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How the Cold Fusion Occurs (2)

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Abstract

Present status of the cold fusion research is surveyed after four years since the former report appeared in this journal in 1994. A model (TNCF model) proposed by the author based on the experimental facts have been used to analyze typical experimental data and have shown its ability to understand whole the cold fusion phenomenon consistently.

More than 40 typical experimental data in the cold fusion phenomenon, which had been accepted as showing only confusion by people, had been analyzed consistently 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 unified explanation of the whole data. The density of the trapped thermal neutron in solids, a single adjustable parameter in the model, was determined in the analyses of various experimental data and was in a range of $10^5 \sim 10^{12} cm^{-3}$ which was not ridiculous from the solid-state point of view.

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. The analysis verified a point of view that the cold fusion phenomenon is an efficient probe to explore the secret of the solid state-nuclear physics, or the physics of neutrons in solids, untouched by conventional tools of solid state and nuclear physics until now.

1. Introduction

In 1989, Fleischmann et al.[1] published a paper showing the discovery of the so-called Cold Fusion, i.e. generations of the excess heat and the nuclear products (tritium t, helium 4 ^{4}He, neutron n, and gamma γ) in solids which seemed to be impossible to explain by the conventional physics. In these 8 years after the discovery of the cold

fusion, it has been recognized that the cold fusion phenomenon contains not only the generation of the excess heat, small nuclei, neutron and the photon but also the nuclear transmutation (NT) including heavy nuclei in metals occluding hydrogen isotopes (D and H) and in compounds including them. The cold fusion is used as such in this paper. The scope of experimental results obtained hitherto are summarized in Table 1.

Table 1 : Matrix Substances, Agent nuclei, Direct and Indirect Evidences in Cold Fusion Phenomenon.

Matrix Substance	Agent	Direct Evidence	Indirect Evidence
Pd	$^{2}_{1}D \equiv d$	$\gamma(\varepsilon)$	Q
Ti	$^{1}_{1}H \equiv p$	$n(\varepsilon)$	^{4}He
Ni	^{6}Li	Transmuted	$^{3}_{1}T \equiv t$
Na_xWO_3	^{10}B	Nuclei(r)	Nuclear
KD_2PO_4	^{39}K		Transmutation
TGS	^{85}Rb,^{87}Rb		X-ray
$SrCe_{0.9}Y_{0.08}Nb_{0.02}O_{2.97}$	$^{1}_{0}n \equiv n$		

After the Third International Conference on Cold Fusion (ICCF3) held at Nagoya, Japan in October, 1992, the author wrote a report "How the Cold Fusion Occurs ?"[2] in this Journal (RFS, SU) based mainly on the experimental data presented at the Conference. In these four years after the Conference, the author have tried to understand the cold fusion phenomenon in the frame of the conventional physics and have constructed a model named TNCF model to interpret complex and confusing data obtained in this field.

The first proposal[3~5] of the phenomenological model (TNCF model) to explain the cold fusion phenomenon was made in the fall of 1993 on an assumption of the fusion reactions catalyzed by trapped thermal neutron in crystals. Recent development of the TNCF model was reported in four papers[6~9] at the Sixth International Conference on Cold Fusion (ICCF6) held at Hokkaido, Japan in October, 1996. The idea of fusing neutron as an agent to realize nuclear reactions in solid has brother trials using "neutron like" stable particles[10~12] with some physical verifications for their existence. The microscopic theory, however, sometimes deceives people with sophisticated techniques difficult to check making its user himself blind and also one who is unfamiliar to it. A typical example was the 'neutron transfer' reaction[13,14]. It is necessary to keep any theory in our research society as a common property as had been asked in the Closing Session of the Third Russian Conference on Cold Fusion and Nuclear Transmutation (RCCFNT3) held at Sochi, Russia in October, 1995 by the author[15].

The trapped neutron catalyzed fusion model (TNCF model) assumes simply an existence of quasi-stable neutrons with a density n_n moving in solid with thermal velocity and with some properties, which will be explained below in the next section. The model with

only one adjustable parameter n_n has been developed[16~18] in these 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[19] had shown that the experimental results on the relations between the excess heat, tritium and neutron were explained consistently by the model[3~9]: The questions solved by the model included the poor reproducibility of the cold fusion 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. N_Q is defined as the excess heat Q_{ex} measured in MeV divided by 5 MeV (an assumed average value of the liberated nuclear energy per a reaction);

$$N_Q = Q_{ex}\ (\mathrm{MeV})/5(\mathrm{MeV}).$$

In this paper, we will give the present form of the TNCF model and result of analysis of more than 40 typical experimental data obtained in the electrochemical and the discharge experiments done in these eight years after the discovery of the cold fusion phenomenon[1]. The results are consistent in themselves and therefore physics of the cold fusion phenomenon could be depicted on the model.

It is, perhaps, advisable to the reader to recollect the nature of a model in science. There were typical models in history of science which at first seemed ridiculous even though they could explain new experimental results which contradicted with old concepts. We take up here two typical examples; the Bohr model for hydrogen atom and the two-fluid model of the superfluidity in liquid helium.

The Bohr model could explain the atomic spectra of hydrogen and finite size of it on the assumption that there are stationary electron orbits even they contradicted classical electrodynamics. Later, these assumptions were systematized as Quantum Mechanics, entirely different physics from classical one.

The two-fluid model was proposed to explain the experimental data of superfluidity in liquid helium assuming a new concept of super-fluid which has no viscosity at all. This new concept contradicted old concept of classical fluid but was able to explain the experimental data and predicted the existence of the second sound which was discovered later experimentally. The physics of the super-fluid evolved into the superfluid hydrodynamics which includes quantum nature of the particles in the system.

Thus, a good model is very effective to promote science if it could systematize a perplexing pile of experimental data even if its basis is ambiguous for a while. The TNCF model is a phenomenological one to try to explain so complex experimental data in the cold fusion phenomenon as majority of scientists, especially physicists, are in deep scepticism for their reality without thorough investigation into them themselves.

In the next section, we explain the basic concepts of the TNCF model as a phenomenological theory. In Section 3, we 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 on the assumed fusion reactions between the neutron and nuclei causing perturbation on the neutron to destabilyze it. In Section 4, we discuss the physics of the cold fusion phenomenon on the success of the analyses envisaged by the TNCF model. In Section 5, we give fundamental ideas to verify the existence of the quasi-stable trapped neutrons in solids with some characteristics.

2. The TNCF model

The TNCF model is a phenomenological one and the basic premises (assumptions) are summarized as follows[20~24]:

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 and by breeding processes (explained later) in the sample.

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 with reactions of the 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 with a time constant 887.4 ± 0.7 s.

Premise 2. The trapped neutron reacts with another nucleus in the surface layer of the solids where it suffers a strong perturbation as if they are in 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) below with $\xi = 0.01$ due to its stability in the volume (except in a special situation such as very high temperature as 3000K).

Following premises on the measured quantities 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 one.

This means that if gamma or neutron spectrum is 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 distribution 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 of the alkali metal layer on the cathode surface will be taken as 1μm (though the experimental evidences show that it is 1~10μm).

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

$$1\ \text{MeV} = 1.6\times10^{-13}\ \text{J},\quad 1\ \text{J} = 6.25\times10^{12}\ \text{MeV}.$$

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, and (2) the neutrons breeded in the sample by chain nuclear reactions triggered by the trapped neutron with perturbing nuclei proposed in the TNCF model.

There are some experimental bases of these premises: Premise 1; Possible existence of trapped neutron. Cerofolini[25] and Lipson[26] 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.[27], Yuhimchuk et al.[28], Celani et al.[29], Stella et al.[30], Lipson et al.[31] and Oya et al.[34] had observed effects of artificial thermal neutron on neutron emission in various materials. Premises 2 and 8; Neutron reactions in the surface layer. Morrey et al.[32] and Okamoto et al.[33,34] 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.[35] 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[36~38].

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

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

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 cross section of the reaction. The factor ξ as taken into the relation (1) expresses an order of the stability of the trapped neutron in the veaction 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 value 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 is the thermal neutron, the volume V should be that of the boundary region where is the nucleus to fuse with the thermal neutron. On the other hand, in a sample without definite boundary layer but disordered array of 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 ${}^{A}_{Z}\mathrm{M}$ with a mass number A and an atomic number Z, there appears an excess energy Q and nuclear products as follows:

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

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

The 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 (breeding reactions) with one of other nuclei in the sample.

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

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

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

The thickness of the surface layer will be assumed as 1μm throughout the following analysis (Premise 8) (allowing one order of magnitude uncertainty in the determined value of n_n) though it has been determined as $1\sim 10\mu$m in experiments. 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.[39] with an abundance of 0.018% ^{6}Li case. Storms also observed characteristics of the excess heat generation in Pd/D/Li system[40].

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 ($\ell_t \simeq 1 \sim 10 \mu$m) 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 on the path with a length 1μm with a cross section $\sim 1.4 \times 10^{-1}$ barn (Premise 9):

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

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. In the following analysis, we assume $\ell_t = 1\mu$m throughout this paper.

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:

$$n(\varepsilon) + d = n' + d'(\varepsilon), \tag{5}$$
$$n(\varepsilon) + d = n' + p + n'', \tag{6}$$

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

When the neutron becomes thermal, it can fuse effectively with a deuteron in volume or with ^{7}Li nucleus in the surface layer:

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

The reaction (7) for a thermal neutron has a cross section 5.5×10^{-4} barn and the reaction (8) has 4×10^{-2} barn which will be used in the calculation 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 (except the last one of 10^{-8} barn):

$$d(\varepsilon) + d = t(1.01\text{MeV}) + p(3.02\text{MeV}), \tag{9}$$
$$= {}^3\text{He}(0.82\text{MeV}) + n(2.45\text{MeV}), \tag{10}$$
$$= {}^4\text{He} + \gamma(23.8\text{MeV}). \tag{11}$$

Depending on the situation in a cold fusion system, the trapped thermal neutron can induce trigger reactions like the reactions (3), (7) and (8) and the generated energetic

particles can sustain breeding chain reactions (4)~(6), (9) and (10) producing a lot of the excess heat and the nuclear products.

In the case of solids with hydrogen but deuterium, the following reactions should be taken up in the analysis as the trigger and the breeding reactions:

$$n+p = d(1.33\text{keV})+\gamma(2.22\text{MeV}), \tag{12}$$

$$d(1.33\text{keV})+p = {}^3\text{He}(5.35\text{keV})+\gamma(5.49\text{MeV}). \tag{13}$$

The fusion cross section of the reaction (12) for a thermal neutron is 3.5×10^{-1} barn.

The photons generated in the reactions (7), (8), (12) and (13) can induce photo-disintegration of deuterons and nuclei if they have more energy than the threshold energies of following reactions, (which is 2.22MeV for the reaction (14)):

$$\gamma+d = p+n, \tag{14}$$

$$\gamma+{}^A_Z\text{M} = {}^{A-1}_{Z}\text{M}+n. \tag{15}$$

In samples with deuteron, this reaction (14) with a cross section $\sim2.5\times10^{-3}$ barn can work as a neutron breeder.

To analyze data in electrolytic systems, we have taken an abundance of ^{6}Li in LiOD as the natural one 7.5%, an average velocity of the trapped neutron $v_n=2.7\times10^5$cm/s ($T=300$K). Then, we can determine the density of the trapped neutron n_n using the relation (1) between n_n and the number of tritium atom N_t ($=N_{He}$) generated in a time τ by the reaction (3);

$$N_t = N_{He} = 0.35 n_n v_n n^6{}_{Li} \ell_0 S \sigma_{nLi} \tau \xi, \tag{16}$$

where S is a surface area of the cathode, ℓ_0 is a thickness of the Li surface layer, $\sigma_{nLi}=10^3$ barn, $n^6{}_{Li}=3.5\times10^{21}\text{cm}^{-3}$. This number of tritium atom is also number of events generating the excess heat of 4.8 MeV;

$$N_t = N_Q \equiv Q(\text{MeV})/4.8(\text{MeV}).$$

Relation between N_n and N_t in D/Li system is given as follows; When the $n-{}^6$Li reaction (3) is predominant in a electrolytic system with D_2O, neutron is generated by the reaction (4) with a relation between N_n and N_t assuming half of the generated triton contribute the reaction (4),

$$N_n \sim 0.5 N_t \ell_t n_d \sigma_{n-d}, \tag{17}$$

where $\ell_t\sim1\mu$m, $n_d\sim6.8\times10^{22}x$ ($x=$D/Pd) and $\sigma_{n-d}\sim1.4\times10^{-1}$ barn.

An Example of Data Analysis

To illustrate the procedure of data analysis, we will show calculations of N_t/N_n, N_Q/N_n and N_Q/N_t with data from an experiment[1].

The triton generated in the reaction (3) induces the reaction (4) producing a neutron

with an energy 14.1 MeV. Taking the path length of the triton in the cathode PdD_x as 1 μm as stated above and using the cross section of the reaction (4) for 2.7 MeV triton $\sigma_{t-d} \sim 1.4\times10^{-1}$ barn, and the density of deuterium near the surface layer as $6.8\times10^{22}cm^{-3}$ (D/Pd=1), we obtain the probability of reaction (4) induced by a triton as 7.1×10^{-6} which gives a ratio of events generating tritium and neutron in a sample

$$N_t/N_n \sim 1.1\times10^{6}.$$

This value is compared with the experimental value $10^4\sim10^7$ obtained in several experiments. The coincidence of these values in one or two orders of the magnitude may be taken as very good if we notice our rough assumptions used in this calculation[19].

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 to evaluate this ratio in the area of the same sample on an assumption that nuclear reactions liberate energy about 5 MeV per reaction in average. Then,

$$N_Q/N_n = N_t/N_n = 1.1\times10^{6}.$$

An experimental value[1] of N_Q/N_n in the sample with 0.4cmϕ is $(1.1\times10^{13}\div5)/4\times10^4 = 5.6\times10^7$. Therefore, there is a difference of one order of magnitude between the experimental and theoretical values of this ratio, in this case.

This experimental 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 $N_t=1.6\times10^{12}$ in a reduced sample with 0.4cmϕ :

$$N_Q/N_t = (1.1\times10^{13}\div5)/(1.6\times10^{12}) = 1.4.$$

In the analysis of experimental data on the TNCF model, we will make the situation simple and tractable using Premises 1~11 explained above.

3. Forty One Typical Quantitative Experimental Data and Their Analysis on the TNCF Model

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

Therefore, it is usually impossible to explain whole data consistently obtained in an experiment including intricately interrelated physical variables. It should be necessary to select data from a 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 41 data including some with quantitative relations between several quantities from excellent experimental results obtained until now.

3−1. Electrolytic system Pd/D(H)/Li(Na)

An experimental system with Pd cathode and D_2O+LiOD electrolytic solution has been used after the first experiment done by Fleischmann et al.[1] to obtain high excess heat value. In this subsection, we will take up experimental data obtained in systems with a Pd cathode and electrolytic solution of Li(Na)OD(H) in $D(H)_2O$. It should be noticed that a combination of Pd cathode and Li electrolyte is very effective in contrast to that of Ni cathode and K electrolyte discussed in the next subsection.

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

In the pioneering paper by Fleischmann et al.[1], the observations were too abundant to treat in a paper on cold fusion phenomenon. We will therefore take up only some features of the phenomenon from them in this analysis. With a Pd rod cathode of dimensions $0.1\text{cm}\phi\times10\text{cm}$ and $0.4\text{cm}\phi\times10\text{cm}$, the following quantities were measured; the excess heats of 0.079J/w and 1.75J/s ($1\text{J/s}=6.29\times10^{12}\text{MeV/s}$), tritium generation of 4×10^{11}/s in the former and neutron generation of 4×10^{4}/s in the latter (perhaps with the same current density but not described explicitly) when the electrolyzing current density was 64mA/cm^2.

In the case of a Pd cathode used in electrolysis with Li electrolyte, surface layers of Li metal and/or $PdLi_x$ alloy have precipitated upon the surface of Pd cathode which have positive neutron affinities. This structure satisfies the condition to trap thermal neutrons described above. In the surface layer, the periodicity of the crystal lattice should be much disturbed and the neutron Bloch wave trapped in the cathode would suffer strong perturbation there inducing fusion reaction (1) with ^{6}Li in the layer if any.

We show here a detailed analysis of the data obtained by Fleischmann et al.[1]. We will take the same thickness of the Li surface for all samples irrespective of the current density applied.

First, their data in a sample with a dimension of $0.1\text{cm}\phi\times10\text{cm}$ generated an excess heat of $0.079\text{J/s}(=4.9\times10^{11}\text{MeV/s})$ by the reaction (1) which determines the density of the trapped neutron

$$n_n = 1.3\times10^{9}\ \text{cm}^{-3}$$

by the relation (9). In this calculation, we have assumed that all the liberated energy in the reaction had been thermalized in the system. On the other hand, a sample with the same size generated tritium of 4×10^{11}/s by the reaction (1) which determines the density

$$n_n = 5\times10^{9}\ \text{cm}^{-3}$$

by the relation (9), also. These two values of the density n_n seems consistent in a difference of factor 4.

Second, their data in a sample with a dimension of $0.4\text{cm}\phi\times10\text{cm}$ generated neutron 4×10^{4}/s which corresponds to the number of tritium of $2.5\times10^{10}/\text{s}(=4\times10^{4}\times6.25\times10^{5})$

by the reaction (2). This value determines the density of the trapped neutron using the relation (9) ;

$$n_n = 3.1 \times 10^8 \text{ cm}^{-3}.$$

On the other hand, the excess energy of 1.75J/s($=1.1 \times 10^{13}$MeV/s) observed in the sample determines the density

$$n_n = 7.1 \times 10^9 \text{ cm}^{-3}.$$

The difference in this case is by factor 20 and coincidence is qualitative.

We can see that all these values of the density n_n are fairly similar. We may assume that there should be tritium in the case of neutron measurement and in the case of heat measurement, etc. though the data of the excess heat, tritium and neutron are not measured simultaneously in the same cathode. This simultaneity might be the truth of the phenomenon in the Pd/D/Li system.

This means in our interpretation of the experimental result that it might be more reasonable to consider that both the reactions (3) and (4) were together in the samples where had been observed the excess heat, tritium or neutron, as assumed above, than to consider those events occurred independently, i.e. once only the excess heat, in other cases only tritium or only neutron. We take this point of view throughout in the analysis of the cold fusion data.

Then, we can calculate ratios of the number of events N_Q, N_t and N_n for the same density of n_n. ($N_Q Q$(MeV)/5(MeV).) Theoretical values of N_t/N_n and N_Q/N_t are 5.3×10^5 and 5.5, respectively. On the other hand, experimental values reduced to the same n_n and the same sample size are 4×10^7 and 1.0, respectively.

The coincidence of the above values of N_t/N_n ratio will be improved largely if we take into our consideration the elongation of the path length by channeling of tritium in the crystal[3,4]. There is an array of deuterons on the axis of each channel through which a triton can pass without energy loss unless it fuses with one of deuterons there.

The problem of helium generation expected from the reaction (4) which was not measured in the experiment[1] had been resolved in the analysis of the following paper.

2) J.R. Morrey et al.[32]

Morrey et al.[32] reported experimental results of measurements in six laboratories on helium content of five identically shaped 2mm$\phi \times$10cm Pd rods supplied by Fleischmann and Pons.

They could not prove that the minimal excess heating in one of the rods (rod 5) reported by Fleischmann and Pons could be attributed to the formation of ^{4}He on the assumption that the ^{4}He had been generated by the reaction (11). Their explanation is as follows: "Rod 5 is reported to have created $1.36 \pm 0.34 \times 10^{11}$erg of heat. The fusion reaction 2D$\rightarrow^4$He would generate 2.30×10^{19}erg/g.atom ^{4}He created. Thus, it could require the generation of $5.91 \pm 1.47 \times$

10^9g.atom ^{4}He ($18.9\pm4.6\times10^{9}$g.atom/cm^3 Pd) to generate the heat reported. The quantity of ^{4}He found in rod 5 does not correlated well with the excess heat generated when the rod was electrolyzed. According to our calculations, it would take 36 ± 25 times as much ^{4}He as was measured to account for the reported excess heat."

This report, accepted as giving strong support to skeptics against the cold fusion, is a result consistent with data obtained afterwards. The reaction generating ^{4}He in Pd/D/Li system should be the reaction (3) instead of the reaction (11): If the liberated energy 4.8MeV was thermalized totally in the system, the number 36 pointed out in the paper[32] as above becomes to 179. As we know from several data[43,47,49,52], main part of the ^{4}He generated in the surface Li layer on the Pd cathode goes out into liquid and gas. So, it is reasonable to assume that only a small part (let us take it as 3%) of the generated ^{4}He remained in the sample in a depth of$\sim25\mu$m determined by them. Then, the factor 179 reduces to 5.4. This value is comparable to a factor$\sim$5 obtained in analyses of many data as we can see in the table of our result of analysis. The factor$\sim$5 might be attributed to reactions in sample generating the excess heat but ^{4}He and other nuclear products.

3) T. Roulette, J. Roulette and S. Pons[41].

A novel high power dissipating heat flow calorimetric system ICARUS 9 developed at IMRA Europe[41] has been used to investigate the generation of excess enthalpy in the electrolysis of D_2O+LiOD electrolytic solutions at Pd and Pd alloy cathodes.

The unique feature of this calorimeter are, by 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.

Experimental data 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$\sim$20.6%). From the amount of the excess heat, we could determine $n_n=10^{11}\sim10^{12}$cm^{-3} according to the procedure explained above without any additional assumption.

4) E. Storms and C. Talbott[39] and Storms[40].

Storms et al.[39] investigated carefully generation of tritium in the electrolytic system Pd/D/Li with LiOD with a lowered composition of 0.018% ^{6}Li. In a case of the maximum tritium generation 1.8×10^2Bq/mℓ in 250h with an electrolyte volume of 60mℓ, the density of the trapped thermal neutron was evaluated[39'] as

$$n_n = 2.2\times10^7 \text{ cm}^{-3}.$$

In the case of the excess heat observation[40], the maximum density of the trapped neutron was calculated as

$$n_n = 5.5\times10^{10}\ \mathrm{cm}^{-3}.$$

5) A. Takahashi, T. Iida, T. Takeuchi, A. Mega, S. Yoshida and M. Watanabe[42].

Next, we will take up an experiment[42] where observed the excess heat, tritium and neutron with $N_t/N_n=6.7\times10^4$ in $Pd/D_2O+LiOD$ system with L-H mode electrolysis. The same analysis as shown above gives following results[42'];

$$n_n = 3\times10^5\ \mathrm{cm}^{-3},\quad N_t/N_n = 5.3\times10^5.$$

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 mechanisms of events in both cases.

6) M.H. Miles, R.A. Hollins, B.F. Bush and J.J. Lagowski[43].

We have given a result[19] of the analysis of an experiment where observed the excess heat and helium in $Pd/D_2O+LiOD$ system[43] using a massive cylindrical Pd cathode with a surface area of $2.6\mathrm{cm}^2$. They measured $10^{21}\sim10^{22}\mathrm{cm}^{-3}$ ^{4}He atoms per watt of the excess power ($N_Q/N_{He}=10\sim1$) while they did not measure tritium. Similar analysis[43'] 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:

$$n_n = 1.1\times10^9\sim10^{10}\ \mathrm{cm}^{-3},\ N_Q/N_{He} = 5.$$

The density n_n is similar to that in 1) and the ratio N_Q/N_{He} shows the main source of the excess heat in this case was the reaction (3).

7) M. Okamoto, H. Ogawa, Y. Yoshinaga, T. Kusunoki and O. Odawara[33].

We give a results[33'] of the analyses of an experiment where observed the excess heat and the nuclear transmutation in the surface layer from Al into Si in $Pd/D_2O+LiOD$[33] system and also the excess heat and gamma spectrum[34].

The change of the density of the elements (up to 80% for Al) occurred in a surface layer of the Pd cathode with a thickness of$\sim1\mu$m. The result of the calculation are given as follows:

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

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[33] as in an experiment[43] discussed before because of the similarity of experimental condition. 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.

8) Y. Oya et al.[34]

In the another experiment with artificial thermal neutron source[34], the authors observed the excess heat and gamma spectrum. The excess heat amounted to the density of the trapped neutron[34']

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

In the gamma spectrum, there are peaks at 0.511, 2.22, 5.49, 6.15, 6.25 and 7.09MeV. The first one was interpreted[34'] 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:

$$n + {}^{62}\text{Ni} \rightarrow {}^{63}\text{Ni} \rightarrow {}^{63}\text{Cu} + e^- + \bar{\nu}_e, \tag{18}$$

$$n + {}^{63}\text{Cu} \rightarrow {}^{64}\text{Cu} \rightarrow {}^{64}\text{Ni} + e^+ + \nu_e, \tag{19}$$

The peak at 2.22 and 6.25MeV can be interpreted as due to reactions (11) and (7), respectively. The peaks at 5.49, 6.15 and 7.09MeV can be due to following reactions:

$$p + d = {}^3\text{He} + \gamma(5.49\text{MeV}), \tag{20}$$

$$n + {}^{108}\text{Pd} = {}^{109}\text{Pd} + \gamma(6.15\text{MeV}), \tag{21}$$

$$n + {}^{104}\text{Pd} = {}^{105}\text{Pd} + \gamma(7.09\text{MeV}), \tag{22}$$

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

9) Y. Arata and Y.C. Zhang[44].

Next, we give a result[44'] of the analysis of an experiment where observed a huge excess heat and a tremendous number of helium atoms as high as 10^{20}~10^{21}cm^{-3} in Pd-black (400nm in diameter) contained in a Pd cylinder cathode. The density n_n and the ratio of events generating triton and neutron were determined as follows:

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

In this calculation, the path length of the 2.7MeV 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 triton assumed in this calculation on the TNCF model.

10) M.C.H. McKubre, S. Crouch-Baker and F.L. Tanzella[45].

The elaborate experimental data in Pd/LiOD+D_2O system gave a semi-quantitative relation between the excess heat Q, the electrolyzing current density i, the density of the occluded deuterium x and the speed of the occlusion $|dx/dt|$[45]:

$$q = C(i - i_0)^a (x - x_0)^b \left| \frac{dx}{dt} \right|,$$

where C, a (~ 1) and b (~ 2) are constants depending on the sample. The data were analyzed on the TNCF model[45'] giving a qualitative explanation of the relation and the density of the trapped neutron in the sample with a size of 1mm$\phi \times$45cm:

$$n_n \simeq 10^9 \sim 10^{10} \text{ cm}^{-3}.$$

11) T.O. Passell[46]

A Pd cathode with a total surface area 60cm^2 and a thickness 25μm (with a weight 0.9g) used in an experiment with an electrolytic solution D_2O+1.0M LiOD+200ppm Al producing the excess heat of 0.56MJ was subjected upon comparing measurements of the prompt gamma activation analysis (PGAA) using thermal neutrons in beams from research reactors. A result showed an$\sim$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

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

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[46'] giving a consistent explanation of this and those obtained in SRI International assuming following reactions between the trapped neutron and the ^{10}B with a large cross section of 3.84×10^3 barn as a whole;

$$n + {}^{10}\text{B} = {}^7\text{Li} + {}^4\text{He} + 2.79 \text{ MeV}, \ (93\%) \tag{23}$$

$$= {}^7\text{Li} + {}^4\text{He} + \gamma \ (0.48\text{MeV}) + 2.79 \text{ MeV}. \ (7\%). \tag{24}$$

The determined value of n_n was about 10^9cm^{-3} consistent with the value obtained in the analysis[45'] of the data by SRI International given in the preceding subsection 10).

12) D. Cravens[47].

The remarkable system[47,48] 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[47'] 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 an enough amount of deuterium, it is possible to generate the observed big amount of the excess

heat by $H_2O+LiOH$ electrolysis. The experimental data[47] of the excess power ($Q_{out}/Q_{in}=1.77W/0.46W=3.8$ with 1200 beads) gave a following value[47] for the trapped neutron density:

$$n_n = 8.5\times10^9 \text{ cm}^{-3}.$$

13) J.O'M. Bockris et al.[49]

Careful measurements of tritium, helium and the excess heat have been done in Pd/D/Li system (with a cathode of $1cm\phi\times1.5cm$) by Bockris et al[49] 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 evaluate the density of the trapped thermal neutron as follows:

$$n_n = 1.1\times10^6 \text{ cm}^{-3}.$$

14) A.G. Lipson et al.[50]

Lipson et al. have been working with ferroelectrics to measure the excess heat and nuclear products. In a recent work[50], 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 $1\mu m$ in the cathode, we obtained the density of the trapped thermal neutron as follows:

$$n_n = 4\times10^5 \text{ cm}^{-3}.$$

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

15) F.G. Will et al.[51]

Will et al. observed tritium generation of $5.1\times10^4\sim2\times10^5 cm^{-2}s^{-1}$ from a Pd wire cathode ($2mm\phi\times2.6cm$) with $D_2O+D_2SO_4$ electrolyte. They had accomplished high loading of D/Pd~1. Assuming the $n+d$ fusion in a surface layer of $10\mu m$, we obtain following values for the trapped thermal neutrons:

$$n_n = 1.4\sim5.6\times10^7 \text{ cm}^{-3}.$$

16) Cellucci et al.[52]

Elaborate experimental works done by Gozzi and his group in the University of Rome

after the discovery of the cold fusion phenomenon in 1989 have shown the reality of the excess heat generation in the PdD_x/Li cathode though the nuclear products had not been proved their existence until ^{4}He was detected in a recent work[52].

The report[52] given in the ICCF6 (Hokkaido, Japan, October 1996) has shown the simultaneous generation of the excess heat up to 80% of the input energy and of ^{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 250μm and a length 40mm. 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[52] analyzed their data on an assumption that the nuclear reaction was (11) or

$$d+d \rightarrow {}^4\mathrm{He}+\gamma \ (23.8\mathrm{MeV}).$$

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 values[52'] of the trapped thermal neutrons:

$$n_n = 2.2\times10^9 \ \mathrm{cm}^{-3}.$$

17) Celani et al.[53]

An Italian group in Frascati made a fine experiment[53] showing the excess heat generation with high qualitative reproducibility. They used thin and long pure Pd wires (mainly 100μm$\phi\times$160cm) wound around a cylinder (with a diameter 4cmϕ) as a cathode for both high voltage DC electrolysis and high power-high frequency electrolysis (peak current up to 25A, peak voltage up to 270V, pulse width 2×10^2~5×10^4 ns, repetition rate 10^2~5×10^4 Hz) in a dilute solution 0.25mN LiOD+D_2O (LiOH+H_2O). The anode was a Pt wire (1mmϕ) wound around a cylinder with a diameter 2cmϕ 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 70W (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[53'] of these data gave us following value n_n in D_2O case:

$$n_n = 1.0\times10^{12} \ \mathrm{cm}^{-3}.$$

18) K. Ota et al.[54,55]

K. Ota and his collaborators had made a fine calorimetric measurement of the excess heat and investigation of minor elements in cathodes in the Pd/D/Li system[54]. In a run of their experiments, an excess heat of 13% over the input energy was measured in Pd cathodes (e.g. a cylinder with a size of 5mmϕ×10mm) for 220h after 1150h electrolysis without any effect. The data was analyzed by the TNCF model[55'] using the sample of 5mmϕ×10mm and the density of the trapped neutron was determined as

$$n_n = 4.3\times10^{10}\ \mathrm{cm}^{-3}.$$

19) D. Gozzi et al.[56]

Gozzi et al.[56] made an experiment in Pd/D/Li system with a multicell set up implemented with mass spectrometric measurements of ^{4}He and a highly improved neutron detector. They made measurement of the excess heat, neutron, ^{4}He and tritium from wires (e.g. a size of 3mmϕ×23mm). They observed the excess heat comparable with the results of other laboratories but no neutrons. The tritium excess was lower than expected from the excess heat Q. ^{4}He has been measured in the electrolysis gases and a tentative correlation of ^{4}He with the excess heat was obtained.

The result was analyzed by the TNCF model[56'] with an assumption that the excess heat, helium ^{4}He and tritium had been generated simultaneously by the reaction (3) if one of them were not measured in the experiment.

The density of the trapped neutron in the sample were determined by the average values of the excess heat ($n_n(Q)$),^{4}He (n_n(He)) and tritium ($n_n(t)$):

$$n_n(Q) = 4\sim8\times10^{10},\ n_n(\mathrm{He}) = 0.1\sim2\times10^{10},\ n_n(t) = 4\sim6\times10^{6}\ \mathrm{cm}^{-3}.$$

There is a possibility that the main part of the generated tritium was remained in the samples as stated in the paper[56] to explain the low value of $n_n(t)$.

20) R.T. Bush et al.[60]

R. Bush and R. Eagleton[60] made a Fleischmann-Pons type experiment with a Pd cathode in the form of a 5-μm thin film electropolated upon a silver substrate with a surface area of ~4.5cm^2. They observed ~15MJ of excess heat over a 54-day period with a peak excess power of ~6W and an average excess power of ~3.2W, with the latter being ~ 28% of the input power.

Normalizing the data to the amount of palladium and assuming that the excess heat effect occurs in the palladium, they can employ this data to evaluate a lower limit for the normalized excess heat produced in the thin Pd film of ~6.3×10^{10}J/mol.

This energy could be compared with the chemical energy, for instance,

$$C + O_2 = CO_2 + 94.05 \text{ kcal/mol},$$
$$2H_2 + O_2 = 2H_2O + 68.32 \text{ kcal/mol}.$$

These energies generated in the chemical reaction correspond to 3.93×10^5J/mol and 2.86×10^5J/mol, respectively in Joule, compared to the above value of 6.3×10^{10}J/mol. There are a difference of the order of five and the energy observed in the cold fusion experiment is too large for it to have been of chemical origin.

21) T. Mizuno et al.[72]

Mizuno et al. observed NT in the surface layer (thickness $\ell \leq 2\mu$m) induced by electrolysis. The identification of isotopes was performed by SIMS (Secondary Ion Mass Spectrometry), AES (Auger Electron Spectroscopy), EPMA (Electron Probe Microanalysis), EDX and γ spectroscopy. Many elements including Pt, Cu, Ni, Mo, Cr, Pd showed shift of isotope ratio from natural one.

We take up here only one data of ^{52}Cr in Pd/D/Li system: isotope ratio of ^{52}Cr observed in the surface layer showed a reduction from 83.8% (natural abundance) to 50% through an electrolysis of 30days. We assume the cause of the isotope change was a reaction between the trapped neutron and one of Cr nuclei with natural abundance (origin of which is ambiguous at present)

$$n + {}^{52}\text{Cr} = {}^{53}\text{Cr} + \gamma.$$

The cross section of this reaction is 0.764barn. Then, we can calculate the parameter n_n by the above change of the isotope ratio occurred in the duration of the electrolysis of 30days as follows:

$$n_n = 2.6\times10^8 \text{ cm}^{-3}.$$

There was data of many NT with decreasing mass number in the paper[72] not easy to explain with the neutron absorption reaction. We might be able to treat these cases by the following reactions like (5) and (6) induced by high energy neutrons generated by such breeding reactions as (4) and (10):

$$n(\varepsilon) + {}^{A}_{24}\text{Cr} = {}^{A-3}_{22}\text{Ti} + {}^{4}_{2}\text{He} - Q,$$
$$n(\varepsilon) + {}^{A}_{46}\text{Pd} = {}^{A-3}_{22}\text{Ru} + {}^{4}_{2}\text{He} - Q'.$$

Numerical data will be given elsewhere.

In some cases, it might be possible to assume even a fission reaction induced by a high energy neutron generated in one of breeding reactions.

22) Y. Iwamura et al.[73]

Iwamura et al. constructed a new type apparatus of Pd/D/Li system: a Pd plate cathode consisted a part of the separation wall between electrolysis region A and a

vacuum region B. Electrolysis was performed with an electrolytic solution $LiOD+D_2O$, the Pd cathode and a Pt disc plate anode (16mmϕ) over the cathode. The excess heat of 4W for an input energy of 20W was measured once. X-ray spectrometers were set for both A and B region. X-ray spectrum with a broad continuous peak up to 100keV was measured only for A region showing the origin of the X-ray was on the A side of the cathode plate. Foreign elements including Ti, Fe, Cr, Si, Cu etc. were observed on the Pd cathode only under the Pt anode.

Using the maximum value of the excess heat 4W and the active region of the Pd cathode with a surface area $S=\pi(0.8)^2 cm^2$, we can calculate the parameter n_n for the event as

$$n_n = 7.4\times10^{10}\ cm^3.$$

The product of NT, i.e. Ti, Fe, Cr, ····· could be treated by successive reactions of (n, α), $(n, 2n)$, (n, np), and so on.

The results of the analyses given above in the subsection 3−1 were summarized in Table 2 amplifying the corresponding data given in the previous paper[57].

Table 2 : Pd/D(H)/Li(Na) System. Neutron Density n_n and Relations between the Numbers N_x of Event x Obtained by Theoretical Analysis of Experimental Data on the TNCF Model ($N_Q \equiv Q(\mathrm{MeV})/5(\mathrm{MeV})$). Typical value of the surface vs. volume ratio S/V (cm^{-1}) of the sample is tabulated, also.

Authors	System	S/V	Measured Quantities	n_n cm^{-3}	Other Results (Remarks)
M. Fleischmann et al.[1]	Pd/D/Li	6~40	Q, t, n $N_t/N_n \sim 4\times10^7$ $N_Q/N_t \sim 0.25$	$10^7 \sim 10^9$	 $N_t/N_n \sim 1.4\times10^5$ $N_Q/N_t = 1.0$
J.R. Morrey et al.[32]	Pd/D/Li	20	Q,^{4}He(^{6}Li→^{4}He) ^{4}He in $\ell \leq 25\mu$m	4.8×10^8	$N_Q/N_{He} \sim 5.4$ (If 3% ^{4}He was in Pd)
T. Roulette et al.[41]	Pd/D/Li	63	Q	$10^{11} \sim 10^{12}$	
E. Storms et al.[39]	Pd/D/Li	9	$t(\sim 1.8\times10^2 \mathrm{Bq/m\ell})$	2.2×10^7	(τ=250h, V=60mℓ)
E. Storms[40]	Pd/D/Li	22	$Q(Q_{max}=7\mathrm{W})$	5.5×10^{10}	
A. Takahashi et al.[42]	Pd/D/Li	2.7	t, n $N_t/N_n \sim 6.7\times10^4$	3×10^5	$N_t/N_n \sim 5.3\times10^5$
M.H. Miles et al.[43]	Pd/D/Li	5	Q, ^{4}He ($N_Q/N_{He}=1\sim10$)	$10^9 \sim 10^{10}$	 $N_Q/N_{He} \sim 5$
M. Okamoto et al.	Pd/D/Li	23	Q, NT(^{27}Al→^{28}Si) $\ell_0 \sim 1\ \mu$m	$\sim 10^{10}$	$N_Q/N_{NT} \sim 1.4$
Y. Oya et al.[34]	Pd/D/Li	41	Q, γ spectrum	3.0×10^9	(with ^{252}Cf source)
Y. Arata et al.[44]	Pd/D/Li	75000	Q, ^{4}He($10^{20} \sim 10^{21}\mathrm{cm}^{-3}$) $N_Q/N_{He} \sim 6$	$\sim 10^{12}$	(Assume t channeling in Pd wall)
M.C. H. McKubre[45]	Pd/D/Li	125	Q(&Formula)	$10^9 \sim 10^{10}$	Qualit. explanation
T.O. Passell[46]	Pd/D/Li	400	NT(^{10}B→^{7}Li+^{4}He)	1.1×10^9	$N_{NT}/N_Q=2$
D. Cravens (PPC)[47]	Pd/H/Li	4000	$Q(Q_{out}/Q_{in}=3.8)$	8.5×10^9	(If PdD exists)
J. Bockris et al.[49]	Pd/D/Li	5.3	$t(\sim 3.8\times10^7/\mathrm{cm}^2\mathrm{s})$	1.1×10^6	$N_t/N_{He} \sim 1$
A.G. Lipson et al.[50]	Pd/D/Na	200	$\gamma(E_\gamma=6.25\mathrm{MeV})$	4×10^5	(If efficiency=1%)
F.G. Will et al.[51]	Pd/D_2SO_4	21	$t(1.8\times10^5/\mathrm{cm}^2\mathrm{s})$	3.5×10^7	(If $\ell_0 \sim 10\mu$m)
F. Cellucci et al.[52]	Pd/D/Li	40	Q, ^{4}He $N_Q/N_{He}=1\sim5$	2.2×10^9	(Assume Q=5W) $N_Q/N_{He}=1$
F. Celani et al.[53]	Pd/D/Li	400	$Q(Q_{max}=7\mathrm{W})$	1.0×10^{12}	(at Q_{max},200%)
K. Ota et al.[54]	Pd/D/Li	10	$Q(W_{out}/W_{in}=1.13)$	3.5×10^{10}	(τ=220h)
D. Gozzi et al.[56]	Pd/D/Li	14	Q, t, ^{4}He	$10^{10} \sim 10^{11}$	($\tau \sim 10^3$h)
R.T. Bush et al.[60]	Ag/Pd/D/Li	2000	$Q(Q_{max}=6\mathrm{W})$	1.1×10^9	(τ=54d, Thin film)
T. Mizuno et al.[72] (If Cr preexists)	Pd/D/Li	3.4	Q, NT(^{52}Cr→^{53}Cr $\ell \leq 2\mu$m)	2.6×10^8	τ=30d, Pd cathode 1cmϕ×10cm
Y. Iwamura et al.[73]	Pd/D/Li	10	Q, NT(Ti, Cr etc.) (4W/2cm^2)	7.4×10^{10}	(NT unexplained)
H. Kozima et al.[75,76]	Pd/D,H/Li	200	$n(2.5\times10^{-4}/\mathrm{s})$	2.5×10^2	Efficiency=0.44%

3−2. Ni/H/K and other systems

Other systems than the typical Pd/D/Li system have been recognized effective to produce the cold fusion phenomenon. Typical such systems are Ti/D_2 and Ni/H/K in addition to other materials with hydrogen isotopes. An interesting combination in this group is a Ni cathode and K electrolyte generating various events including the excess heat, nuclear transmutation and gamma emission. In this subsection, we will take up those systems other than electrolytic Pd/D/Li system.

23) R.L. Mills et al.[58]

Mills and Kneizys made a pioneering experiment on Ni/H_2O+K_2CO_3 electrolyte system to measure the excess heat with Ni plate cathode. Though the interpretation of the result by their model is not necessarily persuasive, the experimental result has been confirmed by many researchers including Notoya et al.[35] and Niedra et al.[71] analyzed in this section.

Their Ni cathode was with a size 7.5cm×5cm×0.125mm in H_2O+0.59M K_2CO_3 and produced the excess heat of 0.13W. Analysis of the data using the reaction (11) in sample volume assuming H/Ni=1.0 and $\xi=0.01$, we obtain the density of the trapped neutron as follows:

$$n_n = 3.4\times10^{10}\ \mathrm{cm}^{-3}.$$

24) R.T. Bush[59].

Bush observed the excess heat generation and nuclear transmutations $^{23}Na \rightarrow {}^{24}Mg$ and $^{39}K \rightarrow {}^{40}Ca$ in electrolytic systems Ni(alloy)/H/K(Na). Electrolytic solutions were 0.57M $K(Na)_2CO_3+H_2O$. In a case of ^{40}Ca production, cell 45, the average excess heat was $Q=0.58\pm0.15$ J/s and the generated calcium atom was 4.8×10^{18}/15d. In the case of ^{24}Mg production, only the relative excess heat to the former case was given as $Q_{Na}/Q_K=1.90\pm0.33$.

The TNCF model predicts following reactions (decay time) between the trapped neutron and alkali metals:

$$n+{}^{23}Na \rightarrow {}^{24}Na \rightarrow {}^{24}Mg+e^-+\bar{\nu}_e+Q,\ (15.0h) \tag{25}$$

$$n+{}^{39}K \rightarrow {}^{40}K \rightarrow {}^{40}Ca+e^-+\bar{\nu}_e+Q.\ (1.2\times10^9y) \tag{26}$$

In these reactions, the absorption cross sections are 0.53 and 2.1barn, and the liberated energies Q including accompanying gamma are 2.72 and 2.78MeV, respectively.

If the decay time of the second reaction of 1.2×10^9y is largely shorten by the neutron capture reaction to a value of the order of few hundred hours (let us take it as 0 in the following analysis, for simplicity), the experimental data showing generations of ^{24}Mg and ^{40}Ca are explained by the TNCF model with values of the parameter n_n given as follows:

$$n_n = 8.2\times10^{11}\ \mathrm{cm}^{-3},\ (^{24}\mathrm{Mg})$$
$$n_n = 8.1\times10^{10}\ \mathrm{cm}^{-3}.\ (^{40}\mathrm{Ca})$$

In this analysis, the size of Ni(alloy) cathode was assumed the same $7.5\times5.0\mathrm{cm}^2\times0.125\mathrm{mm}$ as that used in Mills et al.[58] according to the description in the paper[59]. Also, the thicknesses of the surface alkali layer were assumed as 1μm for both systems and the reaction (12) which contribute a comparable excess heat was ignored.

We have to remember that the decay time of ^{40}K was largely shortened in this calculation. If the NT is understood consistently in the frame of the TNCF model, this result might be considered as showing that the ^{40}K* generated through the absorption of a thermal neutron by ^{39}K is more unstable to decay faster than ^{40}K usually used to determine the decay constant.

25) R. Bush and R. Eagleton[60].

We give a result[60'] of the analysis of an experiment where observed the excess heat and the nuclear transmutation of Rb into Sr in $Ni/H_2O+Rb_2CO_3$ system (with Ni sponge cathode)[60]. The reaction supposed to occur in the system[60'] was

$$n+{}^{A}\mathrm{Rb} = {}^{A+1}\mathrm{Sr}+e^-+\bar{\nu}_e$$

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 $Q_2=5Q_1$. For A=85 and 87 in the above reaction, the absorption cross sections are 0.7 and 0.2 barn, respectively. Using these values in addition to the experimental data, we could calculate the density of the trapped neutron to explain the data.

The density n_n was determined[60'] as follows:

$$n_n = 1.6\times10^{7}\ \mathrm{cm}^{-3}.$$

Correlation of the excess heat and helium generation was explained quantitatively in a factor of 3. About the important parameter S/V ratio, the sponge cathode used here is difficult to determine its surface area. We may assume fairly large value comparable to one used by Notoya et al.[35] ($3.4\times10^4\mathrm{cm}^{-1}$ of sintered Ni powder); $S/V\sim10^4$.

26) I.B. Savvatimova et al.[61]

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 (the cathode was with thickness of 100μm). They measured the excess heat, NT (nuclear transmutation) of various isotopes and elements in the surface layer of the multi-layer cathodes. Here we take up only one data of an increase of ^{107}Ag from 20 to 5000ppm 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:

$$n_n = 9\times10^{10}\ \mathrm{cm}^{-3}.$$

27) V.A. Romodanov et al.[36~38]

Another group in the Institute LUTCH in Podolsk has been working also with a glow discharge experiment[36,37]. They measured a lot of tritium with cylindrical Mo cathode[36] and disk cathodes of ceramics[38] in D_2 gas.

The pressure of the gas in the former case was 1 atm in the cylinder and 0.2 atm outside where the discharge was. With a cylindrical cathode of 2.5cm$\phi\times$10cm with wall thickness of 5mm, they measured tritium production of $10^7\ \mathrm{s}^{-1}$. 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 $\sim5.5\times10^{-4}$ barn, we obtain a following value[36'] for the density of the trapped thermal neutron in MoD_x cathode:

$$n_n = 1.8\times10^{7}\ \mathrm{cm}^{-3},$$

where we assumed $x=1$.

In the case of ceramics cathodes (TiC, VC, ZrC and ZrN) of sizes 25mm$\phi\times$10mm, they observed one order of magnitude lower tritium generation which gave following values for n_n[38']:

$$n_n = 1.9\times10^{5}\sim3.1\times10^{6}\ \mathrm{cm}^{-3}.$$

28) O. Reifenschweiler[62].

Reifenschweiler[62] measured the resulting X-ray induced by β-decay of 'tritium' sorbed by Ti ($TiT_{0.0035}$). The sample was in a shape of extremely small monocrystalline particles with diameter $\phi=15$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, i.e. it was induced by the change of the neutron stability, we could evaluate 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 calculation[62'] gives a value

$$n_n = 1.1\times10^9 \text{ cm}^{-3}.$$

29) J. Dufour[63].

Dufour had observed the excess energy of $Q\sim2.5$W in the sparking experiments in D_2 or H_2 gas ($\sim$1atm) with a cylindrical cathode of Pd or Stainless Steel (SS) with dimensions 10$\sim$11mm$\phi\times$24mm length and thickness $\ell_0=0.5$mm (with a surface area $\sim7.5\text{cm}^2$).

To analyze this data on the TNCF model, we will assume that the D(H)/Pd(SS) ratio is 1 and n - d (p) fusion occurs in the whole volume $\sim0.38\text{cm}^3$ though there is no description in the paper[63] about D(H)/Pd(SS) ratio in the cathode.

Then the excess energy ~2.5W ($\sim1.6\times10^{13}$MeV/s) gives us the numbers N_t and N_d of the fusion reactions n - d and n - p as follows:

$$N_t = 2.6\times10^{12},\ N_d = 7.3\times10^{12}\ \text{s}^{-1}.$$

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

$$N_{t(d)} = 0.35 n_n v_n n_{d(p)} S\ell_0 \sigma_{n-d(p)}\tau,$$

where $\sigma_{n-d(p)}$ is the fusion cross section of the reaction and is 5.5×10^{-4} (0.35) barn. $S\ell_0 = V$ is the volume where the fusion reaction occurs. This relation with the assumptions explained above gives us following values n_n in Pd sample with D(H)/Pd $\sim$1:

$$n_n(\text{d}) = 9.2\times10^{11},\ n_n(\text{p}) = 4.0\times10^9\ \text{cm}^{-3}.$$

This means H_2-Pd(SS) system generate 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 $\sigma_{n-p}=3.5\times10^{-1}$ and $\sigma_{n-d}=5.5\times10^{-4}$ barn for thermal neutron.

30) T.N. Claytor et al.[64]

Claytor et al.[64] measured tritium generated from Pd wire in low pressure D_2 gas (p_{D2} $\sim$200Torr) when high current of $V\sim2$kV, $I\sim3$-5A was applied. The samples were of various form and size including one with 100μm$\phi\times$252cm. The tritium ~12.5nCi/ℓ was measured in the gas with background 5.5nCi/ℓ which gives an generation rate of tritium atom 4.5×10^{11}/s (and also in the surface layer of the cathode with thickness $\sim$15-30μm).

In another experiment reported at ICCF5, they measured tritium in a cathode of 100 $\sim$250μmϕ and 25$\sim$30mm length. The tritium was measured in the gas ($\sim$0.15nCi/h= 3.6×10^4 t/s) and also in the surface layer of the cathode with thickness $\sim$15-30μm. Total amount of the tritium was up to 102nCi ($=2.4\times10^7 t$) in few days.

In the former experiment assuming D/Pd=1, the density of the trapped neutron calculated from the tritium in the gas is given as [64']

$$n_n = 8\times10^{12}\ \mathrm{cm}^{-3}.$$

In the latter, assuming tritium generation of 0.15nCi from a Pd cathode of 0.05cm$\phi\times$3.0cm (in the surface layer of thickness 30μm), we obtain a value for the trapped thermal neutron:

$$n_n = 1.4\times10^{7}\ \mathrm{cm}^{-3}.$$

31) M. Srinivasan et al.[65]

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 (~10^9s) producing ~10^{15} tritium atoms, ……"[65].

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 (16) with values given above by the authors ($N_t=10^{15}$ atoms, $n_dS\ell_0=10^{20}$ atoms by the assumption of the number of pairs equals to the number of atoms and $\tau=10^9$s) together with values v_n~2.7×10^5cm/s (300K), σ_{n-d}~5.5×10^{-4} barn ($=5.5\times10^{-28}$ cm^2), we obtain a value for the density of the trapped thermal neutrons:

$$n_n = 1.9\times10^{8}\ \mathrm{cm}^{-3}.$$

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

32) A. De Ninno et al.[66]

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 (laths with dimensions of 50μmϕ thick and 1 mm large) by the liquid scintillation spectroscopy. One sample (C10) 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 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 τ between the two measurements was 1 week ($=6.0\times10^5$s) and D/Ti ratio was 1 (i.e. the deuteron density in the sample N_d~5.7×10^{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 $=1.0\times10^{-14}t$/s/(D atom), we obtain n_n from the relation (16) as follows:

$$n_n = 1.2\times10^{6}\ \mathrm{cm}^{-3}.$$

In this calculation, 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 $10^5 \sim 10^{12}\mathrm{cm}^{-3}$.

33) S. Focardi et al.[67]

Another Italian group[67] 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 (12) to thermalize in the system, we obtain as the density of the trapped thermal neutron in the sample of 5mm$\phi\times$90mm generating an excess heat of 44W for 24days according to the relation (1) a following value:

$$n_n \sim 3.0\times10^{12}\ \mathrm{cm}^{-3}).$$

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[67'].

34) Oriani et al.[68]

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 until now. Oriani[68], 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 0.7W in optimal cases though the production occurred only in a small ratio in the total experiments. The data analyzed on the TNCF model[68'] gave a following value of the trapped neutron density n_n:

$$n_n = 4.0\times10^{10}\ \mathrm{cm}^{-3}.$$

35) R. Notoya et al.[35]

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.[35] 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 0.511MeV line due to the positron annihilation.

In the case of a porous Ni cathode with a dimension of $1.0\times0.5\times0.1cm^3$ and a density 58% of Ni metal and a electrolytic solution of 0.5M $K_2CO_3+H_2O$ (20 to 30mℓ as a whole), they observed an increase of ^{40}K by 100% after 24 hours electrolysis and the annihilation gamma ray at 0.511MeV. The increase by 100% in the solution corresponds to a generation of ^{40}K by 3.0×10^{16} nuclei.

Analysis of the data on the TNCF model[35'] 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

$$n+{}^{39}K = {}^{40}K+\gamma \ (7.8MeV).$$

with a fusion cross section for the thermal neutron 2.2 barn as follows:

$$n_n = 1.4\times10^9 \ cm^{-3}.$$

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

$$^{62}Ni+n = {}^{63}Ni \rightarrow {}^{63}Cu+e^-+\bar{\nu}_e, \tag{27}$$

$$^{63}Cu+n = {}^{64}Cu \rightarrow {}^{64}Ni+e^++\nu_e, \tag{28}$$

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 following value: $n_n=1.4\times10^9cm^{-3}$ and $(\xi)_{max}=0.01$ in volume.

36) H. Yamada et al.[69]

Yamada et al. observed a neutron burst and precipitation of carbon on the tip surface of positive Pd electrode used in glow discharge with D_2 gas (pressure of 2 atm) and a point-to-plane electrode configuration. The analysis of the experimental data on the TNCF model gave us a possible reaction and a following value of n_n[69']:

$$n+{}^{16}O = {}^{13}C+{}^4He-4 \ MeV, \tag{29}$$

$$n_n = 2.0\times10^{12} \ cm^{-3}.$$

The reaction (30) has a threshold energy ~ 4 MeV and a cross section $\sim 1\times10^{-1}$ barn for a neutron with energy larger than 4 MeV, which is assumed to be generated by a trigger reaction (7) and following reactions like (4) and (10) with an energetic deuteron.

37) F. Cuevas et al.[70]

Cuevas et al.[70] performed experiments to detect 2.45 MeV neutrons expected from direct d-d reaction (10) in a Ti film (with a thickness 74.7μm deposited on a tungsten plate of $40\times2\times0.025mm^3$) with careful alignment of two liquid scintillation counters with different sensitivity. They observed signals above background level by one of two counters, absence of the time correlation made them a conclusion that the d-d reaction did not occur in their sample in the experiment.

The TNCF model predicts production of several neutrons with energy about 2 MeV in a sample with deuteron. The smallness of the production rate might be the cause of the lack of time correlation. From this point of view based on the TNCF model, we have analyzed the neutron detection data and obtained n_n as follows[70']:

$$n_n = 5.4\times10^{11}\ cm^{-3}.$$

38) J.M. Niedra et al.[71]

A group in NASA Checked the excess heat generation in $Ni/H_2O(K_2CO_3)$ system provided from Hydrocatalysis Power Corporation (HPC), where the set used in this experiment gave a result of the excess heat 50 W when input energy was 59.6 W. A long ($5\times103m$) and thin (0.5mmϕ) Ni wire was used as the cathode in the system with the electrolytic solution of $H_2O+0.57$ M K_2CO_3 Solution (28 ℓ). Careful check of calorimetry was conducted for the exact replication of the excess heat production.

The maximum excess heat production measured in this experiment was 11.4 W when the input energy was 59.6 W compared with the value 50 W measured in the HPC. The TNCF analysis assuming n-d reaction (7) with $\xi=0.01$ in the relation (15) gives the following value for the density n_n of the trapped neutron:

$$n_n = 1.4\times10^{9}\ cm^{-3}.$$

In the case of the excess heat of 50 W in the same system, $n_n=6.3\times10^9 cm^{-3}$.

39) S.E. Jones et al.[77]

The first data of neutron measurement in the cold fusion experiment by Jones et al.[77] was analyzed by the TNCF model[78].

Jones et al.[77] made a precise measurement of 2.45 MeV neutrons from electrolytic cells with Pd and Ti cathodes and an electrolytic solution of several electrolytes. The electrolyte was typically a mixture of ~160 g D_2O plus various metal salts in ~0.1 g amount each: $FeSO_4\cdot7H_2O$, $NiCl_2\cdot H_2O$, $PdCl_2$, $CaCO_3$, $Li_2SO_4\cdot H_2O$, $Na_2SO_4\cdot10H_2O$,

Table 3: Ni/H/K(Rb) System and Others. Neutron Density n_n and Relations between the Numbers N_x of Event x Obtained by Theoretical Analysis of Experimental Data on the TNCF Model ($N_Q \equiv Q$ (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	Measured Quantities	n_n cm^{-3}	Other Results (Remarks)
S.E. Jones et al.[77]	Ti/D/Li	8.1	n (2.45MeV)	4.4×10^{11}	(0.4 n/s in 3g Ti)
R.L. Mills et al.[58]	Ni/H/K	160	Q (0.13W)	3.4×10^{10}	($75\times50\times0.125mm^3$)
R.T. Bush[59] (Sample	Ni/H/K	~160	NT($^{39}K\rightarrow^{40}Ca$)	5.3×10^{10}	N_Q/N_{NT}~3.5 (If
size assumed)	Ni/H/Na	~160	NT($^{23}Na\rightarrow^{24}Mg$)	5.3×10^{11}	^{40}K decay time=0)
R.T. Bush et al.[60]	Ni/H/Rb	$\sim10^4$	NT($^{85}Rb\rightarrow^{86}Sr$)	1.6×10^7	N_Q/N_{NT}~3
I. Savvatimova[61]	Pd/D_2	100	NT($^{106}Pd\rightarrow^{107}Ag$)	9×10^{10}	
V.A. Alekseev[36]	Mo/D_2	4.1	t (~10^7/s)	1.8×10^7	(Mo/D=1assumed)
V.A. Romodanov[38]	TiC/D	4.1	t (~10^6/s)	10^5~10^6	(D/Ti~0.5assumed)
O. Reifenschweiler[62]	$TiT_{0.0035}$	7×10^5	β decay reduction	1.1×10^9	(T=0~450°C)
J. Dufour[63] (SS is for	Pd,SS/D_2	48	Q,t,n	9.2×10^{11}	(D(H)/Pd~1
Stainless Steel)	Pd,SS/H_2			4.0×10^9	is assumed)
T.N. Claytor et al.[64]	Pd/D_2	400	t (12.5nCi/h)	1.6×10^{13}	(If D/Pd~0.5)
M. Srinivasan et al.[65]	Ti/D_2	1500	t ($t/d\sim10^{-5}$)	1.9×10^8	
A. De Ninno et al.[66]	Ti/D_2	440	n,t (5.4Bq/g D_2)	1.2×10^6	(D/Ti=1,τ=1week)
S. Focardi et al.[67]	Ni/H_2	8.2	Q	3.0×10^{12}	($N_p=10^{21}$was used)
R.A. Oriani[68]	$SrCeO_3/D_2$	22	Q~0.7W(400°C)	4.0×10^{10}	V=0.31cm^3
R. Notoya et al.[35]	Ni/D,H/K	34000	NT($^{39}K\rightarrow^{40}K$)	1.4×10^9	(Ni powder sintered)
H. Yamada et al.[69]	Pd/D_2	185	n, NT($^{16}O\rightarrow^{13}C$)	2.0×10^{12}	
F. Cuevas et al.[70]	$TiD_{1.5}$	134	n ($102n$/s)	5.4×10^{11}	
J.M. Niedra et al.[71]	Ni/H/K	80	Q (11.4W)	1.4×10^9	Ni (5km×0.5mmϕ)

$CaH_4(PO_4)_2\cdot H_2O$, $TiOSO_4\cdot H_2SO_4\cdot 8H_2O$.

There were 5 runs out of 14 with significant amount of neutrons more than experimental errors. We take up a case, run 6 in the 5 runs, particularly noteworthy one with a statistical significance of approximately five standard deviations above background, as the authors of the original paper[77] described. Fused titanium pellets were used as the negative electrode, with a total mass of ~3g. The neutron production rate increased after about one hour of electrolysis. After about eight hours, the rate dropped dramatically, as shown in the follow-on run 7. The experimental rate of neutron detection was $4.1\pm0.8\times10^{-3}$ s^{-1} with the neutron detection efficiency including geometrical acceptance $1.0\pm0.3\%$. D/Ti ratio was estimated to 2.

This result of the neutron detection means that the observed neutron generation is 0.4/s from a fused Ti cathode of three spheres of 1g each, the volume of which was ~0.22cm^3 and a linear dimension ~7.4mm.

The analysis of the data by the TNCF model was done for generattion of 2.45MeV

neutron by the reaction (19) from the reaction (3) in the surface layer of the assumed Li metal through the successive reactions (4) and (5). The value of the density of the trapped neutron n_n was determined as

$$n_n = 4.4 \times 10^{11} \text{ cm}^{-3}.$$

The results of the analyses given above in the subsection 3-2 were summarized in Table 3 amplifying the corresponding data given in the previous paper[57].

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 on the knowledge of solid state and nuclear physics. A treatment on this problem was given in the previous papers[16,17]. 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, Arata's Pd-black and thin Pd wires.

The conditions to facilitate the existence of the trapped thermal neutron explain the qualitative reproducibility of the phenomenon ; The trapping conditions would be formed by stochastic processes in such a complex system as cold fusion materials and are not reproducible quantitatively by 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[17]. 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 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 14.1MeV can accelerate several deuterons to

enough energies capable to fuse with another deuteron with high probability. Furthermore, a photon can induce the reaction (14) to generate a neutron, the catalyst of the cold fusion on our model.

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[4,74].

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[65] to realize the cold fusion phenomenon like that shown in the experiment analyzed in the paper[41]. The present author had a similar experience in which Pd plate bought many years ago gave a positive result[75] 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.

In relation with the controversial problem of the reproducibility of the cold fusion phenomenon, it is noticed that the higher becomes the S/V ration, the better is the qualitative reproducibility. This tendency can be seen apparently in the experimental data though the quantitative verification is difficult. It is seen in the Tables 2 and 3 that the large S/V ratio corresponds to the large n_n value. We may contemplate a positive correlation of n_n and the qualitative reproducibility.

5. Solid State-Nuclear Physics

The TNCF model is so successful to explain complex phenomenon of the cold fusion. Though the bases of the model have not completely verified by the conventional physics, there are speculations on the possible mechanisms to make the trapped neutron in solid feasible. Fundamental ideas of these speculations are the neutron band and the neutron affinity of lattice nuclei.

5-1. Neutron Band in Solids

Relative position of the allowed and forbidden bands[16,17] proposed by the author works

Table 4 : Neutron affinity of elements $\langle\eta\rangle$ (MeV) defined by the relation (22) between two nuclear states interacting with neutron Bloch wave and with proton Bloch wave averaged over isotopes with natural abundance. (*)The value for Li was calculated with an assumption ${}^{8}_{4}\mathrm{Be}={}^{4}_{2}\mathrm{He}{}^{4}_{2}\mathrm{He}$ because of the absence of ${}^{8}_{4}\mathrm{Be}$ in nature.

${}_{1}$H 2.22	${}_{1}$D −0.0186									
${}_{3}$Li −14.8*	${}_{4}$Be −0.555	${}_{5}$B −10.3	${}_{6}$C 2.20	${}_{7}$N 2.71	${}_{8}$O 2.66	${}_{9}$F −7.02				${}_{10}$Ne 2.84
${}_{11}$Na −5.51	${}_{12}$Mg 3.484	${}_{13}$Al −4.64	${}_{14}$Si 4.71	${}_{15}$P −1.71	${}_{16}$S 5.32	${}_{17}$Cl −1.74				${}_{18}$Ar −2.46
${}_{19}$K −1.462	${}_{20}$Ca 6.302	${}_{21}$Sc 2.37	${}_{22}$Ti 0.959	${}_{23}$V −3.97	${}_{24}$Cr 0.707	${}_{25}$Mn −3.70	${}_{26}$Fe 1.01	${}_{27}$Co −2.82	${}_{28}$Ni 3.87	${}_{29}$Cu −1.21
	${}_{30}$Zn 1.77	${}_{31}$Ga −2.58	${}_{32}$Ge 0.055	${}_{33}$As −2.97	${}_{34}$Se −0.735	${}_{35}$Br −2.54				${}_{36}$Kr −0.850
${}_{37}$Rb −2.75	${}_{38}$Sr −0.780	${}_{39}$Y −2.29	${}_{40}$Zr 0.597	${}_{41}$Nb −2.06	${}_{42}$Mo 0.730	${}_{43}$Tc	${}_{44}$Ru 0.563	${}_{45}$Rh −2.47	${}_{46}$Pd 0.264	${}_{47}$Ag −2.24
	${}_{48}$Cd 0.0125	${}_{49}$In 3.22	${}_{50}$Sn 0.641	${}_{51}$Sb −2.37	${}_{52}$Te −1.17	${}_{53}$I −2.12				${}_{54}$Xe 0.687
${}_{55}$Cs −1.99	${}_{56}$Ba −1.22	LN	${}_{72}$Hf 0.555	${}_{73}$Ta −1.79	${}_{74}$W −0.606	${}_{75}$Re −1.73	${}_{76}$Os −0.0474	${}_{77}$Ir −1.95	${}_{78}$Pt 0.27	${}_{79}$Au −1.38
	${}_{80}$Hg 0.588	${}_{81}$Tl −1.31	${}_{82}$Pb 0.912	${}_{83}$Bi −1.16	${}_{84}$Po	${}_{85}$At				${}_{86}$Rn
	${}_{87}$Fr	${}_{88}$Ra	${}_{89}$Ac							
${}_{57}$La −3.77	${}_{58}$Ce −0.66	${}_{59}$Pr −2.16	${}_{60}$Nd 0.354	${}_{61}$Pm	${}_{62}$Sm 0.364	${}_{63}$Eu −1.90	${}_{64}$Gd 0.151	${}_{65}$Tb −1.84	${}_{66}$Dy 0.151	${}_{67}$Ho −1.86
${}_{68}$Er 0.350	${}_{69}$Tm −0.969	${}_{70}$Yb 0.152	${}_{71}$Lu −1.17							
${}_{90}$Th 1.24	${}_{91}$Pa	${}_{92}$U −1.29								

to trap thermal neutron. A simple example of the neutron band structure was given in the previous paper[16] using the Kronig-Penny model.

5-2. Neutron Affinity of Lattice Nuclei

In the investigation of the quasi-stability of trapped neutron, an idea of the neutron affinity of lattice nuclei similar to the electron affinity of atoms has been proposed by the author[16,17].

Let us assume that the neutron Bloch wave transforms into a proton Bloch wave when it suffer β decay. Furthermore, let us evaluate the stability of the neutron wave by the neutron affinity of a nucleus η defined by the following relation[1];

$$\eta \equiv -({}^{A+1}_{Z}M - {}^{A+1}_{Z+1}M)\,c^2. \tag{30}$$

Here, ${}^{A}_{Z}M$ is the nucleus with a mass number A and a proton number Z composing the lattice nuclei. This definition tells us that the neutron affinity is a quantity expressing an energy difference of two nuclear states, one with an extra neutron and the other with an

extra proton. The positive value of η means the former is lower in energy and more stable.

For a crystal, we define the neutron affinity of the crystal $\langle\eta\rangle$ as an average of η over the lattice nuclei. Therefore, the neutron affinity of a crystal composed of an identical nucleus is the same to that for the nucleus.

Furthermore, we may assume that when a neutron is trapped in a crystal with a positive neutron affinity $\langle\eta\rangle$, then the neutron is stable against beta decay.

We have calculated $\langle\eta\rangle$ for elements using their natural abundance to take an average[16] and the result is tabulated in the Table 4.

Interestingly enough, almost all cold fusion materials have positive neutron affinity where the thermal neutron is stable, as we assumed as its characteristic.

6. Conclusion

The above phenomenological analysis of typical experimental data obtained hitherto in the 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 united by paste have formed a whole figure of the physics of particles in a crystal with the trapped thermal neutron. If we have no appropriate stand point, 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 with some characteristics for nuclear reactions, we could have a consistent understanding of events in the phenomenon with quantitative relationships among them.

Even if the result of our analysis be splendid, there might be raised a question on the poor reproducibility of the cold fusion phenomenon. In reality, the reproducibility of this phenomenon is not good. It is difficult to predict the time and size of a thermal or neutron burst. It might be possible to compare the reproducibility of a cold fusion event to that of the generation of a typhoon ; We have some tens of typhoons every year born in the middle Pacific Ocean near the Equator. Some of them pass through Japan giving much rain and disaster. The number of the typhoon and their sizes vary from year to year. It is impossible to predict them. Even then, it is sure some typhoon will born to pass by Japan, each year. This is a typical example of the qualitative reproducibility. If an event occurs in a complex system as a result of complex processes, the causes of the event are difficult to determine definitely and the effect is not predictable quantitatively but the occurence of the event is for certain.

The assumption of the existence of the quasi-stable thermal neutron in crystal itself has a theoretical verification[16,17] 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 on the TNCF model shows in reverse the reality of the trapped thermal neutron. This feature of the analysis will open a new science, solid state-nuclear physics, 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 not more exciting than the latter. In the present status of the cold fusion research, a phenomenological approach seems more effective than the microscopic ones. It will be 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 easy then to find out 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.

Technology go first usually then science follows it as history shows by a typical example of the steam engine: the invention of the modern condensing steam engine patented in 1769 by J. Watt preceded the discovery by N.L.S. Carnot in 1824 and its proof by R.J.E. Clausius in 1850 of the Carnot's theorem by more than a half century. Establishment of the Second Law of Thermodynamics has given a solid basis to consider any engines sparing time and energy of mankind.

On the other hand, the scientific discovery stays unknown until its application is noticed as the discovery of semiconductivity shows. In 1839, M. Faraday in England discovered the semiconductivity in Ag_2S by observation of a peculiar temperature dependence of its electric resistance. Furthermore, in 1874, K. Braun in Germany discovered non-Ohmic V-I characteristics in PbS crystal. Until the establishment of Quantum Mechanics, these discoveries were kept unnoticed. The former was explained quantum mechanically in 1931 by H. Wilson of England who calculated the band structure of energy spectrum of electron in solids. The discovery of point-contact transistor by W.H. Brattain and J. Bardeen accomplished the application of the non-Ohmic characteristics of crystals to electronics. The quantum mechanical understanding of the semiconductor made possible the exploding development of electronics in late 20th century.

If scientists stay on the chair indifferent to a new phenomenon with complex events difficult to understand from conventional concepts, a new technology will be used in society after a series of trial-and-error processes without any help from science. To shorten the path to realize a new technology necessary for the present world, we have to

be sensitive to a new possibility not only for application but also for development of a new science which attract intelligence of people to creation of a new culture.

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