Precise Neutron Measurements Reveal Nuclear Reactions in Solids- An Analysis Using the TNCF Model

H. Kozima, M. Fujii
K. Kaki, and M. Ohta
Department of Physics
Shizuoka University
Shizuoka 422, Japan

Abstract

The data showing the detection of neutrons during the cold fusion phenomenon in various background environments were analyzed successfully using our TNCF model. The result shows that another phase of the cold fusion phenomenon has been revealed by the precise measurements of the nuclear products which have sometimes been accepted as a negative proof of the existence of the phenomenon itself.

Two of experimental results by Jones et al. are taken up and interpreted consistently with the value of the adjustable parameter n_n in the model, the density of the trapped neutrons supplied from the ambient neutrons, of ~ 10^{11} cm^{-3} for the positive and less than ~ 10^7 cm^{-3} for the negative case. The value of n_n for the former is in the range of values determined hitherto in various materials used in the cold fusion research which have produced positive results.

1. Introduction

It is almost not necessary to speak about the reality of the cold fusion phenomenon which was discovered[1] in 1989 because there has been so much evidence of the generation of the excess heat Q, tritium t, helium ^{4}He, nuclear transmutation (NT), neutrons n and others with a high qualitative reproducibility in various materials and situations. However, there is still some skepticism in the world, mainly rooted in a misunderstanding of the experimental results which have been done with precision measurements.

One of the most careful measurements of nuclear products in cold fusion research has been done by Jones et al.[2] in the presence of ordinary background neutrons. Ths data showed the generation of neutrons with an energy of 2.45 MeV as expected from the probable reactions between deuterons. Similar positive experiments under ordinary conditions have been reported by many, including De Ninno et al.[3,5], Menlove et al.[4], Bressani et al.[6,7] (Ti/D systems), Takahashi et al.[8], Nakada et al.[9] and Sato et al.[10] (Pd/D systems), which have shown the existence of not only 2.45 MeV but also 3 ~ 8 MeV neutrons in the nuclear products of the cold fusion phenomenon.

In a process to refine the measurements, however, Jones et al. was unable to reproduce the cold fusion phenomenon in experiments done in laboratories with almost zero background neutrons[11,12]. These results[2~12] tell us clearly that the cold fusion phenomenon is intimately related to the existence of background neutrons.

The TNCF model[13~19], which I first proposed in 1993 at ICCF4, has been used to examine more than 40 typical experimental data, successfully providing a consistent explanation for them using only one adjustable parameter. The model is a phenomenological one with a single parameter n_n, the density of the assumed trapped neutrons, with several supplementary premises which are not adjustable. The experimental data confirms the premises of the model, including the existence of the cold fusion phenomenon in an environment with background neutrons and the absence of it without background neutrons.

In addition to the experimental data by Jones et al., which shows the relation of the cold fusion phenomenon and amount of the background neutrons, there are several evidences of effects of the thermal neutrons on the cold fusion phenomenon. The first published data by Shani et al.[20] and following by several[21~25], have shown clearly the enhancement of the cold fusion products when the cold fusion materials are irradiated with thermal neutrons.

It is also now well established that the most well known products of the cold fusion phenomenon are excess heat, tritium, helium ^{4}He and transmuted nuclei, but *not* neutrons. The detection of neutrons had been tried successfully, but the occurrence was rare compared with the other products. In addition to the scarcity of neutron generation, the energy of the detected neutrons was widely distributed, up to more than 10 MeV and not restricted to the 2.45 MeV detected by Jones et al.[2]

This riddle about neutrons in the cold fusion phenomenon has lead many to doubt the phenomenon itself. Thus, the cold fusion phenomenon has been ignored by many, leaving it to just the few scientists who have the true pioneering spirit.

We have interpreted the experimental results from data obtained during cold fusion research and have explained some phases of the confusing data produced using the TNCF model[13~19]. The consistency of the experimental data obtained by Jones et al.[2,11] with that produced by many other researchers should again reinforce the reality of the cold fusion phenomenon.

2. Experimental Data of Jones et al. and Others

There are two reports of precision neutron measurements with positive[2] and null[11] results in different environments.

2-1. Positive results of Jones et al.

Jones et al.[2] made a precise measurement of 2.45 MeV neutrons from electrolytic cells with Pd or Ti cathodes and an electrolytic solution of several electrolytes. The electrolyte was typically a mixture of ~ 160g D_2O plus various metal salts in ~ 0.1g each: $FeSO_4 \cdot 7H_2O$, $NiCl_2 \cdot 6H_2O$, $PdCl_2$, $CaCO_3$, $Li_2SO_4 \cdot H_2O$, $Na_2SO_4 \cdot 10H_2O$, $CaH_4(PO_4)_2 \cdot H_2O$, $TiOSO_4 \cdot H_2SO_4 \cdot 8H_2O$.

There were 5 runs out of 14 with significant amounts of neutrons that were more than experimental errors (positive results.) We take up one of 5 cases, run No. 6, which is a particularly noteworthy one with a statistical significance of approximately five standard deviations above background, as the authors of the original paper[2] described.

In this experiment fused titanium pellets were used as the negative electrode, with a total mass of ~ 3g. The neutron production rate increased after about one hour of electrolysis. After about eight hours, the rate dropped dramatically, as shown in the follow-on run 7 in their Fig. 4. The experimental rate of neutron detection was $(4.1 \pm 0.8) \times 10^{-3}\ s^{-1}$ with the neutron detection efficiency including geometrical acceptance 1.0 ± 0.3%. The D/Ti ratio was estimated to 2. The number of background neutrons was 3.6×10^2 n/h.

This result of the neutron detection means that the observed neutron generation is 0.41/s from a fused Ti cathode composed of three spheres of 1g each, the volume of which was ~ 0.22 cm^3 and a linear dimension ~ 7.4 mm. It should be noticed, however, that the detected neutrons were those with energy of 2.45 MeV. From their neutron energy spectrum shown in Fig. 2, we can guess there were other neutrons with higher energies than 2.45 MeV detected by the authors. Their disregard of neutrons with higher energies will be discussed in the Conclusion.

It is also emphasized here that the phenomenon does not always occur, even in a situation with background neutrons, i.e. the necessary condition for the phenomenon is not limited to the existence of the existence of background neutrons.

2-2. A Null Result Of Jones Et Al.

On the other hand, Jones et al.[11] performed precise measurements of nuclear products, neutron, gamma and X-rays, in an environment with low background neutrons of 0.07 n/h and null background gamma. In this experiment, they used a rod shaped Pd cathode with a diameter 6 mmø. The length of the rod was not described in their paper so we will take it as 1 cm arbitrary (allowing one order of magnitude uncertainty for this ambiguity in the final result). The anode was Pt gauze and electrolyte was 0.1 M LiOD.

For background runs they measured 0.07 ± 0.01 n/h burst-like and 0.65 ± 0.1 n/h single signals. The efficiency of the measurements was more than 20% for burst-like and 14% for single signals. For foreground run they obtained almost the same signals of 0.07 n/h burst-like and 0.65 n/h single. Furthermore, they could not detect either gamma or X-rays in the experiment with null background gamma.

From these results[11] they concluded that there were no meaningful signals produced by the cold fusion phenomenon and that there were no fusion reactions between two deuterons in the system (a null result). It should be noted, however, that their conclusion was based on an assumption that sole direct *d - d* reaction is relevant with the cold fusion phenomenon.

2-3. Energy Spectrum of Neutrons Measured in Cold Fusion Experiments

There have been several reports of the neutron energy spectrum detected in cold fusion experiments[6-10].

In the electrolytic system of Pd/D/Li, Takahashi et al.[8] and Nakada et al.[9,10] measured neutrons in the energy range up to about 10 MeV.

Nakada et al.[9,10] have been working with the eletrolytic system with Pd cathode and LiOD + D_2O using L-H mode electric voltage for a period of six hours. They detected neutrons and excess heat during the electrolysis. In the six experiments where they observed the excess heat, neutrons were measured in three cases. The energy distribution of the measured neutrons showed (1) a group with a peak at 2.45 MeV and (2) another with wide spread energies higher than 2.5 MeV up to ~ 8 MeV. The number of neutrons in the first group is less than the second. They also measured in a run two bursts of neutrons 5 and 20 hours after the beginning of the electrolysis.

The data of simultaneous observation of tritium and neutrons obtained by Takahashi et al.[8] also showed an energy distribution of neutrons with more than 3 MeV predominating over 2.45 MeV in the Pd/D/Li system.

On the other hand, in the gas loaded Ti/D and Pd/D systems, Bressani et al.[6,7] made elaborate measurements of the energy spectra of neutrons. They observed significant signals above 1 MeV up to 7 MeV from Ti/D but Pd/D system relative to corresponding protium system.

3. Analysis of the Experimental Data Using the TNCF Model

We analyzed the experimental data[2] of run 6 (a positive result) and those[11] with the null result in this section using the TNCF model. It is advisable to notice here that the applicability of the model to systems of not only Pd, but Ti and others has been shown by analyses given in previous papers[13-19], without taking into account characteristics of matrix solids, but the density of occluded hydrogen isotope and the surface layer of alkali metal (or alloy). We can, therefore, treat the systems where neutrons have been observed using the TNCF model.

From our point of view the trapped neutrons in the TNCF model can exist in a sample with appropriate properties and are supplied initially from the ambient background neutrons. In a situation where there are no background neutrons, therefore, the parameter n_n, the density of the trapped neutrons, should be zero, and no cold fusion phenomena are expected to occur. This is consistent with the null result obtained in a low background experiment[11,12] which was done to precisely check the neutron generation from the electrolytic cell which had shown positive results with background neutrons.

3-1. Fundamental Premises Used in the Analysis.

In the presence of background neutrons, the trapped neutrons with a density n_n, are expected to exist in solids where the conditions are appropriate. Then, the reactions in the TNCF model which are used to analyze the experimental data by Jones et al.[2,11] are written down as follows. The trigger reaction:

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

occurs between a trapped thermal neutron n_n, and one of nuclei ${}^{A}_{Z}$M in the lattice with a mass number A and an atomic number Z generating an excess energy Q and nuclear products ${}^{A'}_{Z}$M's where ${}^{0}_{0}\mathrm{M} \equiv \gamma$, ${}^{0}_{1}\mathrm{M} \equiv n$, ${}^{1}_{1}\mathrm{M} \equiv p$, ${}^{2}_{1}\mathrm{M} \equiv d$, ${}^{3}_{1}\mathrm{M} \equiv t$, ${}^{4}_{1}\mathrm{M} \equiv {}^{4}\mathrm{He}$, etc.

The rate P_f of the above reaction per unit time is expressed by the following relation:

$$P_f = 0.35 n_n, v_n, n_N V \sigma_{nN} \xi, \qquad (2)$$

where $0.35 n_n v_n$ is the flow density of the thermal neutrons per unit area and time, n_N is the density of the nucleus ${}^{A}_{Z}$M in the reaction region with volume V and σn_N is the cross section of the reaction. The factor ξ expresses an order of the stability of the trapped neutrons in the trapping region; we take $\xi = 0.01$ for reactions which occur in volume and $\xi = 1$ for reactions in the surface layer, as explained in the previous papers[16,17].

The energetic particles generated by the trigger reactions react with particles in the lattice and cause the breeding reactions shown below. The rate per unit time of a reaction between an energetic particle with an energy ε and one of stable nuclei in the solid is given by a similar formula as that in vacuum:

$$P_\gamma = N_\varepsilon n_N \sigma_N l, \qquad (3)$$

where N_ε is the number of particles with an energy ε generated in the sample per unit time, l is the path length of the energetic particle, n_N is the density of the nucleus, σ_N is the cross section of the reaction.

In the case of the electrolytic system used in the experiment[2,8-12], the relevant trigger and breeding reactions are written down as follows:

$$n + {}^{6}_{3}\mathrm{Li} = {}^{4}_{2}\mathrm{He}\,(2.1\ \mathrm{MeV}) + t\,(2.7\ \mathrm{MeV}), \qquad (4)$$

$$n + d = t\,(6.98\ \mathrm{keV}) + \gamma(6.25\ \mathrm{MeV}), \qquad (5)$$

$$t(\varepsilon) + d = {}^{4}_{2}\mathrm{He}\,(3.5\ \mathrm{MeV}) + n(14.1\ \mathrm{MeV}) + \varepsilon, \qquad (6)$$

$$n\,(\varepsilon) + d = n\,(\varepsilon') + d\,(\varepsilon''), \qquad (7)$$

$$d\,(\varepsilon) + d = {}^{3}_{2}\mathrm{He}(0.82\ \mathrm{MeV}) + n\,(2.45\ \mathrm{MeV}) + \varepsilon. \qquad (8)$$

Cross sections σ of these reactions are given as follows from data books[26,27]: $\sigma_{n\text{-}Li} = 9.4 \times 10^{2}$ b, $\sigma_{n\text{-}d} = 5.5 \times 10^{-4}$ b, $\sigma_{t\text{-}d} = 1.42 \times 10^{-1}$ b ($\varepsilon_t = 2.7$ MeV), $\sigma_{t\text{-}d} = 3.0 \times 10^{-6}$ b ($\varepsilon_t = 6.98$ keV), $\sigma_{d\text{-}d} = 8.86 \times 10^{-3}$ b ($\varepsilon_d = 12.5$ MeV) and $\sigma_{n\text{-}d} = 5.5 \times 10^{-1}$ b ($\varepsilon_n = 14.1$ MeV). The energy of the deuteron 12.5 MeV, used in the calculation of the reaction (8) for simplicity is the maximum one obtained in the reaction (7).

3-2. Analysis of the Positive Result of Jones et al.

We assume following values as reasonable for parameters in the experimental system, though they have not always been written down explicitly in the paper[2]; the cathode used in the experiment was made of three spheres weighing 3g each, on the surface S of which was a layer of Li with a thickness $l_0 = 1$ µm deposited by electrolysis; $n_{Li} = 3.44 \times 10^{21}$ cm^{-3}, assuming natural abundance 7.4% for ^{6}Li. Following the recipe described before[11], we take the factor $\xi = 0.01$ in the volume and the pass length $l = 1$ µm for all charged particles and $l = L$ (= linear dimension of the sample) for neutrons, for simplicity. We use following values for the sample size; $L = 1$ cm arbitrarily, $S = 3.66$ cm^2 and $V = 0.66$ cm^3. The D/Ti ratio was assumed as 2 and therefore $n_d = 1.14 \times 10^{22}$ cm^{-3}.

By the two four-step-reactions, Series (a) from (4) to (8) through (6) and (7), and Series (b) from (5) to (8) through (6) and (7), generating finally neutrons with 2.45 MeV, we can determine n_n, using the relations (2) and (3) and the experimental data on neutrons explained in Section 2, i.e. $N_n = 0.41$ *n*/s.

If only one of the two series is effective, we can calculate n_n, at the high time of neutron generation for the above series (a) and (b) as follows.

(a) Series from $n - {}^6\mathrm{Li}$ reaction (4).

Numbers of 2.7 MeV tritons N_t generated by the reaction (4), 14.1 MeV neutrons N_n by (6), deuteron N_d by (7) and 2.45 MeV neutron N_n by (8) are written down as follows:

$$N_t = 0.35 n_n v_n n_{Li} S l_0 \sigma_{n\text{-}Li} \xi, \tag{9}$$
$$N_{n'} = N_t l_t n_d \sigma_{t\text{-}d}, \tag{10}$$
$$N_d = N_n L n_d \sigma_{n'\text{-}d}, \tag{11}$$
$$N_n = N_d l'_d n_d \sigma_{d\text{-}d}. \tag{12}$$

The cross sections of these reactions for corresponding particle energy are 9.4 x 10^2, 1.42 x 10^{-2}, 5.5 x 10^{-1} and 6.24 x 10^{-3} b, respectively.

From these relations we can obtain a relation between the parameter n_n, and the number N_n of neutrons determined by the experiment: (13)

$$n_n = \frac{N_n}{0.35 v_n n_d^3 n_{Li} l l' L S l_0 \sigma_{n-Li} \sigma_{t-d} \sigma_{n'-d} \sigma_{d-d}},$$

Using this relation with parameters given above, we obtain the value of the trapped neutrons as follows:

$$n_n = 4.4 \text{ x } 10^{11} \text{ cm}^{-3},$$

(b) Series from $n - d$ reaction (5).

Numbers of 7.0 keV triton N_t generated by the reaction (5), 14.1 MeV neutron $N_{n'}$ by (6), deuteron N_d by (7) and 2.45 MeV neutron N_n by (8) are written down as follows:

$$N_t = 0.35 n_n v_n n_d V \sigma_{n\text{-}d} \xi, \tag{14}$$
$$N_{n'} = N_t l_t n_d \sigma_{t\text{-}d}, \tag{15}$$
$$N_d = N_n L n_d \sigma_{n\text{-}d}, \tag{16}$$
$$N_n = N_d l'_d n_d \sigma_{d\text{-}d} \tag{17}$$

The cross sections of these reactions for corresponding particle energy are 5.5 x 10^{-4}, 3.04 x 10^{-6}, 5.5 x 10^{-1} and 8.86 x 10^{-3} b, respectively.

From these we can obtain a relation between the parameter n_n, and the number N_n of neutrons determined by the experiment: (18)

$$n_n = \frac{N_n}{0.35 v_n n_d^4 n_{Li} l l' L V l_0 \sigma_{n-d} \sigma_{t-d} \sigma_{n'-d} \sigma_{d-d} \xi},$$

Using this relation with parameters given above and the experimental result $N_n = 0.41$ s^{-1}, we obtain the value of the trapped neutron as follows:

$$n_{n'} = 5.9 \text{ x } 10^{19} \text{ cm}^{-3}.$$

Thus, the first series (a) starting from the reaction (4) played a predominant role by a factor of 10^8 in this system and the density of the trapped neutron was ~ 4.4 x 10^{11} cm^{-3}. This value of n_n will change by one order of magnitude, depending on the change of the nature of the surface layer on the cathode, which we assumed as Li metal with a thickness of 1 μm.

It is clear that the former experiment[2] was done in an environment where there were a lot of background neutrons, as shown in Fig.2 of the paper, which guarantees the existence of trapped neutrons in the sample without asking about its density. The surface to volume ratio S/V of the Ti cathode in the above run 6 was 8.1 cm^{-1}. The S/V ratio is an index of the qualitative reproducibility of the cold fusion phenomenon[2] and this value of 8.1 cm^{-1} belongs to the minimum range of values where the cold fusion phenomenon was observed before. This is, perhaps, an origin of the poor reproducibility of the Jones' result of neutron generation[2].

3-3. Analysis of the Null Result of Jones et al.

On the other hand, in the experiment[11] conducted in an environment where there was a very low neutron background of 0.07 n/h for burst-like signal which we consider a result of cold fusion events in the cathode, it was not observed any neutrons above experimental error. If we take the accuracy of the detection as 10% of the background level, i.e. 7.0×10^{-3} /h, we can set the upper bound for the generated neutrons as 9.5×10^{-6}/s, taking the efficiency into our consideration. This value is compared with the value 4.1×10^{-1} is obtained in the positive result (run 6).

This value of 1.3×10^{-5}/s is used to determine the maximum value of the trapped neutrons in the model (with use of the reaction series (a) explained in Section 2) giving a value

$$n_n = 2.3 \times 10^7 \text{ cm}^{-3}.$$

The absence of any gamma in the null result[11] is consistent with reactions (7),(9), (10) and (11), supposedly existing in the system.

3-4. Analysis of Other Results on the Energy Spectra of Neutrons

The other results on the electrolytic system[8-10] are analyzed similarly, giving analogous results to that given above, so it is not necessary to repeat the process again.

On the other hand, some explanation should be given about the results of the gas contact systems. In the case where there is no surface layer of alkali metal on the sample surface, the initial trigger reaction is an $n - d$ reaction (5) in volume, with reaction (6) in the surface layer. In this case, the number of generated neutrons with the energy 2.45 MeV N_n is proportional to the fourth power of the density of the deuterium n_d; $N_n \propto (n_d)^4$. (In the case of the electrolytic system, this dependence is the third power as seen in the relation[13].

The positive result in Ti/D and the null result in Pd/D systems obtained by Bressani et al.[6,7] could be explained by this dependence of N_n on the n_d if other conditions (for instance, n_n) were the same where n_d is 11 and 6.9×10^{23} cm^{-3} for TiD_2 and PdD, respectively. If deuterons are occluded to its maximum value, the ratio of the generated neutrons will be 1.46×10^4 vs. 2.27×10^3 (i.e. 6.4 vs. 1). This difference probably obscures the signal in the Pd/D system in the experiment[7] where the signal-to-error ratio was about 5.

From these estimations we can guess a little about processes in the neutron generation using our model. A negative result is, of course, due to many causes which impair one of the necessary conditions for realization of the cold fusion phenomenon. If we consider only the density of the trapped neutrons, assuming other conditions are the same, we could take the above value of n_n as the threshold for the phenomenon.

The ratio of background neutrons in the positive and in the null results by Jones et al. was ~ 7.7 x 10. The ratio of densities of the trapped neutrons determined above was at least 1.9 x 10^4 for the best positive results. The difference of the two ratios of ~ 2.5 x 10^2 could be attributed to the role of breeding reactions in the best time for positive results if it is reasonable to assume the density of the trapped neutrons in the preparatory period is nearly proportional to the number of background neutrons, as it could not be expected that breeding of the trapped neutrons occurred in the sample before the experiment. In such a situation as this, it is clear by using the TNCF model that the null result reported by the authors is a natural consequence of the circumstance with almost zero ambient neutrons.

4. Conclusion

In the process of the development of a new science the appearance of new experimental facts can require the creation of new concepts to explain them.

A world-wide controversy arose around cold fusion for about two years after its discovery and then enthusiasm for developing the new science shrank as a result of the predominantly negative opinions...which were rooted in the poor reproducibility and inconsistency of experimental data. The group which measured 2.45 MeV neutrons in 1989 had continued their effort to prove the occurence of nuclear reactions in solids in an environment without background neutrons by the detection of neutrons they had measured before. Their precision experiment was done in an environment where there was almost zero ambient neutrons to improve S/N ratio. They obtained a null result[11,12] and concluded that there were no nuclear reactions in solids at near room temperature in this case.

In the controversy after the discovery of cold fusion one of discussions was concentrated at discrepancies between experimental results[1,2] and commonly accepted nuclear reactions:

$$d+d=t(1.01\,\mathrm{MeV})+p(3.02\,\mathrm{MeV}), \quad (19)$$
$$={}^3\mathrm{He}\,(0.82\,\mathrm{MeV})+n(2.45\,\mathrm{MeV}), \quad (20)$$
$$={}^4\mathrm{He}+\gamma(23.8\,\mathrm{MeV}), \quad (21)$$

which is assumed to be the only relevant reactions with the cold fusion phenomenon. The branching ratios of these reactions have been well known in nuclear physics as ~ 1 : 1 : 10^{-7}. This predicts a following relation between the number of generated particles; $N_t = N_n = 10^7 N_{He}$.

Thus the well established knowledge about the reactions told us that (1) the fusion probability of reaction (19) or (20) at room temperature is very low by a factor of 10^{-50} compared with the observed excess heat, (2) neutrons and tritium should be observed, (3) ^{4}He should be absent and (4) the excess heat should be ~ 4 MeV per a neutron (and tritium). These expectations had been betrayed by the experimental data and numerical differences were up to 10^7, except the probability of occurence by 10^{50}, as mentioned above.

These discrepancies, in addition to the poor reproducibility of experimental results, had produced a disbelief in the experimental data of the cold fusion phenomenon. Thus, the theory of simple $d-d$ fusion reactions (19) to (21) were discouraged by the failure to reconcile the theory and the experiments. It was clear that it was necessary to develop a new theory, perhaps a phenomenological one, to explain the above discrepancies and the poor reproducibility of the cold fusion phenomenon. Various events in the cold fusion phenomenon, though some of them were obscured by the patent barrier, together with analyses using the TNCF model, disclosed some phases of a new science to those with an open mind to new concepts. The dogma barrier is not easily overcome.

The problem of the reproducibility was explained by the model as a result of stochastic processes in the formation of a structure optimum to trap thermal neutrons in the solids. Then, the value of the density $n_n = 4.4 \times 10^{11}$ cm^{-3} determined above in the positive result by Jones et al. is in the upper range of values $n_n = 10^7 \sim 10^{13}$ obtained in the previous analyses[13~19]. As a cause of this characteristic of the data, the rather high value of the parameter, by Jones et al.[2], we can point to the special combination of electrolytes used in the experiment. As shown in Section 2, the electrolyte used in the experiment contained several metal salts, so it was probable that the surface layer had a complex structure which worked more effectively to trap neutrons than usual Li or PdLi$_x$ layer.

In the case of the null result by Jones et al., the density of the trapped neutrons was calculated as at most 10^8, if other conditions were the same. This value is lower than the minimum determined for Pd/D/Li systems, where positive results were observed[17]. Only one exception is $n_n = 10^3$ cm^{-3} for the case by Takahashi et al.[8] where tritium and neutrons were measured after a long preparatory run of about seven months. The events in their experiment lasted about a month and the determined value n_n was for average values of tritium and neutron generation. If we consider the value at the high time as for the others, this value of n_n should be multiplied by several orders of magnitude and will be more than 10^8 cm^{-3}.

One point observed in the positive result by Jones et al.[2] and others[6~10] should be considered. In the energy spectrum of neutrons shown in Fig. 2 by Jones et al.[2], it is seen that there are several discrepancies between foreground and background runs at energies above 2.45 MeV which were discarded by the authors. In the later investigations[6~10], it has been confirmed that number of neutrons with energies more than 2.45 MeV is larger than that with about 2.45 MeV. This reflects the difference in of the reactions (6) and (8) in the sample.

To visualize this qualitative investigation of the energy spectrum of the observed neutrons we calculated the energy of neutrons generated in a Pd/D/Li system, taking the reactions (4), (6), (7) and (8) into our consideration. For simplicity, the sample was assumed as Pd metal with two layers of PdD alloy and Li metal on the surface with a thickness 1 μm for each (the thickness of PdD layer 1 μm was used to save calculation time and made the peaks at 3 ~ 8 MeV rather low.) In the calculation, the density of trapped neutrons was assumed as $n_n = 10^{10}$ cm^{-3} and the reactions were assumed the same as in vacuum, i.e. $\xi = 1$ in the relation (9) in the Li layer. The result is shown in Fig. 1. This figure clearly shows the qualitative characteristics of the experimental results described in the preceding paragraph on the energy spectrum of neutrons generated from Pd/D/Li systems[8~10] (and also Ti/D systems[6,7] in the range up to 10 MeV.

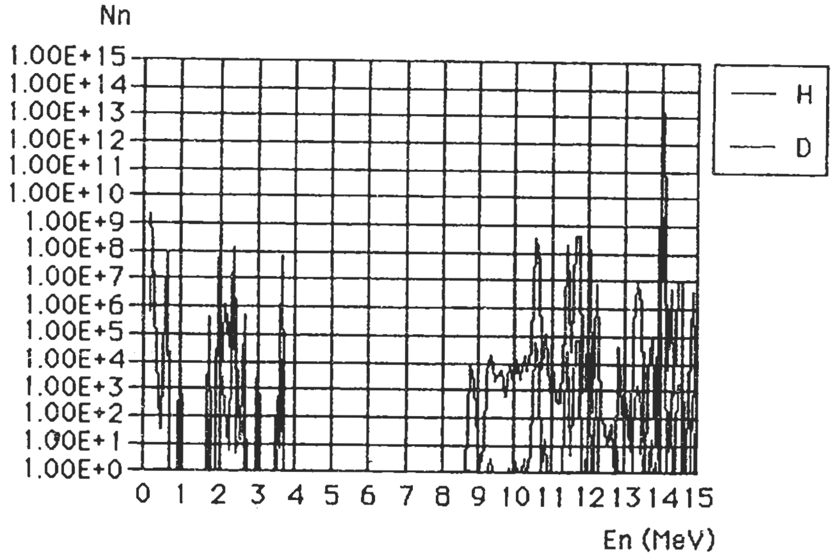

Fig. 1 Numerical result of the energy spectrum of neutrons generated in PdD/Li (PdH/Li) layers (1 μm thick each) of Pd metal including trapped neutrons of $n_n = 10^{10}\,\mathrm{cm}^{-3}$ using the TNCF model.

Unfortunately, there are no experimental data above 10 MeV to compare with the theoretical prediction. Numbers of the neutrons with ~ 10 to 15 MeV will be decreased largely relative to 14.1 MeV peak by elastic collisions with deuterons if we take PdD_x part in the volume of the sample into our calculation, which was neglected in the above calculation to spare calculation time.

In Fig. 1, there is also a curve for the Pd/H/Li system using a similar calculation with reactions including a proton. The curve shows about four orders of magnitude decrease of neutrons with energies less than 10 MeV compared to the curve for Pd/D/Li system in accordance with absence of observations in the protium systems (and also in Ti/H systems). This result confirms the experimental procedure used in the measurement by Bressani et al.[7], where the energy spectrum of Ti/D system is measured relative to that of Ti/H system.

In conclusion, the present interpretation of the fine experimental results for the neutron detection in the cold fusion phenomenon by Jones et al.[2,11] and others[6~10,12], in addition to the results of analyses of more than 40 experimental data[17,19] of the excess heat, tritium, helium and NT, has shown a promising basis for developing a new science, solid state – nuclear physics, or the physics of neutrons in solids.

The technical successes in the application of the cold fusion phenomenon accomplished recently to produce the excess heat[28,29] and transmuted nuclei[30] in addition to those obtained before, will be accelerated by progress in the scientific dsevelopment of the phenomenon.

References

(1) M. Fleischmann, S. Pons and M. Hawkins, "Electrochemically induced Nuclear Fusion of Deuterium," *J. Electroanal. Chem.* **261**, 301 (1989).

(2) S.E. Jones, E.P. Palmer, J.B. Czirr, D.L. Decker, G.L. Jensen, J.M. Thorne and S.E. Taylor, "Observation of Cold Nuclear Fusion in Condensed Matter," *Nature* **338,** 737 (1989).

(3) A. De Ninno, A. Frattolillo, G. Lollobattista, G. Maxtinio, M. Martone, M. Mori, S. Podda and F. Scaramuzzi, "Evidence of Emission of Neutrons from a Titanium-Deuterium System," *Europhys. Lett.* **9,** 221 (1989).

(4) 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).

(5) 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.

(6) T. Bressani, D. Calvo, A. Feliciello, C. Lamberti, F. Iazzi, B. Minetti, R. Cherubini, A.M.I. Haque and R.A. Ricci, "Observation of 2.5 MeV Neutrons Emitted from a Titanium-Deuterium Systems," *Il Nuovo Cimento* **104A**, 1413 (1991).

(7) E. Botta, T. Bressani, D. Calvo, A. Feliciello, P. Giannotti, C. Lamberti, M. Agnello, F. Iazzi, B. NEnetti and A. Zecchina, "Measurement of 2.5 MeV Neutrons Emission from Ti/D and Pd/D Systems," *Il Nuovo Cimento* **105A**, 1662 (1992).

(8) A. Takahashi, T. Iida, T. Takeuchi, A. Mega, S. Yoshida and M. Watanabe, "Neutron Spectra and Controllability by PdD/Electrolysis Cell with Low-High Pulse Operation," *Conference Proceedings* (CSI, Bologna) "Science of Cold Fusion", 93 (1991).

(9) M. Nakada, T. Kusunoki and M. Okamoto, "Energy of the Neutrons Emitted in Heavy Water Electrolysis," Frontiers of Cold Fusion (*Proc. ICCF3*) p.173, ed. H.Ikegami, Universal Academy Press (Tokyo), 1993..

(10) T. Sato, M. Okamoto, P. Kim, Y. Fujii and O. Aizawa, "Detection of Neutrons in Electrolysis of Heavy Water," *Fusion Technol.* **19,** 357 (1991).

(11) S.E. Jones, D.E. Jones, S.S. Shelton and S.F. Taylor, "Search for Neutron, Gamma and X-Ray Emission from Pd/LiOD Electrolytic Cells; A Null Result," *Trans. Fusion Technol.* **26,** 143 (1994). An experimental set[12] done in Japan by supervision of S.E. Jones had given also a null result which significantly slowed cold fusion research in Japan.

(12) T. Ishida, "Study of the Anomalous Nuclear Effects in Solid-Deuterium Systems," Master Degree Thesis, Tokyo University, Februar 1992.(29)

(13) H. Kozima, "Trapped Neutron Catalyze Fusion of Deuterons and Protons in Inhomogencous Solids," Trans. Fusion Technol. (*Proc* *ICCF4*) **26,** 508 (1994).

(14) H. Kozima, "On the Existence of the Trappe Thermal Neutron in Cold Fusion Materials," Progress in New Hydrogen Energy (*Proc* *ICCF6*), 332 (1996).; *Cold Fusion* 20, 5 (1996).

(15) 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).

(16) H. Kozima, M. Ohta and K. Kaki, "The Physics of the Cold Fusion Phenomenon," *Cold Fusion* **22,** 58 (1997).

(17) H. Kozima, K. Kaki and M. Ohta, "Anomalous Phenomenon in Solids Described by the TNCF Model," *Fusion Technol.* **33** No. 1 (1998 (to be published).

(18) H. Kozima, M. Fujii, M. Ohta and K. Kaki "Jones' Neutron Data Explained by the TNC Model -A Short Note," *Cold Fusion* **24,** 60 (1997)

(19) H. Kozima, M. Ohta, K. Yoshimoto, K. Arai M. Fujii, H. Kudoh and K. Kaki, "The Physica Processes in the Cold Fusion Phenomenon," Proc 5th Russian Conference on Cold Fusion an Nuclear transmutation (*RCCFNT5*) (1997, Sochi Russia) (to be published).

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

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

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

(23) B. Stella, M. Corradi, F. Ferrarotto, V Milone, F. Celani and A. Spallone, "Evidence fo Stimulated Emission of Neutrons in Deuterate Palladium," Frontiers of Cold Fusion (*Proc* *ICCF3*) p.437, ed. H.Ikegami, Universal Academy Press (Tokyo), 1993.

(24) A. G. Lipson and D. M. Sakov, "Increase i

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* (1995), 571 (1995).

(25) 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*), 370 (1996).

(26) D.L. Book, *NRL Plasma Formulary,* Naval Research Laboratory, Washington D.C., USA, 1983.

(27) K. Shibata, T. Nakagawa, H. Sugano and H. Kawasaki,"Curves and Tables of Neutron Cross Sections in JENDL-3.2," *JAERI-Data/Code 97-003*," Japan Atomic Energy Research Institute, 1997.

(28) J. Patterson and D. Cravens, "System for Electrolysis," US Patent # 5,607,563: Cold Fusion 22, 2 (1997).

(29) J.M. Niedra, I.T. Myers, G.C. Fralick and R.S. Baldwin, "Replication of the Apparent Excess Heat Effect in a H_2O-K_2CO_3-Ni Electrolytic Cell," NASA Technical Memorandum 107167 (February, 1996); *Cold Fusion* 22, 18 (1997).

(30) G.H. Miley, "Quantitative Observation of Transmutation Products Occurring in Thin-Film Coated Microspheres during Electrolysis," Progress in New Hydrogen Energy (*Proc. ICCF6*), 629 (1996).