Fifth International Conference on Cold Fusion
9-13 April, 1995 - Monte Carlo, Monaco
ICCF5 ©1995

NUCLEAR PROCESSES in TRAPPED NEUTRON CATALYZED MODEL for COLD FUSION

KOZIMA Hideo and WATANABE Seiji
Department of Physics, Faculty of Science, Shizuoka University
836 Oya, Shizuoka 422, JAPAN

Abstract

Results are given of detailed calculations of 1) probability of channeling for particles generated in $n-d$ and $n-p$ fusion reactions, 2) fusion probability of a triton generated in $n-d$ fusion with a deuteron and 3) fusion probability of a deuteron accelerated by $n-d$ elastic collision with another deuteron. A lot of neutrons are generated in a successive reactions of $d-d$ fusion reactions triggered by a trapped thermal neutron enough to explain experimentally observed anomalous excess heat, neutron bursts and tritium anomaly in optimum situations. The results confirms the preliminary estimations used in the previous works.

1. Introduction

There has been observed Cold Fusion Phenomenon in various materials. Those materials are divided into two categories; (1) Materials containing mainly a lot of deuterium (let us call them "deuterides" hereafter) and (2) Materials containing mainly a lot of hydrogen ("hydrides").

We had proposed a model (Trapped Neutron Catalyzed Model for Cold Fusion, TNCF model)[1~4] to explain cold fusion phenomenon and the model could give a consistent qualitative understanding of experimental facts in the phenomenon even though not quantitative.

The reactions having connection with the model are written down as follows:

$$\begin{aligned}
n+p &= d\ (1.33\ \text{keV}) + \gamma\ (2.22\ \text{MeV}) && (1)\\
n+d &= t\ (6.98\ \text{keV}) + \gamma\ (6.25\ \text{MeV}) && (2)\\
p+d &= {}^3\text{He}\ (5.35\ \text{keV}) + \gamma\ (5.49\ \text{MeV}) && (3)\\
d+d &= {}^3\text{He}\ (0.82\ \text{MeV}) + n\ (2.45\ \text{MeV}) && (4)\\
&= t\ (1.01\ \text{MeV}) + p\ (3.02\ \text{MeV}) && (5)\\
&= {}^4\text{He}\ (76.0\ \text{keV}) + \gamma\ (23.8\ \text{MeV}) && (6)\\
t+d &= {}^4\text{He}\ (3.5\ \text{MeV}) + n\ (14.1\ \text{MeV}) && (7)\\
d+{}^3\text{He} &= p\ (14.68\ \text{MeV}) + \alpha\ (3.67\ \text{MeV}) && (8)
\end{aligned}$$

Here, it is useful to give attention to a fact about the difference of fusion cross sections of Res. (1) and (2). The cross sections of these reactions depend on the energy E of the thermal neutron and increase as $E^{-1/2}$ with decrease of the energy. This fact means low temperature is advantageous to realize Cold Fusion for the same density of trapped thermal neutron. Fusion cross section of Re. (1) for a neutron with the energy 25 meV is about 3×10^{-1} barns and that of Re. (2) for the same energy is about 6×10^{-3} barns[5]. So, a thermal neutron is easier to fuse with a proton than with a deuteron by a factor 50.

Some characteristics of the Cold Fusion phenomenon in deuterides and hydrides are pointed out as follows.

(1) Cold Fusion in deuterides.

Once Re. (2) occurs in deuterides between a trapped thermal neutron and a deuteron in the sample, the generated triton and photon will give several effects on the sample. The attenuation lengths ell_{att} of 6.25 MeV and 2.22 MeV photons in relevant metals are given as follows: 8.0 (Ti), 3.4 (Ni) and 2.2 (Pd).

If the sample is large enough to attenuate the photon (2 cm for Pd metal), the sample will be heated drastically as observed by rare experiments[6]. In samples with smaller linear dimensions, the photon will come out from the sample[7] and excess heat will be resulted from other particles generated in reactions induced by the triton. In Ti/D system, however, the attenuation length is too long (~8 cm) to heat usually used samples drastically and no remarkable excess heat has been observed hitherto.

The triton generated in Re. (2) will be observed in the remains as tritium[8,9]. In an optimum situation, the triton will make fusion reaction with a deuteron in the sample to generate ^{4}He and a high energy neutron with energy 14.1 MeV according to Re. (7). ^{4}He generated in this reaction will be observed as helium atom[10,11]or as alpha particle.

The high energy neutron will have two effects; the neutron itself will be observed coming out from the sample[7,12,13] or the neutron will make predominantly elastic collisions with deuterons in the sample. A deuteron accelerated by an elastic collision with the neutron will obtain enough energy to make a fusion reaction with another deuteron in the sample by Res. (4) or (5) (Detailed calculation will be given later).

When the neutron generated in Re. (7) loses almost all its energy by the elastic collisions with deuterons, the neutron contributes to Re. (2) together with the neutron generated in Re. (4). In an optimum situation where Res. (2), (7) and (4) occur successively (a chain reaction), there will be generated a lot of neutrons[14] and a neutron burst will be observed[7~9,15] (Detailed calculation will be given later).

(2) Cold Fusion in Hydrides[4].

Once Re. (1) occurs in hydrides, a deuteron and a photon are generated. The generated photon can heat the sample effectively when it has enough dimension to attenuate the photon[16,17]. The deuteron also contributes to heat the sample losing its energy by elastic collisions with charged particles in the sample. The deuteron can make fusion reaction Re. (3) to generates ^{3}He which will contribute to heat the sample and also be measured in hydrides.

The larger cross section of Re. (1) compared with that of Re. (2) is favorable for stationary heat generation for hydrides. It is possible to say that we will obtain excess heat generation linearly depending on the number of trapped thermal neutrons in a sample. This prediction should be checked experimentally.

On the other hand, the successive reactions feasible in deuterides are absent in hydrides. It is possible to conclude that there are neither neutron bursts nor explosive excess heat generation in hydrides by TNCF mechanism.

(3) Direct evidence for the effect of thermal neutrons in Cold Fusion

Recent private communication[18] reported interesting observation in KD_2PO_4 single crystal. When background neutrons were increased artificially to 100 times the natural one, the enhancement factor (No. of neutrons in the transition region/No. in others) increased from 4 to 25. This result shows that the effect of thermal neutron is nonlinear to its density suggesting a productive effect (chain reactions).

Similar effect of thermal neutrons have been investigated several times until now. The first one was done in 1989[19]. Others were done after then with much care[13,20].

Inexistent results of the Cold Fusion phenomenon[21] were also obtained including Kamiokande experiment in 1992 (in Japan) showing that there are no Cold Fusion without background neutrons.

These data clearly support TNCF model directly.

(4) Irreproducibility

Irreproducibility of Cold Fusion phenomenon (especially gigantic excess heat, neutron burst and tritium anomaly), the remarkable controversial problem throwing a big question to all scientists, had been explained in TNCF model as a result of stochastic processes working in samples to realize the optimum condition to make feasible the Cold Fusion (trapping of thermal neutron, realization of chain reactions, etc.).

The direct supports from experiments with controlled thermal neutron[13,18,20] and the self-consistent interpretation of the whole experimental results except absence of high energy photons show that something true is in TNCF model. The question about the absence of the high energy (6.25 and 2.22 MeV) photons might be related with a fact that the absorption coefficient of a photon in many materials has a minimum at a range from 1 to 10 MeV of the photon energy. A critical review of experimental data given by E. Storms[22] is useful to overlook whole range of the Cold Fusion phenomenon.

We will give some detailed calculations about nuclear processes in TNCF model in this paper.

2. Neutron Mössbauer Effect and Neutron Band

Among the mechanisms responsible neutron trapping, the neutron Moessbauer effect is the one concerned with individual nucleus. As explained in a previous paper[3], a nucleus with a mass number A and even atomic number Z around 26 in a crystal lattice is responsible neutron Mössbauer effect, which works as a mechanism to confine neutrons effectively in the lattice (M-mechanism). The trapped neutron by this mechanism is free from its short life time about 900 seconds of the isolated neutron.

The momentum change of the nucleus in the emission and absorption of a neutron is pertinent with the lattice, while the difference between energy levels in the nucleus with $(A + 1)$ and Z is pertinent with energy levels in the nucleus.

A neutron with an energy 5.33 eV has the same momentum as that of a photon with energy 100 keV which corresponds to photons usually used in the Mössbauer resonance technique. Thus, ordinary crystal can give rise to the neutron Mössbauer effect for neutrons with energies less than 100 keV including the thermal energy (0.025 eV). The neutron Mössbauer effect is legitimated by analogy with the photon Mössbauer effect.

This mechanism of neutron trapping depends on the dynamic character of the local lattice around the pertaining nucleus. In an inhomogeneous material where the Cold Fusion occurs, the dynamical characteristics of the lattice varies place to place. To keep the M-mechanism effective, the size of the locally homogeneous region should have a minimum value. On the other hand, to have a long trapping time T of the neutron in the material, it is desirable to make the total volume of the locally homogeneous region as large as possible.

A compound nucleus (A+1,Z) has another effect on the neutron trapping – a neutron band in the crystal. A Bloch state composed of individual nuclear state (real and virtual) just like the exciton band in oxides or 4f band in rare earth metals will be formed to trap neutrons effectively with an elongated life time.

3. Channeling

There is a propagation of a neutral or a charged particle through crystal without energy loss, i.e. the channeling[23,24]. The channeling occurs when the de Broglie wave length of the particle is short compared with the lattice constant of the crystal and the propagation vector makes a small angle with a crystal axis or a crystal plane[24]. In our case, it occurs when the propagation is around a specific crystal direction (OHS line) through interstitial sites (a channeling axis).

Once a thermal neutron makes a fusion reaction with a deuteron or a proton in an material occluding it, particles generated in the reaction have appropriate energies to channel through the material where the crystal lattice is ideal. High energy triton or deuteron generated in Re. (2) or (1) makes collision with deuteron or proton effectively to fuse with it, shown as follows.

A charged particle can propagate through a channel with a radius r_0 when the angle ψ between its momentum and a channel axis is smaller than a critical angle ψ_{cr}. The ψ_{cr} for a particle with an energy E and a charge Z_1e through a lattice composed of atoms with nuclear charge Z_2e is given by following formulae:

$$\psi_{cr,1} = \sqrt{\frac{2Z_1Z_2e^2}{Ed}}, \quad (E > E'), \tag{9}$$

$$\psi_{cr,2} = \sqrt{\frac{Ca_{TF}\psi_{CR,1}}{\sqrt{2}d}}, \quad (E < E'), \tag{10}$$

where $E' = 2Z_1Z_2e^2d/a_{TF}^2$, $C \simeq \sqrt{3}$ and the Thomas-Fermi atomic radius a_{TF} for this case is given by

$$a_{TF} = 0.8853a_0(Z_1^{1/2} + Z_2^{1/2})^{-2/3}.$$

The parameter d in the above formulae is a distance of matrix atoms along the channel axis.

For the triton with an energy of 6.98 keV, $E/E' < 1$ and $\psi_{cr,2} = 0.105$ rad. A triton which is generated by Re. (2) can propagate along one of twelve main channels through the site where was a deuteron with a probability of 3.3 %. On the other hand, the deuteron which is generated by Re. (1) can propagate along one of twelve main channels with a probability of 7.6 % according to similar estimations. Those probabilities increase with the decrease of particle energy.

Now, we proceed to individual reactions between particles.

4. Tritium Production Rate in Deuterides

As is explained in Section 1 and is well known in the neutron physics[1,5], the fusion cross section of a neutron with a deuteron increases rapidly with the decrease of the impinging neutron energy ε, while the elastic scattering cross section remains constant about 3.2 barns under $\varepsilon = 1$ MeV. The ratio of two cross sections is about 10^{-6} at $\varepsilon = 10^6$ eV and is 10^{-3} at $\varepsilon = 10^{-3}$ eV.

To interpret rare experimental results where observed tritium anomaly, we must be aware of a fact that detections of neutron and tritium are usually not simultaneous. So, we may assume in this case that one or other trapping mechanisms are very effective and a lot of neutrons are trapped in the sample. Then the fusion reaction Re. (2) will occur to produce a lot of triton which will make an effective collision to accelerate deuterons when propagating along an OHS line or to lose energy by the Coulomb interaction with charged particles in the lattice and to remain in the sample.

By the head-on elastic collision of a triton with a static deuteron, the triton lose its 12/25 of the initial energy. The accelerated deuteron makes a collision with another deuteron. If a deuteron with an energy of $(12/25) \times 6.98 = 3.35$ keV propagate along an OHS line in a cylinder with a cross section πr_0^2, it induces about two $d-d$ fusions in 10^{-4} second with occluded deuterons generating one triton by the reaction Re. (5) in an infinite sample[2] in an optimum situation, where r_0 is the radius of the channel. At the same time, the deuteron generates one neutron by Re. (4). Considering the average fusion length of about 8×10^3 cm, we obtain 10^4 neutrons per second in a sample with a size $1 \times 1 \times 1$ cm^3 with 8000 reactions Re. (4) per second.

This mechanism results in two effects: 1) When the trapping mechanisms work effectively for higher energy neutrons in a sample with enough inhomogeneity, the neutrons lose energy effectively and are trapped as a warm or cold neutrons to fuse with deuterons according to Re. (2) and many tritons are generated. 2) When the trapping mechanisms for higher energy neutrons don't work well, the 2.45 MeV neutrons propagating along an OHS line to make sequential neutron-breeding-process generating many neutrons to be observed (as discussed in the next section).

In some experiments[8,25,26] the first mechanism would be predominant and the tritium is generated by a chain reaction Res. (4) and (5) interposed by the $t-d$, $n-d$ and $d-d$ elastic collisions. In the experiment[25], a part of neutron bursts preceding the tritium emission would be stored effectively as trapped neutrons in the sample. After a neutron burst, the sample became the second type by effects of the fusion products including heat and the trapped neutron could worked to initiate the chain reaction generating a lot of tritium to give $t/n \sim 10^6$. In the other experiment[26], there was no neutron burst above the background and the trapped neutrons would be the initiator of the chain reaction to generate a lot of tritons of the order of $t/n \sim 10^4$.

5. Neutron Breeding Rate

The neutron breeding rate is calculated starting from one neutron with an energy 2.45 MeV (or 14.1 MeV) emitted along a OHS line (channeling direction). The neutron makes collisions with deuterons on the line and the recoiled deuterons generate five (or six) neutrons by Re. (4) in 10^{-6} seconds in an infinite sample. In this calculation, simplifications were made assuming 1) the particles always propagate on an OHS line and 2) an amount of energy transferred by elastic collisions is that of the average one with rigid spheres collision model.

It is also assumed arbitrarily that one out of five (or six) neutrons with energy 2.45 MeV generated in Re. (4) is possible to start another propagation along an OHS line to produce five (or six) neutrons again to continue the reaction forever. In this optimum situation, one $n-d$ reaction generates neutrons about 10^6 per second and the neutrons are emitted from the sample if the trapping of high energy neutrons is not effective. This is a story only occurs in an optimum situation achieved very rarely in samples and corresponds to very rare, irreproducible events giving experimental results with neutron bursts[8,15].

6. Conclusion

It is difficult to prove the occurence of the Cold Fusion phenomenon in materials from the first principles because the physics in it include statistical property. The estimations given above illustrate a possibility of the occurence of the Cold Fusion phenomenon in the presence of abundant thermal neutrons in materials pertinent with the phenomenon and possibilities of the existence of many neutrons in appropriate materials had been shown in the preceding papers[1~4]. The photon with energy of 6.25 MeV (or 2.22 MeV) has been measured rarely[7] and should be a target of future enthusiastic experiments.

References

1. H. Kozima, " Trapped Neutron Catalyzed Fusion of Deuterons and Protons in Inhomogeneous Solids", *Proceedings of ICCF 4*, 4, p. 5-1, Electric Power Research Institute, California, USA, 1994; and *Trans. Fusion Tech.* **26**, 508 (1994). And also "Trapped Neutron Catalyzed Model for Cold Fusion", *Cold Fusion Source Book*, EPRI, Salt Lake City, Utah, USA (to be published).

2. H. Kozima and S. Watanabe, "t-d and d-d Collision Probability in the Trapped Neutron Catalyzed Model of the Cold Fusion", *Proceedings of International Symposium "Cold Fusion and Advanced Energy Sources"* (May 24-26, 1994, Minsk, BELARUS.)(in Russian) p. 299.

3. H. Kozima, "Neutron Mössbauer Effect and the Cold Fusion in Inhomogeneous Materials", *Nuovo Cimento* **27A**, 1781 (1994).

4. H. Kozima, "On the Cold Fusion in Ni-H System", *Cold Fusion* **8**, 5 (1995).

5. 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).

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

7. H. Long, S. Sun, H. Liu, R. Xie, X. Zhang and W. Zhang, "Anomalous Effects in Deuterium/Metal Systems", *Frontiers of Cold Fusion* p.447, ed. H.Ikegami, Universal Academy Press (Tokyo), 1993. H. Long, R. Xie, S, Sun, H. Liu, J. Gan, B. Chen, X. Zhang and W. Zhang, "The Anomalous Nuclear Effects Inducing by the Dynamic Low Pressure Gas Discharge in a Deuterium/Palladium system", *ibid.* 455 (1993).

8. R.K. Rout, M. Srinivasan, S. Shyam and V. Chitra, "Detection of High Tritium Activity on the Central Titanium Electrode", *Fusion Tech.* **19**, 391 (1991).

9. T. N. Claytor, D. G. Tuggle and S. F. Taylor, "Evolution of Tritium from Deuterided Palladium Subject to High Electrical Currents", *Frontiers of Cold Fusion* p.217, ed. H.Ikegami, Universal Academy Press (Tokyo), 1993.; S. F. Taylor, T. N. Claytor, D. G. Tuggle and S. E. Jones, "Search for Neutrons from Deuterated Palladium Subject to High Electric Currents", *Proc. Fourth Intern. Conf. on Cold Fusion*, Lahaina, Maui, Dec. 6 - 9, 1993, Vol. **3**, p.17, EPRI TR-104188..

10. E. Yamaguchi and T. Nishioka, "Direct Evidence for Nuclear Fusion Reactions in Deuterated Palladium", *Frontiers of Cold Fusion* p.179, ed. H.Ikegami, Universal Academy Press (Tokyo), 1993.

11. M. H. Miles and B. F. Bush, "Heat and Helium Measurements in Deuterated Palladium", *Trans. Fusion Tech.* **26**, 156 (1994).

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

13. 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* p.437, ed. H.Ikegami, Universal Academy Press (Tokyo), 1993.

14. 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).
15. E.Yamaguchi and T.Nishioka, "Cold Nuclear Fusion induced by Controlled Out-Diffusion of Deuterons in Palladium", *Jpn. J. Appl. Phys.* **29**, L666 (1992).
16. S. Focardi, R. Habel and F. Piontelli, "Anomalous Heat Production in Ni-H System", *Nuovo Cimento* **107A**, 163 (1994).
17. U.S. Pat. No. 5,318,675 "Method for Electrolysis of Water to form Metal Hydride and No. 5,372,688 "System for Electrolysis of Liquid Electrolyte"; and Report by V. Lapuszynski, "The Patterson Power Cell^{TM}", *Cold Fusion*, **7**,1 (1995).
18. A. G. Lipson and D. M. Sokov "Amplification of the Neutron Flux Transmitted through KD_2PO_4 Single Crystal at the Ferroelectric Phase Transition State", *ICCF 5 Book of Abstract* (April 9 - 13, Monte-Carlo, Monaco), Page 320 (1995); *JETP* (in Russian), **76**, 1070 (1993) and *J. Tech. Phys. Lett.* (in Russian), **20**, 46 (1994).
19. 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).
20. F. Celani, A. Spallone, L. Liberatori, F. Croce, L. Storelli, S. Fortunati, M. Tului and N. Sparvieri, "Search for Enhancement of Neutron Emission from Neutron-Irradiated, Deuterided, High-Temperature Superconductors in a Very Low Background Environment", *Fusion Tech.* **22**, 181 (1992).
21. S. E. Jones, D. E. Jones, D. S. Shelton and S. F. Taylor, "Search for Neutron, Gamma and X-Ray Emission from Pd/LiOD Electrolytic Cells: A Null Results", *Trans. Fusion Tech.* **26**, 143 (1994).
22. E. Storms, "A Critical Review of the "Cold Fusion" Effect", *Fusion Techn.* (to be published).
23. V. I. Visotskii and R. N. Kuz'min, "Kanalirobanie Neitral'nib Tyastiz i Kbantob b Kristallaxa", *Uspehi Phizityeskix Nauk* (in Russian) **162** (1992) 1.
24. D. S. Gemmell, "Channeling and related effects in the motion of charged particles through crystals", *Rev. Mod. Phys.* **46**, 129 (1974).
25. P.K. Iyengar and M. Srinivasan, Proc. First Annual Conf. Cold Fusion, Salt Lake, 1990 cited in M.Srinivasan, *Current Science* **60** (1991) 417.
26. M. Nakada, T. Kusunoki and M. Okamoto, "Energy of the Neutrons Emitted in Heavy Water Electrolysis", *Frontiers of Cold Fusion* p.173, ed. H.Ikegami, Universal Academy Press (Tokyo), 1993.; T. Sato, M. Okamoto, P. Kim, Y. Fujii and O. Aizawa, "Detection of Neutrons in Electrolysis of Heavy Water", *Fusion Tech.* **19**, 357 (1991).