TNCF MODEL – A POSSIBLE EXPLANATION OF COLD FUSION PHENOMENON

H. Kozima [1]

ABSTRACT

The TNCF model with a single adjustable parameter for the cold fusion phenomenon (CFP), a complicated phenomenon composed of various events occurring in complex systems, is explained as an example of the phenomenological approach with several Premises based on experimental facts. Applied to many selected data sets, the model has given consistent explanations of CFP and therefore the Premises of the model may be taken as reflections of some phases of physics in the materials where CFP occurred. Selections from more than 60 data sets explained by the TNCF model have a statistical meaning even if each data set may include some faults or errors. Physical bases of the Premises are investigated using physics of neutrons in solids.

A. INTRODUCTION - Necessity of a Phenomenological Model

The cold fusion phenomenon (CFP), more precisely "nuclear reactions and accompanied events in solids with high density hydrogen isotopes," is an extremely complicated phenomenon occurring in complex systems composed of composite solids including hydrogen isotopes of high density covered by surface layers of alloys and/or metals or oxides evolving ambient background radiations, especially neutrons.

After the discovery of some phases of its events in 1989 [1], the various phases of the phenomenon, or events have been explored, ranging from the excess heat production, tritium and helium-4 generation, neutron and photon emissions (with energies up to about 10 MeV), and generation of transmuted nuclei with atomic numbers larger than 4 [4]. These experimental events seem to have been wholly published by now and are divided into two categories, direct or indirect, in terms of their relation to assumed nuclear reactions. Explaining them: *the direct evidence* of nuclear reactions includes spatial distribution of transmuted nuclei and energy spectra of emitted neutrons and gamma photons, and **the indirect evidence** includes the large excess heat (unexplainable by chemical processes) and amounts of generated tritium, helium-4, X-ray, and transmuted nuclei.

Other remarkable characteristics of the phenomenon are its **sporadic occurrence** and **qualitative reproducibility,** which are also characteristics of phenomena occurring in chaotic systems. These phases of CFP together with its various products should be finally explained by a theory (or theories).

There is a plethora of complicated experimental data in CFP, accumulated in these eleven years, waiting to be explained by one or more theories. As a working hypothesis, it is possible, of course, to consider these events in CFP to be caused by several different mechanisms working in the same system. On the other hand, it is also possible to seek a single cause as a fundamental mechanism for all events in CFP. Which viewpoint one takes in the research is a matter of one's aesthetics. An approach to understanding given in this paper belongs to the latter phenomenological approach, i.e. we try to explain CFP as a whole by a theory where a fundamental cause induces various events for the phenomenon.

First of all, it is helpful to summarize the physical situation where CFP occurs, in order to understand the global structure of the phenomenon and the necessity for a phenomenological approach.

Solids are composed of atoms with number densities of about 10^{23} atoms per cm^{-3} or with mutual distances of about 3×10^{-8} cm. Average kinetic energy (thermal energy) of an atom or an electron at 300 K is about 25 meV (= 0.025 eV).

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[1] Present Address: Portland State University, Physics Department, P.O. Box 751, Portland, OR97207-0751, USA.
Future Cold Fusion Research Laboratory, Yatsu 597-16, Shizuoka 421-1202, JAPAN

On the other hand, the fusion reaction between two nuclei, e.g. two deuterons, occurs when they approach mutually to about 10^{-13} cm which is achieved with a mutual energy of more than 100 keV (or 10^5 eV) to overcome the Coulomb repulsion. It is said, therefore, that two deuterons in any solids (and in molecules) need 10^8 times (eight orders of magnitude larger) thermal energies to approach a distance 10^{-5} times shorter than the equilibrium distance in solids (and in molecules).

From these facts, we can conclude the great difficulty of the fusion reaction of two deuterons in solids and in molecules assisted by electrons and phonons having energies of about 25 meV.

It should be briefly explained what a characteristic of the **phenomenological approach** contrasted to the **fundamental approach** is to avoid unnecessary confusion. In the fundamental approach, the logic to explain a phenomenon starts from established Principles and ends up with a Mechanism (or a single functioned model) assumed to explain a phase of the phenomenon even if several appropriate assumptions would be used to develop the logic or mathematics.

On the other hand in the **phenomenological approach**, the logic starts from Premises assumed *a priori* in the Model to explain the phenomenon. The value of the Premises, assumed without justification by principles, are evaluated by the degree of success accomplished by the model in the explanation of the phenomenon. If the usefulness of the assumed Premises is established, then the Premises are accepted as targets of justification on the basis of the Principles. Alternatively, some of the Principles are overthrown by the Premises based on the experimental facts in the phenomenon, as illustrated by many famous examples in the history of science.

Our next step to present the TNCF (trapped neutron catalyzed fusion) model, therefore, is the explanation of its Premises in terms of experimental facts of CFP too complicated to be presently explained by fundamental approaches.

B. PREMISES OF THE TNCF MODEL SUGGESTED BY EXPERIMENTAL FACTS OF CFP

The cold fusion phenomenon (CFP) occurs in solids where the distance between particles is about 10^{-8} cm and the average energy of a particle is about 25 meV as explained above. On the other hand, nuclear reactions between charged particles which occurs at a mutual distance of 10^{-13} cm, can only effectively occur when the mutual energy of reacting particles is above about 100 keV. Therefore, a nuclear reaction in solids, if it occurs, may be catalyzed not by constituent charged particles (electrons, protons and other nuclei) but by neutral particles in solids.

The TNCF model is a phenomenological one using a neutral particle, the neutron, as a catalyst of nuclear reactions in solids and the basic Premises (assumptions) extracted from experimental data sets, are summarized as follows in terms of relevant experimental facts [2~4]:

First, there are many experimental data sets showing the effects of the background neutron starting at the beginning of the controversy about the reality of CFP in 1989. There have been no positive data without the background neutron. All attempts to verify or check the reality of CFP without background neutrons failed without exception. On the other hand, there are several data showing positive effects of thermal neutrons in CFP. These experimental facts result in the first Premise of the TNCF model:

Premise 1. We assume *a priori* the existence of the quasi-stable trapped thermal neutrons with a density n_n in pertinent solids, where the neutron is supplied essentially from the ambient neutron at first, and then by breeding processes in the sample (explained below).

The density n_n, *is* a single adjustable parameter in the TNCF model which will be determined by experimental data set (or sets obtained simultaneously) using the supplementary premises (explained below) concerning reactions between the trapped neutron and 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 free neutron decays spontaneously with a half-life of 886.7 ± 1.9 secondss.

It is anticipated from this nature of CFP (depending on the background neutron) that the well-known "inverse correlation of solar activity with a period of 11 years and neutron flux on the Earth" should be reflected in an annual change of probability of success in experiments of CFP.

Second, there are experimental data showing **localization** of nuclear reactions responsible to CFP, especially the nuclear transmutation (NT) at crystal boundaries or in surface regions as explained more in Section E [4]. To explain this phase of CFP, it is necessary to assume localization of effective reactions between the trapped quasi-stable neutron and nuclei in the crystal lattice (lattice nuclei) which results in the second Premise:

Premise 2. The trapped neutron in a solid reacts strongly with another nucleus in the surface layer of the solid, where the nucleus suffers a strong perturbation. We express this property by taking the parameter (the instability parameter) ξ, defined in the relation (1) written down below, as one (ξ=1), which means the interaction is the same as it is in vacuum.

The instability parameter ξ in the surface layer is not known and it can be more than one ($1 \le \xi$), as noticed recently, making the determined value *of* the parameter n_n smaller. This ambiguity is suggested by recent experimental data *of* various anomalous changes *of* decay character *of* radioactive isotopes and of unexpected fission products in the surface layer. (cf. Discussions in the second paragraph of Section G.)

There are some experimental data sets observed in solids without a surface layer or in volumes far from the boundary region. To treat these data sets, it is necessary to assume reactions in solids expressed in the third Premise:

Premise 3. The trapped neutron reacts with another perturbing nucleus in the volume of a solid by a reaction rate given in the relation (1) below with a value of the instability parameter $\xi \le 0.01$ due to its stability in the volume (except in special situations, such as at very high temperature as 3000 K).

These three Premises are essential ones in the TNCF model. The following Premises (4 to 7) on the measured quantities of nuclear products and the excess heat common for all materials are used for simplicity to calculate reaction rates :

Premise 4. Product nuclei of a reaction lose all their kinetic energy in the sample except if they are emitted without energy loss.

Premise 5. A nuclear product, observed outside of the sample, has the same energy as its initial (or original) energy.

This means that if an energy spectrum of a gamma-ray photon or a neutron are observed outside, it reflects the directly nuclear reactions in the solid sample. The same is true for the distribution of a transmuted nucleus in the sample. Those spectra and the distributions of the transmuted nuclei are **the direct information** of the individual events of the nuclear reaction, in the sample, as explained in the previous section.

Premise 6. The amount of the excess heat is the total liberated energy in nuclear reactions dissipated in the sample except that energy brought out by nuclear products as observed outside.

Premise 7. Tritium and helium measured in a system are accepted, as they are generated in the sample.

The amounts of the excess heat, tritium, and helium are accumulated quantities reflecting three nuclear reactions in the sample and are **the indirect information** of the individual events as explained in the previous section.

Furthermore, Premises 8 to 11 (about structure of the sample and the behavior of product particles) are assumed for simplicity of calculation, as follows:

Premise 8. In electrolytic experiments, the thickness ℓ of the alkali metal layer on the cathode surface (surface layer) will be taken as ℓ = 1 μm (though the experimental evidences show that it should be 1 ~10 μm).

Premise 9. The mean free path or path length ℓ_t of the triton with an energy 2.7 MeV generated by $n + {}^6_3Li$ fusion reaction [Eq.(10) below] will be taken as ℓ_t = 1 μm irrespective of material of the solid. Collision and fusion cross sections of the triton with nuclei in the sample will be taken as the same as those in vacuum.

Premise 10. Efficiency of detectors will be assumed as 100 % except as otherwise described, i.e., the observed quantities are the same as those generated in the sample and as are observed by the detector in experiments, provided there is no description of the detector's efficiency.

A further premise will be assumed in order to calculate the number of events N_Q which produce the excess heat Q.

Premise 11. In the calculation of the magnitude of an event (a nuclear reaction) *NQ* producing the excess heat Q, the average energy liberated in the reactions is assumed as 5 MeV unless the reaction is identified where the liberated energy is known: *NQ* = Excess heat Q (MeV)/ 5 (MeV).

The origin of the trapped thermal neutron can be considered principally as 1) the ambient background neutrons, the existence of which have been recognized widely in public; and secondarily, 2) the neutrons breed in the sample by chain nuclear reactions triggered by reactions of the trapped neutron with perturbing nuclei, as explained in the next Section.

C. REACTIONS BETWEEN THE TRAPPED NEUTRON AND LATTICE NUCLEI AND ITS EFFECTS

If the quasi-stability of the trapped thermal neutron is destroyed by a large perturbation in the surface layer or in the volume, the number of reactions (trigger reactions) between the trapped neutron and one of lattice nuclei ${}^A_ZX$ in a time τ may be calculated by the same formula as the usual collision process in vacuum but with an instability parameter ξ:

$$P_f = 0.35\, n_n\, v_n\, n_X\, V \sigma_{nX} \tau \xi, \tag{1}$$

where $0.35\, n_n v_n$ is the flow density of the trapped thermal neutron per unit area and time, n_X is the density of the nucleus ${}^A_ZX$, V is the volume where the reaction occurs, σ_{nX} is the cross section *of* the reaction determined in vacuum. The instability parameter ξ as taken into the relation (1) expresses an order of the quasi-stability of the trapped neutron in the region as explained in Premises 2 and 3, and also in the next Section.

If a fusion reaction occurs between a trapped thermal neutron and one of the lattice nuclei ${}^A_ZX$ with a mass number A and an atomic number Z, there appears an excess energy Q and nuclear products as follows:

$$n + {}^A_ZX = {}^{A+1-b}_{Z-a}X' + {}^b_aX'' + Q\,, \tag{2}$$

where ${}^0_0X \equiv \gamma$, ${}^1_0X \equiv n$, ${}^1_1X \equiv p$, ${}^2_1X \equiv d$, ${}^3_1X \equiv t$, ${}^4_2X \equiv {}^4He$, etc.

The liberated energy Q may be measured as the excess heat by the attenuation of the nuclear products, γ and charged particles, carrying the liberated energy as generated in the nuclear reaction. Otherwise, the nuclear products may be observed outside with an energy (we assume it as the original one, hereafter) or may induce succeeding nuclear reactions (breeding reactions) with one of other nuclei in the sample.

The particles generated in the trigger reaction (2) can induce nuclear reactions with other particles in the sample due to their high energy before they are dissipated. In these reactions, it is usual to generate one or several neutrons and they can be called **breeding reactions**. Several examples of the breeding reactions are written down as follows;

$$\gamma + {}^A_ZX = {}^{A-1}_{Z}X + n\,, \tag{3}$$

$$n + {}^A_ZX = {}^{A-1}_{Z}X + n + n'\,, \tag{4}$$

$$d + {}^A_ZX = {}^A_ZX + p + n \quad \text{, or} \tag{5}$$

$$d + {}^{A}_{Z}X = {}^{A+1}_{Z+1}X + n \qquad (6)$$

$$t + {}^{A}_{Z}X = {}^{A}_{Z}X + p + n + n' \text{ , or} \qquad (7)$$

$$t + {}^{A}_{Z}X = {}^{A+2}_{Z+1}X + n \qquad (8)$$

D. EXPLANATION OF EVENTS IN A DATA SET WITH A SINGLE PARAMETER n_n

In general, the number of events (reactions) N_{nX} in time τ between the trapped neutron n and the lattice nuclei $^A{}_ZX$ in a reaction region of a volume V is given by a relation similar to (1) :

$$N_{nX} = 0.35\, n_n\, v_n\, n_X\, V \sigma_{nX}\, \tau \xi \text{ ,} \qquad (9)$$

where n_X *is* the density of the nucleus X, Q_{nX} is the cross section of the reaction and ξ is the instability parameter defined in Premises 2 and 3.

In cases where there is a surface layer of Li metal on the cathode, the numbers of tritium N_t and helium-4 atoms N_{He}, generated in a n - ${}^6_3$Li reaction with a cross section 940 b

$$n + {}^6_3\mathrm{Li} = {}^4_2\mathrm{He}\ (2.1 \text{ MeV}) + t\,(2.7 \text{ MeV}) \text{ ,} \qquad (10)$$

are determined by the relation (9) and is also number of the events N_Q generating the excess heat of 4.8 MeV per reaction :

$$N_t = N_{He} = N_Q \equiv Q\,(\text{MeV})\,/4.8\ (\text{MeV}). \qquad (11)$$

A relation between N_n and N_t in D/Li system with the surface layer of Li metal is, then, given as follows; when the n -^{6}Li reaction is predominant in an electrolytic system with D^20, a neutron with an energy 14.1 MeV is generated by the reaction between a deuteron and a triton with an energy 2.7 MeV generated in the $n -$ ${}^6_3$Li reaction (10):

$$t + d = {}^4_2\mathrm{He}\ (3.5 \text{ MeV}) + n\,(14.1 \text{ MeV}). \qquad (12)$$

Number of this reaction is calculated by a relation (13) given below which determines a relation between N_n and N_t assuming half of the generated triton contributes the reaction (12);

$$N_n \sim N_t\, \ell_t\, n_d\, \sigma_{t} - d, \qquad (13)$$

where $\ell_t \sim 1$ μm (Premise 4), the density of deuterons $n_d = 6.8 \times 10^{22}\, X \text{ cm}^{-3}$ (x = D/Pd) and the cross section σ_t - $d \sim 1.4 \times 10^{-1}$ b. For x = 1, we obtain a relation:

$$N_n / N_t = 9.5 \times 10^{-7} \sim 10^{-6} \text{ ,} \qquad (14)$$

$$\text{or } N_t / N_n = 1.1 \times 10^{6} \sim 10^{6}. \qquad (15)$$

These quantitative results (11) and (15) on the number of the events are compared with the lucky experimental data sets where several events are observed in a sample simultaneously. Some of the results are given in Table 1. Several events explained qualitatively by the model with an adjustable parameter n_n shows applicability of the TNCF model for CFP. It seems that the parameter S/V (the surface-to-volume ratio of the sample) should be larger than a limit (~ 5 cm^{-1}) to give a positive result in CFP; the larger the S/V ratio, the higher the qualitative reproducibility of an event.

Table I: TNCF Model Analysis of CFP Data. Neutron Density n_n and Relations between the Numbers N_X of Event X are Determined by TNCF Model (NQ - Q (MeV)/5 (MeV)). Typical value of the surface vs. volume ratio S/V(cm-1) of the sample is tabulated, also.

Authors	System	S/V cm^{-1}	Measured Quantities	n_n cm^{-3}	Other Results (Remarks)
Fleischmann et al.	Pd/D/Li	6 ~ 40	Q, t, n $N_t/N_n \sim 4 \times 10^7$ $N_Q/N_t \sim 0.25$	~ 10^9	(Q =low/cm^3) $N_t/N_n \sim 10^6$ $N_Q/N_t = 1.0$
Morrey et al.	Pd/D/Li	20	Q, ^{4}He ^{4}He in $\ell \leq 25$ μm	4.8×10^8	$N_Q/N_{He} \sim 5.4$ (If 3% ^{4}He in Pd)
Chien et al.	Pd/D/Li	4	^{4}He in surf. layer and t, no ^{3}He	1.8×10^6	$N_t/N_{He} \sim 1$ (If few% ^{4}He in Pd)
Takahashi et al.	Pd/D/Li	2.7	t, n $N_t/N_n \sim 6.7 \times 10^4$	3×10^5	$N_t/N_n \sim$ 5.3×10^5
Miles et al.	Pd/D/Li	5	Q, ^{4}He ($N_Q/N_{He} = 1 \sim 10$)	~ 10^{10}	$N_Q/N_{He} \sim 5$
Okamoto et al.	Pd/D/Li	23	Q, NT_D $\ell_0 \sim 1$ μm	~ 10^{10}	$N_Q/N_{NT} \sim 1.4$ (^{27}Al → ^{28}Si)
Bockris et al.	Pd/D/Li	5.3	t, ^{4}He; $N_t/N_{He} \sim 240$	3.2×10^6	$Nt/N_{He} \sim 8$
Cellucci et al.	Pd/D/Li	40	Q, ^{4}He $N_Q/N_{He} = 1 \sim 5$	2.2×10^9	(IfQ = 5W) $N_Q/N_{He} = 1$
Iwamura et al.	PdD_x and Pd/ $CaOPd_x$/Pd	20	Q ~ 1W, $N_{NT}/N_Q \sim 1$ NT_F (Ti, Fe, Cu etc.)	3.1×10^{10}	$N_{NT}/N_Q)_{th} = 1$ ~ 3

In the case where the solid occluding deuterium (or protium) has no surface layers, we have to consider a trigger reaction between a trapped neutron and a deuteron (or a proton) in addition to those between a trapped neutron and one of lattice nuclei:

$$n + d = t\,(6.98 \text{ keV}) + \gamma\,(6.25 \text{ MeV}), \tag{16}$$

$$n + p = d\,(1.33 \text{ keV}) + \gamma\,(2.22 \text{ MeV}). \tag{17}$$

It should be pointed out here a riddle of rare observation of (or lack of) those photons with energies 2.22 and 6.25 MeV expected from Eqs. (16) and (17). In several experiments, these photons have been observed in reality. The observations are, however, rather rare compared with other events in CFP. There are, therefore, many attempts to seek nuclear reactions assisted by particles or quasi-particles in solids generating no photons. The reason of the lack of photons in CFP will be given in Section F from a viewpoint of the TNCF model.

E. NUCLEAR TRANSMUTATION IN SOLIDS

In these several year, there have been observed occurrences of nuclear transmutation (NT) of elements with the atomic number Z larger than 4 in the surface region of cathodes in electrolytic systems. A characteristic of CFP revealed explicitly by NT is the localization of nuclear reactions in the surface layer (cf.

Premise 2). This property had been suggested by frequent detection of ^{4}He outside of cathodes in electrolytic experiments and confirmed by the localization of nuclear products of NT at the surface region, even if there have been a few observation of transmuted light nuclei in the volume of cathodes (cf. Premise *3).*

The NT is divided into two types; NT_D explained by a decay of elements formed in the system and NT_F by a fission of them. These experimental facts are explained by the TNCF model as follows consistently with other data in CFP.

1. Nuclear Transmutation by a Decay (NTD)

Fundamental reactions used in the explanation of NTD are such reactions Eq. (2) between a trapped neutron and one of nuclei in the material followed by a beta or an alpha decay. Some examples of them are written down as follows:

$$n + {}^{23}_{11}\mathrm{Na} = {}^{24}_{11}\mathrm{Na}^* = {}^{24}_{12}\mathrm{Mg} + e^- + \overline{\nu}_e \;, \tag{18}$$

$$n + {}^{39}_{19}\mathrm{K} = {}^{40}_{19}\mathrm{K}^* = {}^{40}_{20}\mathrm{Ca} + e^- + \overline{\nu}_e \;, \tag{19}$$

$$n + {}^{\mathrm{A}}_{46}\mathrm{Pd} = {}^{\mathrm{A+1}}_{46}\mathrm{Pd}^* \rightarrow {}^{\mathrm{A+1}}_{47}\mathrm{Ag} + e^- + \overline{\nu}_e \;, \tag{20}$$

$$n + {}^{16}_{8}\mathrm{O} = {}^{17}_{8}\mathrm{O}^* = {}^{13}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} \tag{21}$$

These reactions with the assumption of the decay time shortening (the decay time of ${}^{A+1}_{Z}X$ * determined in free space is usually too long to explain NT_D) were used to analyze the data sets showing NT_D and the results were tabulated in the Table 2. [2]

Table II: TNCF Model Analysis of NT Data. Neutron Density n_n and Relations between the Numbers N_X of Event X are Determined by TNCF Model (NQ - Q (MeV)/5 (MeV)). Typical values of the surface vs. volume ratio S/ V (cm-1) of the sample is tabulated, also.

Authors	System	S / V cm $^{-1}$	Measured Quantities	n_n cm $^{-3}$	Other Results (Remarks)
Bush	Ni/H/K Ni/H/Na	~ 160 ~ 160	NT_D (Ca) NT_D (Mg)	5.3×10^{10} 5.3×10^{11}	N_Q / N_{NT} ~3.5 if$_T$ = 0 for ^{40}K)
Bush	Ni/H/Rb	~ 10^4	NT_D (Sr)	1.6×10^7	$N_Q / N_{NT} \sim 3$
Savvatimova et al.	Pd/D_2	100	NT_D (Ag)	9×10^{10}	
Passell	Pd/D/Li	400	NT_D	1.1×10^9	$N_{NT} / N_Q = 2$
Okamoto et al.	Pd/D/Li	*23*	Q, NT_D ℓ_0 ~1 μm	~ 10^{10}	$N_Q / N_{NT} \sim 1.4$ (^{27}Al ~ ^{28}Si)
Yamada	Pd/D_2	185	n , NT_D (C)	2.0×10^{12}	
Miley	Pd/H/Li	150	NT_F (Ni,Zn, ...)	4.5×10^{12}	
Dash	Pd/D, H_2SO_4	57	Q, NT_D	~ 10^{12}	Pt → Au
Notoya	Ni/D, H/K	3.4×10^4	NT_D (Ca)	1.4×10^9	(Sintered Ni)
Bockris et al.	Pd/H/		NT_F (Mg,Si,Cs,Fe, etc. in 1 μm layer)	3.0×10^{11}	Only Fe (10% of Pd) is taken up
Mizuno	Pd/D/Li (If Cr in Pd)	3.4	Q, NT_D $\ell \leq 2$ μm)	2.6 ~ 10^8	τ = 30d, Pd 1 cm ϕ x 10 cm
Ohmori	Au/H/K	*200*	Q, NT_F (Fe)	~ 10^{11}	(Au plate)
Miley	Ni/H/Li	50	NT_D (Fe,Cr,.)	1.7×10^{12}	
Iwamura	PdD_x,and Pd /CaOPd$_x$/Pd	*20*	Q ~ 1W, $N_{NT} / N_Q \sim 1$ NT_F (Ti, Fe, Cu etc.)	3.1×10^{10}	$N_{NT} / N_Q)_{th}$ = 1 ~ 3
Qiao	Pd/H_2	185	NT_F (Zn)	3.8×10^{10}	(40% NT in 1y)

2. Nuclear Transmutation by a Fission (NT_F)

As relevant nuclear reactions in nuclear transmutation by a fission (NT_F), we may consider a fission reaction with emission of several (say υ) neutrons induced by an energetic or a thermal neutron (and/or an energetic charged particle generated by a cold fusion reaction):

$$n(\varepsilon) + {}^{A}_{Z}X = {}^{A-A'+1}_{Z-Z'}X' + {}^{A'}_{Z'}X'' , \tag{22}$$

$$n(\varepsilon) + {}^{A}_{Z}X = {}^{A'}_{Z-Z'}X' + {}^{A''}_{Z'}X'' + \nu\, n, \quad (A + 1 = A' + A'' + \upsilon) . \tag{23}$$

The fusion reactions of a medium nucleus induced by a neutron in free space usually needs several tens MeV. In the CFP, however, the possible maximum energy of a particle generated by a reaction assumed in the TNCF model is that of the neutron generated by a breeding reaction (12) and is 14.1 MeV. Therefore, the experimental results showing NTF should be an evidence of the lowering of threshold energies for fission reactions occurring in materials from those in vacuum.

There is another possibility to induce the fission reactions resulting in NTF in CFP with low energy neutrons. It is a reaction by several neutrons absorbed successively or simultaneously by a nucleus followed by a fission of the so-formed unstable nucleus:

$$\nu n(\varepsilon) + {}^{A}_{Z}\mathrm{X} = {}^{A+\nu}_{\ \ Z}\mathrm{X}^* \tag{24}$$

$$= {}^{A'}_{Z'}\mathrm{X}' + {}^{A-A'+\nu-\nu'}_{Z-Z'}\mathrm{X}'' + \nu' n, \qquad (A+1 = A' + A'' + \nu) \tag{25}$$

The accumulation of neutrons in the boundary region or surface region should be observed in solids as discussed in the next section and be responsive to reaction (24) if the first step of the reaction occurs simultaneously,

The fission reactions illustrated above with the lowering of threshold energies were used to analyze the data sets showing $\mathrm{NT_F}$ and the results were tabulated in the Table 2 together with those of $\mathrm{NT_D}$. [2]

F. LOCAL COHERENCE, NEUTRON DROP, PHYSICS OF CFP

Since its discovery in 1932, the neutron has been investigated as a component of nuclei, as a nucleon itself, and as a particle for material analysis. It is an elementary particle with a mass 939.55 MeV, a spin ½ ħ and a magnetic moment 1.9135 μ_N. The neutron is unstable in free space and decays into a proton liberating an energy of 782 keV with a time constant of 886.7 ± 1.9 s:

$$n = p + e^- + \bar{\nu}_e . \tag{26}$$

However, neutron in materials have not been investigated thoroughly as yet. From our viewpoint, CFP deserves a powerful tool to disclose properties of neutrons in solids.

1. NEUTRON BAND AND LOCAL COHERENCE AT BOUNDARY REGION OF NEUTRON BLOCH WAVES

A phase of behavior of a neutron in a crystal lattice, not noticed clearly until now, is the formation of a band structure in the energy spectrum of the neutron [5]. A neutron in a crystal interacts with nuclei in the crystal lattice (lattice nuclei) by the nuclear force. In a periodic potential of a lattice, the wave function of a neutron, expressed by a plane wave in free space, is a Bloch wave modified by a factor with the same periods to those of the lattice and the energy spectrum becomes stratified to be a band structure.

Due to the strong interaction with very short range ~10^{-13} cm of the nuclear force, a neutron band in the crystal lattice of attractive interaction becomes peculiar compared with the electron band popular in solid state physics. For an appropriate strength of the interaction constant, the lowest neutron band above zero in the standard of free space has the energy minimum at a Brillouin zone boundary. The lowest band in the free space, in this case, is pulled into the negative energy region and represents trapped states. The concept of the **neutron affinity** of a nucleus defined to treat material aptitude for CFP [2] seems to reflect this property of nuclear interaction between a neutron and a lattice nucleus.

The larger the neutron affinity of a nucleus with a positive sign is, the stronger the attractive interaction potential is of the nucleus for a neutron is, and the whole band structure of the energy spectrum of the neutron becomes lower in energy. We have noticed that all nuclei used in CF experiments have positive neutron affinities if they have shown positive results of CFP. [2] This fact suggests a strong correlation between the structure of the neutron band in a solid and occurrence of CFP in such band.

If the energy minimum of a band above zero is at Brillouin zone edge, there appears the **local coherence** of wave functions of neutrons in the band [4]. The local coherence makes the density of neutrons at the boundary region very high. The one-body approximation used to calculate the band structure of the energy spectrum fails here where we must take into consideration the strong mutual nuclear interaction between neutrons.

The characteristics of the trapped neutron assumed in the Premises 1 and 2 of the TNCF model explained in Section 2 [2~ 4] may be interpreted as a demonstration of the feature revealed by the occurrence of the local coherence and such related phenomena as the neutron drop investigated in the next subsection.

2. Neutron Drop $n_{A-Z}\, p_Z$

If the crystal contains many nuclei of hydrogen isotopes as metal hydrides or deuterides used in CF experiments, the high density neutrons in the boundary region can form a neutron drop $n_{A-Z}\, p_Z$ ($Z \ll A$) developed from one of lattice nuclei or from a *n-p* or *n-d* cluster [6].

Some properties of the neutron drop can be investigated using the evaporation model of nuclear reaction. In an equilibrium state, evaporation and condensation are reverse processes in balance and the same situation is also in quasi-equilibrium state which we consider hereafter.

In the evaporation model, the evaporated neutron from a nucleus has the Maxwell energy distribution characterized by a temperature Θ defined by the level density of the residual nucleus. The thermal energy of ~ 25 meV in CF experiments is very small in the scale of that in nuclear reaction and the temperature Θ is almost constant for a neutron drop, a group of many neutrons and a few protons, supposed to be formed in the boundary region. The evaporation channel of the neutron drop is not known at present and we have to estimate it from experimental data obtained in CF experiments if possible.

The formation of the neutron drop $n_{A-Z}\, p_Z$ ($Np \equiv Z \ll N_n \equiv N = A - Z$), or the neutron cluster including several protons, is considered as follows. As the exotic nuclei may be formed from ordinary nuclei in solids at crystal boundaries where high density neutrons are located: the neutron drops can be formed there from *p* or *d* (or even from another lattice nucleus) as a seed when sufficient neutrons be supplied to increase neutron number N_n in the drop. One-body approximations which includes local coherence of neutron Bloch waves in a band loses its validity if the strong interaction between nucleons is addopted.

As is shown in the papers [3,4], a phenomenological approach to CFP is effective in the present stage of investigation. The nuclear transmutation observed in CFP have been explained as consistent with other data with an adjustable parameter n_n of values 10^8 to 10^{12} cm^{-3} [2~4]. By the success of the TNCF model and the polyneutron model [7] in the analysis of data in CF phenomenon (CFP), it is probable that there are high density neutrons in the samples having positive results of CFP.

Assuming high-density neutrons in the surface region suggested by CFP, we could give some information about a possible state of neutrons in the metal hydrides or deuterides, the neutron drop $n_{A-Z}\, p_Z$ with radius R defined by a relation.

$$\frac{4\pi}{3} R^3 n_d = N_n$$

where n_d is the density of neutrons in the drop. The evaporation rate P_e of a neutron is defined by the following equation through parameters of the system [6]:

$$P_e = 0.35 n_d v_d 4\pi R^2 \left(\frac{R}{R_M} \right)^{\beta}, \quad \text{where} \quad R \le R_M\,, \tag{27}$$

and where β is a constant depending probably on N_p (to be determined later using experimental data), v_d is velocity of neutrons in the neutron drop and R_M is the maximum value of *R* depending on p_Z.

Then, the radius R is expressed by parameters of the system as follows:

$$R = \frac{3}{4\pi}(\eta n_n)^{1/\beta} r_0^{(\beta-1)/\beta} \; N_0^{1/3}, \quad \text{where} \quad R \le R_M \ . \tag{28}$$

The numerical factor β is calculated using experimental data as follows: [6]

$$\beta \sim 14.7 \quad (\text{when } \eta = 1) \tag{29}$$

This relation shows a very strong dependence of evaporation rate P_e on the radius R of the drop and suggests stable existence of a neutron drop with $R = R_M$. These conclusions depend strongly on the assumption made about nature of the neutron drop and should be considered as tentative findings.

With these reservations on the quantitative conclusions, we may be able to discuss qualitative nature of the neutron drop. The neutron drop $n_{A-Z}\, p_Z$ ($Z \ll A - Z$) and the exotic nuclei (extremely neutron-rich nuclei) are states of neutrons in the boundary region of metal hydrides (deuterides) formed through their interaction with protons and ordinary nuclei. It might be probable to form an exotic nucleus (Z dai A) than a neutron drop (Z daidai A) when there is a low density neutrons around a seed, proton or another nucleus.

Probability of neutron capture by a deuteron (cross section = 5.5 x 10^{-4} barns (b)) is rather small compared with that by appropriate nuclei in the material, i.e. ${}^{48}_{22}\mathrm{Ti}$, ${}^{58}_{26}\mathrm{Ni}$ and ${}^{104}_{46}\mathrm{Pd}$ with capture cross sections of 7.8, 4.5 and 8.5 b, respectively. This tendency is, probably, the cause of frequent observations of NT products compared with tritium (and helium-4) in systems without ${}^{6}_{3}\mathrm{Li}$ (capture cross section of which is very large as 940 b) in recent experiments. Further, interaction of the neutron drop with the exotic nucleus should be taken into consideration to understand CFP as a whole as done with a primitive assumption in the explanation of the mass spectrum of transmuted nuclei in NT_F [7].

3. Physics of Cold Fusion Phenomenon (CFP)

The estimation given in this paper is based on the assumption that the CFP is real and indicates some states of matter described by Quantum Mechanics. A new phenomenon, if it is really new, should include one or more factors not noticed before and related with the phenomenon. This factor is not known or missing in past and may be called a **missing factor** as noticed already [2]. The CFP should be resolved by a missing factor if it is a real one, according to the author's viewpoint. The missing factor of the CFP **is trapped neutrons** from the viewpoint of the TNCF model [2- 4] and it is the polyneutron in a model[7] proposed for NT_F.

The tentative estimation of several properties of the neutron drop in metal hydrides and deuterides, given in the preceding subsection in terms of experimental data in CFP and knowledge of the neutron band, should be revised by more elaborate calculations of the manybody system with neutrons, hydrogen isotopes, and lattice nuclei distributed heterogeneously in a solid.

The lack of photons in CFP described in Section 4 can be explained by the mechanism of nuclear reactions between a neutron drop and one of lattice nuclei instead of such reactions including a single neutron as in Eqs. (2) and (4). The energy emitted as a photon in two-body reaction as in Eqs. (16) and (17) could be shared by other nucleons in the neutron drop and not emitted outwards as a photon. This might be a reasonable explanation of the lack of photons in CFP consistent with other events.

G. CONCLUSION – VALUES OF N_N, SPORADIC OCCURRENCE AND QUALITATIVE REPRODUCIBILITY OF EVENTS IN CFP

Typical values of the adjustable parameter n_n, determined by experimental data sets, where several events are observed in the same sample are shown in Table 1 and those determined in terms of NT in Table 2. Generally speaking, the values of n_n, determined using more than 60 experimental data sets (including those given in Tables 1 and 2) are between 10^8 and 10^{12} cm $^{-3}$. This is a rather large value and its meaning (assumed at first as a density of the trapped thermal neutrons in solids) has to be reconsidered. This problem with others concerned with Premises should be understood in relation with the evolution of the TNCF model.

Considering new knowledge about neutrons in solids given in the preceding section, the parameter n_n, should be interpreted as the density of neutrons at boundary region where main reactions of CFP occur and where there is local coherence of the neutron Bloch waves. The density of neutrons in a volume is, then, several orders of magnitudes lower than the values given in Tables 1 and 2.

Next, given here are qualitative explanations of the two remarkable characteristics of CFP, i.e. **sporadic occurrence** and poor reproducibility or **qualitative reproducibility** of its events. In the following, we confine our discussion to electrolytic systems with electrolytes of alkali metals.

In the process of a CF experiment, there are many atomic processes with stochastic property: distribution of impurity atoms in the matrix metal, diffusion of hydrogen isotopes in the matrix metal, deposition and diffusion of the electrolyte on and into the cathode, and so on. As a result of those processes, the microscopic structure of the cathodes are different from one to another, even if the macroscopic condition of the electrolysis is the same. It should also be noticed that the chaotic nature of CFP occurring in complex systems, inevitably induces the qualitative reproducibility.

In view of the TNCF model, the microscopic difference of the sample influences sensitively on the trapping of thermal neutrons in the cathode and also on the trigger and breeding reactions between the trapped neutron and one of lattice nuclei. Occurrence of a trigger reaction in the surface layer formed on the cathode is governed by statistical law and is characterized by a statistical reproducibility, or **qualitative reproducibility**. Even if there are enough background neutrons in ambience, there occurs a situation with a various number of trapped neutrons from zero to the maximum value tolerated by the condition not to start the trigger reaction. These neutron values correspond to form a null result to a positive result with the maximum yield of products in experiments.

Thus, the reactions relevant to CFP are divided into trigger and breeding reactions in the TNCF model. When a trigger reaction is induced by one of trapped neutrons piled up in the sample, which may be in the form of neutron drops in a boundary region [6], the start of the succeeding breeding reaction which multiplies trapped neutrons is governed by statistical law as also are the resulting products of CFP. Occurrence of an event with a large yield is not frequent and is sporadically observed.

The qualitative reproducibility, sometimes called irreproducibility by mistake, and sporadic nature of events in CFP are explained consistently (as above) from TNCF model point of view. Notice again that the experimental trials done in large Laboratories in 1989 to confirm and prove reality of CFP are destined to fail due to elimination of background neutrons, among others, to improve S/N ratio in terms of conventional consideration in physics.

As a result of our phenomenological investigation of CFP by the TNCF model, it is obligatory to measure and describe the background neutron density as one of experimental conditions in this field.

There are several theoretical trials to explain CFP using neutrons as catalytic agents in addition to the one cited above [7]. In the TNCF model, the source of neutrons is not defined explicitly but suggested as the ambient thermal neutrons and those produced by the breeding reactions in the materials. An idea to feed neutrons by proton-electron reaction is difficult by the following reason. To create a neutron from a proton and an electron in free space by an inverse reaction of Eq.(26), it is necessary to give at least an energy of 782 keV in addition to fulfill a selection rule for the reaction:

$$p+e = n+\nu_e .$$

This energy of 782 keV is too large to be supplied in solids at room temperature (thermal energy of which are ~ 25 meV) without an inverse-dissipation process to accumulate energy at two reacting nuclei.

Another idea to use the polyneutron [7] to explain NTF has difficulty in explaining the existence of the polyneutron by Principles of physics, even if the trial is successful.

Another theoretical trial to explain some features of CFP by effects of phonons is mentioned. It is an usual **dissipation process** that an energetic charged particle passing through a solid gives its kinetic energy to the solid by interaction with phonons. If an **inverse-dissipation process** occurs in solids where phonons accelerate a charged particle in the solid, a d - d fusion reaction can occur and results in CFP. Any trick to realize such d - d fusion reactions assisted by phonons was sought by the late J. Schwinger and others.

The reaction: $$d + d = {}^4\mathrm{He} + \text{phonons}$$

belongs in this category and is difficult to explain, even if it is revolutionary. From our knowledge of statistical physics, probability of an inverse-dissipation process should be negligible and the phonon assisted CFP and p - e production of a neutron do not occur in reality as far as conventional statistical mechanics applies.

The TNCF model has shown its usefulness as explained in this paper using a neutral particle, the neutron, as an agent which catalyzes nuclear reactions in solids and gives a systematic explanation of CFP even if the Premises assumed in the model is not completely verified yet.

There is plenty of room for developing new solid state-nuclear physics if the existence of the neutron drop and the extremely neutron-rich nuclei (exotic nuclei) is confirmed in the boundary region of CF materials with positive results of CFP. The application of this science may produce great possibility of new energy and material sources.

One of effective methods to verify the existence of the neutron drop is, in the author's point of view, neutron diffraction investigation of CF materials which showed positive results. Another will be NMR investigation of trapped neutrons accumulated in the boundary region. Any method other than used in CF experiments may substantiate the results obtained hitherto in this field.

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