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# Six Sketches on Complexity and Wavefunctions in the Cold Fusion Phenomenon<sup>+</sup>

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## 1. Introduction

Since the discovery of the cold fusion phenomenon (CFP) by Fleischmann et al. in 1989, hundreds of experimental data sets have been accumulated both in transition-metal hydrides and deuterides. The data range widely from the emission of neutron, gamma rays and charged particles to nuclear transmutations generating almost all elements in the periodic table. Excess energy accompany each event. We have to construct a science of the CFP, as H. Poincaré said a hundred years ago: *Science is build up of facts, as a house is built of stones; but an accumulation of facts is no more a science than a heap of stones is a house* [1].

To have a unified point of view for these diverse and complicated experimental data sets, we have developed a phenomenological model (the TNCF model) at first and then the neutron drop model (ND model). These works were published in papers and also in two books [2, 3] and a review paper [4]. Some quantum mechanical investigations on the bases of premises assumed in these models were also performed in recent works [3 – 5].

After publication of the recent book [3], we have further developed the idea of complexity in several phases of the CFP. According to I. Prigogine, almost all CF systems satisfy the sufficient conditions for the occurrence of

complexity which is common in any nonintegrable system with Poincaré resonances (both in classical and quantum). That is, they are **open, non-equilibrium (far-from-equilibrium), many body systems with non-linear interactions** between components [6]. In addition to this general nature of CFP systems, we have many experimental data sets in CFP that show characteristics of complexity. Most outstanding examples of them are the two laws we have found, i.e. (1) **the inverse-power law of  $\mathcal{N}(P_{\text{ex}})$  vs.  $P_{\text{ex}}$  relation**, where  $\mathcal{N}(P_{\text{ex}})$  is the number of events producing excess power  $P_{\text{ex}}$  ([2] §2.12) and (2) **the stability effect in the yield of product elements** by the nuclear transmutation ([3] §2.11). We will point out here a third law, (3) **the bifurcation of the CFP** in occurrence of excess energy and nuclear transmutation reactions. Several features of the CFP related with these laws, especially the third law, are qualitatively depicted in the Sketches presented in this paper.

The six sketches presented in this paper show a new approach to the CFP from our point of view. This approach developed as an extension of our former research. In these sketches (or short notes), we discuss qualitatively rather complicated problems in the CFP. These problems are difficult to treat quantitatively. The complexity, including self-organization and chaos, is a science without certainty and necessarily qualitative, as I. Prigogine declared [6]. Accordingly, the sketches given in this paper have characteristics inherited from complexity itself. We would like to ask the reader's understanding on this point.

The six sketches are presented as follows:

- [Sketch 1] Why the Irreproducibility is Prominent and Remarkable in CFP?
- [Sketch 2] Explosions show Complexity in CFP Experiments
- [Sketch 3] Analysis of Data Sets obtained by Dash et al. in Low Energy Nuclear Laboratory (LENL), PSU in 2006 – 2007
- [Sketch 4] Analysis of Experimental Data Sets with Ni Thin Films deposited on Plastic Plates
- [Sketch 5] Neutron Wavefunctions Extended Out from Nuclear Surface
- [Sketch 6] Proton/Deuteron Wavefunctions in Interstices of *fcc/hcp* Transition Metals

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## 2. [Sketch 1]

### Why the Irreproducibility is Prominent and Remarkable in CFP?

In solid state physics, the effect, e.g. a current density caused by probabilistic processes of electron motion in a crystal lattice under an applied electric field, is measured only as an average over many particles (electrons). The individual motion of each particle does not have any measurable effect, in this example.

The same is true for the current in a vacuum tube, where electrons emitted from a cathode flow toward an anode and constitute as a whole a current from the anode to the cathode when the current density is fairly large or macroscopic.

Imagine now a situation where the current density decreases gradually without limit. Then, the current measured by an ampere meter connected to the circuit decreases gradually to zero in macroscopic sense.

If we could set an imaginary apparatus to make a click at an arrival of an electron to the anode and to record a number of the click (per a small time

interval) as a function of time, the numbers of the clicks at successive times may distribute randomly around an average value at the time, which corresponds to the current density measured by the ampere meter.

In the case of CFP, the cause is atomic processes, which are governed by probabilistic laws, and is similar to the electron motion in the case of electric current, even if the complexity of the former is exceedingly larger than that of the latter.

The effect is nuclear in the CFP, on the other hand, as experimental data sets show and is measured quasi-individually for each event (e.g. neutron emission) as if each electron arriving at the anode makes a click as imagined above.

An example of the sporadic and intermittent effect in CFP, caused by atomic processes that belongs to solid-state physics, is a simultaneous occurrence of nuclear transmutations triggered by some unknown parameters (neutrons in our neutron drop model). The nuclear reactions thus induced in CF materials result in such events in CFP as, 1) heat burst (Fleischmann et al. [1], Zhang et al. [2], Biberian et al. [3], Dash et al [4]. etc.), 2) neutron burst (De Ninno et al [5]. Menlove et al [6]. Mizuno et al. [7] etc.), 3) localized melting of the sample surface (Dash et al. [8], Mizuno et al. [9] etc.) and so forth.

The events with similar characteristics are fairly trivial in many branches of physics. We may consider one example in cosmic-ray physics. An energetic primary particle in the cosmic ray passing through the air causes extensive air showers of generated particles by collisions with nuclei of the component gas of the air. The position where an extensive air shower starts on the path of the primary particle is determined by the probabilistic law and we can not predict it beforehand. However, the large effect of the extensive air shower makes it possible to measure each shower individually. This is a typical example where the effect has only qualitative reproducibility but not quantitative one.

To investigate the irreproducibility or the qualitative reproducibility of the effect in CFP, it is natural to rely on the theory of chaos or complexity developed in recent 30 years. Using words of I. Prigogine, it is possible to say that almost all CF systems are open, unstable, far-from-equilibrium, many body systems with non-linear interactions between components and there is complexity common in any nonintegrable system (both in classical and

quantum) with Poincaré resonances [10]. In these systems, we can not predict an exact trajectory (in classical mechanics) or evolution of wavefunctions (in quantum mechanics) of a particle. We have to use probabilistic (or thermodynamic) description of objects which is illustrated in Fig. 1 (after [10]).

Figure 2.4  
Pitchfork Bifurcation  
Concentration  $X$  is a function of the parameter  $\lambda$ , which measures the distance from equilibrium. At the bifurcation point, the thermodynamic branch becomes unstable, and the two new solutions  $b_1$  and  $b_2$  emerge.

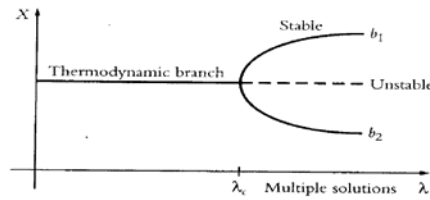


Figure 2.5  
Successive Bifurcations with Increasing Distance from Equilibrium

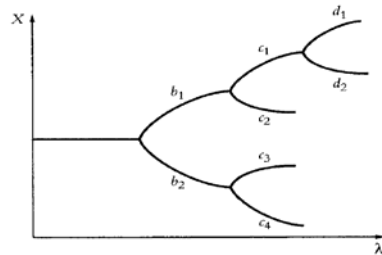


Fig. 1. Pitchfork Bifurcation (upper) and Successive Bifurcations with Increasing Distance from Equilibrium (lower) [10]. In the upper diagram, the Thermodynamic branch is supposed to be the equilibrium state.

In Fig. 1 ([10] Figs. 2.4 and 2.5) the system in an equilibrium state (at left ends of both figures) exerts successive bifurcations when a parameter  $\lambda$  which describes the degree of possible departure from an equilibrium state increases.

This situation is phenomenologically the same to that occurs in many CF experiments; parameters such as D/Pd ratio and temperature of the samples, electric current density flowing into the sample, surface barriers (for an

example of complicated surface states), etc are usually varied artificially (controllable) or automatically (out of our control) to make the system deviates from an initial equilibrium or quasi-equilibrium state. The CFP is considered to be a result (results) of a bifurcation(s) into new, more stable states where we observe many CF events as we seen concrete examples in later Sketches (cf. Sketches 2 – 4).

This analogy tells us that CFP is fundamentally an irreproducible process and we can expect at most the qualitative reproducibility for events in CFP at the same macroscopic initial conditions. Therefore, the long-lasting controversy about the reproducibility of the CFP between supporters and critics has been destined to be fruitless.

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### 3. [Sketch 2]

#### Explosions show Complexity in CFP Experiments

There are several reports of explosions occurred in CFP experiments. The two experiences by Zhang et al. [1] and Biberian [2] were reported in conferences and we have concrete data. In these cases, they used electrolytic system with similar cathodes of Pd pipes. Another example of the explosions in CFP experiments was reported by T. Mizuno [3]. In this case, the experimental system was also electrolytic but a tungsten plate as a cathode with light water and electrolyte  $K_2CO_3$ .

There are further more two cases of explosions which are legendary. The first of them was written in the pioneering paper by Fleischmann, Pons and Hawkins [4]. In the Table 1 of their paper, there are words "Warning! Ignition?" for a cubic sample of  $1 \times 1 \times 1 \text{ cm}^3$ . Details of this explosion was not made clear perhaps due to scant data reserved after the accident in the confused situation induced by the extraordinary event.

The second of them occurred in the SRI (Stanford Research Institute) [5] resulting in fatal human damage. This case was ascribed to an explosion of mixture gas of hydrogen and oxygen. If it is the case, we can exclude this case from the explosion of CF samples due to explosive energy production by cold fusion reactions.

We analyze the first two cases to show that the events are explained as the bifurcation in complexity.

- 1) The case of Zhang et al. [1]

The explosion explained Zhang et al. [1] was analyzed in their paper by the authors themselves and we can use their numerical values given in the paper.

Their cathode was a Pd tube with dimensions  $1.67 \text{ } \phi \times 0.67 \text{ } \phi \times 80 \text{ mm}^3$ .

They concluded that the generated energy  $Q_{\text{ex}}$  is  $1.1 \times 10^4 \text{ J}$ ;

$$Q_{\text{ex}} = 1.1 \times 10^4 \text{ J} = 6.7 \times 10^{16} \text{ MeV.} \quad (1)$$

This value is one order of magnitude larger than the heat of 843 J that could be produced by recombination of  $\text{D}_2$  and  $\text{O}_2$  gas generated in the experiment.

Most important but ambiguous problem is the origin of the excess heat to explain the explosion. They did not give any fact about nuclear products accompanied with the excess energy generation. They used their RDTME model to explain the “explosion” rather arbitrarily.

We can assume any reaction possible in the experimental system to explain the “explosion” if it does not violate laws of physics. Let us examine the case from our point of view using the TNCF model [6]. We assume the reaction is  $n$ - $d$  fusion corresponding to the free-space version

$$n + d = t (6.98 \text{ keV}) + \gamma (6.25 \text{ MeV}), \quad (2)$$

and the energy of 6.25 MeV is thermalized in the sample (not emitted as a photon) in the CF version of  $n$ - $d$  interaction [6];

Then, the above heat given in the relation (1) corresponds to the number of reactions of about  $10^{16}$ . This number is also the number of deuterium atoms participating in this explosion and is only one part of  $10^7$  mol, or one part of ten millions mol.

According to their calculation, the time  $\tau$  in which this total reaction occurred was given as 0.058 s. We can calculate excess power  $P_{\text{ex}}$ , from the energy given in the relation (1) and this time duration of  $\tau = 0.058 \text{ s}$ ;

$$P_{\text{ex}} = 1.9 \times 10^5 \text{ W.} \quad (3)$$

If the reaction occurred in the whole volume  $V$  of the sample ( $V = 0.147 \text{ cm}^3$ ), the excess power density was about  $1 \text{ MW/ cm}^3$ . From our present knowledge, however, we know the reactions occur in surface region of a thickness about  $1 \text{ } \mu\text{m}$  rather than in the whole volume as assumed above. Let us estimate the effective volume  $V_{\text{eff}}$  as follows; the surface area  $S$  of the Pd tube is

$$S = 80 \times \pi (1.67 + 0.67) \text{ mm}^2 = 80 \times 3.14 \times 2.34 \text{ mm}^2 = 0.59 \times 10^3 \text{ mm}^2$$

$$= 5.9 \times 10^{-1} \text{ cm}^2$$

and the volume  $V_{eff}$  of the reaction region is therefore

$$V_{eff} = 5.9 \times 10^{-1} \times 1 \times 10^{-4} \text{ cm}^3 = 5.9 \times 10^{-5} \text{ cm}^3 \quad (4)$$

Using this volume, we obtain the excess power density as

$$P_{ex}/V_{eff} = 2.5 \times 10^9 \text{ W/cm}^3. \quad (5)$$

This is a big amount but nothing we can say about this value itself.

We can use the value  $P_{ex}$  in (3) and the volume  $V_{eff}$  given in (4) to calculate the parameter  $n_n$  in the TNCF model (cf. Sketch 5):

$$n_n = 1.4 \times 10^{20} \text{ cm}^{-3}. \quad (6)$$

This value is more than six orders of magnitude larger than the values of about  $10^6 - 10^{13} \text{ cm}^{-3}$  determined in many data sets [6].

Let us examine how many deuterons participate to the reaction (1) to generate the excess power density of  $2.5 \times 10^9 \text{ W/cm}^3$  (5).

If we assume Eq. (2) for the reaction to produce this energy in the sample, the number density rate of reactions or density rate of deuterons  $\Delta N_d/\Delta t$  corresponding to this power density is

$$\begin{aligned} \Delta N_d/\Delta t &= 2.5 \times 10^9 \times 6.24 \times 10^{12} (\text{MeV/s cm}^3)/6.25 (\text{MeV}) \\ &= 1.56 \times 10^{22} /6.25 \text{ /s cm}^3. \\ &= 2.5 \times 10^{21}/\text{s cm}^3. \end{aligned}$$

The number density of Pd atom and therefore of deuteron in PdD is  $6.88 \times 10^{22} \text{ /cm}^3$  and the above value of  $\Delta N_d/\Delta t (= 2.5 \times 10^{21}/\text{s cm}^3)$  corresponds to the fractional decrease rate of deuterons  $\Delta N_d/\Delta t/N_d$  in the reaction region in the surface area (with a thickness of  $1 \mu\text{m}$ ) of

$$\Delta N_d/\Delta t/N_d = 2.5 \times 10^{21}/6.88 \times 10^{22} \text{ /s} = 3.6 \times 10^{-2} \text{ /s}.$$

This means that about 0.21% ( $= 3.6\% \times 0.058$ ) of deuterons in PdD participated to the explosion which occurred in a time interval of 0.058 s if the reaction occurred homogeneously overall the surface region with a thickness of  $1 \mu\text{m}$ .

However, it is rather probable that the reaction is localized somewhere in the surface region as we know from many experimental data. Then, the reactions might occur in a localized small volume  $V_{loc}$  in the surface region and almost all deuterons ( $\Delta N_d/N_d \approx 1$ ) participated the reactions in addition to Pd nuclei in the volume (which we will not consider here).

If we assume  $\Delta N_d/N_d = 1$  in localized small volume of  $V_{loc}$ , then the ratio of  $V_{loc}/V_{eff} \approx 2.1 \times 10^{-3}$ . This reaction could cause formation of surface pits

and craters observed in such experiments as by Dash, Mizuno and others ([7, 8] in Sketch 2). A simplified calculation of crater formation mechanism was given in our paper [7].

From above estimation of  $V_{loc} / V_{eff}$ , we conclude that pits and craters would occupy about 0.2% of the surface region in the case of Zhang et al. [1]

### 2) The case of Biberian [2]

On the other hand, Biberian [2] observed another explosion with a similar sample to that used by Zhang et al. [1]. The Pd cathode was a tube of  $2.0 \phi \times 1.6 \phi \times 100 \text{ mm}^3$ . We should notice the thinness of the sample in this case also. Common factor of these two explosions are the shape of the samples they used; thin Pd pipes with fairly large length-to-diameter ratios and small inner diameters.

### 3) Experiments by Dash et al. [8]

Dash et al. [8] performed a series of experiments to measure excess energy production with samples of the same size to that used by Zhang et al. [1]. From their data, it was found that excess energy production occurs at higher temperature of the system than a critical temperature  $T_c$  that is higher than 60 degC ( $T_c > 60 \text{ degC}$ ). This fact suggests that the higher the temperature of the system, the more easily cold fusion reactions are induced (cf. Sketch 3).

## Conclusion

The shape of the samples used in the experiments by Zhang et al. [1], Biberian [2], and Dash et al. [8] has a characteristic having a large length-to-diameter ratio and small inner diameter as pointed out above. This fact suggests that the inner surface of the tube is apt to be heated by the energy generated by nuclear reactions and becomes higher temperature and a positive feedback cycle worked to result in an explosion.

In accordance with this speculation, Dash et al. measured many excess energy pulses and also bursts (discriminating isolated larger pulses than about 0.6 W from the smaller pulses) in their experiments. The bursts show characteristics possibly induced by the positive feedback different from rather small pulses as discussed in the following Sketch 3.

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## 4. [Sketch 3]

### Analysis of Data Sets obtained by Dash et al. in Low Energy Nuclear Laboratory (LENL), PSU in 2006 – 2007

In this sketch, we analyze the experimental data sets obtained by John Dash's group in the Low Energy Nuclear Laboratory (LENL) [1, 2].

Sample size of Pd cathode is the same as that used by Zhang et al. [3]

analyzed in the previous Sketch 2: Sample size;  $0.67\phi \times 1.67\phi \times 80 \text{ mm}^3$ .

Using this value we obtain following numerical data about the Pd cathode;

Surface area  $S$ ;  $S = 8 \times \pi (0.067 + 0.167) \text{ cm}^2 = 5.88 \text{ cm}^2$

Effective volume  $V_{\text{eff}}$  (assuming a thickness of 1 micrometer at the surface);

$$V_{\text{eff}} = 10^{-4} S = 5.88 \times 10^{-4} \text{ cm}^3.$$

According to the TNCF model (assuming only the CF version of  $n + d$  reaction) and thermalization of the liberated energy in the sample;

$$n + d = t(6.98 \text{ keV}) + Q(6.25 \text{ MeV}). \quad (1)$$

The number of reactions  $N$  in a time  $\tau$  is given as follows [4];

$$N = 0.35 n_n v_n n_d V_{\text{eff}} \sigma_{\text{nd}} \tau, \quad (2)$$

where  $0.35 n_n v_n$  is the flow density of the trapped thermal neutrons per unit area and time,  $n_d$  is the density of the deuteron,  $\sigma_{\text{nd}} = 5.5 \times 10^{-28} \text{ cm}^2$  is the cross section of the reaction (1) for a thermal neutron..

The number of reactions  $N$  is related to the number of reactions  $N_Q$  producing excess energy  $Q$  (in MeV) defined by a relation

$$N_Q = Q(\text{MeV})/5(\text{MeV}),$$

if we assume the energy liberated in a nuclear reaction is in average 5 MeV (actually, the energy is 6.25 MeV if we assume only the reaction (1)).

Putting

$$n_d = 6.88 \times 10^{22} \text{ cm}^{-3}$$

for the sample composition PdD, and the neutron velocity

$$v_n = 2.2 \times 10^5 \text{ cm/s}$$

for the thermal neutron in (2), we can calculate the density  $n_n$  of the trapped neutrons in the TNCF model using the observed excess energy  $Q$  in a time  $\tau$ .

The value  $n_n$  is given as follows if we assume  $N = N_Q$ ;

$$n_n = (\alpha / 5) (1 / 0.35 v_n n_d V_{\text{eff}} \sigma_{\text{nd}} \tau),$$

where a parameter  $\alpha$  is defined for convenience of the following discussions as

$$\alpha (\text{W}) = Q / \tau = 6.24 \times 10^{12} \alpha (\text{MeV/s})$$

and means the excess energy measured in watt.

Using numerical values given above and also  $\tau = 1$  (s) in the above relation, we obtain the final result

$$n_n = 7.2 \times 10^{15} \alpha (\text{cm}^{-3}). \quad (3)$$

**Experimental data;**

**Case 1.** Active period with excess power pulses in the LENL data.

In the experimental data sets obtained in LENL, there are several active periods with many excess power pulses generating the excess power of about  $\alpha = 0.1 - 0.2$  W. In these periods, we take  $\alpha = 0.1$  for simplicity.

Then, we obtain the density of the trapped neutrons from formula (3);

$$n_n = 7.2 \times 10^{14} \text{ (cm}^{-3}\text{)}. \quad (4)$$

**Case 2.** Bursts in the LENL data.

In the experimental data sets obtained in LENL, there are large excess power bursts with energies reaching up to 2 W. For this case, we take  $\alpha = 2$ , for simplicity.

Then, the density of the trapped neutrons (3) for the bursts is given as

$$n_n = 7.2 \times 10^{16} \text{ (cm}^{-3}\text{)}. \quad (5)$$

**Case 3.** Experiment of Zhang et al. (cf. Sketch 2).

In this experiment with an explosion as explained in their paper [3], we can assume the excess power of

$$P_{\text{ex}} = 1.9 \times 10^5 \text{ W.}$$

This means that the parameter  $\alpha$  defined above is given as  $\alpha = 1.9 \times 10^5$  and we obtain the value of the parameter (3) for the explosion as

$$n_n = 1.4 \times 10^{20} \text{ (cm}^{-3}\text{)}. \quad (6)$$

**Discussion and Concluding remarks.**

In our analyses obtained until 1998 and published as a book [4], we determined the parameter  $n_n$  for more than 50 experimental data sets giving values between  $10^8 - 10^{13} \text{ cm}^{-3}$ ;

$$n_n = 10^8 - 10^{13} \text{ cm}^{-3}. \quad (7)$$

It is interesting to compare the value of the parameter  $n_n$  given in the relation (7) with the values (4) – (6) determined in the above Cases. The experimental data given in the Case 1 have the parameter (4) in the range given in (7). On the other hand, the parameters (5) and (6) of the Cases 2 and 3 are the largest values of  $n_n$  exceeding the range expressed in the relation (7).

This large value of the parameter  $n_n$  in Cases 2 and 3 shows, of course, the large value of the excess energy in a reduced form easy to compare the intensity of the reactions. Then, we have to discriminate the latter cases

(Cases 2 and 3) from such “normal” cold fusions as the Case 1 giving the value  $n_n$  in the equation (7).

This characteristic feature of Case 2 (and Case 3) is also shown by plotting  $N_P$  vs.  $P_{ex}$  diagram where  $N_P$  is the frequency of a definite excess power evolution  $P_{ex}$  such as given in Fig. 2.13 of [5] for the data by McKubre et al. [6].

The corresponding figure in the case of the data sets of LENL (including Cases 1 and 2) is depicted in Fig.1.

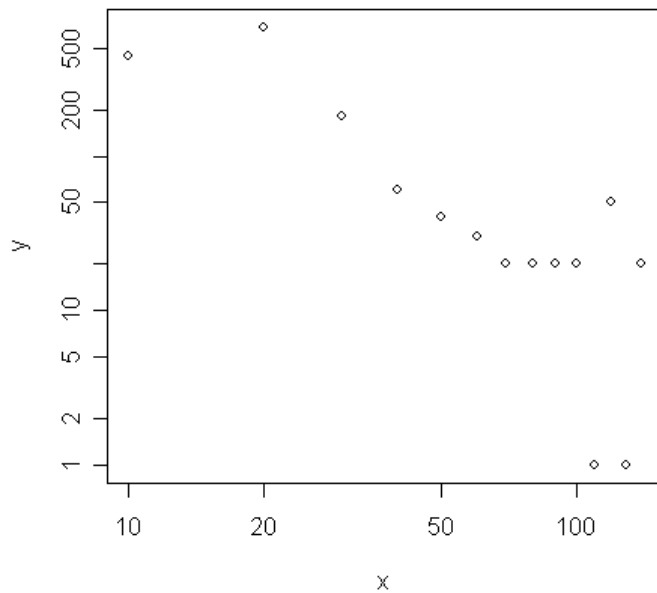


Fig. 1. Distribution of the frequency  $N_P$  ( $= y$ ) producing excess power  $P_{ex}$  ( $= x$ ). To depict log-log curve, values of  $P_{ex}$  and  $N_P$  were arbitrarily multiplied by  $10^n$ . ( $x = 100$  in this figure corresponds to  $P_{ex} = 1$  W)

Fig. 1 shows following facts ( $x = 100$  corresponds to  $P_{ex} = 1$  W in this figure) :

**Region A**,  $x = 20 - 60$ .

The data points in the range from  $x = 20$  to  $60$  are considered to be on a straight line with a gradient  $\approx -2$ .

**Region B**,  $x > 60$ .

The data points in the range  $x > 60$  deviate from the straight line.

The data in the region A is similar to the data depicted in the Fig. 2.13 [5]

for the data obtained by McKubre et al. [6] but a different gradient. In contrary, the data in the region B have a different characteristic and should be analyzed with different factors from that used in the case of the data in the region A.

One possible explanation of the difference in characteristics of the data in the region B and those in the region A is in the behavior of complex systems with nonlinear interaction resulting in self-organization and chaos. We may imagine a following processes 1) – 3).

1) If the temperature of the experimental system is lower than a critical temperature  $T_c$  (from the experiment, we may take it higher than 60 degC;  $T_c \approx$  or  $>$  60 degC), there occurs no cold fusion reactions.

2) Increasing the temperature higher than  $T_c$  ( $T_c <$  90 degC as confirmed by experiments), the cold fusion reactions start to occur and produce excess energy inducing more reactions as we see in the appearance of many pulses.

This means that the critical temperature  $T_c$  in this case is in between 60 and 90 degC.

3) When the temperature goes up higher by any chance due to CF reactions generating more excess energy than dissipating energy from the system (due to the specific shape of the cathodes, inner parts of the sample keep energy longer), there may occur a positive feedback of a cycle to make the temperature of the system higher and to induce more CF reactions.

This positive feedback results in the excess energy bursts as seen in the region B. When the cycle of the positive feedback last long, there may appear negative feedbacks by changes of other parameters (e.g. decrease of D/Pd, change of lattice structure, etc.) to overcompensate the positive feedback and make the sample lower temperature and inactive.

The explosions observed by Zhang et al. [3] and also by Biberian [7] with samples having almost the same shape might be the extreme examples of this positive feed-back when the negative feedback did not work well to prevent the explosion. The other explosions referred in the previous Sketch 2 (references [3] and [4] in Sketch 2) may be explained by similar processes.

Similar figure was obtained by McKubre et al. [6] for a dependence of  $P_{ex}$  on D/Pd ratio. Supplementing the lower D/Pd part not written in their paper for the benefit of eyes and simplifying distribution of data points (taking only a near middle point at a definite value of D/Pd), we obtain Fig. 2 from their Fig.7 [6].

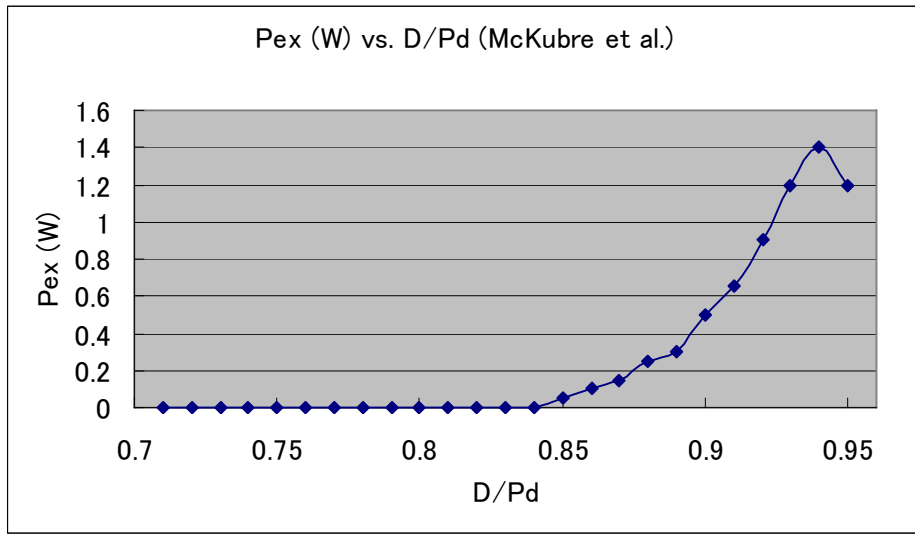


Fig. 2. Loading ratio (D/Pd) dependence of excess energy measured by McKubre et al. [6]

These figures (Fig. 2) remind us the classic graph of the evolution of final equilibrium state of the logistic difference equation (Fig. 3) well-known in the field of complexity [8]:

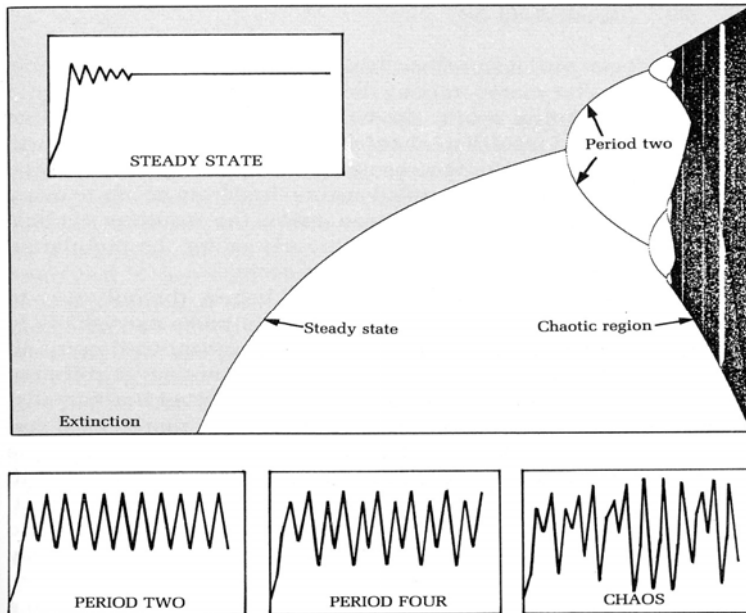


Fig. 3. Period-doubling and Chaos (From “Chaos” by J. Gleick [8]. p.71) Four small figures depict variation of  $x_n$  in terms of the increase of  $n$ . The main figure depicts  $x_\infty$  ( $x_n$  at  $n = \infty$ ) vs. the parameter  $\lambda$  of the logistic difference equation  $x_{n+1} = \lambda x_n(1 - x_n)$  ( $0 < x_0 < 1$ ).

At present, we have only an analogy between data of CFP and the complexity depicted by the logistic difference equation. It seems that there appears a bifurcation in Fig. 2 as those occurred in Fig. 3. If we plot all data points in Fig. 3 from original Fig. 7 [6], the figure might look like the chaotic part of Fig. 4 (right hand side of the figure smeared black).

The author would like to express his thanks to J. Dash for the use of his experimental data prior to the publication.

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## 5. [Sketch 4]

## Analysis of Experimental Data Sets with Ni Thin Films Deposited on Plastic Plates.

After the discovery of the cold fusion phenomenon (CFP) in 1989, there is a huge number of experimental data sets showing complicated features of this phenomenon. These features are outside of understanding from well-established regimes of physics such as nuclear physics and solid-state physics (or condensed matter physics) and are left exterior of the research fields of the orthodox science.

The two books published by the author [1,2] gave a unified explanation of these complicated events in CFP from a phenomenological point of view supplemented with some quantum mechanical investigations. There are many new experimental data sets in recent several years even if essential factors in CFP seems to have appeared by the end of 20<sup>th</sup> century. We take up in this Sketch the Ni/H/Li<sub>2</sub>SO<sub>4</sub> system with Ni films deposited on plastic plates by sputtering [3,4] originated by Violante et al.[3]

In the experiment by Violante et al. [3], there are observed changes of isotopic ratio of <sup>63</sup>Cu to <sup>65</sup>Cu down to 0.94 from natural one 2.24. We can analyze these data using our TNCF model that has been so effective to give an unified view of nuclear transmutation assuming existence of trapped neutrons in cold fusion materials (CF materials) with a density  $n_n$  supposed to be an adjustable parameter. The values of the parameter  $n_n$  determined by analyses of more than 60 data sets ranges from 10<sup>8</sup> to 10<sup>13</sup> cm<sup>-3</sup> as tabulated in the book [1] (c.f. also the relation (7) in Sketch 3).

We can analyze the data obtained by Violante et al.[3] just as we had done for the data sets in former works [1] especially as given in Appendix C7 in [2].

We use the TNCF model to analyze the data assuming absorption of a single neutron by the relevant nuclei <sup>63</sup>Cu and <sup>65</sup>Cu followed by decay of the composite nuclei. Using the absorption cross section for thermal neutrons  $\sigma_1 = 4.506$  b (for <sup>63</sup>Cu) and  $\sigma_2 = 2.168$  b (for <sup>65</sup>Cu), number  $n_1$  of <sup>63</sup>Cu nuclei and that  $n_2$  of <sup>65</sup>Cu after a time interval  $\tau$  were expressed as follows assuming their change from the initial values  $n_{10}$  and  $n_{20}$ , respectively, are small;

$$n_1 = n_{10} (1 - 0.35 n_n v_n \tau \sigma_1),$$

$$n_2 = n_{20} (1 - 0.35 n_n v_n \tau \sigma_2)$$

where  $0.35 n_n v_n$  is the flow density of the trapped thermal neutrons per unit area and time [1,2].

Solving these equations for the parameter  $n_n$ , we obtain following equation for  $n_n$  ;

$$n_n = (\alpha_0 - \alpha) / 0.35 v_n \tau (\alpha_0 \sigma_1 - \alpha \sigma_2),$$

where

$$\alpha = n_1/n_2 \text{ and } \alpha_0 = n_{10}/n_{20}.$$

Using the experimental data  $\tau = 20 \text{ h}$  ( $7.2 \times 10^4 \text{ s}$ ),  $\alpha_0 = 2.24$ ,  $\alpha = 0.94$  and  $1.7$  in addition to the value  $v_n = 2.2 \times 10^5 \text{ cm/s}$  and the cross sections given above, we obtain the values of the parameter  $n_n$  for two cases of  $\alpha = 0.94$  and  $1.7$  determined by experiments;

$$n_n = 2.9 \text{ and } 4.3 \times 10^{13} \text{ cm}^{-3},$$

respectively.

This values of the parameter fit very well with the values obtained in the previous works [1] (and relation (7) in Sketch 3) and give us confidence that the TNCF model is effective also for this data sets obtained by Violante et al.[3]

Experimental data set by Yamada [4] is presented in its essence as follows (details will be presented by H. Yamada elsewhere) in parallel to the data set by Violante et al. given above. In the experiment with a system similar to that of Violante et al., Yamada measured drastically different results on the nuclear transmutation; they could not confirm the change of isotope ratio of copper isotopes as measured by Violante et al. In this case, the mechanism applied effectively to the data by Violante et al. [3] ( $^{63}\text{Cu}/^{65}\text{Cu}$ ) is apparently useless.

We remember the drastic nuclear transmutations observed by Bockris [5], Mizuno [6], Miley [7] etc. showing simultaneous production of many nuclides with largely shifted nucleon and proton numbers from nuclides pre-existed in the CF material. To discuss these nuclear transmutations, we extended our initial model (TNCF model) to the neutron drop model (ND model) supported by microscopic calculations based on the recent knowledge in nuclear and solid state physics [2].

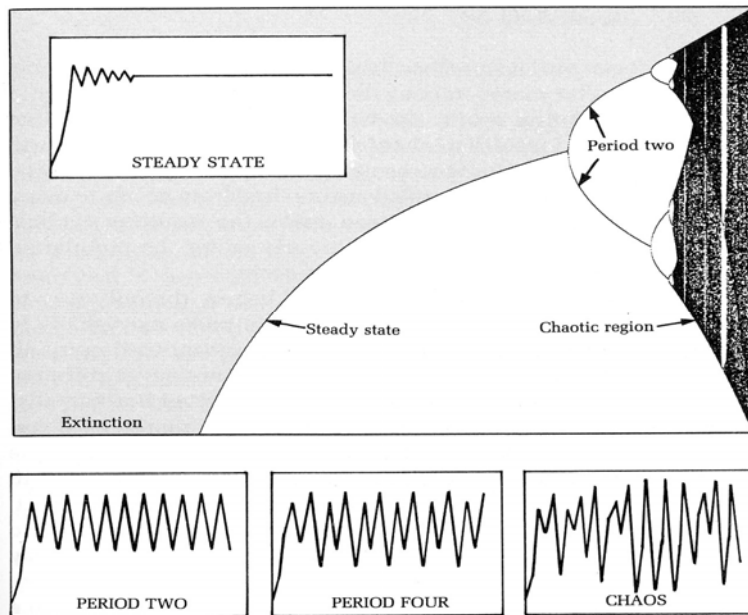


Fig. 1 Period-doubling and Chaos (From “Chaos” by J. Gleick [8]).

The qualitative difference of two data by Violante et al. [3] and Yamada [4] is understood by the nature of complexity of CFP as we had pointed out before [2] (cf. also Sketch 3). Even in such a simple system as the logistic difference equation, the progress of the system experiences bifurcation in terms of increase of a parameter and shows different features from one branch to another as illustrated in Fig. 1 [8] (See also Fig. 4 in Sketch 3 for explanation of this figure).

In the CF materials, the system is extremely complicated than the simple logistic system, and we have to expect more complicated bifurcations in a CF system; generally speaking, the bifurcation in a CF system may be properly depicted in a multi-dimensional diagram giving various, qualitatively different effects in accordance with our experience in CFP research in the long term since 1989.

The author would like to express his thanks to H. Yamada for his information about his experimental data prior to the publication.

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## 6. [Sketch 5]

### Neutron Wavefunctions Extended Out from Nuclear Surface

Nuclear physics has developed substantially from the day Rutherford proposed his nuclear model in 1911 based on the experimental data of alpha particle scattering by gold nucleus. Since then, nuclei in their isolated and quasi-isolated (i.e. in transient interaction) states were investigated minutely to give precise structure and dynamics in interactions with each other.

Nuclear properties in their ground and high-energy excited states have been explored very well applying neutrons, gamma rays and high energy particles accelerated by various machines to make charged nuclei approach each other close enough in the range of the short-range nuclear force overcoming Coulomb repulsion between them.

However, there remained a field kept untouched by these researches until

recently; the nuclei in their low excited state are heterogeneous from those in the ground states and higher excited states. Especially, investigation of the states of nuclei at their so-called neutron evaporation level had started only twenty years ago. Now, there are several review articles on this problem telling following facts by that time [1,2]; there exist many nuclei with the so-called neutron halo extending far out of the nuclear core that is the nucleus figured out in orthodox nuclear physics. It is recognized now the necessity to treat nuclei tenderly to know their behavior in states at or near the neutron evaporation levels.

On the other hand, there appeared a new field of investigation related with the states of nuclei at their low excited states; the cold fusion phenomenon (CFP). At first, this field was considered as a part of the orthodox nuclear physics when a part of its events was discovered and proclaimed in 1989. The content of the phenomenon unexpectedly increased into huge amount with profound variety in these 18 years after its discovery. Now, we know the CFP occurring both in protium and deuterium systems and includes such events as nuclear transmutations producing almost all nuclides from pre-existed nuclei Ti, Ni, Pd,  $n$ ,  $p$ ,  $d$ , Li, K, S, O, and so forth in CF systems, emissions of neutrons, photons, and charged particles ( $p$ , alpha, and so forth) accompanying the excess energy.

The variety of the products of the CFP demands us to have a definite point of view to investigate this phenomenon. It is possible to consider the protium and deuterium systems as independent fields with different mechanisms for their CF events. Or it is possible to explore new nuclear physics independent of the orthodox nuclear physics we have at hand explored in almost a hundred years. A possible reconciliation of the CFP and the nuclear physics may be attained using the neutron as an agent relying on the unexplored nature of neutrons in solids and on nuclear properties at around the neutron evaporation level under development at present.

Our approach is the last one in the ways depicted above supplemented by a new knowledge about proton and deuteron wavefunctions in CF materials (cf. Sketch 6). This approach has been partly explained in our recent papers [3, 4] and a book [5]. In the book, the essential point was expressed as follows without enough knowledge of the research in the nuclear physics; "These theoretical and experimental results about shallow levels below zero suggest

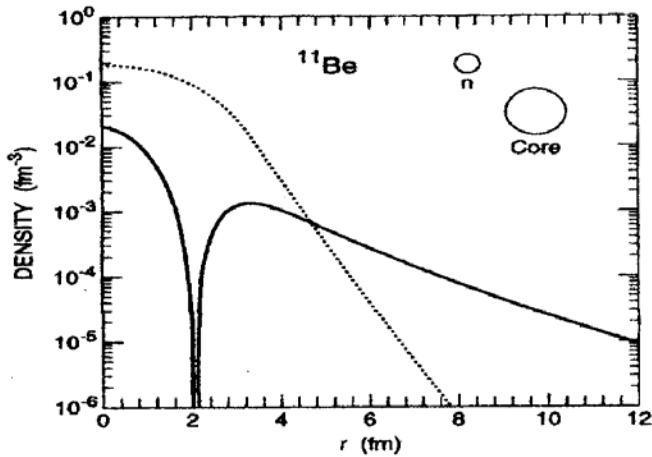


Fig. 1. Plot of the  $^{11}\text{Be}$  density (after Sagawa, 1992). The upper right corner shows the simplified picture of a halo nucleus as a two-body system with an inert core and a halo neutron. Dotted line, core density as a function of radius; solid line, the density obtained in a Hartree–Fock calculation with the neutron in a  $2s_{1/2}$  orbital and a single-neutron separation energy adjusted (to agree better with experiment) to 0.51 MeV. Note the very far-extended, dilute tail that is the characterizing feature of a halo [1].

that wave functions of neutrons with energies near zero in Ti, Ni, Pd (and Pt) may spread out from nuclei and contribute to CFP as investigated in the next Chapter” ([5] Chapter 2).

To show some phases of the recent development in this matter, we cite here a figure (Fig. 1) showing extension of neutron density outside the nuclear core and a table (Table 1) showing confirmed nuclides in the halo states. The investigation of the halo states of nucleus is in an infantile state and only a few data has been obtained for small mass-number nuclides as shown in Table 1.

Table 1. (K. Riisager, [1].)

**TABLE I. Halo states. For each state the excitation and separation energies and the angular momentum of the halo particle(s) are listed.**

Nucleus	$E_x$ (MeV)	$S - E^a$ (keV)	Configuration	$l$	$K$
$^{11}\text{Be}$	g.s.	504	$n + ^{10}\text{Be}$	0	
$^{11}\text{Be}$	0.32	184	$n + ^{10}\text{Be}$	1	
$^{17}\text{F}$	0.50	105	$p + ^{16}\text{O}$	0	
$^6\text{He}$	g.s.	973	$n + n + ^4\text{He}$		2
$^{11}\text{Li}$	g.s.	310	$n + n + ^9\text{Li}$		?
$^{14}\text{Be}$	g.s.	1340	$n + n + ^{12}\text{Be}$		?

<sup>a</sup>From Audi and Wapstra, 1993.

To know the present extent of our knowledge in this field, we summarize the nuclear properties of the neutron halo from [1] and [2] closely related to the CFP from our point of view.

- 1) “Thresholds,” the transition points between bound discrete states and a continuous spectrum, give rise to many fascinating phenomena. Among the newest of them are the so-called **halo states** that occur in some nuclei near the limit of particle stability.
- 2) Only very loosely bound neutrons in an  $s$  state relative to the core provide an ideal halo.
- 3) Arbitrary large values of the mean-square radius could occur in nuclei, at least in principle.
- 4) If a neutron halo is defined as a **divergent r.m.s. radius** of the halo for the neutron separation energy  $S_n$  approaching zero, then a two-body (i.e. single-neutron) halo is possible only if the orbital angular momentum  $l = 0, 1$ .
- 5) The conditions for a three-body (two neutron) halo are more restrictive [7', 8'] and the radius is at most logarithmically divergent.
- 6) The known cases of even- $n$  halos have **the Borromean property** [2'], namely that both the two-body sub-systems ( $A + n$ ) and  $(n + n)$  are unbound.
- 7) Mass calculations suggest that halo states will occur **symmetrically at the neutron drip line** for most elements.
- 8) Our knowledge is restricted **to five cases in total (He, Li, Be)**.
- 9) Halo states have unusually large **nuclear and electric reaction cross sections**.
- 10) The large size of the halo implies a narrow momentum distribution.
- 11) The halo neutron is in a mixed state containing its ground state and continuum states.
- 12) A halo neutron has a probability distribution that extends far beyond the core.

**References in [1] related to the above citation**

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### **An example of the neutron halo size; $^{11}\text{Be}$ ,**

The wave functions for the case of a single-neutron halo correspond to calculated (with Woods – Saxon potential) root-mean-square (r.m.s.) radii of the  $l=0, 1$  states of 5.99 and 5.66 fm, respectively. For comparison, the r.m.s. radius of a normal p-shell nucleus is 2.5 fm.

Thus, we do not know yet exactly what kind of wave functions the halo neutrons have in the medium mass-number nuclides such as Ti, Ni and Pd. However our knowledge about them is scarce yet, there surely exist neutrons with extended wavefunctions in lattice nuclei in CF materials.

We have utilized this property of neutron wavefunctions in the estimation for the possible interaction of two neutrons in different lattice nuclei mediated by interstitial protons or deuterons which we called *the super-nuclear interaction* [5]. The super-nuclear interaction makes possible formation of the neutron bands at the zero-energy level in which high density neutron states are formed (CF-matter). This state of neutrons has been the essential factor to make possible the CFP to occur.

Therefore, it is necessary to have not only the extended neutron wavefunction but also the proton/deuteron wavefunction (cf. Sketch 6) having contact interaction with the neutron wave function to realize the CF-matter and finally CFP.

It should be noticed about the diffusive terms that lie outside the standard quantum mechanics using the wave function [6]. The neutrons and protons/deuterons interacting each other as described above are “in persistent interaction where the diffusive terms become dominant.” Therefore, our approach [3 – 5] might be revised according to the new quantum mechanics where appears time evolution, which includes irreversibility [6].

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## 7. [Sketch 6]

### Proton/Deuteron Wavefunctions in Interstices of *fcc* (*hcp*) Transition Metals

It is a surprising fact that almost all cold fusion phenomenon (CFP) has been observed in *fcc* (and *hcp*) transition-metal hydrides and deuterides exclusively in metals Ti, Ni, and Pd. It is also true that there are selective combinations among the metal and hydrogen isotopes (and alkaline elements and other elements in electrolyte) such as Pd-D-Li, Ni-H-K and others.

On the other hand, the transition-metal hydrides and deuterides have been investigated for more than 100 years for their peculiar diffusion and occlusion properties of hydrogen isotopes.

It is therefore natural to investigate the physical properties of these transition-metal hydrides and deuterides in connection with the occurrence of the CFP. We have had speculated this problem a little in the recent papers and compiled them in a recent report [1] and a book [2].

It is interesting to know that the behavior of hydrogen isotopes in transition metals is divided into two classes; one in *bcc* metals (Zr, V, Nb, Mo, Ta etc.) and the other in *fcc* (and *hcp*) metals (Ti, Ni, Pd etc.). In the first class, atoms (or nuclei) of hydrogen isotopes are localized in an interstitial site (interstice) and there are a few works to determine the profile of their wavefunctions (Figs. 1 and 2). Accordingly, vibration and diffusion properties of these localized hydrogen isotopes have characteristics in accordance with the localization of the nuclei [1, Section 2.2].

On the other hand, in the second class, atoms (or nuclei) of hydrogen

isotopes are not localized in an interstitial site but extend to several interstices [1, Section 2.2]. And, therefore, vibration and diffusion characteristics of hydrogen isotopes are not discussed in parallel to the first class. In this class, there are no work on the wavefunctions of a proton and a deuteron in these metals suggesting difficulty to determine wavefunctions of non-localized particles (proton and deuteron).

In relation to the occurrence of the super-nuclear interaction proposed by us [2, Section 3.7.2], we have to estimate the wavefunction  $\Phi(\mathbf{R}, \mathbf{b}_j)$  of interstitial proton (or deuteron) at around a nearest neighbor lattice nucleus. The super-nuclear interaction determines the width of the neutron band and then the neutron density at a boundary/surface region. The latter is related to the CF matter that interacts with lattice nuclei, included nuclei and adsorbed nuclei at the boundary/surface region.

We have formulated this scenario in the second-order perturbation theory [1 – 3]. On the same line described in these publications, we discuss here a possibility to determine the proton/deuteron wavefunction in terms of the data obtained in the CFP research.

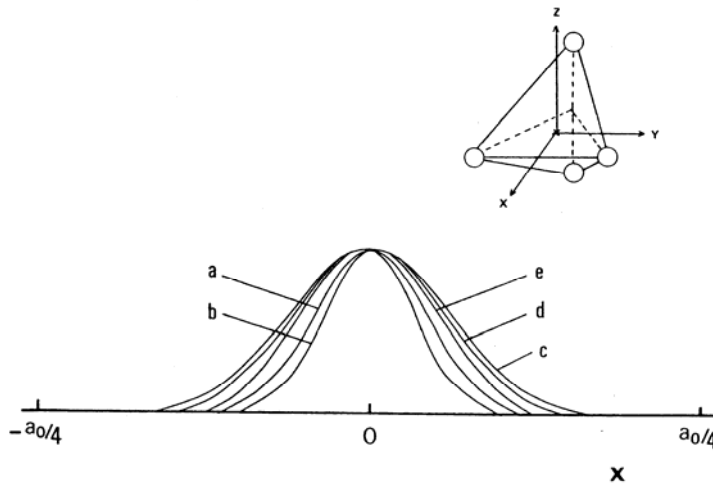


Fig. 1. Density profiles of H and D on T-sites in bcc metals (Nb, V, Ta) in the x-direction shown in the inset. Profiles calculated for a) a H-atom and b) a D-atom in Nb. Profiles observed by Reidinger et al.<sup>21,22)</sup> for c)  $\text{VD}_{0.79}$  at 70 degree C, d)  $\text{NbH}_{0.82}$  at 119 degree C and  $\text{NbD}_{0.73}$  at 140 degree C and e)  $\text{TaH}_{0.20}$  at 150 degree C. (Fig. 5 of H. Sugimoto and Y. Fukai, “Energy and Wave Functions of Interstitial Hydrogen in fcc and bcc Metals” *J. Phys. Soc. Japan* **51** (8), pp. 2554 – 2561 (1982) )

Let us write down the proton/deuteron wavefunction  $\Phi(\mathbf{R}, \mathbf{b}_j)$  at an interstice  $\mathbf{b}_j$  (the suffix  $j$  specifies the interstices) as a linear combination of localized wavefunctions (Wannier functions)  $W(\mathbf{R}, \mathbf{a}_i)$  at nearest-neighbor lattice points  $\mathbf{a}_i$  (the suffix  $i$  specifies the lattice points) around the interstice  $\mathbf{b}_j$  as follows (neglecting the spin part);

$$\Phi(\mathbf{R}, \mathbf{b}_j) = \sum_i A_{ji} W(\mathbf{R}, \mathbf{a}_i). \quad (1)$$

The coefficients  $A_{ji}$  give a density of a proton/deuteron at one of the adjacent lattice points  $\mathbf{a}_i$  of the interstice  $\mathbf{b}_j$ .

If we know  $\Phi(\mathbf{R}, \mathbf{b}_j)$ , the Wannier function  $W(\mathbf{R}, \mathbf{a}_i)$  at the site  $\mathbf{a}_i$  is calculated inversely from  $\Phi(\mathbf{R}, \mathbf{b}_j)$  by an inverse transformation of the equation (1);

$$W(\mathbf{R}, \mathbf{a}_i) = \sum_j B_{ji} \Phi(\mathbf{R}, \mathbf{b}_j). \quad (2)$$

The coefficients  $B_{ji}$  is calculated by  $A_{ji}$  and vice versa. In the simplest case where the Wannier function is expressed as a 1s-type function that has a finite value at the origin, we can determine the wavefunction of the proton/deuteron if we know the value  $A_{ji}$  by some means.

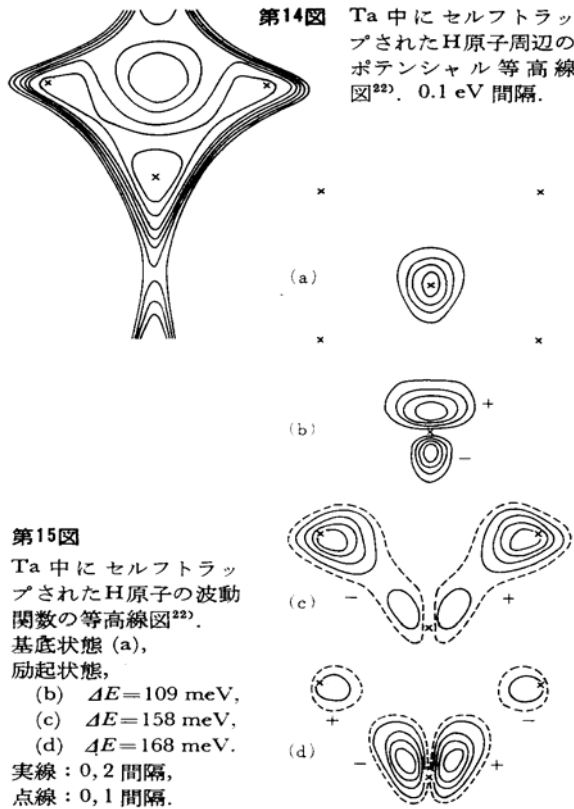


Fig. 2. Localization of a hydrogen atom at an interstice in a bcc transition metal Ta. In excited states, wavefunctions extend to the nearest lattice points and interstices.

**Upper left:** potential contour lines around a self-trapped H-atom in Ta.

**Lower right:** Contour lines of H-atom wavefunction self-trapped in Ta. (a) Ground state, (b) – (d) excited states with excitation energies of  $\Delta E = 109, 158$  and  $168$  meV, respectively. (After Y. Fukai, “Physical Properties of Metal Hydrides (I) and (II)” (in Japanese), *Kotai-Butsuri* 16, No. 4 (1981) and 17, No. 12 (1982))

From the estimation of the width of the neutron valence band ([1] Section 3.2, [3] Section 4) responsible to the experimental data of the CFP, we can determine the matrix element of the proton/deuteron – neutron interaction if we know the latter wavefunction. The neutron wavefunction in a nucleus at its halo state has been investigated intensively in nuclear physics. We will be able to obtain concrete information about neutron wavefunctions in medium mass-number nuclei like Ni and Pd in near future. Then, we might be able to calculate the proton/deuteron wavefunctions from experimental data obtained in the CFP. The resulting wavefunction will give information about the nature of the protons/deuterons related to their diffusion and vibration properties in *fcc/hcp* transition metals.

The interrelation between the solid-state physics of the transition –metal hydrides/deuterides and the CFP is not explored at all yet. However, as we have pointed out recently [1 – 3], there are apparent correlations between them. Intentional researches of this interrelation will be fruitful for both fields which have been investigated independently hitherto as if they are isolated fields.

### References

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2. H. Kozima, *The Science of the Cold Fusion Phenomenon*, Elsevier Science, 2006. ISBN-10: 0-080-45110-1.
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## 8. Conclusion

From the three laws found in the CFP as described in the Introduction and the specification of CF systems sufficient to expect the complexity to occur in them, we understand that the CFP is a phenomenon belonging to the complexity and therefore its investigation should be performed realizing the nature of the complex system. Many controversies around the CFP is resolved by our realization of its nature and new developments are

promising if we establish the science of the cold fusion phenomenon.

There remain unexplored fields of research about halo nuclei with medium mass numbers and also wavefunctions of occluded proton/deuteron in fcc/hcp transition metals. These properties of nuclei, proton and deuteron should be related closely to occurrence of the CFP.