

# A Possible Mechanism For Cold Fusion

**G. Moagăr-Poladian**

*National Institute for Research and Development in Microtechnology-Bucharest, Str. Erou Iancu Nicolae 126A (32B), Bucharest, ROMANIA; E-mail: gabriel.moagar@imt.ro*

**Abstract.** We describe a mechanism for cold fusion that is able to explain how two hydrogen ions may come close enough so as to fusion as well as many of the different and independent experimental observations made during years of experiments. We present the mechanism, its weak points, the way it explains the respective phenomena and suggest some experiments that may validate further the model described by us.

The initial work of Fleischman and Pons [1] was published more than twenty years ago but the acceptance of the facts by the wide scientific community is still to be obtained. While experiments are beginning to become reproducibile (see [www.lenr-canr.org](http://www.lenr-canr.org)), it remains the problem that there is no clear explanation on how two positive ions may get so close, at room temperature, so as to fusion. We show how such a mechanism may exist and explain this “exotic” phenomenon. We start from two observations: a) from the literature [2] it results that in Pd hydrogen exists in Pd as a positive ion; b) the ions are moving in a periodic electrostatic potential given by the periodic location of the host lattice ions, being a superposition between the electrostatic screened potential made by the positively charged metal ions. This last aspect suggests an analogy with the case of electrons in solids [3]. Starting from this point and having in mind also the theory of the Kronig-Penney potential [4] that predicts formation of energy bands in case of periodic potentials, we may conclude that the hydrogen ions exists in such energy bands in the solid. Each type of isotopes has its own energy band structure. A model based on energy band structure for the hydrogen ions was proposed earlier by [5], but we follow another route as compared to it, route that allows us to explain the main aspects of the mechanism and why cold fusion may take place at room temperature. The energy bands may be separated by forbidden energy gaps or may superimpose, as in the case of metals. We refer from now on only to the energy band structure corresponding to hydrogen ions. Following the usual route in solid state physics, we describe the kinetics of the hydrogen ion by its energy  $E$  and its wavevector  $k$ . There is always a relation  $E = E(k)$  between these two parameters, relation that is called the dispersion relation. We may deduce from it the ion effective mass  $m^*$ :

$$\frac{1}{m^*} = \left( \frac{\partial E^2}{\partial k^2} \right) \quad (1)$$

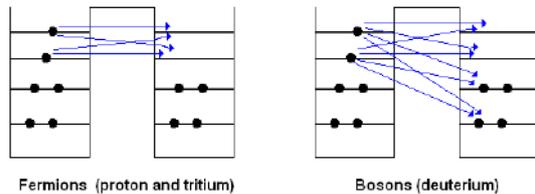
The effective mass (generally, it is a tensor) is applicable especially when considering the particle at one of the energy band edges, namely upper edge or lower edge. At the lower edge the effective mass is positive. At the upper edge the effective mass is negative [3]. An electrically charged particle with negative effective mass behaves in an electric field like a particle of positive effective mass but having an opposite charge [3], which means that a H ion that is excited at the top of an allowed energy band has a negative effective mass and it behaves, in an electric field, as a negative ion with a positive effective mass. This is a very important feature and is the key to our model. A particle may reach the upper part of an energy band only by excitation (thermal or of other nature) and it will stay only a certain interval of time in the respective state because of scattering on different quasi-particles (phonons, lattice ions, impurity ions, etc.). For the sake of simplicity, we consider throughout the work that hydrogen does not form any hydrides or, if it forms, the hydrogen concentration in the material is so high that all the hydride-type bonds are saturated with hydrogen and the remaining hydrogen ions are moving relatively free within the "lattice" formed by the potential wells.

The mechanism we propose is as follows: a hydrogen ion is excited to an upper energy state having negative effective mass. This excited ion will stay a time  $\tau$  in the excited state. During this period, the excited ion may interact electrostatically with another hydrogen ion that has a positive effective mass. The system of two ions behaves similar to two particles of opposite charges attracting each other. They move in a central potential field, similar to electrons in atoms or two electron and hole in an exciton.

Thus, the combination of the Coulomb potential and the negative effective mass is the mechanism that allows the two H ions to approach each other. It is mandatory to mention the fact that the two ions must be in different allowed energy bands (different Brillouin zones [3]) so as they be able to form a closely orbiting system. If we take into account that heavier ions will get closer than lighter ones, the sequence of fusion probability will be given by  $T > D > H$ , where T stands for tritium, D for deuterium and H for proton. For example, deuterium is twice heavier than proton, so that we expect that the orbiting radius for the case of deuterium be approximately half of that corresponding to the proton. In other words, the heavier isotopes are the most probable to fusion by such a mechanism, since the orbiting distance between them will be smaller. Another possibility is that the ions directly collide / coalesce. For the orbiting case, a first temptation is to use the expression of Bohr radius but replacing the electron mass with that of the hydrogen ion. This approach indicates an orbiting radius of few tens of femtometers, small enough so that nuclear fusion takes place with a certain probability. This approach is only generic and useful for showing that, in principle, the two ions may get close enough so as to fusion. The (constant) effective mass formalism is applicable when the interaction potential is of the order of several eV to even few tens of eV. In reality, the overall potential (electrostatic repulsion + lattice) changes as the two ions get close each other. In such a situation, the energy band structure changes as well with the distance between ions and so does also the effective mass. An iterative computation is needed for obtaining a correct estimate of the orbiting distance. Moreover, the host lattice expands as hydrogen is incorporated into it. This means that the band structure (and the effective mass) varies with the content of hydrogen. Such a mathematical computation is complex and, especially, needs a high computational power so as to tackle the problem with sufficient precision. When the two ions get very close to each other, the applicability of the effective mass formalism is not valid anymore. Even if we may still speak about ion mass (positive or negative mass) since the ion is characterized by a certain dynamics inside the periodic crystal, the mathematical use of the respective formalism is questionable. A first approach may be that of considering an effective mass that is energy (and, thus, position) dependent. This approach is based on the observation that the energy band structure is a continuous function everywhere in the lattice, as well as are its first and second derivatives with respect to the coordinates and, respectively, to the wavevector of the ions. It is obvious that the band structure varies dramatically in the region where the two ions interact, but there can still be defined a band structure and a local (energy / position dependent) effective mass. Such an approach may lead to significant computational complexity. Another approach can be that of considering a tight binding model, since the electrostatic interaction at distances useful for fusion process is of the order of tens of keV. Such a starting point model could be that of [6]. However, the aim of this paper is to present the physical mechanism leading to fusion at room temperature and the consequences of it. The elaboration of the mathematical formalism to be used for describing the process is an open matter and does not represent the scope of the paper. However, even with this problem, the model can explain in a unitary manner many experimental results presented in the literature, as will be seen further. This lack of an appropriate mathematical formalism is the weak point of our model. When orbiting, the two ions form a bound system having a discrete energy spectrum, as in the case of excitons in solids [3] and electrons in atoms [4]. Because the interaction energy at such short distances is of the order of tens of keV, we expect that the specific energy spectrum of such a bound system be active in the X-rays region. Emission of X-rays with specific wavelengths was experimentally proven in [7-8]. In [8] the authors claim that the emitted X-ray wavelengths are not specific to any characteristic X-ray spectrum of the known elements. We consider that the X-rays are emitted by the bound system formed by the two orbiting ions, during system de-excitation to a lower energy state, analogue with the case of electrons in excited atoms. Because of the specific, discrete energy levels of the bound system, the emitted X-ray spectrum has wavelengths that are specific for the difference in energy between the levels involved in the de-excitation transition, wavelengths that are not encountered in any of the characteristic X-ray spectra of the known elements. An interesting consequence of our model is that illuminating a hydrogen loaded sample with X-rays having wavelengths identical to these experimentally determined ones (that have a specific emission spectrum during reaction) will reduce the reaction rate. This is so because resonant excitation of the bound system will increase the orbiting radius, similar to electrons in atoms (resonant illumination of an atom excites the electron on a state that is further from the nucleus than is the fundamental state). This is a theoretical prediction that, to our knowledge, was not yet reported experimentally. Its experimental verification will check the validity of our model. Let us now consider the ways in which an ion may be excited to the upper energy state of negative effective mass. One way is by excitation at thermal equilibrium, when collisions with different quasi-particles existing in the lattice may give the ion enough energy to reach the top of the energy band. The higher the temperature is the greater is the number of ions with negative effective mass. Another way is to use external factors such as illumination with photons or bombardment

with energetic particles (electrons, ions) [9]. Since we have an energy band structure, only photons with appropriate wavelengths may excite the ions to the energy states of negative effective mass. Such a resonant / selective excitation is observed in [10]. In this case, the energy of excitation may vary from several meV up to several eV. Such a situation is encountered in [10-11]. We mention that in [11] the energy difference between the two incident light beams is claimed to have effect in enhancing the fusion process. It seems that the two beams excite a phonon in the metal, in the THz frequency range, this quasi-particle being responsible for the enhancement. Such a phonon may interact with a hydrogen ion and excites it resonantly at the top of the energy band. We assert that the Born-Oppenheimer approximation [3] is applicable to the hydrogen ion also. We make this assertion because we expect that the mass of the hydrogen ion in the lattice do not differ significantly with respect to hydrogen mass in vacuum. This assumption is based on the analogy with electrons in crystals. Hydrogen has a relatively high mobility in heavy metals that have an atomic mass of at least tens of hydrogen atomic mass. For example, Pd has an atomic mass that is 106 times greater than hydrogen mass [www.webelements.com]. On the other hand, hydrogen diffusion in metals is a slow process, the hydrogen ions being all the time in thermal equilibrium with the lattice / metal ions. Because of these two reasons, hydrogen ions are approximately ten times faster than the lattice ions, so that Born-Oppenheimer approximation may be applied without introducing great errors, of only few percent. As numerical values, we mention that an error of less than 10 % for proton in Pd and of approximately 16 % for tritium in Pd is obtained. These are acceptable errors. The Born-Oppenheimer approximation indicates to us that we may look at the "lattice" formed by the potential wells (for the hydrogen ions) as being frozen, hydrogen ions moving within this lattice. Because such a potential well is formed by the contribution of several atoms that oscillate in an uncorrelated manner, the potential well is also squeezed at the same frequencies as those of atom oscillations. Since the displacements of atoms, at room temperature, are small compared to the interatomic distance within the metal lattice, we may consider that the deformation / squeezing of the potential wells is small compared to the well size.

A very important aspect is that two hydrogen isotopes are fermions (proton and tritium) while deuterium is a boson. This is a very important feature. Consider two adjacent potential wells, one having a higher



number of hydrogen ions than the other, as depicted in figure 1. In the left part, we have the case of fermions. In the right part, we have the case of bosons. We simplify and consider discrete energy levels, but the explanation may be extended in a straightforward manner to band structure also.

Figure 1 – Sketch of the way in which fermions, respectively bosons, diffuse.

Let consider fermions first. The fermions from the left quantum well may diffuse / tunnel only on the unoccupied states in the right quantum well because of the Pauli exclusion principle. This means a low number of available states for transfer, as seen from figure 1. In the case of bosons, there is no exclusion principle and they may diffuse / tunnel on any of the states existing in the right-side quantum well since several bosons may share the same energy state. This means a higher probability of transfer from one well to the other than in the case of fermions because of the greater number of available states able to receive an ion. The same arguments are applicable also to the boson ions lying on the lower energy states of the left quantum well from figure 1. Because of that all the bosons participate in the diffusion process and not only those from upper energy levels. Thus, the energy band model may explain why deuterium diffuses easier in metals than the other hydrogen isotopes. Because of the same reason, the boson character makes Pd able to load a very high concentration of deuterium as compared to the case of proton. The normal sequence for the diffusion coefficients would be  $H > D > T$ , since the heavier a particle is the lower is its diffusion coefficient. But taking into account the fermion / boson character of each ion and the above arguments, the correct sequence for the diffusion coefficients is  $D > H > T$ , as is observed experimentally. Taking into account that the orbiting distance is smaller for heavier isotopes, it results that the most favorable isotope for observing cold fusion is deuterium. This is due to its higher mass (that allow him a smaller orbiting radius than in the case of proton) and to its bosonic character that allow him to diffuse faster and be incorporated in a greater amount than the other isotopes. As regards the true potential in which the ions move, let's consider a direction in the crystal that is along the great diagonal of the lattice cube of Pd. This great diagonal passes through the center of the cube and also through two of the host lattice nuclei. Taking into account that hydrogen interacts electromagnetically with the screened

electrostatic potential of the lattice ions but has also the ability to present strong interaction, it results that the hydrogen ion sees a potential formed by two kinds of quantum wells: electromagnetic and nuclear, as depicted in figure 2. The nuclear quantum well corresponds to the lattice ion. From the quantum mechanics point of view, there is no formal difference between an electromagnetic potential well and a nuclear potential well. Thus, we may consider that for the hydrogen ions there is a coupling between lattice energy levels and host nuclei levels. This is so because solving the Schrödinger equation for this system of quantum wells will result in energy levels / bands that are common to both types of wells, electromagnetic and nuclear. This phenomenon is specific only to the host lattice in its solid state. This fact suggests the possibility that nuclear reactions in solid state occur in a slightly different manner than in the liquid or gaseous state of the host lattice, cold fusion being only a particular case of that. The situation depicted in figure 5 is idealized, in the sense that we have drawn rectangular walls for the potential wells.

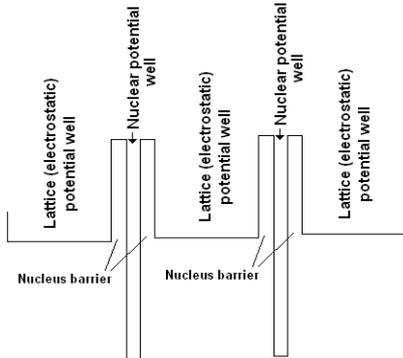


Figure 2 – The true quantum potential for the hydrogen ion in solids.

Let's now consider the behaviour of the system when cold fusion takes place. Suppose that in a certain place in the host metal a fusion process is initiated by using some means. The occurring of the nuclear fusion in that region of the metal produces heat, heat that locally increases the host temperature. Because of the increase in temperature, there will be an increased number of ions excited to higher energy states that are characterized by a

negative effective mass. Thus, the number of ions with negative effective mass is increased. This increase in their number has as a result the increase in fusion processes that, at their turn, increase further the local temperature. In this way, a positive feedback appears, in the sense that, once initiated, the fusion process may go further without the need of any external action and can even be self-sustained as described in [12]. Self-sustainability appears in the case when the system generates more energy than it dissipates. There is also a negative feedback, given by several mechanisms such as: a) the lifetime  $\tau$  in the excited state decreases with increasing temperature because of the increased scattering on lattice specific quasi-particles, thus decreasing the available time for the two ions to approach each other enough for fusing; b) consumption of reactant particles (at that specific site in the lattice) as a consequence of the fusion process, process that is faster than the supply made by diffusion from outside; c) the deterioration, and even melting, of the host lattice as a result of the collisions of the energetic ions resulted from fusion, deterioration that mitigates the local energy band structure and thus mitigates the mechanism for hydrogen ions approaching; d) hydrogen out-diffusion from the regions where fusion takes place, this process being due to the fact that an increase in local temperature produces an increased diffusion of hydrogen ions from the warmer region to the colder ones, this out-diffusion being able to reduce or even reverse the flux of ions coming from regions with a higher ion concentration; e) heat dissipation rate to the exterior, dissipation that allows the crystal to not overheat excessively (as in the case when is mounted in vacuum) and thus to limit the positive feedback loop. This process of dissipation depends on the metal (through density, specific heat and thermal conductivity) and on the cooling boundary conditions. If non-equilibrium (illumination or particle bombardment) excitation of hydrogen ions is made, a good dissipation of the generated heat to the exterior can make the difference between a successful experiment and an experiment having a more violent, explosive character. These negative feedback mechanisms may dominate at higher reactions rates because of the reasons told above. Thus, we may expect a reaction rate that depends on temperature in a non-linear fashion, having a maximum value at a certain temperature, as described in [13]. This happens because below that temperature, the dominant role is taken by the positive feedback, which tends to increase the temperature. Above the temperature corresponding to the maximum of the reaction rate, the negative feedback becomes dominant, which tends to reduce the reaction rate. Thus, an oscillatory behaviour may be expected for the reaction rate. There is necessary a threshold value of the hydrogen concentration because under this value: a) the fusion processes are rare; b) thermal conduction of the metal carries out the heat sufficiently fast so as the positive feedback be insignificant and no experimental observation of the heating be made; c) let "d" be the mean free path of a negative mass ion during its stay in the excited state. If this mean free path is less than the average distance between ions (equal to  $N_0^{-1/3}$  where  $N_0$  is the total ion concentration), then the probability that the excited ion encounter another ion is reduced. As a consequence the reaction rate is reduced correspondingly.

Increasing concentration lowers the average distance between ions and the encounter probability becomes higher, the same happening for the reaction rate. Let denote by “ $f$ ” the fraction of ions having a negative effective mass and  $N_0$  be as above. “ $f$ ” depends on temperature and is equal to 0.5 when temperature tends to infinity. It may be computed from the Fermi-Dirac or Bose-Einstein distribution function (depending on the type of isotope) and the density of states specific to the respective ions. The concentration of ions with negative effective mass is thus equal to  $f \cdot N_0$  while the concentration of ions with positive effective mass is equal to  $(1-f) \cdot N_0$ . The fusion reaction rate is equal to the product of these two concentrations (there is also the reaction cross-section that multiplies these two concentrations), being equal to  $f \cdot (1-f) \cdot N_0^2$ . Thus, from our model, it results that the fusion reaction rate is proportional to the square of the hydrogen ions concentration, as is observed experimentally. There is enough experimental evidence that shows that heat emission takes place only after a certain concentration of hydrogen is obtained in the Pd lattice. This can be explained by two main aspects. First, the observation of rise in temperature produced by the nuclear reaction depends on the sensitivity and speed of the devices used for measuring temperature (thermometer, infrared camera) and by the thermal noise of the Pd+calorimeter system. A very sensitive apparatus and a Pd/calorimeter system with very low noise will show a lower threshold concentration. The generated heat flux must be at least comparable to the heat loss flux in order to produce an observable effect (else, the signal is small and extinguishes fast with time). A system with a lower heat dissipation rate will show a lower threshold concentration. Secondly, it must be taken into account the explanation given above when comparing the average distance between hydrogen ions with the mean free path of the negative mass ion. A higher concentration increases the probability of encounter and thus the reaction rate. As regards the generated heat, there is an infrared emission of the metal surface, the spot corresponding to the highest temperature having a position that varies randomly onto the surface [14]. As we have mentioned earlier, a necessary condition for reaction is the thermal excitation of the hydrogen ions on energy states with a negative effective mass. This is a random process. A greater thermal fluctuation at a point may produce a greater reaction rate, with heat emission. The temperature increases at that point and positive feedback is triggered (above a threshold determined by the heat loss rate). This positive feedback consumes some part of the hydrogen at that point, so the spot extinguishes in time. Then, another fluctuation appears at other place, in a random manner (the temperature and concentration fluctuations are random processes) and the process is repeated. A consequence of this explanation is that the bright spot never appears twice at the same place (or at least appears after a long enough time so as the ions concentration be recovered at that place), since the hydrogen ions in that place are consumed during the first spot. We don't have yet data or experimental results to prove this last assertion, it results from the model proposed by us. The excitation of hydrogen ions to upper energy states with a negative effective mass is taking place all the time. Thus, even if the loading process is finished since a certain time interval, these excitations take place and may generate heat by the mechanism proposed by us. This fact explains why is observed the so-called “heat after death” [12], since the excitation processes are independent on the loading means and are occurring all the time during loading and after that. This has as one of the consequences the fact that emission of X-rays with specific wavelengths should be observed even after the external excitation of the Pd loaded sample is switched off, since the start of orbiting of the two hydrogen ions is not necessary to be made directly on the fundamental state of the ions bound system. This may offer an explanation for the experimental data obtained in [15]. These are some of the experimental results that can be explained by our model. Our model does not contradict that one based on the screening effect made by the free electrons of the metal, since screening proves a support for the ions to get closer. As regards the plasma wave model proposed by [16], the plasma wave may be considered as exciting the ions to upper energy states where they acquire a negative effective mass. However, the [16] model cannot explain why X-ray radiation with specific wavelengths is emitted during reaction and why the effect observed by Letts and Cravens is taking place. A similar effect as in [9-10] must be observed by using THz / mm / sub-mm radiation, with a frequency similar to or close to that mentioned in [10]. This is so because of the resonant excitation (direct or phonon mediated) of ions to energy states with a negative effective mass. However, the use of THz / mm / sub-mm radiation should be more favorable to observe enhancement effects than the use of visible or near-infrared lasers, because the skin penetration depth of the THz / mm / sub-mm radiation is larger than the skin depth corresponding to visible or near-infrared light. This feature makes that a greater number of hydrogen ions be excited with THz / mm / sub-mm radiation than with optical light, fact that will increase the amount of generated heat. This assertion is also a theoretical prediction and should be checked experimentally. Another experiment that should be done is that of cyclotronic resonance in deuterium loaded Pd (both at low and at high hydrogen concentration), so as to measure the effective mass of hydrogen in the metal lattice. This measurement should give an experimental indication when

trying to compute the concrete band structure for the hydrogen ions. In conclusion, some experiments that are based on our prediction may be done so as to check our model: a) illuminating a hydrogen loaded sample with X-rays having wavelengths identical to the specific ones emitted during reaction to see if the reaction rate will be reduced; b) illuminating with THz / mm / sub-mm radiation to see if an enhancement effect greater than that reported by Letts and Cravens is obtained; c) X-ray reflection spectra of hydrogen loaded samples, to check if “unusual” absorption lines appear. Caution should be made when exciting the Pd+deuterium system by non-equilibrium means (photons, particle bombardment), since this may end with very energetic, explosive processes, as could be the case reported in [17].

## References

- [1] M. Fleischman, S. Pons, M. Hawkins – J. Electroanal. Chem., vol. 261, p. 301 (1989), errata vol. 263.
- [2] A.H. Verbruggen, R. Griessen, J.H. Rector – Phys. Rev. Lett. vol. 52, no. 18, p. 1625 (1984).
- [3] A. S. Davidov – *Teoria Tverdogo Tela (Theory of Solid State)*, Nauka, Moscow (1976).
- [4] B. H. Bransden, C. J. Joachain – *Introduction to Quantum Mechanics*, Longman Gr. UK Ltd (1994).
- [5] T. A. Chubb, S. R. Chubb – “*The Ion Band State Theory*”, in 5<sup>th</sup> ICCF, (1995).
- [6] J. Hermanson, J. C. Phillips – “*Pseudopotential Theory of Exciton and Impurity States*”, Phys. Rev. vol. 150 no.2, p. 652, (1966); J. Hermanson – “*Exciton and Impurity States in rare-Gas Solids*”, Phys. Rev. vol. 150 no.2, p. 660, (1966); J. Hermanson – “*Kinematic Resonances in Crystalline Xenon*”, Phys. Rev. vol. 166, no. 3, p. 893, (1968).
- [7] A. B. Karabut, S. A. Kolomeychenko – “Exp. Res. into Charact. of X-ray Emiss. from Solid-State Cathode Medium of High Curr. Glow Disch.”, Proc. of 10<sup>th</sup> ICCF, World Scientific, (2003).
- [8] D. Wang, X. Zhang – High Power Laser and Particle Beams vol. 17, no. 9, p. 1335 – 1340, (2005).
- [9] A. B. Karabut – “*Exp. Res. & Dev.. of Heat Power Supp. Prot. Based on High-Energy Processes in Solid Medium Interacting with Hydrogen Ions Flux*”, Sci. Res. Proj., (2006). <http://www.lenr-canr.org> .
- [10] D. Letts, D. Cravens – “*Laser Stim. of Deut. Pd: Past&Present*”, Proc. 10<sup>th</sup> ICCF, World Scientific (2003).
- [11] D. G. Letts, D. Cravens, P. L. Hagelstein – “*Progress on Dual Laser Exp.*”, Proc. of 15<sup>th</sup> ICCF.
- [12] S. Pons, M. Fleischman – Transaction on Fusion Technology, vol. 26, p. 87 (1994).
- [13] L.C. Case – Proc. 7<sup>th</sup> ICCF, p. 48 (1998).
- [14] S. Szpak, P.A. Mosier-Boss – Tech. rep. 1862, Navy Laboratories, p.7 (February 2002).
- [15] A. B. Karabut, E. A. Karabut – “*X-ray Spectra of Excited Long Living 0.6-6.0 keV Energy Levels from the Solid State Cathodes of Electric Disch. Syst.*”, Proc. of the 15<sup>th</sup> ICCF.
- [16] I. P. Chernov et al. – “*Plasmon Based Mech. on Nucl. React. in Metal Deuterides*”, Proc. 15<sup>th</sup> ICCF.
- [17] X. Zhang, W.-S. Zhang – “On the Explosion in a Deuterium/Palladium Electrolyte System”, Proc. of the 3<sup>rd</sup> ICCF, Universal Academic Press Tokyo, (1992).