

# COLD FUSION PHENOMENON AND SOLID STATE NUCLEAR PHYSICS

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The cold fusion phenomenon (CFP) is investigated in the wider perspective of modern physics including the physics of transition-metal hydrides, nuclear physics, and the science of complexity using quantum mechanics. The characteristics of CFP including the stability effect in nuclear transmutation and the inverse power law of excess power generation are consistently explained using concepts of the cf-matter presented at ICCF10 by the present author.

## 1. Introduction

We investigated the cold fusion phenomenon (CFP) phenomenologically at first<sup>1</sup> and then quantum mechanically.<sup>2,3</sup> Now, we are able to understand<sup>4</sup> the total image of this complex phenomenon as a whole without reference to Fleischmann's hypothesis (immense acceleration of D-D fusion reaction rate in solid transition-metal deuterides) which led to the pioneering work.<sup>5</sup>

The cold fusion phenomenon is an outstanding phenomenon revealing complexity, a science closely related with self-organization and chaos, in solids corresponding to such meteorological and geophysical phenomena as the typhoon, hurricane or the earthquake. Its cause is defined by characteristics of the complex system and the phenomenon destined to be irreproducible in a strict sense conditioned by stochastic and/or chaotic processes occurring in the microscopic atomic milieu in the sample. While atomic processes govern the cause, the effect is nuclear and therefore quantitative ratio of energies relevant with the effect and the cause reaches up to  $10^7$ . The effect accordingly is not completely averaged out as in atomic effects usual in solid-state physics and appears exotic for solid-state scientists. On the other hand, conventional mechanism of nuclear reactions between charged particles to overcome the Coulomb barrier is excluded in this situation: To reach a mutual distance of about 1 fm where the nuclear force works, the kinetic energy of the mutual motion of two charged nuclei should be  $10^5$  times larger than their thermal energy at the equilibrium state in solids.

The large size of the effect (about  $10^7$  times greater than that of the cause in energy scale) combined with the smallness of the effective microscopic process (about  $10^{-5}$  times that of the cause in space dimension) together induce spectacular events

rarely seen in nature. The chaotic nature of the process producing CFP includes qualitative but not quantitative reproducibility, which is popular in simple systems usually treated in modern physics. These features of CFP make it difficult to accept it in the field of scientific investigation for many scientists.

In this paper, we show a consistent explanation of the total feature of CFP using two laws discovered in the experimental data—the inverse power law of the excess power and the stability effect of the nuclear transmutation—as clues to understand this complex phenomenon.

## 2. Solid State-Nuclear Physics of CFP Revealed by Experimental Data

Schematically, the characteristics of CFP are itemized as follows.

### 2.1. *Phenomenological Characteristics of CFP*<sup>1,4</sup>

- A1. There are optimum combinations of the body material and hydrogen isotope. Experimental data obtained in these more than 10 years shows Pd-*d* and Ni-*p* satisfy this condition and are good combinations for CFP.
- A2. Formation of composite system (inhomogeneous and unsteady distribution of occluded hydrogen isotopes in a body metal) is a source of chaotic behavior in CFP.
- A3. There are optimum combinations of the body material and the electrolyte metal to realize active nuclei in the appropriate surface/boundary regions: e.g., Pd-Li, Ni-K, Na, and Ti-Li.
- A4. Production of tritium requires deuterium and that of <sup>4</sup>He requires <sup>6</sup>Li in the surface/boundary regions.
- A5. CFP is fundamentally irreproducible and has at most qualitative reproducibility in short time range.
- A6. The nuclear reactions may destroy necessary condition(s) for CFP and therefore CFP is fragile.

### 2.2. *Microscopic Processes in CFP*<sup>2,4</sup>

- B1. Lattice nucleus should have neutron levels at around the zero energy level (the evaporation level). Pd, Ti, and Ni satisfy this condition.
- B2. Interstitial protons/deuterons with wide spread wave functions which interact with neutrons in lattice nuclei.
- B3. Super-nuclear interaction of neutrons in lattice nuclei mediated by interstitial protons/deuterons.
- B4. Formation of neutron bands around zero level.
- B5. Formation of cf-matter at appropriate boundary/surface regions.
- B6. Neutron drops  ${}^A_Z\Delta$  (in the cf-matter)–nucleus  ${}^A_ZX$  interaction.

### 2.3. *Realization of Necessary Conditions for Neutron Band Formation*<sup>1,2</sup>

- C1. Ordered lattice nuclei with excited neutron levels around zero energy (evaporation level).
- C2. Nearly saturated occluded proton/deuteron with wave functions spread out at lattice nuclei.
- C3. Neutron (in a lattice nucleus) – proton/deuteron interaction by the nuclear force.
- C4. Neutron (in a lattice nucleus) – neutron (in another lattice nucleus) interaction mediated by the occluded protons/deuterons (super-nuclear interaction).
- C5. Formation of neutron bands due to the super-nuclear interaction.
- C6. Local coherence of neutron waves in a band at surface/boundary regions.
- C7. Enough number of neutrons in the band to realize cf-matter where are neutron drops ( $\frac{A}{2}\Delta$ ) composed of neutrons and a few protons.
- C8. Existence of exotic/disordered nuclei (active nuclei) at the surface/boundary regions to realize CFP by interactions with the neutron drops.
- C9. Nuclear reactions between a neutron drop ( $\frac{A}{2}\Delta$ ) and a nucleus ( $\frac{A}{2}X$ ) occur in a chaotic state and production rates of new nuclides governed by their stability.

### 2.4. *On the Wave Functions of Protons/Deuterons in Transition-Metal Compounds*<sup>4</sup>

We give here short explanation of some properties of interstitial protons/deuterons with wide spread wave functions in transition metals.

We know that CFP occurs only in *fcc* and *hcp* transition-metal hydrides and deuterides. In the transition-metal alloys, it is noticed that there are optimum combinations of metal and hydrogen isotopes: Some examples are Pd-*d*, Ni-*p*, and Ti-*d*, *p*.

Data of physical properties of transition-metal hydrides and deuterides show following nature of the wave functions of hydrogen isotopes. In PdH and PdD lattice, hydrogen or deuterium atoms occupy octahedral sites in ground states. In excited states, however, they are in tetrahedral sites and have more spread wave functions over several interstices.

There are several different characteristics in PdD and PdH: In PdD, Pd–D interaction is relatively weak and D–D interaction has the characteristic that the second neighbor D–D interactions is fairly strong comparable to the first neighbor D–D interaction.

In PdH, H–Pd interaction is comparable to H–H interaction even if H–Pd distance (2.03 Å) is less than that of H–H and the large value of the nuclear charge of

Pd ( $Z = 46$ ). Furthermore, it is probable that there is a repulsion of H atoms on next-nearest neighbor sites, which would overcompensate the attraction of nearest neighbor H atoms at high concentrations.

Activation energies for diffusion of D and H in Pd are 0.206 ( $T = 218-333$  K) and 0.23 eV ( $T = 230-760$  K), respectively.

These are some properties of Pd alloys, one of the most well investigated transition-metal hydrides and deuterides. Similar properties have been investigated in other alloys and they should be combined with data of CFP to elucidate quantum mechanical states of protons and deuterons in them.

### 2.5. *Electrochemistry of CFP*<sup>6</sup>

It is now evident that the cold fusion phenomenon occurs mainly in surface/boundary regions of solid materials including high-density hydrogen isotopes.<sup>1,6</sup> Especially in electrolytic systems, we have noticed the existence of optimum combinations of electrodes/electrolytes: some examples are Pd/D<sub>2</sub>O + LiOD/Pt, Ni/H<sub>2</sub>O + KOH/Pt. A special case, in addition to the above ones, successively used by John Dash of Portland State University and others is a combination Pd/D<sub>2</sub>O + H<sub>2</sub>SO<sub>4</sub>/Pt.

Unfortunately, this problem of optimum electrode/electrolyte combinations is not clarified yet. It is clear, however, that the formation of a surface layer with a composition appropriate to occlude hydrogen isotopes into cathode and to initiate nuclear reactions relevant with CFP is decisively important to realize CFP successfully.

## 3. Empirical Facts of CFP Show Its Complexity

There are too many experimental data sets to grasp physics behind them without a sound viewpoint. From those data sets, we could deduce two laws related to the essence of CFP.

### 3.1. *Inverse Power Law of the Excess Power Production*<sup>4</sup>

The analysis of the data by McKubre *et al.*,<sup>7</sup> in this section is far from complete. They will be able to give more extensive and complete analysis of the data along the same line of investigation as ours. We have counted number of observations  $N(P)$  from their Fig. 6 as shown in Table 1 and made a data table to depict a  $\log N$  vs.  $\log P$  graph as shown in Table 2.

The inverse power law of excess power generation is clearly seen in the region from  $\log P = -1$  to  $+0.1$  (from 1 to 12 of the abscissa). The data depicted in Fig. 1 expresses that  $N(P)$  is inversely proportional to  $P$ :

$$N(P) = \text{const. } P^{-a} \text{ with } a \approx 1.$$

The characteristic expressed in the graph of the excess power spectrum reveals that CF system shows "the self-organized criticality." This characteristic is common to

Table 1. Gross number  $N(P)$  of measurement point for the excess power  $P(W)$  grossly counted from Fig. 6 of McKubre et al.,<sup>7</sup> using Pd wire with a dimension 1 mm  $\phi \times$  36 cm (surface area of 11.3 cm<sup>2</sup>).

$P(W)$	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$N(P)$	400	240	160	140	120	100	60	60	40	40
$P(W)$	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2.0
$N(P)$	30	30	20	10	8	8	5	2	5	1

Table 2. Dependence of  $\log N(P)$  on  $\log P$  estimated from the data given in Table 1.

$\log P$	-2.1	-1.7	-1.6	-1.5	-1.4	-1.3	-1.2	-1.15	+0.1	0.2	0.3
$N(P)$	400	240	160	140	120	100	90	70	60	38	21
$\log N$	2.6	2.4	2.2	2.15	2.08	2.00	1.95	1.86	1.78	1.58	1.32

Note: The data given in Table 2 are plotted in Fig. 1.

many phenomena occurring in complex systems: a most well known example is the  $1/f$  noise of electric resistance noticed in 1925 by Johnson (the index  $a = 1$ ).

Other examples include the frequency of earthquakes vs. their intensity (Gutenberg Richter’s law,  $a = 0.47-0.73$ ) and the intensity distribution of winds. The distribution of wind speeds at heights 80 and 150m were measured in Japan at the time of a typhoon. The index for  $a$  (the two heights) was determined to be 1 and  $5/3$ , respectively.

Another interesting example of this behavior is the intensity of the cosmic ray measured at upper atmosphere. It obeys the  $1/f$ -law. The interesting point is its relation with the fluctuation of the inter-galactic magnetic field that obeys also the  $1/f$ -law. It is considered that the fluctuation of the intensity of cosmic ray reflects that of the magnetic field.

### 3.2. Stability Effect of Nuclear Transmutation of CFP<sup>3,4</sup>

The stability effect of nuclear transmutation in good coincidence with the abundance of elements in universe found in experimental data sets<sup>3,4</sup> clearly indicates

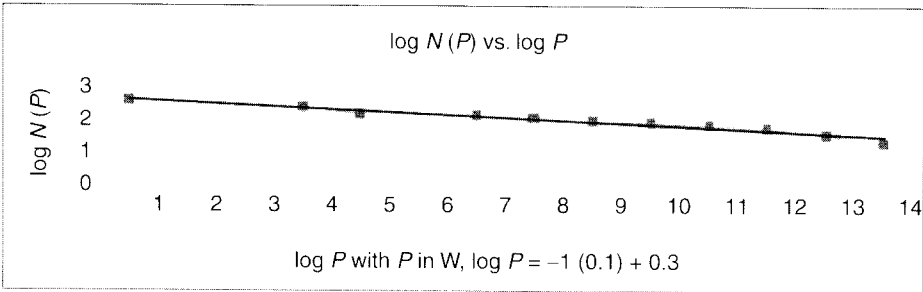


Figure 1. Plot of  $\log N$  vs.  $\log P$  from Table 2 showing linear dependence of  $\log N$  on  $\log P$  with a negative gradient with  $-1$ , the inverse power law. Linear line is drawn for the benefit of eyes.

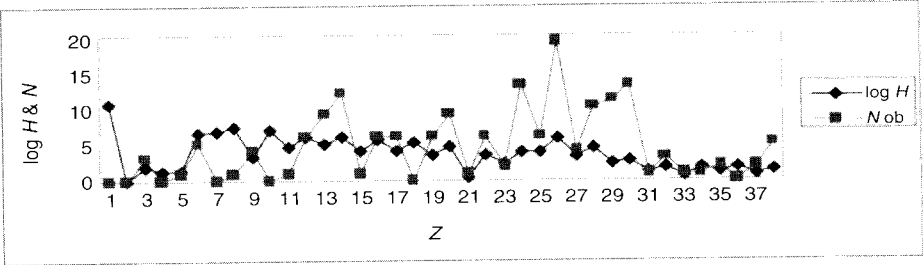


Figure 2. Stability effect of nuclear transmutation.<sup>3,4</sup>

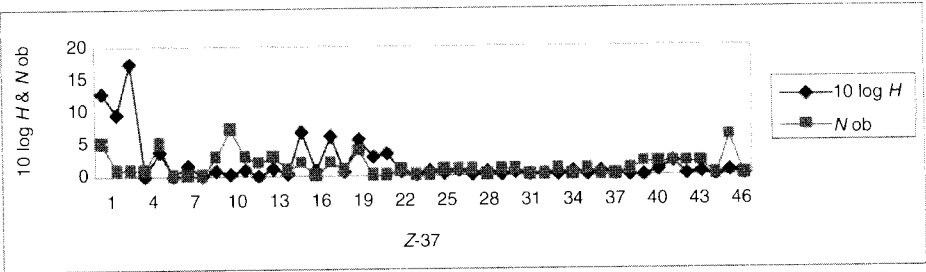


Figure 3. Stability effect of nuclear transmutation.<sup>3,4</sup>

the existence of compound states of nucleons in CF materials where stable configurations of nucleons are easily formed. This is a complex many-body system looked at from a somewhat different point from that given in the preceding subsection about the inverse power law.

4. Discussion

Experimental data sets obtained in the 15 years after the discovery of CFP<sup>5</sup> probably number more than a thousand, and we have concentrated too long on a narrow perspective with poor prospects. In our opinion, the data obtained until now have not been fully utilized to give a sound perspective for future development of CFP research. Perhaps it would be useful to depart from Fleischmann's hypothesis for a while and to look at the whole situation from various different points of view. Our approach has been a trial to reconcile experimental data such as the two laws explained in this paper with principles of modern physics.

We have to recall from statistical stability, a characteristic of the chaos that the trajectory in the phase space of a chaotic system is unstable to a small perturbation and non-reproducible but a time average of a physical quantity on the trajectory is stable and is reproducible.

The most direct evidence of this nature in CFP is shown in Fig. 1 as the inverse power law of the excess power generation and less directly in Figs. 2 and 3 as the stability effect of nuclear transmutation.

As we have emphasized several times,<sup>1-4</sup> the system where the cold fusion phenomenon occurs has the characteristics of complexity and phenomena occurring in them have inevitably qualitative reproducibility but not quantitative one.

A somewhat theoretical verification of the complexity of CFP is seen as follows. There are several situations in the microscopic process crucial to realize CFP. If other necessary conditions are fulfilled, it is necessary to have (a) an appropriate distribution of protons/deuterons to realize the super-nuclear interaction (Section 2, B3, C4), (b) an appropriate boundary/surface conditions to realize the local coherence (C6), (c) high density neutrons (B5, C7) to form the cf-matter including neutron drops, and (d) appropriate exotic nuclei to realize nuclear reactions with the neutron drops (B6, C8).

These conditions can be realized as self-organization, from a chaos-theory point of view.

We have to look at CFP from the above point of view if we notice the existence of the two laws in CFP—the inverse power law of excess power and the stability effect of NT. The necessary conditions for CFP explained in Section 2 from our point of view should be examined more carefully using experimental data.

It should be mentioned about a pioneering computer simulation on the self-organization in nuclear physics. Negele *et al.*,<sup>8</sup> showed a formation of a regular lattice by self-organization in neutron star matter. This is an example of self-organization exactly corresponding to the situation (C7) in CFP discussed above.

## References

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