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Research Article

# Peculiarities of Physics and Chemistry in the Transition Metal Hydrides

Hideo Kozima

*Cold Fusion Research Laboratory, Yatsu, Aoi, Shizuoka, 421-1202 Japan*

**Abstract**

Since the discovery of nuclear reactions in $PdD_x$ alloys in 1989, very many experimental data sets have accumulated showing the existence of nuclear reactions in materials composed of lattice nuclei of transition metals and occluded hydrogen isotopes (let us call them the *CF materials*, for short) resulting in various nuclear products such as transmuted nuclei, tritium, neutrons, and others accompanied by large excess energy at relatively low temperatures up to 1000 C. (Let us call these events as a whole, the *cold fusion phenomenon* (*CFP*) for short). The cause of these nuclear reactions in the CFP is likely to be the existence of the interactions between nucleons in the CF material through the nuclear force, i.e., the *weak interaction* (let us call this interaction the *nuclear-force interaction*), a recognized part in the nuclear physics. It should be emphasized that our phenomenological approach based on the nuclear-force interaction between lattice nuclei and occluded hydrogen isotopes has been successful in giving qualitative and sometimes semi-quantitative explanations for the events in the CFP. In this paper, we consider the effect of the nuclear-force interaction revealed in the CFP on physics and chemistry in transition metal hydrides where phenomena such as super-diffusivity, HER (hydrogen electrode deposition), and UPD (underpotential deposition) have long been observed without satisfactory explanation consistent with other characteristics of the materials. It is shown that the fundamental mechanism giving a consistent explanation of CFP seems to be also an essential factor giving rise to the peculiar characteristics observed in transition-metal hydrides even if the necessary condition for CFP is not satisfied.


*Keywords:*

## 1. Introduction

In the middle of the $20^{\text{th}}$ century, we entered into a new scientific era where it was shown by the science of complexity that the principle of causality does not generally apply in nature where constituent parts of which interact nonlinearly. From the beginning of culture in Greece about 2500 years ago up to present time, geniuses who investigated the world as a whole intuitionally recognized this fact and avoided constructing a closed system of explanations of the world. The most eminent people of them are Plato in Greece and Friedrich W. Nietzsche, Sigmund Freud and Max Weber in $19^{\text{th}}$

E-mail: hjrfq930@ybb.ne.jp, hjrf930@gmail.com, CFRL website: http://www.kozima-cfrl.com/

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century. A system of explanation for the world once contemplated and successful in explaining phenomena consistently is convenient to use to manipulate the present task. It is, however, necessary to recognize the limitations imposed on the model system of explanation extracted from enormous facts abandoning many elements for simplification in the process of forming the system.

The most successful model of such systems in physics is the Newtonian mechanics established at the end of the $17^{\text{th}}$ century. This system is so successfully explained celestial mechanics and the ballistic motion of bullets that it concealed its fundamental limitations. It had an enormous effect on the modern culture until the end of the $19^{\text{th}}$ century. It had been esteemed as a symbol or an ideal of the science established by human beings. Many imitations of this model have been proposed in various fields of sciences including the social sciences and humanities. Its influence lasted very long, and it remains very strong even now.

The science of complexity has had an immense impact on the sciences that remained unexplored due to the difficulty of treating them with mathematics such as biology, sociology and ecology. In physics, such problems as found in irreversible thermodynamics and turbulence contributed to the development of the science of complexity. However, there remain many fields such as elementary particle physics and solid state-nuclear sciences including nonlinear many-body interactions without recognition of fundamental importance of complexity.

One such field related to complexity is the cold fusion phenomenon announced by Fleischmann et al. in 1989 [1] as we have discussed already [2]–[10] giving an insight into a possible consistent explanation of the whole phenomena observed in cold fusion materials composed of transition metals and hydrogen isotopes, as briefly introduced in the next section. Brief explanations of the fundamental common questions related to nuclear transmutation are discussed in the Appendix.

The mechanism assumed in the successful explanation of cold fusion phenomenon, the nuclear interaction of the lattice nuclei and the occluded hydrogen isotopes (protons or deuterons), in the transition-metal hydrides ($PdD_x$, $NiH_x$, $TiD_x$, etc.) is not restricted only to the cold fusion materials where such super-lattices as PdD, NiH and TiD are formed by the self-organization, a specific mechanism of complexity in the non-equilibrium open systems.

There are several fields of physics and chemistry where the materials are composed of transition metals and hydrogen isotopes and where peculiar phenomena have been observed without satisfactory explanations. Several of them are listed as follows: (1) The Cold Fusion Phenomenon, (2) The Super-diffusivity of Hydrogen in Transition Metals and Alloys, (3) The Hydrogen Electrode Reaction (HER) in Electrochemistry, and (4) The Underpotential Deposition (UPD) in Electrolysis.

We discuss these problems in this paper from our point of view based on the nuclear interaction between the lattice nuclei and the occluded hydrogen isotopes.

## 2. The Cold Fusion Phenomenon

The cold fusion phenomenon (CFP) announced in 1989 had shown the existence of nuclear reactions in CF materials composed of specific lattice nuclei and occluded hydrogen isotopes. Nuclear reactions, as we recognize in nuclear physics, are induced only by the nuclear force (or the weak interaction) between elementary particles which becomes effective at distances less than about 1 fm (or $10^{-15}$ m). Many mechanisms have been proposed that will produce a nuclear reaction between elementary particles included in the CF materials where CFP has been observed. We give a brief explanation of the CFP in the following sections based on our phenomenological approach which has given a unified explanation of the many events observed in the CFP [2]–[10].

Even if the existence of the nuclear-force interaction (or the weak interaction) in solids at low temperatures around room temperature had been shown by neutron diffraction by lattice nuclei in 1930's, the cold fusion phenomenon in CF materials (materials composed of transition metals/alloys and occluded hydrogen isotopes) discovered in 1989 have shown the possibility of nuclear reactions due of course to the nuclear-force interaction between or among elementary particles in the system.

However, it has not yet been determined what kind of nuclear-force interaction is effective, and how it works to realize the nuclear reaction. There are very many experimental data sets showing nuclear reactions in CF materials compiled in several books [2], [3], [11] and papers published in *Proceedings* of ICCF's and JCF's and many journals (e.g., [7], [9], [12]).

A model where the assumed existence of quasi-free *trapped neutrons* (TNCF model) was proposed to explain the various experimental data of the cold fusion phenomenon (CFP) observed in CF materials with diverse components [13]. The experimental data includes generation of new elements (including tritium and helium), emission of neutrons with energies up to 10 MeV and generation of excess energy accompanied with these nuclear products. Successful theoretical trials to give a unified explanation of the various experimental data using the model were compiled in a book published in 1998 [1].

The premises assumed in the TNCF model had been investigated quantum mechanically using a possible interaction of lattice nuclei (M) and interstitial protons/deuterons (H/D) in the *ordered superlattice* ($M_1H_1/M_1D_1$) of the CF material through the *nuclear force* [14], [15]. The nuclear-force interaction between a neutron in a nucleus at a lattice point (a lattice nucleus) and interstitial proton/deuteron results in the *super-nuclear interaction* between neutrons in different lattice nuclei mediated by interstitial protons/deuterons [3].

The neutrons in lattice nuclei combined by the super-nuclear interaction result in the *neutron energy bands* (neutron bands) and the neutron in the neutron band works as the trapped neutron assumed in the TNCF model inducing *nuclear reactions* between a trapped neutron and nuclei at disordered sites [3], [14].

The ordered superlattice ($M_1H_1/M_1D_1$) is produced by self-organization in the complexity when the CF material is an open, nonequilibrium and multi-component system with non-linear interaction between components [16]. This is a fundamental cause of the qualitative reproducibility of the CFP sometimes causes serious discussions related to the reality of the CFP.

It is enough to give a brief explanation of the successful result of the phenomenological approach to the CFP obtained in the past roughly 30 years to show the reality of the nuclear reactions in the CF materials composed of hydrogen isotopes with transition metals and alloys, carbons (graphite) and in biological systems [15].

### 2.1. **Characteristics of the CFP**

There are several characteristics of nuclear reactions in the CFP experimentally found and explained qualitatively [2] at least and sometimes quasi-quantitatively [17] by the phenomenological approach.

The most important characteristics found in the CFP are the qualitative reproducibility of experimental data. The quantum mechanical justification of the qualitative reproducibility of events in the CFP was finally given by using the idea of self-organization of the superlattice composed of host elements and hydrogen isotopes in the CF materials, the open, nonequilibrium, multi-component system [16].

One form of evidence of the effectiveness of a theory is the prediction of mutual relations between observables confirmed by comparison with the experimental relations.

The ratio $N_A/N_B$ of the number $N_A$ of an observable A and another $N_B$ of B have been calculated using the TNCF model with an adjustable parameter $n_n$ (supposed to be the density of the trapped neutrons). The theoretical values $N_A/N_B|_{th}$ are compared with the experimental values $N_A/N_B|_{ex}$ determined by experimental data giving a good coincidence in the factor 2 – 4 ([3] Sec. 3.3.1). This result shows the effectiveness of the TNCF model based on the assumed existence of the trapped neutrons in the CF materials which gives support to the neutron bands mechanism based on the super-nuclear interaction ([3] Sec. 3.7).

Looking at the experimental data sets from the phenomenological point of view, we can find out the *regularity* in the observed quantities or the *empirical law* between observed quantities. We formulated *three laws* between the observables in the CFP [3], [18]: (1) **First Law**, the stability effect for nuclear transmutation products and two corollaries, (2) **Second Law**, the inverse power dependence of frequency on intensity of the excess heat production, and (3) **Third Law,** the bifurcation of intensity of events (neutron emission and excess heat production) in time ([17] p. 101). The second law is qualitatively explained by the formation mechanism of the super-lattice for the CFP which works with self-organization in complexity [16]. The third law is qualitatively explained by the bifurcation of events in the nonlinear dynamics [16].

As shown in this section, the phenomenological approach using the TNCF model ([2], [3], [7], [9]) has given a unified explanation of the experimental data obtained in the CFP. Even if we do not satisfy completely with our explanation of experimental results using many premises and assumptions not necessarily proved their validities, it is possible there is something true behind the TNCF model and it is useful to apply the same approach to other phenomena such as the super-diffusivity, HER, UPD and the exotic nuclei in the nuclear-solid material occurring in similar situations to the CF material. Especially with regard to nuclear transmutations in biological systems the investigation of which is at the primitive stage at present despite the long history of its observation [9].

In the following Sections, we give a sketch of these phenomena pointing out unsolved features in them suggesting their possible relation to the nuclear-force interaction. Direct citations of sentences from papers by the researchers in these fields will give vivid images of the difficulty they experienced trying to explain these riddles without the nuclear-force interaction. We first noticed the existence of this interaction in CFP.

## 3. The Super-diffusivity of Hydrogen in Transition Metals and Alloys

Since Graham's discovery of the absorption of hydrogen by palladium metal and palladium-silver alloys in 1866 [19], the physics of the transition metal hydrides has shown great development showing various characteristics especially the extremely high diffusivity of hydrogen in metals (let us call this phenomenon *super-diffusivity*, for short). There are many unsolved questions in this field as pointed out in review papers in this field [20], [21] which seemingly have a close relation to the *nuclear-force interaction* between the occluded hydrogen/deuterons and lattice nuclei.

The most wonderful event in the physics of the transition metal hydrides might be the inverse isotope effect of diffusivity of hydrogen isotopes, which was noted long ago [22], and that of the transition-temperature of superconductivity in $PdH_n$ an $PdD_n$ observed also when the superconductivity was discovered in them [23].

The problem of localization and non-localization of H/D in *bcc* and *fcc* transition metals has been investigated in the physics of the transition-metal hydrides for long in this field. One of the interesting results is the formation of H-sublattice as shown by Schlapbach [21].

In the investigation by Schlapbach [24], he tentatively noticed the appearance of the H-sublattice which we assume forms in the superlattice by self-organization in complexity [13].

"Most host metal lattices expand upon the absorption of hydrogen; the crystal structure changes mostly with a reduction of symmetry, a H-sublattice is formed, order-disorder transitions of the H-sublattice occur, lattice defects are formed, strain fields grow, and even non-crystalline and probably quasi-crystalline materials can be formed." ([24] p. 411).

## 4. The Hydrogen Electrode Reaction (HER) in Electrochemistry

The hydrogen electrode reaction (HER) observed in electrochemistry has attracted strong interest from many chemists without decisive explanation for its mechanism [25]–[30] .

The HER (hydrogen electrode reaction) observed in the electrochemistry has shown a periodic variation of a quantity log $i_0$ (an indicator of the intensity of the electrode for the HER) with the atomic number $Z$ as shown in

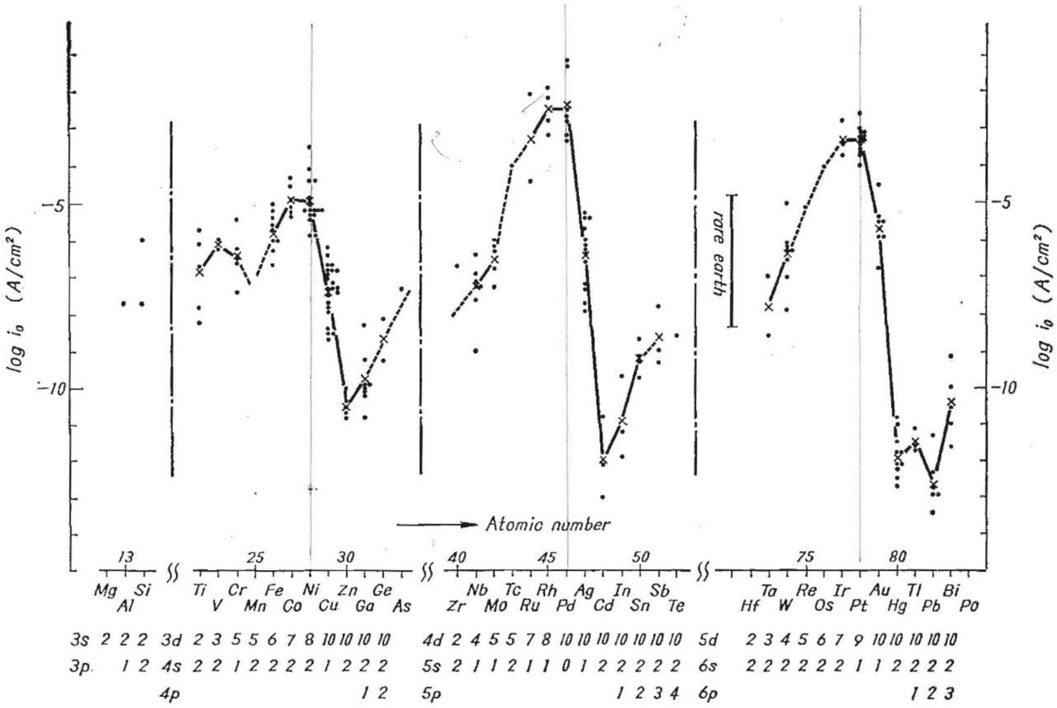


**Figure 1.** Observed log $i_0$ vs. $Z$ on various metals in acidic solutions. The full and dotted lines indicate the periodic variation of log $i_0$ with the atomic number Z. ([29] p. 203, Fig. 1).

Fig. 1. Many researchers who investigated the HER have noticed the correspondence of this periodic variation to the similar variation of the work function of the electrode or to the number of $d$-electrons of the electrode metal atom. They did not, however, take care of the *nuclear-force interaction* between the proton and the nuclei in the cathode materials (transition metals) which is more important than the number of electrons in $d$-shells as seen in the data shown in Fig. 1 from our point of view.

Ion transport in the biological membrane [31] should be mentioned. We have long investigated this physical process in biological systems, a form of CFP ([2] Sec. 10.1, [5] Sec. 3.7).

## 5. Underpotential Deposition (UPD) – A Characteristic of Transition Metals

The underpotential deposition is an important problem noticed but not resolved in electrochemistry (e.g., [32], [33]), which seemingly has a close relation with the HER taken up in the previous section. From our point of view, the *nuclear-force interaction* between the proton and the nuclei in the cathode materials (i.e. transition metals in this case) is a key element not taken up by the researchers in this field until now as shown in the sentences cited below from papers published in this field. The paper by T. Ohmori [34] had shown the relation of the UPD and the HER, but researchers have failed to notice the common factor in both phenomena, which is the nuclear-force interaction mentioned above.

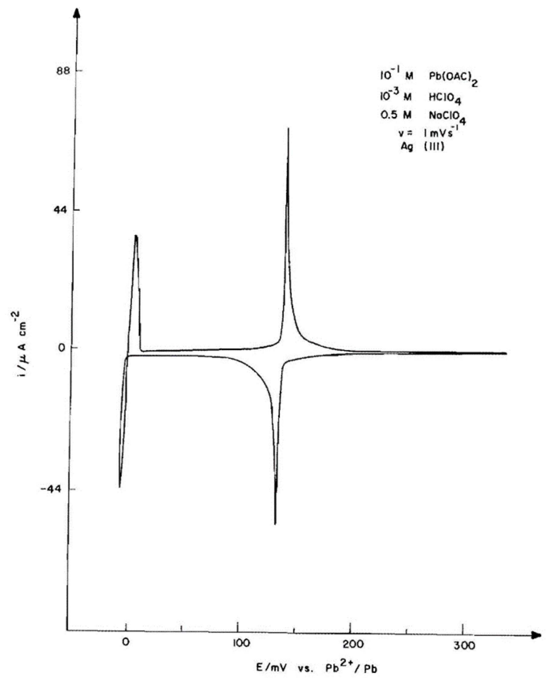


**Figure 2.** Experimentally recorded potential sweep voltammogram for the (111) of a silver single crystal in the solution noted in the figure. (Reprinted from 'A. R. Despic, Deposition and Dissolution of Metals and Alloys. Part B: Mechanisms, Kinetic, Texture, and Morphology,' in *Comprehensive Treatise of Electrochemistry*, Vol. 7, B.E. Conway, J. O'M. Bockris, E. Yeager, S. U. M. Khan, and R. E. White, eds., Plenum, 1983, p. 459."

The underpotential deposition (UPD) on substrate with different component is discussed by J.O'M. Bockris, an expert in this field as follows ([35] pp. 1313 - 1314):

"Deposition from a solution of $M^{Z+}$ upon a substrate of the corresponding metal M (e.g.,$Ag^+$ on Ag) begins at the thermodynamically reversible potential,at least on the surface with the growth site. However,if one attempts to deposit $M^{Z+}$ on M', a substrate differing from M (e.g. $Ag^+$ on Au),some kind of layer formation on the M' surface begins to occur when it is held at a potential many hundreds of millivolts positive to the reversible potential for $M^{Z+}$ onto M.*) The meaning of these statements can be immediately understood by considering Fig. 2.140.

*) This is equivalent to the statement that the deposition started to take place 'too soon,' i.e., from a thermodynamic viewpoint,'before it was expected to occur.'

They had given qualitative explanation of the UPD with different substrates based on the difference of the work functions of substrates on which the depositions occur [35].

As in the case of HER discussed in the preceding paragraph, it will be advisable to take into account the *nuclear-force interaction* between the proton and the nuclei in the substrates to discuss the UPD quantitatively.

The special role of the iron group metals in the UPD has been noticed by Akiyama et al. [36], [37] and Nakano et al. [38] in this field. We cite a sentence showing the authors are puzzled seeing the peculiar role of iron-group metals on the underpotential deposition without any reasonable explanation:

"Zn underpotential deposition with iron-group metals was studied using a Cu substrate in sulfate or chloride baths containing a small amount of $Zn^{2+}$ ions at 5 to 80 °C under potentiostatic conditions. Underpotential deposition occurs only in the presence of iron-group metals and is facilitated when conditions permit decreased inherent deposition overpotential of iron-group metals such as high temperature and $Cl^-$ additive. This is similar to the induced alloy deposition, in which the properties of iron-group metals in a metallic state play an important role. This is clearly different, however, from induced because Zn deposition occurs at more noble potentials than its equilibrium. Iron-group metal properties in a metallic state appear responsible for Zn underpotential deposition, although the detailed mechanism is yet unclear. If the co-depositing iron-group metal consistently reduces the activity coefficient of Zn deposited on the progressively formed cathode surface, the large amount of underpotential deposition is explainable thermodynamically." ([38] p. 1209, Abstract).

The experiments performed by Ohmori [33] showed the decisive effect of the UPD on the HER as shown by the sentences cited below. This strong relation of the UPD and the HER gives a clue to analyze the characteristics of the CFP (cold fusion phenomenon) depending on the favorable combinations of the *cathode metal-electrolyte-solvent* relation noticed for a long time (e.g., [39], [40] p. 45).

"This fact suggests that there are a few sites at the electrode surface having very strong connection with alkaline metal atoms deposited by the UPD and they also work as active sites for the HER, simultaneously." (Translated into English by H.K.) [34]

"This fact suggests that the alkaline metal atoms deposited by the UPD are the intermediate product of the reactions on the cathode surface and determines the velocity of the HER in the alkaline solution with comparatively high concentration of the solute where are no active sites appeared." (Translated into English by H.K.) [34].

## 6. Conclusion

Wonderful events explicable only by the *nuclear-force interaction* (or the *weak interaction*) between lattice nuclei and interstitial protons/deuterons have been discovered. These were not noticed until the discovery of the cold fusion phenomenon (CFP).

Furthermore, the characteristics of CFP, especially the lack of quantitative reproducibility, have been explained by the complexity existing in the mechanism for the realization of the necessary and sufficient conditions for CFP [2]–[10].

As discussed above in this paper, there are several fields of physics and chemistry in the transition metal hydrides and deuterides where peculiar phenomena are made possible by the existence of transition metals remaining without explanation by probable mechanisms in these materials. The nuclear-force interaction is assumed to explain CFP exists in this field where the peculiar phenomena have been observed. It is assumed to consider the nuclear-force interaction is a key factor to explain the riddles of such peculiar phenomena as super-diffusivity, HER and UPD introduced with a brief explanation in this paper.

It should again be emphasized that the role of complexity is closely related to the qualitative reproducibility of events in the CFP. The qualitative but not the quantitative reproducibility had been one of the tumbling stones to discard the CFP from the science of solid state-nuclear physics. The same situation seems to be in the fields of super-diffusivity, HER and UPD preventing from accepting them into the science of solid state-nuclear physics.

We have already sufficiently discussed the CFP hitherto [2]–[10], so we will only summarize the discussion on supe-diffusivity and HER and UPD briefly.

### 6.1. Super-diffusivity of Hydrogen Isotopes in Transition Metals and Alloys

The problem of super-diffusivity of hydrogen isotopes in the transition metals and their alloys has attracted strong interest in science and technology and many papers and reviews have been published [20], [21], [41]. Unfortunately, we have not yet investigated the relationship, in detail [42]. This discussion is tentative.

#### 6.1.1. *Localization of Hydrogen Isotopes in bcc Transition Metals and Alloys*

The discussion about this problem hitherto has lacked an important factor, the nuclear-force interaction between the occluded proton/deuterons and the lattice nuclei discovered in the CFP. We will give a new approach to this problem taking this interaction into consideration in the forthcoming papers.

#### 6.1.2. *Non-localized Hydrogen Isotopes in fcc Transition Metals and Alloys*

The most intriguing problem in this field of research may be the inverse mass effect of super-diffusivity in Pd as pointed out in section 3. The key element to explain this effect in Pd may be the nuclear-force interaction between a neutron and a proton which differs from that between a neutron and a deuteron. This problem will be investigated in our forthcoming paper.

### 6.2. HER and UPD

We have given a sketch of the HER and UPD in sections 4 and 5 of [10].

The most interesting theme from the problems pointed out are the following.

1. The existence of the hydrogen-electrode reaction (HER; $2H^+/D^+ + 2e^- \leftrightarrows H_2$) in the interstitial layer at the surface of the material X; This strongly depends on the crystal plane of the surface of the material.
2. HER ($2H^+/D^+ + 2e^- \leftrightarrows H_2$) produces an accumulation of protons/deuterons (p/d) in the interfacial region when the extension of the wavefunctions $\psi_p/\psi_d$ is not large and the diffusivity of H/D is not large enough to dissipate them into the electrode. Then the generated protons/deuterons are accumulated in the interfacial region and form p/d rich layers; the $X_1H_{1+x}/X_1D_{1+x}$ layers ($1 < x$) act as the H/D source for the further chemical reactions – the HER in this case, behave as a catalyst for the reactions.
3. The protons/deuterons generated by the HER are occluded in the host material X When the diffusivity of the protons/deuterons generated by the HER is large, then they diffuse into the electrode and there occurs the nuclear-force interaction of the interstitial protons/deuterons with neutrons in lattice nuclei when the wavefunctions of protons/deuterons are extended to overlap with lattice nuclei which have evaporation neutron levels. In this case, there may be an opportunity to produce CFP.

We will investigate the problems in the HER and UPD demanding appropriate explanations using the nuclear-force interaction between the neutrons in the lattice nuclei and the interstitial protons/deuterons in the near future.

In conclusion, we want to stress again that the discovery of nuclear reactions in the CF material at around room temperature [1]–[18] revealed the importance of the nuclear-force interaction (or the weak interaction) in some solids where exists the overlapping of the proton/deuteron wavefunctions at interstices with the neutron wavefunctions in lattice nuclei. The situations where such overlapping possibly exist in nuclear-solid materials where various physical and chemical phenomena have been investigated, including such phenomena as super-diffusivity, HER and UPD and possibly the production of new exotic nuclei with large proton numbers $Z$, as we pointed out above.

The examples pointed out above may be only a few out of many possible cases where the nuclear-force interaction (or the weak interaction) plays a decisive role in the realization of interesting physics and chemistry in solids. We do not yet know all of them. One of the most interesting fields of this new phenomena may be the biological system where there have already discovered some examples of the CFP after long investigations since 1799 when Louis-Nicolas Vauquelin observed one of the biotransmutation without satisfactory explanations (e.g., Section 10.1 in [2], [31], [43], [44]).The development of solid state-nuclear sciences will give us a vivid intellectual stimulation looking into the events in the most intimate world around us made out of atoms and molecules interacting through non-linear interactions. Training of our human intellect through the phenomena around us will elevate the intellectual level of human society to build a sustainable global world, a difficult but necessary task we should attain at all costs.

## Appendix. On Some Common Questions about Nuclear Reactions in Cold Fusion Materials

Since the discovery of nuclear transmutations by $\alpha$-particle bombardment on the $^{14}$N nucleus in 1919 by Rutherford et al., artificial nuclear transmutation has been produced and investigated using bombarding particles artificially accelerated by high voltages and also by using neutrons which can penetrate the heavy nuclei on account of its lack of charge as described by E. Rutherford in *Nature*, December 22, 1934 (pp. 964–965).

When we encounter nuclear reactions in materials where there are no specific acceleration mechanisms for particles therein (let us call such materials *cold fusion materials* (or *cf-materials*), for short), we are puzzled with common questions about how the charged nuclei approach each other into the range of the nuclear force about 1 fm compared with the lattice constants of about $2 – 3 \times 10^{-1}$ nm (= 2 – 3 Å). Let us answer typical common questions related to the mechanism to overcome the difficulty mentioned in 1934 by E. Rutherford.

The questions will be enumerated (1), (2), (3), (4) and (5) as follows:

(1) What is special about the nuclear reactions occurring in cold fusion materials compared with those that occur in other systems (in particular, in low-temperature plasma, and in the interaction of individual pairs of particles in a gas composition under a certain external influences)?
(2) How does the interaction of hydrogen isotopes with metal hydride nuclei overcome the Coulomb barrier?
(3) How are the three most important paradoxes in solid state-nuclear physics are explained? (3a) a very high probability of passing through the Coulomb barrier; (3b) the absence of radioactive daughter isotopes among the reaction products; (3c) very strong suppression of gamma radiation in the LENR reaction.
(4) What are the Hagelstein and Widom-Larsen mechanisms to use neutrons, and how do they explain the cold fusion phenomenon? (4a) Hagelstein model with the coherent transfer neutron reaction; (4b) Widom-Larsen model with neutrons produced from the protons that capture "heavy" electrons at the surface of the cold fusion material.
(5) Are there reviews of experimental results and their explanations of experimental data obtained in the cold fusion phenomenon in metal hydrides/deuterides and biological systems obtained in these more than 30 years since the discovery of the cold fusion phenomenon?

## Answers to the Questions enumerated above.

(A1) Answer to question (1).

We have to concentrate our efforts to clarify only the nuclear reactions occurring in such condensed matter as transition metal hydrides and deuterides, biological systems, and hydrated graphite leaving other cases (such as low-temperature plasma and ordinary gas) for future research. Even in cold fusion materials, there is a wide variety in the composition and properties of materials.

(A2) Answer to question (2).

There are several possible approaches to the explanation of nuclear reactions in the condensed matter referred to above. Our approach to this problem was the one using neutrons as a catalyst (the TNCF model) to make possible the nuclear reactions in condensed matter without any specific acceleration mechanism as presented*) at the 4$^{\text{th}}$ International Conference on Cold Fusion (December 6 – 9, 1993, Lahaina, Maui, Hawaii).

*) H. Kozima, "Trapped Neutron Catalyzed Fusion of Deuterons and Protons in Inhomogeneous Solids," *Transactions of Fusion Technology,* **26**, pp. 508–515 (1994).

In this approach, it is not necessary to consider the Coulomb barrier problem which is the key factor in nuclear reactions between charged particles, which some people have worried about.

(A3) Answers to questions (3a) – (3c).

**(3a).** This question is answered already by the use of the TNCF model as mentioned above in the Answer to comment (2). The foundation of the model is investigated quantum mechanically using the proton (deuteron) – lattice nuclei interaction in the book**) (Sec. 3.7) and also in the paper***).

**) H. Kozima, *The Science of the Cold Fusion Phenomenon, – In Search of the Physics and Chemistry behind Complex Experimental Data Sets* –, 1st Edition, Elsevier, Amsterdam, 2006, ISBN-13: 978-0-08045-110-7, ISBN-10: 0-080-45110-1.

***) H. Kozima, "Cold Fusion Phenomenon in Open, Nonequilibrium, Multi-component Systems – Self-organization of Optimum Structure," *Proc. JCF13* **13-19**, pp. 134 - 157 (2013), ISSN 2187-2260.

**(3b).** Several nuclear products such as tritium, neutron, and $^{4}{}_{2}$He accompanying the excess energy besides radioactive and stable daughter nuclei have been observed. The relation of the observed amounts of these particles had been explained by the TNCF model in the factor of 2 – 4 as explained in the book**) (Sec. 3.3.1) published in 2006:

The possible daughter nuclei had been explained also in the book (e.g., Sec. 2.11).

**(3c):** In the TNCF model, the daughter nuclei generated in the nuclear reactions in condensed matter interact with trapped neutrons to dissipate excess energy into lattice energy without emitting gamma rays. This is the reason there is no gamma radiation in the cold fusion phenomenon from our point of view.

(A4) Answer to question (4):

Neutrons are assumed to occur in the TNCF model. Their origin is probably in the proton/deuteron interaction with the lattice nuclei (Pd, Ni, C, etc.), as briefly explained above in Questions (2) and (3). They are formed by an entirely different mechanism from that supposed in the Widom-Larsen model. They are partially trapped in the neutron bands from the background neutrons abundant in the environment, partially deduced from lattice nuclei into the neutron bands. The effects of irradiation of slow neutrons has been observed as explained in our book*).

**(4a) Hagelstein model with the coherent transfer neutron reaction:**

In Hagelstein's model using the coherent transfer neutron**), i.e., the transfer of a neutron (mediated by low frequency electric or magnetic fields) from a donor nucleus to virtual continuum states, is followed by the capture of the virtual neutron by an acceptor nucleus. Using his model, Hagelstein concluded that the reaction D + D → $^{4}$He + 23.8 MeV occurs. Unfortunately, the probability of this reaction calculated on the Hagelstein model are not consistent with the experimental data***). In addition to this difficulty, it is difficult to accept the coherent transfer neutron model as the decisive model for the cold fusion phenomenon because there remain other events (production of tritium and neutron and occurrence of nuclear transmutations) observed in the deuterium systems and also nuclear reactions observed in protium systems to be explained by this model.

**(4b) Widom-Larsen model with neutrons produced from the protons that capture "heavy" electrons at the surface of the cold fusion material.**

The mechanism proposed by Widom-Larsen****) use the neutron produced at metallic hydride system surfaces from the protons and specific "heavy" electrons by the weak interaction. Hagelstein*****) examined the Widom-Larsen model and concluded that the model is not applicable to the real materials where the cold fusion phenomenon occurs.

*) H. Kozima, *Discovery of the Cold Fusion Phenomenon – Development of Solid State-Nuclear Physics and the Energy Crisis in the 21st Century* –, Ohtake Shuppan Inc., 1998, ISBN 4-87186-044-2. (**Sec. 8.2**, *Effect of the Thermal Neutron*).

**) P.L. Hagelstein, "Coherent and Semi-Coherent Neutron Transfer Reactions," *Proc. ICCF3*, pp. 297–300 (1993).

***) 2004 U.S. Department of Energy Cold Fusion Review, Reviewer Comments;
Review #6, http://www.newenergytimes.com/DOE/DOE.htm

****) A. Widom and L. Larsen, "Ultra-low momentum neutron catalyzed nuclear reactions on metallic hydride surfaces," *Eur. Phys. J.* **C 46**, pp. 107–111 (2006).

*****) P.L. Hagelstein, "Electron Mass Enhancement and the Widom–Larsen Model," *J. Condensed Matter Nucl. Sci.,* ISSN2227-3123, **12** , pp. 18–40 (2013).

(A5) Answer to question (5)

It is desirable to have a review of the whole body of work in the cold fusion phenomenon (CFP) despite the lack of the science of solid state-nuclear physics including the CFP. As we all know well, the science of the cold fusion phenomenon has not yet been able to give a consistent system of explanation for all of the data obtained in various cf-materials composed of a multitude of component elements with various structural varieties. Therefore, we have to be content with the list of *Proceedings* *, **) containing the main papers in this field and with a book***) with an extensive list of papers obtained until 2006. We also can cite our books****, *****) which gives a consistent explanation of mutual relations of observables obtained in many cf-materials made of transition metals and alloys with protium and deuterium, hydrogen graphite, or biosystems.

*Proceedings* of International and Domestic Conferences held almost annually since 1989:

*) *J. CMNS including the Proceedings of ICCF:*
https://lenr-canr.org/wordpress/?page_id=1495

**) *Proceeding of JCF Meetings*:
http://jcfrs.org/pubs.html

A Book with an extensive list of papers in this field until 2006;

***) E. Storms, *The Science of Low Energy Nuclear Reactions*, World Scientific Publishing, 2007. ISBN-10 981-270-620-8.

Books where that have given a consistent explanation of many experimental data sets with a model containing an adjustable parameter:

****) H. Kozima, *Discovery of the Cold Fusion Phenomenon – Development of Solid State-Nuclear Physics and the Energy Crisis in the 21st Century* –, Ohtake Shuppan Inc., 1998, ISBN 4-87186-044-2. The "References" in this book is posted at the CFRL (Cold Fusion Research Laboratory) Website: http://www.kozima-cfrl.com/Books/bookse/bookse.html

*****) H. Kozima, *The Science of the Cold Fusion Phenomenon*, *– In Search of the Physics and Chemistry behind Complex Experimental Data Sets* –, 1st Edition, Elsevier, Amsterdam, 2006, ISBN-13: 978-0-08045-110-7, ISBN-10: 0-080-45110-1.

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