# Cold Fusion Phenomenon and the Prospects of Solid State Nuclear Physics

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## 1. Introduction

Analysis of the cold fusion phenomenon has been done by the TNCF (Trapped Neutron Catalyzed Fusion) model using a fundamental point of view summarized as follows.

1) The experimental data are accepted as real as reported.

2) A consistent understanding is possible for all events in the phenomenon from deuterium to protium system.

3) Conventional quantum mechanics is applicable to processes in the phenomenon.

4) A phenomenological approach is effective in the present stage of cold fusion research.

There might be some mistakes in experimental data published hitherto, but those, if any, will be screened out if we use many data in an analysis from a unified point of view. There might, of course, be other points of view used to seek different causes for different effects in the cold fusion phenomenon. As a basis of analysis, we can trust quantum mechanics in the realm of atomic and nuclear physics where the cold fusion phenomenon is taking place. A new phenomenon generally demands a new point of view where there may be a new factor not noticed before, which we called a missing factor in analogy to "the missing ring" in anthropology. Instead of seeking any microscopic explanation for an event in the cold fusion phenomenon, we used whole events in it to construct a phenomenological model where the missing factor is assumed as the thermal neutron, which is trivial in ambient conditions and troublesome experimentally, although its positive role in the solid state - nuclear physics has hitherto not been noticed. We will show that the model applied to the cold fusion phenomenon reveals a tremendous role for the thermal neutron in solids through events in the phenomenon.

## 2. The Cold Fusion Phenomenon

The cold fusion phenomenon was discovered by Fleischmann et al.[2-1] in 1989. The phenomenon had been characterized by the large excess heat ($Q$) and various nuclear products including tritium ($t$), $^4$He, gamma ray ($\gamma$) and neutron ($n$) etc. unexplainable by chemical reactions. Recently it has been recognized that nuclear transmutation (NT) is occurring rather widely. A brief explanation of the phenomenon had been given in our previous papers[2-2~6].

### 2 – 1. Fields and Products (Events)

Materials and products (events) of the cold fusion phenomenon are full of variety as tabulated in Table 1. It is remarkable that not only deuterium D, but also protium H are agents of the phenomenon.

### 2 – 2. Events Observed

The events observed in the cold fusion phenomenon can be classified into two kinds in relation with the relevant nuclear process.

(a) Direct events of nuclear reactions (with energy spectrum or spatial distribution): $\gamma(\varepsilon)$, $n$ $(\varepsilon)$, nuclear transmutation (NT).

(b) Indirect events of nuclear reactions (amounts of products): $Q$, $t$, $^4$He, $n$, NT (with two types in shifts of mass ($A$) and atomic ($Z$) numbers; small (1 ~ 2) $\mathrm{NT}_D$ and large (larger than 3) $\mathrm{NT}_F$, X-ray, etc.

Some experimental results together with results of TNCF analysis were tabulated in Tables 2 and 3, enlarging and revising the Tables given in the previous papers[2-4,5]

### 2 – 3. Characteristics of the Cold Fusion Phenomenon with D and H

The characteristics of the cold fusion phenomenon can be summarized as follows:

(a) Null result without background neutrons.

(b) Enhancement of the phenomenon by thermal neutrons.

(c) Preparatory-run takes a long time, sometimes 3 - 6 months.

(d) Localization of NT products (in surface layers of thickness 10 ~1 μm).

(e) No quantitative reproducibility in the phenomenon.

(f) Qualitative reproducibility is higher in the sample with larger surface-to-volume (S/V) ratio.

(g) Optimum combination of the cathode metal and the electrolyte in electrolytic systems (Pd-Li, Ni-K(Rb)).

(h) Higher $x$ (D/Pd ratio) is preferable to induce events in the Pd-D system ($0.8 \leq x$).

(i) Simultaneity of expected events is probable but observed not every time (especially $\gamma$ ray) .

The facts (a) and (b) demand a careful check of the amount of background neutrons around active substances in the experiment of the cold fusion phenomenon. Brief explanations of e) and f) are given as follows.

Characteristics of the qualitative reproducibility and optimum combination of cathode and electrolyte:

In general, the larger the S/V ratio becomes, the higher the qualitative reproducibility is. This tendency has been observed in many experiments including typical examples of Arata's Pd black[2-7], Patterson's beads[2-8], thin wires used by Celani et al.[2-9], Celluci et al.[2-10] and Niedra et al.[2-11]

Another feature appeared in experience is the necessary matching of the

| Matrix Substance | Agent | Direct Evidence | Indirect Evidence |
|---|---|---|---|
| Pd | ${}^{2}_{1}\mathrm{D} \doteq d$ | $\gamma(\varepsilon)$ | $Q$ |
| Ti | ${}^{1}_{1}\mathrm{H} \doteq p$ | $n(\varepsilon)$ | ${}^{4}\mathrm{He}$ |
| Ni | ${}^{6}\mathrm{Li}$ | NT products ($\tau$) | ${}^{3}_{1}\mathrm{T} \doteq t$ |
| $\mathrm{Na}_x\mathrm{WO}_3$ | ${}^{10}\mathrm{B}$ | | NT ($\mathrm{NT}_D$ and $\mathrm{NT}_F$) |
| $\mathrm{KD}_2\mathrm{PO}_4$ | ${}^{39}\mathrm{K}$ | | X-ray |
| TGS | ${}^{85}\mathrm{Rb}, {}^{87}\mathrm{Rb}$ | | |
| $\mathrm{SrCe}_{0.9}\mathrm{Y}_{0.08}\mathrm{Nb}_{0.02}\mathrm{O}_{2.97}$ | ${}^{1}_{0}\mathrm{n} \doteq n$ | | |

Table 1: Matrix Substances, Agent nuclei, Direct and Indirect Evidences in Cold Fusion Phenomenon. Q is for the excess heat and NT for the nuclear transmutation. Suffices D and F signify Decay and Fission, respectively..

cathode and the electrolyte to realize the cold fusion phenomenon. As is generally recognized empirically, Pd-Li and Ni-K (Rb) are the best combinations in the electrolytic experiment of cold fusion phenomenon. A cause of these combinations will be a chemical condition for formation of the alkali metal (or alloy) layer on the cathode surface. Another possible cause might be a relation among the neutron affinities (cf. 3-4) of the matrix metal, the solute hydrogen isotope (D or H) and the electrolyte: the average neutron affinities of some elements are given as follows (cf. Table 4); 1.2 (Ti), 3.9 (Ni) and 26.5 (Pd); 2.22 (H) and –0.02 (D); and –14.8 (Li), –5.51 (Na), –1.5 (K) and –2.7 (Rb).

### 2 – 4. Difficulty in explanation of events by simple *d* – *d* reactions, even in the Pd-D system, to say nothing of the H system.

(a) Direct $d-d$ fusion reactions: Nuclear reactions assumed by many as responsible to the cold fusion phenomenon;

$$d + d = t\,(1.01\ \mathrm{MeV}) + p\,(3.02\ \mathrm{MeV}), \quad (1)$$
$$= {}^{3}\mathrm{He}\,(0.82\ \mathrm{MeV}) + n\,(2.45\ \mathrm{MeV}), \quad (2)$$
$$= {}^{4}\mathrm{He}\,(76.0\ \mathrm{keV}) + \gamma\,(23.8\ \mathrm{MeV}). \quad (3)$$

The branching ratios of these reactions were well known in nuclear physics as $\sim 1 : 1 : 10^{-7}$. Probability $P_{d\text{-}d}$ of the reaction (1) or (2) for a $D_2$ molecule at room temperature is given as $P_{d\text{-}d} \sim 10^{-74}\ \mathrm{s}^{-1}$ (cf. Jones et al.[3-18]).

(b) Predictions made by the $d-d$ reactions: In PdD crystals these reactions predict following values and relations between numbers $N$'s of generated particles and the excess heat $Q$ at room temperature; $N_t = N_n = 10^7 N_{He}$, and $Q \simeq 3.65\,Nn$ (MeV):

$$P_{d\text{-}d} \sim 10^{-52}\ \mathrm{cm}^{-3}\,\mathrm{s}^{-1},\quad N_t/N_n)_{d\text{-}d} = 1,\quad N_{He}/N_t)_{d\text{-}d} \sim 10^{-7},\ Q_{d\text{-}d} \simeq 4N_n(\mathrm{MeV}).$$

Thus, the following predictions are deduced: (a) Probability; probability $P_{p\text{-}p}$ of the reaction (1) or (2) is very low as $10^{-12}$ per $\mathrm{cm}^{-3}\,\mathrm{s}^{-1}$ in PdD at room temperature, ($\beta$) Events of $n$ and $t$ generation; neutron and tritium should be observed even, ($\gamma$) Absence of ${}^4$He; ${}^4$He could not be generated, ($\delta$) Amount of the excess heat; $Q$ should be $\sim 4$ MeV per a neutron (and a tritium) and ($\varepsilon$) Reproducibility; each event should occur with a definite probability (and not sporadic) in PdD.

(c) Numerical discrepancy with experiments in the Pd-D system. These expectations had been betrayed by the experimental data (maximum values) where numerical differences were up to $10^{42}$ for $P_{d\text{-}d}$ (determined by the excess

heat when $Q = 10$ W/cm$^3$ in PdD, assuming the $d - d$ reactions (1) and (2) like in a $D_2$ molecule), $10^7$ for $N/N_n$, $N_{He}/N_t$ and the excess heat:
$P)_{exp} \sim 10^{-10}$ cm$^{-3}$ s$^{-1}$, $N/N_n)_{exp} \sim 10^7$, $N_{He}/N_t)_{exp} \sim 1$, $Q)_{exp} \sim 10^7 N_n$(MeV).

These events have been observed sporadically and almost without definite probability, especially for striking burst-like events which occur mainly in massive samples.

## 3. TNCF Model A new phenomenon demands a new concept not noticed before (a missing factor) for its explanation.

A phenomenological model[3-1~3] was proposed in 1993 to explain the cold fusion phenomenon in both deuterium and protium systems as a whole — TNCF (the Trapped Neutron Catalyzed Fusion) model. The missing factor of the TNCF model is the trapped neutron. The results of applying the TNCF model to many experimental data were given in previous papers[2-2~6] and a brief explanation is given in Section 3–3. The physical basis of the model are discussed in Section 3–4.

### 3 – 1. Premises of the TNCF Model

The TNCF model is a phenomenological one applicable to materials with D and/or H. The basic premises (assumptions) are summarized in the previous paper and given below.

Following premises (assumptions) are used in the TNCF model.

Premise 1. We assume a priori the existence of the trapped neutron (a missing factor not noticed before) with a density $n_n$ in pertinent solids, to which the neutron is supplied essentially from the ambient neutrons and breeding reactions (explained later) in the sample.

The density $n_n$ is an adjustable parameter in the TNCF model and 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.

Premise 2. The trapped neutrons react with another nucleus in the surface layer (with thickness $l_0$) of the solids as if they are in vacuum. We express this property by taking the parameter $\xi$ defined below in the relation (4) as $\xi = 1$.

Premise 3. The trapped neutrons react with another perturbing nucleus in volume by the relation (4) below with $\xi = 0.01$ due to its stability in the volume (except in such a special situation as very high temperature as 3000 K where we use $\xi = 1$).

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 direct information of the individual events of the nuclear reaction in the sample.

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

Premise 7. The 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 <u>indirect information</u> of the individual events.

Premises about structure of the sample are expressed as follows:

<u>Premise 8</u>. In electrolytic experiments, the thickness of the alkali metal layer on the cathode surface will be taken as l0 = 1 μm, except as otherwise noticed (though the experimental evidences show that it is 1 ~ 10 μm or more).

<u>Premise 9</u>. The mean free path of the triton with an energy 2.7 MeV generated by $n + {}^6\mathrm{Li}$ fusion reaction will be taken as 1 μm, irrespective of the solid material. Collision and fusion cross sections of the triton with nuclei in the sample will be taken as the same as those in vacuum.

<u>Premise 10</u>. Efficiency of detectors will be assumed as 100% except as 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 assumed to calculate the number of events $N_Q$ producing the excess heat $Q$.

<u>Premise 11</u>. In the calculations of a number of events (nuclear reactions) $N_Q$ producing the excess heat $Q$, the average energy liberated in the reactions is assumed as 5 MeV: $N_Q$ = excess heat $Q$ (MeV)/ 5 (MeV).

The origin of the trapped neutrons can be considered as (1) the ambient background neutrons, the existence of which have been recognized widely in public, and (2) the neutrons bred in the sample by chain nuclear reactions induced by reactions between the trapped neutrons and perturbing nuclei.

There are some experimental bases of these premises.

Premise 1; The possible existence of trapped neutron. Cerofolini[3-4] and Lipson[3-5] observed temporal changes of neutron intensity irradiated in a sample without a change in the total number.

Premises 2 and 3; Nuclear products induced by thermal neutrons. Shani et al.[3-6], Yuhimchuk et al.[3-7], Celani et al.[3-8], Stella et al.[3-9], Lipson et al.[3-10] and Oya et al.[3-11] had observed the effects of artificial thermal neutrons on neutron emission in various materials.

Premises 2 and 8; Neutron reactions in the surface layer. Morrey et al.[3-12], Okamoto et al.[3-13] and Mizuno et al.[3-14] showed helium production and nuclear transmutation in the surface layer of a Pd cathode with a thickness l0 of 2.5 ~ 1 μm.

Premise 3; Low reactivity of volume nuclei. Notoya et al.[3-15] observed nuclear transmutation and positron annihilation gamma in a 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 a high production rate of tritium[3-16] was observed.

## 3 - 2. Reactions used in the TNCF Model

Relations between quantities in the trigger reactions are summarized as follows ($P_f$ = Number of fusion between the trapped neutron $n$ and a nucleus ${}^A_Z M$ in unit time, $\xi$ = a numerical factor of a value 1 ~ 0.01):

$$P_f = 0.35 n_n v_n n_M V \sigma_{nM} \xi, \qquad (4)$$

$$n + {}^{A}_{Z}M = {}^{A+1-b}_{Z-a}M' + {}^{b}_{a}M'' + Q \ldots\ldots\ldots (5)$$

$$n + {}^{A}_{Z}M = {}^{A+1}{}_{Z}M = {}^{A+1}_{Z+1}M' + e^{-} + \nu_e \ldots (6)$$

$n + d = t\,(6.98\ \mathrm{MeV}) + \gamma(6.25\ \mathrm{MeV})$,(7)
$n + p = d\,(1.33\ \mathrm{keV}) + \gamma(2.22\ \mathrm{MeV})$,(8)
$n + {}^{6}\mathrm{Li} = {}^{4}\mathrm{He}\ (2.1\ \mathrm{MeV}) + t\,(2.7\ \mathrm{MeV})$,(9)
$n + {}^{7}\mathrm{Li} = {}^{8}\mathrm{Be} + \gamma = 2\ {}^{4}\mathrm{He} + e- + \nu_e + 16.2\ \mathrm{MeV} + \gamma.$ (10)

The energetic particle $a$ generated by a trigger reaction, with a number $N_a$ per unit time, induces breeding reactions between another nucleus ${}^{A}{}_{Z}\mathrm{M}$, the number $P_a$ of which is given as follows ($l_0$ is the path length of the particle $a$ in the material);

$$P_a = N_a l_a n_M \sigma_{aM}. \qquad (11)$$

Relevant breeding reactions induced by a particle with an energy $\varepsilon$:
$n\ (\varepsilon) + d = n' + d'\ (\varepsilon')$, (12)
$n\ (\varepsilon) + d = n' + p + n''$, (13)
$t\ (2.7\ \mathrm{MeV}) + d = {}^{4}\mathrm{He}\ (3.5\ \mathrm{MeV}) + n\ (14.1\ \mathrm{MeV}) + 2.7\ \mathrm{MeV}.$ (14)
$d(\varepsilon) + d = t\,(1.01\ \mathrm{MeV}) + p\,(3.02\ \mathrm{MeV}) + \varepsilon$, (15)
$= {}^{3}\mathrm{He}\,(0.82\ \mathrm{MeV}) + n\,(2.45\ \mathrm{MeV}) + \varepsilon.$ (16)
$d(1.33\ \mathrm{keV}) + p = {}^{3}\mathrm{He}\ (5.35\ \mathrm{keV}) + \gamma\ (5.49\ \mathrm{MeV}) + 1.33\mathrm{keV}.$ (17)
$\gamma(e) + d = p + n$, (18)

$$\gamma(\varepsilon) + {}^{A}_{Z}M = {}^{A-1}{}_{Z}M + n \ldots\ldots\ldots\ldots\ldots (19)$$

$$n(\varepsilon){}^{A}_{Z}M = {}^{A-1}{}_{Z}M + n' + n'' \ldots\ldots\ldots\ldots (20)$$

$$n(\varepsilon){}^{A}_{Z}M = {}^{A-A'}_{Z-Z'}M' + {}^{A'}_{Z'}M'' + n' \ldots\ldots (21)$$

The maximum energy of the neutron generated in the reaction (14) is 19.6 MeV which makes the reactions (20) and (21) easier to occur.

### 3–3. Explained events with the adjustable parameter $n_n = 10^7 \sim 10^{13}$ cm$^{-3}$.

The TNCF model could give a consistent explanation for almost all events in the cold fusion phenomenon with the single parameter nn of $10^7 \sim 10^{13}$ cm$^{-3}$.

(a) Probability $P$ and ratios $N_a/N_b$ of events $a$ and $b$ in the Pd/D/Li system.

$$P)_{tncf} \equiv P)_{exp},\ Nt/N_n)_{tncf} \simeq 10^6,\ N_{He}/N_t)_{tncf} \simeq 1,\ Q)_{tncf} \simeq 5 \times 10^6 N_n (\mathrm{MeV}).$$

Probability $P_{d\text{–}d})_{tncf}$ in the TNCF model is determined by the stochastic process in the formation of an appropriate structure for neutron trapping (and for trigger and breeding reactions) in the sample. (→ Qualitative reproducibility)

(b) Possible reactions in light water systems.

(c) S/V ratio vs. reproducibility (experimental facts)

The larger SIV ratio (4 cm$^{-1}$ ~ 7 x 10$^5$ cm$^{-1}$), the higher the qualitative reproducibility in electrolytic systems. cf. Tables 2 and 3 on the end of this section.

(d) Nuclear transmutation with a small shift of $A$ and/or $Z$ by a $\beta$ or an $\alpha$ decay (NT$_D$).

(e) Nuclear transmutation with a large shift of $A$ and $Z$ by a fission[3-17] (NT$_F$).

(f) Threshold value of $n_n$. Our analysis of the data by Jones et al.[3-18,19] suggests the existence of a threshold value[3-20] of $n_n$, an order of magnitude $10^7$ cm$^{-3}$, to trigger the cold fusion phenomenon.

(g) Upper Bound of $n_n$. Our analysis of the data given in Tables 2 and 3 suggested existence of an upper bound of $n_n$, an order of magnitude $10^{13}$ cm$^{-3}$, to trigger the cold fusion phenomenon. Above this value of $n_n$, the system might be unstable and not make the cold fusion phenomenon possible. This might be the reason there are no cold fusion phenomenon in and around nuclear piles, where are too many neutrons.

### 3 – 4. Physical Bases of the TNCF Model

The success of the TNCF model suggests an existence of a physical basis for the model. The following speculation has been given for the physics of trapped neutrons by the author.

(a) Neutron band in solids and Neutron Cooper pair[3-2].

The relative position of allowed and forbidden bands in adjacent crystals works to trap thermal neutrons in optimum situations. The structure of the neutron band suggested a possibility of Cooper pair formation to intensify the stability of the trapped neutrons.

(b) Neutron affinity of lattice nuclei[3-2].

The quasi-stability of neutrons trapped in crystals is explained by an assumption of neutron affinity of lattice nuclei interacting with the trapped neutrons. Inversely, lattice nuclei are destabilized by the interaction with the trapped neutrons, which results in $NT_F$. A brief explanation of the idea is given in the following paragraph.

Let us assume that the neutron Bloch wave transforms into a proton Bloch wave when it suffers a $\beta$ decay. Furthermore, let us estimate the stability of the neutron wave by the neutron affinity $\eta$ of a nucleus defined by the following relation;

$$\eta \equiv -({}^{A+1}_{Z}M - {}^{A+1}_{Z+1}M)c^2 \qquad (22)$$

Here, ${}^{A}_{Z}M$ is the nucleus with a mass number $A$ and an atomic number $Z$ of a nucleus 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 $\eta$ means the former has lower energy than the latter and is more stable.

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

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

We have calculated $< \eta >$ for elements using their natural abundance to take an average and the result is tabulated in the Table 2 of a previous paper[2-2].

It is remarkable that the experimental data tell us that all materials which show the cold fusion phenomenon have positive values of $< \eta >$.

### 4. Prospect of the Solid State - Nuclear Physics

The success of the model and speculation on its basis show a possible development of a new science: solid state nuclear physics:

Solid state nuclear physics = physics related with effects of lattice nuclei with properties of elementary particles and nuclei in it and vice versa. (a) Moessbauer effect. Recoilless emission and absorption of photons and particles by lattice nuclei.

| Authors | System | $S/V$ $\mathrm{cm}^{-1}$ | Measured Quantities | $n_n$ $\mathrm{cm}^{-3}$ | Other Results (Remarks) |
|---|---|---|---|---|---|
| M.Fleischmann et al. | Pd/D/Li | 6 ~40 | $Q, t, n$<br>$N_t/N_n \sim 4\times10^7$<br>$N_Q/N_t \sim 0.25$ | $10^7 \sim 10^9$ | ($Q_{max}$=10W/cm$^3$)<br>$N_t/N_n \sim 1.1\times10^6$<br>$N_Q/N_t = 1.0$ |
| J.R.Morrey et al | Pd/D/Li | 20 | $Q$, $^4$He($^6$Li→ $^4$He+$t$)<br>$^4$He in $\ell_0 \leq 25\mu$m | *1.8 ×$10^8$ | $N_Q/N_{He} \sim 5.4$ ( If 3% $^4$He was in Pd) |
| T. Roulette et al. | Pd/D/Li | 63 | $Q$ | $10^{11} \sim 10^{12}$ | |
| E. Storms et al | Pd/D/Li | 9 | $t(\sim 1.8\times10^2$Bq/m$\ell$) | $2.2\times10^7$ | ($\tau$=250h,$V$=60m$\ell$) |
| E. Storms | Pd/D/Li | 22 | $Q(Q_{max}$=7W) | $5.5\times10^{10}$ | ($\tau$=120h) |
| A. Takahashi et al. | Pd/D/Li | 2.7 | $t, n$<br>$N_t/N_n \sim 6.7\times10^4$ | $3\times10^5$ | $N_t/N_n \sim 5.3\times10^5$ |
| M.H. Miles et al. | Pd/D/Li | 5 | $Q$, $^4$He<br>($N_Q/N_{He}$=1~10) | $10^9 \sim 10^{10}$ | $N_Q/N_{He} \sim 5$ |
| M. Okamoto et al | Pd/D/Li | 23 | $Q$, NT($^{27}$Al→ $^{28}$Si)<br>$\ell_0 \sim 1\ \mu$m | $\sim 10^{10}$ | $N_Q/N_{NT} \sim 1.4$ |
| Y. Oya et al. | Pd/D/Li | 41 | $Q$, $\gamma$spectrum | $3.0\times10^9$ | (with$^{252}$Cf source) |
| Y. Arata et al. | Pd/D/Li | 75000 | $Q$, $^4$He ($10^{20} \sim 10^{21}$ cm$^{-3}$)<br>$N_Q/N_{He} \sim 6$ | *$\sim 10^{12}$ | (Assume $t$ channeling in Pd wall) |
| M.C. H.McKubre | Pd/D/Li | 125 | $Q$(& Formula) | $10^9 \sim 10^{10}$ | Qualit.explanation |
| T.O. Passell | Pd/D/Li | 400 | NT($^{10}$B→ $^7$Li+$^4$He) | $1.1\times10^9$ | $N_{NT}/N_Q$=2 |
| D. Cravens (PPC) | Pd/H/Li | 4000 | $Q(Q_{out}/Q_{in}$=3.8) | $8.5\times10^9$ | (If PdD exists) |
| J.Bockris et al | Pd/D/Li | 5.3 | $t(\sim 3.8\times10^7$/cm$^2$s) | $1.1\times10^6$ | $N_t/N_{He} \sim 1$ |
| A.G. Lipson et al. | Pd/D/Na | 200 | $\gamma(E_\gamma$=6.25MeV) | $4\times10^5$ | (If efficiency=1%) |
| F.G. Will et al. | Pd/$D_2SO_4$ | 21 | $t$ ($1.8\times10^5$/cm$^2$s) | $3.5\times10^7$ | (If $\ell_0 \sim 10\mu$m) |
| F. Cellucci et al. | Pd/D/Li | 40 | $Q$, $^4$He<br>$N_Q/N_{He}$=1~5 | $2.2\times10^9$ | (Assume $Q$=5W)<br>$N_Q/N_{He}$=1 |
| F. Celani et al. | Pd/D/Li | 400 | $Q(Q_{max}$=7 W) | $1.0\times10^{12}$ | (at $Q_{max}$,200%) |
| K. Ota et al. | Pd/D/Li | 10 | $Q(W_{out}/W_{in}$=1.13) | $3.5\times10^{10}$ | ($\tau$=220 h) |
| D. Gozzi et al. | Pd/D/Li | 14 | $Q, t$, $^4$He | $10^{10} \sim 10^{11}$ | ($\tau \sim 10^3$h) |
| R.T.Bush et al. | Ag/PdD/Li | 2000 | $Q(Q_{max}$=6W) | $1.1\times10^9$ | ($\tau$=54d,Thin film) |
| T. Mizuno et al. (If Cr preexists) | Pd/D/Li | 3.4 | $Q$, NT($^{52}$Cr→ $^{53}$Cr<br>$\ell_0 \leq 2\ \mu$m) | *$2.6\times10^8$ | $\tau$=30d,Pd cathode 1cm$\phi\times$10cm |
| Y. Iwamura et al. | Pd/D/Li | 10 | $Q$, NT(Ti, Cr etc.)<br>(4 W/2 cm$^2$) | $7.4\times10^{10}$ | (NT unexplained) |
| G.S. Qiao et al | Pd/$H_2$ | 118 | NT(Pd→ Zn + S) in surface layer | 3.8 ×$10^{10}$ | (Discharge $\tau$=1 y. $\ell_0$=40$\mu$m) |
| H. Kozima et al. | Pd/D.H/Li | 200 | $n(2.5\times10^{-4}$/s) | 2.5 ×$10^2$ | Efficiency=0.44% |

Table 2: Pd/D(H)/Li(Na) system. Neutron density $n_n$ and relations between the numbers $N_x$ of event x obtained by a theoretical analysis of experimental data using the TNCF model ($NQ \equiv Q$(MeV)/ 5(MeV)). Typical value of the surface vs. volume ratio S/V(cm$^{-1}$) of the sample is tabulated, also. PPC stands for Patterson Power Cell. The mark * in the result signifies use of an additional assumption in the analysis.

(b) Solid state nuclear physics. The trapping of thermal neutrons in solids, quasi-stability of the trapped neutron, and de-stabilization of lattice nuclei by the neutron trapping.

(c) The cold fusion phenomenon. Each event in the cold fusion phenomenon is a probe for solid state nuclear physics.

### 4 - 1. Neutron

Properties of the neutron is summarized as follows.

(a) Free neutron: The neutron is an elementary particle with no electric charge and is one of two components of the nucleon, which constitutes the nucleus. Another component of the nucleon is the proton, with a charge of $e = 4.8 \times 10^{-10}$ e.s.u. = $1.6 \times 10^{-19}$ C.

| Authors | System | S/V (cm$^{-1}$) | Measured Quantities | $n_n$ (cm$^{-3}$) | Other Results (Remarks) |
|---|---|---|---|---|---|
| S.E. Jones et al. | Ti/D/Li | 8.1 | $n$(2.45 MeV) | $3.1\times10^{11}$ | (0.4 $n$/s in 3 g Ti |
| R.L. Mills et al. | Ni/H/K | 160 | $Q$(0.13 W) | $3.4\times10^{10}$ | (75×50×0.125mn |
| R.T. Bush (Sample size assumed) | Ni/H/K<br>Ni/H/Na | ~160<br>~160 | NT($^{39}$K→ $^{40}$Ca)<br>NT($^{23}$Na→ $^{24}$Mg) | $^*5.3\times10^{10}$<br>$^*5.3\times10^{11}$ | $N_Q/N_{NT}$~3.5 (I<br>$^{40}$K decay time = |
| R. Bush et al. | Ni/H/Rb | ~$10^4$ | $Q$,NT(Rb→ Sr) | $1.6\times10^7$ | $N_Q/N_{NT}$~3 |
| I. Savvatimova | Pd/$D_2$ | 100 | NT(Pd→ Ag) | $9\times10^{10}$ | (Discharge) |
| V.A.Alekseev et. al. | Mo/$D_2$ | 4.1 | $t$ (~$10^7$/s) | $1.8\times10^7$ | (If sample is Mol |
| V.A.Romodanov | TiC/D | 41 | $t$ (~$10^6$/s) | $10^5$~$10^6$ | (D/Ti~0.5assum |
| O. Reifenschweiler | $TiT_{0.0035}$ | $7\times10^5$ | $\beta$decay reduction | $1.1\times10^9$ | ($T$=0~450°C) |
| J. Dufour(SS is for Stainless Steel) | Pd,SS/$D_2$<br>Pd,SS/$H_2$ | 18 | $Q$, $t$, $n$ | $9.2\times10^{11}$<br>$4.0\times10^9$ | (D(H)/Pd~1<br>is assumed) |
| T.N. Claytor et. al. | Pd/$D_2$ | 400 | $t$ (12.5 nCi/h) | $1.6\times10^{13}$ | (If D/Pd~0.5) |
| M. Srinivasan et. al. | Ti/$D_2$ | 1500 | $t$ ($t/d$~$10^{-5}$) | $1.9\times10^8$ | (Aged target plat |
| A. De Ninno et. al. | Ti/$D_2$ | 140 | $n$, $t$ (5.4 Bq/g $D_2$) | $1.2\times10^9$ | (D/Ti=1,$\tau$=1wee |
| S. Focardi et. al. | Ni/$H_2$ | 8.2 | $Q$ | $3.0\times10^{12}$ | ($N_p$=$10^{21}$ was use |
| R.A. Oriani | $SrCeO_3$/D | 22 | $Q$~0.7W(673K) | $4.0\times10^{10}$ | V=0.31cm$^3$ |
| R. R. Notoya | Ni/D/K<br>(Ni plate) | 26 | $Q_{ex}/Q_{in}$~2.5<br>NT($^{39}$K→ $^{40}$Ca) | $^*3.5\times10^{12}$ | $N_Q/N_{NT}$~2.6 (If<br>$^{40}$K decay time = |
| R. Notoya et. al. | Ni/D,H/K | 34000 | NT($^{39}$K→ $^{40}$K) | $1.4\times10^7$ | (Ni powder sinter |
| H. Yamada et al | Pd/$D_2$ | 185 | $n$, NT($^{16}$O→ $^{13}$C) | $2.0\times10^{12}$ | (Discharge) |
| F. Cuevas et. al. | $TiD_{1.5}$ | 134 | $n$(102 $n$/s) | $5.4\times10^{11}$ | ($TiD_x$ plate with |
| J.M. Niedra et. al. | Ni/H/K | 80 | $Q$(11.4 W) | $1.4\times10^9$ | (Ni 5km×0.5mm$\phi$ |
| T.Ohmori et. al. | Au/H/K | 200 | $Q$,NT(Au→ Fe) | ~$10^{11}$ | (Au 0.1mm thick) |

Table 3: Ni/H/K system and others. Neutron density $n_n$ and relations between th numbers $N_x$ of event x obtained by theoretical analysis of experimental data usin 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. The mark * in the resul signifies use of an additional assumption in the analysis.

The mass of the neutron is 939.55 MeV, which is a little heavier than that of the proton at 938.27 MeV. The value of its spin is 1/2 $h$ and of the magnetic moment 1.9135 $\mu_N$. The neutron as an elementary particle which exhibits wave properties with a characteristic wave length

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2m_n E}}$$

which takes a value 1 x $10^{-8}$ cm for a kinetic energy of 0.13 eV or 2.28 x $10^{-8}$ cm for 0.025 eV (the thermal energy).

The neutron is unstable in its free state and decays by beta disintegration with a constant of 887.4 +/- 0.7 s into a proton, electron and neutrino, liberating an energy of 0.77 MeV.

As a building block of nuclei, neutrons interact with each other and wit protons in a nucleus through the nuclea force, having a range of about 3 x $10^{-1}$ cm. As a result of this interaction, neutrons in a stable nucleus become stabl against the beta decay.

**(b) Interaction of neutron with a nucleus**

Due to the lack of electric charge neutrons can approach a nucleus without being repelled by its positive charge Therefore, a neutron can enter a nucleu no matter whether it is fast or slow causing, several types of reaction with th nucleus.

The reaction can be classified a follows;

1) Scattering of neutron (elastic and inelastic),

2) Nuclear reaction leading to the emission of charged particles $(n,\beta)$, $(n,p)$ and $(n,a)$,

3) Nuclear reactions leading to the emission of several neutrons $(n, 2n)$ and $(n,3n)$,

4) Capture of neutron $(n,\gamma)$,

5) Fission of lattice nuclei by an energetic neutron (or reaction products).(cf. (c) 2) below.)

**(c) Interaction of neutron with lattice nuclei**

1) Dynamical effects

Neutron diffraction

Neutron band

Neutron Cooper pair

Reaction with aperiodic nuclei

There are experimental evidences for the neutron band structure; Neutron trapping [4-1] (another phase of neutron diffraction + the neutron band) and lattice effect on the neutron effective mass of +/- $10^{-6}\, m_n$[4-2]) (an evidence of the neutron band structure).

2) Energetic effects

Stabilization of neutron by interaction with lattice nuclei

De-stabilization of lattice nuclei by the trapped neutron.

Success of the TNCF model might be an evidence of the first effect and an evidence of the second might be the NT with a large shift of $A$ and $Z$[3-15,4-3~5] ($NT_F$).

We noticed that the neutron activation analysis was used to detect transmuted elements in an remarkable data by Miley et al.[4-5] where they observed a large amount of nuclear transmutation of cathode elements up to more than 40 %. From our point of view, the thermal neutrons used in this analysis can induce additive transmutation of elements to those induced in the electrolysis process. Thus, their data of the puzzlingly large amount of transmuted elements is understandable by using the TNCF model[3-17].

**(d) Electrons, photons and neutrons in a crystal lattice**

1) Electrons

Electrons in a lattice = Electrons + Ion lattice

Electron-electron interaction

→Collective motion + individual motion with short-range interaction

≅Collective motion + free electrons

Electrons + ion lattice ≅ collective motion + (free electron + ion lattice)

→Collective motion + Electron bands

2) Photons

Photon + Photonic crystal → Photon bound state

3) Neutrons

Neutron-nucleus interaction ← free electron-ion interaction

Neutron diffraction ← electron diffraction

Neutron band ← electron band

Neutron effective mass ← electron effective mass

Neutron Cooper pair ← electron Cooper pair (superconductivity)

Neutron "reactor" ← electron acceptor

Stabilization of neutrons in a lattice ← metallic binding

De-stabilization of lattice nuclei ← LED (light emitting diode)

**4 – 2. Prospect of Neutron Physics**

(a) Neutron as an elementary particle

(b) Neutron in a crystal

(c) Neutron in a nucleus

(d) Neutron in a star

(e) Neutron physics and the cold fusion phenomenon

Quasi-stabilization of trapped neutrons

De-stabilization of lattice nuclei

Application of the nuclear reactions induced by the trapped neutrons

1) Energy source and 2) Decrease of radioactivity

## 5. Remaining problems concerned with the TNCF model:

(a) Justification of the neutron affinity introduced to investigate the quasi-stability of the trapped neutrons.

(b) Determination of the threshold value of $n_n$ for the trigger reactions deduced by the analysis.

(c) Explanation of the scarcity of gamma rays observed in the experiments.

(d) Lack of expected simultaneity of events in some experiments.

(e) Meaning of the parameter $n_n$. Is it the density of the real thermal neutrons trapped in solids ?

## 6. Summary of nuclear reactions used in the TNCF model and the conclusion.

The following reactions, well known in the nuclear physics, which have been used in the analysis.

### 6–1. Reactions

(a) Trigger reactions (by a trapped thermal neutron);

$n + \mathrm{d} = t + \gamma + 6.25\ \mathrm{MeV},$ (23)

$n + p = d\,(1.33\ \mathrm{keV}) + \gamma\,(2.22\ \mathrm{MeV}),$ (24)

$n + {}^6\mathrm{Li} = {}^4\mathrm{He}(2.1\mathrm{MeV}) + t\,(2.7\ \mathrm{MeV}),$ (25)

$n + {}^7\mathrm{Li} = {}^8\mathrm{Be} + \gamma = 2\ {}^4\mathrm{He} + e^- + \nu_e + 16.2\ \mathrm{MeV} + \gamma.$ (26)

(b) Breeding reactions (by an energetic paxticle with an energy $\varepsilon$ generated by trigger reactions);

$n(\varepsilon) + d = n' + d'\ (\varepsilon'),$ (28)

$n\,(\varepsilon) + d = n' + p + n'',$ (29)

$t\ (2.7\ \mathrm{MeV}) + d = {}^4\mathrm{He}\ (3.5\ \mathrm{MeV}) + n\ (14.1\ \mathrm{MeV}),$ (30)

$d(\varepsilon) + d = t(1.01\ \mathrm{MeV}) + p(3.02\ \mathrm{MeV}) + \varepsilon,$ (31)

$= {}^3\mathrm{He}(0.82\ \mathrm{MeV}) + n(2.45\ \mathrm{MeV}) + \varepsilon,$ (32)

$d\ (1.33\mathrm{keV}) + p = {}^3\mathrm{He}\ (5.35\ \mathrm{keV}) + \gamma\ (5.49\ \mathrm{MeV}),$ (33)

$\gamma(\varepsilon) + d = p + n,$ (34)

$\mathrm{NT}_D$ is explained by one of the reactions (27), (35) and (36) and $\mathrm{NT}_F$ by (37).

### 6–2. Predictions and experimental results in systems with deuterium results of sections 2–4 and 3–3 are summarized as follows:

(a) Simple $d - d$ reactions

$P_{d\text{-}d} \sim 10^{-52}\mathrm{cm}^{-3}\mathrm{s}^{-1}$, $N_t/N_n)_{d\text{-}d} = 1$, $\mathrm{NHe}/N_t)_{d\text{-}d} \sim 10^{-7}$, $Q_{d\text{-}d} \simeq 4N_n(\mathrm{MeV})$.

(b) The TNCF Model

$P)_{tncf} \equiv P)_{exp}$, $N_t/N_n)_{d\text{-}d} \simeq 10^6$, $N_{He}/N_t)_{tncf} \simeq 1$, $Q)_{tncf} \simeq 5 \times 10^6 N_n(\mathrm{MeV})$.

(c) Experimental results (maximum values)

$P)_{exp} \sim 10^{10}\mathrm{cm}^{-3}\mathrm{s}^{-1}$, $N_t/N_n)_{exp} \sim 10^7$, $N_{He}/N_t)_{exp} \sim 1$, $Q)_{exp} \sim 10^7 N_n(\mathrm{MeV})$.

### 6–3. Conclusion

The theoretical analysis given above depicts clearly a possible mechanism of the cold fusion phenomenon as a physics of thermal neutrons in appropriate solids and shows the possibilities of its application for an energy source and a radioactivity extinguisher.

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