The Physics of the Cold Fusion Phenomenon

Hideo Kozima, Kaori Kaki
Masayuki Ohta
Department of Physics
Faculty of Science
Shizuoka University
836 Oya, Shizuoka 422, JAPAN
e-mail sphkoji@sci.shizuoka.acjp

Synopsis

More than 25 typical experimental data on the cold fusion phenomenon had been analyzed phenomenologically by the TNCF (trapped neutron catalyzed fusion) model based on an assumption of the quasi-stable existence of the thermal neutrons in solids with special characteristics, giving a consistent explanation of the whole data. The densities of the assumed thermal neutron in solids were determined in the analyses from various experimental data and were in a range of $10^3 \sim 10^{12}\ cm^{-3}$. The success of the analyses verifies the validity of the assumption of the trapped thermal neutron. Physical bases of the model were speculated facilitating the quasi-stable existence of the thermal neutron in the crystals satisfying definite conditions.

1.Introduction

In 1989, Fleischmann et al.[1] published a paper showing the discovery of the so-called Cold Fusion, i.e. the generation of the excess heat and the nuclear products (tritium t, helium-4 ^4He, neutron n, and gamma γ) in solids which seemed to be impossible to explain by the conventional physics. After the discovery of cold fusion, it has been recognized that the cold fusion phenomenon includes not only the generation of the excess heat, small nuclei, neutron and the photon, but also nuclear transmutation, including heavy nuclei in metals occluding and in compounds including hydrogen isotopes (D and/or H). The cold fusion is used as such in this paper.

To explain the cold fusion phenomenon, the first proposals[2,3] of a phenomenological model were made in the fall of 1993 on an assumption of the trapped thermal neutron catalyzing fusion reactions in crystals (TNCF model). The idea of the fusing neutron as an agent to realize nuclear reactions in solids has brother trial using "neutron like" stable particles[4-7] with some physical verifications for their existence. The trapped neutron model assumes simply an existence of quasi-stable neutrons moving in a solid with thermal velocity and some properties, which will be explained below in the next section.

The model has been developed[8-10] in three years to fit the various phases of the phenomenon. The electrolytic experiments including the first one by Fleischmann et al.[1] were analyzed and the results[11] had shown that the experimental results on the relations between the excess heat, tritium and neutron were explained consistently by the model. The questions solved by the model included the poor reproducibility of the events, large N_t/N_n (≡ t/n) ratio, large N_Q/N_n ratio and also the large value of N_{He} comparable to N_Q where N_t, N_n, N_Q and N_{He} are the number of events generating tritium, neutron, the excess heat and ^{4}He, respectively.

In this paper we will show that 28 typical experimental data of the electrochemical and the discharge experiments obtained in these almost eight years after the discovery of the cold fusion phenomenon[1] were consistent by the TNCF model and therefore the physics of the cold fusion phenomenon could be depicted using the model.

In the next section, we will explain the basic concepts of the TNCF model. In section 3 we will give results of analyses of the experimental data on the basic assumption of the model (the quasi-stable existence of the trapped thermal neutrons in the solid) and also the assumed fusion reactions between the neutron and nuclei causing perturbation on the neutron to destabilize it. In section 4 we will discuss the physics of the cold fusion phenomenon using the success of the analyses envisaged by the TNCF model.

2.The TNCF model

The TNCF model is a phenomenological one and the basic premises (assumptions) are summarized as follows'):

Premise 1. We assume a priori existence of the trapped neutron with a density n_n in pertinent solids, to which the neutron is supplied essentially by the ambient neutron.

The density n_n is an adjustable parameter in the TNCF model which will be determined by experimental data using the supplementary assumptions which will be explained below concerning to reactions of the neutron with other particles in the solids.

Premise 2. The trapped neutron reacts with another nucleus in the surface layer of the solids as if they are in a vacuum. We express this property by taking the parameter ξ defined below in the relation (1) as $\xi = 1$.

Premise 3. The trapped neutron reacts with another perturbing nucleus in volume by the relation (1) with $x = 0.01$ due to its stability in the volume (except in a special situation such as a very high temperature as 3000 K).

• The following premises on the measured quantities are used to calculate reaction rates, for simplicity:

Premise 4. Products of a reaction

lose all their kinetic energy in the sample except that they go out without an energy loss.

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

This means that if the gamma or neutron spectrums are observed outside, they directly reflect nuclear reactions in the solid sample. The same is true for the distribution of the transmuted nucleus in the sample. Those spectra and the distribution of the transmuted nuclei are the direct information 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 being 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 of the alkali metal layer on the cathode surface will be taken as 1 μm.

Premise 9. The mean free path of the triton with an energy 2.7 MeV generated by $n + {}^6Li$ fusion reaction will be taken as 1 μm irrespective of the 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 a vacuum.

Premise 10. Efficiency of detectors will be assumed as 100 % except otherwise described, i.e. the observed quantities are the same as that generated in the sample and to be observed by the detector.

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

Premise 11. In the calculations of a number of events (nuclear reactions) producing the excess heat N_Q, the average energy liberated in the reactions is assumed as 5 MeV: N_Q = Excess heat Q (MeV)/ 5 (MeV). Following relation combines the energy units MeV and J:

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

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, and (2) the neutrons bred in the sample by nuclear reactions between the trapped neutron and perturbing nuclei proposed in the TNCF model.

There are some experimental bases for these premises: Premise 1. Possible existence of trapped neutron. Cerofolini[13] and Lipson[14] observed temporal changes of neutron intensity irradiated to sample without change of total number. Premises 2 and 3. Nuclear products induced by thermal neutrons. Shani et al.[15], Yuhimchuk et al.[16], Celani et al.[17], Stella et al.[18] and Lipson et al.[19] had observed effects of artificial thermal neutron on neutron emission in various materials. Premises 2 and 8. Neutron reactions in the surfarce layer. Morrey et al.[20] and Okamoto et al.[21,22] showed helium production and nuclear transmutation in the surface layer of Pd cathode with a thickness of 2.5 and 1

μm, respectively. Premise 3. Low reactivity of volume nuclei. Notoya et al.[23] observed nuclear transmutation and positron annihilation gamma in porous Ni sample which showed a low reactivity of nucleus in volume of the sample.

An exception to the reaction rate in volume is illustrated in an experiment of Mo cathode at 3000 K, where there was observed a high production rate of tritium [24].

If the stability of the trapped neutron is lost by a large perturbation in the surface layer or in volume, the fusion probability between a thermal neutron and a nucleus may be calculated by the same formula as the usual collision process:

$$P_f = 0.35 n_n v_n n_N V \sigma_{nN} \xi, \qquad (1)$$

where $0.35 n_n v_n$ is the flow density of the neutron per unit area and time, n_N is the density of the nucleus, V is the volume where the reaction occurs, σ_{nN} is the fusion cross section for the reaction. The factor ξ in the relation (1) expresses an order of the stability of the trapped neutron in a region where it is.

In the electrolytic experiments, we have taken $\xi = 1$ in the surface layer and $\xi = 0$ in the volume except where otherwise stated (Premises 2 and 3). The values of $\xi = 0.01$ instead of $\xi = 0$ in the relation (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 paper, we will cite previous data with $\xi = 0$ as they were.)

In the case of a sample with a definite boundary layer surrounding a trapping region where there is the thermal neutron, the volume V should be that of the boundary region where the nucleus is to fuse with the thermal neutron. On the other hand, in a sample without a definite boundary layer, but is a disordered array of a minor 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 ${}^A_Z M$ with a mass number A and an atomic number Z, there appears an excess energy Q and nuclear products as follows:

$$n + {}^A_Z M = {}^{A+1-b}_{Z-a} M' + q, \qquad (2)$$

where

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

The excess energy Q may be measured as the excess heat by the attenuation of the nuclear products γ and charged particles generated in the reaction (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 with one of other nuclei in the sample.

Typical reactions related with TNCF model are written down as follows.

The trapped thermal neutron can fuse with ^6Li nucleus in the surface layer formed on the cathode by electrolysis of D_2O (H_2O) + LiOD (LiOH) with a large cross section ~ 1 x 10^3 barn (at 300 °C):

$$n + {}^6Li = {}^4He\ (2.1\ MeV) + t\ (2.7\ MeV). \qquad (3)$$

The thickness of the surface layer will be assumed as 1 μm throughout the following analysis (Premise 8) though it has been determined as 1 - 10 μm in experiments (allowing one order of magnitude uncertainty in the determined value of n_n). Also, the abundance of the isotope ^6Li 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.[21] with 0.018% ^6Li case.

The triton with an energy of 2.7 MeV generated in this reaction can pass through the crystal along the channeling axis on which is an array of occluded deuterons or can proceed a finite path with a length ($\approx 1 \sim 10\ \mu m$) determined by the interaction with charged particles in the crystal. In the process of triton penetration through a crystal, the triton can fuse with a deuteron on the path with a length 1 μm with a cross section ~1.4×10^{-1} barn (Premise 9):

$$t\,(2.7\text{ MeV}) + d = {}^4\text{He}\,(3.5\text{ MeV}) + n\,(14.1\text{ MeV}). \quad (4)$$

It has been a defect in experimental research not trying to detect higher energy neutrons up to 15 MeV expected to be generated in this reaction.

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

$$n + d = n' + d', \quad (5)$$
$$n + d = n' + p + n'', \quad (6)$$

In these reactions, the original high energy neutron will be thermalized or generate another low energy neutron to be trapped in the sample (breeding process).

When the neutron become thermal, it can fuse effectively with a deuteron in volume or with ^6Li nucleus in the surface layer:

$$n + d = t + \gamma + 6.25\text{ MeV}, \quad (7)$$
$$n + {}^7\text{Li} = {}^8\text{Be} + \gamma = 2\,{}^4\text{He} + e^- + \nu_e + 16.2\text{ MeV} + \gamma. \quad (8)$$

The reaction (7) for a thermal neutron has a cross section 5.5×10^{-4} and the reaction (8) has 4×10^{-2} barn which will be used in the estimation given in the following section.

The deuteron having an energy up to 12.5 MeV accelerated elastically in the scattering (5) by the neutron with 14.1 MeV can fuse with another deuteron in two modes with a fairly large cross section of the order of 0.1 barn:

$$d + d = t\,(1.01\text{ MeV}) + p\,(3.02\text{ MeV}), \quad (9)$$
$$= {}^3\text{He}\,(0.82\text{ MeV}) + n\,(2.45\text{ MeV}). \quad (10)$$

Depending on the situation in a cold fusion system, the trapped thermal neutron can induce trigger reactions like the reaction (2) and the generated energetic particles sustain breeding chain reactions producing a lot of the excess heat and the nuclear products.

In the case of solids with hydrogen but deuterium, the following reaction should be taken up in the analysis:

$$n + p = d\,(1.33\text{ keV}) + \gamma(2.22\text{ MeV}), \quad (11)$$

$$d(1.33\text{keV}) + p = {}^3\text{He}\,(5.35\text{ keV}) + \gamma(5.49\text{ MeV}). \quad (12)$$

The fusion cross section of the reaction (11) for a thermal neutron is 3.5 x 10^{-1} barn.

The photons generated in the reactions (2), (7), (11) and (12) can induce photodisintegrations of deuterons and nuclei if they have more energy than the threshold energies of the following reactions, 2.22 MeV for the reaction (13):

$$\gamma + d = p + n, \qquad (13)$$

$$\gamma +_{Z}^{A} M =_{Z}^{A+1} M + n. \qquad (14)$$

In samples with deuteron, this reaction with a cross section ~ 2.5 x 10^{-3} barn works as a neutron breeder.

In the analysis of experimental data using the TNCF model, we will make the situation simple and tractable using Premises explained above.

3.Typical Quantitative Experimental Data and Their Analysis Using the TNCF Model

In the measurements of some cold fusion events it is possible to obtain several quantities simultaneously. A lack of the general understanding of relations between physical quantities makes the description of the results vague or sometimes even chaotic. Generally speaking, there are too many data observed without a definite relation between them.

Therefore, it is usually impossible to explain all of the data obtained in an experiment, including intricately interrelated physical variables. It should be necessary to select data from one point of view, neglecting others for a while, leaving them for a future program to explain in relation with known factors. We will take up only 25 data, including some with quantitative relations between several quantities from excellent experimental results obtained so far.

1) M. Fleischmann, S. Pons and M. Hawkins[1].

From the abundant data in the first cold fusion paper[1], we take up a case of a thin rod Pd cathode with dimensions 0.4 cmø x 10 cm. When the electrolyzing current density was 64 mA/cm^2, the system with the Pd cathode, Pt anode and LiOD+D_2O gave the excess power 1.75 W (= 1.1 x 10^{12} MeV/s) and neutrons 4 x 10^4/s and tritium atoms 4 x 10^{11}/s (only this data was in a sample of 0.1 cmø x 10 cm with unknown current density).

To analyze these data we take the thickness of the surface layer of Li atoms on the surface (area S) of the cathode as $l_0 = 1\ \mu$m, an abundance of ^{6}Li in LIOD as the natural one 7.5%, an average velocity of the trapped neutron $v_n = 2.7 \times 10^5$ cm/s (T = 300 K). Then, we can determine the density of the trapped neutron n_n using a relation between n_n, and the number of tritium atoms N_t generated in a time τ by the reaction (1);

$$N_t = 0.35 n_n v_n n_{6Li} l_0 S \sigma_{nLi} \tau \xi, \qquad (15)$$

where S = 12.8 cm^2, $\sigma_{nLi} = 10^3$ barn, $n_{6Li} = 3.5 \times 10^{21}$ cm^{-3}. The observed value of N_t per unit time 1.6 x 10^{12}/s in 0.1 cmø sample reduced to a sample with 0.4 cmø gives us a density of the trapped neutron as

$$n_n = 6.0 \times 10^7 \text{ cm}^{-3}.$$

Then, we will assume the same density n_n and the thickness l_0 in the samples with 0.4 and 0.1 cmø and tritium generation in all samples by the relation (15).

The triton generated in the reaction (1) induces the reaction (2) producing a neutron with an energy 14.1 MeV. Taking the path length of the triton in the cathode PdD_x as 1 μm and using the cross section of the reaction (2) for 2.7 MeV triton $\sigma_{t\text{-}d}$ - 1.4 x 10^{-1} barn, and the density of deuterium near the surface layer as 6.8 x 10^{22} cm^{-3} (D/Pd = 1), we obtain the probability of reaction (2) induced by the triton as 1.6 x 10^{-6} which gives a ratio of events generating tritium and neutron in a sample

$$N_t/N_n \sim 5.3 \times 10^5.$$

This value is compared with the experimental value 10^7. The coincidence of these values by one order of magnitude may be taken as very good if we consider the rough assumptions used in this estimation[11].

Another quantity we can use as an index of the cold fusion phenomenon is the ratio of events producing the excess heat and neutron N_Q/N_n. The values given above allows us to estimate this ratio on an assumption that nuclear reactions liberate energy about 5 MeV per reaction in average. Then,

$$N_Q/N_n = N_t/N_n = 5.3 \times 10^7.$$

Experimental value of N_Q/N_n in the sample with 0.4 cmø is (1.1 x 10^{13} ÷ 5)/ 4 x 10^4 = 5.6 x 10^7. Therefore, there is a difference of an order of 2 between the experimental and theoretical values of this ratio.

This value of N_Q gives a ratio of events producing the excess heat and tritium N_Q/N_t as follows, using the experimental value of N_t = 1.6 x 10^{12} in a reduced sample with 0.4 cmø:

$$N_Q/N_t = (1.1 \times 10^{12} \div 5)/(1.6 \times 10^{12}) = 1.4,$$

which is compared with the theoretical value of 1.0.

2) T. Roulette, J. Roulette and S. Pons[26].

A novel high power dissipating heat flow calorimetric system ICARUS 9[26] developed at IMRA Europe has been used to investigate the generation of excess enthalpy in the electrolysis of D_2O electrolytes at Pd and Pd alloy cathodes.

The unique feature of this calorimeter are, say the authors, (a) the ability to make long term measurements for (b) extended time periods (up to several months) at (c) high input powers and at high electrolyte temperatures (up to the atmospheric pressure boiling point of the electrolyte, and (d) there is negligible loss of the electrolyte due to evaporation and (e) there is no recombination of the evolved deuterium and oxygen in the cell.

They obtained the data shown in Table 1 (copied from a view graph shown in the presentation 0-014 at ICCF6, by courtesy of Dr. S. Pons). Experimental data shown in this table exhibits characteristics of the cold fusion phenomenon: (1) Qualitative reproducibility of the events (excess heat generation in this case) in an experimental set-up, (2) a long time (few months in this case) necessary to realize the condition to generate cold fusion products (the excess heat) and (3) contrast of the high maximum output-to-input power ratio (up to 250%) and the moderate average ratio (6.6 ~ 20.6%). From the amount of the excess heat, we could determine $n_n = 10^{11} \sim 10^{12}$ cm^{-3} according to the procedure explained above without any additional assumption.

3) E. Storms and C. Talbot[25].

Table 1: Neutron Density n_n and Relations between the Numbers N_x of Event x Obtained by Theoretical Analysis of Experimental Data on TNCF Model ($N_Q \equiv Q(\mathrm{MeV})/5\,(\mathrm{MeV})$)

Authors	System	Measured Quantities	n_n (cm^{-3})	Other Results (Remarks)
M.Fleischmann et al.[1)]	Pd/D/Li	Q, t, n $N_t/N_n \sim 10^7$ $N_Q/N_t \sim 5.5$	$\sim 10^9$	$N_t/N_n \sim 5.3 \times 10^5$ $N_Q/N_n \sim 5.3 \times 10^5$ $N_Q/N_t = 1.0$
T.Roulette et al.[26)]	Pd/D/Li	Q	$10^{11} \sim 10^{12}$	
A.Takahashi et al.[27)]	Pd/D/Li	t, n $N_t/N_n \sim 6.7 \times 10^4$	10^3	$N_t/N_n \sim 5.3 \times 10^5$
M.H.Miles et al.[28)]	Pd/D/Li	Q, ^4He (N_Q/N_{He}=1~ 10)	$10^9 \sim 10^{10}$	$N_Q/N_{He} \sim 5$
R.Bush et al.[29)]	Ni/H/Rb	NT ($^{85}Rb \to {}^{86}Sr$)	1.6×10^7	$N_Q/N_{NT} \sim 3$
M.Okamoto et al.[21)]	Pd/D/Li	Q, NT($^{27}Al \to {}^{28}Si$)	$\sim 10^{10}$	$N_Q/N_{NT} \sim 1.4$
Y.Oya et al.[22)]	Pd/D/Li	Q, γ spectrum	3.0×10^9	(with ^{252}Cf source)
Y.Arata et al.[30)]	Pd/D/Li	Q, ^4He ($10^{20} \sim 10^{21}$ cm^{-3})	$\sim 10^{12}$	$N_Q/N_{He} \sim 6$ (Assume t channeling in cathode wall)
M.C.H.McKubre[31)]	Pd/D/Li	Q (Formula)	$10^9 \sim 10^{10}$	Qualit. explanation
T.O.Passell[32)]	Pd/D/Li	NT ($^{10}B \to {}^7Li + {}^4He$)	1.1×10^9	$N_{NT}/N_Q = 2$
D.Cravens (P.P.C.)[33)]	Pd/H/Li	Q (Q_{out}/Q_{in}=3.8)	8.5×10^9	(If PdD exists)
E. Storms et al.[25)]	Pd/D/Li	t ($\sim 1.8\times 10^2$ Bq/ml)	2.2×10^6	(τ=250 h, V= 60 ml)
J.O'M.Bockris et al.[35)]	Pd/D/Li	t ($\sim 3.8\times 10^7/cm^2s$)	1.1×10^6	$N_t/N_{He} \sim 1$
I.Savvatimova[36)]	Pd/D_2	NT ($^{106}Pd \to {}^{107}Ag$)	9×10^{10}	
V.A.Alekseev et al.[37)]	Mo/D_2	t ($\sim 10^7$ /s)	1.8×10^7	(If sample is MoD)
A.G.Lipson et al.[38)]	Pd/PdO/D,Na	γ (E_γ=6.25 MeV)	4×10^5	(If efficiency = 1 %)
O.Reifenschweiler[39)]	$TiT_{0.0035}$	Reduction of β decay	1.1×10^9	($T = 0 \sim 450$ °C)
J.Dufour[40)] (SS is for Stainless Steel)	$Pd,SS/D_2$ $Pd,SS/H_2$	Q, t, n	9.2×10^{11} 4.0×10^9	(D(H)/Pd ~ 1 is assumed)
T.N.Claytor et al.[41)]	Pd/D_2	t (0.15 nCi/h)	1.4×10^7	(If D/Pd ~ 1.)
F.G.Will et al.[42)]	Pd/D_2SO_4	t ($\sim 1.8 \times 10^5/cm^2s$)	3.5×10^7	(If $\ell_0 \sim 10$ μm)
M.Srinivasan et al.[43)]	Ti/D_2	t ($t/d \sim 10^{-5}$)	1.9×10^8	
A.DeNinno et al.[44)]	Ti/D_2	t (5.4 Bq/g D_2)	1.2×10^6	(D/Ti=1,τ=1 week)
S.Focardi et al.[45)]	Ni/H_2	Q	3.0×10^{12}	($N_p = 10^{21}$ was used)
F. Cellucci et al.[46)]	Pd/D/Li	Q,^4He N_Q/N_{He}=1~ 5	2.2×10^9	(Assume Q= 5 W) $N_Q/N_{He} = 1$
F.Celani et al.[47)]	Pd/D/Li	Q(Q_{max}=7 W (200%))	1.0×10^{12}	(at Q_{max})
R.A. Oriani[48)]	$SrCeO_3/D_2$	Q~ 0.7 W (400 °C)	4.0×10^{10}	V=0.31 cm^3
R.Notoya et al.[23)]	Ni/H(D)/K	NT($^{39}K \to {}^{40}K$)	1.4×10^9	

Storms et al.[25] investigated carefully the generation of tritium in the electrolytic system Pd/D/Li with LiOD with a lowered composition of 0.018% ^6Li. In a case of the maximum tritium generation 1.8 x 10^2 Bq/ml in 250 h with a electrolyte volume of 60 ml, the density of the trapped thermal neutron was estimated as

$$n_n = 2.2 \times 10^6\ cm^{-3}.$$

4) A. Takahashi, T. Iida, T. Takeuchi, A. Mega, S. Yoshida and M. Watanabe[27]

Next, we will take up an experiment[27] where observed the excess heat, tritium and neutron with $N_t/N_n = 6.7 \times 10^4$ in Pd/D_2O+LiOD system with L-H mode electrolysis. The same analysis as shown above gives following result[27];

$$n_n = 10^2\ cm^{-3},\quad N_t/N_n = 5.3 \times 10^5.$$

The density of the trapped neutron was very low in this case but the ratio N_t/N_n was comparable with the one given above. This result shows similarity of mechanism in both cases.

5) M.H. Miles, R.A. Hollins, B.F.Bush and J.J. Lagowski[28].

Third, we will give a result[11] of the analysis of an experiment where observed the excess heat and helium in Pd/

D_2O+LiOD system[28] using a massive cylindrical Pd cathode with a surface area of 2.6 cm^2. They measured $10^{21} \sim 10^{22}$ cm^{-3} ^{4}He atoms per watt of the excess power (N_Q/N_{He}, = 10~1), while they did not measure tritium. Similar analysis to these given above in 1) resulted in the following conclusion with the density of the trapped neutron n_n and the ratio of numbers of events N_Q and N_{He} producing ^{4}He:

$$n_n = 1.1 \times 10^9 \sim 10^{10} cm^{-3}, \quad N_Q/N_{He} = 5.$$

The density n_n is similar to that in 1) and the ratio N_t/N_n shows the main source of the excess heat in this case was the reaction (3).

6) R. Bush and R. Eagleton[29].

Fourth, we will give a result[29] of the analysis of an experiment the excess heat and the nuclear transmutation of Rb into Sr in Ni/H_2O+$RbCO_3$ system[29] was observed. The reaction supposed to occur in the system were

$$n + {}^{A}\text{Rb} = {}^{A+1}\text{Sr} + e^- + \nu_e,$$

in the surface layer of Rb on the Ni cathode. They observed the isotope ratio ^{88}Sr/^{86}Sr changed from 8.5 to 3.5 when the excess heat was Q_1 and to 2.7 when it was $Q_2 = 5Q_1$. The density n_n was determined[29] as follows:

$$n_n = 1.6 \times 10^7 cm^{-3}.$$

Correlation of the excess heat and helium generation was explained quantitatively in a factor of 3.

7) M. Okamoto, H. Ogawa, Y. Yoshinaga, T. Kusunoki and 0. Odawara[21,22].

Fifth, we will give a results[21,22] of the analyses of an experiment the excess heat and the nuclear transmutation in the surface layer from Al into Si in Pd/D_2O+LiOD[21] system and also the excess heat and gamma spectrum[22] was observed.

The change of the density of the elements (up to 80% for Al) occurred in a surface layer of the Pd cathode with a tmckness of ~ 1 μm. The result of the calculation are given as follows:

$$n_n \sim 10^{10} cm^{-3}, \quad N_Q/N_{NT} = 1.4.$$

In the calculation of the number of events inducing the nuclear transmutation N_{NT}, we assumed the same value 10^{22} /s of N_Q in this experiment[21] as in Ref.(9) because of the similarity of situation. This value of N_Q/N_{NT} shows that the number of events generating the excess heat and the nuclear transmutation are almost the same in this case within the assumption made above.

In the another experiment with artificial thermal neutron source[22], the authors observed the excess heat and gamma spectrum. The excess heat amounted to the density of the trapped neutron [21]'

$$n_n = 3.0 \times 10^9 cm^{-3}.$$

In the gamma spectrum, there are peaks at 0.511, 2.22, 5.49, 6.15, 6.25 and 7.09 MeV. The first one was interpreted[22]' as due to positron from ^{64}Cu existed beforehand or generated by two step reactions in a material including ^{62}Ni in the experimental system:

$$n + {}^{62}\text{Ni} \rightarrow {}^{63}\text{Ni} \rightarrow {}^{63}\text{Cu} + e^- + \nu_e, \quad (16)$$

$$n + {}^{63}\text{Cu} \rightarrow {}^{64}\text{Cu} \rightarrow {}^{64}\text{Ni} + e^+ + \nu_e, \quad (17)$$

The peak at 2.22 and 6.25 MeV can

be interpreted as due to reactions (11) and (7), respectively. The peaks at 5.49, 6.15 and 7.09 MeV can be due to following reactions:

$$p + d = {}^{3}\mathrm{He} + \gamma(5.49\ \mathrm{MeV}), \qquad (18)$$

$$n + {}^{108}\mathrm{Pd} = {}^{109}\mathrm{Pd} + \gamma(6.15\ \mathrm{MeV}), \quad (19)$$

$$n + {}^{104}\mathrm{Pd} = {}^{105}\mathrm{Pd} + \gamma(7.09\ \mathrm{MeV}), \quad (20)$$

Natural abundance of the isotopes ^{108}Pd and ^{104}Pd are 26.46 and 11.14%, respectively.

8) Y. Arata and Y.C. Zhang[30].

Next, we will give a result[30] of the analysis of an experiment a huge excess heat and a tremendous number of helium atoms as high as $10^{20} \sim 10^{21}$ cm^{-3} in Pd-black contained in a Pd cylinder cathode were observed. The density n_n and the ratio of events generating triton and neutron were determined as follows:

$$n_n \sim 10^{12}\mathrm{cm}^{-3}, \quad N_Q/N_{He} = 6.$$

In this calculation, the path length of the 2.7 MeV triton generated by the reaction (3) was taken as large as 1 cm, considering the channeling of triton to enter into Pd-black part of the cathode from the wall surface of Pd container. It was difficult to understand such a high value of ^{4}He density in their Pd-black cathode without the large path length of tritium assumed in this calculation on the TNCF model.

9) M. C. H. McKubre, S. Crouch-Baker and F. L. Tanzella[31].

The elaborate experimental data in Pd/LiOD+D$_2$O system gave a senii-quantitative relation between the excess heat Q_l the electrolyzing current density i, the density of the occluded deuterium x and the speed of the occlusion |dx/dt|[31]:

$$q = C(i - i_0)^a(x - x_0)^b\ |dx/dt|$$

where C, a (~1) and b (~ 2) are constants depending on the sample. The data were analyzed on the TNCF model[31]' giving a qualitative explanation of the relation and the density of the trapped neutron: $n_n = 10^9 \sim 10^{10}$cm^{-3}.

10) Passel[32]

A Pd cathode with a total surface area 60 cm^2 and a thickness 25 μm (with a weight 0.9g) used in an experiment with an electrolytic solution D$_2$O + 1.0 M LiOD + 200 ppm Al producing the excess heat of 0.56 MJ was subjected upon comparing measurements of the prompt gamma activation analysis (PGAA) using thermal neutrons in beams from research reactors. A result showed an ~ 18% reduction in the boron impurity ^{10}B. The author (T. O. Passell) had tried to interpret the result on the hypothesis that some reaction other than D + D was the likely heat and helium-4 producing nuclear reaction and took up a reaction

$${}^{10}\mathrm{B} + d \rightarrow {}^{4}\mathrm{He} + {}^{8}\mathrm{Be},$$

followed by the breakup of ^{8}Be into two more ^{4}He.

The reaction assumed above is compatible with the absence of gamma, the author's most troubling experimental fact, but is equally difficult to understand to occur in solid as D + D fusion reaction without an energetic deuteron or a boron.

This data had been analyzed on the TNCF model[32'] giving a consistent explanation of this and those obtained in SRI International. The determined value of n_n was about 10^9 cm^{-3}.

11) D. Cravens[33].

The remarkable system[33,34] generating the excess energy up to about 2000 times the input energy with very high qualitative reproducibility in Pd/H_2O+LiOH system was analyzed on the TNCF model[33'] giving following results.

The analysis showed that it is necessary to have enough deuterium in the cathode by a preliminary treatment to accomplish the reported excess power. If the special multi-layer Pd cathode invented by Dr. Patterson is treated previously to occlude enough deuterium, it is possible to generate the observed big amount of the excess heat by H_2O+LiOH electrolysis. The experimental data[34] of the excess power (Q_{out}/Q_{in} = 1.77 W/0.46 W = 3.8 with 1200 beads) gave a following value[34'] for the trapped neutron density:

$$n_n = 8.5 \times 10^9 \text{cm}^{-3}.$$

12) J.O'M. Bockris et al.[35].

Careful measurements of tritium, helium and the excess heat have been done by Bockris et al.[35] with remarkable results with coincidence of tritium and helium-4 production. Unfortunately, the quantitative measurement was only for tritium generation. Here we take up only one data giving a maximum tritium generation of 3.8×10^7 s^{-1}cm^{-2} per unit surface area. With the same assumptions made above, we could estimate the density of the trapped thermal neutron as follows:

$$n_n = 1.1 \times 10^6 \text{cm}^{-3}.$$

13) I.B. Savvatimova et al.[36]

The researchers in the Institute LUTCH in Podolsk near Moscow have been working in the glow discharge experiments with D_2 and other gases and with cathodes of Pd and other transition metals. They measured the excess heat, NT (nuclear transmutation) of various isotopes and elements in a multi-layer cathode. Here we take up only one data of an increase of ^{107}Ag from 20 to 5000 ppm in the glow discharge with D_2 gas and Pd cathode. After the discharge of 4 hours, the sample was sent to mass spectrometry (SIMS) and was analyzed its isotope composition there about 3 months later. Assuming continuous production of ^{107}Ag by n–^{106}Pd fusion reaction through 3 months at the surface layer of the cathode, we obtain a following value for the density of the trapped thermal neutron:

$$n_n = 9 \times 10^{10} \text{cm}^{-3}.$$

14) V.A. Romodanov et al.[24,37]

Another group in the Institute LUTCH in Podolsk has been working also with a glow discharge experiment[37]. They measured a lot of tritium with a cylindrical Mo cathode in D_2 gas. The pressure of the gas was 1 atm in the cylinder and 0.2 atm outside where the discharge was. With a cylindrical cathode of 2.5 cmø x 10 cm with wall thickness of 5 mm, they measured tritium production of 10^7 s^{-1}. In this case the temperature of the cathode was very high (up to 3000 °C) and we may assume that deuterons in the cathode interact to fuse with the trapped thermal neutron in the whole volume of the cathode. Then, taking the volume of the interaction V for the $n - d$ reaction as the sample volume and using the fusion cross section for the thermal neutron ~ 5.5 x 10^{-4} barn, we obtain a following value[37'] for the density of the trapped thermal neutron in MoD. cathode:

$$n_n = 1.8 \times 10^7 \text{ cm}^{-3},$$

where we assumed $x = 1$.

15) A.G. Lipson et al.[38]

Lipson et al. have been working with ferroelectrics to measure the excess heat and nuclear products. In a recent work[38], they measured gamma radiation in the energy range up to 10 MeV from a cathode - electrolyte system PdO/Au/Pd/PdO/NaOD+D_2O (KOH+H_2O). There are several peaks in the gamma spectrum at 2.2, 3.5 to 4.2, 6.3 and small peaks up to 9 MeV in the system with deuterium. Here, we take up the peak at 6.3 MeV and interpret it as a result of the reaction (7) between n and d. Assuming that the reaction occurs at boundary layer between Pd and PdO with thickness 1 μm in the cathode, we obtained the density of the trapped thermal neutron as follows:

$$n_n = 4 \times 10^5 \text{ cm}^{-3}.$$

In the calculation, we assumed the efficiency of the gamma measurement as 1%.

16) 0. Reifenschweiler[39].

Reifenschweiler[39] measured the resulting X-ray induced by β-decay of 'tritium' absorbed by Ti ($TiT_{0.0035}$). The sample was in a shape of extremely small monocrystalline particles with diameter ø = 15 nm. In a heating process of sample there had been observed a decrease of the radioactivity, i.e. decrease of intensity of X-ray from the sample Ti/T, up to 40% in a temperature range between 115 and 275 °C.

Assuming a different cause of the change of the radioactivity from that proposed by Reifenschweiler that it was induced by the change of the neutron stability, we could estimate the density of the trapped thermal neutrons in the sample knowing the change of the radioactivity from experimental data. If the neutron became quasi-stable where the decrease of radioactivity was measured, the estimation[39'] gives a value

$$n_n = 1.1 \times 10^9 \text{ cm}^{-3}.$$

17) J. Dufour[40]

Dufour had observed the excess energy of Q ~ 2.5 W in the sparking experiments in D_2 or H_2 gas (~ 1 atm) with a cylindrical cathode of Pd or Stainless Steel (SS) with dimensions 10 ~ 11 mmø x 24 mm length and thickness to = 0.5 mm (with a surface area ~ 7.5 cm^2).

To analyze this data on TNCF model, we will assume that the D(H)/Pd(SS) ratio is 1 and n–$d(p)$ fusion occurs in the whole volume ~ 0.38 cm^3 though there is no description in the paper[40] about the D(H)/Pd(SS) ratio in the cathode.

Then the excess energy 2.5 W (~ 1.6 x 10^{13} MeV/s) gives us the numbers N_t and N_d of the fusion reactions n-d and n-p as follows:

$$Nt = 2.6 \times 10^{12},\ N_d = 7.3 \times 10^{12}\ s^{-1}.$$

The relation between the number of events $N_{d(p)}$ and the density of the trapped thermal neutron n_n is given by the relation (13) as follows:

$$N_{t(d)} = 0.35 n_n v_n n_{d(p)} S l_0 \sigma_{n\text{-}d(p)} \tau,$$

where $\sigma_{n\text{-}d(p)}$ is the fusion cross section of the reaction and is 5.5×10^{-4} (0.35) barn. This relation with the assumptions explained above gives us following values n_n in Pd sample with D(H)/Pd ~ 1:

$$n_n(d) = 9.2 \times 10^{11},\ n_n(p) = 4.0 \times 10^{9}\ cm^{-3}$$

This means the H_2-Pd(SS) system generates about 10^2 times the more excess energy per a trapped neutron than D_2–Pd(SS) system if the D(H)/Pd(SS) ratio and the thickness l_0 are the same in the both system. The result might be relevant with a fact that the difference in the cross sections $\sigma_{n\text{-}p} = 3.5 \times 10^{-1}$ and $\sigma_{n\text{-}d} = 5.5 \times 10^{-4}$ barn for thermal neutron.

18) T.N. Claytor et al.[41]

Claytor et al. measured tritium generated in low voltage D_2 discharge (p_{D2} ~ 200 Torr, V ~ 2 kV, I 3 ~ 5 A) with Pd cathode of 100 - 250 µmø and 25 - 30 mm length. The tritium was measured in the gas (~ 0.15 nCi/h = 3.6×10^4 t/s) and also in the surface layer of the cathode with thickness ~15-30 µm. Total amount of the tritium was up to 102 nCi (= 2.4×10^7 t) in few days.

Assuming tritium generation of 0.15 nCi/h from a Pd cathode of 0.05 cmø x 3.0 cm (in the surface layer of thickness 30 µm), we obtain a value for the trapped thermal neutron:

$$n_n = 1.4 \times 10^7 cm^{-3}.$$

19) F.G. Will et al.[42]

Will et al. observed tritium generation of 5.1×10^4 ~ 2×10^5 $cm^{-2}s^{-1}$ from Pd wire cathode with D_2+D_2SO_4 electrolyte. They had accomplished high loading of D/Pd ~ 1. Assuming the $n + d$ fusion in a surface layer of 10 µm, we obtain following values for the trapped thermal neutrons:

$$n_n = 1.4 \sim 5.6 \times 10^7\ cm^{-3}.$$

20) M. Srinivasan et al.[43]

Srinivasan et al. examined "aged deuterated Ti targets" used in the accelerated (*d–d*) fusion reaction experiment done in 1972 ~ 1981. Their conclusion was summarized in a sentence cited below:

"...... a typical target containing 10^{20} ($d - d$) pairs supports cold fusion reactions uniformly and continuously over a period of a few years (~ 10^9 s) producing ~ 10^{15} tritium atoms......."[43]

We can use these data in this explanation to calculate the density of the trapped neutrons in the "aged" Ti sample, though the explanation had been written to discuss a possibility of (*d–d*) reactions (9) and (10).

Using the relation (13) with values given above by the authors ($N_t = 10^{15}$ atoms, $n_d S l_0 = 10^{20}$ atoms on the assumption of the number of pairs equals to the number of atoms and $\tau = 10^9$ s) together with values $v_n \sim 2.7 \times 10^5$ cm/s (300 K), $\sigma_{n\text{-}d} \sim 5.5 \times 10^{-4}$ barn (= 5.5×10^{-28} cm^2), we obtain a value for the density of the trapped thermal neutrons:

$$n_n = 1.9 \times 10^8 \, cm^{-3}.$$

In this calculation, it was assumed that $n + d$ fusion had occurred in the whole volume of the sample.

21) A. De Ninno al.[44]

An Italian group which made the first Ti/D_2 experiment with a result of the neutron burst had observed tritium activity in a D_2 gas desorbed from fine Ti samples of 50 g with dimensions of 50 μmø x 1 mm by the liquid scintillation spectroscopy. One sample (C1O) with a composition $Ti_{0.86}V_{0.06}Al_{0.06}Sn_{0.02}$ (Ti662) showed a radioactivity of 5.4 Bq per gram of deuterium gas.

We will assume following parameters to calculate the density of the trapped thermal neutrons in Ti because there was no details about the treatment of samples from the neutron measurements to the tritium measurements; The time r between the two measurements was one week (= 6.0×10^5 s) and D/Ti ratio was 1 (i.e. the deuteron density in the sample $N_d \sim 5.7 \times 10^{22}$ cm^{-3}). Also, we neglect the composite nature of the sample Ti662 and take it as pure Ti.

Then, using a value 5.4 Bq/g D_2 gas = 1.0×10^{-14} t/s/D atom, we obtain n_n from the relation (13) as follows:

$$n_n = 1.2 \times 10^6 \, cm^{-3}.$$

In this estimation, we assumed the *n-d* reaction occurred in the whole volume of the fine Ti sample.

The values obtained above are also comparable with the values in other samples of $10^5 \sim 10^{12}$ cm^{-3}.

22) S. Focardi et al.[45]

Another Italian group[45] discovered the excess heat generation in Ni-H system without any nuclear products. If we can assume an entire attenuation of the gamma generated by the reaction (11) to thermalize in the system, we obtain as the density of the trapped thermal neutron in the sample of 5 mmø x 90 mm generating an excess heat of 44 W for 24 days according to the relation (1) a following value:

$$n_n \sim 3.0 \times 10^{12} \, cm^{-3}.$$

Here we assumed the reaction occurred in the whole volume of the sample (V = the sample volume) occluding 3×10^{21} protons as a whole with $\xi = 1$ due to the high temperature and the small mass of proton as described in the paper[45]'.

23) Cellucci et al.[46]

Elaborate experimental works done by Gozzi and his group in the Uidversity of Rome after the discovery of the cold fusion phenomenon in 1989 have shown the reality of the excess heat generation in the PdD./Li cathode though the nuclear products had not been proved their existence until ^{4}He was detected in a recent work[46].

The report[46] given in the ICCF6 (Hokkaido, Japan, October 1996) has shown the simultaneous generation of the excess heat up to 80% of the input energy andof ^{4}He well above the background level. The X-ray of an energy 89 ± 1 keV was measured and identified its origin as from the central part of the cathode, which was a bundle of Pd wire of a diameter 250 μm and a length 40 nm. This result showed clearly that the origin of the excess heat was a nuclear reaction in or on the Pd wire of the cathode.

The authors of the work[46] analyzed their data on an assumption that the nuclear reaction was

$$d + d = {}^4\text{He} + \gamma(23.8\text{MeV}). \quad (21)$$

They concluded on this assumption that the ratio of the events generating the excess heat N_Q and helium N_{He} was smaller than unity; $N_Q/N_{He} \leq 1$, with almost all values in a range 0.2 ~ 0.4.

Analysis of these data on the TNCF model gave us a more reasonable explanation of the ^{4}He generation by the reaction (3) and following value[46'] of the trapped thermal neutrons: 2.2 x 10^9 cm^{-3}.

24) Celani et al.[47]

An Italian group in Frascati made a fine experiment[47] showing the excess heat generation with high qualitative reproducibility. They used thin and long pure Pd wires (mainly 100 μmø x 160 cm) wound around a cylinder (with a diameter 4 cmø) as a cathode for both high voltage DC electrolysis and high power-high frequency electrolysis (peak current up to 25 A, peak voltage up to 270 V, pulse width 2 x 10^2 ~ 5 x 10^4 ns, repetition rate 10^2 - 5 x 10^4 Hz) in a dilute solution 0.25 mN LiOD - D_2O (LiOH - H_2O). The anode was a Pt wire (1 mmø) wound around a cylinder with a diameter 2 cmø co-axial to the cathode.

The excess heat was measured by a flow calorimeter. They detected the excess heat with a high qualitative reproducibility. The average excess heat was ~ 20% (D_2O) and ~ 10% (H_2O) of the input energy. The maximum excess heat in the case of D_2O was 70 W (200%). It should be remarked that the excess heat was measured not only in D_2O but also in H_2O case in this fine experiment. Analysis[47'] of these data gave us following value n_n in D_2O case: n_n = 1.0 x 10^{12}cm^{-3}.

25) Oriani et al.[48]

In cold fusion materials, the proton conductor has characteristics different from others, for instance transition metals occluding hydrogen isotopes. The proton conductor belongs to ceramics and their high melting points seems to be advantageous as a substance to be used in a cold fusion pile. Hydrogen isotopes in the proton conductor have rather higher mobility and therefore the mechanism of the excess heat generation might be different from that in the hydrogen occluding metals.

Difficulty in the calorimetry for the proton conductor made the experimental data obtained in it rather qualitative and out of the object of our theoretical analysis. Oriani[48], however, made a very careful measurements of the excess heat Q by the Seebeck calorimeter and confirmed the relative amount of the excess heat as 0.7 to 0.8%, or 0.7 W in optimal cases though the production occurred only in a small ratio in the total experiments. The data analyzed on the TNCF model[48'] gave a following value of the trapped neutron density n_n:

$$n_n = 4.0 \times 10^{10}\ \text{cm}^{-3}.$$

26) R. Notoya et al.[23]

In a series of experiments with Ni cathode in H_2O (and D_2O) solution of electrolytes K_2CO_3 (and Li_2CO_3,

Na_2CO_3, Rb_2SO_4, Cs_2SO_4), Notoya et al.[23] observed NT and positron generation in the system by the observation of the gamma ray spectrum. In addition to the production of ^{40}K, ^{56}Co, ^{64}Cu and ^{65}Zn, they detected a 0.511 MeV line due to the positron annihilation.

In the case of a porous Ni cathode with a dimension of 1.0 x 0.5 x 0.1 cm^3 and a density 58% of Ni metal and a electrolytic solution of 0.5 M K_2CO_3 + H_2O (20 to 30 ml as a whole), they observed an increase of ^{40}K by 100% after 24 hours electrolysis and the annihilation gamma ray at 0.511 MeV. The increase by 100% in the solution corresponds to a generation of ^{40}K by 3.0 x 10^{16} nuclei.

Analysis of the data on the TNCF model[23'] was performed with success giving following results. The density of the trapped neutron n_n was determined by the experimental value of the change of ^{40}K by the reaction: n + ^{39}K = ^{40}K + g (7.8 MeV) with a fusion cross section for the thermal neutron 2.2 barn as follows: $n_n = 1.4 \times 10^9$ cm^{-3}.

The positron generation to result in the observed 0.511 MeV photon was explained by the following series of reactions in addition to the pair creation by the gamma generated in the above reaction:

$$^{62}Ni + n = {}^{63}Ni \rightarrow {}^{63}Cu + e^- + v_e \quad (22)$$

$$^{63}Cu + n = {}^{64}Cu \rightarrow {}^{64}Ni + e^+ + v_e, \quad (23)$$

Analysis of the experimental data gave us that the stability factor ξ is at most 0.01 in volume where the above two reactions occurred in the case of negligible pair creation by the gamma.

Thus, analysis of the NT of ^{39}K and positron generation in a porous Ni cathode gave us the following value: n_n = 1.4 x 10^9 cm^{-3} and $(x)_{max}$ = 0.01 in volume.

The results of the analyses given above were summarized in Table 1, amplifying the data given in the previous report[49].

4. Physics of the Cold Fusion Phenomenon depicted by Experimental Results

The success of the explanation of the cold fusion phenomenon on the TNCF model given in the preceding section has shown the reality of the assumption made in the model and it will depict the physics of the cold fusion processes occurring in materials.

First of all, the supposed existence of the trapped thermal neutron should be investigated using the knowledge of solid state and nuclear physics. A treatment on this problem was given in the previous paper[8]. There are several causes to reflect a thermal neutron to trap it in a crystal; the difference of the neutron band structure, the Bragg reflection and the total reflection at a boundary. The difference of the neutron band structure seems effective in massive samples and the total reflection in the case of special samples with such an appropriate geometry as the Patterson's beads and Arata's Pd-black.

The conditions to facilitate the existence of the trapped thermal neutron explain the poor reproducibility of the phenomenon. The trapping conditions would be formed by stochastic processes and are not reproducible quantitatively from its nature. The cold fusion phenomenon induced by the trapped thermal neutron, therefore, has no quantitative reproducibility.

Second, the trapped thermal neutron behaves as a Bloch wave in the crystal and it might be possible to become quasi-stable through the interactions with the lattice nuclei against the beta decay and also against the fusion with one of lattice nuclei[8]. The trapped thermal neutron, though, can fuse with a nucleus in the surface layer or in the volume of the crystal if a perturbation is strong enough there to destroy the stability of the neutron. From the results of the analyses, we can say that it occurs usually near the surface of the sample where the neutron is reflected, i.e. where it stays long in classical words. Otherwise, when the temperature of the sample is fairly high, it occurs even in the volume of the sample.

Third, the fusion reaction between the neutron and nuclei becomes as a trigger reaction inducing successive reactions breeding the excess heat and nuclear products. The particles generated by a trigger reaction such as the reaction (3) or (7) react with particles and nuclei in the sample. The triton reacts with a deuteron to generate ^{4}He and a neutron; the neutron with an energy 14.1 MeV can accelerate several deuterons to enough energy capable of fusing with another deuteron with high probability. Furthermore, a photon can induce the reaction (14) to generate a neutron, the catalyst of the cold fusion.

These breeding reactions can occur successively and then generate gigantic amount of heat and particles in optimum situations. These processes would be the causes of some experimental data showing such an extraordinary result as explosion and neutron bursts. This phase of the cold fusion phenomenon was not fully analyzed yet, though some possibilities were shown with model calculations[50,51].

Fourth, the variety of values of the trapped thermal neutron n_n from 10^3 to 10^{12} cm^{-3} determined by experimental data shows variety of the trapping ability of materials used hitherto in the cold fusion experiments. Also, the variety of events from the excess heat and several nuclear products, tritium, helium-4, neutron and gamma, to the transmuted nuclei shows how the TNCF model is universally applicable in nuclear processes occurring in cold solids.

Though the values of n_n distribute rather widely for the explanation of various events, the variety of materials and events from which the values were obtained impress us the effectiveness of the TNCF model.

Fifth, there were many experiences showing the effect of the aging of samples[43] to realize the cold fusion phenomenon like that shown in the experiment analyzed in the paper[27']. The present author had a similar experience in which Pd plate bought many years ago gave a positive result[52] but a newly bought one did not (though this point was not written in the paper). Such experiences are explained by the TNCF model if the aged Pd samples had the surface layer, for instance, by oxidation in the air, to trap the thermal neutron and kept much neutrons in them.

5. Conclusion

The above phenomenological analysis of typical experimental data obtained in cold fusion experiments with electrolysis or discharge gave us a unified consistent concept of physics of the cold fusion. The reliable data showed clearly several facets of truth in the solid state - nuclear physics. The facets all put together have formed a whole figure of the physics of particles in a crystal with the trapped thermal neutron. If we have no appropriate viewpoint, phenomena appear as chaos, giving no idea of understanding. It is true that the cold fusion phenomenon had appeared to some amateurs as only a confusion of the experimental results.

Though the analysis given above has been confined to the limited data in experiments with electrolysis and discharge, the result was remarkable. Assuming only the existence of the quasi-stable thermal neutrons with a density n_n as an adjustable parameter in cold fusion materials, we could have a consistent understanding of events in the phenomenon with quantitative relationships among them.

The assumption of the existence of the quasi-stable thermal neutron in crystal itself has a theoretical verification[8,9] based on the neutron-lattice nuclei interaction with a new concept "neutron affinity of lattice nuclei."

The success in the analysis of the cold fusion phenomenon using the TNCF model shows in reverse the reality of the trapped thermal neutron. This feature of the analysis will open a new science of the low energy neutron in solid interacting with lattice nuclei through the nuclear force. The existence of the trapped neutron in appropriate systems as Pd-black will be checked by the neutron spin resonance (nSR) like NMR or ESR used in the solid state physics and in the physical chemistry.

Other systems than the electrolytic and discharge ones have also shown the characteristic cold fusion phenomenon. no less exciting than the latter. In the present status of the cold fusion research a phenomenological approach seems more effective than a microscopic one. It will be a fascinating program to analyze various experimental data in various systems on a model such as the TNCF model as done above. If we have a hint to get rid of riddles disturbing our route to a goal it is easier then to find paths to reach the goal. Exploration of the cold fusion phenomenon as an answer to the energy crisis will be accelerated by the new idea to unify the abundant separate facts obtained hitherto in experiments.

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