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Research Article

The Cold Fusion Phenomenon in the Gas-Solid System – A Review

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Abstract

The cold fusion phenomenon (CFP) observed in the materials composed of host elements and hydrogen isotopes (CF materials) is reviewed from a phenomenological point of view based on the TNCF (trapped neutron catalyzed fusion) model, which is the only model that give a comprehensive understanding of this field. The CFP observed in the gas-solid system is considered for detailed research in relation to the science of adsorption due to its importance, that was recently recognized. It is pointed out that such peculiarities of physics and chemistry noticed in the transition-metal hydrides as the cold fusion phenomenon, the superfluidity of hydrogen isotopes, HER (hydrogen electrode deposition), and UPD (the underpotential deposition) might be not independent of characteristics of the adsorption in the gas-solid system where CFP is observed. We have contemplated possible applications of CFP for an energy source and the remediation of hazardous radioactive products in relation to the characteristics of the adsorption of hydrogen in the gas-solid system.
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Keywords: Adsorption, Cold fusion phenomenon, Deuterium, Gas-solid system, Hydrogen, Nuclear reaction, Phenomenological approach

1. Introduction

Thirty-five years have passed since the announcement [1] of the discovery of cold fusion phenomenon, nuclear reactions at room temperature in solids containing enormous amounts of deuterium atoms [2], [3]. Later, it became apparent that this phenomenon occurs not only in systems containing deuterium D but also in systems containing protium (light hydrogen) H [4]. In following discussions, we will refer the solids in which cold fusion occurs to as *CF materials*, the experiment of the cold fusion phenomenon in CF material as the *CF experiment*, and the cold fusion phenomenon as *CFP*.

Based on the experimental results to date, the cold fusion phenomenon is defined more precisely as follows; The Cold Fusion Phenomenon (CFP) stands for

> "*Nuclear reactions and accompanying events occurring in open (with external particle and energy supply), non-equilibrium system composed of solids with high densities of hydrogen isotopes (H and/or D) in ambient radiation*" belonging to Solid State-Nuclear Physics (SSNP).

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CFP includes a wide variety of phenomena in CF materials with various compositions and morphologies [5], [6], [7], [8], [9] where observed events that cannot be understood by conventional science, especially solid-state physics and nuclear physics [4], [10]. For this reason, CFP takes on various forms depending on how the phenomenon is managed.

The following presumption made in this paper should be kept in mind that the essential feature of CFP remains the same whether CF material is fabricated in a gas-solid, in a liquid-solid, or in other various types of systems. This presumption may be reasonable according to our experience obtained by now; the most reliable evidence is the Second Law in CFP, the *Inverse-Power Dependence of the Occurrence Frequency on the Intensity of Excess Heat Production* explained in Sec. 2-3b. We have confirmed this law not only for the data obtained in a single CF material (e.g. [11], [12]) but also for the data sets obtained in various CF materials [13].

The basis of the argument in this paper is the phenomenological approach (i.e., the TNCF model) [4], [10], [14], [15], which is the only standpoint that provides a unified understanding of the diverse events of CFP (as surveyed in Sec. 2-1). The quantum mechanical basis of the model has been given by the investigation of the superlattice (regular lattice) composed of the host atom (e.g., Pd or Ni) and the hydrogen isotope (e.g., D or H) [10], [16], [17], [18]. The neutron-proton or neutron-deuteron interaction works to stabilize the superlattice and also brings about the formation of neutron bands in the superlattice.

In this paper, we will explain CFP from this standpoint, analyze its characteristics in gas-solid systems, and consider its potential applications.

In Section 2, we summarize the cold fusion phenomenon (CFP) from our perspective. In Section 3, we investigate the characteristics of CFP in the Gas-Solid System in relation to the adsorption on, absorption into, and occlusion in the host material of hydrogen isotopes. The science of the Adsorption of Protium and Deuterium at Gas–Solid Interface given in Subsection 3B will be useful in the investigation of gas-solid systems especially with nanocomposite compounds. In Section 4, we contemplate possible applications of CFP based on the present knowledge summarized in Sections 2 and 3.

2. The Cold Fusion Phenomenon

As defined in Introduction, the cold fusion phenomenon (CFP) is induced by nuclear reactions occurring in specific materials (which we call *CF materials*) in which included almost the same number of hydrogen isotopes (H or D) as host nuclei (Ni or Pd or C). We show the complex diversity of CFP tabulating elements in CF materials in Table 1 in Section 2-1. Then, we give a brief explanation of our phenomenological approach based on the TNCF model in Section 2-2. From Sections 2-3 to 2-6, we give fundamental explanations of CFP on the TNCF model.

2-1. Summary of the Experimental Results Obtained in the Cold Fusion Phenomenon

We have tabulated the essential features of the experimental results obtained in the cold fusion experiments in Table 1.

In the second row of Table 1, we notice the neutron n as an important agent in CFP. This should be emphasized here again as already explained in the early stage of CF research (e.g., [4 (Sec. 8.2)]. The necessity of existence of background neutron for and the positive effect of the artificial irradiation of thermal neutrons on CFP have been proved.

System (host solids), Agents (hydrogen isotopes + activation agents) and Obtained evidence of CFP. Listed in Table 1 are host solids, agents, experimental methods, direct and indirect evidence. Q and NT express the excess heat and the nuclear transmutation, respectively. Direct evidence of nuclear reactions in CFP are (1) the energy (ε) and the position (r) dependences of reaction products, (2) decrease of decay constants of radiative nuclides [10 (Sec. 2.5.1.1)], and (3) decrease of fission threshold energy of compound nuclei [10 (Sec. 2.5.3)].

Table 1. Summary of CF materials and evidence of CFP

Host solids	C, Pd, Ti, Ni, KCl + LiCl, $ReBa_2Cu_3O_7$, $NaxWO_3$, KD_2PO_4, TGS, $Pd_xNi_{0.35-x}Zr_{0.65}$, NiH_x coated by guest materials, Nanocomposite compounds
Agents+hydrogen isotope	*n*, *p*, *d*, $^6{}_3$Li, $^{10}{}_5$B, $^{12}{}_6$C, $^{39}{}_{19}$K, $^{85}{}_{37}$Rb, $^{87}{}_{37}$Rb, (ion beam)
Experimental methods	Electrolysis, gas discharge, gas contact, (ion beam irradiation)
Direct evidence of CFP	Gamma ray spectrum $\gamma(\varepsilon)$, neutron energy spectrum $n(\varepsilon)$, Space distribution of NT products NT($\boldsymbol{r}$), decrease of decay constants, lowering of fission threshold energy
Indirect evidence of CFP	Excess energy Q, number of neutrons N_n, amount of tritium atom N_t, number of helium atom N_{He-4}, NT (NT_D, NT_F, NT_A), X-ray spectrum X(ε)
Cumulative observables	NT(r), NT products, amount of tritium atom N_t and helium-4 N_{He-4} in appropriate systems
Dissipative observables	Excess energy Q, number of neutrons Nn, neutron energy spectrum $n(\varepsilon)$, gamma ray spectrum $\gamma(\varepsilon)$, X-ray spectrum X(ε)

2-2. The TNCF Model – A Phenomenological Approach

As explained in Introduction, there is only one approach, a phenomenological explanation by the TNCF model (the trapped neutron catalyzed fusion model), that successfully explains many diverse experimental facts consistently [4], [10], [14].

In the TNCF model, we assume the following premises: that there are trapped quasi-stable thermal neutrons with a density of n_n, an adjustable parameter, in CF material. The trapped neutrons interact only with nuclei in disordered position displaced from the ordered lattice points. Let us consider a situation when we have determined two observables $N_n|_{\rm ex}$ and $N_t|_{\rm ex}$ for the number of neutrons N_n and the number of tritium N_t, simultaneously. On the other hand, we can calculate theoretical values of $N_n|_{\rm th}$ and $N_t|_{\rm th}$ according to the premises of our model. To determine the adjustable parameter n_n, we compare, e.g., $N_n|_{ex}$ and $N_n|_{\rm th}$. Using the value n_n thus determined, we can determine the value $N_t|_{\rm th}$ uniquely to be compared with $N_t|_{\rm ex}$. Thus, we can check the validity of the model to apply for CFP.

With this process, we have determined the value n_n in more than 50 experimental data sets. Fortunately, in eight experimental data sets more than two observables were measured simultaneously, so we could check the integrity of the model by the comparison of the theoretical value $N_x|_{\rm th}/N_y|_{\rm th}$ with the experimental value $N_x|_{\rm ex}/N_y|_{\rm ex}$ for the observables X and Y [4], [14].

The analysis of more than 50 experimental data sets that were produced by 1998 where the experimental results of excess energy, tritium, neutron, ^{4}He, transmuted nuclei are explained with the values n_n in the range of 10^6–10^{12} cm^{-3} in addition to the above mentioned consistency between several observables measured simultaneously in the numerical factors in around 5 [4 (Tables 11.2 and 11.3); the tables were in [10 (Tables 2.2 and 2.3)]].

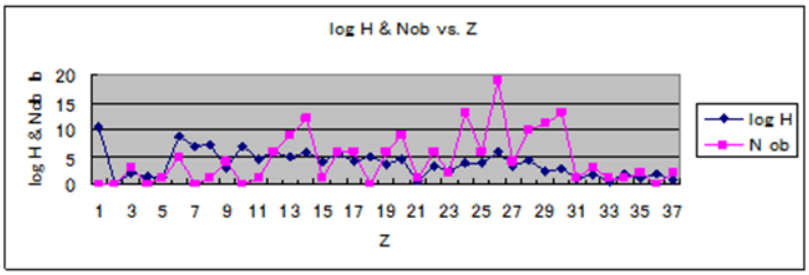
Thus, we can use the phenomenological approach by the TNCF model as a principal basis for the investigation of CFP. Furthermore, we can use the quantum mechanical verification of the model as an effective basis for the analysis of nuclear reactions in CF material [10 (Sec. 3.7), 2013].

2-3. Three Laws in the Cold Fusion Phenomenon Deduced From the Experimental Data

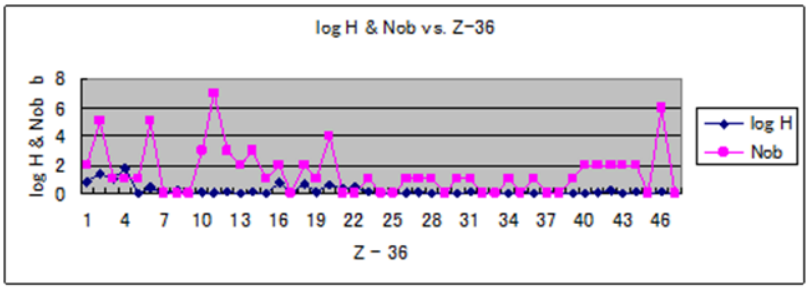
We have noticed three laws or regularities between observables in the cold fusion phenomenon as listed in the following Subsections [19]. These laws suggest that the cold fusion phenomenon should be treated by the science of complexity extensively discussed in our paper [20], [21] and also in a paper to be published in the near future [22].

2-3a. *The First Law; Stability Effect for Nuclear Transmutation Products ([10 (Sec. 2.11), 19, 20, 21, 23])*

If we survey numbers of elements generated by the nuclear transmutation in CFP, we notice the frequency obtaining an element has a positive correlation with the amount of the element in the universe. Plotting out (i) the number of



(a)



(b)

Figure 1. Correspondence between the frequency N_{ob} observing elements in CFP and the relative abundances $\log_{10}H$ of elements [Suess 1956] in the universe: (a) $Z = 3 - 38$ and (b) $Z = 39 - 83$ [10 (Fig. 2.11)].

experiments where observed an elements X together with (ii) that of the amount in the universe compiled by H.E. Suess and H.C. Urey [24] against its proton number *Z*, we obtain a diagram shown in Fig. 1 [10]. The coincidence of the peaks of numbers (i) and (ii), gives the stability effect for nuclear transmutation products.

2-3b. *The Second Law; Inverse-Power Dependence of Frequency on Intensity of Excess Heat Production ([10 (Sec. 2.12), 19, 21])*

In several experimental data sets, we can count the numbers N_Q of an event (excess heat) with a specific amount of the excess energy *Q* (or an excess power *P*) and plot them as a function of *Q* (or *P*) obtaining N_Q vs. *Q* (or *P*) plot. We plotted the data by McKubre et al. [11] as shown in Fig. 2 [10] to show the inverse-power dependence of the frequency on the intensity. Another plot using data of *Q* obtained in various CF materials was given by H. Lietz [13] as shown in Fig. 3. This plot clearly shows that there is a relation of frequency vs. intensity with an exponent of one, famous in complexity. We call this regularity as the *inverse-power dependence of frequency on intensity* of the excess heat production. Similar regularity in the N_Q vs. *Q* (or *P*) plot is seen for other data, too [12].

2-3c. *The Third Law; Bifurcation of Intensity of Events (Excess Heat Production) in Time*

The third law in CFP is a little subtle statistically compared with the former two. Even if the number of examples is scarce, we have several fortunate data sets of temporal evolution of effects in CFP [19].

By the nature of events in complexity, we can give only qualitative explanation of experimental result in analogy to the mathematical results of numerical simulations using the logistic difference equation. We have given the analogical

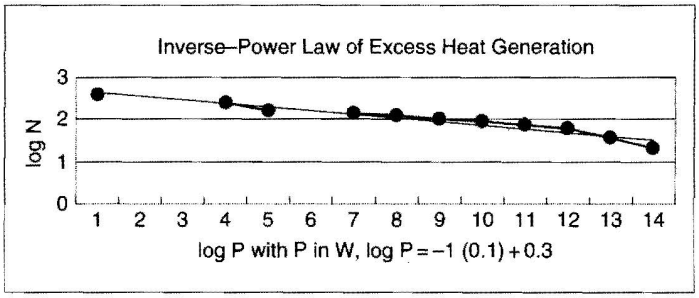


Figure 2. Inverse power law revealed by excess power generation [10 (Fig. 2.13)]. H. Kozima et al. compiled the experimental data measured by McKubre et al. [11 (Fig. 6)].

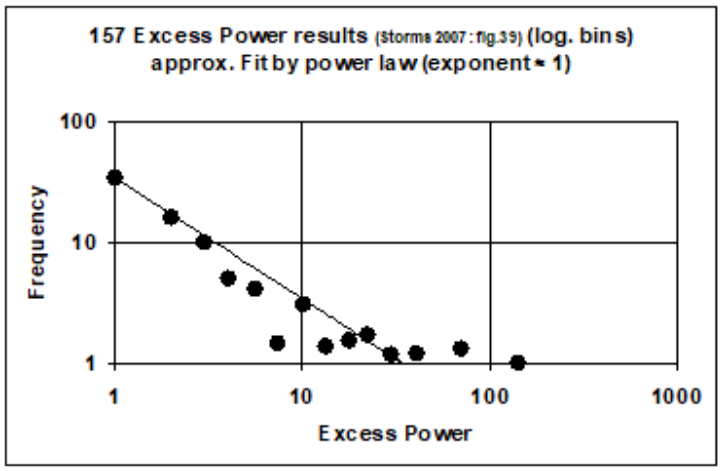


Figure 3. Inverse power law revealed by the frequency vs. excess power plot [13 (Fig. 3)]. The 157 data sets of excess heat generation compiled by Storms [25] have been manipulated by H. Lietz. Values have been stored in bins of size ten. The line shows a power-law fit to the binned data with an exponent of 1.0 ($r^2 = 90\%$)

explanations of the laws observed in CFP (such as shown in Figs. 4 and 5) using the nature of an equation of nonlinear dynamics, Feigenbaum's theorem [26], shown in our paper [21]. We cite two examples of experimental results showing the bifurcation of intensity below. The explanation of the relation of these experimental results and the bifurcation in the logistic difference equation is given in the paper published before [19].

McKubre et al. [11] had made extensive measurements of the excess power with the electrolytic system Pd/D/Li changing widely the D/Pd ratio. A data set showing the bifurcation of the intensity of events (excess power) in time is shown in Fig. 4 [11].

The features of the temporal evolution of events shown in Fig. 4 shows the chaotic turbulence of nuclear reactions generating excess power [19] by the reactions assumed in the TNCF model [4 (Sec. 11.3b)].

Furthermore, we can cite another example of the temporal evolution of excess power generation measured by Kozima et al. [12] in Fig. 5. In this experiment, excess energy was measured with a Seebeck envelope calorimeter in

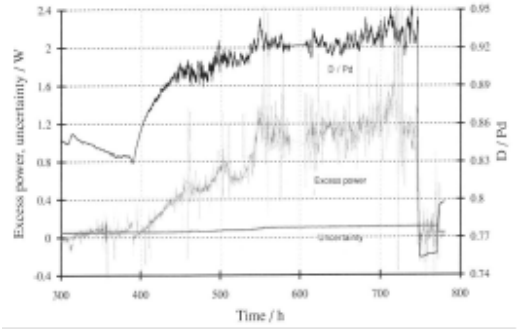


Figure 4. Variation of Excess Power, Uncertainty and Loading ratio [11 (Fig. 5)].

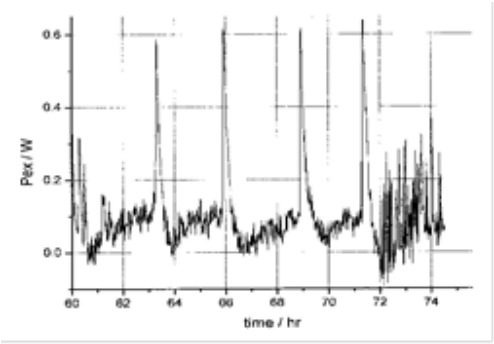


Figure 5. Excess power pulses during a 14 hour period of an experiment (070108) which lasted 12 days as a whole [12 (Fig. 3)].

an electrolytic system of $Pd/D_2O + H_2SO_4/Pt$ with a Pd tube cathode having a 2 mm φ (The ratio of . D_2O/H_2SO_4 was 6.7/1). We discussed the temporal variation of the excess power shown in Fig. 5 in relation to the bifurcation behavior observed in the nonlinear dynamics in our paper [12].

The temporal evolution of events shown in Fig. 5 reminds us that there are hypotheses of events as discussed in the adsorption hypothesis [27 (Sec. 17.6)]

2-4. Localization of Nuclear Reactions Causing CFP

One of the characteristics of the cold fusion phenomenon (CFP), i.e., low energy nuclear reactions in solids with high density hydrogen isotopes at near room-temperature in ambient radiations, is the localization of nuclear reactions relevant to the phenomenon.

Iyengar et al. at BARC obtained the earliest data sets showing the localization of nuclear reactions for product tritium localized in spots (fraction of a millimeter or less in size) at surfaces of a Ti sample [28 (B3), 29]. M. Okamoto et al. [30] observed nuclear transmutation of minor elements in surface layers of Pd samples, especially $^{27}{}_{13}$Al into $^{28}{}_{14}$Si, in a layer of about 2 μm. Bockris et al. [31] observed new elements within 1 μ from the surface. Iwamura et al. [32] have shown localized generation of Pr from Cs in their specific structure called “Pd complex.” Celani et al. [33]

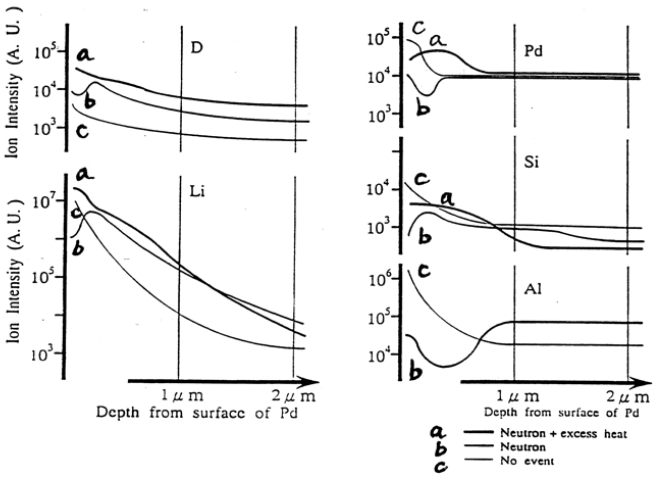


Figure 6. Depth profile of D, Li, Pd, Si and Al in the Pd cathode observed by Okamoto et al. [30 (Fig. 1)]

observed changes of amounts of elements (Ti, Cr, Co, As, Ir; Ti is increased and Sr, Pd are decreased) and changes of isotope ratios of Pd and B ($^{105}{}_{46}$Pd and $^{10}{}_{5}$B/$^{11}{}_{5}$B ratio decreased) while the amounts of Fe and Ni are constant.

We give brief explanation of these data for the last four papers mentioned above.

2-4a. *Experiment by Okamoto et al. [30]*

The data by Okamoto et al. [30 (Fig. 6)] obtained in a Pd/D_2O+LiOD/Pt system was successfully analyzed by the single neutron absorption mechanism of the TNCF model [34]. The result explains the observed decrease of Al and increase of Si by the following reactions;

$$n + {}^{27}_{13}\mathrm{Al} = {}^{28}_{13}\mathrm{Al}^{*} = {}^{28}_{14}\mathrm{Si} + e^{-} + \nu_{\mathrm{e}},$$

where ν_{e} is the electron neutrino.

2-4b. *Experiment by Bockris et al. [31]*

J.O'M. Bockris and Z. Minevski performed experiments in which hydrogen was electrolyzed from water in contact with a palladium electrode [31]. They measured the concentration and depth profiles of host elements and impurities in the Pd electrodes as a function of the electrolysis time. It was found that after 3 weeks, two different sets of impurities could be observed; there are new elements in the Pd electrodes inside the metal (1) elements preexisted in the system (Pt, Si, Zn) in the range within 50Å of the surface as shown in their Table 1 [31 (Table 1)] and (2) elements not existed in the system before the experiments (Mg, Ag, Si, Cl, Ca, Fe, Zn and others) in the range about 1 μm from the surface as shown in their Table 2 [31 (Table 2)].

The concentrations of the new atoms are in the range 1$\sim$10 atomic percent and have no relationship to the impurities in the solution and supposed to be generated there within 1 μm from the surface.

We analyzed the data obtained by Bockris et al. using the TNCF model [35].

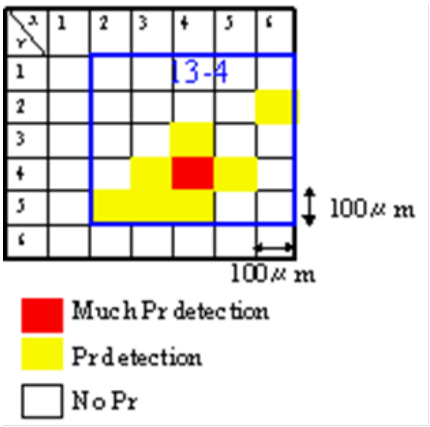


Figure 7. Nuclear transmutations from Cs to Pr in the Pd complex (Pd/CaO/Pd substrate) surface [32 (Fig. 10(b))].

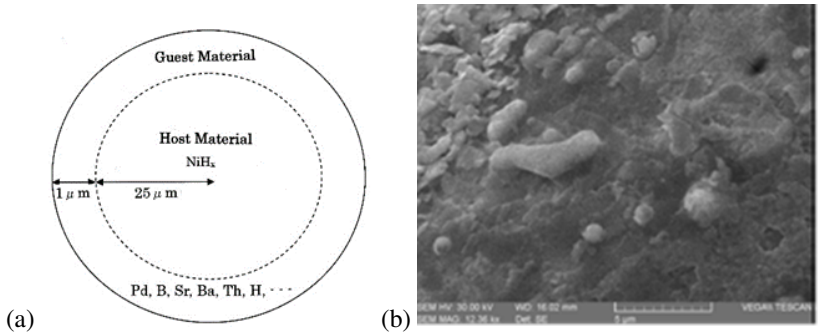


Figure 8. (a) Schematic cross section of the multiple nanocoated Ni wire used by Celani et al. [7 (Fig. 1)]. (b) Surface morphology of Ni coated wire after experiment [33].

2-4c. *Experiment by Iwamura et al. [32]*

One of the most remarkable of the many data sets showing the localization of nuclear reactions is the data by Iwamura et al. [32]. The data shown in Fig. 7 shows localized generation of Pr from Cs in their specific structure called "Pd complex." Details of analysis of their data including that one shown in Fig. 7 are given in our paper [36].

2-4d. *Experiment by Celani et al. [33]*

F. Celani et al. [33] performed experiments with new type samples of Pd and Ni wire coated with thin multilayer nano-materials and treated in D_2 and H_2 gas with sample temperature up to 900 C (Fig. 8a).

In the case of Ni wire [33], they observed the change of surface morphology (Fig. 8b) and changes of amounts of elements in the multilayer (Ti, Cr, Co, As, Ir; Ti was increased and Sr and Pd were decreased) and changes of isotope ratios of Pd and B ($^{105}_{46}$Pd and $^{10}_{5}$B/$^{11}_{5}$B ratio decreased) while the amounts of Fe and Ni are constant. The experimental results were explained using the TNCF model [7].

2-4e. *Explanation of the Localized Nuclear Reactions in CFP*

Some data from experiments with nuclear reactions confined in surface/boundary layers of a few micrometers, is shown in the previous sub-sections 2-4a–2-4d. This might be a characteristic of CFP in protium and deuterium systems. This characteristic of CFP is explained by the structure of a CF material composed of (1) a host material composed of a metal and a hydrogen isotope and (2) a guest material including agents for CFP on the surface of the former [36], [37].

2-5. Formation of the Superlattice of Host Elements and Hydrogen Isotope

In the open and non-equilibrium dynamical system where energy and component materials are fed from outside, there appears patterns energetically unstable compared to the homogeneous structure without any structure by the mechanism explained by the complexity [38].

Many researchers in CFP feel that one of necessary conditions for the success in the CF experiment using the host element, say Ni (or Pd), and the hydrogen isotope, say H (or D), is to have as highest ratio of H/Ni (or D/Pd) as possible in CF material. The reason for this requirement is, from our point of view, the ease of formation of superlattice NiH (or PdD) by the self-organization mechanism due to complexity. We have given a preliminary considerations of the relation between the nuclear reactions for CFP and the self-organization of the superlattice [17] and are now preparing for deeper research on the relation [22].

2-5a. *Self-Organization of the Superlattice*

The mechanism of formation of the superlattice of host elements and a hydrogen isotope is explained as follows [17]; The wavefunction of a proton ψ_p in Ni metal is not localized at the interstitial site where the proton is and the wavefunction ψ_p overlaps with wavefunctions of neutrons ψ_n's in lattice Ni nuclei at lattice points surrounding the site of the proton in the superlattice NiH [39]. Then, there appears the nuclear force interaction between the proton and the neutrons in Ni which makes the superlattice thus formed more stable and the self-organization mechanism works to form it selectively [17], [39].

In the case of CFP, the addition of the hydrogen isotope (e.g. H) to a host material (e.g. Ni) to form CF material NiH_x is made usually by adsorption in the gas-solid system or electrolysis in the liquid-solid system. Then, the optimum superlattice NiH of the host element Ni and hydrogen isotope H is formed by the self-organization in localized regions at surface layers where the number ratio $\eta = N_p/N_{Ni}$ of the hydrogen isotope p and the host metal Ni is expected higher than other parts of the sample. Experimental data show that the formation of superlattice occurs within a width of about several microns from the surface when the ratio η becomes larger than ~ 0.8.

2-5b. *Stability of the Superlattice*

The neutron-neutron interaction mediated by the interstitial protons/deuterons in CF material makes the superlattice NiH/PdD more stable than the case when there are no interaction between neutrons in different lattice nuclei Ni/Pd [39]. This is the reason we can construct CF materials and produce CFP stochastically as explained by the complexity when an appropriate condition is satisfied by chance.

The condition for CFP produced by the self-organization depends, however, on the subtle conditions easily lost by the change of the construction and the composition of CF material induced by the nuclear reactions bringing about CFP; changes of the component by nuclear transmutation and the change of the construction by heat generated by nuclear reactions and so forth.

Even if the superlattice is stable after being formed by the self-organization, it is fragile, and it can be destroyed by the result of nuclear reactions in CFP. This characteristics of the cause of CFP should be warily considered when we consider the application of CFP.

2-5b. *Qualitative Reproducibility of Events in CFP*

It is noticed that the characteristic of CFP produced by complexity is inherently flawed by the lack of quantitative reproducibility but it does have qualitative reproducibility [4 (Sec. 12.1a), 10 (Sec. 2.14), 17]. Even if we set the initial condition as precisely as possible in our ability to arrange the initial situation, there remain undetermined conditions out of our control which induce uncertainty in the final result by the principle of complexity in nonlinear dynamics. There are very many examples in science where we can obtain a final result having qualitative reproducibility. One of these examples is the nuclear reactions induced by high energy deuterons on the deuteron target;

$$\begin{aligned} d + d \rightarrow {}^{4}_{2}\mathrm{He}* &\rightarrow t(1.01\mathrm{MeV}) + p(3.12\mathrm{MeV}), \\ &\rightarrow {}^{3}_{2}\mathrm{He}(0.82\mathrm{MeV}) + n(2.45\mathrm{MeV}), \\ &\rightarrow {}^{4}_{2}\mathrm{He}(0.08\mathrm{MeV}) + \gamma(23.8\mathrm{MeV}), \end{aligned}$$

with the branching ratios $1 : 1 : 10^{-7}$ determined *experimentally*. We can obtain only one of the three results statistically when we bombard one high-energy deuteron on the target containing deuterons. In other words, the result we obtain in the experiment is only qualitatively reproducible not quantitatively because we cannot control the nuclear process, the decay of the excited state ${}^{4}{}_{2}\mathrm{He}^{*}$.

For too long, it has been asserted that the lack of reproducibility of events in CFP is an evidence that CFP is not a science but a fantasy or fiction or hoax. The cold fusion phenomenon has not been accepted in the science world and papers have been rejected from many science journals due mainly to the lack of reproducibility (to be more precise, the quantitative reproducibility is lacking) even if it has qualitative reproducibility, one of characteristics of phenomena destined by complexity.

Considering the cause of the qualitative reproducibility due to the complexity in the formation of the superlattice formation and the occurrence of nuclear reactions generating excess energy accompanied to the nuclear reactions, we have to satisfied with the qualitative reproducibility of events in CFP. In the application of this phenomenon, we have to keep in mind this characteristic and must use it rather actively.

2-7. Bibliography of Papers on the Cold Fusion Phenomenon (CFP)

Papers and books cited in our papers are listed in the References of our books; [4], [10]. There are extensive bibliographic References in the Storms' book [25].

Papers presented at ICCFs (the International Conference on the Cold Fusion) have been published in the P*roceedings of ICCFs* and uploaded to the LENR-CANR.org website: https://lenr-canr.org/wordpress/?page_id=2130.

Papers presented at the Annual Meetings of JCFs (the Japan CF-research Society) have been published in the *Proceedings of JCFs* and uploaded to the JCF website: https://jcfrs.org/proceedings/.

3. Characteristics of CFP in the Gas-Solid System

The characteristics of CFP as a whole have been surveyed in the preceding Section which are deviated from our common sense in modern natural science established in the first three quarters of 20^{th} century. Therefore, it has been very difficult for many scientists to take CFP seriously as a part of either solid state physics or a part of nuclear physics. As we have shown in Section 2, however, it is possible to understand the complicated and diverse experimental facts obtained in CFP consistently in accordance with knowledge of science obtained in relevant fields of physics and chemistry.

In CFP where various events have been observed in diverse systems as shown in Table 1, the gas-solid system has given valuable results to elucidate the mechanism of the nuclear reactions in CFP. It is also emphasized the new solids

of Ni-based nanocomposite alloys have shown remarkable characteristics in excess heat production. We investigate the characteristics of CFP in the gas-solid system centered on the nanocomposite alloys in the following sections. In Section 3A, we give a brief explanation of typical data sets obtained in the gas-solids CF materials. In Section 3B, we show a brief explanations of the adsorption of protium and deuterium at gas–solid interface in relation to CFP from several fundamental books and handbooks on the science of adsorption. Finally, we give a suggestion to promote the investigation of CFP in the nanocomposite alloys, with a method of discriminating between the excess heat from chemical, physical and nuclear origins.

3A. The Cold Fusion Phenomenon in the Gas-Solid System

In this Subsection, we take up typical experimental facts observed in CF materials formed by the adsorption of hydrogen isotope in the gas-solid system.

Experiments in the gas-solid system have been performed in many laboratories from the initial stage of the CF investigation in 1989 up to now. We consider only typical reliable experimental results obtained in several laboratories where the work was performed continuously for several years.

3A-1. *Experiments in the BARC, India*

In 1989, the BARC (Bhabha Atomic Research Center) of India performed extensive CF experiments and published a Report "*BARC Studies in Cold Fusion* (April – September 1989)" containing a huge number of papers on the nuclear reactions in CF materials [28]. In the Report, there is a Part B "*D_2 Gas Loading Experiments*" containing 4 papers. They investigated evidence of nuclear reactions in deuterated metallic Ti and Pd. They observed $^3{}_1$H production in both deuterated Ti and Pd. Later, the same group observed localized production of $^3{}_1$H near the surface of the sample [29]. Additional work along these lines was presented at ICCF5 held in 1995 [40].

3A-2. *Experiments by a Group in Siena and Bologna, Italy [41], [42], [43], [44], [45], [46]*

The first experiment of this group [41] was performed in 1992 using a sample of Ni cylinder with 5 mm φ and 90 mm length heated by Pt wire of l mm φ forming 42 turns of 20mm φ up to 400°C. Hydrogen pressure was controlled 0 to 570 mbar. They did not obtain CFP in the first experiment.

They reported that the Ni-H gas-solid system generated large amounts of excess heat [42]. Two cells which ran for long periods (about 300 days) producing an excess energy of 600MJ and 900MJ, respectively.

In 2000, the group summarized their works on the Ni-H system performed over several years [43]. Heat production was observed in different cells for long periods, with a maximum power of 70 W. On several occasions, they detected gamma ray emission and in one case also a neutron emission. The analysis of Ni samples which loaded hydrogen gas showed the existence of other elements which were not present in the original specimens. Finally, they presented tracks detected in a diffusion chamber of ionizing particles from a specimen which produced heat.

In the next set of experiments [44], the group reported evidence of photon emission in three experiments with hydrogen loading of Ni slabs, during the degassing phase, when hydrogen was introduced into the cell, and during thermal cycling.

In the papers published in 2004, they reported experimental results in Ni-H systems on photon and particle emission, heat production and surface transmutation [45], [46].

Some of their experimental results on the nuclear transmutation in protium systems had been explained by our model [47].

3A-3. *Experiments by Researchers in Tsinghua University, China*

The researchers in the Tsingha University and the General Research Institute for Non-Ferrous Metals, Beijing, China have performed experiments on the gas-loading Pd/D and Pd/H systems since 1996 [48]. In the experiment on the H/Pd system [49], they observed the change of distribution of the zinc component in the palladium wire which has been loaded with hydrogen in a gas-loading system for one year. The Zn component increased by a factor of 160 in comparison with the original palladium wire. Zn spreads over the whole cross-section of the reacted palladium wire and therefore the origin of Zn should be the nuclear transmutations in the gas-loading H/Pd system.

We have explained their experimental results of Zn generation by our model [50].

In the paper published in 2002, they reported observation of excess heat in a gas-loading D/Pd system using current-constant mode or temperature-constant mode [51]. In the paper published in 2019, they investigated the temperature dependence of excess heat in both electrolysis and gas-loading experiments observed in many experiments and contemplated the cause of nuclear reactions in CFP [52].

3A-4. *Experiments by Researchers in the INFN-LNF, Italy*

F. Celani et al. in INFN-LNF and other Institutions in Italy started a new experiment in 2001 with Ni wires [33] with the following characteristics: the wires are low cost and they work even with H_2 (not only D_2). The general approach of their experiment was to use as much host metal as possible, the same overall materials, coatings (nano-materials, multilayer, two main kinds of materials) and measurement procedures as previously adopted for Pd wires by them.

They reported their experimental results in the next paper [53]; They could show in detail how even a low cost material, like commercial Cu-Ni-Mn alloy (named constantan ($Cu_{55}Ni_{44}Mn_1$) and ISOTAN 44), when its surface is properly modified from the point of view of dimensionality, can be used as material able to produce anomalous heat effects (AHE) due to close interaction with hydrogen (or deuterium, but at lower intensity) at high temperature.

They have investigated many variations in the components of multilayers of CF material after the investigation of the original system and published many papers some of them cited below [54], [55].

In the paper published in 2018, they tried to improve the intrinsic, excellent catalytic properties of constantan (CST) in $H_2 \rightarrow$2H dissociation. They subjected the surface to repeated cycling of "flash" oxidation (pulsed power up to 20 kVA/g), obtaining sub-micrometric particles of mixed composition (CST–NiO_x–CuO_y–$Cu_xNi_yO_z$) and reducing deleterious self-sintering problems with nano-materials at high temperatures [54].

Furthermore, they summarized their former research up to 2020 [55]. Using an empirical approach they identified the effect of surface modification of the Constantan wires with coatings comprised of elements that enhance the absorption behavior, and oxides with low work function for electron emission. They also explored certain geometrical arrangements of the wires such as knots and coils in order to induce local thermal gradients and predictable hot-spots. Moreover, the DC polarization of the wires by a counter-electrode proved to be a versatile approach to induce non-equilibrium conditions that are essential for the production of excess heat, especially when a dielectric barrier discharge (DBD) is produced.

We have analyzed the experimental data of excess heat generation and nuclear transmutation obtained in the nano-coated Ni wire with Pd and a compound of B, Sr, Ba and Th at temperatures up to 900 °C [33] using the TNCF model [7] (cf. Sec. 2-4d in this paper). It is possible to understand the data of the excess heat and the nuclear transmutation consistently in themselves and also with other experimental data sets obtained since 1989 [4], [10].

3A-5. *Experiments by Iwamura et al. in Japan*

As we noted above in Sec. 2-4, the paper by Iwamura et al. (Mitsubishi Heavy Industries Co., MHI) [32] showed the localization of nuclear reactions. These experiments employ a system with a multi-layer Pd that contains low work function material (CaO, TiC, Y_2O_3, etc.) where continuous diffusion of deuterium through the material occurs [56].

Iwamura et al. have worked on multi-layer Pd system for a long time and obtained various experimental results showing the nuclear transmutations in CF material [32], [57], [58]. Their nuclear transmutation experimental results were successfully explained by our model [18 (Sec. 5.2)].

After their transfer to Tohoku University from the MHI, they changed their main theme of their research to the metal nano-composite compounds [59], [60], [61] initially used by the research group in Kobe University hosted by A. Kitamura.

3A-6. *Experiments by Kitamura et al. in Kobe University, Japan*

Kitamura et al. worked with the gas-solid system in CFP [62].

Their experiments in 2006 were on the system similar to that used by Imamura et al (vacuum/CaO/Sr/PdO_x/D_2). From 2009, they joined with researchers in Technova Inc. and developed new system for CF materials, so-called Pd/PdO/ZrO_2 nano-composite samples [63], which have developed to the nano-composite system with Pd/SiO_2 and $CuNi_{10}$/SiO_2 [64], [65], [66].

Kitamura et al. summarized their experimental results performed with CF materials composed of metal nanocomposites supported by zirconia or by silica in the hydrogen isotope gas [67]. The work was performed by the researchers in a group composed of Kobe University, Technova Inc., Tohoku University and other Institutions for the investigation of CFP in these CF materials. The abstract of the paper shows the essence of the work as follows [67]:

> "*Anomalous heat effect by interaction of hydrogen isotope gas and metal nanocomposites supported by zirconia or by silica has been examined. Observed absorption and heat evolution at the room temperature were not too large to be explained by some chemical processes. At elevated temperatures of 200–300 °C, most samples with binary metal nanocomposites produced excess power of 3∼24 W lasting for up to several weeks. The excess power was observed not only in the D-Pd/Ni system but also in the H-Pd/Ni system and H-Cu/Ni system, while single-element nanoparticle samples produced no excess power. The Pd/Ni ratio is one of the keys to increase the excess power. The maximum phase-averaged excess heat energy exceeded 270 keV/D, and the integrated excess heat energy reached 100 MJ/mol-M or 90 MJ/mol-H. It is impossible to attribute the excess heat energy to any chemical reaction; it is possibly due to radiation-free nuclear process*."

To understand what "*the metal nanocomposite supported by zirconia or by silica,*" is, this is a shortcut to show how their Z-type sample, one of several types of their nanocomposite samples, is fabricated. We cite a part of their explanation below:

> "*The Z-type samples were prepared by the melt-spinning method similar to that used in Ref. (19). The alloy compounds of* $Pd_xNi_{0.35-x}Zr_{0.65}$*, e.g., were prepared by arc melting of the component metal blocks. The alloys were melted again by RF heating, and rapidly solidified with a melt spinning machine to make ribbon-like thin sheets of amorphous* $Pd_xNi_{0.35-x}Zr_{0.65}$ *compounds. The thin sheets were calcined in air at a temperature of 450 °C for 60 h, during which preferential formation of* ZrO_2 *supporter zone with isolated distribution of nano-structure zones of* $Pd_xNi_{0.35-x}$ *is expected. They were then ground in a mortar to make the sample particles with diameter of several to tens of mm. The composition parameter x is 0.044 (Pd/Ni=1/7) for most samples tested in Kobe Univ. including the CNZ-type with Cu/Ni=1/7, except for PNZ6 and PNZ6r with x=0.032 (Pd/Ni=1/10). It will be found that the composition parameter x is one of the most important variables for excess power production.*

[(19)] Y. Arata and Y. Zhang, "The Special Report on Project for Creation of New Energy," *J. High Temperature Society*, **34**, pp. 85–93 (2008)." ([67 (p. 16189)]

We have commented on this paper [Kitamura 2018] to accept their results as a part of the cold fusion phenomenon even if there has been no confirmation of the nuclear nature of the observed excess heat by them due to the complex structure of their samples [68].

3B. Adsorption of Protium and Deuterium at Gas–Solid Interface

"*$Whenagas^{*)}$ is brought into contact with a solid or liquid and equilibrated, the gas concentration near the surface is always higher than the gas phase free space. This does not depend on the properties of the gas or the surface. The process that causes this surface excess is called* ***adsorption***. *In any solid or liquid, surface atoms experience an unbalanced attractive force in a direction perpendicular to the surface, and when gas molecules adsorb, the balance of forces is partially restored.*

**) Gas and steam are collectively called gas. When it is necessary to distinguish between the two, we will use the term "permanent gas" for gas and "condensable gas" for steam.*" [69 (Sec. 1.1)]

As defined above by D.M. Young and A.D. Crowel, the absorption is a common process of atomic or molecular interactions between two media when they come into contact with each other. The science of adsorption is interesting scientifically and also important in many applications in various technologies related to our daily life. There are many works on the science of adsorption and the results were published in several books including the one by Young et al. [69] and others including following ones; *The Solid-Gas Interface* by E.A. Flood [27], *Adsorption, Surface Area and Porosity by* S.J. Gregg and K.S.W. Sing [70], *Chemisorption of Gases on Metals* by F.C. Tompkins [71] and *Thermal Accommodation and Adsorption Coefficients of Gases* by S.C. Saxena and R.K. Joshi [72].

In the study of the adsorption, it is usual to divide the adsorption into two types; physical adsorption (physisorption) and chemical adsorption (chemisorption).

To confirm the fundamental knowledge of adsorption, we cite the definition of them using the definition by Young et al. as follows.

"*Depending on the nature of the adsorption force, adsorption processes are classified into physical adsorption (physisorption) and chemical adsorption (chemisorption). The formation of a physisorption layer is related to the liquefaction of vapor due to the action of force. Not only is the heat of physisorption comparable to the heat of liquefaction, but also the formation of a physisorption layer, especially when the physisorption film is thick with several molecular layers. In many ways things behave like two-dimensional liquids. On the other hand, in chemisorption, electron transfer between a solid (adsorbent) and a gas (adsorbate) is a process in which chemical bonds are necessarily created between the outermost atoms of the adsorbate and the adsorbent. .*

The distinction between physisorption and chemisorption is usually clear, but in cases of doubt it can be determined by the following scale:

(a) The heat of physisorption is comparable to the heat of liquefaction of the adsorbent.

(b) Physisorption is a general phenomenon similar to condensation, so it can occur in any gas-solid system if the temperature and pressure conditions are suitable.

(c) The physisorption layer can be removed even at the temperature at which adsorption occurs by lowering the pressure.

(d) Under suitable temperature and pressure conditions, the physisorbed layer is often several molecular layers thick.

(e) Since physisorption is a relative of the liquefaction process, adsorption occurs to a noticeable degree only when pressures and temperatures are close to liquefaction conditions.

Table 2. The process to produce and apply the cold fusion phenomenon (CFP) in the gas-solid system.

Stages	Events
Stage 1	Selection and/or fabrication of host solid and hydrogen isotope gas
Stage 2	Adsorption of gas on the solid surface
Stage 3	Absorption of gas into the solid
Stage 4	Occlusion of gas in the solid
Stage 5	Superlattice formation of host element(s) and gas element(s)
Stage 6	Nuclear reactions to induce CFP
Stage 7	Science and Application of CFP

(1) In the *Stage 1*, the host solid as a metal, an alloy or a compound is selected or fabricated considering the final object of Stage 7. (2) In the *Stage 2*, the adsorption depends strongly on the component and the structure of the host solid. (3) In the *Stage 3*, the absorption depends on the physical characteristics of the solid which have been investigated thoroughly in Physics of Hydrogen in Metals. (4) In the *Stage 4*, the wave-functions of proton and deuteron in transition metals investigated in the research field related to the *Stage 3* are essential factor. (5) In the *Stage 5*, the superlattice of host elements and H or/and D is formed by the self-organization as summarized in Section 2. (6) In the *Stage 6*, the nuclear reactions to induce CFP occur automatically or accelerated artificially changing parameters. (7) In the *Stage 7*, we investigate the science and applications of CFP considering the artifice in the *Stage 1*.

(f) Physisorption occurs essentially instantaneously, but in porous or finely powdered adsorbents, the diffusion of gas within the mass is slow, especially at low temperatures." [69 (Sec. 1.2 *Physisorption and Chemisorption*) <Summarized freely by H.K.>]

The situation of adsorption of hydrogen isotopes on CF materials in CFP introduced in Section 2 and in Section 3A above seems to have slightly different characteristics from those discussed in the field of the science of adsorption introduced in the previous paragraphs in this Subsection 3B.

As we have pointed out in a recent paper, peculiarities of physics and chemistry in several fields of research on the transition-metal hydrides and deuterides such as cold fusion phenomenon, the super-fluidity of hydrogen, and the hydrogen electrode reaction have been observed [73].

Therefore, we depict the process occurring in the gas-solid systems in Table 2 schematically to consider the characteristics of the adsorption in CFP. The *Stage 1* the selection and/or fabrication of a host solid is the first stage in the program to investigate the science of the cold fusion phenomenon to the last *Stage 7* where we complete our work establishing the science, and we look possible applications of CFP through complicated manipulations in several stages to arrange the best situations for the final results.

In short, in the process of the adsorption of the gas of a hydrogen isotope A (H_2, D_2, or possibly H_2+D_2 gas) on the surface of the host solids B, we have to consider the following factors as essential points; (1) the specificity of the solid B to occlude A and (2) the super-fluidity of A in the solids B and then (3) the combination of A and B to form the superlattice (e.g. [39], [21], [17]).

The special combination of A and B pointed out in our paper [73] may influence the adsorption of A on B even if there is no mention about this in adsorption science. The fact that A is occluded in B might be *a special factor* in adsorption different from the physisorption and chemisorption considered hitherto in it. We consider this problem in the next section.

3B-1. *Adsorption of Atoms From Gas to Solid Surface*

There was a controversial problem in the initial stage of CF experiments for several years following 1989. The issue was what kind of the host metal, especially Pd metal, is appropriate to induce nuclear reactions in CF materials PdD_x. An example of the situation is seen in the Acknowledgement of the paper by Fleischmann et al. published in 1989 [1]. They say as follows; "*We thank Johnson Matthey PLC for the loan of precious metals for this project.*"

We also had experience of this kind in our experiment performed in 1989, which we described as follows [74]; "*The effect of aging of the cathode in the process of electrolysis observed by Jones et al.*[(1)] *was also found in our experiments. When the same palladium plate was used as the cathode for the second time, the production of neutrons went generally down to the background level in contrast with the brand-new plate which showed excess neutron production.*

[(1)]S.E. Jones et al., Observation of Cold Nuclear Fusion in Condensed Matter," *Nature*, 338, pp. 737–740 (1989)." [74 (p. 33)]

The above sentences illustrate the subtlety of the events in CFP, and this situation has not changed much up until now. We have to keep this fact in our mind in the further investigation of the cold fusion phenomenon (CFP).

The experimental results obtained in the Gas-Solid System briefly introduced in Sec. 3A give us many problems in relation to the atomic processes in the science of the cold fusion phenomenon concealed behind the main object of the research in this field. The investigation of CFP has been concentrated on high excess energy production rather than the science of the nuclear reactions occurring in CF material. In the stages tabulated in Table 2, the Stage 6 has been directly combined to Stage 1, giving insufficient attention to the intermediate stages.

We should place more emphasis on progress along the way from Stage 1 to Stage 6. In this Section 3B, we try to practice this approach not only for its scientific value but also for the necessity in the application of this science.

3B-2. *Physisorption, Chemisorption, or Suprasorption (?)*

We can use a simple definition of the physisorption and the chemisorption by S.J. Gregg and K.S.W. Sing [70];

> "*Those bringing about physical adsorption always include "dispersion forces"*[(16)] *(which are attractive in nature) and short range repulsive forces*[(17)]*. In addition there may be forces due to permanent dipoles within the adsorbed molecule.*
>
> *In chemisorption a transfer of electrons between the solid and the adsorbed molecule occurs; in effect a chemical compound is formed,but it is confined to a single layer of atoms of or molecules on the surface of the solid. One may thus say that valency forces are involved in the process of chemisorption.*
>
> [(16)]F. London,Z. Physik. **63**, 245 (1930); *Z. Physik. Chem.* **11**, 222 (1930).
>
> [(17)]M. Born and J.E. Mayer, *Z. Physik*. **75**, 1 (1932)." [70 (p. 10)]

In the case of CF materials, the interaction of protons (or deuterons) with host element(s) is different from that of the dispersion force (or the Van der Waals force) in physisorption and also from that in chemisorption. We are not sure that the force working in the adsorption of hydrogen isotopes on the surface of the host solids for CF material differs from those mentioned in the above definition given by S.J. Gregg and K.S.W. Sing.

It is a probable assumption that the force between hydrogen isotopes and the host solids in CF material formation differs from those in the cases of the physisorption and the chemisorption. In that case the adsorption should be called by another name, e.g., *suprasorption*. The situation should be carefully investigated through further works on CF materials from the science of adsorption.

The concept of the suprasorption, if it is appropriate to use, may be defined as follows; "*Adsorption of H_2/D_2 molecule on the surface of a transition metal (or a transition metal alloy) which takes H_2/D_2 into it as an occluded*

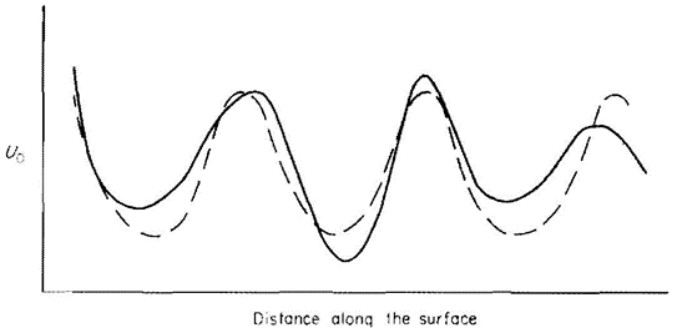


Figure 9. Variation of the value of U_0 (the energy of adsorption) as the centre of the adsorbed atom moves along a straight line parallel to the surface of a solid and distant r_0 (the equilibrium distance from the surface) from it: — — — — For a real surface, ... For an ideal surface. [70 (Fig. 1.13)]

proton/deuteron (p/d) and then to form such superlattice of the nucleus of the host element(s) and proton/deuteron as NiH or PdD in situations satisfying the conditions for the self-organization."

For the discussion of the proposed concept of the suprasorption, see the discussion of chemisorption, incorporation and absorption by F.C. Tompkins [71] cited in the Appendix.

3B-3. *Types of the Solid; Massive Solid With and Without Structure, Fine Porous Solid, or Fine Particles*

Several researchers have devised structures for host solids to make it easier to induce nuclear reactions in them regardless of the adsorption style with gas-solid or liquid-solid system. One of the well-known examples was the Patterson Power Cell devised by Patterson et al. with microspheres composed of multi-layers of Cu, Ni and/or Pd on the polystyrene sphere of a diameter $\sim$1 mm [75]. Celani et al. [33] used similar host solids in their gas-solid system obtaining excess heat and nuclear transmutations (cf. Section 2-4d).

3B-4. *Quality of the Solid; Simple Metal, Alloy, Compound*

There are various kinds of host solids as metals, alloys and compounds. It seems the investigation of H_2/D_2 adsorption on the surface of these host solids has not been eagerly performed due perhaps to the lack of knowledge about the situation in the CF investigation. We hope the situation improved rapidly for the promotion of the science and application of CFP.

3B-5. *Structure of the Solid Surface on the Adsorption; Simple Surface, Complicated Surface, Porous Surface*

The structure of the solid surface has a large effect on the adsorption. There are many papers about this effect. We give a commonsense investigation from a textbook [70]. The variation of the surface potential to the adatom is shown schematically in Fig. 9 which suggest large influence of the surface structure on the behavior of adatoms and therefore on the adsorption [70].

(1) Effect of Surface Smoothness on alpha-D_2

In an attempt to investigate the character of the sites retaining alpha-D_2, Grunze et al. carried out experiments on a disordered Ni(111) crystal which had been subjected to sputter roughening by Ar^+ ion bombardment (600 eV $\times$ 2.9

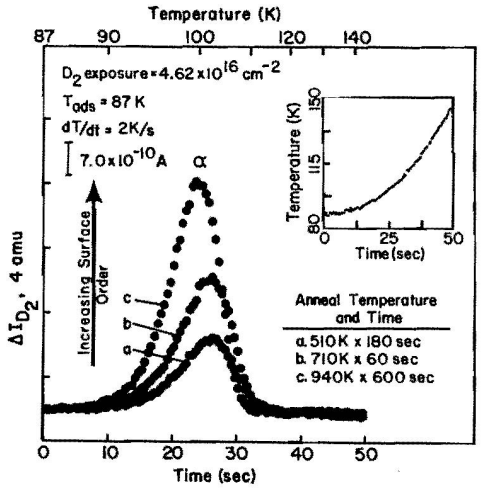


Figure 10. Effect of induced surface roughness on the alpha-D_2 state. The crystal surface has been roughened by Ar ion bombardment (600 eV $\times$ 1200 sec $\times$ 2.9 μA at T = 480 K). The alpha-D_2 TPO spectra are generated after exposing the surface to D_2 after annealing the clean crystal at different temperatures. The insert is a digitized plot of the crystal at different temperature versus time during programmed desorption. [76 (Fig. 8)]

μA $\times$ 1200 sec.) [76]. From this initial disordered condition,three increasing degrees of surface order were achieved by annealing the crystal as shown in Fig. 10 ([76], where sequential D_2 adsorption experiments were carried out.

Many excellent experimentalists have had their own secret technologies to improve experimental results even if they are subtle or small techniques. My collaborator, the late Dr. John Dash, had one to improve occurrence of excess heat generation in the $Pd/D_2O + D_2SO_4/Pt$ system. His secret technique in this case was rubbing the surface of Pd plate with a sandpaper. He made the surface of the cathode of Pd plate rough increasing surface area to make higher possibility of adsorption of D on the surface and therefore higher D/Pd ratio in the sample and higher probability of CFP.

(2) Effect of Surface Transformation by Pore Formation

Despite its arbitrariness the distinction between an external and an internal surface is useful in practice: a wide range of porous solids have an internal surface greater by several orders of magnitude than the external surface, the total surface of the solid thus being predominantly internal. When aggregation of such particles occurs,then part of the external surface becomes converted into an internal surface (Fig. 11) and a pore system is developed [70].

In the simplest case, adsorption on microporous solids is explained by a classical idea developed by I. Langmuir [77] using a schematic pictures shown in Fig. 12 [70 (Fig. 4.3)]. The extension from the simple adsorption on an open surface depicted in (a) to the microporous adsorbents represented as a channel in (b) is a very long extrapolation,especially as the channels may be many hundreds or thousands of molecular diameters in length as noticed by Gregg [70].

There are several works on the adsorption of gases (hydrogen isotopes and nitrogen) by zeolite [78 (Appendix E)]. The works cited in the Data Handbook by D.P. Valenzuela and A.L. Myers [78] and the explanations of the "Physical Adsorption of Gases by Microporous Solids" by S.J. Gregg and K.S.W. Sing [70] will give a valuable hint for the investigation of adsorption and CFP in the recent works with nanocomposite samples (cf. Sec. 3B).

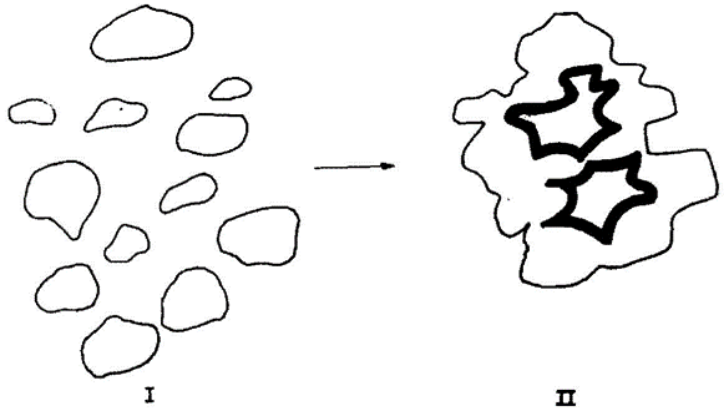


Figure 11. The external surface in I is partially converted into an internal surface (denoted by heavy lines) in II. [70 (Fig. 1.2)]

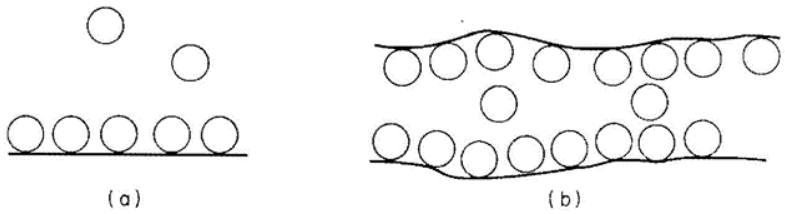


Figure 12. (a). Diagrammatic representation of molecules adsorbed on a surface freely exposed to the gas phase. (b). Diagrammatic representation of molecules adsorbed on the walls of a micropore [70 (Fig. 4.3)].

(3) Use of Porous Body in the Recent Investigation of CFP

The science of adsorption in relation to the porous body has been fully discussed by Linsen and van den Heuvel in the book edited by E.A. Flood [27 (Chapter 35)] and S.J. Gregg and K.S.W. Sing [70 (Chapters 3 and 4)]. The properties of an adsorbent are largely determined by its detailed pore structure and by the nature of the solid surface. It is also very important to investigate the changes in pore systems associated with sintering since we note the fact that CF materials with nanocomposites have been used frequently in the CF research in recent years (cf. Sec. 3B).

The technique used in the adsorption science may be used to determine the shape, the width and the pore-size in the nanocomposite CF materials as explained by B.G. Linsen and A. van den Heuvel [27 (Chapter 35)]. Fundamental data of these characteristics of nanocomponents will be useful for improving CF materials and for scaling up the experiments.

(4) Composition of Gas; Single Component Gas or Mixed Gas

By monitoring the difference in the buildup in D and H coverage at 87 K,as shown in Fig. 13 [76],it is clear that there is a retardation of D_2 adsorption relative to H_2 adsorption from an equal mixture of H_2 and D_2 over the entire coverage range. The data have been corrected for the small (<0.08 $\times$ 10^{15} H/cm^2) contribution due to ambient H_2 adsorption. From these data, we estimate $S_0^{D2} = 0.7\ S_0^{H2}$ or $S_0^{H2} = 1.43\ S_0^{D2}$.

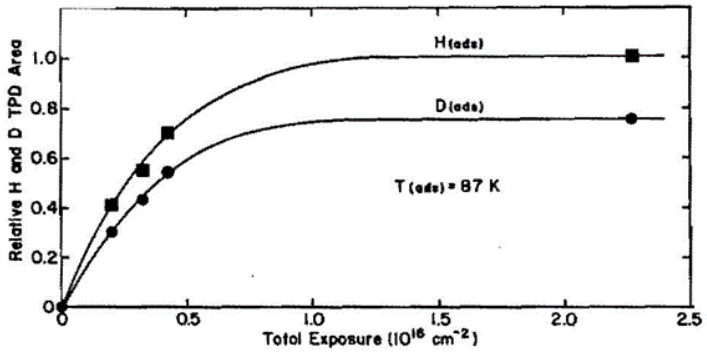


Figure 13. Relative coverages plotted as a function of $H_2 + D_2$ total exposure. Ni (111) temperature = 87 K. [76 (Fig. 6)]

To give a necessary explanation of the sticking coefficient S, the S_0 in the above explanation is the initial sticking coefficient for the adsorption, i.e., a ratio of the number of adsorbate atoms (or molecules) that adsorb, or "stick," to a surface to the total number of atoms that impinge upon that surface during the same period of time. Therefore, the result $S_0^{D2} = 0.7\ S_0^{H2}$ means that the H_2 molecule is sticky than the D_2 molecule to be adsorbed by Ni (111) surface.

This fact might be the reason why Ni-H system is feasible to CFP than Ni-D system the well-known and the wonderful fact noticed for long in the CF research [79 (Sec. 4)]. The similar fact that Pd-D system is better than Pd-H system for CFP, a well-known fact in CF research, has been explained by the characteristic diffusion coefficients D_0 of hydrogen isotopes in Pd, the so-called inverse isotope effect, that D_0 of D is larger than that of H in the range of room temperature (e.g., [39 (Sec. 2)]). If we can use a similar data of S_0 for Pd, it is possible to discuss the fact that Pd-D is better than Pd-H from wider bases of physics of palladium hydrides.

It is regrettable that we have not enough space to discuss the interesting problems related to the adsorption as a whole not restricted to the gas-solid system. We have various experimental data sets obtained in CF material composed of various transition metals as W, Re, Pt and Au not confined to the popular Ni and Pd. One of analyses on the experimental data obtained with these CF materials is in our paper published in 2017 [81].

Saxena and Joshi have given a bibliography of the adsorption of hydrogen on metals including Al, Cu. Fe, Pt and W in addition to Ni [72 (Chapter VI)]. The papers on the Nickel-Hydrogen system in their Data Book (Sections "Nickel-Hydrogen System" and "Nickel (Film)-Hydrogen System") must be useful for the investigation of CFP in Ni-H system used frequently in the recent investigations. The papers on the other metals included in their Data Book might be also useful for cultivation of new fields on such works as taken up and analyzed in our paper [79].

3B. Discrimination of the Excess Heat Between Chemical, Physical and Nuclear Origins

The experiments using the nanocomposite solids (e.g., [67] and papers cited in this paper) have attracted attention resulting in many works reporting large excess heat even if there are few data of nuclear products [68]. It is desirable to confirm occurrence of effective nuclear reactions of CFP in the nanocomposite solids. We propose a trial to discriminate the excess heat between chemical, physical and nuclear origins using the adsorption heat long investigated in the field of the science of the solid-gas interface (for instance [80]).

Most of the work on the adsorbate-adsorbent systems done in the Beebe laboratory has been performed using constant-temperature baths around the calorimeter involving liquid oxygen (67) or nitrogen (89),solid carbon dioxide (81),ice water or other freezing mixtures (9),and higher temperature furnaces (87). To illustrate the type of data obtained,a summary of some of the measured heat values is given in Table 3 (Numbers in parentheses such as (67) in the explanation are those used in the original explanation in [80]).

Table 3. Calorimetric Heats of Adsorption ([80] Fig. 5-1)

Adsorbent	Adsorbate	Temp. °C	ΔH, kcal/mole $\theta = 0$	$\theta = 1$	Ref.
Chromic oxide	N_2	−183	8.2	3.0	67
Chromic oxide	Ar	−183	4.2	3.0	67
Chromic oxide	O_2	−183	ca. 26.0	4.0	67
Synthetic ammonia catalyst	CO	−183	ca. 18.0	4.0	69
Synthetic ammonia catalyst	CO	−78	30-35	8-10	69
Synthetic ammonia catalyst	CO_2	−78	32	8.0	69
Silica gel	1-Butene	0	15.8	10.0	74
Silica gel	n-Butane	0	11.0	8.2	74
Silica gel	Propene	0	11.0	7.8	74
TiO_2 (anatase)	N_2	−195	4.4	2.2	47
TiO_2 (anatase)	O_2	−195	4.8	2.2	47
Spheron 6	1-Butene	0	16.0-16.5	8.0	72,74
Spheron 6	n-Butane	0	ca. 13.5, 16.0	7.2, 8.0	72
Spheron 6	N_2	−195	4.4	2.2	47, 71
Spheron 6	n-Pentane	0	ca. 16.0	9.0	75
Spheron 6	Neo-pentane	0	12.5	8.0	75
Spheron 6	Cyclopentane	0	13.5	7.5	75
Spheron 6	Ar	−195	4.0, 2.5	2.8, 2.2	71,77
Spheron 6	n-Decane	100	22.0	14.6	76
Graphon	1-Butene	0	10.0	8.4	72
Graphon	N_2	−195	2.9	1.7	71
Graphon	n-Decane	100	21.0	17.1	77
Saran charcoals	N_2	−195	3.5, 4.7	2-2.5	77
Saran charcoals	Ar	−195	3.5, 3.8	ca. 2.5	77
Wear dust	N_2	−195	5.0	2.4	77
Wear dust	Ar	−195	3.5	2.5	77
Sterling FT (2700)	CO_2	−79	6.4	5.3	81
Sterling MT (2700)	CO_2	−79	4.5	5.9	81
Sterling MT (2700)	NH_3	−79	7.2	6.2	81
Promoted iron catalyst	H_2	−195	5.5	ca. 1.8	87
Promoted iron catalyst	H_2	0	17.0	ca. 9.0	87
Promoted iron catalyst	H_2	214	26.0	<15	87

The data included in the table show the variety of systems studied by Beebe and co-workers. Even if the data in this old table is confined to only several adsorbent-adsorbate combinations, similar investigations on the system corresponding to the combinations of materials used in recent experiments of nanocomposite solids will be beneficial to estimate the excess heat by the nuclear reactions separating from those by the heat of adsorption and the heat of crystallization which had been pointed out already in our previous paper [68].

If we can discriminate the excess heat by chemical, physical and nuclear origins, the investigation of CFP in the nanocomposite solids will produce effective guidelines in experiments.

4. Possible Applications of the Cold Fusion Phenomenon

When thinking about the applications of the cold fusion phenomenon, the first thing that comes to mind is probably as an energy source. Since the initial idea was to consider the possibility that d – d reactions occur in solids, it is natural to think so, but there are some difficulties in applying it as an energy source. First of all, there is the problem of

deterioration of CF materials due to nuclear reactions occurring in them. Second, there is the issue of activation of the surrounding environment due to neutron radiation. Thirdly, there is the issue of biological exposure caused by neutron radiation itself.

Perhaps the most promising application of cold fusion is the removal of hazardous radioactive waste. At least the first difficulty mentioned above should become less important.

In addition, various other applications such as biological nuclear transmutation may be considered.

5. Concluding Remarks

As mentioned in the Introduction, there is still no theory that comprehensively explains the entire cold fusion phenomenon (CFP) with diverse and varied experimental facts as tabulated in Table 1. In Section 2, therefore, we used a phenomenological approach with the TNCF model to provide an overview of CFP.

On the other hand, the science of adsorption plays an important role in many phenomena and contributes to various applications. However, because CFP tends to jump from Stage 1 to Stage 6 in the research stage classification shown in Table 2, the science of adsorption, which corresponds to Stage 2 to Stage 3, has received little attention.

It is clear that the future development of the science and the possible application of CFP will require exploration of the science in each step in Table 2 based on experimental facts. In particular, the importance of studying the science of adsorption in multilayered host materials, various alloys and porous compounds cannot be overemphasized.

In this paper, the author used basic books and handbooks on adsorption phenomena to examine the relationship between nuclear reactions in solids and adsorption phenomena in the cold fusion phenomenon (CFP) that developed after 1989, but until now it has been neglected. I would be happy if I was able to fill in the gaps in the scientific basic mechanism of CFP.

Finally, the author would like to add several comments to emphasize the key points for the development of the solid state-nuclear physics where CFP occupies an important part in it.

Comment 1. The solid state-nuclear physics, an interdisciplinary science between solid state and nuclear physics, is a new field of science. Its importance is clearly recognized by the discovery of CFP. It is important because of the unique nature of CFP, and possible energy application. However, there have long been observed other wonderful phenomena in chemistry and physics of metal-hydrogen systems. We give notes on CFP in the following Subsection 1.1 and on others in Subsection 1.2 below.

1.1 The cold fusion phenomenon (CFP) in the gas-solid system reviewed in this paper treats mainly the system composed of transition metals and hydrogen isotopes. However, it should be emphasized that the carbon (C) in Table 1 is related to the important phenomena of CFP in CF materials composed of carbon and hydrogen as XLPE [5], hydrogen graphite [6], and biological molecules [9].

1.2 We can enumerate such typical examples as the super-diffusivity of hydrogen in transition metals and alloys, the hydrogen electrode reaction, and the underpotential deposition in peculiarities of physics and chemistry as investigated in our recent paper [73].

Comment 2. In our phenomenological approach using the TNCF model [4], [10], [14], we have used several premises not necessarily explained theoretically even if there are incomplete trials to understand them [17]. Two of important problems related to the premises of the model should be investigated seriously.

2.1 Formation of neutron bands by the super-nuclear interaction between neutrons in different lattice nuclei [10 (Sec. 3.7)].

2.2 Dissipation of excess energy in an excited nucleus into lattice through its interaction with neutrons in the neutron bands [4 (Sec. 11.1, Premises 4 and 6), 10 (Sec. 2.4), 15 (Sec. II)].

Comment 3. Confirmation of nuclear reactions is the most important evidence of CFP and its application. In the experiment where several processes such as the adsorption of gases, the recrystallization of solids and CFP take place

simultaneously, we have to discriminate the cause of measured excess heat especially that by nuclear reactions in the system.

It is an urgent demand to investigate the adsorption energy of solids used in or related to recent experiments with nanocomposite compounds [67], [68] where seems the three processes referred above coexist.

3.1 It is desirable to develop the science of hydrogen adsorption to the solids used actively in recent experiments of excess heat generation.

I hope that this personal review of the cold fusion phenomenon (CFP) will arouse interest in the atomic and nuclear processes in CFP among researchers of adsorption phenomena, and motivate them to contribute to the science and application of this phenomenon.

Appendix A. On the Characteristics of Adsorption of Hydrogen Isotopes on the Transition Metals in the Cold Fusion Phenomenon

As we discussed the peculiarities of physics and chemistry in the transition metal hydrides in Sec. 3B-2, it seems necessary to take up the characteristics of the cold fusion phenomenon in relation to the adsorption and absorption of hydrogen isotopes in Stages 2 and 3 explained in Sec. 3B. Even if the characteristics of adsorption of hydrogen isotopes on the surface of transition metals have not been noticed in the science of adsorption hitherto, it is needless to say, important to investigate these characteristics for the development of science and application of the cold fusion phenomenon.

To supplement the discussion so far, we cite an overview of the process from the adsorption to absorption given by F.C. Tompkins in his book [71].

> "*Atoms at the surface of a solid exert an attractive force normal to the surface plane. Consequently,at a gas/solid interface,the concentration of gas exceeds that in the gas phase. The excess concentration at the surface is termed adsorption; the solid is the adsorbent and the gas the adsorbate. The amount adsorbed is the difference between the number of adsorbate molecules in the adsorbed layer and that in an equivalent layer in the absence of the adsorbent. Its magnitude depends on the physical and chemical properties of both adsorbent and adsorbate,the temperature of the gas/solid system and the ambient pressure of the gaseous adsorbate.*
>
> *The term adsorption is restricted to the accumulation of adsorbate at the gas/solid interface. For porous adsorbents,gas molecules can diffuse down capillaries and channels and be adsorbed on their walls. Gas molecules can also penetrate the lattice of the adsorbent by a process akin to dissolution. This internal uptake is termed absorption. A process involving both adsorption and adsorption is called sorption. Adsorption may also be followed by a chemical process which is continued into the lattice,finally resulting in a three-dimensional compound,such as an oxide when oxygen is in contact with some transition metals. This process is termed incorporation,and the surface is said to have undergone reconstruction or reconstitution* (Fig. A.1)." [71(pp. 1–2)]

F.C. Tompkins did not contemplate the influence of the incorporation and the absorption on the adsorption itself which is naturally out of his interest in his book. However, his words cited below indicate that his thought was not limited to the conventional concept but extended to wider interests.

> "*Since chemisorption involves short-range chemical forces,it is normally limited to the monolayer. Nevertheless,at higher gas pressures and at moderately low temperature, the formation of a physisorbed or/and a weak chemisorbed layer of a different character may,in some systems,proceed over the primary chemisorbed layer.*" [71 (p. 5)]

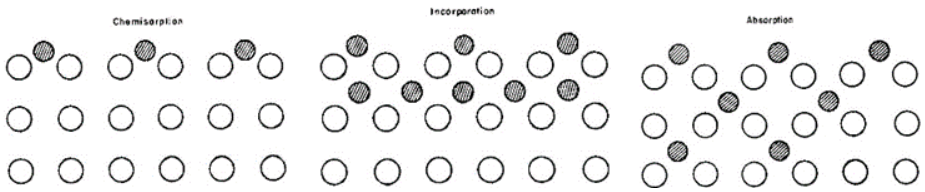


Figure 14. Diagrammatic representations of chemisorption, incorporation and absorption. [71 (Fig. 1.1)]

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