HOW THE COLD FUSION OCCURS ?

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Abstract

Origin of the Cold Fusion phenomena is explained putting weight on the typical and recent experimental results. The Trapped Neutron Catalyzed Fusion Model is used to explain consistently almost all experimental data obtained in this field until now.
Key Words ; Cold Fusion, Nuclear Fusion, Neutron Emission, Excess Heat.

§ 1. Introduction

Since the declarations of the discovery of the Cold Fusion phenomena (an extraordinarily big amount of heat[1)] and a neutron emission[2)] in electrolytic cells with Pd and Ti cathodes, respectively, with D_2O electrolyte solution) in March 1989, there have been controversies on the reliability of experimental results on those and related phenomena[1].

The most critical points of the controversy were, in author's opinion, reproducibility of the experimental results and disappearence of the phenomena in the most careful experiments with the least background condition such as done in Japan (the Kamiokande experiment in 1992). Relevant fusion reactions are usually considered as follows :

$$d + d = {}^3\mathrm{He}\,(0.82\ \mathrm{MeV}) + n\,(2.45\ \mathrm{MeV}) \tag{1}$$

$$= t\ (1.01\ \mathrm{MeV}) + p\,(3.02\ \mathrm{MeV}) \tag{2}$$

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[1] To understand the impact of this discovery, it is helpful to know the difficulty of the realization of the thermonuclear fusion on the Earth. The thermonuclear reactions based on the d-d reaction (Eqs. (1) and (2)) and d-t reaction (Eq.(8)) requirs ion energy of 35 (4.2×10^5 K) and 4 keV (4.8×104 K), respectively. In addition, it is necessary to satisfy the *Lawson criterion* for the ion density n and the confinement time τ :
$n\tau \leq 10^{16}$ and 10^{14} cm^{-3}s,
respectively for the above reactions. These conditions are too severe to realize in existing machines and there is pessimistic opinion for the accomplishment of the ongoing plan in this half a century.

$$= {}^4\mathrm{He}(76.0\ \mathrm{keV}) + \gamma(23.8\ \mathrm{MeV}) \quad (3)$$

Branching ratios of these reactions were known as $1 : 1 : 10^{-7}$ in the Nuclear Physics. To solve riddles found in the Cold Fusion phenomena, following rather difficult reactions in solids were taken up in literatures;

$$p + d = {}^3\mathrm{He}(5.35\ \mathrm{keV}) + \gamma(5.49\ \mathrm{MeV}) \quad (4)$$

$$d + d + d = {}^4\mathrm{He}(7.95\ \mathrm{MeV}) + d(15.9\ \mathrm{MeV}) \quad (5)$$

$$= {}^3\mathrm{He}(4.76\ \mathrm{MeV}) + t(4.76\ \mathrm{MeV}) \quad (6)$$

$$p + d + d = {}^4\mathrm{He}(4.77\ \mathrm{MeV}) + p(19.08\ \mathrm{MeV}) \quad (7)$$

If a lot of tritium exists, a following reaction is an effective one:

$$d + t = {}^4\mathrm{He}(3.5\ \mathrm{MeV}) + n(14.1\ \mathrm{MeV}) \quad (8)$$

To clarify the key points of the controversy, it is helpful to review experimental results from a new stand point. The origin of the confusion in the discussion of the Cold Fusion was in the diversity of experimental results. There are very many reaction products: neutrons with various energies, excess heat of various amounts, tritium with various amounts, ^{4}He or alpha particles with various amounts and energies, sometimes protons, ^{3}He or gamma and X rays. And also there is variety in the experimental condition: Pd or Ti or alloy or ceramics as a matrix, electrolysis or gaseous contact to load deuterium into the matrix, variation of electric voltage or temperature or gas pressure to make the sample inhomogeneous, and etc.

First, we will give extensive introduction of experimental results mainly obtained recently in an order of the main reaction products;

I) excess heat, II) neutron, III) ^{4}He, IV) tritium,

V) radiation (γ, X) and others (p, α), VI) explosion.

Subdivision will be made according to the methods of hydrogen isotope loading to matrix;

A) electrolysis, B) gaseous contact, C) discharge, implantation and others.

Sub-subdivision will be made according to the combination of matrix and the hydrogen isotope;

a) Pd-D, b) Ti-D, c) other metals, alloys, ceramics-D.

d) any matrix-H, e) others.

Also, parameters are varied sometimes as excitation methods to make the sample inhomogeneous or nonequilibrium, and it is denoted by following symbols if used intentionally;

i) electric voltage, ii) temperature, iii) pressure,

iv) neutron irradiation, v) others.

References are divided according to this classification, and if special notification is necessary, a full sign in parenthesis (sign) will be added after the citation symbol.

§ 2. Experimental Results

As we can see in this section, there is wide variety in the samples, detection objects and methods. And also it will be noticed that the reproducibility of the results are, generally speaking, very poor despite of vast effort of researchers in these several years. To understand the complexity of the Cold Fusion phenomena, it is necessary, however, to know some details and variety in the positive experimental results not mentioning negative ones. We will introduce typical and recent results in the order given at the last part of §1. .

2-1. Excess Heat.

In March 1989, Fleischmann and Pons[1] declared the discovery of *d-d* fusion of a new type in Pd-D combination in the procedure of heavy water lectrolysis. Huge thermal energy was observed to melt one of electrodes. Theamount of the excess heat reduced to neutron counts was imbalance with the measured neutron counts by eight orders of magnitude. Many experiments have been done to confirm the results but the results were rathernegative. One character of the phenomena is its stochastic nature already noticed by the discoverers themselves. Despite of the difficulty in the experimental technique including calorimetry, many efforts have been continuing in the initial line of experiment. A mystery of extraordinary excess heat without relevant reaction products made many theoretical efforts to discover new mechanisms unknown hitherto, but we do not touch with this too sophisticated trials in this paper.

I *Aa. Electrolysis with* Pd-D *combination.*

McKubre et al.[3] observed excess power generation with use of a system of novel design and reported it as a function of electrochemical current and cathode loading. Storms[4] observed excess heat of 20% and the excess volume of the samples (0.8 ~ 13.5%). He concluded that heat production was prevented if excess volume was too large. Kunimatsu et al[5]. used a novel electrolytic cell pressurized by D_2 in which deuterium loading ratio D/Pd in a palladium cathode can be determined *in situ* during the calorimetric measurements of excess heat. The results showed that the critical loading ratio and the current density to generate excess heat are ca. 0.83 and 100 mA/cm^2, respectively. The maximum D/Pd of 0.89 had been achieved in this study, at which excess heat generation of ca. 35 % with respect to the input electrolytic power had been observed. Fleischmann et al.[6] observed high rate of specific excess enthalpy generation (>1 kW cm^{-3}) at temperatures close to (or at) the boiling point of electrolytic solution.

Oyama et al.[7] used a closed type calorimeter to observe excess heat generation. They observed excess heat genaration (2.4%) once out of 5 experiments when the electric power of 0.2 W was employed. In the case where the electric power of 0.3 W was employed, excess heat was observed (2.7%) for more than one month in the presence of 200 ppm aluminum. Ota et al.[8] (I Aa(c)) used also closed cell with Pd and Pd-Ag cathodes and observed excess heat with burst three times out of 13 runs when mechanically treated Pd cathode were used. One of these was for Pd-Ag alloy (90 : 10) which began at 1,155 h after the start of the electrolysis, lasting for 240 h. The average output power was 105 % of the input during that time. Wan et al.[9] (I Aa(v)) used static and dynamic loading conditions. In the dynamic test, cyclic torsion was applied to the Pd electrode during the deuterium loading. No abnormal reaction was found during the torsion, but sometimes repeated occurence of heat burst was observed after the cease of torsion.

Takahashi et al.[10] (I (II)Aa) used the L-H (low-high) mode pulse operation of electrolytic voltage, deviced themselves before. Anomalously large excess heat (32 W in average for 2 months, 100-130 W at peaks and averaged output/input power ratio 1.7) was once observed associating very few (~1 n/s) neutron emission. With a modified cell, they could reproduce excess heat generation but with much smaller amount of heat (8 W in average and 15 W at peak) and twice larger neutron emission rates.

Celani et al.[11] (I (IV)Aa) used a gas-closed flow calorimeter to perform L-H mode pulsed current electrolysis. Four cold-worked Pd sheets were tested and two of them produced 7.5 and 6 % of mean excess heat for many weeks. Tritium analysis was carried out and some coincidence between tritium production and excess heat was found. Miles et al.[12] (I (III)Aa) observed relations between excess heat and ^{4}He. They found that eight electrolysis gas samples collected during episodes of excess power production in two identical cells showed the presence of ^{4}He. Rate of ^{4}He production was estimated as 10^{11}-10^{12} ^{4}He/s•W which was the correct magnitude for typical fusion reactions that yielded helium as a product.

Bertalot et al.[13] (IA(B)a) used a particular geometry in which the cathode is immersed on one side in the electrolytic solution, while the other side faced a gaseous D_2 (or H_2). Also, they used palladium anodes to prevent poisoning on the Pd cathode surface. They confirmed the production of ^{4}He in electrolytic cells with heavy water and palladium cathodes. Mizuno et al.[14] (I Aa(i)) measured excess heat H_{ex} as a function of D/Pd loading ratio. The excess heat was observed when a Pd sample was filled with deuterium to D/Pd $\approx$ 0.90 by cathodic charging. The excess heat increased with D/Pd in an exponential manner ; H_{ex} was of the order of magnitude of 0.1 W/cm^2 at D/Pd $\sim$ 1.0.

Hasegawa et al.[15] (I Aa(i)) observed the dependence of excess heat generation on D/Pd up to D/Pd=0.88 with the maximum output/input ratio of 1.35. The minimum D/Pd to produce the excess heat has been found around 0.83 $\sim$ 0.84. Kobayashi et al.[16] (I Aa(i)) used the saw-tooth and the L-H current modes to measure excess heat in two batches of Pd sheet cathodes. Excess heat of 10 ~ 30% of input power was observed in a cathode but not in the other. The saw-tooth and the L-H mode operation had no effect to enhance D/Pd. Wan et al.[17] measured an anomalous heat generation and absorption in the Pd cathode. An anomalous heat generation was measured for the annealed cathode which was deuterium-loaded for 3500 min. An anomalous heat absorption was regularly repeated from 4000 th to 7500 th min. of deuterium loading in the same cell.

Miyamaru et al.[18] (I Aa(i)) observed the correlation between current density and excess heat production in the D_2O/Pd electrolysis with modulated currents. They used a new type measurement system with open type calorimeter. Only in a palladium plate of No.1 batch a slight excess heat was observed during step-up mode. Though the relation between applied current patterns and excess heat level was not clear, suggestion was obtained that palladium material feature had an important role in excess heat production.

I *Ad. Electrolysis with Any materials*-H *combination.*

Notoya et al.[19] measured excess heat in electrolysis of H_2O solution of K_2CO_3 with Ni electrodes. The cell was cooled by a constant rate air stream and maintained at 20°C during the electrolysis. Typical results indicated that the excess heat production rate was proportional to the input power in the range of measurements (up to 2 W) and the excess heat observed was 3 to 4 times greater than the input power. Ohmori et al.[20] measured excess heat produced during electrolysis of H_2O on Ni, Au, Ag and Sn electrodes in alkaline media. As an electrolytic solution, they used K_2CO_3, Na_2CO_3, Na_2SO_4 and Li_2SO_4 aqueous solutions. Steady evolution of excess heat was measured in various electrode/electrolyte systems except Ni/(Na_2CO_3, Na_2SO_4, Li_2SO_4). The largest excess heat observed was 907 mW on Sn in K_2SO_4.

2-2. Neutron

II *Aa. Electrolysis with* Pd-D *combination.*

After the experiment of Jones et al.[2], many experiments have been done to confirm the neutron emission from the electrolystically deuterium occluded materials keeping in mind an advice of the first discoverers that the phenomena would occur in a non-equilibrium situation. We also observed neutrons emitted in the process of electrolysis without determining its energy.[21]

Gozzi et al.[22](II(I ,III)Aa) assembled improved experimental apparatus for neutron measurement. They observed the production of excess heat up to 43 % without any appreciable neutron and tritium excesses compared to the respective background. Dalun et al.[23] (II (IV, VI) Aa (ii , iii)) measured neutron and tritium produced in the process of electrolysis changing temperature and pressure cyclically. They also experienced two cases of explosion. Nakada et al.[24] (II Aa(i)) observed neutron emission with L-II pulse mode electrolysis. Among 6 runs of the electrolysis, 3 of them gave appreciable neutron emission. The neutron energy spectra were found to have two components (2.45 MeV peak and a broad band in higher energy region). The intensity of the 2.45 MeV neutron was smaller than that of the higher energy.

Arata et al.[25] (IIAa(c)) made electrolysis experiment with a complex cathode consisting of a nickel rod coated with a 300 μm palladium layer (Pd(Ni)). Generation of neutrons from the deuterated cathodes was continuously detected, indicating the occurence of cold fusion, but not from hydrogenated cathode. Isagawa et al.[26] (II(I)Aa) measured heat and neutron emission. No coincidence between only one heat burst and a rare neutron emission is observed. The latter showed an abnormal increase for only short term. The increase of about 3σ above the background level lasted 9 hours. The emission rate amounts to 27.2 ± 11.2 neutrons s^{-1}, which is equivalent to about 700 times as much as the background level. Neither excess heat nor tritium anomalies were, however, observed.

Fujii et al.[27] used 2N DCl of deuterated methanol as an electrolyte solution in the experiments. They observed three neutron trains continuing 2 or 3 hours as the excess flux during an electrolysis at low temperature range (210 K). Average value of D/Pd was 0.7. Fujiwara et al.[28] (IIAa(i)) observed the neutron count rate in the processes of loading and unloading of deuterium. Highly significant difference of 1 % level in statistics was observed between filled and emptied states in one sample among the four samples tested. The excess neutron count rate corresponds to the fusion rate of $0.8 \times 10^{-23)} \sim 3.2 \times 10^{-23}$ fusions/deuteron pair/s. Fan et al.[29] (II(IV)Aa) observed neutron and tritium in the same sample. Anomalous neutron burst and an increase in tritium concentration were measured simultaneously. They concluded strong dependence of the production of neutron and tritium from D_2O electrolysis on the constitution and the state of the cathode.

Nakada et al.[30] investigated the depth profile analysis of Li and D in Pd cathode in terms of SIMS (secondary ion mass spectrometry). There are very clear differences in the profile of samples with the neutron emission and without it. The depth profile were also found to depend on the mode of the electric current employed.

II*Ab. Electrolysis with* Ti-D *combination*

In March 1989, another discovery in the Cold Fusion phenomena was done by Jones et al.[2] They measured neutrons with energy 2.45 MeV emitted in the reaction (1) in a similar experimental set up as Fleischmann and Pons[1] but with Ti and Pd cathodes. They confirmed the neutron emission of 2.5 MeV from Ti cathode. Their results along with that of Fleischmann et al[1] stirred the enthusiasm for the investigation of the Cold Fusion.

II *Ae. Electrolysis with other electrolyte.*

Yuan et al.[31] used LiD-KCl molten salt saturated by LiD at cell temperature about 400°C. For long time monitoring, the significant reproducible neutron bursts appeared at several runs of cells during electrolytic processing. The neutron counting rate increased about a factor of two above the level of the background measurement. The pulse height signals were verified of neutron energy ranging from thermal to 350 keV.

II *Ba. Gaseous Contact with* Pd-D *combination.*

Shani et al.[32] assumed that the discovery of Jones et al.[2] was an neutron induced fusion of deuterons by the reaction (1). They could explain the experimental data of compressed D_2 gas consistently with their assumption, but not the data of Jones et al. by a difference of three orders of magnitude. There are many experiments along this line of consideration.[43]

Stella et al.[33] (II Ba(iv)) measured neutron intensity from metallic deuterated Pd sample irradiated with partly modulated Am/Be neutrons by the Fermi apparatus. An excess of 13.0 ± 0.6 neutrons per sec. has been detected. Assuming 2.45 MeV energy for the neutrons emitted by the irradiated sample, the resulting rate corresponds to several outgoing neutrons for every neutron impinging on the Pd-D sample. Similar measurements with Cd absorber gave lower effects. They did not observe any effect with gaseous deuterium and they considered that the palladium lattice strongly increased the probability of d-d fusion induced by neutrons even the neutrons were almost at rest.

Yamada et al.[34] (II Ba(i)) used point-to-plane electrode configuration in gases with strong DC electric fields. Pd, Ni and tungsten(W) points were used in D_2 and H_2 gas atmospheres. Excess neutron counts were observed in the case of D_2 loaded Pd points under DC high-voltage applications. The observed highest counting rate of 61 counts for 10 seconds from the Pd is equivalent to the neutron emission of $\sim 1 \times 10^5$ n/s · cm^3.

II *Bb. Gaseous Contact with* Ti-D *combination.*

In 1989 immediately after the discovery of the Cold Fusion phenomena, de Ninno et al.[35] tried a new method of loading deuterium into a matrix using Ti metal instead of Pd. Their method was gaseous contact of D_2 with the matrix varying temperature of the sample between room and liquid nitrogen temperatures. They observed several neutron bursts which seemed to occur accidentally. Many experimental efforts were dedicated in this type of experiment.

Angello et al.[36] (II Bb(a)) measured neutron emission from Ti and Pd/D system. The temperature and pressure controls of the gas loading apparatus were improved. The results concerning the Ti/D system showed the presence of a small 2.5 MeV neutron emission with a signal having a statistical significance of $\sim 5\sigma$. The results on the Pd/D system did not show a statistically significant signal ($\leq 2\sigma$).

II *Bc. Gaseous Contact with other materials than* Pd *or* Ti-D *combination*

Research of the Cold Fusion phenomena in variety of matrix were tested other than classical deuterium occluded Pd and Ti. Astonishingly enough, positive results were obtained in several materials. Kaliev et al.[37] (II(I)Bc(iii)) used a tungsten plate cathode and $Na_{0.9}WO_3$/tungsten plate anode, with distance and the DC voltage between the plates 2 mm and 500 ~ 1000 V, respectively. Deuterium (or hydrogen) was introduced into the chamber where is the apparatus till the pressure became 1 mmHg. Neutron flow intensity after deuterium introduction increased sharply and went down to the level of the background in 10 to 20 min. Shirakawa et al.[38] (II Bc(v)) used Litium-Niobate ($LiNbO_3$ as a matrix. Neutron emission was studied in the crushing process of the single crystal sample in deuterium gas atmosphere. They observed excess neutrons 3 counts/h with a confidence level of 99.95 % that corresponds 120 neutrons/h emission from process.

II *C. Discharge, Implantation and Others*

Other loading methods of deuterium into matrix other than the electrolysis and gaseous contact had been tried. They include discharge in D_2 gas and ion implantation.

II *Ca.* Pd-D *combination*

Liang et al.[39] used discharge method to load deuterium into palladium matrix. Discharge is produced by an AC voltage (300 ~ 600 V, 50 Hz) applied between two Pd coaxial electrodes in a glass tube filled deuterium gas with pressure in the range of 0.1 to tens Torr. After 20 minutes discharge cleaning with 350 V AC, the voltage was increased up to 500 V, then the neutron counts are suddenly increased to the level higher than 4 times of the background. Fifteen minutes later, increasing deuterium pressure a little again, the neutron counts rose to a level of 10 times higher than the background. Long et al.[40] (II(V)Ca) also used gas discharge method. Neutron emission whose average rate was 13 ~ 330 n/s and X-ray whose average energy > eU_{max} were continuously detected from a gas discharge reaction bulb, these neutrons were divided into two groups of 2-2.5 MeV and 2.5-7 MeV, the emission of neutron was 100 % reproducible.

II *Cc. Other Materials than* Pd *or* Ti-D *combination*

Long et al.[41] used Pt, Nb, W, Cu, Mo, Ag or Fe as a metal interacting with deuterium gas in a flow discharge bulb. These metals were deposited on the inner surface of glass reaction bulb. The average energy of the neutron detected was 3.55 MeV : different heights of peak appeared at 0.5-1.0, 3.0-3.5, 5.0-5.5, 8.0-8.5, 9.0-9.5 and 10.0-10.5 MeV ; but the neutrons of 2.0-2.5 MeV appeared in a valley of the energy spectrum and their yield was only 7-8% of the total yield of neutrons. The highest yield of neutron appeared in D/Pt system. Intense γ-ray emission was detected at the same time.

2-3 Helium Isotopes

Helium isotopes were also detected in experiments fairly often. ^4He is sometimes observed despite of the generally accepted knowledge of low branching ratio of the reaction (3). Experiments have been done with variety of loading materials and sample compositions. To solve the mysterious detection of ^4He, many theoretical efforts were exhausted including reactions (4) to (7), but we will not touch with this rather sophisticated theoretical investigations in this paper.

III*Ab*. *Electrolysis with any materials*-D *combination.*

Zhang et al.[42] measured ^4He for samples which showed remarkable phenomenon of excess heat by SIMS (secondary ion mass spectrometry) in the experiment with Ti cathode. The special mass peak of 4 amu in SIMS spectra of Ti cathode had been detected by a series of experiments. It was concluded that the mass peak of 4 amu was that of ^4He in Ti cathode produced in cold fusion.

III*Ba*. *Gaseous Contact with* Pd-D *combination.*

Yamaguchi et al.[43] (III(I ,IV)Ba) constructed new *in vacuo* machine with a hetero-structure of deuterated Pd (Pd : D) to detect ^4He *in situ*. The real time observation had been performed. The amount of ^4He gas produced was closely correlated with the evolution of excess heat, and it increased with the loading ratio of D to Pd. At the highest loading ratio, they had observed T production also by detecting HT. The amount of HT increased in the final stage of ^4He production. Alpha particle and proton were also detected.

III*Bc*. *Gaseous Contact with Other Materials than* Pd *or* Ti-D

combination. Sakaguchi et al.[44] used $LaNi_5$ as a matrix for the occlusion of deuterium. They analyzed Helium isotopes (^3He and ^4He) from D_2 or H_2 gases absorbed in $LaNi_5$ with a noble gas mass spectrometer. The reproducible increase in ^3He corresponding to a fusion probability of $> 6.0 \times 10^{-24}$ d-d/s was observed on the D_2 experiment. ^4He production was unreliable.

III*Cc*. *Discharge, Implantation, & others with Other Materials*-D *combination*

Kamada[45] (III(IV)Cc(d)(v)) used electron bombardment to induce nuclear fusion in solids. H^+ and D^+ ion implanted Al thin crystals were bombarded with 200 and 400 keV electrons. H-H and D-D fusion reaction occured producing $1 \sim 2 \times 10^3$ particle emission, including both hydrogen and helium isotopes. Collisions between recoiled D atoms due to the high energy electron impact give only 10^{-12} to 10^{-26} times smaller fusion rates than the data in this experiments. This results suggest the presence of a new kind of fusion reaction which occurs with negligible kinetic energy of the reacting nuclei.

2-4 Tritium

Tritium was also measured with so much amount as explained by the reaction (2). This mistery has been pursued by many reserchers.

IV*Aa. Electrolysis with* Pd-D *combination.*

Bockris et al.[46] (IV(III)Aa) used electrolytic method controlling the total potential applied to the cell. Massive production of tritium at a Pd electrode was measured. Production continued for ~ 750 hours after which time it was arbitrarily curtailed. A logarithmic relation between the rate of tritium production and the overpotential of the electrode reaction was established. Helium production was found to accompany that of T. No ^3He was found but ^4He was measured in nine specimens out of ten examined.

Matsumoto et al.[47] (IV(II)Aa) measured neutron and tritium in the process of D_2O-D_2SO_4 electrolyte with Pd cathode. They detected neutron emission rate not exceeding background rate which was 2 neutrons/cm^2s. The tritium production rate was estimated to be 10^4 T atoms /cm^2s in the Pd metal. The branching ratio (T/n) was estimated to be 10^4.

Stella et al.[48] measured tritium and gamma in the process of D_2O-LiOD electrolysis with Pd cathode. Loading the Pd with variable currents, an elongation of 130 μm in 25 mm sample (with much larger radial broadening) in 25mm sammple was observed in the first few days accompanied by a 60-100% excess tritium detected in the combined water. The measured neutron rate in the same period was consistent with the background. Lee et al.[49] used a U-type and bell jar type electrolytic cells to detect tritium in the process of electrolysis of D_2O. Some electrolysis of LiOD/D_2O in Pt/Pd system with U-type cell showed the increase of T above 100%. In bell jar type closed cell with palladium cathode covered by different porous materials, one cell showed the increase of T activities significantly.

IV*Ac. Electrolysis with Other Materials*-D *combination.*

Srinivasan et al.[50](IV(I)Ac) used nickel as the cathode and aqueous solution of K_2CO_3, Na_2CO_3 and Li_2CO_3 as electrolyte to detect tritium produced in the electrolysis. In some cases, a mixture of H_2O and D_2O was used. Electrolyte samples before and after electrolysis were analyzed for tritium content after microdistillation to eliminate chemiluminescence effects. Samples from 18 out of 29 experiments analyzed have indicated tritium levels varying in the region of 46 Bq/ml to 3390 Bq/ml. One cell with enriched Li_2CO_3 solution in H_2O which was monitored continuously for over a month indicated that tritium generation is continuous. Although the highest amount of tritium produced so far was with a K_2CO_3 in 25% D_2O cell, the generation of tritium in cells containing only H_2O was a new finding.

IV*Ba*. *Gaseous Contact with* Pd-D *system.*

Claytor et al.[51] (IVBa(i)) measured tritium level applying a high pulsed current to Pd sample with gas loading of deuterium. Various configurations of palladium foil or powder and silicon wafers or powder were subject to a high pulsed current. The deuterium at over one atmosphere pressure was circulated in a sealed loop containing the cell and an ionization chamber to measure the tritium as a function of time. A reproducible methode of tritium generation had been demonstrated. The tritium output scales with the current applied to the cells. The tritium yield was found to depend strongly on the type of palladium metal used (powder or foil).

2-5 Radiations (γ, X) and Other particles(p,α)

Radiations and other particles are also the target of researchers to confirm nuclear reaction in solids occluding deuterium. A few experiments were directed in this line.

V*Aa*. *Electrolysis with* Pd-D *combination*

Bush et al.[52] (VAa(c,d)) measured X-ray and heat generation experiments with Pd-D(H) combination in electrolytic experiments. They measured X-rays systematically for both the heavy and light water cases andcorrelated with excess power. They considered that the results strengthened the argument that the light water and heavy water excess heat effects are, indeed, nuclear effects.

Taniguchi et al.[53] measured charged particles from Pd cathode of D_2O electrolysis. The electrolysis was continued at low temperature at 4°C for 3 hours. After then, the cell was warmed up to several ten degrees of Celsius scale. During the warming-up, they caught some anomalous pulse emission of charged particles. The pulse shapes of the bursts were found to be complicated and the duration of the bursts was distributed from 40 to 100 ns. Comparison of these pulse shapes and standard response for a single particle suggested that the burst was a pile-up pulse and consisted of many particles.

Uchida et al.[54] (VAa(b)(i)) measured radioactive emission in the electrolytic deuteriding-dedeuteriding reactions of Pd and Ti with GM counter. For the Pd samples annealed or cold worked, the excess counts higher than BG(background level) by factors 1.5 to 2 in average were measured almost continuously and reproducibly during the pulse modulated electrolysis over 600 mA/cm^2. For the Ti samples annealed or cold worked, the burst-like GM counts over 200 cpm were often measured at low current densities below 10 mA/cm^2. After electrolysis, some GM counts were measured in both cases.

Mo et al.[55](VBa(ii)) measured the charged particles and burst in a loading D_2 gas system as a function of D/Pd ratio. The charged particles bursts were observed at about 20°C (near the transition point 19°C of Pd-D system) when vessel was vacuumed. Chen et al.[56] (VBa(b)(i , ii)) used X-ray film to study anomalous effects of metals loaded with deuterium. The experimental results showed that the sensitization of X-ray film was derived from the chemical reaction and the anomalous effect of the sample.

V*Ba*. *Gaseous Contact with* Pd-D *combination*

Rout et al.[57](VBa(d)) used X-ray film to measure anomalous emission from H/D loaded Pd. Investigations seeking identification of the nature/energy of the detected radiation through transmission measurements using various filters tentatively indicated that the radiations could be low energy electrons having an energy of around 300 to 400 eV.

V*Ca*. *Discharge, Implantation etc. with* Pd-D *combination*

Karabut et al.[58] measured impurity concentration in Pd cathode before and after flow discharge in deuterium gas. They observed 1) Generated excess heat with output a few times larger than input, 2) Weak neutron signals with intensity 10 ~ 10^7/s, 3) weak gamma-radiation with intensity < 10^5/s, 4) Characteristic X-rays with intensity < 10^9/s, 5) Tritium formation, 6) Helium isotopes, mostly 4He with intensity < 10^8/s, 7) Charged particles with high energy up to 10 MeV and more.

Iida et al.[59](VCa(b)) used D implanted Ti and Pd foils. 240 keV deuteron accelerator was used to implantation of deuteron. In addition to the signals from the well-known d-d reaction, they measured 8 MeV helium and some inexplicable weak 3-5 MeV peaks during the deuteron implantation for 20 μm thick foils with alminum-oxide layer on their surface.

V*Cb*. *Discharge, Implantation etc. with* Ti-D *combination*

Kasagi et al.[60] measured energetic protons in the bombardment of 150 keV deuteron on highly deuterated Ti rods. It had been shown that these protons are originated from the D + ^{3}He reaction. The observed spectrum can be explained very well by the sequential reaction process, except for the three cases which require anomalous concentration of ^{3}He in TiD_x.

2-6 Explosion

Explosions were experienced in the process of electrolysis experiments several times. Though the causes of these explosions were not known exactly, some cases were not possible to attribute to chemical origins. Three examples are given here.

VI*Aa*. *Electrolysis with* Pd-D *combination*

Smedley et al.[61] reviewed the accident that occured at SRI International on January 2, 1992. A plausible explanation for the cause of the accident was proposed and recommendations were made pertaining to the safety of future experiments. Zhang et al.[62] reported three explosions in their D/Pd electrolytic experiments which happened in April 1991. They concluded that the explosion was caused by cold fusion in Pd tube after measuring remains of an explosion. Dalun et al[23] reported two experiences of explosion.

§ 3. Theoretical Explanation.

A neutron with an energy $\varepsilon = p^2/2m$ carries a de Broglie wave with a wave length

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2\,m\varepsilon}}. \tag{9}$$

If the energy of the neutron is measured in eV, the wave length in Åis given by the following relation:

$$\lambda = 2.86 \times 10^{-1} \varepsilon^{-1/2}. \quad (\text{Å}) \ (\varepsilon \text{ in eV}) \tag{10}$$

Therefore, a thermal neutron with an energy of 1/40 eV (~ 300 K) has a wave length 1.80 Å comparable with lattice parameters of ordinary crystals. A neutron as a wave is reflected by a boundary of an ordered array of deuterons (and protons) in matrix lattices. The reflection occurs as results of the Bragg reflection and/or the total reflection. The Bragg reflection occurs when the Bragg condition

$$m\lambda = 2d \sin\theta. \tag{11}$$

On the other hand, the total reflection occurs when the θ is smaller than or equal to an critical angle

$$\theta_c = \pi/2 - \sin^{-1} n_r \ (n_r < 1), \tag{12}$$

where $n_r = n_2/n_1$ is the relative refractive index of a medium 2 to a medium 1 and the neutron enters from 1 to 2 in the case of refraction. The refractive index ni of the medium i is given according to the following relation:

$$n_i^2 = 1 - \lambda^2 N_i \bar{a}_{coh}^{(i)}/\pi \tag{13}$$

where N_i is a number of nuclei per unit volume in the medium and $\bar{a}_{coh}^{(i)}$ is a weighted mean of the thermal scattering lengths of the nuclei in it. Because of a positive value of a_{coh} for deuteron, we can expect a total reflection by the occluded deuteron lattice in a matrix. However, because of a negative value of a_{coh} for proton, a neutron will be trapped in an occluded proton lattice surrounded by pure (low impurity) matrix.

Neutrons with energies of the order of the thermal one behave as waves in a solid and are then possible to be reflected by a boundary of an array of occluded deuterons (protons) with a characteristic spacing a_0 when a_0 is comparable with or smaller than λ. If a region with linear dimension L larger than a_0 ($a_0 \leq L$) is bounded by walls of such a structure reflecting neutrons, a neutron might be trapped in the region for a time, say T. The time T will be determined by the state of the walls (atomic species in and widths of the walls, the geometry of the region, etc.).

On the other hand, the transit time τ of a neutron with velocity v is given as follows for the region :

$$\tau = \frac{L}{v} = \frac{mL}{p}. \tag{14}$$

When a condition

$$\tau \ll T \tag{15}$$

Fusion probability is, in the order of magnitude, becomes T/τ times the value where there is no confinement.

Thus, the Cold Fusion is explained as a trapped neutron catalyzed fusion. The scenario of the explanation is summarized as follows :

(a) A particle of ambient (or artificial) neutrons incident on a sample (say inhomogeneous solids which occluded deuterons (or protons)) becomes thermal in an effect of collision with atoms in it and the neutron propagates as a wave through the sample ;

(b) the neutron is trapped as a standing wave in a region bounded by reflecting "walls" made of boundaries of ordered arrays of deuterons (protons) ;

(c) the neutron as a standing wave interacts with one of deuterons (protons) in the region (and in the walls) to fuse into a triton (deuteron),

$$n + d = t\ (6.98\mathrm{keV}) + \gamma (6.25\mathrm{MeV}) \tag{16}$$

$$n + p = d\ (1.33\mathrm{keV}) + \gamma (2.22\mathrm{MeV}) \tag{17}$$

Smallness of the cross section of the reaction (16) (two orders of magnitude smaller than the cross section of d-d fusion in Eqs. (1) and (2)) will be compensated with the large number and trapping of the relevant neutrons ;

(d) the triton produced in the reaction (16) may interact with deuterons in the sample to fuse into ^{4}He and a neutron according to the reaction (8) ;

(e) the high energy neutron produced in the reaction (8) may collide with many deuterons occluded in the matrix and accelerates them to high energy enough to induce d-d fusion reactions (1) and (2) in the sample resulting in excess neutrons or tritons.

(f) γ-ray born in the reaction (16) (or (17)) may induce the pair creation of electron and positron when it passes by a nucleus ;

$$\gamma \rightarrow e^+ + e^- \tag{18}$$

The probability of the pair creation is proportional to Z^2 where Z is the atomic number of the nucleus. The γ-ray also loose it energy by Compton scattering with electrons ;

$$\gamma + e^- \rightarrow \gamma' + e^{-1} \tag{19}$$

The probability of this reaction is proportional to Z.

(g) a lot of tritium is also observed as an intermediate product of this process in the reaction (16) depending on the situation.

We will explain typical experimental results in terms of the trapped neutron catalyzed model given above.

(A) In the experiment done by Bockris et al.[46], Matsumoto et al.[47], Stella et al.[48] and Lee et al.[49], tritium was found as a main product of the Cold Fusion. Their results correspond to the reaction (16) not acompanied with the following reactions (8), (1) and (2), though Bockris et al. measured some amount of ^4He.

(B) Zhang et al.[42] and Yamaguchi et al.[43] observed ^4He as a result of the Cold Fusion. The latter authors observed excess heat and tritium along with ^4He. These data should be explained with reactions (16) and (8).

(C) Neutron is one of the main objects pursued as a reaction product of the Cold Fusion. There are very many data[21~41] including pioneering ones by Jones et al.[2] and de Ninno et al.[35]. Recent experiments show the existence of higher energy neutrons than 2.45 MeV expected in the reaction (1). This is favorable results for the reaction (8) in our interpretation. The explanation of the process given above in (e) may be incompatible with the heat producing process explained above because of the rapidity of the cascade shower including the reactions (18) and (19) and Bremsstrahlung. Perhaps, this is the reason that the simultaneous observation of neutron and excess heat did not occur frequently. The production of the neutrons acompanies several by-products depending on the situation. This is also favorable for our model.

(D) Excess heat is the original problem raised by Fleischmann et al.[1] in the Cold Fusion. There are very many experiments in this genre[3~18]. Reproducibility, raised sometimes as a proof against the phenomena, has been improved largely. Though there are several by-products, such neutrons as Takahashi et al.[10] measured, these data support effectiveness of the reaction (16), (18) and (19) and following procceses of energy conversion to the thermal energy of the matrix. Especially, it might be explained by those reactions that the astonishing phenomenon occured in Pd/D system of large excess heat without remarkable reaction products. As the probability of the reaction (18) is proportional to Z^2, the process is $(46/22)^2 \approx 4.4$ times easier to occur in Pd/D than in Ti/D. Also the probability of the reaction (19) is proportional to Z and the the process is twice easier to occur in Pd/D than in Ti/D. If the process repeat to produce a cascade shower, these differences of the factors 4.4 and 2 in the single reactions will become decisive factors for the excess heat generation.

(E) The experiments done with light water[19,20] seem to indicate the occurence of the reaction (17) in appropriete situation.

Recent experiment[63] has shown that the Cold Fusion occurs in ceramics, too. Proton conductor solids of $SrCeO_3$ structure was used as electrolyte plates maintained at 300 ~ 400°C in the atmosphere of deuterium containing hydrogen gas. An anomalous level of excess heat evolution of the order of 100 W cm^{-3} was observed during absorption/desorption cycles of the atmosphere under application of an alternate electric field.

This result seems to show that the nature of the matrix is irrelevant to the Cold Fusion phenomena and the rather important factor is the inhomogeneity of the material in the matrix. And also, the large excess heat was observed in a matrix containing nuclei with large proton number Z. The trapped neutron catalyzed model is obviously effective to explain this result.

Thus, it is possible to say almost all experimental results are explained consistently at least qualitatively with the trapped neutron catalyzed fusion model.

Direct confirmation of the reactions (16) and (17) is now planned in several institutions in cooperation with us. Finally, from the discrepancy of the data with neutron irradiated homogeneous sample[32] (neutron not trapped by our interpretation) and the Cold Fusion[2] (with trapped neutron), we can estimate the enhancement factor due to the "walls" as follows. The discrepancy of the fusion cross section observed in the experiment[32] was 10^3 in favor of the Cold Fusionwhere high energy neutrons were assumed relevant to the induced fusion. Let us take the energy of the relevant background neutrons as in the range of 100 keV from the observed recoil proton spectrum[32]. The fusion cross section for the reaction (8) with an incident triton energy 6.98 keV is two orders of magnitude smaller than the reaction (1) with incident deuteron energy of 100 keV. So, we can infer that in the experiment[2] the triton flow density was five orders of magnitude larger than the flow density of deuterons accelerated by the ambient neutrons. Therefore, for the sample used in the experiment[2], a relation is obtained,

$$\sum_i P^{(i)}_t P^{(i)}_f \sim 10^5, \tag{20}$$

where $P^{(i)}_t$ is the neutron trapping probability in the i-th trapping region, $P^{(i)}_f$ is the fusion probability of a neutron with a deuteron in the region while the neutron is trapped there, and the summation is over all trapping regions in the sample. In the case of our model, the relevant neutrons include all neutron with energy until less than thermal one and their number occupies a large part in the background counts. So, the number on the right hand side of the relation (20) may be reduced few orders of magnitude.

Let us consider a simple situation where identical cubic trapping regions are distributed uniformly through a sample of Pd metal occluding deuterium according to the line considered in deducing the relation (20). If the size L of the region is ten times a_0 ($L = 10a_0$) and the width of the wall is also L, the number of the region in a sample of 1 mol ($\sim$100 g) is estimated roughly as $10^{24}/8 \times 10^3 \sim 10^{20}$. From the relation (20), we obtain a relation

$$P^{(i)}_t P^{(i)}_f \sim 10^{-15} \tag{21}$$

for each region in this case. If the low energy neutrons in the background spectrum are taken into consideration, the number on the right hand side of this relation may be reduced few orders of magnitude as in the case of relation (20). These numerical relations will be checked recently.

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