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ANOMALOUS PHENOMENON IN SOLIDS DESCRIBED BY THE TNCF MODEL

NUCLEAR REACTIONS IN SOLIDS

KEYWORDS: *excess heat, nuclear transmutation, TNCF model*

HIDEO KOZIMA,* KAORI KAKI, and MASAYUKI OHTA
Shizuoka University, Department of Physics, Faculty of Science
836 Oya, Shizuoka 422, Japan

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

I. INTRODUCTION

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

To explain the cold fusion phenomenon, the first proposal[2,3] of a phenomenological model was made in the fall of 1993 based on an assumption of trapped thermal neutron catalyzing fusion (TNCF) reactions in crystals (the TNCF model). The idea of fusing a neutron as an agent to realize nuclear reactions in solids generated a companion trial using neutronlike stable particles[4–7] with some physical verifications for their existence. The trapped neutron model assumes simply an existence of quasi-stable neutrons moving in solid with thermal velocity and some other properties, which will be explained in Sec. II.

The model was developed[8–11] in 3 yr 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[12] showed that the experimental results on the relations between the excess heat, tritium, and neutron were explained consistently by the model. The questions solved by the model included the poor reproducibility of the events, large N_t/N_n ($\equiv t/n$) 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, neutrons, excess heat, and ^{4}He, respectively.

In this paper, we show that 28 typical experimental data sets of the electrochemical and the discharge experiments obtained in the ~8 yr after the discovery[1] of the cold fusion phenomenon were explained by the TNCF model consistently, and therefore, physics of the cold fusion phenomenon can be depicted on the model.

In Sec. II, we explain the basic concepts of the TNCF model. In Sec. III, we give results of analyses of the experimental data on the basic premise of the model (the quasi-stable existence of the trapped thermal neutrons in the solid) and also the assumed fusion reactions between the neutron and nuclei causing perturbation on the neutron to destabilize it. In Sec. IV, we discuss the physics of the cold fusion phenomenon envisaged by the TNCF model based on the success of the analyses given in Sec. III.

II. THE TNCF MODEL

The TNCF model is a phenomenological one, and the basic premises (assumptions) are summarized as follows[13]:

*E-mail: sphkoji@sci.shizuoka.ac.jp

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

The density n_n is an adjustable parameter in the TNCF model that will be determined by experimental data using the supplementary assumptions that will be explained later concerning reactions of the neutron with other particles in the solids. The special characteristics of the solids to trap the thermal neutron were supposed to be realized by stochastic processes in the solids.

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

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

The following additional premises on the measured quantities are then used to calculate reaction rates, for simplicity.

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

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

This means that if a gamma or neutron spectrum is observed outside, it directly reflects 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 information of the individual events of the nuclear reaction 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 information of the individual events.

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.

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

Premises about structure of the sample are expressed as follows:

8. In electrolytic experiments, the thickness of the alkali metal layer on the cathode surface will be taken as 1 μm.

9. The mean free path of the triton with an energy 2.7 MeV generated by the $n + {}^6Li$ 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.

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

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

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:

$$N_Q = \text{excess heat } Q \text{ (MeV)}/5 \text{ (MeV)} .$$

The following relation combines the energy units of mega-electron-volts and joules:

$$1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J} , \quad 1 \text{ J} = 6.24 \times 10^{12} \text{ MeV} .$$

The origin of the trapped neutron can be considered as (a) the ambient background neutrons, the existence of which have been recognized widely in public, and (b) the neutrons breeded in the sample by nuclear reactions between the trapped neutron and perturbing nuclei proposed in the TNCF model.

There are some experimental bases of these premises. Premise 1, the possible existence of trapped neutron: Cerofolini et al.[14] and Lipson et al.[15] 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.,[16] Yuhimchuk et al.,[17] Celani et al.,[18] Stella et al.,[19] and Lipson and Sakov[20] 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.,[21] Okamoto et al.,[22] Oya et al.,[23] and Yamada et al.[24] showed helium production and nuclear transmutation in the surface layer of the palladium cathode with a thickness of $\leq$25 μm, ~1 μm, and 3 nm, respectively. Premise 3, low reactivity of volume nuclei up to ~1% of the value in vacuum: Notoya et al.[25] observed nuclear transmutation and positron annihilation gamma in a porous nickel sample that showed a low reactivity of nucleus in volume at most 1% of the value in vacuum.

An exception to the reaction rate in volume is illustrated in an experiment of molybdenum cathode at 3000 K where a high production rate of tritium is observed.[26,27]

If the stability of the trapped neutron is lost by a large perturbation in the surface layer or in volume, the reaction probability between a thermal neutron and a nucleus may be calculated by the same formula to the usual collision process but with a numerical factor ξ:

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

where

$0.35 n_n v_n$ = flow density of the neutron per unit area and time

n_N = density of the nucleus

V = volume where the reaction occurs

σ_{nN} = cross section for the reaction.

The factor ξ in relation (1) expresses an order of the stability of the trapped neutron in a region where it is. Volume V will be taken as $l_0 S$ in the electrolytic experiments, where l_0 and S are the thickness and area of the surface layer on the cathode, respectively.

In the electrolytic experiments, we took $\xi = 1$ in the surface layer and $\xi = 0$ in the volume except as otherwise stated (premises 2 and 3). The value of $\xi = 0.01$ instead of $\xi = 0$ in relation (1) will result in lower n_n in the electrolytic data by a factor of more than 2 than that determined with a value $\xi = 0$ as had been used in our former analyses. (In this paper, we 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 the thermal neutron exists, volume V should be that of the boundary region where the nucleus reacts with the thermal neutron (as in electrolytic experiments). On the other hand, in a sample without a definite boundary layer but with a disordered array of minor species of lattice nuclei in the sample, the volume should be the whole volume of the sample (as in discharge experiments).

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

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

where

${}^0_0 M \equiv \gamma$

${}^0_1 M \equiv n$

${}^1_1 M \equiv p$

${}^2_1 M \equiv d$

${}^3_1 M \equiv t$

${}^4_2 M \equiv {}^4\mathrm{He}$

and so forth.

The excess energy Q may be measured as the excess heat by the attenuation of the nuclear products γ and charged particles generated in reaction (2). Otherwise, the nuclear products may be observed outside with an energy (we assume it as the original one hereafter) or may induce succeeding nuclear reactions with one of other nuclei in the sample.

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

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

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

The thickness of the surface layer will be assumed as 1 μm throughout the following analysis (premise 8), although it has been determined as 1 to 10 μm in experiments (allowing one order of magnitude uncertainty in the determined value of n_n). Also, the abundance of the isotope ^{6}Li will be assumed as the natural one, i.e., 7.4%, except as otherwise described.

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 located an array of occluded deuterons, or it can proceed a finite path with a length ($\simeq 1$ to 10 μm) determined by the interaction with charged particles in the crystal. In the process of triton penetration through a crystal, the triton can fuse with a deuteron on the path with a length (take as 1 μm) with a cross section of $\sim 1.4 \times 10^{-1}$ b (premise 9):

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

It has been a defect in experimental research to not try to detect the higher energy neutrons (from 10 to 15 MeV) expected to be generated in this reaction.

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

$$n(14.1\ \mathrm{MeV}) + d = n' + d' \tag{5}$$

$$= n' + p + n'' \ . \tag{6}$$

The threshold energy of the latter reaction is 2.2 MeV with a cross section of 0.2 b. In these reactions, the original high-energy neutron will be thermalized or generate another low-energy neutron to be trapped in the sample (breeding process).

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

$$n + d = t + \gamma + 6.25\ \mathrm{MeV} \tag{7}$$

and

$$n + {}^7\mathrm{Li} = {}^8\mathrm{Li} + \gamma = 2\,{}^4\mathrm{He} + e^- + \bar{\nu}_e + 16.2\ \mathrm{MeV} + \gamma \ . \tag{8}$$

Reaction (7) for a thermal neutron has a cross section of 5.5×10^{-4}, and reaction (8) has 4×10^{-2} b, 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 b:

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

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

Depending on the situation in a cold fusion system, the trapped thermal neutron can induce such trigger reactions as reactions (3) and (7), and the generated energetic particles can sustain breeding chain reactions, producing much of the excess heat and nuclear products.

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

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

and

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

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

The photons generated in reactions (7), (8), (11), and (12) can induce photodisintegrations of deuterons and nuclei if they have more energy than the threshold energies of the following reactions [2.22 MeV for reaction (13)]:

$$\gamma + d = p + n \tag{13}$$

and

$$\gamma + {}^A_Z M = {}^{A-1}_{\ \ Z}M + n\ . \tag{14}$$

In samples with deuterons, reaction (13) with a cross section $\sim 2.5 \times 10^{-3}$ b works as a neutron breeder.

In the analysis of experimental data on the TNCF model, we make the situation simple and tractable using premises 4 through 11 explained earlier.

III. EXPERIMENTAL DATA AND THEIR ANALYSIS ON THE TNCF MODEL

In the experiments of cold fusion phenomenon, there are many data sets reflecting nuclear reactions occurring in the solid sample. Among the data sets, there is direct and indirect evidence of the nuclear reaction in solids. The direct evidence includes gamma and neutron spectra and distribution of transmuted nuclei in the sample. The gamma and neutron with high energy scarcely loose their energy in a small sample usually used in the experiments and are observed as its original forms outside. The indirect evidence includes the excess heat; amounts of tritium, ^{4}He, neutrons, and gamma and X rays; and transmuted nuclei that are impossible to explain without nuclear reactions.

We pick up typical experimental data of each event and explain the characteristics by the TNCF model. The TNCF model assumes nuclear reactions between the trapped neutron and another nucleus in the sample as trigger reactions, and it is expected that there are several effects occurring in conjunction with the reactions. In the analysis of experimental data, we assume the existence of all expected events together even though some are detected in the experiment.

The detailed process of the analysis is given only for some cases to illustrate the process of analysis, and only the resulting parameter n_n is given for others taken up by us.

III.A. Null Result and Effect of Thermal Neutrons

There are many results of unsuccessful experiments and some experimental data showing effects of background neutrons on the cold fusion phenomenon.

III.A.1. Null Result

Several experimental data sets have been published that failed to detect the cold fusion phenomenon as well as many unpublished sets. There is also a general tendency to believe that the cold fusion phenomenon occurs less frequently in careful conditions that reduce background neutrons to improve the S/N ratio. In the published data, one fundamental set was that by Jones et al.,[28] and the one by Ishida[29] was reliable. Although the number of unsuccessful experiments overwhelms that of successful ones, it is ridiculous to discuss the reality of the cold fusion phenomenon with a statistical average of the results.

Those cited earlier and many uncited data sets have shown that the cold fusion phenomenon did not occur in a situation where there is a very low density of the ambient background neutrons. This is negative evidence of the decisive role of thermal neutrons in the cold fusion phenomenon.

III.A.2. Effect of Thermal Neutrons

There are several experimental data sets showing the effect of an artificial irradiation of thermal neutrons under low ambient background neutron density: Shani et al.,[16] Yuhimchuk et al.,[17] Celani et al.,[18] Stella et al.,[19] Lipson and Sakov,[20] and Oya et al.[23] These data have shown clearly that the thermal neutron induces the cold fusion phenomenon. This is positive evidence of the decisive role of thermal neutrons in the cold fusion phenomenon.

Using the premises given in Sec. II, we could determine the density n_n of the trapped thermal neutrons[30] in the samples used in the experiments by Oya et al.[23] as follows: $n_n = 3.0 \times 10^9\ \text{cm}^{-3}$.

III.A.3. Qualitative Reproducibility

It is normal that the cold fusion phenomenon occurs with poor reproducibility. The first premise of the TNCF model is supposed to be fulfilled in crystals with special characteristics to trap thermal neutrons from ambient and to breed them inside. The characteristics were supposed to be realized only when there was a structure formed by atomic processes in the multicomponent solid sample that was essentially stochastic. This point will be discussed later in Sec. IV.

Therefore, the realization of the characteristics for the cold fusion phenomenon has only qualitative reproducibility but not quantitative.

III.B. Direct Evidence of the Nuclear Reaction in Solids

In the experimental data of the cold fusion phenomenon, there is some evidence of nuclear reactions in the solids, including energy spectra of gamma-ray and neutron and spatial distributions of transmuted nuclei in the sample. These data could be considered as direct evidence of the nuclear reactions because the gamma and neutron could be observed with a negligible energy loss and because the transmuted nuclei could be observed where the transmutation occurred.

III.B.1. Gamma Spectrum

Experimental results on the gamma were rare until 1996. The data sets until 1996 were without clear spectra, including those by Fleischmann et al.,[1] Long et al.,[31] and Jorne.[32] Recent data were with gamma spectra, which include Lipson et al.,[33] Notoya et al.,[25] and Oya et al.[23] It should be emphasized that the positron annihilation gamma with energy of 0.511 MeV was measured in the latter two measurements. An analysis of the data by Notoya et al.[25] showed that the interaction between the trapped neutron and lattice nuclei in volume was at most 1% of that in vacuum and justified neglect of the interaction in the analyses of the indirect evidence of cold fusion such as excess heat and the amounts of tritium and helium atoms. This is the basis of premise 3.

The data by Lipson et al.,[33] Notoya et al.,[25] and Oya et al.[23] were analyzed on the TNCF model, and the parameter n_n was determined as $n_n = 4 \times 10^5$, 1.4×10^9, and $\sim 10^{10}$ cm^{-3}, respectively.

III.B.2. Neutron Spectrum

The first neutron spectrum was measured by Jones et al.[28] Several data sets by Takahashi et al.[34] and Nakada et al.[35] were then presented. They have shown that there are neutrons with energies ~2.45 MeV and with energies up to 10 MeV, and the number of the latter are exceeding the former by several factors. This result shows that reaction (10) is occurring in the cold fusion materials but is not the main reaction. There are few data sets of the neutron spectrum above 10 MeV, and it is difficult to verify the occurrence of reaction (4), but the broad peaks above 3 MeV could be a result of deceleration of the neutron in the matter.

The data by Takahashi et al.[34] were analyzed on the TNCF model, and the parameter n_n was determined as $n_n = 1 \times 10^6$ cm^{-3}.

III.B.3. Distribution of Transmuted Nuclei

Distribution of transmuted nuclei, including ^{4}He, was measured by several scientists. The first were Morrey et al.,[21] who analyzed samples used by Fleischmann et al.[1] From then, several data sets were obtained that showed local distribution of the transmuted nuclei, including Okamoto et al.,[22] Savvatimova et al.,[36] Savvatimova and Karabut,[37] and Yamada et al.[24]

These data have shown that the nuclear reactions in electrolytic materials occurred in surface layers with thickness of several microns. This is the basis of premise 2.

The data by Okamoto et al.,[22] Savvatimova et al.,[36] Savvatimova and Karabut,[37] and Yamada et al.[24] were analyzed on the TNCF model and the parameter n_n was determined as $n_n = 1 \times 10^{10}$, 9×10^{10}, and $\sim 10^{11}$ cm^{-3}, respectively.

III.B.4. Miscellaneous

Kasagi et al.[38] observed a small but sharp peak of protons with 14.1 MeV in an experiment with 150-keV deuteron irradiation on the TiD sample. This proton could be interpreted as a recoil proton by a 14.1-MeV neutron generated in the $t + d$ reaction (4).

III.C. Indirect Evidence of the Nuclear Reaction in Solids

In the experimental data sets of the cold fusion phenomenon, there is evidence that quantitatively shows the occurrence of nuclear reactions in the solids. The excess heat too large to be explained by chemical reactions is the first example. The appearances of enough tritium and helium in the experimental system are the second and third examples. To the goal of a new energy source, the excess heat is the most important quantity and has been examined extensively.

III.C.1. Excess Heat

There are many data sets on the excess heat generation in a Pd/D, Ni/D(H) system but with qualitative reproducibility. Those data sets include Fleischmann et al.,[1] Roulette et al.,[39] Miles et al.,[40] Okamoto et al.,[22] Oya et al.,[23] Arata and Zhang,[41] McKubre et al.,[42] Cravens,[43] Dufour,[44] Focardi et al.,[45] Gozzi et al.,[46] Cellucci et al.,[47] Celani et al.,[48,49] Oriani,[50] and Iwamura et al.[51]

We show here a detailed analysis of the data obtained by Fleischmann et al.[1] First, their data in a sample with a dimension of 0.1-cm diameter × 10 cm generated an excess heat of 0.079 J/s (= 4.9×10^{11} MeV/s) by reaction (3), which determines the density of the trapped neutron

$$n_n = 1.3 \times 10^9 \text{ cm}^{-3}$$

by relation (1). In this calculation, we assumed that all the liberated energy in the reaction was thermalized in the system. On the other hand, a sample with the same size generated tritium of 4×10^{11} s^{-1} by reaction (3), which also determines the density

$$n_n = 5 \times 10^9 \text{ cm}^{-3}$$

by relation (1). These two values of the density n_n seem consistent with a difference of a factor of 4.

Second, their data set in a sample with a dimension of 0.4-cm diameter × 10 cm generated neutron 4×10^4 s^{-1}, which corresponds to the number of tritium of 2.5×10^{10} s^{-1} (= $4 \times 10^4 \times 6.25 \times 10^5$) by reaction (4). This value determines the density of the trapped neutron

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

On the other hand, the excess energy of 1.75 J/s (= 1.1×10^{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 a factor of 20, and coincidence is qualitative.

We can see that all these values of the density n_n are fairly similar. We may assume that although the data of the excess heat, tritium, and neutron are not measured with the same cathode, there should be tritium in the case of neutron measurement and in the case of heat measurement, etc. This might be the truth of the phenomenon in the Pd/D/Li system. This means that it might be more reasonable to consider that both reactions (3) and (4) were together in the samples generating the excess heat, tritium, and neutron, as assumed at the end of the introduction to Sec. III, than to consider that those events occurred independently. We take this point of view in the analysis of the cold fusion data.

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

The data by Roulette et al.,[39] Miles et al.,[40] Arata and Zhang,[41] McKubre et al.,[42] Cravens,[43] Dufour,[44] Focardi et al.,[45] Gozzi et al.,[46] Cellucci et al.,[47] Celani et al.,[48,49] and Oriani[50] were analyzed on the TNCF model, and the parameter n_n was determined as $n_n = 10^{11}$ to 10^{12}, 10^9 to 10^{10}, $\sim 10^{12}$, 10^9 to 10^{10}, 8.5×10^9, 9.2×10^{11}, 3.0×10^{12}, 2.2×10^9, 1.0×10^{12}, and 4.0×10^{10} cm^{-3}, respectively.

In the analysis of the data by Arata and Zhang,[41] it was assumed that reaction (3) occurred in the surface of the palladium cylinder and the generated triton in the reaction penetrated into its inside where there was palladium-black, in which ^{4}He was detected.

III.C.2. Tritium Generation

Tritium generation was observed more frequently than neutron generation, and the amount was very large with a factor up to 10^7 compared with that of neutron generation. The data include that by Fleischmann et al.,[1] Romodanov et al.,[27] Takahashi et al.,[34] Storms and Talcott,[52] Srinivasan et al.,[53] Rout et al.,[54] Bockris et al.,[55] Claytor et al.,[56] Will et al.,[57] and De Ninno et al.[58]

The data by Storms and Talcott[52] (^{6}Li: 0.018%), Bockris et al.,[55] Romodanov et al.,[27] Claytor et al.,[56] Will et al.,[57] Srinivasan et al.,[53] Rout et al.,[54] and De Ninno et al.[58] were analyzed with the TNCF model, and the parameter n_n was determined as $n_n = 2.2 \times 10^6$, 1.1×10^6, 1.8×10^7, 1.4×10^7, 3.5×10^7, 1.9×10^8, and 1.2×10^6 cm^{-3}, respectively. In the analysis of the data by Romodanov et al.,[27] the volume V was taken as the volume of the sample where the temperature was ~3000 K and the reaction was supposed to occur in volume.

III.C.3. Helium-4 Generation

The observation of helium was also rather frequent and the amount very large compared with that of neutron generation. Miles et al.,[40] Arata and Zhang,[41] and Yamaguchi and Nishioka[59] were several of the many data sets reporting the detection of helium.

The data by Miles et al.[40] and Arata and Zhang[41] were analyzed with the TNCF model, and the results were given in Sec. III.C.1.

III.C.4. Neutron Generation

Neutron generation without energy spectrum was observed many times. The first one was by De Ninno et al.[60] followed by Menlove et al.,[61] and Iyengar and Srinivasan.[62]

III.C.5. Gamma and X-Ray Generation

Gamma generation without its energy spectrum was first measured by Fleischmann et al.[1] and then by Long et al.[31] and others. The observed energy spectrum was discussed in Sec. III.B.1.

III.C.6. Transmuted Nuclei

Transmuted nuclei without spatial distribution have been measured very often in electrolytic and discharge experiments, which include data sets by Savvatimova et al.,[36] Savvatimova and Karabut,[37] Bockris et al.,[55] Ohmori and Enyo,[63] Mizuno et al.,[64] Bush and Eagleton,[65] Passel,[66] and Miley et al.[67]

The data by Bush and Eagleton[65] and by Passel[66] were analyzed with the TNCF model, and the parameter n_n was determined as $n_n = 1.6 \times 10^7$ and 3.7×10^{10} cm^{-3}, respectively.

III.C.7. Miscellaneous

Reifenschweiler[68] measured the resulting X rays induced by beta-decay of tritium sorbed by titanium ($TiT_{0.0035} \equiv Ti/T$ system). The sample was in the shape of extremely small monocrystalline particles with a diameter of ϕ = 15 nm. In the heating process of the sample between 0 and 450°C, he observed a decrease in radioactivity (i.e., an intensity of the X ray) from the sample Ti/T up to 40% in a definite temperature range of 115 to 275°C. From the experimental result, he concluded that there was a reduction of radioactivity of tritium sorbed by titanium.

This data set about a curious temperature dependence of radioactivity from $TiT_{0.0035}$ sample was analyzed with the TNCF model, assuming an existence of the trapped neutron in the sample and stabilization of the

TABLE I

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)]

Authors	System	Measured Quantities	n_n (cm^{-3})	Other Results (Remarks)
Lipson et al.[33]	Pd/PdO/D,Na	γ (E_γ = 6.25 MeV)	4×10^5	(If efficiency = 1%)
Notoya et al.[25]	Ni/H(D)/K	NT ($^{39}K \to {}^{40}K$)	1.4×10^9	
Oya et al.[23]	Pd/D/Li	Q, γ spectrum	3.0×10^9	(with ^{252}Cf source)
Takahashi et al.[34]	Pd/D/Li	t, n $N_t/N_n \sim 6.7 \times 10^4$	10^3	$N_t/N_n \sim 5.3 \times 10^5$
Okamoto et al.[22]	Pd/D/Li	Q, NT ($^{27}Al \to {}^{28}Si$)	$\sim 10^{10}$	$N_Q/N_{NT} \sim 1.4$
Savvatimova and Karabut[37]	Pd/D_2	NT ($^{106}Pd \to {}^{107}Ag$)	9×10^{10}	
Yamada et al.[24]	Pd/D_2	n, NT ($^{16}O \to {}^{13}C$)	2.0×10^{12}	^{13}C not confirmed
Fleischmann et al.[1]	Pd/D/Li	Q, t, n $N_t/N_n \sim 10^7$ $N_Q/N_n \sim 5.6 \times 10^7$	$\sim 10^9$	$N_t/N_n \sim 5.3 \times 10^5$ $N_Q/N_n \sim 8.6 \times 10^7$ $N_Q/N_t \sim 1.0$
Roulette et al.[39]	Pd/D/Li	Q	$10^{11} \sim 10^{12}$	
Miles et al.[40]	Pd/D/Li	Q, ^4He (N_Q/N_{He} = 1 to 10)	$10^9 \sim 10^{10}$	$N_Q/N_{He} \sim 5$
Arata and Zhang[41]	Pd/D/Li	Q, ^4He (10^{20} to 10^{21} cm^{-3})	$\sim 10^{12}$	$N_Q/N_{He} \sim 6$ (assume t channeling in cathode wall)
McKubre et al.[42]	Pd/D/Li	Q (formula)	$10^9 \sim 10^{10}$	Qualitative explanation
Cravens[43] (Patterson Power Cell)	Pd/H/Li	Q (Q_{out}/Q_{in} = 3.8)	8.5×10^9	(If PdD exists)
Dufour[44] (SS is for stainless steel)	$Pd,SS/D_2$ $Pd,SS/H_2$	Q, t, n	9.2×10^{11} 4.0×10^9	[D(H)/Pd ~ 1 is assumed]
Focardi et al.[45]	Ni/H_2	Q	3.0×10^{12}	($N_p = 10^{21}$ was used)
Gozzi et al.[46]	Pd/D/Li	Q, ^4He N_Q/N_{He} = 1 to 5	2.2×10^9	(Assume Q = 5 W) $N_Q/N_{He} = 1$
Celani et al.[48]	Pd/D/Li	$Q[Q_{max}$ = 7 W (200%)]	1.0×10^{12}	(At Q_{max})
Oriani[50]	$SrCeO_3/D_2$	$Q \sim 0.7$ W (400°C)	4.0×10^{10}	V = 0.31 cm^3
Storms and Talcott[52]	Pd/D/Li	t ($\sim 1.8 \times 10^2$ Bq/ml)	2.2×10^6	(τ = 250 h, V = 60 ml)
Bockris et al.[55]	Pd/D/Li	t ($\sim 3.8 \times 10^7$/cm^2·s)	1.1×10^6	$N_t/N_{He} \sim 1$
Romodanov et al.[27]	Mo/D_2	t ($\sim 10^7$/s)	1.8×10^7	(If sample is MoD)
Claytor et al.[56]	Pd/D_2	t (0.15 nCi/h)	1.4×10^7	(If D/Pd ~ 1)
Will et al.[57]	Pd/D_2SO_4	t ($\sim 1.8 \times 10^5$/cm^2·s)	3.5×10^7	(If $l_0 \sim 10$ μm)
Srinivasan et al.[53]	Ti/D_2	t ($t/d \sim 10^{-5}$)	1.9×10^8	
DeNinno et al.[58]	Ti/D_2	t (5.4 Bq/g D_2)	1.2×10^6	(D/Ti = 1, τ = 1 week)
Bush and Eagleton[65]	Ni/H/Rb	NT ($^{85}Rb \to {}^{86}Sr$)	1.6×10^7	$N_Q/N_{NT} \sim 3$
Passell[66]	Pd/D/Li	NT ($^{10}B \to {}^7Li + {}^4He$)	1.1×10^9	$N_{NT}/N_Q = 2$
Reifenschweiler[68]	$TiT_{0.0035}$	Reduction of β decay	3.7×10^{10}	(T = 0 to 450°C)

neutron in the temperature range where the radioactivity decreased. The parameter n_n was determined to be 3.7×10^{10} cm^{-3} if the whole trapped neutron was stabilized in the temperature range.

The results of the analyses of all the experimental data sets are tabulated in Table I with brief comments in the last column.

IV. CONCLUSION

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

Therefore, it is usually impossible to explain whole data sets obtained in an experiment, including intricately interrelated physical variables. It should be necessary to select data from a certain point of view while neglecting others for a while, leaving them for a future program to explain in relation with known factors.

To apply the TNCF model, we took up only 28 data sets, including some with quantitative relations between several quantities, from the excellent experimental results obtained to this point. The results of this analysis show that the phenomenological model is effective to obtain an overview of the characteristic behavior of crystals containing hydrogen isotopes with or without a surface layer of alkali metal. The basic premise of the model—the existence of quasi-stable trapped neutrons in the crystal and reactions between the trapped neutron and another nucleus—is supported by the success of the analysis given in Sec. III. The reality of the premises has not been verified by microscopic theory though, and the premises could be replaced by a more reasonable one if some new phases of the cold fusion phenomenon tested the old and discarded it. The progress of the scientific idea should go like that. Efforts to develop theoretical investigation along this line have been continued also by the authors.

REFERENCES

1. M. FLEISCHMANN, S. PONS, and M. HAWKINS, "Electrochemically Induced Nuclear Fusion of Deuterium," *J. Electroanal. Chem.*, **261**, 301 (1989).

2. H. KOZIMA, "Trapped Neutron Catalyzed Fusion of Deuterons and Protons in Inhomogeneous Solids," *Trans. Fusion Technol.*, **26**, 508 (1994).

3. H. KOZIMA, K. KAKI, T. YONEYAMA, S. WATANABE, and M. KOIKE, "Theoretical Verification of the Trapped Neutron Catalyzed Model of Deuteron Fusion in Pd/D and Ti/D Systems," *Rep. Fac. Science, Shizuoka Univ.*, **31**, 1 (1997).

4. J. L. RUSSEL, "Virtual Electron Capture in Deuterium," *Ann. Nucl. Energy*, **18**, 75 (1991).

5. P. I. HAGELSTEIN, "Update of Neutron Transfer Reactions," *Proc. ICCF5*, Monte Carlo, Monaco, April 9–13, 1995, p. 327 (1995).

6. J. P. VIGIER, "New Hydrogen (Deuterium) Bohr Orbits," *Proc. ICCF4*, **4**, 7-1 (1994).

7. J. DUFOUR, J. FOOS, J. P. MILLOT, and X. DUFOUR, "From Cold Fusion to Hydrex and Deuterex States of Hydrogen," *Progress in New Hydrogen Energy* (*Proc. ICCF6*), Hokkaido, Japan, October 13–17, 1996, p. 482 (1996).

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

9. H. KOZIMA, "Neutron Band, Neutron Cooper Pair and Neutron Life Time in Solid," *Cold Fusion*, **16**, 4 (1996); see also *Proc. 3rd Russian Conf. Cold Fusion and Nuclear Transmutation* (*RCCFNT3*), Sochi, Russia, October 2–6, 1995, p. 224 (1996).

10. H. KOZIMA, "Cold Fusion Phenomenon on the TNCF Model," *Cold Fusion*, **20**, 31 (1996); see also *Proc. 4th Russian Conf. Cold Fusion and Nuclear Transmutation*, Sochi, Russia, May 23–27, 1996 (to be published).

11. H. KOZIMA, "On the Existence of the Trapped Thermal Neutron in Cold Fusion Materials," *Progress in New Hydrogen Energy* (*Proc. ICCF6*), Hokkaido, Japan, October 13–17, 1996, p. 332 (1996).

12. H. KOZIMA, S. WATANABE, K. HIROE, M. NOMURA, M. OHTA, and K. KAKI, "Analysis of Cold Fusion Experiments Generating Excess Heat, Tritium and Helium," *J. Electroanal. Chem.*, **425**, 173 (1997).

13. H. KOZIMA, "The TNCF Model—Its Fundamentals," *Cold Fusion*, **21**, 19 (1997).

14. 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).

15. 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.

16. 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).

17. A. A. YUHIMCHUK et al., "Registration of Neutron Emission in Thermocycle of Vanadium Deuterides," *Kholodnyi Yadernyi Sintez*, p. 57, R. N. KUZ'MIN, Ed., Sbornik Nauchnykh Trudov (Kariningrad) (1992) (in Russian).

18. F. CELANI et al., "Search for Enhancement of Neutron Emission from Neutron-Irradiated, Deuterated High-Temperature Superconductors in a Very Low Background Environment," *Fusion Technol.*, **22**, 181 (1992).

19. B. STELLA, M. CORRADI, F. FERRAROTTO, V. MILONE, F. CELANI, and A. SPALLONE, "Evidence for Stimulated Emission of Neutrons in Deuterated Palladium," *Frontiers of Cold Fusion* (*Proc. ICCF3*), p. 437, H. IKEGAMI, Ed., Universal Academy Press, Tokyo (1993).

20. 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. ICCF5*, Monte Carlo, Monaco, April 9–13, 1995, p. 571 (1995).

21. J. R. MORREY et al., "Measurements of Helium in Electrolyzed Palladium," *Fusion Technol.*, **18**, 659 (1990).

22. 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).

23. Y. OYA, H. OGAWA, T. ONO, M. AIDA, and M. OKAMOTO, "Hydrogen Isotope Effect Induced by Neutron Irradiation in Pd-LiOD (H) Electrolysis," *Progress in New Hydrogen Energy* (*Proc. ICCF6*), Hokkaido, Japan, October 13–17, 1996, p. 370 (1996).

24. H. YAMADA, H. NONAKA, A. DOHI, H. HIRAHARA, T. FUJIHARA, X. LI, and A. CHIBA, "Carbon Production on Palladium Point Electrode with Neutron Burst under DC Glow Discharge in Pressurized Deuterium Gas," *Progress in New Hydrogen Energy* (*Proc. ICCF6*), Hokkaido, Japan, October 13–17, 1996, p. 610 (1996).

25. R. NOTOYA, T. OHNISHI, and Y. NOYA, "Nuclear Reaction Caused by Electrolysis in Light and Heavy Water Solution," *Progress in New Hydrogen Energy* (*Proc. ICCF6*), Hokkaido, Japan, October 13–17, 1996, p. 675 (1996).

26. 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*, Sochi, Russia, September 1994, p. 99 (1995).

27. V. A. ROMODANOV, V. I. SAVIN, and Ya. B. SKURATNIK, "Tritium Generation at Transfusion of Hydrogen Isotopes Through Target in Plasma of Powerful Glow Discharge," *Progress in New Hydrogen Energy* (*Proc. ICCF6*), Hokkaido, Japan, October 13–17, 1996, p. 585 (1996).

28. S. E. JONES, E. P. PALMER, J. B. CZIRR, D. L. DECKER, G. L. JENSEN, J. M. THORNE, and S. E. TAYLER, "Observation of Cold Nuclear Fusion in Condensed Matter," *Nature*, **338**, 737 (1989).

29. T. ISHIDA, "Study of the Anomalous Nuclear Effects in Solid-Deuterium Systems," MS Thesis, Tokyo University, Japan (Feb. 1992).

30. H. KOZIMA, M. OHTA, M. NOMURA, and K. HIROE, "Analysis of Neutron Irradiation Effects in Pd-LiOD(H) System," *Cold Fusion*, **21**, 35 (1997).

31. H. LONG et al., "The Anomalous Nuclear Effects Inducing by the Dynamic Low Pressure Gas Discharge in a Deuterium/Palladium System," *Frontiers of Cold Fusion* (*Proc. ICCF3*), pp. 455, 447, H. IKEGAMI, Ed., Universal Academy Press, Tokyo (1993).

32. J. JORNE, "Neutron and Gamma-Ray Emission from Palladium Deuteride Under Supercritical Conditions," *Fusion Technol.*, **19**, 371 (1991).

33. A. G. LIPSON, B. F. LYAKOV, D. M. SAKOV, V. A. KUZNETSOV, and T. S. IVANOVA, "Heat Production, Nuclear Ashes and Electrophysical Processes in Heterostructure PdO/Pd/PdO Saturated with Deuterium by Electrochemical Method," *Proc. RCCFNT4*, Sochi, Russia, May 20–25, 1996 (to be published); see also *Progress in New Hydrogen Energy* (*Proc. ICCF6*), Hokkaido, Japan, October 13–17, 1996, p. 433 (1996).

34. 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* [*Conf. Proc. SIF* (*Italy*)], Vol. 33, p. 93 (1991).

35. M. NAKADA, T. KUSUNOKI, and M. OKAMOTO, "Energy of the Neutrons Emitted in Heavy Water Electrolysis," *Frontiers of Cold Fusion* (*Proc. ICCF3*), p. 173, H. IKEGAMI, Ed., Universal Academy Press, Tokyo (1993).

36. I. B. SAVVATIMOVA, Y. R. KUCHEROV, and A. B. KARABUT, "Cathode Material Change after Deuterium Glow Discharge Experiment," *Trans. Fusion Technol.*, **26**, 389 (1994).

37. I. B. SAVVATIMOVA and A. B. KARABUT, "Change of Elemental and Isotope Contents in Cathode after Ion Bombardment in Glow Discharge," *Proc. RCCFNT3*, Sochi, Russia, October 2–7, 1995, p. 20 (1996), and Private Communication.

38. J. KASAGI, K. ISHII, M. HIRAGA, and K. YOSHIHARA, "Observation of High Energy Protons Emitted in the TiD_x + D Reaction at E_d = 150 keV and Anomalous Concentration of ^3He," *Frontiers of Cold Fusion* (*Proc. ICCF3*), p. 209, H. IKEGAMI, Ed., Universal Academy Press, Tokyo (1993).

39. T. ROULETTE, J. ROULETTE, and S. PONS, "Results of ICARUS9 Experiments Run at the IMRA Europe," *Progress in New Hydrogen Energy* (*Proc. ICCF6*), Hokkaido, Japan, October 13–17, 1996, p. 85 (1996).

40. M. H. MILES, R. A. HOLLINS, B. F. BUSH, and J. J. LAGOWSKI, "Correlation of Excess Power and Helium Production During D_2O and H_2O Electrolysis Using Palladium Cathodes," *J. Electroanal. Chem.*, **346**, 99 (1993).

41. Y. ARATA and Y. C. ZHANG, "Achievement of Solid-State Plasma Fusion ('Cold Fusion')," *Proc. Jpn. Acad.*, **71B**, 304 (1995); see also "A New Energy Caused by 'Spillover-Deuterium,' " *Proc. Jpn. Acad.*, **70B**, 106 (1994).

42. 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*, Monte Carlo, Monaco, April 9–13, 1995, p. 17 (1995); see also *Proc. 3rd Russian Conf. Cold Fusion and Nuclear Transmutation (RCCFNT3)*, Sochi, Russia, October 2–6, 1995, p. 123 (1996).

43. D. CRAVENS, "Flowing Electrolyte Calorimetry," *Cold Fusion*, **11**, 15 (1995); see also *Proc. ICCF-5*, p. 79 (1995).

44. J. DUFOUR, "Cold Fusion by Sparking in Hydrogen Isotopes," *Fusion Technol.*, **24**, 205 (1993).

45. S. FOCARDI, R. HABEL, and F. PIANTELLI, "Anomalous Heat Production in Ni-H System," *Nuovo Cimento*, **107A**, 163 (1994).

46. D. GOZZI et al., "Calorimetric and Nuclear Byproduct Measurements in Electrochemical Confinement of Deuterium in Palladium," *J. Electroanal. Chem.*, **380**, 91 (1995).

47. F. CELLUCCI et al., "X-Ray, Heat Excess and ^{4}He in the Electrochemical Confinement of Deuterium in Palladium," *Progress in New Hydrogen Energy (Proc. ICCF6)*, Hokkaido, Japan, October 13–17, 1996, p. 3 (1996).

48. F. CELANI et al., "Reproducible D/Pd Ratio > 1 and Excess Heat Correlation by 1-μs-Pulse, High-Current Electrolysis," *Fusion Technol.*, **29**, 398 (1996).

49. F. CELANI, A. SPALLONE, P. TRIPODI, D. DI GIACCHINO, P. MARINI, V. DI STEFANO, A. MANCINI, and S. PACE, "Electrolytic Regimes and Geometrical Configurations to Obtain Anomalous Results in Pd(M)-D Systems," *Progress in New Hydrogen Energy (Proc. ICCF6)*, Hokkaido, Japan, October 13–17, 1996, p. 93 (1996).

50. R. A. ORIANI, "A Confirmation of Anomalous Thermal Power Generation from a Proton-Conducting Oxide," *Fusion Technol.*, **30**, 281 (1996); see also R. A. ORIANI, "A Confirmation of Anomalous Thermal Power Generation from a Proton-Conducting Oxide," *Progress in New Hydrogen Energy (Proc. ICCF6)*, Hokkaido, Japan, October 13–17, 1996, p. 557 (1996).

51. Y. IWAMURA, T. ITOH, N. GOTOH, and I. TOYODA, "Correlation Between Behavior of Deuterium in Palladium and Occurrence of Nuclear Reactions Observed by Simultaneous Measurement of Excess Heat and Nuclear Products," *Progress in New Hydrogen Energy (Proc. ICCF6)*, Hokkaido, Japan, October 13–17, 1996 (1996).

52. E. STORMS and C. TALCOTT, "Electrolytic Tritium Production," *Fusion Technol.*, **18**, 680 (1990).

53. M. SRINIVASAN et al., "Observation of Tritium in Gas/Plasma Loaded Titanium Samples," *Proc. Int. Conf. Anomalous Nuclear Effects in Deuterium/Solid Systems AIP Conf. Proc.*, Utah, October 22–23, 1990, Vol. 228, p. 514 (1991).

54. R. K. ROUT, A. SHYAM, M. SRINIVASAN, and A. B. GARG, "Reproducible, Anomalous Emissions from Palladium Deuteride/Hydride," *Fusion Technol.*, **30**, 273 (1996).

55. 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," *Frontiers of Cold Fusion (Proc. ICCF3)*, p. 231, H. IKEGAMI, Ed., Universal Academy Press, Tokyo (1993).

56. T. N. CLAYTOR, D. D. JACKSON, and D. G. TUGGLE, "Tritium Production from a Low Voltage Deuterium Discharge on Palladium and Other Materials," presented at ICCF5, No. 306; see also *Trans. Fusion Technol. (Proc. ICCF4)*, **26**, 221 (1994).

57. T. G. WILL, K. CEDZYNSKA, and D. C. LINTON, "Tritium Generation in Palladium Cathodes with High Deuterium Loading," *Trans. Fusion Technol. (Proc. ICCF4)*, **26**, 207 (1994).

58. A. DE NINNO et al., "The Production of Neutrons and Tritium in Deuterium Gas-Titanium Interaction," *The Science of Cold Fusion (Proc. ICCF2), Conf. Proc.*, **33**, 129 (1991).

59. E. YAMAGUCHI and T. NISHIOKA, "Direct Evidence for Nuclear Fusion Reactions in Deuterated Palladium," *Frontiers of Cold Fusion (Proc. ICCF3)*, p. 179, H. IKEGAMI, Ed., Universal Academy Press, Tokyo (1993).

60. A. DE NINNO et al., "Evidence of Emission of Neutrons from a Titanium-Deuterium System," *Europhys. Lett.*, **9**, 221 (1989).

61. H. O. MENLOVE, M. M. FOWLER, E. GARCIA, M. C. MILLER, M. A. PACONI, R. R. RYAN, and S. E. JONES, "Measurements of Neutron Emission from Ti and Pd in Pressurized D_2 Gas and D_2O Electrolysis Cells," *J. Fusion Energy*, **9**, 495 (1990).

62. P. K. IYENGAR and M. SRINIVASAN, "Overview of BARC Studies on Cold Fusion," *Proc. 1st Annual Conf. Cold Fusion (ICCF1)*, Salt Lake City, Utah, 1990, p. 62.

63. T. OHMORI and M. ENYO, "Excess Heat Produced During Electrolysis of H_2O on Ni, Au, Ag and Sn Electrodes in Alkaline Media," *Frontiers of Cold Fusion (Proc. ICCF3)*, p. 427, H. IKEGAMI, Ed., Universal Academy Press, Tokyo (1993).

64. T. MIZUNO, T. OHMORI, and M. ENYO, "Changes of Isotope Distribution Deposited on Palladium Induced by Electrochemical Reaction," *J. Electroanal. Chem.* (to be published).

65. R. T. BUSH and D. R. EAGLETON, "Evidence for Electrolytically Induced Transmutation and Radioactivity Correlated with Excess Heat in Electrolytic Cells with Light Water Rubidium Salt Electrolytes," *Trans. Fusion Technol.*, **26**, 344 (1994).

66. T. O. PASSELL, "Search for Nuclear Reaction Products in Heat-Producing Palladium," *Progress in New Hydrogen Energy (Proc. ICCF6)*, Hokkaido, Japan, October 13–17, 1996, p. 282 (1996).

67. G. H. MILEY, G. NAME, M. J. WILLIAMS, J. A. PATTERSON, J. NIX, D. CRAVENS, and H. HORA, "Experimental Observation of Massive Transmutations Occurring in

Multilayer Thin-Film Microspheres after Electrolysis," *Progress in New Hydrogen Energy* (*Proc. ICCF6*), Hokkaido, Japan, October 13–17, 1996, p. 629 (1996).

68. O. REIFENSCHWEILER, "Reduced Radioactivity of Tritium in Small Titanium Particle," *Phys. Lett.*, **A184**, 149 (1994); see also *Fusion Technol.*, **30**, 261 (1996).

Hideo Kozima (BSc, physics, Tokyo College of Science, Japan, 1958; MSc, physics, Tokyo University, Japan, 1960; PhD, physics, Tokyo University of Education, Japan, 1976) is a professor in the Department of Physics, Faculty of Science, Shizuoka University, Japan. He has worked on solid-state and plasma physics. He has been working on solid-state nuclear physics for the past 8 years. He proposed the TNCF model to explain the anomalous phenomenon in solids consistent with other phenomena in physics.

Kaori Kaki (DSc, physics, Tokyo Institute of Technology, Japan, 1991) is a research associate in the Department of Physics at Shizuoka University. She has been interested in relativistic nuclear reaction theory and, in particular, the analysis of nucleon-nucleus scattering based on the Dirac equation, and meson (pion/eta) production reactions in a relativistic framework.

Masayuki Ohta (BSc, physics, Shizuoka University, Japan, 1996) is a graduate student in the Department of Physics at Shizuoka University. He has studied nuclear reaction in solids, and analyzed the results for experiments of the anomalous phenomenon in solids.