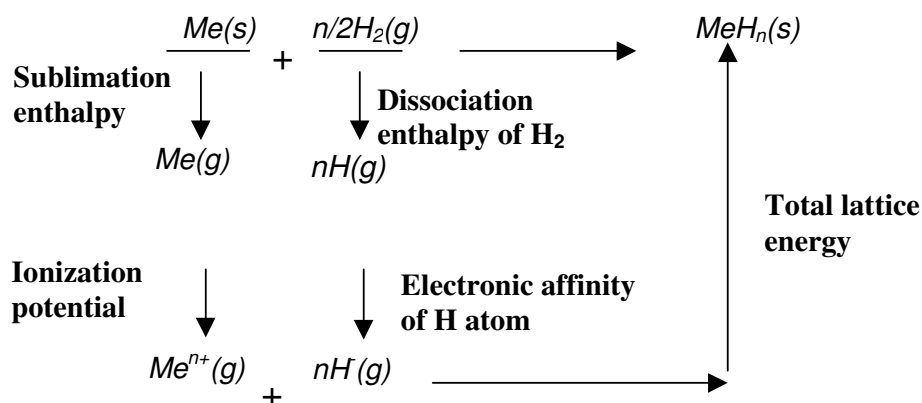


Figure 6. (a) RBS of Pd on Si compared with a simulation of 9000 Å thick slab of Pd; (b) RBS of the cathode exposed to negative corona discharge compared with a simulation of 40 Å of Pd-Pt-Ni Si on 20 000 Å of Si; (c) same as above but on back side of the sample compared with a simulation of 300 Å of Pd-Pt-Ni Si on 20 000 Å; (d) ERDA measures the hydrogen content in a 6000 Å depth. The peak shows the hydrogen content inside (on the left) and outside (on the right) the sample. See further details in the text.



Thus it is very important to state which is the real state of hydrogen inside the lattice, i.e. if it is in form of H_2 , H_+ or H_- . In 1929 Alfred Cöhn showed in an experiment on electromigration that hydrogen diffuses like a positive charge when it enters the Pd lattice. This result was confirmed by other authors [16,17] and the positive fractional charge was measured to be in the range of 0.3–0.7. Even modeling the electronic structure [18] confirms that the H drift appears to involve partially positive charged ions. Moreover, the same calculations show that, increasing the loading, H hopping through tetrahedral sites is energetically more promoted than through octahedral sites. The latter items may be just another sign of the $\beta \rightarrow \beta'$ transitions.

In order to behave like a (partially) positive ion inside the Pd lattice the hydrogen atom (or molecule) must find very strong electric fields in order to maintain itself in the ionized state (or to dissociate into two ions). The electric field inside the lattice must be able to produce a very high energy (13.6 eV over a distance of the Bohr radius 0.57 Å).

Clearly this requires a very peculiar electron distribution !

In a paper of 1994 [19], M. Fleischmann, S. Pons and G. Preparata wrote: “The hydrogen in the Palladium lattice is present as protons and the second surprising feature is that the extremely dense proton plasma is present in an electron concentration of 600–1000 M . . . we are driven to the conclusion that a satisfactory explanation of the stable existence of the dense plasma must be based on an appropriate many-body model”. They centered their statement on the analysis of the peculiarity in the Pd–H system described above.

As conclusion, Pd hydride behaves like a solid plasma inside a lattice. Such a perspective allows to explain the influence of an external electric field on hydrogen dynamics inside the Pd from a different point of view.

The chemical potential of hydrogen dissolved in Pd, in the α -phase can be set equal to

$$\mu_{\text{H}} = \mu_{\text{H}}^0 + RT \ln \left(\frac{x}{1-x} \right) + \Delta\mu_{\text{H}}, \quad (1)$$

where μ_{H}^0 is the standard chemical potential, $x = \text{H/Pd}$, the second term is the configurational term for the ideal statistic standard distribution among octahedral sites and the last one stands for the excess potential. At equilibrium the chemical potential of hydrogen in gas equals the chemical potential of hydrogen inside the lattice

$$\mu_{\text{H}} = \frac{1}{2}\mu_{\text{H}_2} + \frac{1}{2}RT \cdot \ln p_{\text{H}_2}$$

and, introducing the Sievert constant $K = \exp \left[\left(\mu_{\text{H}}^0 - \frac{1}{2} \mu_{\text{H}_2}^0 \right) / RT \right]$ one obtains

$$\ln(p_{\text{H}_2}) = \ln \left(K \cdot \frac{x}{1-x} \right) + \frac{1}{RT} (\Delta\mu_{\text{H}^+} + \Delta\mu_{\text{e}}).$$

The term $\Delta\mu_{\text{e}}$ represents the excess potential contribution of both protons and H^- electrons. It is straightforward to see that when the last term is omitted the equation represents the behavior in ideal solution state. This is actually true in the α -phase $x < 0.02$ where hydrogen is an ideal solid solution in the host lattice. Increasing the hydrogen concentration the elastic contribution $\Delta\mu_{\text{H}^+}$ generates a distortion in the octahedral cage which, in turn, introduces an attractive interaction between H-atoms and leads to the formation of clusters of high H density, namely the β -phase. From this point on, in case the rigid band model is assumed, the electronic contribution to the excess potential is due to the steep increase of the Fermi level caused by the electrons of the dissolved hydrogen, thus the loading is very hard to be increased.

The experimental findings listed above point toward the growth of a new phase at $x = x_{\beta'}$ (namely the β') where protons occupy the tetrahedral sites and become tentatively unbound. In this phase the second (configurational) term in Eq. (1) does not hold any more.

In case a potential V is applied to the metal, the excess potential $\Delta\mu_{\text{e}}$ will include its effect according to [20]

$$\Delta\mu : |e|z^*V. \quad (2)$$

In case the metal has a negative potential, the chemical potential of hydrogen inside the lattice fall below the chemical potential μ_{ext} of the hydrogen outside. The profile of the chemical potential μ is thus lowered by: (a) the phase transition and (b) the $\Delta\mu_{\text{e}}$ due to the voltage difference between inside and outside the metal. A new equilibrium point will be reached at $x' = x_{\text{eq}} + \delta x$, where the first term is related to the phase transition and the latter to the applied potential according to (2). Consequently, if we apply a negative potential to the Pd/H system when the system is in the new phase β' at $x \equiv x_{\beta'}$ a current flow j' adds up to the electrolytic current j_{el} :

$$j(x) = j_{\text{el}}(x) + j'(x) = j_{\text{el}} \left(1 + \frac{\mu(x_{\beta'}) - \mu(x)}{\mu(x') - \mu(x_{\beta'})} \right),$$

which disappears when $x \equiv x_{\beta'}$. It is worthwhile observing that the transverse field effect described above is not the longitudinal electric field generated by a voltage drop across the cathode accountable for electromigration.

A quantitative analysis of this effect can be obtained measuring the R/R_0 behavior during the LiOD electrolysis on a Pd strip, 1 μm thick sputtered on Vycor glass (see Fig. 7). The deposition was shaped in such a way to have a high electric resistance (about 1.5 k Ω) so that the voltage drop across the cathode was maximized and the longitudinal current along the strip was limited. According to the well-known Baranowski relationship between the PdH(D) resistivity and the loading ratio it can be seen that the loading increases (the resistance decreases above $R/R_0 \sim 1.8$) whenever the voltage across the cathode increases.

In case the resistance of the cathode is not negligible (a strip, a wire, a patterned deposition) the electrostatic equation for the cell has the following solution:

$$V(z) = \frac{V_{\text{ac}}}{\cosh(\xi L)} \cosh[\xi(L-z)],$$

where z is the curvilinear coordinate, V_{ac} is the voltage drop between anode and cathode, L is the total length of the cathode and

$$\xi^2 = \frac{\rho_{\text{c}}}{\rho_{\text{el}}} \frac{1}{\delta d} F.$$

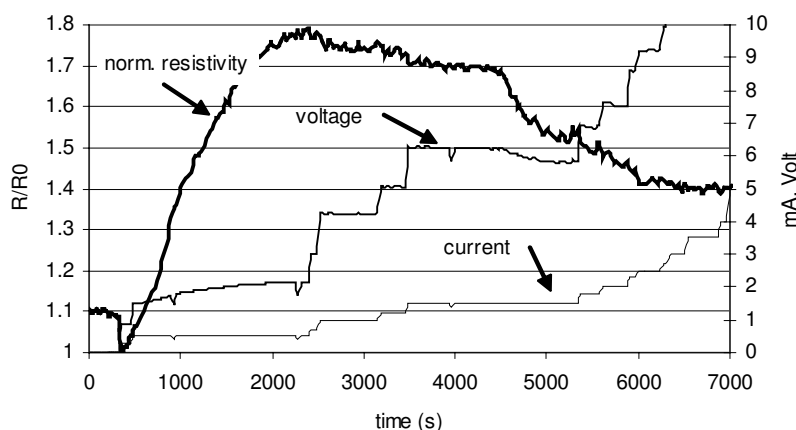


Figure 7. Normalized resistance of a Pd deposition on Alumina substrate in LiOD electrolysis.

F is a factor accounting for the cell geometry, δ the cathode thickness and d its width, ρ_c and ρ_{el} the electrical resistivity of the cathode and the cell.

This potential acts as a source of the additional current flux which is not uniform across the sample but depends on the distance of the point where the voltage V_{ac} is applied. The result is an inhomogeneous loading along the sample.

6. PD–H(D) System and Low-energy Nuclear Reactions

The above analysis of PdH(D) systems pictures a quite peculiar system looking like a *solid plasma*. This may answer the thoughtful question about the reality of Low-Energy Nuclear Reactions (LENR) in condensed matter. Such a question is usually asked in the context of Quantum Mechanics which shows that “Cold Fusion” should not be possible: nuclear physics of deuterons in the lattice (with a space–time scale six orders of magnitude smaller than the space–time scales of the lattice) *should not differ* from nuclear physics in vacuum. However since 1989 several scientists posed the problem in the framework of Quantum Electro Dynamics (QED). Preparata et al. [21] observed that the ground state in condensed matter involves the atoms/molecules of a macroscopic piece of matter in an intricate dynamical interplay mediated by large amplitude (classical) e.m. fields. This intuition was substantially shared by Julian Swinger [22], one of the fathers of QED: deuterons inside the Pd lattice can be described as a plasma in condensed matter having a strong electromagnetic coupling with the lattice. In such a picture LENR appear as a natural development of the very first concept of nuclear fusion.

The very first nuclear fusion reaction used 100-kV powerful gas discharge developed by Mark Oliphant, heavy water for the Deuterium was produced by Paul Harteck while the analysis of the cloud chamber was done by Lord Rutherford [23]. First attempts to develop the reaction into an energy source were done by Oliphant in 1937 who tried to produce extremely intense deuterium or deuterium–tritium beams from gas discharges, having an energy of about 100 keV, to hit targets containing deuterium or deuterium–tritium. These attempts were radically rejected by Spitzer (1957) who argued that such beam experiments do well result in fusion reactions but it is absolutely impossible to produce more energy by fusion than is put in for the beams. The Spitzer objection was that the ion energy goes mostly into heating of the electrons in the target, never permitting an exothermal fusion reaction. Spitzer’s option led to the

decision that instead of bombarding a cold target, one has to heat the reacting particles as in the sun, up to the plasma state at a temperature of dozens of million degrees so that ions do not lose their energy by collisions with electrons and the desired fusion reactions can take place. Following Spitzer's argument, the handling of the fusion plasma within the magnetic confinement is at a stage at which a test reactor ITER is going to be built by 2015, which may lead, hopefully, to a power station to supply 4 GW fusion energy output by 2040.

Spitzer's argument keeps its full validity as long as the beam-irradiated target remains at ordinary state of matter.

The basic concept of thermonuclear fusion is to produce extremely high temperature plasmas with a suitable density in order to sustain the reaction.

But, what if a solid-state plasma can be naturally available in nature at room temperature!

If we study the dynamics of particles moving as a screened ion gas in condensed matter we must pay attention to the boundary conditions due to the very complex disposition of the atoms and their electronic clouds in the equilibrium positions of the lattice. The dynamics of deuterons in the Pd lattice is similar to the motion of charged particles stored in a radiofrequency electric quadrupole trap subjected to the Mathieu's equations. Pd electrons of the outer bands oscillate around their equilibrium sites producing strong electric fields; due to the peculiar structure of the Pd lattice a radio frequency trap is formed among Pd atoms in (101) and (101) planes. It can be shown [24] that the combined effect of the trap force, electrostatic interaction, non linearity and damping produce, under proper conditions, the increase of the collision probability between quasi-free deuterons. The initial conditions, i.e. the deuterons density, their velocity and their initial coordinates determine the overall percentage of colliding particles. Thus experimental conditions able to affect the dynamics of deuterons in a way that an external electric field or a suitable deuteron flux from side to side can significantly increase the collision rate. This may explain the different experimental approaches to the phenomenon and the variety of experimental results in terms of nature and yield of nuclear products: (a) static approach means that the material has a very high loading ratio, at which a significant part of the lattice fulfills the condition described by Preparata et al. in [21]; (b) dynamical approach based on deuteron or D₂ gas flux through the Pd target.

Physical mechanisms responsible for the observed nuclear event have been proposed [25,26] but their discussion is out of the scope within this paper. From the above description of PdH(D) systems three major considerations result: (a) at high loading ratios a phase transition occurs so that hydrogen (or Deuteron) behave like almost unbound charged particles; the strong coupling of these particles with the electromagnetic field that exists inside the matter makes the familiar picture of nuclear reactions in vacuum unsuited to describe the energy release typical of a localized nuclear event; (b) hydrogen or Deuteron are in a quasi-plasma state and their dynamics inside the lattice is strongly influenced not only by the local structure of the lattice but also by their kinetic conditions. This may explain why so many different experimental approaches have been proposed so far to trigger LENR; (c) the energy resulting from a nuclear event is shared among several components which implies the existence of high energy classic fields which can, in turn, induce secondary nuclear reactions, such as transmutations.

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References

- [1] T. Graham, *Phyl. Trans. Roy. Soc.* **156** (1866) 415.
- [2] Z. Cohn, *Elektrochem.* **35** (1929) 676.
- [3] A.H. Verbruggen, R. Griessen, J.H. Rector, *Phys. Rev Lett.* **52** (1984) 1625.

- [4] H. Peisl, Lattice strains due to hydrogen in metals, in *Hydrogen in Metals I*, Ch. 3, G. Alefeld, J. Volkl (eds.), Springer, Berlin, 1978.
- [5] R. Wisniewski, J. Rostocki, *Phys. Rev. B* **3**(2) (1971) 251.
- [6] G. Bambakidis, R.J. Smith, D.A. Otterson, *Phys. Rev.* **177** (1969) 1044.
- [7] K. Kandasamy, *Int. J. hydrogen Energy* **20** (1995) 455.
- [8] R. Felici, L. Bertalot, A. De Ninno, A. La Barbera, V. Violante, *Rev. Sci. Instrum.* **66** (1995) 3344.
- [9] A. De Ninno, A. la Barbera, V. Violante, *J. Alloys and compounds* **253–254** (1997) 181–184.
- [10] A. De Ninno, V. Violante, A. La Barbera, *Phys. Rev. B* **56**(5) (1997) 2417–2420.
- [11] A. De Ninno, M. Vittori Antisari, C. Giangiordano, *ICCF7 International Conference on Cold Fusion*, Vancouver, 1998, pp. 103–107.
- [12] Di Pascasio F., Gozzi D., Trionfetti C., *J. Appl. Phys.* **97** (2005) 043304.
- [13] A. Tomaszewska, Z.M. St.pie., XIII International Seminar on Physics and Chemistry of Solids IOP Publishing, *J. Phys. Conf. Series* **79** (2007) 012028.
- [14] J. Zhou, Q. Wang, Q. Sun, P. Jena, X.S. Chen, *PNAS* **107** (2010) 2801–2806.
- [15] B. Dandapani, M. Fleischmann, *J. Electroanal. Chem.* **39** (1972) 323.
- [16] A. Herold, J.C. Rat, *Bull. Soc. Chim. Fr.* **1** (1972) 80.
- [17] M. Tamaki, S. Hara, I. Kondoh, K. Yoneda, A. Tsuruno, H. Kobayashi, *Nucl. Instrum. Meth. Phys. Res. A* **377** (1996) 166.
- [18] N. Luo, G.H. Miley, A.G. Lipson, *Appl. Surface Sci.* **219** (2003) 167–173.
- [19] M. Fleischmann, S. Pons, G. Preparata, *Il Nuovo Cimento* **107**(1) (1994) 143–156.
- [20] M. Cola, E. Del Giudice, A. De Ninno, G. Preparata, *ICCF8 International Conference on Cold Fusion*, SIF Conference Proceed. Vol. 70, F. Scaramuzzi (ed.), SIF, Bologna, 2000, pp. 349–356.
- [21] T. Bressani, E. Del Giudice, G. Preparata, *Nuovo Cimento* **101A** (1989) 845.
- [22] J. Schwinger, Nuclear energy in an atomic lattice, In *Proceedings of the First Annual Conference on Cold Fusion*, Salt Lake City – Utah, March 28–31, 1990, pp. 130.
- [23] M.C. Oliphant, P. Harteck, Lord Rutherford, *Nature* **113** (1934) 413.
- [24] V. Violante, A. De Ninno, *Fusion Technol.* **31** (1997) 219–227.
- [25] see “Theory, Mechanism and Modeling” in *Low Energy Nuclear Reaction Sourcebook*, Jan Marwan, Steven B. Krivit (eds.), ACS Symposium Series 998, 2008, pp. 39–122.
- [26] A. Widom, L. Larsen, *Eur. Phys. J. C* (2006) (DOI) 10.1140/epjc/s2006-02479-8.