Anomalous Nuclear Reactions in Solids Revealed by CF Experiments

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Abstract

Anomalous nuclear reactions in solids detected through events in the so-called cold fusion (CF) phenomenon are investigated from a viewpoint of the TNCF model where interaction of the neutron Bloch waves and a nucleus in crystal boundary plays a key role. Using the experimental facts of nuclear transmutation (NT) in the surface region, it is shown that a compound nucleus, formed by absorption of a neutron, interacting with residual neutron waves has different characteristics responsible to the anomalous reactions observed in the cold fusion phenomenon from those of the isolated compound nucleus. A unified picture of the anomalous nuclear reactions in solids is given on the interaction of the trapped neutron Bloch waves and a lattice nucleus.

1. Introduction

After the discovery of the so-called cold fusion (CF) phenomenon[1] in 1989, there have been observed various events telling anomalous nuclear reactions in solids not noticed before and out of conventional knowledge of nuclear physics which has mainly been developed for nuclei interacting each other in free space. To investigate those anomalous nuclear reactions, there are two fundamental ways; one is in the traditional frames of nuclear and solid state physics based on the quantum mechanics and another in some new frames with such a key to solve them as new principles not known before. We have been working with this problem from a viewpoint on the first way using a phenomenological theory (the TNCF model[2,3]) with success but limited by nature of the model. The result of the pioneering work,[1] which has been sometimes a target of unfair blame, was consistently explained by the TNCF model[1′,1″]) without ambiguity.

The nuclear reactions suggested by events in the CF phenomenon could be considered as signals showing new phases in the characteristics of nuclear interaction in solids. We investigate this problem on the line assumed in the TNCF (Trapped Neutron Catalyzed Fusion) model which has given a consistent phenomenological explanation of various events, the excess heat, tritium, ^{4}He and neutron production and nuclear transmutation observed in compound solids containing hydrogen isotopes. Before investigation of the characteristics of nuclear reaction in solids revealed by CF experiments, it is advisable to review properties of nucleus and nuclear reactions in free space[4] in this section.

1.1 Stability of a Nucleus

The Weizsäcker-Bethe semi-empirical formula (W-B formula) for nuclear ground state energies E of a nucleus (Z, A) (Z, A and N are proton, mass and neutron numbers of the nucleus and $A = N + Z$) is written down[4] as follows:

$$E = -B = -u_v A + 4u_r \frac{T_\xi^2}{A} + 4u_c Z(Z-1)A^{-1/3} + u_s A^{2/3}, \quad (1)$$

where B is the binding energy of the nucleus, $T_\xi \equiv (N - Z)/2$ is *the neutron excess*, $u_v(\simeq$ 14 MeV), $u_r(\simeq$ 18.1 MeV), $u_c(\simeq$ 0.146 MeV) and $u_s(\simeq$ 13.1 MeV) are constants for volume, symmetry, Coulomb and surface energies, respectively.

Using this formula, we can estimate at measures for stability limits of a nucleus (Z, A) against β-decay, α-decay and fission.

1.1a Beta-decay

Using the W-B formula, we can estimate at the energy ΔE_β liberated by β-decay as follows:

$$\Delta E_\beta = +4u_r(T_\xi - \frac{1}{4}) - 8u_c Z A^{-1/3}. \quad (2)$$

The criterion of β-decay, $(Z, A) \to (Z+1, A)$, is therefore given by a relation

$$\Delta E_\beta \leq 0.$$

This criterion gives us a relation between Z and A of a nucleus (Z, A) at the stability limit;

$$Z = \frac{u_r A}{2u_r + 4u_c A^{2/3}}. \quad (3)$$

Assuming a relation for the neutron excess $T_\xi = 0.06\ A$ suggested by the linearly-interpolated empirical relation between A and Z, we obtain the value A of the stability limit against β-decay;

$$A_\beta \simeq 26. \quad (4)$$

This relation should be repaired by selection rules for the β-decay to give the more realistic stability limit.

1.1b Alpha-decay

The splitting of an alpha-particle (2, 4) from a nucleus (Z, A), i.e. a reaction $(Z, A) \to (Z-2, A-2) + (2, 4)$, is energetically favorable if the energy of the emitted alpha-particle ε_α calculated by the W-B formula and given below is positive;

$$\varepsilon_\alpha(Z, A) \equiv -4u_v - 16u_r\frac{T_\zeta^2}{A^2} + 16u_cZA^{-4/3} + \frac{2}{3}u_sA^{-1/3} + B_\alpha \geq 0, \tag{5}$$

where $B_\alpha = 28$ MeV is the binding energy of the alpha-particle.

This relation gives us the stability limit of the mass number A_α against the alpha-decay

$$A_\alpha \simeq 191. \tag{6}$$

The *Coulomb barrier* at nuclear surface works against splitting of an alpha-particle which is lower than that in the case of fission reaction considered below.

1.1c Fission

If the nucleus (Z, A) splits into two nuclei $(\frac{1}{2}Z, \frac{1}{2}A)$ each, the energy ΔE_f liberated in this process is given as follows:

$$\Delta E_f = 4u_c(1 - 2^{-2/3})Z(Z-1)A^{-1/3} - 4u_s(2^{1/3} - 1)A^{2/3}. \tag{7}$$

This relation gives us a relation between A and Z at the stability limit

$$\frac{Z^2}{A} \simeq 1.76, \tag{8}$$

which corresponds to a nucleus with a mass number A_f given as

$$A_f \simeq 80, \tag{9}$$

i.e. a nucleus with a mass number A larger than $A_f = 80$ is unstable for fission, although empirically we know that *the Coulomb barrier* at nuclear surface prevent spontaneous fission of nuclei less than 240:

$$A_{f,spont} \simeq 240. \tag{10}$$

Anyway, there are stability limits for β-decay, α-decay and fission even if the values given above just give measures of atomic numbers beyond which the nucleus (Z, A) is unstable for these transformation channels. The time constants of these channels $(\tau_\beta, \tau_\alpha, \tau_f)$ of a nucleus (Z, A) (or we may write it as ${}^A_Z$M) depend strongly on Z and A due to Coulomb barriers, selection rule and other causes even if the channels are not closed, i.e. energetically allowed.

1.2 Interaction of a Neutron and a Nucleus

A system C consisting of *the incident neutron* n and *the target nucleus* $X(Z, A)$ (or ${}^A_ZX$) consisting of Z proton and $N(\equiv A - Z)$ neutrons, is called *the compound system*. The system C is either in *an excited state* or in *the ground state*. This nucleus, *the compound* *nucleus*, forms a series of *stationary states* with *the excitation energies* 0, E_1, E_2, E_3, $\cdots$. These states are stable and the nucleus would stay indefinitely in one of these states were it not for the electromagnetic radiation, which makes it possible to perform a transition to a lower state with the emission of a photon.

This stability ceases if the excitation energy is larger than S_{min} where S_{min} is the smallest of *the separation energy* S_a of any particle a within the nucleus (or of the fission energy S_f to split the nucleus into two nuclei and some neutrons or of β-ray emission energy S_β, the probability of these processes is usually very small and can be neglected for stable nuclei ${}^A_Z\mathrm{X}$ in free space). If the excitation energy is larger than S_{min}, the spectrum of the nucleus C is a continuum, since then particles a can be split off and can assume any amount of kinetic energy.

All the states of a nucleus except the ground state have a finite lifetime because of the possibility of *radiative transitions* to lower states. The life time of the states with $E > S_{min}$ is merely shortened some more by the possibility of ejection of particles. The reciprocal value of the lifetime τ_s of the level s is the *emission probability* per unit time of a photon or a particle. The emission probability is expressed customarily in energy units by multiplying it by $\hbar$;

$$\Gamma^s = \frac{\hbar}{\tau_s}. \tag{11}$$

Γ^s is also called the "*width*" of level s because of the uncertainty relation between time and energy : $\delta t \delta E \simeq \hbar$.

If the finite lifetime is due to the possibility of different kinds of emissions, the total emission probability Γ^s is the sum of partial probabilities :

$$\Gamma^s = \Gamma^s_{rad} + \sum_a \Gamma^s_a \tag{12}$$

where Γ^s_{rad} is the probability per unit time to emit a photon and Γ^s_a is the same magnitude for a particle a. Γ^s_{rad} is also called "*radiation width*" and Γ^s_a is a "partial width" or a "*particle width*" corresponding to the emission of a. The width of levels with $E < S_{min}$ consists only of the radiation width.

In order to obtain a discrete spectrum of levels with an excitation energy larger than S_{min}, the lifetime must be long enough to make the width Γ^s smaller than *the level distance* D, energy distance to the neighboring levels, i.e.

$$\Gamma^s < D. \tag{13}$$

With sufficient excitation energy E_s, the nucleus C can emit particles a with different energies, corresponding to the different states in which *the residual nucleus* can be left behind. We can thus subdivide Γ^s_a into partial widths :

$$\Gamma^s_a = \sum_{a'} \Gamma^s_{aa'}, \tag{14}$$

where $\Gamma^s_{aa'}$ corresponds to the probability of an emission of a with the special condition that the residual nucleus be left in the state a'.

The relation (12) is rewritten using the concept of "*channel.*" Every decay for which the products are specified completely (including their quantum states) corresponds to a specific channel, which we denote by the letter α. Then, the total width is expressed using the *channel emission probability* or *channel width* Γ^s_α:

$$\Gamma^s = \Gamma^s_{rad} + \sum_\alpha \Gamma^s_\alpha, \tag{15}$$

where the sum is extended over all open channels into which state s can decay. Γ^s_α can be defined as follows ; Let N_s be the population in the excited state s, then $N_s\Gamma^s_\alpha/\hbar$ is the number of decays into channel α per unit time.

There is a simple relation between the level distance D and the level width Γ in a limit of large quantum number.

The period P of the motion is the time after which the initial grouping of particles recurs. The time P is shown, using *the correspondence principle* applicable to highly excited states, intimately connected with the level distance D of the states used in the linear combination when the energies E_n of these states (say their number is N) are expressed using an integer n as follows :

$$E_n = E_0 + \mathrm{n}D. \tag{16}$$

The period of the motion is given as[4)]

$$P = 2\pi\hbar/D. \tag{17}$$

This conclusion holds only if the levels are equally spaced, which is approximately the case in simple systems at high excitation.

The considerations used to deduce relation (17) lose its accuracy in complicated systems like atomic nuclei but they still remain valid qualitatively and can be used for a pictorial description using the average level spacing D instead to equidistant level spacing. Approximately, the time P is of the order of the period of the motion and again we expect the relation

$$P \sim 2\pi\hbar/D. \tag{18}$$

Because the nuclear surface is equivalent to a strong and sudden change of potential, the particle reappeared there is very likely to be reflected at this surface and start the motion inward into the nucleus again. Thus, for existence of well-defined compound states, *the life time* τ_s of the state must satisfy a relation

$$\Gamma^s \equiv \frac{\hbar}{\tau_s} \ll \mathrm{D}. \tag{19}$$

We then obtain an interesting interpretation of the significance of the probability Γ^s_α for the decay through channel α. $\Gamma^s_\alpha/\hbar$ is the probability per unit time that the system decays through the channel α if all other channels are closed by some artifice. $\tau_\alpha = \hbar/\Gamma^s_\alpha$ should, therefore, be the lifetime of the state if only channel a is open. Evidently, this lifetime must be at least of the order P. Because of the reflection of a at the inner side of the surface, τ_a may be larger than P.

Let us call $T(a)$ *the transmission coefficient* toward the outside:

$$T(a) = \frac{\text{No. of particle escape through channel } a}{\text{No. of particle arrive at surface}}. \tag{20}$$

We then get

$$\tau_a \simeq \frac{P}{T(a)}, \tag{21}$$

$$\Gamma_a^s \sim T(a)\frac{D}{2\pi} \tag{22}$$

which shows that the partial width Γ_a^s must be smaller than $D/2\pi$. In order to have well-defined levels, $T(a)$ must be a very small number, making the motion in the state an almost periodic one.

Using wave numbers k of the incident neutron 'outside the nucleus' (or outgoing) and K_0 that of nucleon a inside the nucleus, the transmission coefficient $T_\ell(a)$ of a partial wave with angular momentum ℓ is given generally as[4)]

$$T_\ell(a) \simeq \frac{4k}{K}v_\ell, \tag{23}$$

$$K = (K_0^2 + k^2)^{1/2}. \tag{24}$$

The factor $4k/K$ comes from the reflection at the surface of the nucleus, and the factor v_ℓ expresses the combined effect of the centrifugal and Coulomb barriers. For $\ell = 0$ and no Coulomb barrier (in the case of neutrons), we get

$$\Gamma_a^s \sim 2\frac{k}{K}\frac{D}{\pi}, \tag{25}$$

where k is the wave number of the neutron.

We see from (25) that the neutron width of a level is small compared to the level distance and the relation (13) is satisfied only if $k \ll K$. We do not expect resonances, therefore, if the energy of the compound state is so high that the wave number k of the emitted neutron is of the order of K. Actually, however, the total width Γ^s of a level may become equal to, or larger than, D even at energies where $k < K$, since Γ^s consists of the sum of all partial widths Γ_a^s.

From these and similar considerations,[4)] we can deduce following conclusion on the interaction of a neutron with an energy ϵ and a nucleus with a mass number A.

1.2a Intermediate nucleus, low- and intermediate-energy neutron ($0 \leq \epsilon < 0.5$ MeV)

For intermediate nuclei ($25 \leq A < 80$), the most important reactions with neutrons of low ($0 \leq \epsilon < 1$ keV) or intermediate (1 keV $< \epsilon < 0.5$ MeV) energy, are elastic scattering and radiative capture. *All other reactions are energetically impossible or negligibly* *weak*. Inelastic neutron scattering is not possible since, in general, the first excited state of the target nucleus is several hundred kilo-volt above the ground state. The (n, p) or (n, α) reactions are weak because of the Coulomb barrier which acts as an obstacle to the emission of charged particles with low energy.

1.2b Heavy nucleus, low-energy neutron ($0 \leq \epsilon < 1$ keV)

The only reactions possible for low-energy neutrons ($0 < \epsilon < 1$ keV) on heavy nuclei ($80 < A < 240$) are elastic scattering, radiative capture, and in a very few cases, neutron-induced fission. The effect of the Coulomb barrier prohibiting the emission of charged particles of low energy is even more pronounced than with intermediate nuclei. Only neutrons with $\ell = 0$ can produce any reaction in this group, since the de Broglie wave length $\lambda/2\pi$ is very large compared with radius R of the nucleus ;

$$\lambda/2\pi \gg R.$$

1.2c Heavy nucleus, High-energy neutron ($0.5 \leq \epsilon < 10$ MeV)

When the energy of the incident neutron is of the order of 1 MeV or higher (high-energy neutrons, $0.5 < \epsilon < 10$ MeV), new types of processes occur in reactions between the neutron and heavy and intermediate nuclei. We observe inelastic scattering ((n, n) reaction) and reactions in which charged particles are emitted. The compound nucleus can decay by channels different from the entrance channel. The yields of the (n, p) and (n, α) reactions are naturally very small because of the strong competition of the (n, n) process.

2. Reaction of the Trapped Neutrons (Neutron Bloch Waves) and a Nucleus in Lattices

The present knowledge about two-body nuclear reactions summarized in the previous section can be used to investigate a many-body interaction of trapped neutrons (the neutron Bloch waves) and a lattice nucleus (a nucleus in a crystal lattice) although its exact treatment is too complicated to accomplish in this paper.

2.1 As was shown in the preceding papers,[5~8] probability density of a neutron Bloch wave becomes very large at boundary region where the neutron is reflected by the band structure effect (by mismatching of energies corresponding to the allowed and forbidden bands in the adjacent crystals). For a low energy neutron with energy ϵ, capture cross section by a nucleus is proportional to $1/\sqrt{\epsilon}$ and the nuclear reaction occurs more frequently at the boundary as seen from the consideration of the two-body reaction.

When a large number N of neutrons are in Bloch states in the lowest band in a crystal A, their wave number vectors $\boldsymbol{k}$ differ much in their direction and magnitude while their energy ϵ_k differ little as shown by a model calculation with one-dimensional Kronig-

Penny potential.[5] Then, the wave functions of the neutrons in the crystal B with a forbidden band at ϵ_k are almost the same exponential function and the phases of wave functions in the crystal A are in phase near the boundary (i.e. they are locally coherent each other). Then, the total probability amplitude of N neutrons is N times that of a single neutron and the total probability density is N^2 times that of a single neutron. The similarity of the phase of wave functions diminishes with distance from the boundary in the crystal A and the local coherence is lost in volume of A far from the boundary.

2.2 Let us consider reaction of N neutrons in the lowest band of crystal A and a nucleus ${}^A_Z$M in the boundary region where wave functions of these neutrons have the local coherence.

Because the cross section of the reaction is proportional to the probability density of the neutrons in the energy region we are concerned (up to 10 MeV), the nucleus turns out into a compound nucleus ${}^{A+1}_Z$M* with large probability (cf. Subsection 1-2). When the system is composed of a neutron n and a nucleus ${}^A_Z$M, the compound nucleus ${}^{A+1}_Z$M is left essentially alone and its state s is characterized by the width Γ^s defined and expressed by Eqs. (11) and (15) in the previous section. The width, a characteristic of the compound nucleus expressed as Eq. (25), has a relation with the level distance D. The compound nucleus ${}^{A+1}_Z$M* can in general decay by photon emission, particle (proton or ^{4}He) emission, β-decay, or nuclear fission depending on the criterion given in Subsection 1-1. These processes are characteristics of the nucleus and have general properties described at the end of the previous Subsection 1-2.

In the case of present situation where is many (say N) Bloch neutrons in an allowed band of a crystal interacting with a nucleus ${}^A_Z$M, we have no recipe to treat the reaction occurring there correctly. If we can apply two-body interaction approximation for this situation, the interaction of the Bloch neutrons with a nucleus is replaced by a summation of the interaction between a Bloch neutron and the nucleus. Then, we can simplify the interaction process as follows ; a neutron can be absorbed by the nucleus (cf. Subsection 1.2) and the compound nucleus thus formed interacts with remaining neutrons.

The compound nucleus C $\equiv {}^{A+1}_Z$M* formed by $n - {}^A_Z$M reaction is not left alone but is in a state interacting with remaining $(N - 1)$ neutrons in the band. The interaction of the compound nucleus C with the $(N - 1)$ Bloch neutrons should have strong influence on the decay behavior of C. Because we have no reliable means to treat this problem appropriately, we have to rely on experimental facts seemingly related with it.

We have many data sets of nuclear transmutation obtained in the so-called cold fusion phenomenon which can only be understood as results of nuclear reactions between the mother nucleus in the system and a neutron followed by an α- or β-decays, or nuclear fission of the compound nucleus. We introduce these data sets in Section 3 to use them in Section 4 for investigation of the neutron Bloch wave = lattice nucleus interaction.

3. Anomalous Nuclear Reactions observed in CF Experiments and its Explanation on the TNCF Model

From many various data sets in the cold fusion (CF) phenomenon, we introduce here those showing nuclear transmutation (NT) observed in materials used in the experiments. The product elements and isotopes could only be explained by an assumption of decays or nuclear fission of compound nuclei formed by fusion of mother nuclei and a neutron in the material if we pay respect to present knowledge of nuclear physics. We give possible explanation of NT on a model proposed by us after the introduction of the experimental data sets in this Section.

3.1 The TNCF Model

The so-called TNCF model[2,3] (Trapped Neutron Catalyzed Fusion model) assumes a common origin of the various events in the CF phenomenon, i.e. it does not take a point of view that each event has own cause independent to others. Next, it assumes an existence of *the quasi-stable trapped thermal neutrons*, TN, in solids and express its density by n_n in a unit cm^{-3}. The n_n is a single adjustable parameter in the model and is determined by experimental data using several auxiliary premises on the nature of TN. If number of the events is more than 2 and the parameter is determined uniquely to give consistent explanation of them, then the model shows it effectiveness for the phenomenon. In the process of analysis of more than sixty data sets, we have had no contradictory results which show consistency and effectiveness of the model for CF phenomenon.

The initial origin of the trapped neutron (TN) is assumed as the ambient thermal and epi-thermal neutrons in relation with the fact that there was no CF phenomenon without background neutrons.

3.1a Candidates of Nuclear Reactions in Solids

The quasi-stability of the trapped neutron (TN) means that it does not interact at all with lattice nuclei in solids (or interact very weakly with them). The TN interacts only with nuclei in the surface layer strongly in accordance with the fact that nuclear transmutation occurs in or near the surface layer of samples and this corresponds to its strong interaction with nuclei at the turning point in the classical sense. We use a premise that *the trapped neutron is in thermal equilibrium with lattice and confined in it by reflection at the surface layer where the interaction of TN and a nucleus is described by the same one in vacuum*. This assumption should be supplemented by a fact that the interaction in the surface layer is stronger than that in free space. (See the discussion below Eq. (36).)

3.1b Trigger and Breeding Reactions

It is possible to take up several similar reaction chains to explain various events in systems as shown in our analyses.[2,3,8,9] In this paper, however, we take up only that for Pd/D/Li system as an illustration.

In the Pd/D/Li system, surface layers $PdLi_x$ alloy and/or Li metal with a thickness $\sim$ 1 μm is formed on the Pd cathode in progress of the electrolysis, as shown by experiments, and a reaction of TN and ^6_3Li occurs there as assumed above (*Trigger reaction*):

$$n + {}^6_3\mathrm{Li} = {}^4_2\mathrm{He}(2.1\ \mathrm{MeV}) + t(2.7\ \mathrm{MeV}). \tag{26}$$

The charged particles, especially tritium, generated in this reaction, make collisions and reactions with occluded deuterons (*Breeding reaction*):

$$t(\epsilon) + d = {}^4_2\mathrm{He}(3.5\ \mathrm{MeV}) + n(14.1\ \mathrm{MeV}). \tag{27}$$

(In the calculation, the possible path length of the energetic tritium is assumed as 1 μm, for simplicity.)

The energetic neutron generated in this reaction lose its energy by elastic collisions with d and a lattice nucleus $^A_Z\mathrm{M}$ and make breeding reactions with them generating n and other nucleus (*Breeding reactions*):

$$n(\epsilon) + d = n + d(\epsilon'), \tag{28}$$

$$n(\epsilon) + d = p + n + n - Q, \tag{29}$$

$$n(\epsilon) + {}^A_Z\mathrm{M} = {}^{A+1}_{Z}\mathrm{M}^*, \tag{30}$$

$$n(\epsilon) + {}^A_Z\mathrm{M} = {}^{A-A'+1}_{Z-Z'}\mathrm{M}' + {}^{A'}_{Z'}\mathrm{M}'' \pm Q, \tag{31}$$

$$n(\epsilon) + {}^A_Z\mathrm{M} = {}^{A-A'}_{Z-Z'}\mathrm{M}' + {}^{A'}_{Z'}\mathrm{M}'' + n \pm Q, \tag{32}$$

$$n(\epsilon) + {}^A_Z\mathrm{M} = {}^{A-A'-1}_{Z-Z'}\mathrm{M}' + {}^{A'}_{Z'}\mathrm{M}'' + 2n \pm Q. \tag{33}$$

The energetic deuteron generated in the reaction (28) can fuse with a deuteron or a proton:

$$d(\epsilon) + p = {}^3_2\mathrm{He}(5.35\ \mathrm{keV}) + \gamma(5.49\ \mathrm{MeV}), \tag{34}$$

$$d(\epsilon) + d = {}^3_2\mathrm{He}(0.82\ \mathrm{MeV}) + n(2.45\ \mathrm{MeV}), \tag{35}$$

$$= t(1.01\ \mathrm{MeV}) + p(3.02\ \mathrm{MeV}), \tag{36}$$

$$= {}^4_2\mathrm{He}(26.0\ \mathrm{keV}) + \gamma(23.8\ \mathrm{MeV}). \tag{37}$$

The number of reactions N_M between thermal neutrons with a density n_n and nuclei $^A_Z\mathrm{M}$ in a time interval τ is given by a following relation:

$$N_M = 0.35 n_n v_n n_M V \sigma_{nM} \tau \xi, \tag{38}$$

where $0.35 n_n v_n$ is the flow density of the thermal neutron per unit area and time, n_M is the density of the nucleus ^A_ZM in the reaction region with volume V and σ_{nM} is the cross section of the reaction between n and the nucleus determined in free space. The factor ξ expresses an order of instability of the trapped neutron in the reaction region ; we take $\xi = 0.01$ for reactions which occur in volume and $\xi = 1$ for reactions in surface layer according to the recipe of the TNCF model.[2,3]

The value $\xi = 1$ in the surface layer which shows the reaction there is the same to that in free space, is tentative. There are many theoretical[5~9] and experimental evidences showing strong interaction of the trapped neutron with nuclei in the surface layer suggesting a possibility of $\xi \gg 1$ (up to $\xi \sim 10^5$ in experiments where observed micro-craters on the electrode surface[21,23]). The Eq. (38) shows that the larger the factor ξ, the smaller the parameter n_n calculated from the number of reactions N_M determined in the experiment.

In this model, the reactions (26) and (27) determine relations between amounts N_x of products x in electrolytic system with Li electrolyte as follows :

$$N_Q \equiv Q(\text{MeV})/4.8(\text{MeV}) = N_{He} = N_t \sim 10^6 N_n. \tag{39}$$

It is especially emphasized that these relations obtained by the TNCF model are in accordance with the typical empirical relations determined by data obtained in experiments in one order of magnitude. The path length of the energetic deuteron in the above calculation was assumed as 1 μm, for simplicity. (It should be also pointed out that there are wide diversity in experimental values of ratios of above quantities.)

The abundance of the neutrons with energy more than 3 MeV observed in several experiments has been explained qualitatively by the reactions (27) $\sim$ (29).

3.1c The Values of n_n determined by the Experimental Data

The experimental data sets more than 50 have been analyzed by the TNCF model[2,3] and the result have given consistent explanations of events in the systems with n_n between $10^8 \sim 10^{12}$:

$$n_n = 10^8 \sim 10^{12}\ \text{cm}^{-3}$$

About the value of n_n given above, there are critical arguments from scientists against its large figure as high as $10^8 \sim 10^{12}$ cm^{-3}. As explained above, however, the value of n_n is inversely proportional to the factor ξ. If the value of ξ decreases by a factor 10^{-5} as suggested by experiments[20,22], n_n becomes as low as $10^3 \sim 10^7$ cm^{-3}. It should be noticed, also, that the value is determined for predominant events in experiments and is a value for high times of events. The value should be interpreted as a final result of chain breeding reactions giving typical events initiated by the trigger reaction with initial trapped neutrons.

3.1d Behavior of the neutron Bloch wave at the crystal boundary

It has been shown[6~8)] that the neutron Bloch waves trapped in a crystal bounded by another have local coherence at the boundary region of the two crystals where interaction of a nucleus and the Bloch waves, therefore, becomes very strong if number of the trapped neutron is large. This is the same situation as coherent photons from a laser having peculiar properties than those photons from incandescent lamps.

The neutrons in Bloch states can therefore be responsible to anomalous events observed in CF experiments due to surface reactions.[8,9)]

In this Subsection, we give experimental data where detected new elements and/or isotopes not present in the initial state. Detected representative new element or isotope is given first next to the Subsection title followed by a semicolon and possible reaction responsible to it.

Before introduction of data sets on n-induced nuclear transmutation, we give an analysis of experimental data performed by experienced researchers in US to check the nuclear product ^{4}He in a sample which generated excess heat (Q).

3.1e Typical nuclear reactions confirmed by detection of $^4_2$He by Morrey et al.[10)]

$$^4_2\mathrm{He}\ ;\ ^6_3\mathrm{Li} \rightarrow {}^7_3\mathrm{Li}^* \rightarrow {}^4_2\mathrm{He} + t$$

One of the earliest examples of helium detection was the data by Morrey et al.[10)] After the declaration of the discovery of CF by M. Fleischmann et al.[1)] in 1989, many people tried to check the reality of the cold fusion phenomenon from various points of view. One substantial trial to check the possible nuclear reactions in the system was the search for helium in Pd cathodes which generated the excess heat in the experiment of the pioneers performed by Morrey et al. in six reliable laboratories in US.

The Pd sample supplied by S. Pons was distributed to six laboratories with dummies to blind check the existence of helium in them, the presupposed $d - d$ reaction in volume of the sample suggested it. The result was not decisive to show consistency of the observed amounts of helium and the excess heat (announced by S. Pons). In their analysis,[10)] it was assumed the occurrence of the reaction (37) and existence of whole generated helium in the cathode. (If the responsible reaction occurred in volume, the generated helium was expected to remain in the Pd metal cathode.)

They could not prove that the minimal excess heating in one of the rods (rod 5) reported by M. Fleischmann and S. Pons could be attributed to the formation of ^{4}He on the assumption that the ^{4}He had been generated by the reaction (37).

Their explanation[10)] is as follows : "Rod 5 is reported to have created $1.36 \pm 0.34 \times 10^{11}$ erg of heat. The fusion reaction 2D $\rightarrow$ ^{4}He would generate 2.30×10^{19} erg/g.atom ^{4}He created. Thus, it could require the generation of $5.91 \pm 1.47 \times 10^9$ g. atom ^{4}He (18.9 $\pm$

4.6×10^{-9} g. atom/cm^3 Pd) to generate the heat reported. The quantity of ^{4}He found in rod 5 does not correlated well with the excess heat generated when the rod was electrolyzed. According to our calculations, it would take 36 $\pm$ 25 times as much ^{4}He as was measured to account for the reported excess heat."

Though this result[10)] was sometimes supposed to show a decisive disproof against the cold fusion, we will show its true value for the cold fusion phenomenon below.

Experimental data by Morrey et al.[10)] cited above, accepted as giving strong support to skeptics against the cold fusion, is a result consistent with data obtained afterwards. The reaction generating ^{4}He in Pd/D/Li system should be the reaction (26) instead of the reaction (37).

If the liberated energy 4.8 MeV in the reaction (26), instead of 23.8 MeV as Morrey et al. assumed according to the reaction (37), was thermalized totally in the system, the figure 36 pointed out in the paper[10)] becomes to 179.[10′,10″)] As we know from several data sets,[3,13″)] main part of the ^{4}He generated in the surface Li layer on the Pd cathode goes out into liquid and gas. So, it is reasonable to assume that only a small part (let us take it as 3 %) of the generated ^{4}He remained in the sample in a depth of $\sim$ 25 μm determined by them, showing surface reactions of CF phenomenon. Then, the factor 179 given above reduces to 5.4. This value is comparable to the factor $\sim$ 5 obtained in our analyses of many data sets. The factor $\sim$ 5 might be attributed to reactions in the sample generating the excess heat with other nuclear products but ^{4}He.

3.2 Decay-time shortening of β-decay

There are many data sets showing generation of new elements and isotopes which could only be explained by nuclear transmutation by decay (NT_D) of compound nuclei. In this Subsection, we give data of the nuclear transmutation (NT) by β-decay of compound nuclei formed from stable nuclei in materials by neutron absorption ; $n + {}^{A}_{Z}M \to {}^{A+1}_{Z}M^*$. Some of the β-decays supposed to be relevant with the NT_D have too long decay-time determined in free space to be effective in explanation of the experimental results in CF research. This dilemma should be resolved only by peculiarity of nuclear processes in solids with characteristics responsible to CF phenomenon as treated in Section 4.

Some typical examples of NT_D explained by β-decay of the compound nuclei are introduced below with explanations based on the TNCF model. In the following, decay time τ determined in free space is written in parenthesis after the decay formula assumed to explain the observed isotopes.

3.2a Detection of ${}^{24}_{12}$Mg and ${}^{40}_{20}$Ca by R.T. Bush[11)]

$${}^{24}_{12}\mathrm{Mg}\ ;\ {}^{23}_{11}\mathrm{Na} \to {}^{24}_{11}\mathrm{Na}^* \to {}^{24}_{12}\mathrm{Mg}\ (\tau = 15.0\ \mathrm{h})$$

$${}^{40}_{20}\mathrm{Ca}\ ;\ {}^{39}_{19}\mathrm{K} \to {}^{40}_{19}\mathrm{K}^* \to {}^{40}_{20}\mathrm{Ca}\ (\tau = 1.2 \times 10^9\ \mathrm{y})$$

R. Bush observed the excess heat generation and nuclear transmutation ${}^{23}_{11}$Na $\to$ ${}^{24}_{12}$Mg and ${}^{39}_{19}K \rightarrow {}^{40}_{20}Ca$ in electrolytic systems Ni(alloy)/H/K(Na). In a case of ${}^{40}_{20}Ca$ production with a Ni cathode, cell 45 of their experiment, the average excess heat was $Q = 0.58 \pm 0.15$ J/s and the generated calcium atom was 4.8×10^{18} atoms/15 d. In the case of ${}^{24}_{12}Mg$ production with a Ni alloy cathode, only the relative excess heat to the former case was given as $Q_{Na}/Q_K = 1.90 \pm 0.33$.

It should be noticed that the decay time of ${}^{40}_{19}K$ into ${}^{40}_{20}Ca$ by β-decay is known as $\sim 10^9$ y in nuclear physics.

The data set by R.T. Bush[11] was analyzed using the TNCF model.[11] The TNCF model predicts following reactions (decay time) between the trapped neutron and alkali metals :

$$n + {}^{23}_{11}Na \rightarrow {}^{24}_{11}Na^* \rightarrow {}^{24}_{12}Mg + e^- + \bar{\nu}_e + Q, \ (15.0 \text{ h})$$

$$n + {}^{39}_{19}K \rightarrow {}^{40}_{19}K^* \rightarrow {}^{40}_{20}Ca + e^- + \bar{\nu}_e + Q'. \ (1.2 \times 10^9 \text{ y})$$

In these reactions, the absorption cross sections are 0.82 and 3.2 b, and the liberated energies Q and Q' including accompanying gamma are 2.72 and 2.78 MeV, respectively.

If we can assume that the decay time of the second reaction of 1.2×10^9 y is largely shorten by interaction with the neutron Bloch waves to a value of the order of few hundred hours (let us take as 10^2 h), the experimental data showing generations of ${}^{24}_{12}Mg$ and ${}^{40}_{20}Ca$ are explained by the TNCF model with values of the parameter n_n given as follows :

$$n_n = 5.3 \times 10^{11} \text{ cm}^{-3}, \ ({}^{24}_{12}Mg)$$

$$n_n = 5.3 \times 10^{10} \text{ cm}^{-3}. \ ({}^{40}_{20}Ca)$$

We have to remember that the decay time of ${}^{40}_{19}K$ in this calculation was assumed to be largely shortened from the value determined in free space. This decay time shortening was noticed also in other elements as ${}^{107}_{46}Pd \rightarrow {}^{107}_{47}Ag$ in experimental data (as introduced below in 3.2d).

3.2b Detection of ${}^{86}_{38}Sr$ and ${}^{88}_{38}Sr$ by R.T. Bush and R. Eagleton[12]

$${}^{86}_{38}Sr \ ; \ {}^{85}_{37}Rb \rightarrow {}^{86}_{37}Rb^* \rightarrow {}^{86}_{38}Sr \ (\tau = 19.5 \text{ d})$$

$${}^{86}_{38}Sr \ ; \ {}^{87}_{37}Rb \rightarrow {}^{88}_{37}Rb^* \rightarrow {}^{88}_{38}Sr \ (\tau = 17.8 \text{ m})$$

R.T. Bush and R. Eagleton observed the excess heat and the nuclear transmutation of Rb into Sr in $Ni/H_2O + Rb_2CO_3$ system (with Ni sponge cathode).[12] The reaction supposed to occur in the system was that of Eq. (30) with rubidium isotope ${}^{A}_{37}Rb$,

$$n + {}^{A}_{37}Rb = {}^{A+1}_{37}Rb^* = {}^{A+1}_{38}Sr + e^- + \bar{\nu}_e,$$

in the surface layer of Rb on the Ni cathode. Natural abundance of ${}^{85}_{37}Rb$ and ${}^{87}_{37}Rb$ are 72.15 and 27.85 % and decay times of ${}^{86}_{37}Rb$ and ${}^{88}_{37}Rb$ are 19.5 d and 17.8 m, respectively.

They observed decrease of the isotope ratio ${}^{88}_{38}Sr/{}^{86}_{38}Sr (\equiv 1/\eta)$ from the original value of $1/\eta)_{orig} = 8.5$ to $1/\eta)_1 = 3.5$ when the excess heat was Q_1 and to $1/\eta)_2 = 2.7$ when it was

Q_2 (= $5Q_1$).

We give a result of the analysis of this experimental data set by R.T. Bush and R. Eagleton[12] on the TNCF model.[12'] The analysis[12'] gives the following value for the adjustable parameter n_n :

$$n_n = 1.6 \times 10^7 \text{ cm}^{-3}.$$

Correlation of the excess heat and NT was explained quantitatively in a factor of 3.

3.2c Detection of $^{28}_{14}Si$ by M. Okamoto et al.[13]

$$^{28}_{14}\text{Si}\ ;\ ^{27}_{13}\text{Al} \to {}^{28}_{13}\text{Al}^* \to {}^{28}_{14}\text{Si}\ (\tau = 2.3 \text{ m})$$

M. Okamoto of Tokyo Institute of Technology, Japan had been working with Pd/D/Li system. In an experiment,[13] M. Okamoto et al. observed the excess heat and the changes of key and minor elements in the surface region of the cathode. We take up here, the nuclear transmutation from Al into Si in the surface layer with a thickness ~ 1 μm on the cathode in Pd/ D_2O + LiOD system.[13] The change of the density of the elements (up to 80 % for Al) occurred in the surface layer as shown in their figures. The natural abundance of $^{27}_{13}Al$ is 100 % and the decay time of $^{28}_{13}Al$ is 2.3 m.

We give a result of the analysis[13'] of the experiment by M. Okamoto et al.[13] The result of the calculation gives following values for the parameter n_n and the ratio of events N_Q/N_{NT} :

$$n_n \sim 10^{10} \text{ cm}^{-3},\ N_Q/N_{NT} \sim 1.4.$$

In the calculation of the number of events inducing the nuclear transmutation N_{NT}, we assumed the same value ~ 10^{22} s^{-1} of N_Q in this experiment as in an experiment[13''] by M. H. Miles et al. because of the similarity of the both experimental conditions. This value of N_Q/N_{NT} shows that the number of events generating the excess heat and the nuclear transmutation are almost the same in this case within the assumption made above.

3.2d Detection of $^{107}_{47}Ag$ by I. Savvatimova et al.[14]

$$^{107}_{47}\text{Ag}\ ;\ ^{106}_{46}\text{Pd} \to {}^{107}_{46}\text{Pd}^* \to {}^{107}_{47}\text{Ag}\ (\tau = 6.5 \times 10^6 \text{ y})$$

Savvatimova et al. have been working in the glow discharge experiments with D_2 and other gases and with cathodes of Pd and other transition metals (the cathode was a film with thickness of 100 μm). They measured the excess heat, NT (nuclear transmutation) of various isotopes and elements in the surface layer of the multi-layer cathodes. After the discharge of 4 hours, the sample was sent to SIMS (Secondary Ion Mass Spectrometry) and was analyzed its isotope composition there about 3 months later to give the data discussed below.

Here we take up only one data set of an increase of $^{107}_{47}Ag$ from 20 to 5000 ppm on the surface of the Pd cathode in the glow discharge with D_2 gas. This data seem to be explained by following reactions:

$$n + {}^{106}_{46}\mathrm{Pd} \rightarrow {}^{107}_{46}\mathrm{Pd}^* \rightarrow {}^{107}_{47}\mathrm{Ag} + e^- + \bar{\nu}_e.$$

The decay time of ${}^{107}_{46}$Pd is known as $\sim 6.5 \times 10^6$ y in nuclear physics.

An analysis of this data set was performed[14'] assuming the decay time shortening (discussed in Subsection 3.2a) of ${}^{107}_{46}$Pd in the surface layer. Assuming continuous production of ${}^{107}_{47}$Ag by n – ${}^{106}_{46}$Pd fusion reaction through 3 months at the surface layer of the cathode by the decay time shortening of ${}^{107}_{46}$Pd* to less than few days, we obtain a following value for the density of the trapped thermal neutron:

$$n_n = 9 \times 10^{10}\ \mathrm{cm}^{-3}.$$

3.2e Detection of Ag and Au by J. Dash et al.[15]

$$\mathrm{Ag}\,;\ {}^{109}_{46}\mathrm{Pd} \rightarrow {}^{109}_{46}\mathrm{Pd}^* \rightarrow {}^{109}_{47}\mathrm{Ag}\ (\tau = 13.6\ \mathrm{h})$$

$$\mathrm{Au}\,;\ {}^{196}_{78}\mathrm{Pt} \rightarrow {}^{197}_{78}\mathrm{Pt}^* \rightarrow {}^{197}_{79}\mathrm{Au}\ (\tau = 18\ \mathrm{h})$$

There were two kinds of the Pd cathodes used in the experiment by Dash et al.[15] The Pd cathodes were (A) a cold-rolled 0.35 mm-thick poly-crystalline sheet and (B) a 5.5×10^{-2} mm thick foil. The anodes were Pt foils of 3×10^{-2} mm thickness in both cases.

Experiment A with a recombination catalyst and Pd sheet of 0.35 mm thick.

Pd cathodes were a) in H_2O and b) in D_2O. In both experiments, Au and Pt were detected on the concave side of the Pd cathodes.

Experiment B with Pd foil of 0.055 mm thick and without recombination catalyst.

The same cells used in Experiment A were used in series with the same electrolytes (0.06 mol fraction H_2SO_4) but without the recombination catalyst. The two identical open electrolytic cells were run in series, using 0.03 mm Pt foil anodes and 0.055 mm Pd foil cathodes. The electrodes were made from the same lots used for the electrodes in Experiment A.

We take here only the most effective reactions involving ${}^{196}_{78}$Pt with a large natural abundance in Pd surface layer condensed from solution;

$$n + {}^{196}_{78}\mathrm{Pt} = {}^{197}_{78}\mathrm{Pt}^*,$$

$${}^{197}_{78}\mathrm{Pt}^* = {}^{197}_{79}\mathrm{Au} + e^- + \bar{\nu}_e + 0.719\ \mathrm{MeV},$$

Using the fusion cross section 0.6 b for this reaction and above values for experimental parameters, we obtain a value of the parameter n_n as follows:

$$n_n = 3.8 \times 10^{12}\ \mathrm{cm}^{-3}.$$

The natural abundance of the isotope ${}^{196}_{78}$Pt is 25.3 % and the cross section for a thermal neutron is 0.6 b. The decay time of ${}^{197}_{78}$Pt is 18 h.

Using this value of n_n, we can calculate expectation value of the excess heat Q_{th} as

$$Q_{th} = 2.4 \times 10^6 \text{ J},$$

compared with the experimental value $Q_{exp} = 6.4 \times 10^5$ J.

2) Analysis of Experiment B

According to the experimental data showing Ag production, we take the average composition of the surface layer as $Pd_{0.85}Pt_{0.15}Ag_x$ ($x < 0.001$). To treat the generation of Ag (mass number not identified in the experiment) from the Pd cathode, we use only the most effective reaction between a trapped neutron and an isotope ${}^{108}_{46}Pd$ in the surface layer for its large abundance and cross section:

$$n + {}^{108}_{46}\text{Pd} = {}^{109}\text{Pd}^*,$$

$${}^{109}_{46}\text{Pd}^* = {}^{109}_{47}\text{Ag} + e^- + \bar{\nu}_e + 1.166 \text{ MeV}.$$

The natural abundance of the isotope ${}^{108}_{46}Pd$ is 26.71 % and the reaction cross section for a thermal neutron is 8.69 b. The decay time of ${}^{109}_{46}Pd$ is 13.6 h.

Using the experimental data of NT that Ag generation of $100x$ % in the surface layer (with a parameter x) and assuming $\xi = 1$ there and taking the value of the unknown experimental parameter x as the maximum 0.001 in the assumed range of values, we obtain following values for the parameter n_n and the expectation value of the excess heat Q_{th}:

$$n_n = 3.6 \times 10^{11} \text{ cm}^{-3},$$

$$Q_{th} = 1.7 \times 10^3 \text{ J}.$$

This value for the excess heat is compared well with the experimental value $Q_{exp} = 1.8 \times 10^3$ J. The accordance of the expectation and the experimental values of the excess heat in this case is very good although the ambiguity in the value of x is large (one order of magnitude).

3.3 Decay-time shortening of α-decay

There are a few data sets showing the nuclear transmutation (NT_D) by α-decay of compound nuclei formed from stable nuclei in materials by neutron absorption. Some of the α-decays supposed to be relevant with the NT is improbable or have too long decay-time determined in nuclear physics in free space to be effective in explanation of the experimental results in CF research. Reality of the experimental data obtained in CF materials is a sign of peculiarity of nuclear reactions in solids with characteristics endowed by techniques in CF experiments.

Some typical examples of NT explained by α-decay of the compound nuclei are introduced below.

3.3a Detection of C by H. Yamada et al.[16)]

$$C ;\ {}^{16}_{8}O \rightarrow {}^{17}_{6}O^* \rightarrow {}^{13}_{6}C + {}^{4}_{2}He \text{ (stable)}$$

To confirm the cold fusion phenomenon under glow discharge condition, a point-to-plane electrode configuration for highly non-uniform electric field in slightly pressurized (2 atm) deuterium gas was employed by Yamada et al.[16)] of Iwate University, Japan. A neutron burst took place in 2 runs out of total 37 runs.

Using an optical microscope, black deposit was observed covering the tip surfaces of two positive Pd electrodes which was used in the runs with neutron bursts. X-ray photo-electron spectroscopy (XPS) have revealed the black deposit to be carbon, mixed with palladium on the surface of Pd point electrode. The total amount of carbon impurity in the Pd electrode and in environment deuterium gas did not account for the large amount of carbon on the tip surface of electrode.

The analysis[16')] on the TNCF model of the experimental data set by Yamada et al.[16)] gave us a possible reaction and a following value of the parameter n_n :

$$n + {}^{16}_{8}O = {}^{17}_{8}O^* = {}^{13}_{6}C + {}^{4}_{2}He - 4 \text{ MeV}, \tag{40}$$

$$n_n = 2.0 \times 10^{12}\ \text{cm}^{-3}.$$

The above reaction has a threshold energy $\sim$ 4 MeV and a cross section $\sim 1 \times 10^{-1}$ b for a neutron with energy larger than 4 MeV, which is assumed to be generated by such breeding reactions as (32) $\sim$ (34) induced by thermal and energetic neutrons as discussed in Section 3.4 below.

3.3b Observation of ${}^{10}_{5}B$ by T.O. Passell[17)] (Decrease of ${}^{10}_{5}B$)

$${}^{10}_{5}B ;\ {}^{10}_{5}B \rightarrow {}^{11}_{5}B^* \rightarrow {}^{7}_{3}Li + {}^{4}_{2}He\ (\tau = 0.03 \text{ s})$$

A Pd cathode with a total surface area 60 cm^2 and a thickness 25 μm (with a weight 0.9 g) used in an experiment with an electrolytic solution D_2O + 1.0 M LiOD + 200 ppm Al producing the excess heat of 0.56 MJ was subjected upon comparing measurements of the prompt gamma activation analysis (PGAA) using thermal neutrons in beams from research reactors. A result showed an $\sim$ 18 % reduction in the boron impurity ${}^{10}_{5}B$ in the Pd cathode.

The data set by P.O. Passell[17)] introduced above had been analyzed on the TNCF model[17')] giving a consistent explanation of this and those excess heat data obtained in SRI International assuming following reactions between the trapped neutron and the ${}^{11}_{5}B$ (with natural abundance of 81 %) with a large cross section of 3.84×10^3 b as a whole and the succeeding α-decay of ${}^{12}_{5}B$;

$$n + {}^{10}_{5}B = {}^{11}_{5}B^* = {}^{7}_{3}Li + {}^{4}_{2}He + Q, \tag{41}$$

$$= {}^{7}_{3}\text{Li} + {}^{4}_{2}\text{He} + \gamma\,(0.48\ \text{MeV}) + Q, \qquad (42)$$

where $Q = 2.79$ MeV. The branching ratios of these reactions are 0.93 and 0.07, respectively and the decay time of ${}^{11}_{5}\text{B}$ is 0.03 s.

The determined value of n_n was about $10^9\ \text{cm}^{-3}$ consistent with the value obtained in the analysis[17'')] of the data set of the excess heat by SRI International:

$$n_n \sim 10^9\ \text{cm}^{-3}.$$

3.3c Observation of ${}^{53}_{24}\text{Cr}$ and ${}^{108}_{46}\text{Pd}$ by T. Mizuno et al.[18)] (Reduction of elements)

$${}^{52}_{24}\text{Cr}\,;\ {}^{52}_{24}\text{Cr} \rightarrow {}^{53}_{24}\text{Cr},$$

$${}^{50}_{24}\text{Cr} \rightarrow {}^{51}_{24}\text{Cr}^* \rightarrow {}^{47}_{22}\text{Ti} + {}^{4}_{2}\text{He}, \ (\tau = 27\ \text{d})$$

$${}^{108}_{46}\text{Pd}\,;\ {}^{108}_{46}\text{Pd} \rightarrow {}^{109}_{46}\text{Pd}^* \rightarrow {}^{105}_{44}\text{Ru}^* + {}^{4}_{2}\text{He}. \ (\tau = 13.6\ \text{h})$$

From the experimental data set by T. Mizuno et al.,[18)] we take up here only data on ${}^{52}_{24}\text{Cr}$ and ${}^{108}_{46}\text{Pd}$ in Pd/D/Li system.

Isotope ratio of ${}^{52}_{24}\text{Cr}$ observed in the surface layer showed a reduction from 83.8 % (natural abundance) to 50 % through an electrolysis of 30 days. We assume that the cause of the isotope change was a reaction between the trapped neutron and one of Cr nuclei with the natural abundance (origin of which is ambiguous at present)

$$n + {}^{52}_{24}\text{Cr} = {}^{53}_{24}\text{Cr}^* = {}^{53}_{24}\text{Cr} + \gamma$$

The cross section of this reaction is 0.764 b. Then, we can calculate the parameter n_n by the above change of the isotope ratio occurred in the duration of the electrolysis of 30 days as follows:

$$n_n = 2.6 \times 10^8\ \text{cm}^{-3}.$$

There were many data of NT with decreasing mass number in the paper[18)] not easy to explain without reactions induced by neutron absorption. We might be able to treat these cases by such reactions as (31) ~ (33) induced by thermal or high energy neutrons as follows:

$$n + {}^{A}_{24}\text{Cr} = {}^{A-3}_{22}\text{Ti} + {}^{4}_{2}\text{He} - Q,$$

$$n + {}^{A}_{46}\text{Pd} = {}^{A-3}_{44}\text{Ru} + {}^{4}_{2}\text{He} - Q'.$$

It is noticed that the last reaction has been used to produce Ru in technology.

3.4 Threshold energy lowering of *n*-induced fission

There are very many data sets showing generation of new elements and isotopes which could only be explained by nuclear transmutation by fission (NT_F) of compound nuclei. In this Subsection, we give typical data of the nuclear transmutation by a fission of compound nuclei formed from stable nuclei in materials by neutron absorption. Many of the fission supposed to be relevant with the NT have too high threshold energy Ethr determined in free space to be effective in explanation of the experimental results in CF research. This dilemma should be resolved only by peculiarity of nuclear reactions in solids with characteristics responsible to CF phenomenon.

Some typical examples of NT to be explained by fission of the compound nuclei are introduced below.

3.4a Detection of $^{64}_{30}Zn$ by G.S. Qiao et al.[19]

$$^{64}_{30}\mathrm{Zn}\ ;\ ^{108}_{46}\mathrm{Pd} \to {}^{109}_{46}\mathrm{Pd}^* \to {}^{64}_{30}\mathrm{Zn}\ (+\ ^{45}_{16}\mathrm{S}^* + 2n)\ (E_{thr} \geqq 9.5\ \mathrm{MeV})$$

Experiment on the Pd/D_x and Pd/H_x systems[19] were performed in a stainless steel Dewar with a piece of incandescent tungsten filament in it. The vacuum annealed palladium wire (900 °C in a pressure of 10^{-3} Pa for 3 hours) was sealed in the Dewar and hydrogen isotope gas with a pressure of less than 1 atm was filled.

After one year of loading and de-loading process of the above experiment, the resistance of the palladium wire increased to 5.5 ohms from the initial value of 2.7 ohms meaning that the atomic loading ratio, H/Pd, should be close to 0.74.

The element composition was measured at six points from the surface (Point 1) to the center (Point 6) of the Pd wire with a diameter of 3.4×10^{-2} cm (= 340 μm). Point 4 is at 40 μm from the surface and Points 5 and 6 are in the central region.

Two tables (Tables 1 and 2 of G. Qiao et al.[19]) showing changes of the element composition show the large change of element composition of Pd and Zn, if it correlate, could only be explained by nuclear transmutation by a fission (NT_F), in the surface region of the sample.

In the data of the nuclear transmutation obtained by G. Qiao et al.,[19] we take up only that of zinc (Zn) and analyze it by the TNCF model. The probable reaction inducing the transmutation of Pd into Zn is a type of the reaction (31) and written down as follows:

$$n + {}^{A}_{46}\mathrm{Pd} \to {}^{A+1}_{46}\mathrm{Pd}^* \to {}^{A'}_{46}\mathrm{Zn} + {}^{A+1-A'}_{16}\mathrm{S} \tag{43}$$

with $A = 102 - 110$ and $A' = 64 \sim 70$ for stable isotopes and therefore

$$A + 1 - A' \equiv A'' \geq 32.$$

The cross section σ for the absorption reaction in the above reaction ranges from 0.2 to 20 barns; σ = 3.36, 0.52, 20.25, 0.30, 8.50 and 0.23 b for A = 102, 104, 105, 106, 108 and 110, respectively. Assuming the intermediate nucleus $^{A+1}_{46}Pd^*$ in the above reaction is unstable and decays by and by into Zn and S, we can calculate the number of Zn atoms N_{Zn} generated in a time τ as a function of the density of the trapped neutron n_n by the relation of the type (38).

Using an average value $N_{Zn} = 4.065 \times 10^{-3} n_{Pd} V$ of the experimental data at Points 1 to 4 (therefore $V = (1.7^2 - 1.3^2) \times 10^{-4}\,\mathrm{cm}^3 = 1.2 \times 10^{-4}\,\mathrm{cm}^3$ per unit length of the Pd wire) generated in $\tau = 1$ y ($= 3.15 \times 10^7$ s), we obtain the parameter n_n as follows ($\xi = 1$ in Eq. (38) is assumed);

$$n_n = 9.9 \times 10^8\,\mathrm{cm}^{-3}. \qquad (44)$$

Thus, the curious result of Zn generation from the heated Pd wire in H_2 in the process of the loading and de-loading process of hydrogen isotopes observed by G. Qiao et al.[19] has been explained as a result of nuclear fission reaction triggered by the trapped neutron assumed in the TNCF model.

3.4b Detection of ${}^{57}_{26}\mathrm{Fe}$ by T. Ohmori et al.[20]

$${}^{57}_{26}\mathrm{Fe}\,;\ {}^{197}_{79}\mathrm{Au} \rightarrow {}^{198}_{79}\mathrm{Au}^* \rightarrow {}^{57}_{26}\mathrm{Fe}\ (+\ {}^{141}_{53}\mathrm{I}^*)\ (E_{thr} \geqq ?\ \mathrm{MeV})$$

A group in Hokkaido University, Japan have been working with the light water system. T. Ohmori et al. observed NT, i.e. increases of ${}^{57}_{26}\mathrm{Fe}$ and ${}^{54}_{26}\mathrm{Fe}$, generation of C and S, in light water electrolysis with electrodes Au and Pd and electrolytes Na_2SO_4, K_2CO_3 and KOH in H_2O. There were observed micro-craters of diameters $\sim 20\ \mu$m and heights $\sim 30\ \mu$m on the surface of cathodes.

In the electrolysis with a gold electrode and an electrolyte Na_2SO_4 (or K_2SO_4, K_2CO_3, KOH) in H_2O for a week, a notable amount of iron atoms in the range of 1.0×10^{16} to 1.8×10^{17} atoms/cm^2 are detected at surface together with the generation of a certain amount of excess energy. The isotopic abundance of iron atoms, measured at the top surface of a gold electrode, are 6.5, 77.5 and 14.5 % for ${}^{54}_{26}\mathrm{Fe}$, ${}^{56}_{26}\mathrm{Fe}$ and ${}^{57}_{26}\mathrm{Fe}$ and are obviously different from the natural abundance of 5.84, 91.68 and 2.17 %, respectively. The content of ${}^{57}_{26}\mathrm{Fe}$ tends to increase up to 25 % in the more inner layers of the electrode.

This Experimental data set by T. Ohmori et al. is an example out of many reporting the nuclear transmutation with large shifts of mass and atomic numbers.

From experimental data sets obtained by T. Ohmori et al.[20] introduced above, we can imagine that the threshold energy of those elements like Ni, Pd and Au, where observed NT_F, is lowered largely down to few MeV or less which is possible energy to have the particles generated in the trigger and breeding reactions (26) $\sim$ (37) in the TNCF model.

We can cite an example of energy balance in the fission of a gold isotope ${}^{198}_{79}\mathrm{Au}$ into iron (Fe) and iodine (I) in vacuum (though we don't know the branching ratio of this channel):

$$n + {}^{197}_{79}\mathrm{Au} \rightarrow {}^{57}_{26}\mathrm{Fe} + {}^{141}_{53}\mathrm{I} + Q, \qquad (45)$$

with Q = + 97.9 MeV. Preliminary analysis by the TNCF model showed $n_n \sim 10^{11}\,\mathrm{cm}^{-3}$ in this case assuming the branching ratio equals 1 and the threshold energy of this reaction ~ 0. This shows that the threshold energy for the above reaction in an appropriate material with the trapped neutron becomes very small (even zero) making this channel predominant even if the threshold energy is positive and large and the branching ratio is small in vacuum.

3.4c Detection of $^{20}_{13}$Al and others by G. Miley et al.[21)]

$$^{27}_{13}\mathrm{Al}\,;\ ^{108}_{46}\mathrm{Pd} \rightarrow {}^{109}_{46}\mathrm{Pd}^* \rightarrow {}^{27}_{13}\mathrm{Al}\ (+\ {}^{80}_{33}\mathrm{As}^* + 2n)\ (E_{thr} \geqq 9.5\ \mathrm{MeV})$$

The electrolytic experiments with cathodes of the packed-bed cell (about 1000 microspheres (MS's) in a electrolyte 1M $LiSO_4$ + H_2O were performed with nickel, palladium and Pd-Ni multi-layer cathodes and titanium electrodes. Voltages across the bed were held at about 2 ~ 3 V, with several mA of current, giving an electrical input power of approximately 0.06 W. Inlet-outlet thermocouples provided a measure of the temperature increase of the flowing electrolyte. Positive but often very small increases in temperature across the cell ranging from 0.1 to 4 °C were observed in all cases.

We take in this analysis only one data set, Run #11, where Pd thin-film of 200 μm was on the polystyrene microsphere. The volume and mass of the film was 7.05×10^{-7} cm^3 and 8.46×10^{-6} g, respectively. The number of Pd atoms in the film was, therefore, 4.76×10^{16}.

The analysis of the sample microspheres by NAA (Neutron Activation Analysis) after an experiment in 211 hours showed appearance of elements Al, Cu, V, Ni, Fe, Co, Cr, Zn and Ag with yields 233, 277, 4.06, 388, 153, 2.18, 60.4, 806 and 70.6×10^{-3} μg/MS, respectively, or number of atoms 520, 262, 4.80, 398, 165, 223, 699, 742 and 39.4×10^{13} atoms/MS, respectively.

Possible explanation of the data sets introduced above showing various NT in PPC could be given as follows.[21',21'')]

To interpret the data set of NT_F given above, we take only relevant reactions from (31) ~ (33) as follows ($A'' = A - A' + 1$);

$$n + {}^{A}_{46}\mathrm{Pd} = {}^{A+1}_{46}\mathrm{Pd}^*,$$

$$^{A+1}_{46}\mathrm{Pd}^* = {}^{A'}_{13}\mathrm{Al} + {}^{A''}_{33}\mathrm{As},$$

$$= {}^{A+1}_{47}\mathrm{Ag} + e^- + \bar{\nu}_e,$$

and similar fission reactions generating pair elements ($^{29}_{A'}$Cu, $^{17}_{A''}$Cl), ($^{23}_{A'}$V, $^{23}_{A''}$V), ($^{28}_{A'}$Ni, $^{18}_{A''}$Ar), ($^{26}_{A'}$Fe, $^{20}_{A''}$Ca), ($^{27}_{A'}$Co, $^{19}_{A''}$K), ($^{24}_{A'}$Cr, $^{22}_{A''}$Ti), ($^{30}_{A'}$Zn, $^{16}_{A''}$S).

The mass number A for the stable isotopes of Pd are 102, 104, 105, 106, 108 and 110 with abundance of 0.96, 10.97, 22.33, 27.33, 26.71 and 11.81 %, respectively. If the intermediate nucleus $^{A+1}_{46}$Pd* is unstable, i.e. A = 102, 106, 108 and 110, the above fission reactions into two nuclei with mass numbers A' and $A'' = (A - A' + 1)$ occur with respective decay constants (or branching ratios).

There are some experimental facts showing acceleration of nuclear reaction (in other word, enlarging of the instability factor ξ larger than 1) in the surface layer of materials including the trapped neutrons. (Examples interpreted by acceleration of β-decay were observed for ${}^{40}_{19}K$ ${}^{107}_{46}Ag$ as discussed above in 3.2a and 3.2d.) Taking into this fact, we assume in the following analysis that the time constants of the above fission or decay reactions are all very short and can be taken zero in the calculation.

The number of events N_{A+1} in unit time and in unit volume generating the unstable isotopes ${}^{A+1}_{46}Pd^*$ is expressed in the TNCF model by the relation (38) as follows;

$$N_{A+1} = 0.35 n_n v_n N_A \sum (\sigma_A P_A). \tag{46}$$

Using the data of decreased number of Pd atoms, or total number of generated atoms, i.e. $N_{A+1} = 3.05 \times 10^{16}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-3}$, we can determine the adjustable parameter n_n by the relation (46) as follows;

$$n_n = 4.5 \times 10^{12}\,\mathrm{cm}^{-3}.$$

We can guess the branching ratios of the above decaying reactions of ${}^{A+1}_{46}Pd^*$ if we have data on the isotope ratio of the generated elements. However, we have only the number of elements as given above and we can calculate only an average of the branching ratios over A and A' from them. The average branching ratios calculated by the above data are given in Table 1. If we know branching ratios of the above decaying reactions for relevant A and A', we can check above treatment based on the TNCF model. Unfortunately, we have no data about the branching ratios for the isotopes or elements as a whole in the published data books to compare with values thus calculated.

Table 1: Average branching ratios over A' of the reactions generating transmuted nuclei observed in the experiment.

Generated Element	Al	Cu	V	Ni	Fe	Co	Cr	Zn	Ag
Average Branching Ratio (%)	17	8.6	0.16	13	5.4	7.3	23	24	13

This table shows the same tendency observed in the branching ratio of fission products of a compound nuclei formed by the $n - {}^{235}_{92}U$ absorption reaction known in Neutron Physics that the larger the difference of masses of product nuclei is, the larger the branching ratio of the fission reaction is, although this fact is not explained yet. It is interesting to notice that the same tendency is seen in the curious event, the nuclear transmutation by fission, in the cold fusion phenomenon.

3.4d Detection of ${}^{56}_{26}Fe$ and ${}^{52}_{24}Cr$ by T. Ohmori et al.[22]

$${}^{56}_{26}\mathrm{Fe}\,;\ {}^{186}_{74}\mathrm{W} \to {}^{187}_{74}\mathrm{W}^* \to {}^{56}_{26}\mathrm{Fe} + {}^{131}_{50}\mathrm{Sn}^* + Q\ (E_{thr} \geqq 7.3\ \mathrm{MeV})$$

$$^{52}_{24}Cr\ ;\ ^{186}_{74}W \to ^{187}_{71}W^* \to ^{52}_{24}Cr + ^{135}_{52}Te^* + Q\ (E_{thr} \geqq 7.3\ \mathrm{MeV})$$

Excess heat and NT data[22] obtained in tungsten cathode with light water and Na_2SO_4 or K_2CO_3 were analyzed on the TNCF model.[22'] Production of the observed new elements Fe and Cr in the micro-craters on Au cathode[20] introduced in 3.4c were explained by nuclear fission of compound nuclei formed by $n + ^{A}_{74}W$ reaction. The adjustable parameter n_n in the model was determined using the data of NT at the boundary of the micro-crater as $1.2 \times 10^{14}\ \mathrm{cm}^{-3}$, two orders of magnitude larger than the values determined in other experimental situations. This large value of the parameter n_n might be attributed to the amount of NT in the micro-crater used in the calculation as the value for overall surface. The data of the excess heat and NT, however, were explained quantitatively and consistently in a factor of 2. The formation of the micro-crater on the surface of the electrodes[20,22] of W and Au were explained[9] by the TNCF model as an evidence of a strong reaction in surface layer expressed by a large value of the factor $\xi \sim 10^5$.

The experimental data sets explained in this Subsection assuming nuclear fission in the surface layer of cathodes suggest that nuclear fission of isotopes, which are considered stable against fission by energetic neutrons with energies up to several tens MeV in vacuum, occurs there induced by the trapped thermal neutrons in the cathodes. This is a new feature of solid state-nuclear physics in systems composed of trapped neutrons and solids with the surface layer of an isotope with a large value of the mass number.

3.5 Scarce observation of γ-ray

It is well known in CF experiments that γ-ray has not been observed as often as expected from other nuclear products of tritium, helium 4 and transmuted nucleus.[2,3] This fact may be an evidence of peculiarity of nuclear reactions in solids used in the CF research different from those in free space.

3.6 Decay-time lengthening of the trapped neutron

The success[2,3] of the TNCF model with a single adjustable parameter n_n to explain various more than 60 data sets in CF experiments substantiate the assumed existence of the quasi-stable thermal neutrons in CF materials.

In addition to this indirect evidence, there is another, in our opinion, of the decay time lengthening of the neutron trapped in the crystal shown by experimental data obtained by O. Reifenschweiler.[23] We introduce his data in some detail below.

3.5a O. Reifenschweiler[23] (Change of β-activity)

Reifenschweiler[23] measured the resulting X-ray induced by β-decay of 'tritium' sorbed by Ti ($TiT_{0.0035} \equiv Ti/T$ system). The sample was in a shape of extremely small mono-crystalline particles with a diameter $\phi = 15$ nm (150 Å). In the heating process of the sample between 0 and 450 °C, he observed a decrease of the radioactivity, i.e. intensity of X-ray from the sample Ti/T in a definite temperature range of 115 ~ 275 °C. From the experimental result, he had concluded the reduction of radioactivity of tritium sorbed by Ti.

We have to note,[23′] at first, that the X-ray he had measured was the result of not only the decay of tritium but also that of thermal neutron if any in the sample. As we have known now, it is possible that the thermal neutron can be trapped stably or quasi-stably in some transition metals (including Ti) showing the cold fusion phenomenon if definite conditions are satisfied.

In addition to the trapping, the thermal neutron could be elongated its life time due to the interaction with lattice nuclei. The trapping is a necessary condition but not the sufficient for the stability of the trapped neutron against the β-decay or against a fusion reaction with one of lattice-nuclei.

Because of the abundant background neutrons in ambient, it is apt to measure β-decays of tritium and neutron simultaneously not discerning their origin. If the stability of the trapped thermal neutron appears in a temperature range of 115 ~ 275 °C (we call it "range A" hereafter) where the reduction of the radioactivity was observed, the intensity of the emitted electron from the sample, and also the resulting X-ray decrease there.[23′] This is the most reasonable explanation of "the reduction of radioactivity of tritium sorbed by titanium" on the conventional physics as shown quantitatively below.

Knowing the change of the radioactivity from experimental data, we can estimate the density of the trapped thermal neutrons in the sample as shown also below.

To analyze the experimental data observed by O. Reifenschweiler[23], we will assume for simplicity the experimentally observed change of the radioactivity is induced only by the change of the neutron stability neglecting a possible change of the radioactivity of tritium in a crystal by the interaction with the trapped thermal neutron. Furthermore, we will assume that the neutron density changes only through the β-decay in the time of the experiment though it can change by the change induced by other causes than the β-decay.

The β-decays of tritium and neutron in their free states are with decay times $T_t^{(0)} =$ 12.262 y (= 3.87×10^8 s) and $T_n^{(0)} = 8.87 \times 10^2$ s and with the maximum electron energies 18.6 and 780 keV, respectively. In general, we can express their decay behaviors as follows:

$$n_t(t) = n_t(0)e^{-t/T_t}, \tag{47}$$

$$n_n(t) = n_n(0)e^{-t/T_n}, \tag{48}$$

where $n_t(0)$ and $n_n(0)$ are the initial densities of the sorbed tritium and the trapped neutron contributing to the change of radioactivity, respectively.

Number of the event emitting electrons from tritium $N_{e1}(t)$ and that from neutron $N_{e2}(t)$ at time t per unit time and unit volume of the sample are given as follows (T_t is taken as $T_t^{(0)}$ as explained above):

$$N_{e1}(t) = \frac{n_t(0)}{T_t} e^{-t/T_t}, \tag{49}$$

$$N_{e2}(t) = \frac{n_n(0)}{T_n} e^{-t/T_n}, \tag{50}$$

Therefore, the number of the emitted electron as a whole at time t in a unit time is expressed as follows:

$$N_e(t) = N_{e1}(t) + N_{e2}(t) = \frac{n_t(0)}{T_t} e^{-t/T_t} + \frac{n_n(0)}{T_n} e^{-t/T_n}. \tag{51}$$

As explained above, the decay time T_n of the neutron is a variable because of the neutron-lattice nuclei interaction. To analyze the experimental data, we will assume for simplicity that T_n takes two values, an infinity in the stable state and $T_n^{(0)} = 887.4$ s in the free state.

Then, we have two values for the number of emitted electrons, $N_e^{(1)}(t)$ in a state where the trapped neutron is stable and $N_e^{(2)}(t)$ in another state where it decays with the same constant as in the free state:

$$N_e^{(1)}(t) = \frac{n_t(0)}{T_t} e^{-t/T_t}, \tag{52}$$

$$N_e^{(2)}(t) = \frac{n_t(0)}{T_t} e^{-t/T_t} + \frac{n_n(0)}{T_n^{(0)}} e^{-t/T_n^{(0)}}. \tag{53}$$

If we consider $N_e^{(2)}(t)$ is a result of only a hypothetical tritium decay not noticing the existence of the trapped thermal neutron with a density $n_n(0) \sim n_t(0)$, the hypothetical decay time T_t^* is given by a following relation taking into our account a relation $T_n^{(0)} \ll T_t$:

$$N_e^{(2)}(t) \equiv \frac{n_t(0)}{T_t^*} e^{-t/T_t} \tag{54}$$

$$\frac{1}{T_t^*} - \frac{1}{T_t} = \frac{1}{T_n^{(0)}} \frac{n_n(0)}{n_t(0)} e^{-t/T_n^{(0)}}. \tag{55}$$

Therefore, the change of "the triton decay time" can be detected if

$$\frac{1}{T_n^{(0)}} \frac{n_n(0)}{n_t(0)} e^{-t/T_n^{(0)}} \geq \frac{(T_t - T_t^*)_{min}}{T_t T_t^*}, \tag{56}$$

where $(T_t - T_t^*)_{min}$ is the accuracy of the measurement of the life time.

Assuming an accuracy of the measurement $(T_t - T_t^*)_{min} \sim \xi T_t \sim 4 \times 10^8 \xi$ s with a numerical factor ξ, we obtain a condition for the measurability of the neutron density affecting the experimental result:

$$\frac{n_n(0)}{n_t(0)} \geq 10^{-8} \xi T_n^{(0)} e^{t/T_n^{(0)}} \sim 10^{-5} \xi e^{t/T_n^{(0)}}. \tag{57}$$

If the time t is 10 $T_n^{(0)}$, the condition is expressed as follows:

$$\frac{n_n(0)}{n_t(0)} \geq 2.2 \times 10^{-1} \xi. \tag{58}$$

This means that if $t \sim 10\,T_n^{(0)}$ and $\xi \sim 1$ a neutron density 20 % more than the tritium density affects the apparent life time of the tritium determined by the experiment without energy discrimination.

From the experimental data of $T_t - T_t^*$, we can determine the density of trapped thermal neutrons as follows. Putting $T_t - T_t^* \equiv \eta T_t$ and the time of the experiment $t = \alpha T_n^{(0)}$, we obtain a relation between η, $n_n(0)$ and $n_t(0)$;

$$\frac{n_n(0)}{n_t(0)} = 2.3 \times 10^{-6}\ \eta e^{\alpha}. \tag{59}$$

Taking values $\alpha = 1$ (corresponding to the temperature change of 450 °C in 10 hours[23], i.e. 11 °C in 15 min.), $\eta = 0.4$ and $n_t(0) = 9 \times 10^{15}\ \text{cm}^{-3}$ corresponding to the experimental data with the sample $TiT_{0.0035}$, we obtain a value for the density of the trapped thermal neutron contributing to the measurement, i.e. of the neutron stabilized in the temperature range A,

$$n_n(0) \sim 1.1 \times 10^{9}\ \text{cm}^{-3}.$$

This is the density the same order of magnitudes we have determined from the experimental data of strange phenomena showing generation of the excess heat and nuclear products in solids ($10^8 \sim 10^{12}$), though in the present case there may be another kind of the trapped thermal neutrons not changing their stability in the range A in the sample used in the experiment[23].

4. Characteristics of the Interaction between a Lattice Nucleus and Neutron Bloch Waves told by the Anomalous Nuclear Reaction in Solids

It has been shown a possibility to give a unified explanation of whole experimental data sets, including null results without ambient neutrons, obtained in the CF phenomenon on the TNCF model.[2,3] If we accept the explanation of these vast experimental data sets including those of nuclear transmutation given in the preceding Subsection as meaningful, the interaction of the compound nucleus, formed from a stable nucleus by absorption of a thermal neutron with neutron Bloch waves should be inferred from the consistent system of explanation for those events in the CF phenomenon.

The local coherence of the neutron Bloch wave at in the surface layer intensifies nuclear reaction in it ; 10^5 neutrons in a one-dimensional band gives probability amplitude of 10^5 times and reaction probability of 10^{10} times those of a single neutron, respectively, in the surface layer. The coherence length is $4a$ where $\xi = 10^8$ if $\Delta k = \pi/4a$(10^4 neutrons in it) and $40a$ where $\xi = 10^6$ if $\Delta k = \pi/40a$(10^3 neutrons) and 4 μm($4 \times 10^3 a$) where $\xi = 10^4$ if $\Delta k = \pi/400a$ (10^2 neutrons).

4.1 Widening of the gate to beta-emission channel

In Section 3.2, we have introduced experimental data sets showing generation of new elements or isotopes by β-decay in the surface region of solids used as the cathodes for electrolysis or discharge in CF experiments. In this Subsection, we give phenomenological discussion on the meaning of these experimental results in nuclear physics of β-decay. Energy balance for this process is surveyed in 1.1a.

We summarize here the experimental data sets introduced in Section 3.2. There are NT in materials used in CF experiments showing generation of new elements and isotopes which are explained naturally by β-decay of compound nuclei formed from stable nuclei pre-existed in the materials by neutron absorption. The decay-times (τ) determined by ordinary techniques in free space, however, are not always consistent with time scale of the experiments where observed these new elements. Two examples of them are ${}^{40}_{19}K(\tau = 1.2 \times 10^9$ y) and ${}^{107}_{46}Pd(\tau = 6.5 \times 10^6$ y). The β-decay products ${}^{40}_{20}Ca$ and ${}^{107}_{47}Ag$ coexist with new elements generated by processes with rather short decay-times than the time scale of the experiments. This fact should be an evidence of decay-time shortening of β-decay elements interacting with neutron Bloch waves.

As discussed in Subsection 1.2, the compound nucleus formed by neutron absorption in free space is not responsible to β-decay. Many examples of NT related with β-decay, however, seem to indicate strong effect of the trapped neutrons to weak interaction working in nucleus to induce β-decay of the compound nucleus.

The β-decay is described by wave functions of nuclei at initial and final states, of emitted electron and neutrino and the weak interaction.

The Bloch neutron interacting with a compound nucleus will influence its wave function ; i.e. the wave functions of the initial and final states of the nucleus Φ_i and Φ_f in the matrix element determining transition probability of β-decay of the nucleus :

$$H'_{if} = \sum_n F(r_n)(\Phi_f^* K_n \Phi_i) d\tau, \tag{60}$$

where $F(r_n)$ is a quantity which depends on the emitted "field" (i.e. on the wave functions of the electron and neutrino) at the position of the n-th nucleon (the one that undergoes the β-decay) ; K_n is some operator connected with the β-decay of the n-th nucleon.

4.2 Widening of the gate to alpha-emission channel

In Section 3.3, we have introduced experimental data sets showing generation of new elements or isotopes in the surface region of solids used as the cathodes of electrolysis or discharge in CF experiments. In this Subsection, we give phenomenological discussion on meaning of these experimental results in nuclear physics of α-decay. Energy balance for this process is surveyed in 1.1b. As was summarized in Subsection 1.2, it was a common sense in nuclear physics that the yields of the (n, p) and (n, α) reactions are naturally very small because of the strong competition of the (n, n) process.

We summarize the experimental data sets introduced in Section 3.3. There are NT in materials used in CF experiments showing generation of new elements and isotopes which are explained naturally by α-decay of compound nuclei formed from stable nuclei pre-existed in the materials by neutron absorption. The decay-times(τ) determined by ordinary techniques in free space, however, are not always consistent with time scale of the experiments where observed these new elements as surveyed in Subsection 1.2 and discussed in the above paragraph.

The α-decay is described by the liquid-drop model of nucleus considering transmission of alpha-particle in the nucleus through the Coulomb barrier at nuclear surface as surveyed in 1.1b: The influence of Bloch neutrons on the alpha-decay may mainly be through their effect on the Coulomb barrier.

However, scarcity of experimental data showing α-decay in CF experiment might be an evidence that the trapped neutrons do not give strong influence to tunneling of an α-particle through the Coulomb barrier at surface of nucleus despite β-decay and fission of compound nuclei have been drastically suffered by the trapped neutrons as experiments show.

4.3 Widening of the gate to nuclear fission channel

In Section 3.4, we have introduced experimental data sets showing generation of new elements or isotopes in the surface region of solids used as the cathodes of electrolysis or discharge in CF experiments. In this Subsection, we give phenomenological discussion on meaning of these experimental results in nuclear physics of fission. Energy balance for this process is surveyed in 1.1c.

A stable nucleus in a crystal lattice containing the trapped neutron can stabilize the neutron in the lattice through the strong interaction between the neutron and lattice nuclei as assumed in the TNCF model and supported by the success of the model in the analysis of many experimental data sets.[2,3] In this process of neutron stabilization, the lattice nuclei, which are stable usually, are destabilized by the same interaction, inversely. Therefore, the lattice nuclei in the cold fusion materials, in which are many trapped neutrons, decay by fission more easily than those in vacuum.

We summarize the experimental data sets introduced in Section 3.4. There are NT in materials used in CF experiments showing generation of new elements and isotopes which are explained naturally by fission of compound nuclei formed from stable nuclei pre-existed in the materials by neutron absorption. This fact should be an evidence of threshold energy lowering of fission elements interacting with neutron Bloch waves. The multitude of NT by fission might be an evidence of strong effect of the trapped neutron on the nuclear deformation responsible for fission.

In addition to this general conclusion of the neutron Bloch wave-lattice nucleus interaction, a noticeable fact is the position where NT occurs. Main products of NT detected hitherto localize near surfaces of electrodes. This fact could be explained by the local coherence of the neutron Bloch waves near the crystal boundary.[6~8] If the number of trapped neutrons becomes as large as 10^3, the local coherence near the surface layer intensities the reaction cross section of neutron and nucleus by a factor 10^6. This effect results in strong instability of the compound nucleus which is energetically feasible to fission(cf. 1.1c). This interaction might be responsible to lower surface tension keeping the compound nucleus from large deformation.

The fission reaction is described also by the liquid-drop model of nucleus considering deformation of the nucleus leading to separation of two parts each other as summarized in 1.1c : The influence of Bloch neutrons on the fission is mainly through their effect on deformability of the nucleus.

4.4 Closing of the gate to γ-emission channel

The experimental fact of scarceness of γ-rays detected in CF experiments seems to show a following general tendency ; In cold fusion materials, the excited states of a compound nucleus formed in the process of nuclear reactions lose energy by other channels than γ-emission while the general tendency of nuclear reaction observed in free space[4] summarized in Subsection 1.2 shows that γ-emission channel is predominant in the decay scheme of excited states. It is possible to express this fact by saying that the gate to γ-emission channel is substantially closed in comparison with other channels wide open in the CF materials.

This fact could only be explained by interaction of the compound nucleus with the neutron Bloch waves in the material which take energy to make the compound nucleus stable.

4.5 Stabilization of neutrons in Bloch states

In addition to the investigation on the anomalous nuclear reactions detected by CF experiments given above, there is a strong suggestion about a possible stabilization of trapped thermal neutrons in solids from the analysis of CF data on the TNCF model. We will give brief discussion on this problem in this subsection.

The analysis[2,3] of experimental data sets obtained in CF experiments has shown that the single adjustable parameter n_n in the TNCF model has a value of $10^8 \sim 10^{12}\ \mathrm{cm}^{-1}$ if we take the instability parameter $\xi = 1$ in the surface layer. There are several experimental[20,22] and theoretical[7~9] suggestions that ξ should be more than 1 and may be as large as 10^5 in special situations where occurred micro-crater formation at cathode surface.[20,22] If we take this fact into our model, we have to assume $\xi \gg 1$ and might be as large as 10^5. Thus, the value of the parameter n_n should be $10^3 \sim 10^7\ \mathrm{cm}^{-1}$.

Even if we assume the largest value of ξ in our analysis, the value of $n_n \sim 10^7\ \mathrm{cm}^{-1}$ may be too large to be accepted by many neutron physicists as natural considering the life time of free neutron of 887 s and background thermal and epi-thermal neutron densities of $10^{-2}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.[29] This conclusion of the TNCF model suggests that the life time of the trapped neutron in solids should have quasi-stable nature not decay unless strong perturbation works.

This quasi-stability can be brought about from the nuclear interaction of the neutron with lattice nuclei which resulted in the neutron band. We give a brief consideration on this problem using a new concept of neutron affinity of a nucleus.[3)]

Let us assume that the neutron Bloch wave transforms into a proton Bloch wave when it suffers a β-decay. Furthermore, let us estimate the stability of the neutron wave interacting with a nucleus ${}^{A}_{Z}\mathrm{M}$ with *a neutron affinity* η defined by a following relation ;

$$\eta \equiv -({}^{A+1}_{Z}M - {}^{A+1}_{Z+1}M)c^2 \tag{61}$$

Here, c is the light speed in vacuum, ${}^{A}_{Z}M$, in this case, is the mass of the nucleus with a mass number A and an atomic number Z composing the lattice nuclei. This definition tells us that the neutron affinity is a quantity expressing an energy difference of two nuclear states, one with an extra neutron and the other with an extra proton. The positive value of η means the former is in lower energy than the latter and is more stable.

5. Discussion

Starting from the discovery of the atomic nucleus by A. Rutherford in 1913 and restarting from that of neutron by J. Chadwick in 1932, nuclear physics has reached its prosperity and sophistication by the end of this century. It should be, however, recognized that the progress of this science is confined mainly to the properties of isolated nucleus and to two-body nucleon-nucleus and nucleus-nucleus interactions in free space.

Only one of few exceptions is the Mössbauer effect where a transition process (gamma[24)] and neutron[25)] emission) in a nucleus is influenced by the crystal lattice where the nucleus exists. The anomalous events showing occurrence of nuclear reactions in solids at near room temperature without high-energy acceleration observed in CF experiments puzzled, therefore, physicists accustomed with nuclear reactions taking place in free space. Production of ^{4}He in electrolytic system with heavy water is the most wonderful event difficult to explain from the common sense of nuclear physics because $d - d$ fusion reaction produce only 10^{-7} ^{4}He for a neutron, a proton, a triton and ^{3}He, the latter, especially the neutron and ^{3}He are observed only by dubious amount.

In the process of CF investigation, another unbelievable events from the conventional view point, nuclear transmutation (NT) from original elements in electrodes into elements and isotopes have been observed with remarkable amounts up to several tens % of original atoms. These transmuted nuclei could only be explained by decay or fission of original atoms, which are stable as they should be in ordinary condition, in the environment of the CF experiment.

To construct a consistent system of explanation of these events of nuclear reactions observed in CF materials, we have taken a view point based on the present quantum mechanics and sought a key unnoticed before instead leaving quantum mechanics established in history of physics more than 70 years. Some of experimental facts showing important role of background neutrons and artificial thermal neutron irradiation suggested importance of neutron-nucleus interaction in solids. Looking for data of the interaction, we noticed there are wide open space in the investigation of neutron-lattice nuclei interaction although there are pioneering works[26,27] about the cold neutrons.

The properties of the thermal neutron, almost the same to that of the cold neutron, should be taken into consideration of the explanation of nuclear events in CF experiments although a phenomenological attempt, the TNCF model,[28] to use the thermal neutron as a key element in the CF phenomenon had been started five years ago. The progress of experimental work in this field has given nutrition to the model to grow into one applicable almost all events of the CF phenomenon with only one adjustable parameter n_n. The success of the model demanded physical justification of the bases of the model. The nuclear reactions, however, are not established yet to afford a measure for the model due to difficulty of many-body problem inherent in nucleus as a compound system of nucleons.

We have to change our viewpoint to investigate nuclear properties through events observed in the CF experiments instead to explain them from knowledge of nuclear physics. The investigation given above is the result of our effort on this line. Assuming the quasi-stable existence of thermal neutrons in appropriate materials, we can explain whole events related with anomalous nuclear reactions observed in CF experiments using only one adjustable parameter. This result should be taken seriously to proceed investigation of state of thermal neutrons in solids which has not been cultivated yet at all theoretically and also experimentally due to lack of recognition and difficulty in practice. Once the problem is recognized, progress will be rapid in view of present stage of technology and needs. We hope more progress of experimental work in this field and successful application of this new branch of solid state-nuclear physics.

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