Chapter 11

Cold Fusion Phenomenon is Explained by TNCF Model

– Science of the Cold Fusion (1) –

In the preceding Chapters from 6 to 10, we have examined the experimental data sets in the cold fusion phenomenon obtained in this nine years spreading out into various events in solids not noticed until now. A. Einstein once compared a physicist with a detective in his famous book *The Evolution of Physics* written by him with L. Infeld. Knowing complicated facts in the cold fusion phenomenon introduced in these chapters, we are tempted to clarify necessary conditions of various events in them, to solve the many riddles contained in them, to determine sufficient conditions of the phenomenon and finally to built a new science of the solid state - nuclear physics. This is a challenging theme for genuine scientists who are always going to solve riddles of nature and society and to use the results to promote social welfare.

Why don't you start to a new spiritual adventure from now on as if you impersonate the talented detective Sherlock Holmes facing a new case.

11.1 The TNCF Model – Trapped Neutron Catalyzed Fusion Model

To interpret various experimental data sets with poor reproducibility (or irreproducibility) and their absence in low background neutron environment, the author had the first idea to construct a model, named later the TNCF model, in August, 1993.[205)] The TNCF model has several premises based on the experimental data as explained in this section. These fundamental premises are symbolization of several necessary conditions of the cold fusion phenomenon extracted from the pile of experimental data by the author's eyes. The necessary conditions clarified by now can be expressed as 1) existence of hydrogen isotopes (protium and/or deuterium) in appropriate solids (Pd, Ti, Ni, and so forth), 2) existence of the background thermal neutron, 3) existence of an appropriate alkali-metal layer (Li, K, Na and so forth) on the surface of the metal hydride (in the case of electrolytic system) and 4) inhomogeneous distribution of the hydrogen isotope in the solid. It should be emphasized that sufficient conditions of the cold fusion phenomenon are not determined yet although these necessary conditions have been recognized in the experimental data sets obtained hitherto.

The TNCF model has been applied to analyze more than fifty data sets until now obtained in various circumstances and materials and the results have been published one by one as cited in the third part of Chapter 18 (18.3). The results were published also in compiled forms recently.[255,266,270,275]

The fundamental premises of the TNCF model, similar in its nature to 'the stationary electron orbits' in Bohr's model of hydrogen atom and 'the superfluid' in the two-fluid model of liquid helium (cf. Section 10.3), are the existence of quasi-stable trapped neutrons in cold fusion materials and their selective reaction with nuclei giving large perturbation on them.

In the model, there is one adjustable parameter n_n, the density of the trapped thermal neutron, which is used to analyze the cold fusion phenomenon containing several events specified by some physical quantities supposed to be results of various physical processes in the material. Some examples of these quantities are 1) gamma ray spectra, neutron energy spectra and distribution of transmuted nuclei in the material and 2) the excess heat, amounts of generated tritium and helium in a definite time, X ray and other charged particles if any. The quantities in group 1) are *direct evidences* of the cold fusion having direct information of the events and those in group 2) *indirect evidences* of the cold fusion showing accumulated results of the events.

The premises[241,255,270] in the TNCF model which connect n_n and the observed quantities are explained in the next subsection. With these premises, more than fifty typical experimental data sets including those by Fleischmann et al.,[1] Morrey et al.,[1-4] Miles et al.,[18'] Storms et al.,[4] Gozzi et al.,[51'',51-3] Bush et al[27''] and others were analyzed[229~232,249,265] successfully with consistency in them. The results are summarized as follows:

In the pioneering work[1] where observed the excess heat, tritium and neutron in the electrolytic system with Pd cathode in D_2O + LiOD electrolytic solution (Pd/D/Li system), the controversial relations between these quantities were interpreted by our model[249] consistently with values of $n_n = 10^7 \sim 10^9$ cm^{-3} if we permit inconsistency in the experimental results which showed lack of expected simultaneity of events from the model.

The difficulty to explain production of ${}^4_2$He in the electrolytic system of Pd/ D/ Li[1−4,14″,18′] were resolved by the reaction (5.3) between the trapped neutron and ${}^6_3$Li occurring in the surface layer of Li metal (and/or $PdLi_x$ alloy) on the cathode. The parameter n_n was determined[265,266] from the data sets in these experiments as $10^8 \sim 10^{10}$ cm^{-3}.

In the experiment[4] where observed the excess heat and tritium in Pd/D/Li system but without expected simultaneity, the parameter n_n was determined[256] as $10^7 \sim 10^{11}$ cm^{-3} with the same reservation for the simultaneity of events. In the experiment[51″] where observed the excess heat, tritium and ^{4}He in Pd/D/Li system, the data were interpreted[262] with $n_n = 10^{10} \sim 10^{11}$ cm^{-3} consistently altogether but again with the same reservation for the expected simultaneity of events.

In the experiment[27″] with Ni cathode and $H_2O + Rb_2CO_3$ electrolytic solution, the excess heat and a nuclear transmutation (NT) from ${}^{85}_{37}$Rb to ${}^{86}_{38}$Sr were observed. The result was explained consistently by the TNCF model[218,260] with $n_n = 1.4 \times 10^7$ cm^{-3}.

Thus, it is possible to interpret various, sometimes more than two events in the cold fusion phenomenon consistently assuming only one adjustable parameter n_n with a reservation of inexplicable problem of poor reproducibility and lack of simultaneity of several events. To understand these unexplained points more clearly, it will be necessary to take details of the object materials into the analyses on the TNCF model.

In this section, we will explain fundamental concepts of the TNCF model and relevant reactions in detail and renumber reactions listed in Chapter 5 for the later use.

11.1a Premises of the TNCF Model

The TNCF model is a phenomenological one and the basic premises (assumptions) extracted from experimental data sets are summarized as follows:[241,255,266,279]

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

The density n_n is an adjustable parameter in the TNCF model which will be determined by an experimental data set using the 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 free neutron decays with a time constant of 887.4 ± 0.7 s.

Premise 2. The trapped neutron in a solid reacts with another nucleus in the surface layer of the solid, where it suffers a strong perturbation, as if they are in vacuum. We express this property by taking the parameter (the instability parameter) ξ, defined in the relation (11.1) written down below, as $\xi = 1$.

We have to mention here that the instability parameter ξ in the surface layer is not known at all and it can be, as noticed recently, more than one ($1 \leq \xi$) making the determined value of the parameter n_n smaller. This ambiguity is suggested by various anomalous changes of decay character of radioactive isotopes and by unexpected fission products in the surface layer.

Premise 3. The trapped neutron reacts with another perturbing nucleus in volume by a reaction rate given in the relation (11.1) below with a value of the instability parameter $\xi \leq 0.01$ due to its stability in the volume (except in special situations such as at very high temperature as 3000 K).

Following premises on the measured quantities of nuclear products and the excess heat are used to calculate reaction rates, for simplicity:

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

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

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

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

Premise 7. Tritium and helium measured in a system are accepted as all of them generated in the sample.

The amounts of the excess heat, tritium and helium are accumulated quantities reflecting nuclear reactions in the sample indirectly and are the indirect informations of the individual events.

Premises about structure of the sample are expressed 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 $\ell = 1\ \mu$m (though the experimental evidences show that it is $1 \sim 10\ \mu$m).

Premise 9. The mean free path or path length ℓ_t of the triton with an energy 2.7 MeV generated by $n + {}^6$Li fusion reaction will be taken as $\ell_t = 1\ \mu$m 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 otherwise described, i.e. the observed quantities are the same as those generated in the sample and to be observed by the detector in experiments if there are no description of its efficiency.

A premise will be made to calculate the number of events N_Q producing the excess heat Q.

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

Following relation combines two energy units, the million-electron-volt (MeV) and the joule (J):

$$1\ \text{MeV} = 1.6 \times 10^{-13}\ \text{J}, \quad 1\ \text{J} = 6.25 \times 10^{12}\ \text{MeV}.$$

The origin of the trapped neutron can be considered as 1) the ambient background neutrons, the existence of which have been recognized widely in public,[69)] and 2) the neutrons breeded in the sample by chain nuclear reactions triggered by reactions of the trapped neutron with perturbing nuclei, proposed in the TNCF model.

We explain here the experimental bases of these premises briefly:

Premise 1. Possible existence of trapped neutron.

Cerofolini[39)] and Lipson[15−3)] observed temporal changes of neutron intensity irradiated to sample without change of total number (cf. Section 8.3).

Premises 2 and 3. Nuclear products induced by thermal neutrons.

Shani et al.[30)], Yuhimchuk et al.[31)], Celani et al.[32)], Stella et al.[33)] and Lipson et al.[15)] had observed effects of natural or artificial thermal neutron on neutron emission in various materials (cf. Section 8.2).

Premises 2 and 8. Neutron reactions in the surface layer.

Morrey et al.,[1−4)] Okamoto et al.,[12″,12−5)] Mizuno et al.[26−3)] and Li et al.[57′)] showed helium production and nuclear transmutation in the surface layers of Pd cathodes (and wire) with a thicknesses of from 1 to 40 μm.

Premise 3. Low reactivity of volume nuclei.

In addition to the data noticed in the preceding paragraph, Notoya et al.[35−3)] observed nuclear transmutation and positron annihilation gamma in porous Ni sample which showed low reactivity of nucleus in volume of the sample.

Exception of the reaction rate in volume was illustrated in an experiment of Mo cathode at 3000 K where observed high production rate of tritium.[44∼44−4)]

If the stability of the trapped neutron is lost by a large perturbation in the surface layer or in volume, the number of trigger reactions (per unit time) between trapped thermal neutrons and a nucleus ${}^A_Z$M may be calculated by the same formula as the usual collision process in vacuum but an instability parameter ξ:

$$P_f \ = \ 0.35 n_n v_n n_M V \sigma_{nM} \xi, \tag{11.1}$$

where $0.35 n_n v_n$ is the flow density of the trapped thermal neutron per unit area and time, n_M is the density of the nucleus, V is the volume where the reaction occurs, σ_{nM} is the cross section of the reaction. The instability parameter ξ as taken into the relation (11.1) expresses an order of the stability of the trapped neutron in the region as explained in premises 2 and 3, and also in the next paragraph.

In the electrolytic experiments, we have taken $\xi = 1$ in the surface layer and $\xi = 0$ in the volume except otherwise stated (Premises 2 and 3). The values of $\xi = 0.01$ instead of $\xi = 0$ in the relation (11.1) will result in lower n_n in the electrolytic data by a factor 2 than that determined with a value $\xi = 0$ as had been used in our former analyses. (In this Chapter, we will cite previous results with $\xi = 0$ as they were.)

In the case of a sample with a definite boundary layer surrounding a trapping region where is the thermal neutron, the volume V should be that of the boundary region where is the nucleus to react with the thermal neutron. On the other hand, in a sample without definite boundary layer but disordered array of minority species of lattice nuclei in the sample, the volume should be the whole volume of the sample.

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

$$n + {}^A_Z\mathrm{M} \;=\; {}^{A+1-b}_{Z-a}\mathrm{M}' + {}^b_a\mathrm{M}'' + Q,$$

where ${}^0_0\mathrm{M} \equiv \gamma$, ${}^1_0\mathrm{M} \equiv n$, ${}^1_1\mathrm{M} \equiv p$, ${}^2_1\mathrm{M} \equiv d$, ${}^3_1\mathrm{M} \equiv t$, ${}^4_2\mathrm{M} \equiv {}^4\mathrm{He}$, etc.

The liberated energy Q may be measured as the excess heat by the attenuation of the nuclear products, γ and charged particles, as generated in the reaction (5.2). 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.

11.1b Nuclear Reactions relevant with the TNCF Model

Typical reactions relevant with TNCF model had been written down in Chapter 5 as Eqs. (5.1) to (5.11). We recite them again with new equation numbers as follows with supplementary explanations.

(1) Trigger reactions.

The trapped thermal neutron can fuse with ^{6}Li nucleus by the reaction (5.3) in the surface layer formed on the cathode by electrolysis of D_2O (H_2O) + LiOD (LiOH) with a large cross section $\sim 1 \times 10^3$ b (1 b = 10^{-24} cm^2) (at 300 K):

$$n + {}^6_3\mathrm{Li} \; = \; {}^4_2\mathrm{He}\ (2.1\ \mathrm{MeV}) + t\ (2.7\ \mathrm{MeV}). \tag{11.2}$$

The thickness of the surface layer will be assumed as 1 μm throughout the following analysis (Premise 8) although it has been determined as 1 $\sim$ 10 μm in experiments (allowing one order of magnitude uncertainty in the determined value of n_n). Also, the abundance of the isotope ^{6}Li will be assumed as the natural one, i.e. 7.4 % except otherwise described. Perhaps, the first quantitative observation of abundant tritium in the electrolytic experiment was by Storms et al.$^{4)}$ with an abundance of 0.018 % ^{6}Li. Storms also observed characteristics of the excess heat generation in Pd/D/Li system.$^{4-3)}$

A trapped thermal neutron can fuse effectively with a deuteron by the reaction 5.2) in volume or with ^{7}Li nucleus by the reaction (5.4) in the surface layer:

$$\begin{aligned} n + d \; &= \; t\ (6.98\ \mathrm{keV}) + \gamma\ (6.25\ \mathrm{MeV}), && (11.3)\\ n + {}^7_3\mathrm{Li} \; &= \; {}^8_3\mathrm{Li} \; = \; {}^8_4\mathrm{Be} + e^- + \bar{\nu}_e + 13\ \mathrm{MeV}, && (11.4)\\ {}^8_4\mathrm{Be} \; &= \; 2\ {}^4_2\mathrm{He} + 3.2\ \mathrm{MeV}. && (11.5) \end{aligned}$$

The reaction (11.3) for a thermal neutron has a cross section 5.5×10^{-4} b and the reaction (11.4) has 4×10^{-2} b which will be used in the calculation given in the following sections.

In the case of solids with protium but deuterium, the reaction (5.1) should be taken up in the analysis as the trigger reaction:

$$n + p \; = \; d\ (1.33\ \mathrm{keV}) + \gamma\ (2.22\ \mathrm{MeV}). \tag{11.6}$$

The fusion cross section of the reaction (11.6) for a thermal neutron is 3.5×10^{-1} b, which is fairly large compared with that of the reaction (11.3).

(2) Breeding reactions.

The triton with an energy ε = 2.7 MeV (or 6.98 keV) generated in the reaction (11.2) (or (11.3)) can pass through the crystal along the channeling axis on which is an array of occluded deuterons or can proceed a finite distance with a path length ℓ_t ($\simeq 1 \sim 10$ μm) determined by the interaction with charged particles in the crystal. In the process of penetration through a crystal, the triton can react with a deuteron by the reaction (5.10) on the path with a length 1 μm (Premise 9):

$$t\ (\varepsilon) + d \ = \ {}^4_2\mathrm{He}\ (3.5\ \mathrm{MeV}) + n\ (14.1\ \mathrm{MeV}) + \varepsilon. \qquad (11.7)$$

The cross section of this reaction is $\sigma_{t-d} \sim 1.4 \times 10^{-1}$ b for $\varepsilon = 2.7$ MeV and 3.04×10^{-6} b for 6.98 keV.

It has been a defect in experimental researches not trying to detect higher energy neutrons up to 15 MeV expected to be generated in this reaction (11.7). In the following analysis, we assume the path length of 2.7 MeV triton as $\ell_t = 1$ μm throughout this paper.

The neutron with 14.1 MeV generated in the reaction (11.7) can interact with particles in the crystal, especially with a deuteron elastically giving a large amount of energy to it or inelastically dissociating it:

$$\begin{aligned} n\ (\varepsilon) + d \ &= \ n'\ (\varepsilon') + d'\ (\varepsilon\prime\prime), & (11.8)\\ n\ (\varepsilon) + d \ &= \ n' + p + n\prime\prime, & (11.9)\\ n\ (\varepsilon) + {}^A_Z\mathrm{M} \ &= \ {}^{A-1}_{Z}\mathrm{M} + n + n', & (11.10)\\ n\ (\varepsilon) + {}^A_Z\mathrm{M} \ &= \ {}^{A-A'+1}_{Z-Z'}\mathrm{M}' + {}^{A'}_{Z'}\mathrm{M}''. & (11.11) \end{aligned}$$

In these reactions, the original high energy neutron loses its energy to be thermalized or generate another low energy neutron to be trapped in the sample (breeding processes) or generate transmuted nuclei.

The deuteron having an energy up to 12.5 MeV accelerated elastically in the scattering (11.8) by the neutron with 14.1 MeV can fuse with another deuteron in two modes by the reactions (5.7) and (5.8) with a fairly large cross sections of the order of 0.1 b each:

$$\begin{aligned} d\ (\varepsilon) + d \ &= \ t\ (1.01\ \mathrm{MeV}) + p\ (3.02\ \mathrm{MeV}), & (11.12)\\ &= \ {}^3_2\mathrm{He}\ (0.82\ \mathrm{MeV}) + n\ (2.45\ \mathrm{MeV}), & (11.13) \end{aligned}$$

Branching ratios of these reactions are, as is well known, 1 : 1. Another possibility noticed in Chapter 5 is the reaction (5.9) with small probability 10^{-7} compared with the above two:

$$d\ (\varepsilon) + d \ = \ {}^4_2\mathrm{He}\ (76.0\ \mathrm{keV}) + \gamma\ (23.8\ \mathrm{MeV}). \qquad (11.14)$$

In the case of solids with protium but deuterium, the following breeding reaction (5.6) between the energetic deuteron and a proton is possible:

$$d\ (1.33\mathrm{keV}) + p \ = \ {}^3_2\mathrm{He}\ (5.35\ \mathrm{keV}) + \gamma\ (5.49\ \mathrm{MeV}) \qquad (11.15)$$

The following reaction (5.11) is also probable with the energetic deuteron:

$$d\ (\varepsilon) + {}^3_2\mathrm{He} \ = \ {}^4_2\mathrm{He}\ (3.67\ \mathrm{keV}) + p\ (14.68\ \mathrm{MeV}). \qquad (11.16)$$

Depending on the situation in a cold fusion system, the trapped thermal neutron can induce trigger reactions like the reactions (11.2) ~ (11.6) and the generated energetic particles in them can sustain breeding chain reactions (11.7) ~ (11.13), (11.15) and (11.16) producing a lot of the excess heat and/or the nuclear products.

The photons generated in the reactions (11.3), (11.4), (11.6) and (11.14) can induce photo-disintegration of deuterons and nuclei if they have more energy than the threshold energies of following reactions;

$$\gamma + d \ = \ p + n, \qquad (11.17)$$

$$\gamma + {}^A_Z\mathrm{M} \ = \ {}^{A-1}_{\ \ Z}\mathrm{M} + n. \qquad (11.18)$$

The threshold energy of the reaction (11.17) is 2.22 MeV. In samples with deuteron, this reaction (11.17) with a cross section $\sim 2.5 \times 10^{-3}$ b can work effectively as a neutron breeder.

To analyze experimental data in electrolytic systems, we have taken an abundance of ${}^6_3\mathrm{Li}$ in LiOD as the natural one 7.42 %, an average velocity of the trapped neutron $v_n = 2.2 \times 10^5$ cm/s ($kT \sim 1/40$ eV at $T = 300$ K). Then, we can determine the density of the trapped neutron n_n using the above relation (11.1) between n_n and the number of tritium atom N_t (= number of helium atom N_{He}) generated in the surface layer in a time τ;

$$N_t \ = \ N_{He} \ = \ 0.35 n_n v_n n_{{}^6Li} \ell_0 S \sigma_{nLi} \tau \xi, \qquad (11.19)$$

where S is a surface area of the cathode, ℓ is the thickness of the Li surface layer, $\sigma_{nLi} = 10^3$ b, $n_{{}^6Li} = 3.5 \times 10^{21}$ cm^{-3} and ξ is the instability parameter (which we take as 1 in the surface layer).

In general, the number of events (reactions) N_{nM} in time τ between the trapped neutron and the lattice nuclei ${}^{A}_{Z}\mathrm{M}$ in a volume of a sample is given by similar relation;

$$N_{nM} = 0.35 n_n v_n n_M V \sigma_{nM} \tau \xi, \qquad (11.20)$$

where V is the volume of the sample, n_M is the density of the nucleus M, σ_{nM} is the cross section of the reaction and ξ is the instability parameter (which we take as 0.01 for the reaction in volume as explained in 11. 11f).

The number of tritium atom determined by the relation (11.19) is also number of events N_Q generating the excess heat of 4.8 MeV per a reaction;

$$N_t = N_Q \equiv Q\ (\mathrm{MeV})/4.8\ (\mathrm{MeV}). \qquad (11.21)$$

A relation between N_n and N_t in D/Li system is given as follows; when the $n - {}^6\mathrm{Li}$ reaction (11.2) is predominant over the reaction (11.3) in an electrolytic system with D_2O, neutron is generated by the reaction (11.7) giving a relation between N_n and N_t assuming half of the generated triton in (11.2) contribute the reaction (11.7),

$$N_n \sim N_t \ell_t n_d \sigma_{t-d}, \qquad (11.22)$$

where $\ell_t \sim 1\ \mu\mathrm{m}$, $n_d = 6.8 \times 10^{22}\ x\ \mathrm{cm}^{-3}$ ($x = \mathrm{D/Pd}$) and $\sigma_{t-d} \sim 1.4 \times 10^{-1}$ b. For $x = 1$, we obtain a relation

$$N_n/N_t = 9.5 \times 10^{-7} \sim 10^{-6}, \qquad (11.23)$$

$$\text{or } N_t/N_n = 1.1 \times 10^{6} \sim 10^{6}. \qquad (11.24)$$