

## **Analysis of Experimental Data in Cold Fusion Phenomenon on TNCF Model\***

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### **Synopsis**

The TNCF model proposed by the author three years ago was applied to analyze typical quantitative experimental data obtained in these seven years after the discovery of the cold fusion phenomenon, i.e. the generation of the excess energy and the nuclear products unable to explain by usual physical and chemical processes occurring in solids with hydrogen isotopes.

Fundamental assumptions of the model, the existence of stable thermal neutrons trapped in cold fusion materials and their fusion reaction with lattice nuclei at boundary region were verified by the success of the analyses itself. Furthermore, the success of the model has given a consistent interpretation for the wide spread spectrum and the curiosity of the phenomenon denying understanding of them in the frame of the conventional science of nuclear physics, solid state physics and electrochemistry.

Predictions for the new phenomena are given to be tested by experiments.

### **1. Introduction**

Atomic physics including nuclear phenomenon have been developing in more than a century including discoveries of Faraday's law of electrolysis, of Thomson's electron, of Bohr's model of H-atom, and of neutron as a constituent of the nucleus. In the history of the development, the theory and

the experiment have played characteristic roles showing their own specialties as two inevitable complementary partners of science.

Because of the difference of the pertinent energies in nuclear physics and in solid state (atomic) physics, the two branches of the modern physics have been existed almost independently with several exceptions including the Mössbauer effect. Nuclear physics has been studied in the energy region over  $\approx$  keV per particle. Solid-state physics, on the other hand, has been studied by phenomena with energies up to 100 eV per an event. Interactions between energetic particles and solids have bridged the two sciences in special rare cases.

Therefore, the cold fusion phenomenon in solids where occur processes with energies up to few MeV per event, i.e. the generation of huge amount of excess energy unexplainable by chemical processes and the accompanied production of elementary particles and nuclei usually observed in nuclear processes with high energy particles, attracted much attention in scientific world.

The characteristics of the cold fusion phenomenon as shown by experiments have denied simple interpretation in the conventional solid state and nuclear physics. The poor reproducibility, one of the characteristics of the phenomenon, has even raised disbelief to the facts themselves. Those situations destroyed the indispensable sound relation between the theory and the experiment, i.e. the dialogue between them.

This unfortunate situation together with the relation with technical applicability of the phenomenon have made the progress of the cold fusion research somewhat biased.

To recover the sound relation between the theory and the experiment, we want to give direct dialogue between them using a model, named the trapped neutron catalyzed fusion (TNCF) model, proposed before as a tool to analyze the cold fusion phenomenon.

## **2. The TNCF model**

The model assumes a stable existence of the trapped thermal neutrons in some crystals showing cold fusion phenomenon. Possible mechanisms for the neutron trapping are difference of the neutron band structures in two media, Bragg reflection and total reflection at boundaries. The condition for the trapping depends on stochastic processes in the sample. This will result in

irreproducibility of the cold fusion phenomenon.

This assumption itself has been a target of a study based on the quantum statistical treatment of a system composed of the thermal neutron and the lattice nuclei. The treatment resulted in a birth of a new idea "neutron affinity of the lattice nuclei" and a calculation of neutron band in the lattice. The difference of the band structures in two crystals is supposed to reflect the neutron at the boundary to trap it in a crystal. On the other hand, a positive value of the neutron affinity represents stability of the trapped neutron in the crystal against beta decay.

It is considered that the formation of a neutron Cooper pair makes the stability of the trapped thermal neutron higher against beta decay and also against fusion with one of lattice nuclei.

Assuming the existence of the trapped thermal neutron as a neutron Bloch wave in the sample crystal, the TNCF model predicts nuclear reactions between the thermal neutron and a nucleus in the lattice or on the surface when the nucleus works on the neutron as a perturbing center. Though the trapped neutron is fairly stable against the perturbation, the neutron suffers much especially at the boundary surrounding a region where the neutron is trapped.

If there is a large perturbation in the boundary region where is a nucleus possible to fuse with a neutron, the trapped thermal neutron lose its stability and be fused with the nucleus. Otherwise, the trapped neutron may be fused with a nucleus in the trapping region if the perturbation for the neutron become large by some reason there, for instance by high temperature.

If the stability of the trapped neutron is lost, the fusion probability will be calculated by the same formula to the usual collision process between a thermal neutron and a nucleus:

$$P_f = 0.35 n_n v_n n_N V \sigma_{n-N}, \quad (1)$$

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 is the nucleus,  $\sigma_{n-N}$  is the fusion cross section for the reaction.

In the case of a sample with a definite boundary surrounding a trapping region where is the thermal neutron, the volume  $V$  should be the boundary region where is the nucleus to fuse with the thermal neutron. On the other

hand, in a sample without definite boundary but disordered array of minor species of lattice nuclei, 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  ${}^A_Z\text{M}$  with a mass number  $A$  and an atomic number  $Z$ , there appears an excess energy  $Q$  and nuclear products:

$$n + {}^A_Z\text{M} = {}^{A+1-b}_{Z-a}\text{M}' + {}^b_a\text{M}'' + Q, \quad (2)$$

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

The excess energy  $Q$  may be measured as the excess heat by the attenuation of the nuclear products  $\gamma$  or charged particles in the reaction (2). Otherwise, the nuclear products may be observed outside or may induce succeeding nuclear reactions in the sample with one of other nuclei there.

Typical reactions related with TNCF model are written down as follows. The trapped thermal neutron can fuse with  ${}^6_3\text{Li}$  nucleus in the surface layer formed on the cathode by electrolysis of  $\text{D}_2\text{O} + \text{LiOD}$  with a large cross section  $\approx 1 \times 10^3$  barns:

$$n + {}^6_3\text{Li} = {}^4_2\text{He} (2.1 \text{ MeV}) + t (2.7 \text{ MeV}). \quad (3)$$

The triton with 2.7 MeV generated in this reaction can pass through the crystal along the channeling axis on which is an array of occluded deuterons or can proceed a finite path with a length ( $\approx 1 - 10 \mu\text{m}$ ) determined by the interaction with charged particles in the crystal. In these processes, the triton can fuse with a deuteron with a cross section  $\approx 1.4 \times 10^{-1}$  barns:

$$t (2.7 \text{ MeV}) + d = {}^4_2\text{He} (3.5 \text{ MeV}) + n (14.1 \text{ MeV}). \quad (4)$$

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

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

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

$$n + d = t + \gamma + 6.25 \text{ MeV}, \quad (7)$$

$$n + {}^7_3\text{Li} = {}^7_4\text{Li}^* \rightarrow {}^8_4\text{Be} = {}^4_2\text{He} + e^- + \bar{\nu}_e + 16.2 \text{ MeV}. \quad (8)$$

The reaction (7) for a thermal neutron has a cross section  $5.5 \times 10^{-4}$  barns which will be used in the estimation given in the following section.

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

$$d + d = t(1.01 \text{ MeV}) + p(3.02 \text{ MeV}), \quad (9)$$

$$= {}^3_2\text{He}(0.82 \text{ MeV}) + n(2.45 \text{ MeV}). \quad (10)$$

Depending on the situation in the cold fusion system, the trapped thermal neutron can induce trigger reactions like the reaction (1) and the generated energetic particles sustain breeding chain reactions producing a lot of the excess heat and the nuclear products.

### 3. Typical quantitative experimental data and their analysis on 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 obtained in an experiment including complexly 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 a couple of events including quantitative relations between observed quantities from excellent experimental results obtained until now

1) M. Fleischmann, S. Pons and M. Hawkins.<sup>13)</sup>

From the abundant data in the first cold fusion paper,<sup>13)</sup> we take up a case of a thin rod Pd cathode with dimensions  $0.4 \text{ cm } \phi \times 10 \text{ cm}$ . When the

electrolyzing current density was 64 mA/cm<sup>2</sup>, the system with the Pd cathode, Pt anode and LiOD+D<sub>2</sub>O gave the excess power 1.75 W (= 1.1 × 10<sup>13</sup> MeV/s), tritium atoms 4 × 10<sup>11</sup>/s and neutrons 4 × 10<sup>4</sup>/s.

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

$$N_t = 0.35 n_n v_n n_{\text{Li6}} S l_0 \sigma_{\text{nLi}} \tau \quad (1)$$

Where  $S = 12.8 \text{ cm}^2$ ,  $\sigma_{\text{nLi}} = 10^3 \text{ barns}$ ,  $n_{\text{Li6}} = 3.5 \times 10^{21} \text{ cm}^{-3}$ . The observed value of  $N_t$  per unit time 4 × 10<sup>11</sup> /s gives us

$$n_n = 1.5 \times 10^7 \text{ cm}^{-3}.$$

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

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

This value is compared with the experimental value 10<sup>7</sup>. The coincidence of these values in one order of magnitude may be taken as very good if we notice our assumptions used in this estimation.<sup>14)</sup>

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 estimate this ratio on an assumption that nuclear reactions liberate energy about 5 MeV per reaction in average. Then,

$$N_Q/N_n = (1.1 \times 10^{13} \div 5) / (4 \times 10^{11} \times 1.6 \times 10^{-6}) = 8.6 \times 10^7.$$

Experimental value of  $N_Q/N_n$  is  $(1.1 \times 10^{13} \div 5)/4 \times 10^4 = 5.6 \times 10^7$ . Therefore, there is only a small difference of a factor 1.5 between the experimental and theoretical values of this ratio.

This value of  $N_Q$  gives a ratio of events producing the excess heat and tritium  $N_Q/N_t$  as follows, using the experimental value for  $N_t = 4 \times 10^{11}$ :

$$N_Q/N_t = (1.1 \times 10^{13} \div 5)/(4 \times 10^{11}) = 5.5.$$

2) A. Takahashi, T. Iida, T. Takeuchi, A. Mega, S. Yoshida and M. Watanabe.<sup>15)</sup>

Next, we will take up an experiment<sup>15)</sup> where observed the excess heat, tritium and neutron with  $\#n = 8.7 \times 10^5$ . Similar analysis as shown above gives following results;<sup>16)</sup>

$$n_n = 10^2 \text{ cm}^{-3}, \quad \#n = 5.3 \times 10^5.$$

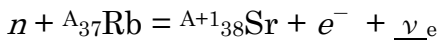
3) M.H. Miles, R.A. Hollins, B.F. Bush and J.J. Lagowski.<sup>17)</sup>

Third, we will give a result<sup>18)</sup> of the analysis of an experiment where observed the excess heat and helium in Pd/D<sub>2</sub>O+LiOD system<sup>17)</sup> using a massive cylindrical Pd cathode with a surface area of 2.6 cm<sup>2</sup>. Similar analysis to these given above in 1) resulted in the following conclusion with the number of events  $N_{\text{He}}$  producing <sup>4</sup>He:

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

4) R. Bush and R. Eagleton<sup>19)</sup>

Fourth, we will give a result<sup>20)</sup> of the analysis of an experiment observed the excess heat and the nuclear transmutation of Rb into Sr in Ni/H<sub>2</sub>O+RbCO<sub>3</sub> system.<sup>19)</sup> The reaction supposed to occur in the system were



in the surface layer of Rb on the Ni cathode. The density was determined as follows:

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

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

5) M. Okamoto, H. Ogawa, Y. Yoshinaga, T. Kusunoki and O. Odawara<sup>21)</sup>

Fifth, we will give a result<sup>22)</sup> of the analysis of an experiment where observed the excess heat and the nuclear transmutation in the surface layer of Al into Si in Pd/D<sub>2</sub>O+LiOD system<sup>21)</sup> as follows:

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

In the calculation of the number of events inducing the nuclear transmutation  $N_{NT}$ , we assumed the same value of  $N_Q$  in this experiment<sup>21)</sup> as in Ref.(17). 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.

6) Y. Arata and Y.C. Zhang<sup>23)</sup>

Next, we will give a result<sup>24)</sup> of the analysis of an experiment where observed a huge excess heat and a tremendous number of helium atoms as high as  $10^{20} - 10^{21} \text{ cm}^{-3}$  in Pd-black contained in Pd cylinder cathode as follows:

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

In this calculation, the path length of the 2.7 MeV triton generated by the reaction (3) was taken as large as 1 cm considering the channeling of triton to enter into Pd-black part of the cathode from the wall surface of Pd container. It was difficult to understand such a high value of  ${}^4_2\text{He}$  density in their Pd-black cathode without the large path length of tritium assumed in this calculation.

7) M. C. H. McKubre, S. Crouch-Baker and F. L. Tanzella<sup>25)</sup>

The elaborate experimental data in Pd/LiOD+D<sub>2</sub>O system giving a semi-quantitative relation between the excess heat, the electrolyzing current density, the density of the occluded deuterium and the speed of the occlusion<sup>25)</sup> were analyzed on the TNCF model<sup>26)</sup> giving a qualitative

explanation of the relation and the density of the trapped neutron:

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

8) D. Cravens<sup>27)</sup>

The remarkable system <sup>27,28)</sup> generating the excess energy up to about 2000 times the input energy with very high qualitative reproducibility in Pd/H<sub>2</sub>O+LiOH system was analyzed on the TNCF model<sup>29)</sup> 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<sub>2</sub>O+LiOH electrolysis. The experimental data of the excess power gave a following value for the trapped neutron density:

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

9) J.O'M. Bockris et al.<sup>30)</sup>

Careful measurements of tritium and the excess heat have been done by Bockris et al.<sup>30)</sup> with remarkable results. Here we take up only one data giving a maximum tritium generation of  $3.8 \times 10^7 \text{ s}^{-1} \text{ cm}^{-2}$  per unit surface area. With the same assumptions made above, we could estimate the density of the trapped thermal neutron as follows:

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

10) I.B. Savvatimova et al.<sup>31)</sup>

The researchers in the Institute LUTCH in Podolsk near Moscow have been working in the glow discharge experiments with D<sub>2</sub> and other gases and Pd and other transition metal cathodes. They measured the excess heat, NT (nuclear transmutation) of various isotopes and elements with multi-layer cathode. Here we take up only one data of an increase of <sup>107</sup><sub>47</sub>Ag from 20 to 5000 ppm in the glow discharge with D<sub>2</sub> 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  $^{107}_{47}\text{Ag}$  by  $n - ^{106}_{46}\text{Pd}$  fusion reaction through 3 months at the surface layer of the cathode, we obtain a following value for the density of the trapped thermal neutron:

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

11) V.A. Romodanov et al.<sup>32)</sup>

Another group in the Institute LUTCH has been working also with a glow discharge experiment.<sup>32)</sup> They measured a lot of tritium with cylindrical Mo cathode in  $\text{D}_2$  gas. The pressure of the gas was 1 atm in the cylinder and 0.2 atm outside. With a cylindrical cathode of  $2.5 \text{ cm } \phi \times 10 \text{ cm}$  with wall thickness of 5 mm, they measured tritium production of  $10^7 \text{ s}^{-1}$ . In this case, the temperature of the cathode was very high (up to  $3000 \text{ }^\circ\text{C}$ ) 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  $V$  in the  $n-d$  reaction as the sample volume and using the fusion cross section for the thermal neutron  $\approx 5.5 \times 10^{-4}$  barns, we obtain a following value for the density of the trapped thermal neutron in  $\text{MoD}_x$  cathode:

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

where we assumed  $x = 1$ .

12) A.G. Lipson et al.<sup>6)</sup>

Lipson et al. have been working with ferroelectrics to measure the excess heat and nuclear products. In a recent work,<sup>6)</sup> they measured gamma radiation in the energy range up to 10 MeV from a cathode and electrolyte system  $\text{PdO}/\text{Au}/\text{Pd}/\text{PdO}/\text{NaOD}+\text{D}_2\text{O}$  ( $\text{KOH}+\text{H}_2\text{O}$ ). 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 the reaction occurs at boundary layer between Pd and PdO with thickness  $1 \text{ } \mu\text{m}$  in the cathode, we obtained the density of the trapped thermal neutron as follows:

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

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

13) O. Reifenschweiler<sup>33)</sup>

Reifenschweiler<sup>33)</sup> measured the resulting X-ray induced by  $\beta$ -decay of 'tritium' sorbed by Ti (TiT<sub>0.0035</sub>). The sample was in a shape of extremely small mono-crystalline particles with diameter  $\phi = 15$  nm. In a heating process of sample, he observed a decrease of the radioactivity, i.e. intensity of X-ray from the sample Ti/T, up to 40 % in a temperature range between 115 and 275 °C.

Assuming the change of the radioactivity was caused by the change of the neutron stability, we could estimate the density of the trapped thermal neutrons in the sample knowing the change of the radioactivity from experimental data. If the neutron became stable where the decrease of radioactivity was measured, the estimation<sup>34)</sup> gives a value

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

14) J. Dufour<sup>35)</sup>

Dufour had observed the excess energy of  $Q \approx 2.5$  W in the sparking experiments in D<sub>2</sub> or H<sub>2</sub> gas ( $\approx 1$  atm) with a cylindrical cathode of Pd or Stainless Steel (SS) with dimensions 10–11 mm  $\phi \times 24$  mm length and thickness 0.5 mm (with a surface area  $\approx 7.5$  cm<sup>2</sup>).

To analyze this data on TNCF model, we will assume that the D(H)/Pd(SS) ratio is 1 and  $n-d(p)$  fusion occurs in the whole volume  $\approx 0.38$  cm<sup>3</sup> though there is no description in the paper<sup>35)</sup> about D(H)/Pd(SS) ratio in the cathode.

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

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

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

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

where  $\sigma_{n-d(p)}$  is the fusion cross section of the reaction  $5.5 \times 10^{-4}$  or 0.35 barns, respectively. This relation with the assumptions explained above gives us

following values  $n_n$  in Pd with  $D(H)/Pd \approx 10^{-6}$ :

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

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.

15) T.N. Claytor et al.<sup>36)</sup>

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

Assuming tritium generation of 0.15 nCi/h from a Pd cathode of  $0.05 \text{ cm} \phi \times 3.0 \text{ cm}$  (in the surface layer of thickness  $30 \mu\text{m}$ ), we obtain a value for the trapped thermal neutron:

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

16) F.G. Will et al.<sup>37)</sup>

Will et al. observed tritium generation of  $5.1 \times 10^4 - 2 \times 10^5 \text{ cm}^{-2}\text{s}^{-1}$  from Pd wire cathode with  $D_2O + D_2SO_4$  electrolyte. They obtained high loading of  $D/Pd \approx 1$ . Assuming the  $n + d$  fusion in a surface layer of  $10 \mu\text{m}$ , we obtain following values for the trapped thermal neutrons:

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

17) M. Srinivasan et al.<sup>38)</sup>

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 ( $\approx 10^9$  s) producing  $\approx 10^{15}$  tritium atoms, -----."<sup>38)</sup>

We can use these data to calculate the density of the trapped neutrons in the "aged" Ti sample, though this explanation was written by the authors to discuss a possibility of ( $d-d$ ) reaction.

Using the relation (11) with values given above ( $N_t = 10^{15}$  atoms,  $n_d S l_0 = 10^{20}$  atoms on the assumption of the number of pairs equals to the number of atoms and  $\tau = 10^9$  s) together with values  $v_n \approx 2.7 \times 10^5$  cm/s (300 K),  $\sigma_{n-d} \approx 5.5 \times 10^{-4}$  barns ( $= 5.5 \times 10^{-28}$  cm<sup>2</sup>), we obtain a value

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

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

18) A. De Ninno al.<sup>39)</sup>

An Italian group which made the first Ti/D<sub>2</sub> experiment with the neutron burst had observed tritium activity in a D<sub>2</sub> gas desorbed from fine Ti samples of 50 g with dimensions of  $50 \mu\text{m} \phi \times 1 \text{ mm}$  by the liquid scintillation spectroscopy. One sample (C10) with a composition Ti<sub>0.86</sub>V<sub>0.06</sub>Al<sub>0.06</sub>Sn<sub>0.02</sub> (Ti662) showed a radioactivity of 5.4 Bq per gram of deuterium gas.

We will assume following parameters to calculate the density of the trapped thermal neutrons in Ti because there was no details about the treatment of samples from the neutron measurements to the tritium measurements; The time  $\tau$  between the two measurements was 1 week ( $= 6.0 \times 10^5$  s) and D/Ti ratio was 1 (i.e. the deuteron density in the sample  $N_d \approx 5.7 \times 10^{22}$  cm<sup>-3</sup>). 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<sub>2</sub> gas =  $1.0 \times 10^{-14}$  t/s/D atom, we obtain  $n_n$  from the relation (11) as follows:

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

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

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

The results of the analyses given above were summarized in Table 1.

Table 1. Neutron Density  $n_n$  and Relations between the number of events  $N$  Obtained by Theoretical Analysis of Experimental Data on TNCF Model ( $N_Q \equiv Q(\text{MeV})/5(\text{MeV})$ )

Authors	System	Measured Quantities	$n_n$ ( $\text{cm}^{-3}$ )	Other Results (Remarks)
M. Fleischmann et al. <sup>13)</sup>	Pd/D/Li	$Q, t, n$ $N_t/N_n \approx 10^7$ $N_Q/N_n = 5.6 \times 10^7$	$\approx 10^9$	$N_t/N_n = 5.3 \times 10^5$ , $N_Q/N_n = 8.6 \times 10^7$ , $N_Q/N_t = 5.5$
A. Takahashi et al. <sup>15)</sup>	Pd/D/Li	$t, n$ $N_t/N_n \approx 8.7 \times 10^4$	$10^3$	$N_t/N_n = 5.3 \times 10^5$
M.H. Miles et al. <sup>17)</sup>	Pd/D/Li	$Q, {}^4\text{He}$ $N_Q/N_{\text{He}} \approx 1-10$	$10^9 - 10^{10}$	$N_Q/N_{\text{He}} \approx 5$
R. Bush et al. <sup>19)</sup>	Ni/H/Rb	${}^{85}\text{Rb} \rightarrow {}^{86}\text{Sr}$	$1.6 \times 10^7$	$N_Q/N_t \approx 3$
M. Okamoto et al. <sup>21)</sup>	Pd/D/Li	$Q, \text{NT} ({}^{27}\text{Al} \rightarrow {}^{28}\text{Si})$	$\approx 10^{10}$	$N_Q/N_{\text{NT}} \approx 1.4$
Y. Oya et al. <sup>21)</sup>	Pd/D/Li	$Q, \gamma$ spectra	$3.0 \times 10^9$	
Y. Arata et al. <sup>23)</sup>	Pd/D/Li	$Q, {}^4\text{He} (10^{21} - 10^{22} \text{ cm}^{-3})$	$\approx 10^{12}$	$N_Q/N_{\text{He}} \approx 6$ (If $t$ channeling in cathode wall)
M.C.H.McKubre <sup>25)</sup>	Pd/D/Li	$Q, \text{Exp. formula}$	$10^9 - 10^{10}$	Qualitative explan.
D. Cravens(P.P.C.) <sup>27)</sup>	Pd/H/Li	$Q,$	$5 \times 10^9$	(If PdD exists)
J.O'M. Bockris et al. <sup>30)</sup>	Pd/D/Li	$t (3.8 \times 10^7 / \text{cm}^2\text{s})$	$1.1 \times 10^6$	$N_t/N_{\text{He}} = 1$
A.G. Lipson et al. <sup>6)</sup>	Pd/PdO/D,Na	$\gamma (E_\gamma = 6.25 \text{ MeV})$	$4 \times 10^5$	(If efficiency = 1 %)
V. Romodanov et al. <sup>32)</sup>	Mo/D <sub>2</sub>	$t$	$1.8 \times 10^7$	(If sample is MoD)
I. Savvatimova <sup>31)</sup>	Pd/D <sub>2</sub>	$\text{NT} ({}^{106}\text{Pd} \rightarrow {}^{107}\text{Ag})$	$9 \times 10^{10}$	
O.Reifenschweiler <sup>33)</sup>	TiT <sub>0.0035</sub>	Reduction of $\beta$ decay	$1.1 \times 10^9$	$T \approx 450^\circ\text{C}$

J.Dufour <sup>35)</sup> (SS is for Stainless Steel)	Pd,SS/D <sub>2</sub> Pd,SS/H <sub>2</sub>	$Q, t, n$	$9 \times 10^{11}$ $4 \times 10^9$	(D(H)/Pd $\approx$ 1 is assumed)
T.N. Claytor et al. <sup>36)</sup>	Pd/D <sub>2</sub>	$t$ (0.15 nCi/h)	$1.4 \times 10^7$	(If D/Pd $\approx$ 1.)
F.G. Will et al. <sup>37)</sup>	Pd/D <sub>2</sub> SO <sub>4</sub>	$t$ ( $\approx 1.8 \times 10^5$ /cm <sup>2</sup> s)	$3.5 \times 10^7$	(If $l \approx 10 \mu$ m)
M. Srinivasan et al. <sup>38)</sup>	Ti/D <sub>2</sub>	$t$ ( $t/d \approx 1.8 \times 10^{-5}$ )	$1.9 \times 10^8$	
A. De Ninno et al. <sup>39)</sup>	Ti/D <sub>2</sub>	$t$ (5.4 Bq/g D <sub>2</sub> )	$1.2 \times 10^6$	(D/Ti=1, $\tau=1$ w)
S. Focardi et al. <sup>40)</sup>	Ni/H <sub>2</sub>	$Q$	$3 \times 10^{12}$	( $n_p=10^{21}$ was used)
D. Gozzi et al. <sup>41)</sup>	Pd/D/Li	$Q, ^4\text{He}$ $N_Q/N_{\text{He}}=1-5$	$2.2 \times 10^9$	(Assume $Q=5$ W), $N_Q/N_{\text{He}}=1$
T. Roulette et al. <sup>42)</sup>	Pd/D/Li	$Q$	$10^{11} - 10^{12}$	
F. Celani et al. <sup>43)</sup>	Pd/D/Li	$Q$ ( $Q_{\text{max}}=7$ W (200%))	$10^{12}$	(at $Q=Q_{\text{max}}$ )
R. Notoya et al. <sup>44)</sup>	Ni/H(D)/K	NT ( $^{39}\text{K} \rightarrow ^{40}\text{K}$ )	$1.4 \times 10^9$	
R.A. Oriani <sup>45)</sup>	SrCeO <sub>3</sub> /D <sub>2</sub> (2 cm $\phi \times$ 0.1 cm)	$Q \approx 0.7$ W (at 400°C)	$4 \times 10^{10}$	(Assume D/O=0.05)
T.O. Passell. <sup>46)</sup>	Pd/D/Li	NT ( $^{10}\text{B} \rightarrow ^7\text{Li}+^4\text{He}$ )	$1.1 \times 10^9$	$N_{\text{NT}}/N_Q \approx 2$

#### 4. Conclusion

The above 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 a paste have formed a whole figure of the physics of particles in a crystal with the trapped thermal neutron.

If we have no appropriate standpoint, 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 stable thermal neutrons in cold fusion

materials, we could have a consistent understanding of events in the phenomenon with quantitative relationships among them.

The assumption of the existence of the stable thermal neutron in crystal itself has a theoretical verification<sup>4)</sup> 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 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 magnetic resonance (nMR) like NMR or ESR used in the solid state physics and in the physical chemistry.

Other systems than the electrolytic and discharge ones have shown the characteristic cold fusion phenomenon not even more exciting than the latter. It will be fascinating program to analyze various experimental data in various systems on 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 answering to the energy crisis will be accelerated by the new idea to unify the separate facts obtained by experiments.

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## References

- (1) H. Kozima, "Trapped Neutron Catalyzed Fusion of Deuterons and Protons in Inhomogeneous Solids", *Trans. Fusion Technol.* **26**, 508 (1994).
- (2) H. Kozima and S. Watanabe, " $t$ - $d$  and  $d$ - $d$  Collision Probability in the Trapped Neutron Catalyzed Model of the Cold Fusion", *Proc. Intern. Sympos. Cold Fusion and Advanced Energy Sources* (May 24–26, 1994, Minsk,

Beralus) p. 299 (in Russian).

(3) H. Kozima and S. Watanabe, "Nuclear Processes in Trapped Neutron Catalyzed Model for Cold Fusion" *Proc. ICCF5* (April 9–13, 1995, Monte Carlo, Monaco), p.347 (1995); *Cold Fusion* **10**, 2 (1995).

(4) H. Kozima, "Neutron Band, Neutron Cooper Pair and Neutron Life Time in Solid", *Cold Fusion*, **16**, 4 (1996); *Proc. 3rd Russian Conference on Cold Fusion and Nuclear Transmutation* (RCCFNT3) (Sochi, Russia, Oct. 2–6, 1995), 224 (1996).

(5) G. F. Cerofolini, G. Boara, S. Agosteo and A. Para, "Giant Neutron Trapping by a Molecule Species Produced during the Reaction of  $D^+$  with  $H^-$  in a Condensed Phase", *Fusion Technol.* **23**, 465 (1993).

(6) A. G. Lipson, D. M. Sakov and E. I. Saunin, "Suppression of Spontaneous Deformation in Triglycine Sulfate Crystal ( $D_{0.6}H_{0.4}$ ) by a Weak Neutron Flux" *JETP Lett.* **62**, 828 (1995) and private communication.

(7) G. Shani, C. Cohen, A. Grayevsky and S. Brokman, "Evidence for a Background Neutron Enhanced Fusion in Deuterium absorbed Palladium", *Solid State Comm.* **72**, 53 (1989).

(8) A.A. Yuhimchuk, V.I. Tichonov, S.K. Grischechkin, N.S. Ganchuk, B.Ya. Gujofskii, Yu.I. Platnikov, Yu.A. Soloviev, Yu.A. Habarov, A.B. Levkin, "Registration of Neutron Emission in Thermocycle of Vanadium Deuterides", *Kholodnyi Yadernyi Sintez*, p. 57, ed. R. N. Kuz'min, Sbornik Nauchnykh Trudov (Kariningrad) 1992. (in Russian)

(9) F. Celani, A. Spallone, L. Libaratori, F. Groce, A. Storelli, S. Fortunati, M. Tului and N. Sparviari, "Search for Enhancement of Neutron Emission from Neutron-Irradiated, Deuterated High-Temperature Superconductors in a Very Low Background Environment", *Fusion Technol.* **22**, 181 (1992).

(10) B. Stella, M. Corradi, F. Ferrarotto, V. Milone, F. Celani and A. Spallone, "Evidence for Stimulated Emission of Neutrons in Deuterated Palladium", *Proc. ICCF3* (October 21 - 25, 1992, Nagoya, Japan), p.437 (1993)

(11) A. G. Lipson and D. M. Sakov, "Increase in the Intensity of the External Neutron Flux in the Irradiation of  $KD_2PO_4$  Crystal at the Point of the Ferroelectric Phase Transition", *Proc. ICCF 5* (April 9 - 13, 1995, Monte Carlo, Monaco), p.571 (1995).

(12) T. Nakagawa, T. Asami and T. Yoshida, "Curves and Tables of Neutron Cross Sections", *JAERI-M* 90-099, NEANDC(J)-153/U INOC(JPN)-140/L} (July, 1990).

- (13) M. Fleischmann, S. Pons and M. Hawkins, "Electrochemically Induced Nuclear Fusion of Deuterium", *J. Electroanal. Chem.* **261**, 301 (1989).
- (14) H. Kozima, K. Hiroe, M. Nomura and M. Ohta, "Analysis of the First Cold Fusion Experiment on TNCF Model", *Cold Fusion* (to be published).
- (15) A. Takahashi, T. Iida, T. Takeuchi, A. Mega, S. Yoshida and M. Watanabe, "Neutron Spectra and Controllability by PdD/Electrolysis CELL with Low-High Current Pulse Operation", "*The Science of Cold Fusion*" (Conference Proceedings of SIF (Italy)) **33**, 93 (1991).
- (16) H. Kozima, M. Nomura K. Hiroe and M. Ohta, "Analysis of Tritium and Neutron Generation in Pd+LiOD/D<sub>2</sub>O System", *Cold Fusion* **19** (1996) (to be published);
- (17) M.H. Miles, R.A. Hollins, B.F. Bush and J.J. Lagowski, "Correlation of Excess power and Helium Production During D<sub>2</sub>O and H<sub>2</sub>O Electrolysis Using Palladium Cathodes", *J. Electroanal. Chem.* **346**, 99 (1993).
- (18) H. Kozima, S. Watanabe, K. Hiroe, M. Nomura and M. Ohta, "Analysis of Cold Fusion Experiments Generating Excess Heat, Tritium and Helium", *J. Electroanal. Chem.* (to be published).
- (19) R. Bush and R. Eagleton, "Evidence for Electrolytically Induced Transmutation and Radioactivity Correlated with Excess Heat in Electrolytic Cells with Light Water Rubidium Salt Electrolytes", *Trans. of Fusion Technol.* **26**, 344 (1994).
- (20) H. Kozima, K. Hiroe, M. Nomura and M. Ohta, "On the Elemental Transmutation in Biological and Chemical Systems", *Cold Fusion* **16**, 30 (1996).
- (21) M. Okamoto, H. Ogawa, Y. Yoshinaga, T. Kusunoki and O. Odawara, "Behavior of Key Elements in Pd for the Solid State Nuclear Phenomena Occurred in Heavy Water Electrolysis", *Proc. ICCF4*, **3**, 14-1 (1994).
- (21') Y. Oya, H. Ogawa, T. Ono, M. Aida and M. Okamoto, "Hydrogen Isotope Effect Induced by Neutron Irradiation in Pd-LiOD (H) Electrolysis" *Proc. ICCF6* (Oct. 14 - 17, 1996, Hokkaido, Japan) (to be published)).
- (22) H. Kozima, M. Ohta, M. Nomura and K. Hiroe, "Another Evidence of Nuclear Transmutation in Cold Fusion Experiment", *Cold Fusion* **18** (1996) (to be published).
- (23) Y. Arata and Y.C. Zhang, "Achievement of Solid-State Plasma Fusion ("Cold Fusion")", *Proc. Jpn Acad.* **71B**, 304 (1995); and "A New Energy caused by 'Spillover-Deuterium'", *Proc. Jpn Acad.* **70B**, 106 (1994).

- (24) H. Kozima, S. Watanabe, K. Hiroe, M. Nomura and M. Ohta, "Analysis of Excess Heat and  $^4\text{He}$  Generation in Pd-black Cathode by  $\text{D}_2\text{O}+\text{LiOH}$  Electrolysis", *Cold Fusion* (to be published).
- (25) M. C. H. McKubre, S. Crouch-Baker and F. L. Tanzella, "Conditions for the Observation of Excess Power in the D/Pd System", *Proc. ICCF5* (April 9 - 13, Monte-Carlo, Monaco) (1995) 17 and also in *Proc. 3rd Russian Conference on Cold Fusion and Nuclear Transmutation* (RCCFNT3) (Oct. 2 - 6, 1995, Sochi, Russia), p.123 (1996).
- (26) H. Kozima, "Excess Energy Data in Pd/D System Examined", *Cold Fusion* **17**, 12 (1996).
- (27) D. Cravens, "Flowing electrolyte Calorimetry", *Cold Fusion* **11**, 15 (1995) and also *Proc. ICCF-5* (1995) p.79.
- (28) Report by V. Lapuszynski, *Cold Fusion* **7**, 1 (1995); U.S. Pat. No. 5,318,675, U.S. Pat. No. 5,372,688.
- (29) H. Kozima, "Analysis of Patterson Power Cell by TNCF Model", *Cold Fusion* **17**, 8 (1996).
- (30) J. O'M. Bockris, C-C. Chien, D. Hodko and Z. Minevski, "Tritium and Helium Production in Palladium Electrodes and the Fugacity of Deuterium Therein", *Proc. ICCF3* (October 21 - 25, 1992, Nagoya, Japan), p.231 (1993).
- (31) I.B. Savvatimova, A. B. Karabut, "Change of Elemental and Isotope Contents in Cathode after Ion Bombardment in Glow Discharge", *Proc. RCCFNT3* (Oct. 2 - 7, 1995, Sochi, RUSSIA), p.20 (1996) and private communication.
- (32) V.A. Romodanov, V.I. Savin and Ya.B. Skuratnik, "The Demands to System Plasma-Target for Obtaining a Balance Energy from Nuclear Reactions in Condensed Media", *Proc. RCCFNT2* (Sept. 1994, Sochi, RUSSIA), p.99 (1995); V.A. Alekseev, V.I. Vasil'ev, V.A. Romodanov, Yu.F. Ryshkov, S.V. Rylov, V.I. Savin, Ya.B. Skuratnik and V.M. Strunnikov, "Tritium Production in the Interaction of Dense Streams of Deuterium Plasma with Metal Surfaces", *Tech. Phys. Lett.* **21**, 231 (1995) and private communication.
- (33) O. Reifenschweiler, "Reduced Radioactivity of Tritium in Small Titanium Particle", *Phys. Lett.* **A184**, 149 (1994).
- (34) H. Kozima, "On the 'Reduced Radioactivity of Tritium' Sorbed by Titanium", *Physics Letters* (submitted).
- (35) J. Dufour, "Cold Fusion by Sparking in Hydrogen Isotopes", *Fusion*

*Technol.* **24**, 205 (1993).

(36) T.N. Claytor, D.D. Jackson and D.G. Tuggle, "Tritium Production from a Low Voltage Deuterium Discharge on Palladium and Other Materials", Presentation at ICCF5, No.306 and also *Trans. Fusion Technol.* **26**, 221 (1994).

(37) T.G. Will, K. Cedzynska and D.C. Linton, "Tritium Generation in Palladium Cathodes with High Deuterium Loading", *Trans. Fusion Technol.* **26**, 207 (1994).

(38) M. Srinivasan, R.K. Rout, S.C. Misra, M. Lai, A. Shyam, P.S. Rao and P.K. Iyengar, "Observation of High Tritium Levels in Aged Deuterated Tritium Targets as Possible Evidence of Cold Fusion", *Fusion Technol.* **18**, 88 (1990).

(39) A. De Ninno, F. Scaramuzzi, A. Frattolillo, S. Migliori, F. Lanza, S. Scaglione, P. Zeppa and C. Pontorieri, "The Production of Neutrons and Tritium in Deuterium Gas - Titanium Interaction", *The Science of Cold Fusion (Proc. ICCF2)* (Conference Proceedings) **33**, 129 (1991), SIF, Bologna.

(40) S. Focardi, R. Habel and F. Piontelli, "Anomalous Heat Production in Ni-H System", *Nuovo Cimento*, **107A**, 163 (1994).

(41) D. Gozzi, P.L. Cignini, M. Tomellini, S. Frullani, F. Galibaldi, F. Ghio, M. Jodice and G.M. Urciuoli, "Neutron and Tritium Evidence in the Electrolytic Reduction of Deuterium on Palladium Electrode", *Fusion Technol.* **21**, 60 (1992).

(42) T. Roulette, J. Roulette and S. Pons, "The ICARUS 9 Calorimeter: Summary of Three Years Designing, Testing and Operation of this Device at the IMRA Europe Science Center", *Proc. ICCF6* (to be published).

(43) F. Celani, A. Spallone, P. Tripodi, D. Di Giacchino, S. Pace, P. Marini, V. Di Stefano, M. Diocianiuti and A. Mancini, "High Power  $\mu$  s Pulsed Electrolysis Using Long and Thin Pd Wires in Very Dilute LiOD-D<sub>2</sub>O Solution: Observation of Anomalous Excess Heat", *Proc. ICCF6* (October 14 - 17, 1996, Hokkaido, JAPAN) (to be published).

(44) R. Notoya, T. Ohnishi and Y. Noya, "Nuclear Reaction Caused by Electrolysis in Light and Heavy Water Solution" *Proc. ICCF6* (October 14 - 17, 1996, Hokkaido, Japan) (to be published).

(45) R.S. Oriani, "An Investigation of Anomalous Thermal Power Generation from a Proton-Conducting Oxide" *Fusion Technol.* **30**, 281 (1996).

(46) T.O. Passell, "Search for Nuclear Reaction Products in Heat-Producing

Palladium", Preprint to be published in *Proc. ICCF6* (1996).