Terminology

To describe and explain the various events in the cold fusion phenomenon, we have to use several new words to express exactly what have been observed as a whole without self-contradiction in this field.

A few of these new words are explained briefly in this Section with reference to each in the text as [Sec. 1.7] in the case of the word in the 1st edition or both in the 1st and the 2nd editions but as [II Sec. 2.5.6.1] in the case of the word only in the 2nd edition.

Affinity, neutron (→ Neutron affinity)
Bacteria and Microbial culture [II Sec. 2.5.6.3]
Bifurcation law [II Sec. 2.13.3] (also Three empirical laws)
Biotransmutation [II Sec. 2.5.6.3]
CF-matter [Sec. 3.7.5.1]
CF material [II Sec. 3.6.2]
CFP (→ Cold fusion phenomenon)
Cold fusion phenomenon (CFP) [Chapter 1]
Cross-linked polyethylene (XLPE) [II Sec. 2.5.6.1]
Decay-time shortening [Sec. 2.5.1.1, II Sec. 2.5.7]
Exotic nucleus [Sec. 3.5.3.1]
Fleischmann's hypothesis [Sec. 1.7]
Hydrogen graphite [II Sec. 2.5.6.2]
Instability factor [Secs. 2.4.1, 3.2.3]
Interstice [Sec. 3.7.2] (→ Superlattice)
Interstitials [Sec. 3.7.2] (→ Superlattice)
Inverse-power law [II Sec. 2.13.2] (also Three empirical laws)
Lattice nucleus [Sec. 3.7.2] (→ Superlattice)
Neutron, trapped (→Trapped neutron)
Neutron affinity [Sec. 3.5.4.3, II Sec. 3.7.8]
Neutron band [Sec. 3.7.2.2]
Neutron drop [Sec. 3.7.4] (→ CF-matter)
Number N_x of Reaction Product x [Sec. 2.3]
Qualitative reproducibility [Sec. A1]
Reproducibility (→ Qualitative reproducibility)
Stability law [II Sec. 2.13.1] (also Three empirical laws)

Superlattice [II Sec. 3.7.2]
Super-nuclear interaction [Sec. 3.7.2]
Three empirical laws in the CFP [II Sec. 2.13]
TNCF model [Secs. 2.4 and 3.2, II Sec. 3.2.3]
Transition-metal hydrides (deuterides) [Sec. 2.2.1]
Trapped neutron [Sec. 3.2.1]
XLPE (→Cross-linked polyethylene)

Bacteria and Microbial culture [II Sec. 2.5.6.3]

The experimental data sets in biological systems have been obtained in these about 20 years mainly by V.I. Vysotskii and his collaborators. In the papers by Vysotskii et al., there are data sets showing (1) production of $^{57}_{26}$Fe from $^{55}_{25}$Mn and also (2) acceleration of the decay of radioactive nucleus $^{157}_{55}$Cs, $^{140}_{56}$Ba and $^{140}_{57}$La in several bacterial cultures. These data were successfully explained by the TNCF model. To realize the complex structure of bacteria and microbial (microbiological) cultures used in their experiments, their fundamental structures are also shown [II Sec. 2.5.6.3].

Bifurcation law [II Sec. 2.13.3]

The bifurcation law in the CFP is a little subtle compared to other two laws, the stability law and the inverse-power law, which are statistically justified.

By the nature of events in complexity, we can give only *qualitative* explanation of experimental results in analogy to the mathematical results obtained by numerical simulations using the logistic difference equation. The analogical explanations of the law, called "the **bifurcation law**," for several experimental data observed in the CFP have been given [Kozima 2012a] using the nature of an equation of nonlinear dynamics, Feigenbaum's theorem [Feigenbaum 1978].

Biotransmutation [II Sec. 2.5.6.3]

Biotransmutation means the nuclear transmutation in biological systems observed for more than two centuries [Kozima 1998a (Sec. 10.19)]. The investigation of this phenomenon has been developed into microscopic stage by Vysotskii et al. in recent 20 years using microbial cultures and measuring new elements appeared in the system and temporal changes of the radioactivity of radioactive elements contained in the system.

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CF-matter [Sec. 3.7.5.1]

As we know in the case of the neutron star matter with a neutron density N_n, there appears a lattice of ordered neutron drops ${}^{A}{}_{Z}\Delta$ made of Z protons and $(A - Z)$ neutrons when N_n is as high as 10^{30} cm^{-3} [Negele 1973].

The calculation of the density $n_{\rm n}$ of neutrons in the neutron energy bands formed in CF materials suggested us the possibility of such a high density neutrons in surface regions where neutron Bloch waves are reflected cooperatively. The neutron liquid composed of neutrons and protons in these regions of the CF material is called the **CF-matter** where are formed **neutron drops** ${}^{A}{}_{Z}\Delta$ composed of $(A - Z)$ neutrons and Z protons [Sec. 3.7.5].

Formation of the CF-matter is therefore the key elements of the CF material to show the cold fusion phenomenon. We have shown that the conditions for the formation of the CF-matter is best fulfilled in such CF materials as ordered transition-metal deuterides and hydrides (PdD_x, NiH_x), hydrogen graphite (HC_6) and cross-linked polyethylene $(CH_2)_n$ (x ≈ 1, $n = 10^y$ ($y \approx 10^{10}$).

Cold fusion phenomenon (CFP) [Chapter 1]

CFP (Cold Fusion Phenomenon) stands for

"Nuclear reactions and accompanying events occurring in open (with external particle and energy supply), non-equilibrium system composed of solids with high densities of hydrogen isotopes (H and/or D) in ambient radiation" belonging to Solid-State Nuclear Physics (SSNP) or Condensed Matter Nuclear Science (CMNS).

Cross-linked polyethylene (XLPE) [II Sec. 2.5.6.1]

The cross-linked polyethylene (XLPE) is used as a shielding material in high-voltage electric current transportation. There is a serious problem of deterioration of the shielding accompanied with water-tree formation. In the course of the investigation of the deterioration, it was found that the deterioration accompanies generation of new elements – nuclear transmutation and emission of gamma rays. The structure of XLPE is shown in Fig. 1 which shows a regular arrangement of carbon and hydrogen common in the CF materials of transition-metal hydrides.

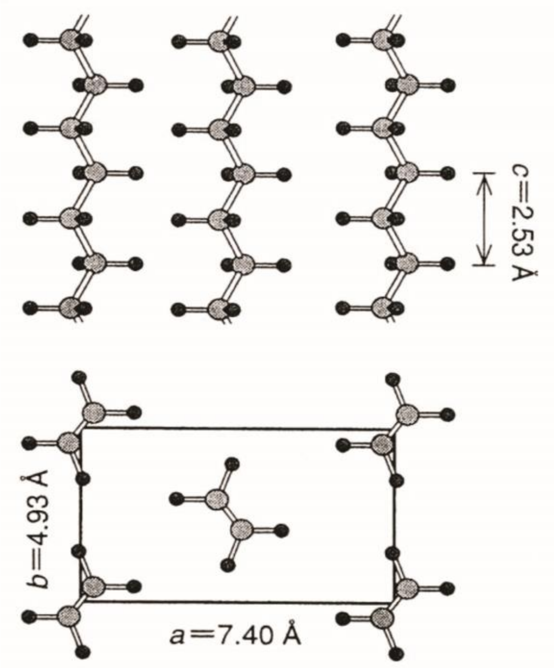

Fig. 1 Lattice structure of XLPE orthorhombic lattice with lattice constants, *a* = 7.40 Å (740 pm), *b* = 4.93Å (493 pm), *c* = 2.53 Å (253 pm) [Kozima 2010 (Fig. 5)].

The experimental data of the nuclear transmutation and emission of gamma rays in XLPE are explained by the TNCF model [II Sec. 2.5.6.1].

Decay-time shortening [Sec. 2.5.1.1, II Sec. 2.5.7]

In the nuclear transmutations, there are several cases where the decay times τ_d of the intermediate compound nuclide ${}^{A}_{Z}X^*$ in free space are very long of orders of 10^6 to 10^9 years (10^{12} – 10^{15} s). The time elapsed in experiments is at most several months ($\approx 10^5$ s). Therefore, if the decay products with such long decay times are observed, there should be drastic shortening of the decay times [Sec. 2.5.1.1].

In addition to this experimental fact in the CFP, there are several experiments showing the same effect in radioactive nuclides when they have been placed in the CF material: e.g. ${}^{235}_{92}U$ in U_3O_8 deposited on NiH_x, and ${}^{140}_{56}Ba$ and ${}^{140}_{57}La$ in biological systems [II Sec. 2.5.7].

Exotic nucleus [Sec. 3.5.3.1]

Existence of exotic nuclei with large imbalance of the proton number *Z* and the neutron number N (= A – Z) in isolated states of a nucleus ${}^{A}{}_{Z}X$ has attracted strong attention and has been extensively investigated in recent years. In recent works, it was confirmed existence of ${}^{32}{}_{12}Mg$, ${}^{42}{}_{14}Si$, ${}^{69}{}_{29}Cu$, ${}^{73}{}_{29}Cu$, ${}^{92}{}_{42}Mo$ which were investigated in relation to the bases of the shell model of nucleus.

These investigations of exotic nuclei at the large proton number elements in nuclear physics might be the signal of existence of such exotic nuclei as ${}^{A}{}_{6}C$, ${}^{A}{}_{28}Ni$, and ${}^{A}{}_{46}Pd$ with the nucleon numbers *A's* exceeding largely the values of ordinary isotopes. Existence of these exotic nuclei of elements participating in the cold fusion phenomenon gives a positive factor for formation of neutron bands and realization of CF-matter necessary for nuclear reactions in the CF materials (cf. Super-nuclear interaction).

Fleischmann's hypothesis [Sec. 1.7]

M. Fleischmann and his collaborators had performed their experiments on the PdD_x according to the hypothesis (***Fleischmann's hypothesis***) that the occluded deuterons in the Pd lattice might be able to fuse together due to their specific properties in the alloy. This fact has been expressed explicitly and implicitly in their papers [Fleischmann 1989, 1998a, 1998b].

We can cite sentences expressing this hypothesis explicitly or implicitly.

"*In view of the very high compression and mobility of the dissolved species there must therefore be a significant number of close collisions and one can pose the question: would nuclear fusion of* D^+ *such as*

$${}^{2}D + {}^{2}D \rightarrow {}^{3}T\ (1\ 01\ \text{MeV}) + {}^{1}H\ (3\ 02\ \text{MeV}) \qquad \text{(v)}$$

or

$${}^{2}D + {}^{2}D \rightarrow {}^{3}He\ (0.82\ \text{MeV}) + n\ (2.45\ \text{MeV}) \qquad \text{(vi):}$$

be feasible under these conditions?" [Fleischmann 1989].

"*The observation of the generation of neutrons and of tritium from electrochemically compressed* D^+ *in a Pd cathode is in itself a very surprising result and, evidently, it is necessary to reconsider the quantum mechanics of electrons and deuterons in such host lattices*." [Fleischmann 1989].

"*As is well-known the outcome of our experiments was radically different from our expectations. It became evident that there were markedly enhanced rates of nuclear reactions as shown by the generation of excess enthalpy at levels far above those which can be accounted for by chemical reactions. Moreover, this generation of excess enthalpy was not accompanied by the expected levels of the "nuclear ashes", tritium and neutrons*." [Fleischmann 1998b]

Despite of the oversimplified assumption of ***the Fleischmann's hypothesis***, their work guided by this hypothesis revealed a miraculous achievement to open the new field of solid-state nuclear physics, or condensed matter nuclear science, called now *the cold fusion phenomenon*, phenomenon accompanying nuclear reactions in room-temperature solids.

Hydrogen graphite [II Sec. 2.5.6.2]

It is known that graphite forms intercalation compound with alkaline metals such as potassium graphite KC_8 or calcium graphite CaC_6. About the hydrogen, it is not known the formation of intercalation compound HC_x, (x = 6 – 8?) at around room temperature. While at higher temperature around 3000 K, the diffusivity of hydrogen in graphite becomes very high compared with the almost zero values at lower temperatures. So, we may assume formation of an intercalation compound of hydrogen and carbon at high temperatures above 3000 K with a composition HC_x, (x = 6?) and structure similar to that of CaC_6 shown in Fig. 1. The formation of hydrogen graphite with the structure assumed above will give our explanation of nuclear transmutations observed in carbon arc experiments [II Sec. 2.5.6.2].

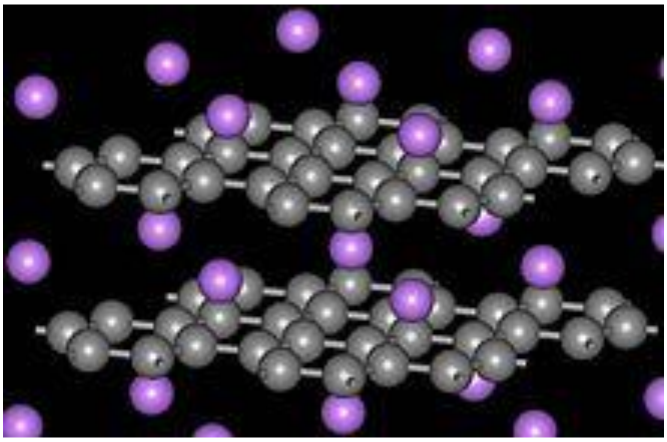

Fig. 4 Structure of CaC_6 (after Wikipedia): violet spheres represent Ca nuclei between layers of carbon nuclei (grey spheres).

Instability factor [Secs. 2.4.1 and 3.2.3]

In the original idea of the trapped neutron, neutrons were assumed to be similar to free electrons in metals itinerant over CF materials freely. In this case, it was necessary to take into some artifice to express experimental result of local nature of nuclear reactions in the CFP. So, we assumed following characteristic for the trapped neutrons;

"The trapped thermal neutron is assumed to react with another nucleus in the surface layer of the solid with a ratio expressed by a parameter (the instability parameter) ξ. The parameter ξ is assumed to be $\xi = 1$ in the surface layers and $\xi < 0.01$ in volume."
"If the stability of the trapped neutron is lost by a large perturbation in the surface/ boundary layer or in volume, the number of trigger reactions (per unit time) between trapped thermal neutrons and a nucleus ${}^{A}{}_{Z}X$ may be calculated by the same formula as the usual collision process in a vacuum but with an instability parameter ξ:

$$P_f = 0.35\, n_n\, v_n\, n_X V \sigma_{nX} \xi, \qquad (2.4\text{-}1)$$

where $0.35\, n_n\, v_n$ is the flow density of the trapped thermal neutrons per unit area and time, n_X is the density of the nucleus ${}^{A}{}_{Z}X$, V is the volume where the reaction occurs, σ_{nX} is the cross section of the reaction. The instability parameter ξ as taken into the relation (2.4-1) expresses an order of the stability of the trapped neutron in the region as explained above."

Investigation of neutron bands in CF materials developed after the year of 2001 gave us a basis of the "assumption $\xi = 1$ in the surface layers" by the accumulation of neutrons by the coherent reflection there (Sec. 3.7.2.3). So, we do not need the instability factor ξ in such an equation (2.4-1) just writing it as

$$P_f = 0.35\, n_n\, v_n\, n_X V \sigma_{nX},$$

applying it only to irregular nuclei at surface regions. This is the reason we do not include the factor ξ in many reaction formulae used in Chapter 3.

Inverse-power law [Sec. 2.12, II Sec. 2.13.2]

In several experimental data sets, we are able to count numbers N_Q of an event (excess heat) with a specific amount Q (or an excess power P) and plot them as a function of Q (or P) obtaining a N_Q vs. Q (or P) plot. The first plot was obtained for the data by McKubre et al. [McKubre 1993, Kozima 2006a (Sec. 2.12)]. This plot clearly has shown that there is a relation of frequency vs. intensity with an exponent of 1 famous in complexity. This regularity has been shown later for the data sets obtained by Dash et al. [Kozima 2008d] and for extensive experimental data sets accumulated by E. Storms [Storms 2007, Lietz 2008].
This regularity is called the "**inverse-power law,"** or inverse-power dependence of frequency on intensity, of the excess heat production.

Neutron affinity [II Sec. 3.7.8]

The neutron affinity η is defined by a following relation;

$$\eta \equiv -\left({}^{A+1}{}_{Z}M - {}^{A+1}{}_{Z+1}M \right) c^2. \qquad (1)$$

Here, c is the light speed in vacuum, ${}^{A}{}_{Z}M$, in this case, is the mass of the nucleus with a mass number A and an atomic number Z composing the lattice nuclei [Kozima 1998a (Sec. 12.6)].

Neutron band [Sec. 3.7.2.2]

Neutron band is a band structure of the energy of neutrons interacting with each other corresponding to the electron energy band popular in solid state physics. The neutron band is formed in neutrons interacting through the super-nuclear interaction in CF materials.

Number N_x of Reaction Product x [Secs. 2.3 and 3.2.3]

If any nuclear reaction is pertinent to CFP, it is desirable to determine the number of reactions, or the number of events, by experimental results related to events in the CFP. Usually, several physical quantities relate to one nuclear reaction and there exists a relation (or relations) among numbers of measured quantities.

Let us explain this relation using a following reactions between two deuterons, for instance;

$$d + d \rightarrow {}^{4}{}_{2}\mathrm{He}^{*} \rightarrow t\ (1.01) + p\ (3.12), \qquad Q_1 = 4.13, \qquad (1)$$

$$\rightarrow {}^{3}{}_{2}\mathrm{He}\ (0.82) + n\ (2.45), \qquad Q_2 = 3.27, \qquad (2)$$

$$\rightarrow {}^{3}{}_{2}\mathrm{He}\ (0.08) + \gamma\ (23.8), \qquad Q_3 = 23.8. \qquad (3)$$

where energies are in MeV.

In these reactions, observables are triton $t = {}^{3}{}_{1}\mathrm{H}$ (or tritium T = ${}^{3}\mathrm{H}$), proton $p = {}^{1}{}_{1}\mathrm{H}$ (or hydrogen H), helium-3 ${}^{3}{}_{2}\mathrm{He}$, neutron n , photon γ and the liberated energy as excess heat *Q's if it is thermalized in the material or system* where the reaction occurred. Observing numbers of tritium N_t and hydrogen atoms N_p together with excess heat Q_1 (MeV) in the case of the reaction (1), and confirming relations between them

$$N_t = N_p = N_{Q1} \equiv Q_1/4.13, \qquad (4)$$

we can confirm almost definitely the occurrence of the reaction (1) in the system. Here, we defined the number of nuclear reactions N_{Q1} producing excess heat Q_1 by

$$N_{Q1} \equiv Q_1\ (\mathrm{MeV})/4.13\ \mathrm{MeV}. \qquad (5)$$

According to the knowledge in nuclear physics of *d-d* fusion reactions in free space, the branching ratios of the reactions (1) – (3) are known to be 1 : 1 : 10^{-7}. If the branching ratios of these reactions in CF materials are the same to those in free space by any reason, we obtain following relations among N_x's as a whole using the average number $< N_Q >$ of reactions by the observed value of excess energy $Q = Q_1 + Q_2$, while

$N_{Q1} = N_{Q2} = 10^7 N_{Q3}$ in this case,

$$< N_Q > \equiv (Q_1/4.13 + Q_2/3.27)/2 = (N_{Q1} + N_{Q2})/2; \quad (6)$$

$$N_t = N_p = N_{He\text{-}3} = N_n = 10^7 N_{He\text{-}4} = 10^7 N_Y = < N_Q >. \quad (7)$$

It is then the litmus test of a theory to compare these values N_x's calculated by the theory with the values determined by experiments.

The generalization of above consideration is an easy work and given in Sec. 2.3 and Sec. 3.2.3.

Qualitative reproducibility [Sec. A1]

Qualitative reproducibility or Statistical reproducibility characterizes processes occurring in complex systems contrasting to the quantitative reproducibility of the cause-effect relation of events occurring in simple systems described by differential equations. The origin of the qualitative or statistical reproducibility may be in the uncertainty principle in quantum mechanics for microscopic objects.

Stability law [Sec. 2.15, II Sec. 2.13.1]

If we survey numbers of elements produced by the nuclear transmutation in the CFP, we notice the frequency obtaining an element has a positive correlation with the amount of the element in the universe. Plotting out (i) the number of experiments where observed an elements $_Z$X together with (ii) that of the amount in the universe compiled by Suess and Urey [Suess 1956] against its proton number Z, we obtain a diagram in which we see the coincidence of the peaks of numbers (i) and (ii). This correspondence is called the stability effect for nuclear transmutation products at first [Sec. 2.15]. Investigating experimental data statistically, we found regularity in the experimental data, the inverse-power dependence of the frequency of observations on their intensity. Then we may call these regularities the empirical laws and the stability effect explained above is called the "**stability law**" for nuclear transmutation in the CFP.

Superlattice [II Sec. 3.7.2]

In such CD materials as transition-metal hydrides/deuterides (e.g. PdD_x and NiH_x), the host metal nuclei are distributed on **lattice points** of an *fcc* lattice and the protons/deuterons are distributed on a lattice composed of **interstitial points** (or **interstices**) of the fcc lattice. The whole system is considered to be a **superlattice** composed of two sublattices, one of the host nuclei and another of protons/deuterons.

A schematic two-dimensional structure of the superlattice of PdD/NiH is shown in Fig. 1 by wavefunctions of host nuclei and protons/deuterons. In this figure, host nuclei on an *fcc* sublattice are shown by small dots and protons/deuterons on an interstitial sublattice are shown by large circles.

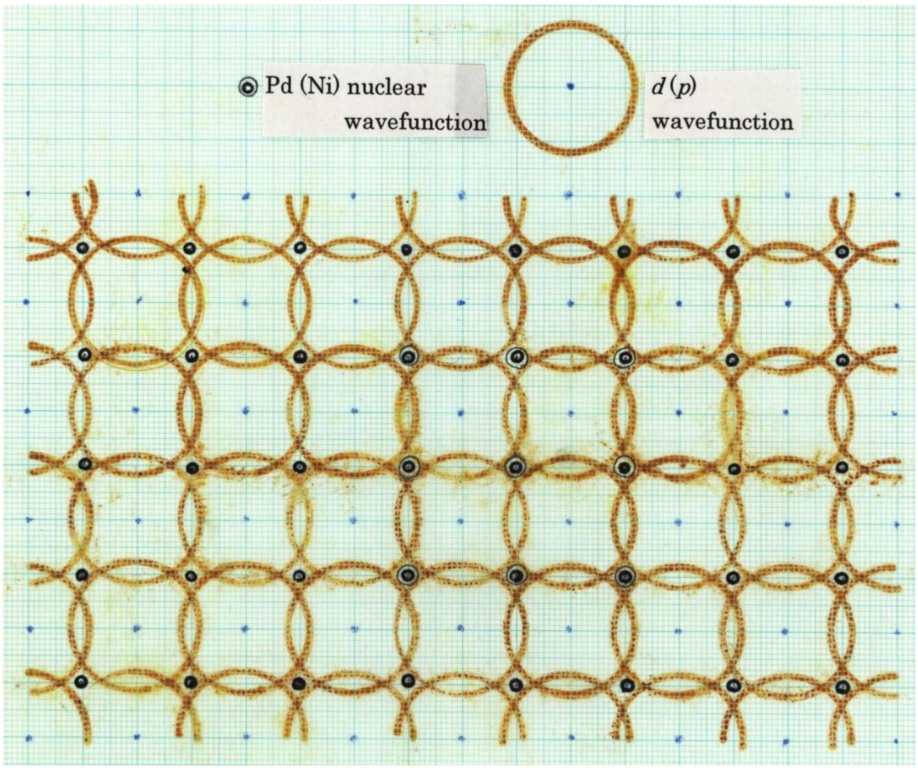

Fig. 1 Schematic two-dimensional figure of a superlattice PdD (NiH) formed of host nuclei Pd/Ni and deuterons/protons.

Host nuclei at lattice points are sometimes called **lattice nuclei** and protons/deuterons at interstitial sites are called **interstitials**.

Super-nuclear interaction [Sec. 3.7.2]

Super-nuclear interaction is an interaction between two nucleons (neutrons) in different lattice nuclei mediated by a proton (or a deuteron) interacting with the nucleons through the strong interaction (nuclear force). This mediation is possible only when the wavefunction of the proton (or deuteron) extends to both lattice nuclei as in the cases of transition-metal hydrides (e.g. PdD and NiH) and of carbon-hydrogen systems in hydrogen graphite and hydrocarbons.

Three empirical laws in the CFP [II Sec. 2.13]

There have been discovered three empirical laws in the CFP;

1: **The First Law** – the effect of stability of nuclei in nuclear transmutation products on the production frequency (**the stability law**),

2: **The Second Law** – the inverse power dependence of the frequency on the intensity of the excess heat production (**the inverse-power law**), and

3: **The Third Law** – bifurcation of the intensity of events (neutron emission and excess heat production) in time (**the bifurcation law**).

There are two corollaries of the first law:

The corollary 1-1 – Production of a nuclide ${}^{A'}_{Z+1}X'$ from a nuclide ${}^{A}_{Z}X$ in the system.

The corollary 1-2 – Decay-time shortening of unstable nuclei in the system.

These laws and the necessary conditions for the CFP tell us a new situation in the CF materials that has not been known before.

TNCF model [Secs. 2.4 and 3.2, II Sec. 3.2.3]

The TNCF model is a phenomenological one and the main basic premises (assumptions) extracted from experimental data sets are summarized as follows

Premise 1. We assume a priori existence of the quasi-stable trapped thermal neutrons with a density n_n in pertinent solids (CD materials), to which the neutron is supplied essentially from the ambient neutron at first and then by breeding processes (explained below) in the sample [Kozima 1998a]. The origin of the trapped neutron is reconsidered to include the neutrons in neutron energy bands composed of neutron states in lattice nuclei due to the super-nuclear interaction [II Sec. 3.2.3].

The density n_n in a sample is a single adjustable parameter in the TNCF model, which will be determined by an experimental data set using the common supplementary premises, which will be explained below concerning reactions of the trapped neutron with other particles in the solids. The quasi-stability of the trapped neutron means that the neutron trapped in the crystal does not decay until a strong perturbation destroys the stability while a neutron in the free space decays with a time constant of 887.4±0.7 s (the half-life of 615 s).

Premise 2. The trapped thermal neutron reacts with another disordered nucleus in the surface/boundary regions and in volume of a CF material, where it suffers a strong perturbation. The fusion reaction between a trapped thermal neutron and one of lattice nuclei ${}^{A}_{Z}X$ is described as in Eq. (1) where an excess energy Q and nuclear products are written as follows:

$$n + {}^{A}_{Z}X = {}^{A+1-b}_{Z-a}X' + {}^{b}_{a}X'' + Q, \qquad (1)$$

where ${}^{0}_{0}X \equiv \gamma$, ${}^{1}_{0}X \equiv n$, ${}^{1}_{1}X \equiv p$, ${}^{2}_{1}X \equiv d$, ${}^{3}_{1}X \equiv t$, ${}^{4}_{2}X \equiv {}^{4}_{2}He$, etc.

Premise 3. The reaction probability of the nuclear reaction explained above is assumed to be given by the Eq. (2) as if they are in the free space:

$P_f \;= 0.35\, n_n\, v_n\, n_X\, V\, \sigma_{nX}$, (2)

where 0.35 n_n v_n is the flow density of the trapped thermal neutrons per unit area and time, n_X is the density of the nucleus $^{A}{}_{Z}X$ in a volume V where the reaction occurs, σ_{nX} is the cross section of the reaction.

It is assumed that the cross-sections of the above reactions are the same to the values determined in the free space.

Premise 4. The liberated energy Q in the nuclear reactions (e.g. in Eq. (2)) explained above is distributed in the CF material due to the strong interaction between neutrons in the neutron band which are strongly coupled with superlattice of the host and hydrogen.

Transition-metal hydrides (deuterides) [Sec. 2.2.1]

Transition-metal hydrides and deuterides of *fcc* structure are most popular CF material in the CFP and most often used to show positive results. Fig. 1 shows palladium deuteride PdD crystal as an example of the atomic structure of transition-metal deuterides and hydrides.

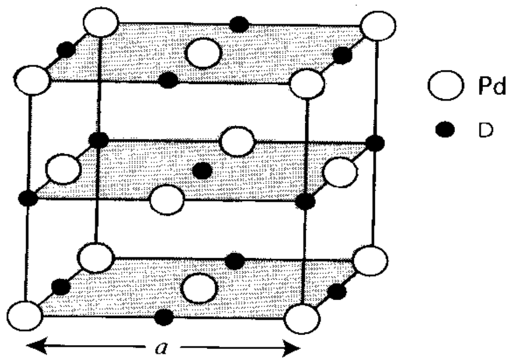

Fig. 1 Lattice structure of PdD crystal where deuterons are located at octahedral sites of the *fcc* lattice of Pd.

It is an empirical law that PdD and NiH are suitable to the CFP than PdH and NiD which was explained by our TNCF model and neutron band formation due to the super-nuclear interaction [Kozima 2014c (Appendix A3)].

The use of the transition-metal hydrides is preferred by many experimentalists may due to their stability in ordinary experimental conditions over other CF materials such as hydrogen graphite, XLPE and bacteria.

Trapped neutron [Sec. 3.2.1]

Trapped neutron is a neutron itinerant in CF materials like a conduction electron in metals and semiconductors. The origin of the trapped neutrons is the thermal neutrons trapped in the material by reflections at boundary surfaces or the neutrons in neutron bands formed in the CF materials. The characteristics of the trapped neutrons in terms of their interaction with irregular nuclei in the lattice or at surfaces of CF materials are not well developed yet even if it is assumed in the TNCF model as similar to thermal neutrons in free space interacting with isolated nucleus.