TRAPPED NEUTRON CATALYZED FUSION OF DEUTERONS AND PROTONS IN INHOMOGENEOUS SOLIDS

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ABSTRACT

A proposal of a mechanism of the trapped neutron catalyzed fusion of deuterons and protons in inhomogeneous solids[1] had been made to explain the Cold Fusion phenomena in materials occluding the deuterium (hydrogen). In this paper, some detailed analyses of the theoretical problems in the cold fusion are given in terms of the physics of thermal and cold neutrons in the inhomogeneous solids and the cascade shower induced by 6.25 MeV γ-ray in matrix solid. The Cold Fusion phenomena were explained semi-quantitatively and consistently by the trapped neutron catalyzed fusion model.

I. THEORETICAL BACKGROUND

The trial to realize the nuclear fusion on the earth has F. Paneth[2] as a modern pioneer though its root could be traced to the medieval alchemists. In 1989, Fleischmann and Pons[3] have opened a new passage to investigate the problem with a large possibility. Many positive results done until now show the reality of the fusion of deuterons (and protons) in transition metals. The complexity and the poor reproducibility of the experimental results obtained hitherto including the production of large excess heat, neutron bursts, much amounts of ^{4}He and tritium etc. made the Cold Fusion phenomena[1)]one of controversial problems in the history of science. A key to open the door to solve riddles of the Cold Fusion has been neglected by researchers until now is the thermal and cold neutrons existing everywhere abundantly. The neutron is able to fuse with another nucleus without Coulomb repulsion which is the stumbling block to realize d-d fusion by any existing methods. We will see that the difficulty to solve riddles in the Cold Fusion disappears if we take the catalytic role of the thermal and cold neutrons trapped in the sample into our consideration.

We will review the model first and then give theoretical verification of some key points assumed in it.

A. Neutron as a Wave

Neutron behaves as a wave in a situation where the distribution of other object interacting with the neutron have a period a_0 comparable with de Broglie wave length of the neutron. The de Broglie wave length λ is given as

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2m\varepsilon}}. \qquad (1)$$

where $\varepsilon = p^2/2m$ is the energy of the neutron. If the energy of the neutron is measured in eV, the wave length in Å is given by the following relation:

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

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

$$m\lambda = 2d \sin\theta \qquad (3)$$

is satisfied, where m is an integer, θ is the complementary angle of the incident one and d is the lattice spacing. On the other hand, the total reflection occurs when the θ is smaller than or equal to an critical angle

$$\theta_c = \pi/2 - \sin^{-1} n_r \quad (n_r < 1), \qquad (4)$$

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 n_i of

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[1] Perhaps it is necessary to discriminate two phenomena ; the one is the excess heat generation accompanied with particle emission (n, p, t, γ, ^{4}He, ^{3}He, etc.) and the other is without particle emission. We will call the former as the Cold Fusion phenomena. The latter may be explained as a mere chemical reaction or chemical reactions[17] .

the medium i is given according to the following relation :

$$n_i = 1 - \lambda^2 N_i \overline{a}^{(i)}_{coh}/2\pi \tag{5}$$

where N_i is a number of nuclei per unit volume in the medium and $\overline{a}^{(i)}_{coh}$ is a weighted mean of the thermal scattering lengths of the nuclei in it.

For neutrons with energy down to that of cold neutron, n_i differs not much from 1, and the critical angle of the total reflection θ_c is given as follows:

$$\begin{aligned} \theta_c &= \lambda \left(\frac{\Delta}{\pi}\right)^{1/2}, \qquad (6) \\ \Delta &= N_2 \overline{a}^{(2)}_{coh} - N_1 \overline{a}^{(1)}_{coh}. \end{aligned}$$

Therefore, the total reflection is feasible to occur at a boundary between two media with atomic nuclei whose neutron scattering lengths differ very much. The larger the difference in the scattering length, the larger the critical angle of the total reflection.

As a result of Quantum Mechanics, each elementary particle has wave-particle duality, Though we put our eyes only on the neutron, the wave nature of other particles, e.g. deuteron[4] might be relevant with the Cold Fusion phenomenon. The neutron trapping time T is specified for a region surrounded by the neutron reflecting walls and depends on the geometry of the region. Because of a positive value of a_{coh} for deuteron, we can expect a total reflection by the occluded deuteron lattice in a matrix.

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 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:

$$\tau = \frac{L}{v} = \frac{mL}{p}. \tag{7}$$

When a condition

$$\tau \ll T \tag{8}$$

is satisfied in the above mentioned situation, we may say the neutron is trapped in the region. Fusion probability is, in the order of magnitude, becomes T/τ times the value where there is no confinement. In an optimum situation, the neutron could be trapped with a large value of T/τ in the sample making the fusion probability with one of deuterons very high.

B. Scenario of the Cold Fusion

Thus, the scenario of the Cold Fusion in this model is summarized as follows:

(a) A particle of ambient (or artificial) thermal or cold neutrons incident on a sample (say inhomogeneous solids which occluded deuterons or protons) losing its energy in an effect of collision with nuclei in it 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). The trapping occurs as results of the Bragg and/or total reflections:

(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);

$$\begin{aligned} n + d &= t\,(6.98\text{keV}) + \gamma\,(6.25\text{MeV}), \qquad (9) \\ n + p &= d\,(1.33\text{keV}) + \gamma\,(2.22\text{MeV}). \qquad (10) \end{aligned}$$

Smallness of the cross section of the reaction (9) (two orders of magnitude smaller than the cross section of d-d fusion in Eqs. (12) and (13) with appropriate energy) will be compensated with the large number and trapping of the relevant neutrons:

(d) the 6.98 keV triton produced in the reaction (9) may interact with deuterons in the sample to fuse into ^{4}He and a neutron,

$$t + d = {}^4\text{He}\,(3.5\text{MeV}) + \text{n}\,(14.1\text{MeV}) : \tag{11}$$

(e) the high energy neutron produced in this reaction may collide with many deuterons and accelerates them to induce d-d fusion reactions in the sample resulting in excess neutrons or tritons in an optimum situation;

$$\begin{aligned} d + d &= {}^3\text{He}\,(0.82\text{MeV}) + \text{n}\,(2.45\text{MeV}), \qquad (12) \\ &= t\,(1.01\text{MeV}) + \text{p}\,(3.02\text{MeV}) : \qquad (13) \end{aligned}$$

(f) γ-ray born in the reaction (9) (or (10)) may induce the pair creation of an electron and a positron when it passes by a nucleus A;

$$\gamma + A \rightarrow e^+ + e^- + A^*. \tag{14}$$

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

$$\gamma + e^- \rightarrow \gamma' + e^{-\prime}. \tag{15}$$

The probability of this reaction is proportional to Z.

(g) a lot of tritium may also be observed as an intermediate product of this process in the reaction (9) depending on the situation.

In the step (c), it is possible to occur absorption of the neutron by the matrix nuclei. The most probable result of this reaction will be a formation of a stable isotope or a reemission of a neutron in the case of Pd or Ti metal, though other reactions will be possible for other nuclei. Anyway, no remarkable events will occur between the neutron and the matrix nuclei in the case of our present interest.

C. Explanation of Experimental Results

A qualitative explanation of the typical experimental results[3,5~15] obtained hitherto in the Cold Fusion phenomena can be given using the trapped neutron catalyzed fusion model as follows.

First of all, it is recognized that the Cold Fusion phenomena have a stochastic character. Even in positive experiments, the phenomena occur accidentally[2] as emphasized especially in a pioneering work[3]. And it was also emphasized and observed that the non-equilibrium condition is necessary to realize the phenomena[5,6]. These characters are understandable in terms of the stochastic nature of the formation of a trapping region for neutrons in Pd(Ti)-D system depending strongly on the quality of the sample and the condition of the experiments [7,8].

Secondly, the much number of tritium sometimes observed[9,10,12] than expected in the reaction (13) is understandable, if neutrons are trapped effectively in Pd(Ti)-D system and the reaction (9) occurs frequently.

Thirdly, observation of unexpectedly much heat with a little reaction products[4] should be related with the reaction (9) and a successive reactions (14) and (15) in optimum situations. The well-known fact that the large excess heat is more observed in Pd/D system than in Ti/D system may be explained by the higher probability of pair creation (14) and Compton scattering (15) near a nucleus with a larger atomic number Z where the probability is proportional to Z^2 and Z, respectively. So, the reactions (14) and (15) are $(46/22)^2 \approx 4.4$ times and twice easier respectively to occur in Pd/D than in Ti/D. If the process repeat to produce a cascade shower, this difference of the factor 4.4 and 2 in the single reaction becomes decisive factor for the excess heat generation.

Fourthly, the production of a large number of ^{4}He [8,10,11] should be related with the reaction (9) and a successive reaction (11) in an optimum situation. Because of the triton energy 6.98 keV produced in the reaction (9), the rate of the reaction (11) is fairly large in the system.

Fifthly, the neutron bursts observed sometimes[6,8] may be explained as follows; the high energy neutron produced in the reaction (11) collide with many deuterons occluded in the matrix and accelerates them to high energy enough to induce d-d fusion reactions (12) and (13) effectively in the sample resulting in excess neutrons or tritons. This process is competitive with the heat producing process explained above with rapidity of the cascade shower process including the reactions (14) and (15). Perhaps, this is the reason that the simultaneous observation of neutron and excess heat did not occur frequently in Pd/D system.

In addition to the number of neutrons, there is another problem of neutron energy. The neutrons with the higher energy than 2.5 MeV were sometimes observed abundantly in Pd/D[14] and in other metal deuterides[15]. These data may be explained in terms of the neutron generated in the reaction (11).

Though the experimental data on cross sections of neutron interactions with other nuclei are fairly well known, the problems on our hands are new ones - behavior of the light atoms (deuterium and hydrogen) in the more or less inhomogeneous matrix lattice, geometry of submacroscopic regions with homogeneous density of occluded light atoms, neutron reflection and refraction probability at boundaries (walls) of the regions , trapping probability of a neutron in the region with adequate walls, fusion probability of a trapped neutron with a deuteron or other nuclei in the region, fusion of energetic deuteron (or triton(with deuterons in an inhomogeneous solids and behavior of γ-ray induced cascade shower in Pd metal and etc.

II. THEORETICAL INVESTIGATION OF PROBLEMS INVOLVED IN THE MODEL

We will give a theoretical investigation of some problems in the model described above. The region is assumed to be surrounded with ordered deuteron lattices with spacing a_0 parallel to the boundary and a number density of deuteron N.

A. Model Calculation of Neutron Trapping

Neutrons with energies of the order of or less than 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 the wave length λ. If a region with linear dimension L larger than a_0 ($a_0 \le L$) is bounded by walls of such a structure reflecting neutrons, a neutron might be trapped in the region for a time T. The time T will be determined by the state of the walls i.e. atomic species in and widths of the walls, the geometry of the region, etc.

Total reflection

Let us consider a plane boundary between media 1 and 2 through which a neutron passes from 1 to 2. The critical angle θ_c of the total reflection is given by Eq. (6). The thermal scattering lengths a_{coh} are listed in Table 1 for several nuclei along with the number density of nuclei in typical solids.

Table 1: Thermal scattering length a_{coh} (10^{-12}cm) and number density of atoms N (10^{23} cm^{-3}). (numbers with * mean negative values).

	^{1}H	^{2}D	^{7}Li	$_{22}$Ti	$_{28}$Ni	$_{46}$Pd
a_{coh}	0.38*	0.65	0.25*	0.38*	0.87*	0.63
N			0.46	0.57	0.90	0.69

Table 2: The critical angle θ_c (in degree and radian x 10^{-2}) of total reflection for neutrons with $\lambda = 10\mathring{A}$ and specific number of totally reflected neutrons $\Omega_c/2\pi$ (in %)

	PdH	PdD	TiH$_2$	TiD$_2$	NiH	NiD
θ_c°	0.52	0.68	0.67	0.88	0.68	1.20
θ_c	1.8	2.4	2.3	3.1	1.2	2.1
$\frac{\Omega_c}{2\pi}$	1.8	2.4	2.3	3.1	1.2	2.1

Using these data, we can calculate the critical angle θ_c of lattices of occluded deuterons in PdD and TiD$_2$ for a neutron with wave length 10 Å and the results are shown in Table 2. There are also included the specific number of totally reflected neutrons $\Omega_c/2\pi$, assuming an isotropic distribution of neutron velocity where Ωc is the solid angle corresponding to an angular range $0 \leq \theta \leq \theta_c$.

The critical angles for the total reflection in PdH and TiH$_2$ lattices by a boundary between Pd and Ti lattices, respectively, are also listed in this table. An interesting feature occurs in relation with the difference of sign in the scattering length b.

This result shows that a neutron with wave length 20 Å ($E = 2\times10^{-4}$eV $= 2.5$ K) has a critical angle 1.32° in the case of Pd/D system. For an optimum situation where the neutron is in a region surrounded by 270-sided pillar and collides with each side with an angle θ_c, the neutron in the plane perpendicular to the axis of the pillar is completely trapped in this region.

The longer the wave length of the neutron is, the less the number of side of the pillar is needed to satisfy this condition. This is, of course, an extreme example but shows a possibility making the time T very long compared with the transit time τ of the neutron for the region defined by Eq. (7).

Bragg reflection

If a neutron is in a region surrounded by a lattice with spacing d satisfying the condition (3), the neutron with wave length λ can not pass through the lattice and reflected totally by the lattice.

Let us consider a simple example of a one dimensional lattice with spacing d where a neutron travels. From knowledge of the band calculation in solids, it is known that at the wave vector $k = m\pi/d$, there is an energy band gap $\Delta E = 2|V_n|$, where

$$V_n = \frac{1}{d}\int_0^d V(x)\exp(2\pi inx/d)\,dx \qquad (16)$$

and $V(x)$ is the periodic potential for the neutron with a period d.

In three dimensional lattice with $\theta = \pi/2$ and for a value $d = 2$ Å(3 Å), the energy at the center of the gap is given by

$$E(\frac{\pi}{d}) = \frac{\hbar^2}{2m_n}(\frac{\pi}{d})^2 = 5.12\ (2.28) \times 10^{-3}\text{eV}.$$

This value corresponds to the energy of the cold neutron. So, some cold neutrons coming from outside with an energy in the range of $E(\pi/d) \pm |V_n|$ are reflected totally by the lattice:

$$E(\pi/d) - |V_n| < E < E(\pi/d) + |V_n| \qquad (17)$$

The value of $|V_n|$ in a deuteron lattice was estimated to be 0.211 (0.063) $\times10^{-6}$ eV using the Fermi pseudopotential

$$\widehat{V}_N = \frac{2\pi\hbar^2}{m_n} b\,\delta(\boldsymbol{r} - \boldsymbol{R}). \qquad (18)$$

The bound scattering length b is taken as 0.67×10^{-12} cm (for D) in the above calculation (S.W.Lovesey, Theory of Neutron Scattering from Condensed Matter, Vol.1, Oxford U.P.).

The value given above for $\widehat{V}_n$ means that 0.01% of the cold neutrons are trapped by a single gap at $k = \pi/d$. This number of neutrons seems sufficient to explain ordinarily observed amount of excess heat and emitted neutrons from inhomogeneous Pd/D and Ti/D systems if we consider the large number of background neutrons: For instance, in the data of Jones et al.[5] the number of background neutrons above 100 keV is of the order of 10^4 compared with the 2.45 MeV neutrons of 23.2 ± 4.5. Their data indicate that the number of lower energy neutrons is more abundant. This fact supports strongly our hope to explain the Cold Fusion by the trapped neutron catalyzed fusion model.

In the case of the proton, b = - 0.38 $\times10^{-12}$ cm (average value for singlet and triplet states), and $|V_n|$ is 55 % of the deuteron case. If, however, it is possible to use polarized state of proton and neutron, the scattering lengths for triplet and singlet states can be used for effective trapping;

$$b^{(+)} = 1.04 \times 10^{-12}\ \text{cm}, \quad \text{triplet} \qquad (19)$$

$$b^{(-)} = -4.70 \times 10^{-12}\ \text{cm}. \quad \text{singlet} \qquad (20)$$

In the case of singlet scattering, the band gap ΔE becomes wider by a factor of $4.74/0.67 = 7.1$ than in deuteron lattice. In contrast, in the case of the deuteron, the difference of the scattering length is not so large (0.95 and 0.10 $\times 10^{-12}$ cm), and the use of polarized state makes not so large effect as in the proton lattice.

Thus, the neutron is fully trapped in the region surrounded by such lattices in the optimum situations.

From our knowledge of the band structure of electron spectrum in solids, it is possible to infer that the shorter the wave length satisfying the condition (3) for a fixed d is, the wider the energy range of neutrons reflected by the lattice is. So, the longest wave length reflected effectively by this mechanism is d when the neutron collide with $\theta = \pi/2$. Thus, the Bragg reflection is preferable for thermal neutrons with large θ if the Bragg condition (3) is satisfied while the total reflection is for cold neutrons with small θ.

We would like to emphasize here the stochastic nature of the formation of boundaries around a region favorable to trap the neutrons. This nature reflects in the lack of reproducibility of experimental data of the Cold Fusion phenomena, which is one of main reasons the phenomena could not get full confidence from some researchers.

B. Fusion Probability of Low Energy Neutron and a Deuteron

Using an optical model with square well potential, we calculated the fusion cross section of thermal and cold neutrons with a deuteron. The result is shown in Fig. 1. In this figure, the fusion cross section in barns are plotted as a function of neutron energy in eV. This data is consistent with existing data at higher energy (e.g. T.Nakagawa, T.Asami and T.Yosida, JAERI-M 90-099, NEANDC(J)-153/U INOC(JPN)-140/L) and shows $E^{-1/2}$ increase of the capture cross section with decrease of neutron energy. In the process of deceleration in ambient or in matrix, the neutron loses its kinetic energy and becomes thermal or cold neutron having a large probability f trapping and also a large fusion cross section with a deuteron when it is trapped.

This result verifies the assumption of the effective occurence of fusion reaction (9) made in the model[1]. The effect of the neutron trapping (the existence of a standing wave) will work further positive for our model at least by a factor T/τ.

We did not consider a possibility of neutron fusion with matrix nuclei in this paper. In reality, the fusion reaction may occur and the difference of the matrix will influence some features of the Cold Fusion phenomena.

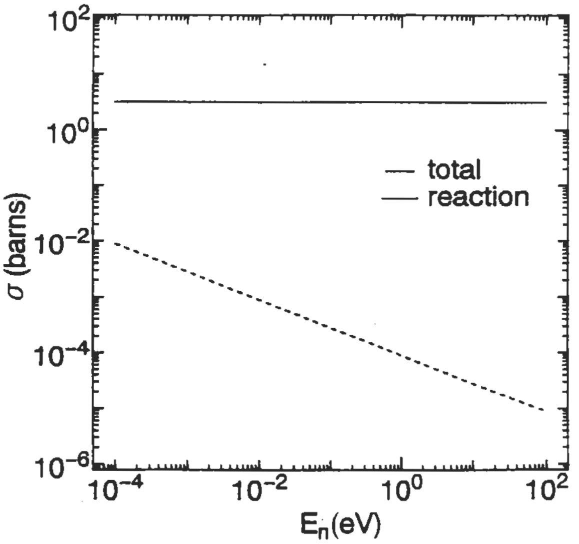

Fig. 1 Fusion and total cross section (barns) of neutron (energy E_n in eV) with a deuteron extrapolated to lower energy using the optical model.

C. Fusion of 6.98 keV Triton with Deuterons occluded in Solids

The triton generated by the reaction (9) in a matrix occluding deuterons has an energy of 6.98 keV. The triton passes through the matrix suffering deceleration and collides with deuterons occluded there. The $t + d$ fusion cross section of the reaction (11) as a function of triton energy E is given by the following formula:

$$\sigma(E) = \frac{A_5 + [(A_4 - A_3 E)^2 + 1]^{-1} A_2}{E[\exp(A_1/\sqrt{E}) - 1]}. \qquad (21)$$

Here, σ is in barns, E in keV, and the coefficients have following values:

$$A_1 = 56.27, \quad A_2 = 7.53 \times 10^4, \quad A_3 = 0.912 \times 10^{-2}, \quad A_4 = 1.076, \quad A_5 = 614. \qquad (22)$$

For the triton energy 6.98 keV, this formula gives the fusion cross section of 3.05×10^{-6} barns.

This result means that in a Pd metal sample (density 12.16 g/cm^3) of 1 mol occluding the same number of deuterium as palladium atoms, the triton suffers about 10^{-6} fusion reactions before it comes out from the sample if we ignore deceleration in the matrix. Slowing down of the triton in the matrix will result in the decrease of $t - d$ fusion probability in the sample.

D. Chain Reaction Process of Fusions Breeding Neutrons

The neutron generated in the reaction (11) may make elastic collision with deuterons in the sample and give them kinetic energy. When the collision is head-on, the neutron loses its 8/9 of the initial energy and on the average its 16/27. A deuteron accelerated by $n-d$ elastic collision makes elastic collisions with other deuterons losing its total initial energy by head-on collision and and about its 5/6 in average in a strong screening case. The cross section of $d-d$ elastic collision $\sigma_{d-d}{}^{(el)}$ is about 10^{-2} barns in this energy range.

Therefore, one 14.1 MeV neutron accelerates $n_d \sim 250\,\sigma_{d-d}{}^{(el)} N_d \overline{v}_d$ deuterons to energy higher than 100 keV where $\overline{v}_d$ is an average deuteron velocity between $E = 14.1 \times 16/27$ MeV and 100keV.

If we take the fusion cross section σ_{d-d} as 10^{-2} barns, the number of $d-d$ fusion reaction is

$$n_d N_d \sigma_{d-d} \overline{v}_d \simeq 250\, \sigma_{d-d}^{(el)} N_d^2 \overline{v}_d^2.$$

Each fusion reaction generates 0.5 neutrons of energy 2.45 MeV. The 2.45 MeV neutron makes 6 elastic collisions with deuterons to accelerate them more energy than 100 keV. Considering $d-d$ elastic collision, one 2.45 MeV neutron causes 70 candidates to realize $d-d$ fusion. The number of $d-d$ fusion thus induced is

$$70\, \sigma_{d-d}^{(el)} N_d^2 \overline{v}_d^2.$$

This process succeeds endlessly to produce neutrons one by one but with limitations by sample size, change of the situation by generated heat, etc. in an optimum situation where the neglect of the slowing down induced by the interaction with the matrix is justified and the number given above is larger than 1. So, in such an situation, the collision of the neutron and deuterons occluded in the sample occurs frequently, and a neutron accelerates about 9 deuterons to higher energies than 100 keV necessary to accomplish $d+d$ fusions (12) and (13) effectively. This process may explain the neutron bursts observed in experiments[6,8] .

Recent experiment[16] shows explicitly effective trapping of the background neutrons by HH, DH and DD molecules. This fact indicates there is another mechanism to trap thermal and cold neutrons in materials occluding protons and deuterons and supports indirectly our assumption of the neutron trapping in inhomogeneous media.

Thus, the neutrons with an energy 2.45 MeV observed sometimes[5] should be explained by the successive reactions (9), (11) and (12). As in the case of $n-d$ fusion, we did not consider interactions of the triton with matrix nuclei which certainly occur with finite probability. We will leave this problem for future.

E. Cascade Shower in Pd and Ti Metal induced by 6.25 MeV γ-ray and Excess Heat

For photons passing through a homogeneous medium of density ρ (g/cm^3) and thickness t (cm), the intensity I remaining is given by the expression

$$I = I_0\, e^{-\mu t} \equiv I_0\, e^{-\rho t/\lambda_m}. \tag{23}$$

Here μ is the mass attenuation coefficient (cm^{-1}), $\lambda_m = \rho/\mu$ is the mass attenuation length (g/cm^2), and I_0 is the initial intensity (number of photons). The data for elements Pb, Fe, Ar, C and H in the energy range from 10^{-2} to 10^2 MeV are given in TRIUMF Kinematics Handbook (Table VII-16). Interpolation to other atomic number Z are done by scaling the cross section (cm^2)

$$\sigma = \frac{A}{\lambda_m N_A}, \tag{24}$$

where A is the atomic weight of the absorber material (g/mol) and N_A is the Avogadro number (mol^{-1}). For a mixture, the formula

$$\lambda_{eff}^{-1} = \Sigma_i f_i \lambda_m{}^{-1} \tag{25}$$

is used, where f_i is the proportion by weight of the i-th component.

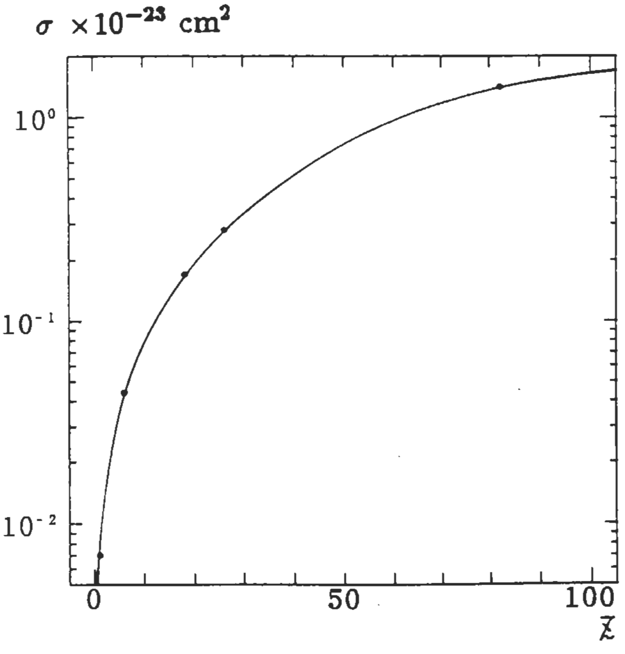

Fig. 2 Cross section of photon absorption by Eq. (29) to interpolate the photon mass attenuation coefficient for Ti and Pd.

The plot of the cross section σ as a function of Z is shown in Fig. 2 for a photon energy $E = 6.25$ MeV. From this figure by interpolation, we can estimate σ for Ti and Pd metals as 0.22 and 0.66×10^{-23} cm^2, respectively.

Table 3: The e-folding length ℓ (cm) of 6.25 MeV photons in Ti and Pd. A (g/mol), σ (barns), λ_m (g/cm^2) and ρ (g/cm^3).

	Z	A	σ	λ_m	ρ	ℓ
H	1	1.00	0.07	23.7		
D	1	2.01	0.14	23.7		
Ti	22	47.9	2.2	36.2	4.5	8.0
Pd	46	106.4	6.6	26.8	12.16	2.2

Table 4: Effective e-folding length ℓ_{eff} of 6.25 MeV photons in hydrides

	λ_{eff} (g/cm^2)	ρ (g/cm^3)	ℓ_{eff} (cm)
TiH	35.8	4.6	7.8
TiH_2	355.5	4.7	7.6
PdH	26.8	12.3	2.2
TiD	35.5	4.7	7.6
TiD_2	34.8	4.9	7.1
PdD	26.7	12.4	2.2

Using these values of σ, we calculated the e-folding length $\ell = 1/\mu$ for the 6.25 MeV photon in Ti and Pd using a relation

$$\ell = \mu^{-1} = \frac{\lambda_m}{\rho}. \tag{26}$$

The result is shown in Table 3.

The effective e-folding length ℓ_{eff} of photon attenuation for hydrides and deuterides of Ti and Pd are given in Table 4, where the volume of the sample is assumed to be the same as the metal without hydrogen isotopes.

This table shows the effect of the hydrogen isotope occlusion on the photon attenuation is not large if the volume change is neglected. The volume change of the order of 5 % observed in the experiments gives density change of the same order to the opposite direction. This change of the density will give the fractional decrease of ℓ_{eff} by the same order of percentage.

The estimated e-folding lengths l of the 6.25 MeV photon in Ti and Pd metals are 8.0 and 2.2 cm, respectively, as shown in Table 3. This result confirms our speculation made above and shows clearly that in Pd the photon created in the fusion reaction (9) lose its energy rapidly and the energy is given mainly to electrons and dissipate to increase thermal energy of the matrix solid. While in Ti matrix, the sample size used usually in the Cold Fusion experiment is not enough to decay the photon in the sample even if the fusion reaction (9) occurs there. This may be the main reason that the large excess heat has not been observed in Ti/D system though fusion products has been observed frequently.

Let us consider an extreme example of the Cold Fusion events; melting of Pd sample with dimension $1 \times 1 \times 1$ cm^3. If all the sample is melted away, the thermal energy to heat it from 0 °C to its melting point (1554 °C) 4.72 kJ and its heat of fusion 1.91 kJ must be supplied by 6.25 MeV photons in our model. So, the number of the photons N_γ for the process is 6.63 $\times 10^{16}$. On the other hand, the number of neutrons generated by $t-d$ fusion N_n in the sample is 1.4 $\times 10^{10}$ neglecting triton deceleration by matrix (minus effect) and the competitive chain process of $d-d$ fusion by deuteron acceleration (plus effect). In this case, we obtain a ratio

$$N_\gamma / N_d \sim 10^7$$

which is a value very close to the experimental result obtained by Fleischmann and Pons[4].

III. CONCLUSION

The discussion given above is not fully quantitative in points that it is not derived only from the first principle and that the absolute value of the numbers of the fusion products and the excess heat generated in Pd/D system is not determined. Not considering the former claim, it is necessary to know the exact situation of the sample and environments in the experiments to solve the latter problem and it is not possible to realize it now. Even so, the Cold Fusion phenomena observed in Pd/D and Ti/D solids are explained consistently in terms of the trapped neutron catalyzed mechanism of deuteron fusion. Especially, successfully explained were several hitherto unsolved problems in the phenomena, such as 1) the stochastic nature of the occurence of phenomena, 2) the large excess heat with a little neutron production[4], 3) the large amount of tritium with no neutron emission[13], 4) the large amount of ^{4}He observed with some amount of heat and tritium[8], 5) the fact that the large excess heat is observed mainly in Pd/D but not in Ti/D system, and 6) the higher energy neutrons than 2.5 MeV observed in several experiments in Pd/D[14] and in other metal deuterides[15].

In addition, 7) the mass number 3 peak in Pd/H system[8] accompanied with excess heat generation might be explained by deuteron formation by neutron - proton fusion (Eq.(10)) and the formation of HD molecules in the system.

Thus, it is possible to say that the Cold Fusion phenomena are the trapped neutron catalyzed fusion of deuterons (protons) occluded in Pd, Ti and other materials in its essential parts. To realize the Cold Fusion, it is desirable to have a submacroscopic structure where deuteron occluding and not occluding regions exist alternatively. A stratified alternative layers of Pd and Oxide is a candidate. Another candidate may be sintered structures of ceramics having characteristics of the proton conductor.

To make the resulting energy of the photons thermal, it is desirable to use elements as large Z as possible in those hydrogen occluding or proton conducting materials.

ACKNOWLEDGEMENTS

The author would like to express his sincere thanks to Dr. J.Guokas of J & J Manufacturing, USA for his information about the recent paper[16] showing trapping of background neutrons by molecules. He would also like to express his thanks to Dr. K.Sasaki of NEDAC for his encouragements and helps obtaining some data during this work. He is also indebted to Messrs. S.Watanabe, Y.Okumura and H.Miyagi of his laboratory for their assistance in correcting errors in the manuscript. Dr. P.Glueck of Institute for Isotope and Molecular Technology, Romania helped the author in bibriography in the final version for whom he is very grateful.

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