Development of the Solid State-Nuclear Physics

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1 author:

Hideo Kozima
Kozima's Cold Fusion Research Laboratory (Established 1999)

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Hideo Kozima
Cold Fusion Research Laboratory, Shizuoka, Japan
E-mail: hjrfq930@ybb.ne.jp
CFRL website: http://kozima-cfrl.com/

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Abstract

Investigation of the cold fusion phenomenon (CFP) for about 30 years since its discovery in PdD_x by M. Fleischmann et al. in 1989 has revealed existence of nuclear reactions in specific solids (CF materials) at near room-temperature without any mechanism of acceleration for particles in the system. The *Cold Fusion Phenomenon* (*CFP*) is defined as a phenomenon including nuclear reactions observed in such materials (CF materials) composed of host elements and hydrogen isotopes as transition-metal hydrides and deuterides, hydrogen graphite, XLPE (cross-linked polyethylene) and microbial cultures. The diverse and complex experimental data, obtained in the CF materials and piled up in vast amounts in these years, have been riddles for almost all scientists. The experimental facts observed in this field, however, suggest existence of new mechanisms for nuclear reactions in the CF materials. The new mechanism for the CFP should be a fundamental element of a new physics, the solid state-nuclear physics (SSNP), in between solid state physics (condensed matter physics) and nuclear physics. It should be noticed that we have observed some effects belonging to the SSNP in solid state physics and in nuclear physics prior to the discovery of the CFP in which there are mechanisms related to the CFP.

We have developed a phenomenological approach to the CFP with a model (TNCF Model) to understand the complex data sets obtained in this field, as a whole. The approach has been successful to give a unified interpretation for the CFP and suggests an outline of the SSNP where neutrons in the CF materials play the leading role for realization of the nuclear reactions. The fundamental premises assumed in the TNCF model have been investigated quantum mechanically taking up properties of protons (p) and deuterons (d) in CF materials and also novel features of the nuclear structure of host

elements (M) in them. The extended wavefunctions of protons *p* (or deuterons *d*) at interstitial sites and the intranuclear structure of nuclei at lattice sites (lattice nuclei) seem to be essential to the CFP when the interstitial protons (deuterons) and the lattice nuclei form a superlattice (metal-hydrogen superlattice).

The inductive reasoning and meta-analysis applicable to the complex experimental data sets have given logical legitimation of our phenomenological approach performed using the TNCF model. The successes of the TNCF and the succeeding ND model to understand the CFP as a whole should be understood as an evidence of the fundamental role of neutrons assumed in the models to understand the CFP. The existence of neutron energy bands (neutron bands, for short) with neutrons in them, when there is a metal-hydrogen superlattice, is a new important fact in the solid state-nuclear physics discovered by the CFP. The neutrons in the CF materials are responsible not only to the CFP but also to the super-diffusivity of hydrogen in some transition metals observed for more than 100 years.

Keywords: solid state-nuclear physics, carbon-hydrogen superlattice, cold fusion phenomenon, nuclear transmutation, CF materials, metal-hydrogen superlattice, super-nuclear interaction, neutron energy band, cf-matter

1. Introduction

Quantum mechanical treatments of microscopic objects, atoms, nuclei and elementary particles, have a common difficulty related to the many-body problem common in classical mechanics and quantum mechanics; the three-body problem is, in general, impossible to solve exactly in the classical mechanics as well-known in the history of mechanics. The situation is the same in quantum mechanics; we have to depend on some approximations to treat the many-body system even if there are only linear but not nonlinear interactions between components. In the systems where are nonlinear interactions, we have to encounter with complexity leaving the fundamental equations applicable only to linear systems in classical and also in quantum mechanical objects.

Since 1920s when the quantum mechanics was established we have investigated the physical events occurring in the microscopic world around us at energy ranges from 1 K to 10^4 K on a temperature scale (1 K = 1.38 × 10^{-23} J) in nuclear physics and also in solid state physics (a part of the condensed matter physics).

Nuclear physics is the physics of a system where the principal interaction between components of the system is the nuclear force; the short-range, strong interaction between nucleons with some other characteristics. The other interactions such as electromagnetic and contact interactions work in such subordinate cases as the Knight shift and the electron capture by an unstable nucleus.

Solid state physics is the physics of a system composed of atomic nuclei and electrons where the principal interaction between particles is electromagnetic. The nuclear interaction works in such subordinate phenomena in this field as the neutron diffraction and Moessbauer effect.

Solid State-Nuclear Physics (*SSNP*) in between the nuclear physics and the solid state physics may be defined as "the physics of a system composed of atomic nuclei, including protons and neutrons, and electrons in which the nuclear force between nucleons plays an essential role in addition to the electromagnetic force." Though this definition includes some ambiguities, we have not much trouble with them in the following discussion.

It is convenient to define the cold fusion phenomenon as follows for further discussion. The *Cold Fusion Phenomenon* (*CFP*) is a phenomenon including nuclear reactions observed in such materials composed of host elements and hydrogen isotopes (CF materials) as transition-metal hydrides and deuterides, hydrogen graphite, XLPE (cross-linked polyethylene) and microbial cultures. It should be noticed that the CFP has given a decisive influence since its discovery on the establishment of the Solid State-Nuclear Physics as explained in this paper.

It is also emphasized that the investigation of the CFP revealed the restoration of the induction (or the inductive reasoning) superior over the deduction (or deductive reasoning) for such a problem in dynamical systems as the CFP where the behavior of particles interacting nonlinearly is governed by complexity. The deduction considered to be the most effective logic to deduce a conclusion starting from an established principle becomes ineffective when the principle does not define a logic leading to a conclusion but to indefinite conclusions with probabilities.

In Section 2, we briefly overview the microscopic world to understand the situation treated in atomic physics and nuclear physics developed in the 20th century. We also give examples of events belonging to the SSNP in solid state and nuclear physics investigated prior to the discovery of the CFP. The discovery of the CFP by chance in the search of new energy source have given a motivation to establish the solid state-nuclear physics as explained in this paper.

In Section 3, we explain that the novel feature of the SSNP revealed by the CFP has been explained by formation of a new state of neutrons, the *neutron energy band*, in the CF materials. The formation of the neutron energy band is realized when there is a *metal-hydrogen superlattice* [Bradley 1932] which is self-organized in a host lattice (transition metal or carbon) containing a hydrogen isotope (H or D) with high concentration. The *super-nuclear interaction* between neutrons in different lattice nuclei, mediated by protons/deuterons at interstices coupled with lattice nuclei through the nuclear interaction plays the principal role in the formation of the neutron energy band.

In Section 4, we discuss the meaning of the development of the solid state-nuclear physics in terms of logical structure of science in general. Possible applications of the CFP will be discussed briefly.

2. Solid State Physics and Nuclear Physics in terms of the Cold Fusion Phenomenon

In this section, we recollect the solid state physics and the nuclear physics from the viewpoint of the solid state-nuclear physics (SSNP) to notice that the effects of the nuclear force have appeared in the former and the effect of environments outside nucleus in the latter already prior to the discovery of the CFP. The fundamental characteristic of the CFP is the nuclear reaction occurring in the CF materials while there have been observed no events related to nuclear reactions in the SSNP before the year of 1989 even if the nuclear force works there in addition to the electromagnetic force.

To show the outline of the historical developments, a flowchart of the SSNP in relation to the solid state physics and the nuclear physics is given in Appendix A as Fig. A1.

2.1 Effects of the Nuclear Force in Solid State Physics

The solid state physics is a science of atoms and molecules in the condensed state. It is inevitably a science of the many-body system where the leading actors are atoms and electrons interacting mainly with the long-range electromagnetic force and occasionally with other interactions like the hyperfine interaction between an electron and a nucleus and the strong interaction between nucleons. The latter interactions have given a few examples of the solid state-nuclear physics in the extended fields of the solid state physics.

It should be noticed here that the extraordinary large diffusivity (let us call it the *super-diffusivity*) of hydrogen isotopes in some transition metals and their alloys has been a riddle for more than 150 years since the phenomenon was observed by T. Graham [Graham 1866]. In the materials where occurs the super-diffusivity (e.g. [Voelkl (1978), Fukai (2005)], there has been observed the CFP as we have noticed already [Kozima 2006 (Sec. 3.6), 2014 (Appendix A3)]. The close relation of the super-diffusivity and the CFP is discussed in Sec. 3 and it is suggested that the super-diffusivity should be treated as a phenomenon in the solid state-nuclear physics.

2.1-1 Electromagnetic and Hyperfine Interactions

Even if almost all phenomena occurring in condensed matters, solids and liquids, reflect the electromagnetic interaction among particles in the system, there are some effects reflecting the hyperfine interaction between a nucleus and an electron, such as the Knight shift [Knight 1949, 1956], and the nuclear interaction (strong force) between a proton and a neutron as pointed out in the next subsection.

2.1-2 Nuclear Interaction between Atoms and Nucleons in Solids

In a condensed matter, there occur sometimes the nuclear interactions between nuclei of host atoms and a nucleon or a nucleus of an exotic atom [Seitz 1956]. Most popular phenomena in this genre are the radiation damage and the Moessbauer effect. We give their brief explanation below from our present viewpoint.

Radiation Damage

Since Silk and Barnes [Silk 1959] observed the tracks of uranium fission fragments on the mica films, the formation of latent tracks by heavy charged particles in solids has been recognized as one of fundamental phenomena of the radiation damage. And then, the investigation of the latent tracks became an important device for detection of charged particles by the success of etch-pit technique developed by Price and Walker [Pryce 1962]. The technique to identify incident charged particles using their latent tracks in target solid-state detectors, especially CR-39, has been developed enthusiastically and used widely in many fields of science including the CFP [Kozima 2013a].

Radiation damages are the most widely investigated theme in the solid state-nuclear physics due to their importance in modern world where various kinds of radiation are influencing human activities. Its importance will surely increase furthermore in future. We give only a glimpse on the present status of this theme leaving its further discussion elsewhere.

The radiation damages have been investigated mainly in three cases where one of three radiations, charged particles, electromagnetic waves (mainly X-rays and gamma rays) and neutrons, interacts with matter.

Mòssbauer Effect [Mòssbauer 1958]

The **Mössbauer effect**, or **recoilless nuclear resonance fluorescence**, is a physical phenomenon discovered by R. Mössbauer in 1958. It involves the resonant and recoil-free emission and absorption of gamma radiation by atomic nuclei bound in a solid. Its main application is in Mössbauer spectroscopy [Frauenfelder 1962, Silsbee 1964].

In the Mössbauer effect, a narrow resonance for the nuclear gamma emission and absorption results from the momentum of recoil being delivered to a surrounding crystal lattice rather than to the emitting or absorbing nucleus alone. When this occurs, no gamma energy is lost to the kinetic energy of recoiling nuclei at either the emitting or absorbing end of a gamma transition; emission and absorption occur at the same energy, resulting in strong, resonant absorption.

2.1-3 Neutron Diffraction and Neutron Waveguides

In addition to the above examples of the solid state-nuclear physics, we have an important genre of the solid state-nuclear physics caused by the interaction between a neutron and host nuclei in the solids (e.g. [Kothari 1959]). The neutron-nuclear interaction is most effectively investigated and utilized as the neutron diffraction [Shull 1956, 1995] for the structural analysis in solid state physics and recently as the neutron waveguide to guide a neutron beam from the source to a place where the beam is used.

Looking for historical basis of the neutron-solid interaction, we have noticed profound researches originating from the work by E. Fermi in 1936 [Fermi 1936, Golub 1990]. Especially interesting is the interaction of thermal neutrons with solids reviewed by Kothari and Singwi [Kothari 1959]. There have been many works on the neutrons in crystals interacting with lattice nuclei through the strong interaction [Scheckenhofer 1977, Steinhauser 1980] in addition to that due to the magnetic interaction [Hino 1998] as discussed in our paper [Kozima 2016a], however, lacking the formation of the neutron energy band we have noticed in our previous works [Kozima 1998a (Sec. 12.4), 1998b, 2004, 2006a (Sec. 3.7.2)], perhaps, due to the finite life of free neutrons. We will give our opinion on this problem and our answer in this paper (especially in Section 3.3).

In the metal-hydrogen superlattice in CF materials, the interaction of neutrons in host nuclei and protons/deuterons at interstices through the nuclear force should be treated as a many-body problem. In this paper, however, we have to consider the situation in a simplified manner using a single-particle approximation as a problem of neutron energy band formation mediated by the proton/deuteron sublattice in CF materials, a specific array of host elements and hydrogen isotopes [Kozima 2013b (Figs. 3.8 and 3.9), 2016a]. This situation reminds us the liquid drop and the shell models for the nucleus composed of nucleons interacting through the nuclear force. In our case, the correspondence to these models is many-body and single-particle approximations for the neutrons interacting with the super-nuclear interaction.

It is an obvious one-step by above investigations to attain the neutron energy band structure such as the electron energy band [Kozima 2016a (Fig. A3)] while the step is not traced due, perhaps, to the finite life time 889 ±3 s of the free neutron. However, it is easy to infer from the experimental data for neutron transmission obtained in the potential steps similar to the Kronig-Penny potential [Steinhauser 1980 (Fig. 3), Kozima 2016a (Fig. 5.3)] that the neutron energy band is formed in such a potential as the Kronig-Penny one for an electron [Kozima 2016a (Fig. A2)].

2.2 Effects of Environment to Nucleus in Nuclear Physics

The nuclear physics is a science of protons and neutrons in a close distance of about 10^{-15} m (meter), mainly in a nucleus and at close encounters of nucleons and nuclei in free space (the scattering and the collision) (e.g. [Blatt 1952]). It is also a science of the many-body system but the number of participating particles is drastically few compared to that in the solid state physics. Another characteristic of this science is the shortness and large strength of the nuclear force – the force among protons and neutrons – with a range R_0 of about 1 fm = 10^{-15} m (meter) and energy/R_0 of about 1 MeV/R_0. Another characteristic of the nuclear force is its saturation property – the number of particles with simultaneous interaction has a limit while the electromagnetic force in the solid state physics has no such limitation.

2.2-1 Stable and Unstable Nuclei

Atomic nuclei in their stable state with definite numbers of a proton number Z and a nucleon number A have been investigated extensively in these 100 years after their discovery. On the other hand, the atomic nuclei at their unstable or quasi-stable states are in their investigation especially if they are in the exotic composition with large imbalances of A and Z from their values of the stable nuclei. The exotic nuclei are in quasi-stable state but are able to participate new phenomena in the solid state-nuclear physics as shown in Section 3.3 and also discussed in Section 3.5. Several phases of the exotic nuclei is taken up in the next subsection.

2.2-2 Quasi-stable Nuclei

The exotic nuclei with large shifts of A or Z from those in stable nuclei have been extensively investigated recently [Caurier 2005, Cizewski 2010, Sharp 2013, Morfouace 2014, Sahin 2015, Stroberg 2015]. The properties of the exotic nuclei, especially their life time and distribution of neutrons in them, are interesting from our point of view in terms of the interaction between the interstitial proton/deuteron and neutrons in lattice nuclei in the CF material. The instability of the exotic nuclei may be decreased by their interaction with interstitial protons/deuterons in the CF material as discussed in our papers (e.g.

[Kozima 2016a]).

2.2-3 Effects of Environment on the Nuclear Properties

In the nuclear physics, there are a few examples of events where the environment around a nuclear particle (a nucleus or a nucleon) affects the properties of the particle; the electron capture (EC) by an unstable nucleus (a radioactive decay mode of unstable nuclei) (e.g. [Blatt 1952 (XIII, 3 Orbital electron capture)], the neutron trap and waveguide to confine neutrons [Kozima 2016a], the chain reaction of fission reactions of uranium or plutonium (e.g. [Anderson 1939]), the successive reaction of fusion reactions of hydrogen isotopes (e.g. [Chen 1974 (Chapter 9 Introduction to Controlled Fusion)]).

The Mössbauer Effect discussed in Section 2.1-2 is a process in which a nucleus emits or absorbs gamma rays without loss of energy to a nuclear recoil. It was discovered by the German physicist Rudolf L. Mössbauer in 1958 and has proved to be remarkably useful for basic research in physics and chemistry. It has been used, for instance, in precise measurement of small energy changes in nuclei, atoms, and crystals induced by electrical, magnetic, or gravitational fields.

These examples in the nuclear physics, however, are not necessarily recognized as the events in the solid state-nuclear physics due, perhaps, to the fact that this field is not established yet.

3. Solid State-Nuclear Physics (SSNP)

The solid state-nuclear physics (SSNP) is the physics between the solid state physics and the nuclear physics, both of which have developed accompanied with the development of the quantum mechanics from the beginning of the 20th century. The solid state-nuclear physics developed faintly in between the two key branches of physics, the solid state physics and the nuclear physics, as described briefly in Sec. 2 until 1989, when astonishing phenomenon called the cold fusion phenomenon (CFP) including various events showing unexpected nuclear reactions in solids was discovered.

It is difficult to believe in occurrence of nuclear reactions in solids at near room temperature without any acceleration mechanism for particles in them if we have no own experience to detect events inexplicable without nuclear reactions in the solids. The author has had such an experience to observe neutron emission from an electrolytic system Pd/LiOH+D_2O/Pt that gave him confidence in existence of the CFP [Kozima 1990].

We would like to emphasize the fact that the CF materials (i.e. the materials where occurs the CFP) are not confined to deuterium but also protium systems. And then, the

CF materials are classified into two groups by the mechanism of formation of the active structure, the superlattice of the host element and hydrogen [Kozima 2013b], for the nuclear reaction in the CFP; (1) metal-hydrogen system; transition-metal hydrides (e.g. NiH_x, AuH_x) and deuterides (e.g. PdD_x, TiD_x) and hydrogen graphite (HC_x), and (2) carbon-hydrogen system; XLPE, microorganisms, microbial cultures and biological tissues.

In the first group (1), the *metal-hydrogen superlattice* (the metal includes transition metals and graphite in this division) responsible to the CFP is formed in the CF materials by the self-organization, a process characterized by complexity, in the dynamical process of component particles [Kozima 2013b]. In the second group (2), on the other hand, the carbon-hydrogen superlattice, i.e. C-H superlattice, is a rearranged ready-made structure in the hydrocarbons in the system [Kozima 2016b, 2018].

In the discussion of the quantum mechanical explanation of the CFP, it is convenient to use a word "*metal-hydrogen superlattice*" for the superlattice composed of a sublattice of the host element (C, Ti, Ni, Pd, - - -) and another of a hydrogen isotope (H, D, (T)). Carbon is classified usually into the non-metals with other elements silicon, germanium, tin, and lead in the same Group IVA. However, it is also well-known that graphite, one of carbon's two allotropic forms, is unique among nonmetals showing a high conductivity [Sorum 1955 (p. 493)], a characteristic of the metal. Graphite is one of two forms of carbon where we have observed the CFP in addition to another ready-made superlattice in carbon-hydrogen system, XLPE and organic molecules in microorganism. Therefore, graphite shows similar characteristics to other metals, Ti, Ni, and Pd, in the CFP. Due to the property of carbon in the form of graphite, we may be able to classify the carbon, in the form of graphite, as a metal in our discussion of the neutron energy band for the basis of the TNCF model [Kozima 1998b, 2013b, 2015].

As we have discussed in a recent paper [Kozima 2018], the CFP in the CF materials belonging to the second group (2) is interesting in terms of the application of the nuclear transmutation. On the other hand, in the first group (1), there are many materials interesting in terms of the solid state physics. Therefore, we concentrate our discussion to them in this paper.

We have to notice two characteristics of the CFP. At first, it should be noticed that the energy scale we encounter in the CFP ranges very wide from 10 meV to 10 MeV on an electron volt scale: The outcome of the nuclear reactions of an order of 1 MeV has been enormously larger than the thermal energies of participating particles of an order of 25 meV by about nine orders of magnitude. This large difference of the liberated energy and the energy of environmental particles may have some decisive effects on the physics of the CFP. Secondly, one of the characteristics of the CFP we have to notice is the variety of products; we observed particles from neutron, helium-4, and various transmuted nuclei. These two extraordinary characteristics of the CFP opened a new perspective of the SSNP as we show in this section.

Because of the complex nature of the physics of the CFP related closely with the complexity based on the nonlinear interactions among participating elements in the CF materials [Kozima 2013b], the essential nature of the events in the CFP had not been recognized at first just as the case of the continental drift theory in geophysics as illustrated in our recent paper [Kozima 2019a (Appendix B)]. A brief explanation of the situation by the figure is cited in Appendix B in this paper.

The success of a phenomenological approach using the TNCF model [Kozima 1998a, 2006a] as explained briefly in Sec. 3.2 and the quantum mechanical explanation of the premises of the model [Kozima 2006a, 2019b] as explained briefly in Sec. 3.3 have shown new features of the SSNP where the neutrons in host nuclei at lattice sites (lattice nuclei) and the hydrogen isotopes at interstices (interstitial hydrogens) play fundamental roles. This situation in the solid state-nuclear physics developed by the CFP is explained in Secs. 3.4 and 3.5.

3-1 Cold Fusion Phenomenon (CFP)

In specific solid state materials at near room temperature, various observables have been measured which are explicable only by assuming nuclear reactions since 1989; the most typical observables have been neutrons and new nuclei different from those existed in the materials prior to the experiment. And then, therefore, the extravagant excess heat has been also observed which is inexplicable by chemical reactions and physical processes without nuclear reactions.

This phenomenon should be called the cold fusion phenomenon (CFP) to distinguish it from other events in the SSNP occurring in similar materials explicable physically without nuclear reactions. The phenomenon is fairly complex and it is necessary to explain them thorough investigation of experimental conditions for the CFP which are given in the next section.

It is well-known that the CFP defined above has had an unfortunate fate destined by its initial start at 1989. Details of this situation have been explained in a paper published in 2017 [Kozima 2017].

In the following sections, we give facts in the CFP revealed by experiments obtained in these about 30 years. We have given a unified explanation for the whole experimental data sets by a phenomenological approach with a model with an adjustable parameter (the

TNCF model). Investigation of the bases of the TNCF model successful to give a unified explanation for the CFP is left to the next chapter.

3-1-1 Experimental Facts of the CFP

The CFP is characterized by events explained only by assuming nuclear reactions in CF materials as briefly explained above. Furthermore, the events in this field are irreproducible or have no quantitative reproducibility and have only the qualitative reproducibility. This characteristic of the events in the CFP is best illustrated by the elaborate experimental result obtained by McKubre et al. [McKubre 1993]. In their experiment, they obtained various CF materials with different average D/Pd values and different excess powers for the same D/Pd value, for example as shown in their Fig. 7 [McKubre 1993 (Fig. 7)]. This characteristic of the CFP has been explained in our papers by the formation of the metal-hydrogen superlattice by the self-organization process of complexity (e.g. [Kozima 2013]).

It should be added another cause of irreproducibility of events in the CFP. As we have mentioned several times (e.g. [Kozima 1998a, 2006a]), the liberated energy in the nuclear reaction is in the energy range of about million electron volts (MeV) that is eight orders of magnitude larger than the thermal energy of particles in the CF material. Therefore, the liberated energy heat up the lattice around the reaction site over the melting points of the CF material. This phenomenon has been observed very often as shown in many papers, e.g. in our book [Kozima 2006a (Fig. 2.3)] and in a paper by Ohmori [Ohmori 2016 (Fig. 34)]. This phenomenon shows that the CF material is damaged badly by the liberated heat of the nuclear reactions and the metal-hydrogen superlattice responsible to the nuclear reactions is deteriorated by the loss of the *cf-matter* (cf. Section 3.3). Thus, the nuclear reaction of the CFP has a finite life and the CF material should be renovated to recover its ability for the CFP. This is another cause of the irreproducibility or qualitative reproducibility of the events in the CFP.

We explain fundamental characteristics of the CFP in the following subsections.

3-1-1a Characteristics of CF Materials or Necessary Conditions for the CFP

As we have shown in our books and papers (e.g. [Kozima 2006a, 2013]), the CF materials where observed the CFP have common characteristics that the concentrations of the host element and the hydrogen isotopes are comparable. Furthermore, the host elements are limited to some of the transition metals and carbon. We can list up the CF materials as follows;

(a) Transition metal hydrides (and deuterides) with a ratio x_1 of the concentration C_H of

H (or D) and that C_M of the host element M (M = Ti, Ni, Pd, Au, Pt, - -), $x_1 = C_H / C_M$, larger than a threshold value $x_1 \geq x_{1th} \approx 0.8$. Typical CF materials in this group are PdD_x, NiH_x, AuH_x, PtH_x, - - - ($x_1 \approx 1$). Let us call the ratio x_1 the *concentration index,* or *Index* 1.

(b) Hydrogen-Graphite
CH_x ($x_1 \leq 1$ or ≈ 1)

(c) XLPE (cross-linked polyethylene)
$(C_2H_4)_x$ ($x = \infty$) ($x_1 = 2$)

(d) Microorganisms
Microbial cultures (microbiological culture), yeast, biological textures and organs. ($x_1 = 1 – 2$)

In other words, the characteristics of the CF materials listed up above in items (a) – (d) are the necessary conditions for the materials where the CFP occurs in them. *The concentration index, Index 1, should be close to or more than 1 for a material to be the CF material.*

As we have given a brief explanation at the beginning of Section 3, the CF materials listed up above are classified into two groups by another standard; (A) Metal-hydrogen system and (B) carbon-hydrogen system according to their characteristics in formation of the *superlattice*, a structure responsible for the CFP. Their characteristics are explained as follows;

(A) Metal-hydrogen system.
In this classification, the metal includes graphite in addition to such transition metals as Ti, Ni, Pd, Pt, and Au. In this system, the CF material is formed increasing the hydrogen isotopes to make the Index 1, x_1, close to or more than 1.
The *metal-hydrogen superlattice* in this group is composed of a sublattice of the host element M (i.e. C, Ti, Ni, Pd, Pt and others) and another of the hydrogen isotope (H or D) and is formed by the *self-organization* in the process of experiments.

(B) Carbon-hydrogen system.
The CF materials in this group include XLPE (cross-linked polyethylene) and microorganisms. In this system, the Index 1, x_1, is automatically larger than 1. The superlattice of C and H are formed by appropriate rearrangements of polymers composing the material. Therefore, it is easier to obtain the *carbon-hydrogen superlattice* responsible to the CFP compared to it in the case (A) where the concentration of M and H/D has to be adjusted to be comparable and the superlattice

is formed by the self-organization, a process governed by complexity.

It is convenient to define the second index, *Index* 2, x_2, specifying the metal-hydrogen superlattice in the case (A) and the carbon-hydrogen superlattice in the case (B) for the CF material related to the realization of the CFP. The Index 2, the *superlattice index* x_2, is defined as the proportion of the superlattice to the whole CF material. It is essential to increase x_2 in an experiment for realization of the CFP.

As a whole, there are two important indices characterizing the CF materials for the CFP;

(1) *The concentration index* x_1 (Index 1), defined as $x_1 = C_H / C_M$ where C_H is the concentration of H (or D) and C_M is the concentration of the host element M (M = Ti, Ni, Pd, Au, Pt, - -). (Threshold value of x_1 for the CFP is supposed to be $x_{1th} \approx 0.8$)

(2) *The superlattice index* x_2 (Index 2), defined as the proportion of the superlattice to the whole CF material. ($0 \leqq x_2 \leqq 1$)

3-1-1b Nuclear Structure of Specific Elements composing Host Lattices of the CF Materials

The host elements in the CF materials for the CFP taken up in Sec. 3-1-1a are rearranged according to their physical characteristics as follows;

(a) Transition metals,
Ti, Ni, Pd, Au, Pt, - - -

(b) Carbon in the following forms;
b-1 Graphite (C)
b-2 Polyethylene $(C_2H_4)_x$ ($x = \infty$)
b-3 Microbial (Microbiological) cultures

These elements, transition metals and carbon, have following common characteristics in their nuclear structure [Kozima 2004 (Sec. 2.4), 2006b, 2014a]; the neutron energy levels are located at around the evaporation level of their nuclei. These energy levels may be responsible to the formation of the superlattice through the neutron-proton/deuteron interaction discussed in Section 3.3.2.

3-1-2 Three Laws found in Experimental Data in the CFP

We have induced three laws (or regularities) between observables from experimental data sets obtained in more than 20 years using the meta-analysis [Kozima 2006a (Sec. 3.8), 2012, 2019a]. The three laws are explained briefly as follows.

1) The First Law; The stability law for nuclear transmutation products

This law is induced using many experimental data obtained in various CF materials having different characteristics. The induction of this law is an example of the meta-analysis explained in another paper [Kozima 2019a] presented in this Conference. The process inducing this law in our phenomenological approach gives also an example of the inductive logic rather than the deductive logic as explained there.

2) The Second Law; The inverse power dependence of the frequency on the intensity of the excess heat production

This law shows also the effectiveness of the meta-analysis in the CFP. The deduction of the inverse-power law by Lietz [Lietz 2008] had used 157 excess heat results obtained by different authors in various CF materials. This is a miniature meta-analysis for the process used in the medical science as illustrated in another paper presented in this Conference [Kozima 2019a].

3) The Third Law; Bifurcation of the intensity of events (neutron emission and excess heat production) in time

These laws and the necessary conditions for the CFP given in Sec. 3-1-1a tell us that the CFP is a phenomenon belonging to complexity induced by nonlinear interactions between agents in the open and nonequilibrium CF materials [Kozima 2013b]. The characteristics of the CF materials for the CFP are investigated using our knowledge of the microscopic structure of the CF materials consulting to the complexity investigated in the nonlinear dynamics in relation to the three laws explained above [Kozima 2013b]. A computer simulation is proposed to reproduce an essential feature of the CFP using a simplified model system (a superlattice) composed of two interlaced sublattices; one sublattice of host nuclei with extended neutron wavefunctions and another of protons/deuterons with non-localized wavefunctions [Kozima 2012].

3-2 Explanation of the CFP by Phenomenological Models (TNCF Model and ND Model)

We have given a unified and comprehensive explanation for the vast experimental data sets in the CFP obtained hitherto since 1989 using a phenomenological approach with the TNCF (trapped neutron catalyzed fusion) model proposed in 1994 [Kozima 1994] and ND (neutron drop) model developed from the TNCF model in 2000 [Kozima 2000, 2004, 2006a]. Investigation of the foundation of these models are given in recent papers [Kozima 2014a, 2014b].

Flow chart for the development of the solid state-nuclear physics is given in Appendix A which gives an outline of the relation between the two models and the nuclear physics.

The brief explanation of the TNCF model and the ND model is given below.

3-2-1 TNCF Model (Trapped Neutron Catalyzed Fusion Model)

The TNCF model is a phenomenological model with an adjustable parameter n_n, assumed to be a density of trapped neutrons behaving as a free particle interacting with only nuclei at disordered position in the CF material. In the interaction, the absorption cross section σ_{nX} by a nucleus X is taken tentatively the same as that determined in nuclear physics [Kozima 1998a, 2006a]. Other premises of the model than the existence of neutrons are assumed based on the experimental data. Quantum mechanical justification of the premises in the TNCF model is introduced in Section 3.3.

3-2-1a Experimental Data explained by the TNCF Model

The experimental data sets obtained in the cold fusion experiments until 1998 had been explained by the TNCF model as tabulated in Tables 11.2 and 11.3 of our book [Kozima 1998a] which are cited in Appendix C as Tables C-1 and C-2.

These Tables show that the parameter n_n of the model takes appropriate values for various experiments (Sec. 3-2-1b) and the model gives the semi-quantitative explanation for the numerical relations among observables (Sec. 3-2-1c).

3-2-1b Value Range of the Parameter n_n

The values of n_n determined by the TNCF model for experimental data sets are in a range $10^8 - 10^{12}$ cm^{-3} as seen in Tables C-1 and C-2. This finite range of the value n_n might be an indirect evidence of the applicability of the model for the CFP.

3-2-1c Relations between Observables explained

Another evidence of the availability of the TNCF model for the CFP is the quantitative explanation of the numerical relations between several observables by the model [Kozima 2006a (Sec. 2.15.1)].

The experimental data sets showing nuclear transmutations along with other observables such as excess energy Q, the number and the energy of emitted neutrons n, and generated tritium t, had been analyzed by the TNCF model as shown in Tables C-1 and C-2. The results of the analyses had shown the applicability of the model to explain the CFP as a whole; the parameter n_n is determined as in between $10^8 - 10^{12}$ cm^{-3} as explained in Sec. 3-2-1b and the theoretical ratio $N_a/N_b|_{th}$ of the numbers N_a and N_b of events a and b is in accordance with the experimental ratio $N_a/N_b|_{ex}$ in a factor 3.

$N_a/N_b|_{th} = m\ N_a/N_b|_{ex}$ ($m \leq 3$).

3-2-2 ND Model (Neutron Drop Model)

The experimental data sets had been explained by the TNCF model when there is a single trapped neutron participating to the nuclear reactions in the CFP. While the model had given semi-quantitative explanations for many data in the CFP including the nuclear transmutations, there remained a large number of data sets where observed nuclear transmutations with large shifts of proton and neutron numbers from pre-existed nuclei. In these cases, we have to assume existence of neutron drops ${}^{A}_{Z}\Delta$ consisted of several neutrons and protons [Kozima 2006a (Sec. 3.7)] in addition to the possibility of nuclear fissions as discussed already [Kozima 1998a (Sec. 9.2), 2014a (Sec. 2.4)]. In this paper, we concentrate to the development of the TNCF model to the ND (neutron drop) model as explained in the next Section.

3-3 Development of the Solid State-Nuclear Physics – Formation of the Metal-Hydrogen Superlattice and a New State realized by Neutron-Proton/Deuteron Interaction

The experimental facts in the CFP and a unified phenomenological explanation for them have been given in the preceding section 3.2 using the TNCF model with an adjustable parameter n_n. The premises assumed in the TNCF model should be key concepts in the solid state-nuclear physics closely related to physics involved in the CFP if we consider the success of the model.

In this section, we investigate the physics of the CFP through the investigation of premises in relation to the physical properties of the CF materials where observed the CFP.

3-3-1 Physical Foundation for the Parameter n_n assumed in the TNCF Model – The cf-matter and the neutron drop

The central premise of the TNCF model, existence of neutrons in the CF material is investigated quantum mechanically in the solid composed of a lattice of host element M and another lattice of hydrogen isotope (H or D) interlaced to the former. Because of the nonlinear interaction among M and H/D, the system is governed by complexity and we cannot expect the cause-effect correspondence existing in linear dynamical systems. Furthermore, there occur various processes inherent in the system governed by complexity. One of the interesting effects closely related to the CFP is the self-organization of a low energy state, in our case the superlattice of M and H/D [Kozima 2006a (Sections 2.4, 3.5 and 3.7), 2016a]. This point is summarized below in the next section 3-3-2 in terms of the CFP.

3-3-2 Formation of the Metal-Hydrogen Superlattice and Origin of the Trapped Neutrons

In the CF materials composed of a metal and hydrogen (metal-hydrogen system), the ordered array of the metal atom and proton (or deuteron) forms a stable structure, i.e. the metal occludes hydrogen (deuterium) [Wicke 1978]. Therefore, the metal-hydrogen superlattice may be realized there by the self-organization, a process of complexity, when the densities of both components are comparable.

The CF materials, thus, are classified into two materials, (1) the metal-hydrogen system and (2) the carbon-hydrogen system. And then, the situation proceeds as follows for the realization of the CFP;

(1) In the metal-hydrogen system, the first process is *occlusion of H(D)* into the solid of host element ${}^{A}_{Z}$X up to a considerable (average) ratio of H(D)/X ≥ H(D)/X$|_{th}$ ≈ 0.8 by a dynamical process (electrolysis, gas contact, discharge, etc.).
(2) Then, there is t*he self-organization of the superlattice XH/D* composed of a sublattice X and another H/D at a region where the ratio H (D)/X ≈ 1 [Kozima 2013b]. The threshold value for the self-organization of the superlattice was given experimentally as D/Pd$|_{th}$ ≃ 0.85 [McKubre 1993].

The following processes are common to both systems.

(3) The nuclear interaction between a neutron in a lattice nucleus and a proton/deuteron at an interstice (the neutron-proton/deuteron interaction) results in *the super-nuclear interaction* between two neutrons in adjacent lattice nuclei.
(4) Formation of *neutron energy bands* by the super-nuclear interaction between neutrons in lattice nuclei.
(5) Formation of *high density neutrons* by accumulation of neutrons in the neutron energy bands at boundaries of the superlattice [Kozima 2006a (Sec. 3.7.3)].
(6) Formation of *the cf-matter* of neutrons and protons including *neutron drops* ${}^{A}_{Z}\Delta$ composed of *Z* protons and (*A* – *Z*) neutrons fed by the dynamical process. [Kozima 2006a (Sec. 3.7.4)]
(7) Interaction of neutron drops with disordered nuclei at boundaries of and in the superlattice resulting in *nuclear reactions*; nuclear transmutations, emission of neutrons and charged particles, and liberation of excess energy (cf. Sec. 3-4 below).
(8) Destruction of the optimum structure to realize the cf-matter by the nuclear products

and liberated energy in the nuclear reactions.

We give brief explanations of these individual processes in the following subsections.

3-3-2a Self-organization of Metal-Hydrogen Superlattice [Kozima 2013b].

In the CF materials composed of a metal and hydrogen (metal-hydrogen system), the process (2) is responsible to the CFP. It should be noticed that the formation of the metal-hydrogen superlattice makes energy of the system lower than before and therefore realize stabilization of specific states such as exotic nuclei with large extents of neutron numbers and formation of interstitial hydrogens with largely extended wavefunctions. These effect are the cause of and also the result of the metal-hydrogen superlattice.

It should be noticed that the shape of the CF materials has essential importance for occlusion of hydrogen isotopes into and for formation of the metal-hydrogen superlattice in them. The former is related to the Index 1 and the latter to the Index 2 defined in Sec. 3-1-1a. It is easier to have a more homogeneous distribution of hydrogen isotopes and therefore to realize a metal-hydrogen superlattice in the CF material with smaller size as far as it is durable. This point is exemplified by many data sets such as Notoya et al. [Notoya 1993, 1994a, 1994b], Miley et al. [Miley 1996a, 1996b], Kitamura et al. [Kitamura 2016, 2018] and Iwamura et al. [Iwamura 2018] (cf. also [Kozima 1998a (Sec. 7 Cold Fusion occurs in Hydrated Materials, Too)]).

3-3-2b Materials formed of Units with Superlattice Structure

On the other hand, there are the wonderful natural substances containing molecules composed of the regular arrays of C and H; the XLPE (cross-linked polyethylene) and also microorganisms contain carbon-hydrogen superlattice by itself, as shown in our papers [Kozima 2015, 2016b]. The hydrocarbons can form a carbon-hydrogen superlattice only by regular arrangement of polymers. The specific effects of these superlattice existing in nature, however, have not attracted our interest if there have not observed the CFP in the XLPE as the water tree generation and in the microorganisms as the biotransmutation [Kozima 2018].

It has been a riddle of two centuries to observe nuclear transmutations in biological systems since the discovery of the increase of CaO in the daily excretion of chicken by Vauquelin in 1799 [Kozima 1998a (Sec. 10.1)].

The CF materials composed of intrinsic superlattice of C and H have an advantage in application of the CFP because of the ease to form the cf-matter in them [Kozima 2018].

3-3-3 The Super-Nuclear Interaction – Indirect Neutron-Neutron Interaction mediated by Protons/Deuterons

It is known that the interstitial proton/deuteron has an extended wavefunctions overlapping with the nuclei at the nearest neighbor lattice sites in some metals such as Pd [Kozima 2006a (Section 3.6)]. The non-local wavefunction of occluded proton/deuteron seems to have close correlation with the super-diffusivity of hydrogen/deuterium [Kozima 2009]. In such a case, there appears the nuclear interaction between an interstitial proton/deuteron and neutrons in a lattice nucleus (the *nuclear proton/deuteron-neutron interaction*).

When there is a metal-hydrogen superlattice with the nuclear proton/deuteron-neutron interaction, the neutrons in lattice nuclei interact each other by the *indirect neutron-neutron interaction* mediated by interstitial protons/deuterons [Kozima 2006a (Sec. 3.7), 2016a]. This interaction is attractive and lowers the total energy of the system. One of the effects of this indirect neutron-neutron interaction is the lowering of the neutrons in lattice nuclei and the formation of the neutron energy bands in the single-particle approximation.

3-3-4 Neutron Energy Band and Neutron Drops

For the many-body system composed of neutrons in lattice nuclei and protons/deuterons at interstitial sites, we can use the single-particle approximation for neutrons connected with the super-nuclear interaction [Kozima 2006a (Section 3.7)] as used in the energy band theory of electrons in solid state physics (e.g. [Kittel 1976 (Chapter 7)]). As noticed above, this situation corresponds to the liquid drop and the shell models for the nucleons interacting with the nuclear force which may give indirect support for the single-particle approximation for our trapped neutrons and for the neutron band formation figured out in our papers.

3-3-4a Neutron Energy Bands

Using the tight-binding approximation for the energy band formation, we have given a formal deduction of the *neutron energy bands* [Kozima 2006a (Sec. 3.5.2), 2016a]. This is a quantum mechanical justification of the premise of the trapped neutron assumed in the TNCF model [Kozima 1994].

The analyses of experimental data sets given in our papers and compiled in our book had shown that the density of neutrons in a neutron energy band n_n should be larger than a threshold value $n_n|_{th} \approx 10^8$ cm^{-3} in the region of CF materials where the nuclear reactions occurred.

3-3-4b CF-Matter and Neutron Drops

To explain the experimental data where observed nuclear transmutations with large shifts of the proton number Z and the nucleon number A, we proposed extension of the TNCF model to the ND (neutron drop) model where we assumed existence of *neutron drops* ${}^{A}{}_{Z}\Delta$ composed of Z protons and $(A - Z)$ neutrons in the *cf-matter*. [Kozima 2000, 2006a (Sec. 3.7)]

The density of neutrons in an energy band increases at a boundary region where a neutron Bloch wave reflected coherently and reaches very high as assumed in the simulation for the neutron star matter [Negele 1973]. In analogy, we can assume possibility to have the cf-matter, a state of the neutron in the neutron energy bands with very high density at the boundary of the CF material, similar to the neutron star matter investigated in nuclear physics in terms of the neutron star formation [Negele 1973].

In the neutron star matter, there appeared the Coulomb lattice as the neutron density increased in a neutron star matter assumed at first as homogeneous [Negele 1973]. In the CF material, there are a sublattice of host nuclei from the beginning. This difference of the initial condition may influence the final distribution of the neutron drops in the cf-matter while we assumed just their existence and interaction with disordered nuclei. This point is a serious problem to be investigated in relation to the formation of the neutron drops in the cf-matter in the CF material.

3-3-5 New State composed of Neutrons and Protons/Deuterons

The nuclear interaction among neutrons in lattice nuclei and interstitial protons/deuterons resulting in the neutron energy band discussed above should induce a new state composed of neutrons and protons/deuterons where the neutron energy band is only its component seen from the neutron phase. The new state may be seen to contain the proton/deuteron energy band in the single-particle approximation if we see from the phase of the occluded hydrogen isotope. Even if the single-particle approximation for the neutrons in the CF material has given a foundation of the TNCF and ND models, the extent of the applicability of the neutron energy band figured out by the single-particle approximation is not certain.

The new state, however, is essentially a many-body state composed of neutrons and protons/deuterons interacting nonlinearly each other. Therefore, the images of the neutron energy band and the proton/deuteron energy band as used in explanation of the CFP by the single-particle approximation may be spurious and at most be partial views. We have to investigate the new state as the many-body state composed of neutrons and protons/deuterons interacting nonlinearly each other. Then, we are able to induce nuclear and atomic properties to give explanations for observables (in CFP, super-diffusion, etc.) measured in the CF materials hitherto.

In the following discussion, we remain in the single-particle approximation leaving the many-body treatment elsewhere. The nuclear fission for the nuclear transmutation in the CFP considered in our explanation of some experimental data sets [Kozima 2006a (Sec. 2.5.3)] may have close connection with the latter case.

3-4 Interaction between Neutrons and Disordered Nuclei in the Metal-Hydrogen Superlattice resulting in Nuclear Reactions responsible to the CFP

Neutrons in a neutron energy band in perfect superlattice (without disordered lattice nuclei and disordered hydrogen isotopes) do not interact neither with a lattice nucleus nor with a proton/deuteron. On the other hand, when there are disordered lattice nuclei or disordered protons/deuterons in the CF material, then band neutrons interact with them. The most popular disordered lattice nuclei exist at boundaries of the CF material which result in nuclear transmutations observed very often there in CF experiments [Kozima 1998a, 2006a, 2011, 2018].

3-5 Sold State-Nuclear Physics

The formation of the metal-hydrogen superlattice by the interaction of lattice nuclei and interstitial protons/deuterons results in the cold fusion phenomenon on one hand and in the super-diffusivity (the extraordinary large diffusivity) of H/D in the solid state physics on the other. These events are fully understood only when we understand the physics of the metal-hydrogen superlattice composed of the specific host nuclei and the interstitial protons/deuterons [Kozima 2013b].

The interaction between lattice nuclei at lattice points and hydrogen isotopes at interstitials results in lowering of the energy of the whole CF materials composed of lattice nuclei and interstitial protons/deuterons. The formation of the neutron energy bands is an example of this interaction by the super-nuclear interaction between neutrons in different lattice nuclei [Kozima 2006a].

Another possible result in the lattice nuclei may be the stabilization of exotic nuclei with far excess neutron numbers over that of stable nuclei [Kozima 2014a]. The exotic nuclei are quasi-stable in free space but may possibly be stabilized by the interaction with occluded protons/deuterons.

The interaction between lattice nuclei and interstitial protons/deuterons results in stabilization of protons/deuterons occluded in CF materials. It has been noticed for more than 150 years that hydrogen is occluded in such transition metals as Ti, Ni, Pd, and their alloys and shows an extremely large diffusivity [Graham 1866]. In the transition-metal hydrides, the interaction of protons/deuterons mediated by neutrons in lattice nuclei may generate the proton/deuteron energy bands. In the low density limit, the protons in the proton valence band will move with a large diffusivity without interaction with lattice as observed by experiments.

We can cite several sentences by solid state physicists.

"Casella has suggested that the hydrogen states excited in neutron scattering are *wave-mechanical band states*, and shows this to be in accord with experimental findings." [Puska 1984 (p. 5393)]

"On the other hand, according to the calculations, self-trapping in the tetrahedral site is improbable, and thus hydrogen would not be localized at the tetrahedral site during the activation process, but *its wave function should be spread over several interstices*." [Puska 1984 (p. 5383)]

There are several interesting facts in the behavior of protons in transition-metal hydrides not explicable with common sense of solid state physics.

"The pronounced maximum appearing in the longitudinal optic branch indicates *strong second neighbor D-D interactions* whose strength is comparable to *the first neighbor D-D interaction*." [Springer 1978 (p. 85)]

"Consequently, Burch introduced the idea of *a repulsion of H atoms on next-nearest neighbor sites*, which would overcompensate *the attraction of nearest neighbor H atoms at high concentrations*." [Wicke 1978 (p. 101)]

We may be able to shed a light to these problems using the formation of the proton/deuteron energy band, a counterpart of the neutron energy band, realized by the interaction among lattice nuclei and protons/deuterons.

The neutron energy band and the proton/deuteron energy band are in the single-particle approximation for the many-body system as we know well in the theory of the electron energy band. Therefore, the explanation of the CFP by the TNCF model based on the neutron energy bands is not complete and we are aware of some missing factors remaining outside of our treatment by our model. It is desirable to develop a many-body treatment of the neutron-proton/deuteron system in the metal-hydrogen superlattice.

Finally, we have to give a word on the electronic contribution to the solid state-nuclear physics. In the discussions of the transition-metal hydrides and deuterides, it has been discussed the effect of electronic states on the energy of the system (e.g. [Wicke 1978 (Section 3.2)]). Therefore, the effect of electronic states on the solid state-nuclear physics is not negligible and should be taken into consideration in addition to the nuclear interactions among host elements and interstitial hydrogen isotopes emphasized in this paper.

4. Conclusion

In the history of science in the 20^{th} century, the solid state physics has developed where the various phenomena occurring in solids have been explained by quantum mechanics considering mainly the electromagnetic interaction between particles in the solids (e.g. [Seitz 1940, Kittel 1976]). The physics of these treatments composes the solid state physics containing very wide fields of phenomena depending on the variety of materials, observables and environments in the energy range from 10^{-3} K up to 10^{4} K on a temperature scale, or 10^{-7} eV up to 10 eV on an energy scale.

On the other hand, the nuclear physics has developed where the phenomena occurring in the nucleus and among nuclei are investigated by quantum mechanics also where the main interactions are the strong and the weak interactions between participating particles, nucleons and mesons (e.g. [Blatt 1952, Bohr 1969]. There are very many features of phenomena in the energy range from a few million electron volts (MeV) up to a few giga electron volts (GeV) in this field.

There have been investigated few phenomena observed and investigated by quantum mechanics in the solid state-nuclear physics, the interdisciplinary region between the solid state physics and the nuclear physics, as pointed out in the Introduction of this paper. However, the situation changed drastically by the discovery of the CFP, a phenomenon including various events explicable only by nuclear reactions, in CF materials, characteristic solids composed of specific host elements and hydrogen isotopes, at near room temperature without any acceleration mechanism for the particles in the system. We have used the name the "*CF material*" to designate the material where observed the CFP.

In the process of unified explanation of the CFP observed in the metal-hydrogen system defined in Section 3-1-1a using a phenomenological approach with a model, it has been noticed importance of neutrons in the CF materials composed of host metals (including carbon) and hydrogen isotopes. In the investigation of the basic premises of the model, we could develop a new phase of the solid state-nuclear physics, the physics of metal-hydrogen superlattice which has not been recognized in the solid state physics and the nuclear physics.

The phenomena in solid state-nuclear physics, explained by the super-nuclear interaction between neutrons at different lattice nuclei mediated by interstitial hydrogen isotopes through the strong neutron-proton/deuteron interaction, have been observed in CF materials with a ratio x_1, the Index 1, of concentrations H/D vs. host elements X (X = C, Ti, Ni, Pd, Au, Pt, - -) larger than a threshold value $x_{th} \approx 0.8$ for the CFP; $x_1 \geq x_{1th}$. This fact should be emphasized that the CFP has been observed in CF materials with $x_1 \geq x_{1th} \approx 0.8$.

This characteristic of the CFP is explicable by the self-organization of the superlattice of the lattice nuclei and the interstitial protons/deuterons [Kozima 2013b]. The favor of deuterium than protium in palladium systems (PdD_x and PdH_x) for the CFP was explained by the larger diffusivity of deuteron than that of proton [Kozima 2013b (Fig. 3.2)].

The characteristic of nickel systems (NiH_x) where is observed a lot of nuclear transmutations than in PdD_x system might be explained, from our point of view, by the higher densities of trapped neutrons in the cf-matter in the former than in the latter which will be shown by detailed investigation of the structure of both systems; their lattice structures, states of hydrogen isotopes, nuclear levels of host elements, and so forth.

In addition to the metal-hydrogen system discussed in this paper, there is another group in the CF materials, the carbon-hydrogen system including the XLPE and the microorganisms, where the Index 1, x_1, is larger than 1 by nature [Kozima 2008, 2016b, 2018]. The CFP has been observed in this carbon-hydrogen system for long [Kozima 1998 (Sec. 10.1), 2018]. It is amazing to know that our phenomenological approach successful for the CFP in the metal-hydrogen system has been similarly successful in the carbon-hydrogen system [Kozima 2008, 2016b].

We have to notice that there are several characteristics of host nuclei and interstitial hydrogen isotopes for the realization of the CFP. The host nuclei seem desirable to have excited neutron levels at around the evaporation level as seen in our paper [Kozima 2016a (Fig. 4.1)]. On the other hand, the proton/deuteron at an interstice should have wavefunctions extended to lattice points surrounding the interstitial site [Kozima 2009]. These conditions for the component particles guarantee the occurrence of the CFP on one hand and the super-diffusivity of hydrogen/deuterium in the host lattice on the other.

Finally, we want to discuss the logical structure of reasoning in science. As we have shown in another paper presented at this Conference [Kozima 2019a], induction and deduction are two logical methods used in mental activities for more than 2500 years since the Greek culture. The physics of the CFP may be one of typical examples of the inductive reasoning. In the method of analysis, the analyses used in the phenomenological approach to the CFP might be classified into the meta-analysis used from the 18th Century in astronomy and frequently in modern EMB (the evidence-based medicine) [Plackett 1958, Tsutani 2003, Walker 2008]. We have given an extensive discussion on the meaning of the meta-analysis in another paper [Kozima 2019a].

We are able to add a word on the comparison of the continental drift and the CFP given in Appendix B. The famous example of the success of the inductive logic in modern science is the continental drift model (e.g. [Gould 1977]) to explain the many facts suggesting the drift of continents; topographical, geophysical, geological, paleontological, biogeographical and paleoclimatology [Kozima 2019a]. In the continental drift, the problem is the unknown mechanism of driving force for the drift in addition to disbelief in the inductive reasoning. In the CFP, the problem is lack of recognition that the CFP is a problem of complexity in which we could not expect the quantitative reproducibility.

The success of the phenomenological approach with the TNCF and ND models has been the natural result of approach based on the experimental results and unintentionally use of inductive logic and the meta-analysis in the investigation of the science of the CFP as a part of the solid state-nuclear physics.

In conclusion, the knowledge of neutrons in the CF materials we have had through the investigation of the CFP will give a first step to the science of the metal-hydrogen and the carbon-hydrogen systems in the solid state-nuclear physics. We can expect abundant fruits in this field where the investigation has just started.

Appendices

Appendix A. *Flow Chart of the History of the Solid State Physics, the Nuclear Physics and the Solid State-Nuclear Physics*

Appendix B. *Continental Drift vs. Cold Fusion Phenomenon*

Appendix C. *Experimental Data Sets Explained by the TNCF Model*

Appendix A. Flow Chart of the History of the Solid State Physics, the Nuclear Physics and the Solid State-Nuclear Physics

The development of the solid state-nuclear physics in relation to those of the solid state physics and the nuclear physics is shown in the flowchart in Fig. A1.

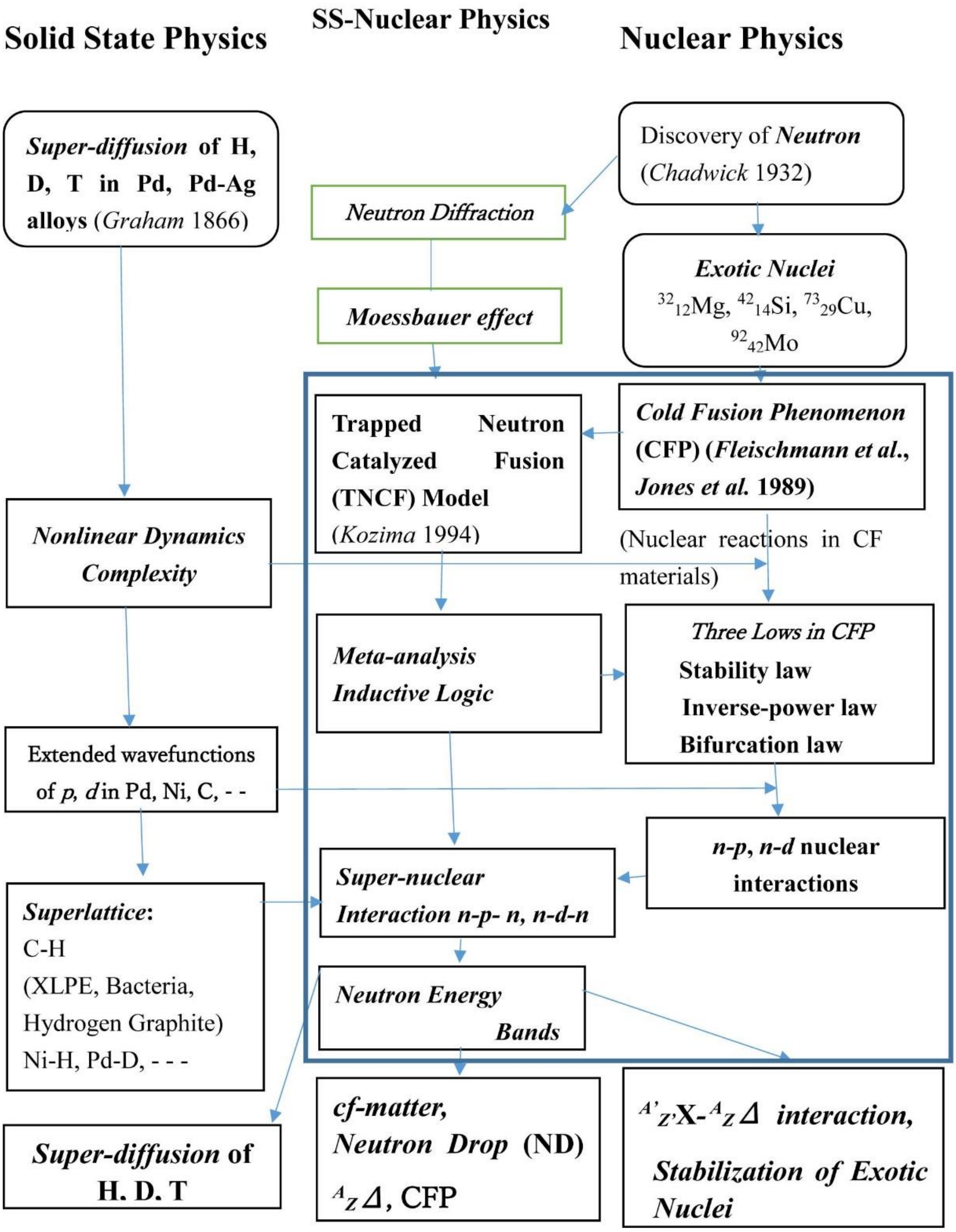

Fig. A1 Flowchart of the developments of the solids state-nuclear physics in relation to those of the solid state physics and the nuclear physics.

Appendix B. Continental Drift vs. Cold Fusion Phenomenon

Continental Drift	Cold Fusion Phenomenon
1. Phenomenon	
1. The complementary arrangement of the facing sides of South America and Africa 2. Similar plant and animal fossils are found around the shores of different continents 3. The same animals being found on two continents 4. Widespread distribution of Permo-Carboniferous glacial sediments	1. Space distribution of Nuclear Transmutation products NT(r) 2. Neutron energy spectrum $n(\varepsilon)$ 3. Stabilization of unstable nuclei 4. Decrease of decay constants 5. Enormous excess energy Q 6. Lowering of fission threshold energy
2. Phenomenological Explanation	
Continental drift	1. TNCF Model and 2. Neutron Drop (ND) Model
3. Physical Bases of the Explanation	
The theory of plate tectonics explains all following facts, including the movement of the continents, better than Wegener's theory.	1. Super-nuclear interaction of neutrons 2. Formation of neutron energy bands 3. Generation of the cf-matter at boundary regions 4. Formation of neutron drops in the cf-matter ${}^{A}_{Z}\Delta$ 5. Interaction of neutrons in the energy bands 6. TNCF and ND models explain almost all experimental data in CFP

Fig. B1 Explanation of the logical structure of the continental drift theory (left) in contrast to the case of the cold fusion phenomenon (CFP) (right).

Appendix C. Experimental Data Sets Explained by the TNCF Model

Tables of experimental data sets of CFP in Pd/D/Li and Ni/H/K systems with explanation by the TNCF model.

Table C-1 Pd/D/Li System and Others. Neutron Density n_n and Relations between the Numbers N_x of Event *x* Obtained by Theoretical Analysis of Experimental Data on TNCF Model ($N_Q \equiv Q$ (MeV)/5 (MeV)). Typical value of the surface vs. volume ratio *S*/*V* (cm^{-1}) of the sample is tabulated, also. Reference numbers are those of the original book. [Kozima 1998a] (Revised May, 2002) and the References is posted at CFRL website; http://www.kozima^cfrl/Books/bookse/bookse01.html

Authors	System	S/V cm^{-1}	Measured Quantities	n_n cm^{-3}	Other Results (Remarks)
Fleischmann et al.[1)]	Pd/D/Li	6 ~40	Q, t, n N_t/N_n~4×10^7 N_Q/N_t~0.25	~10^9	(Q=10W/cm^3) N_t/N_n~10^6 $N_Q/N_t = 1.0$
Morrey et al.[1−4)]	Pd/D/Li	20	Q, ^{4}He ^{4}He in $\ell \le 25\mu$m	4.8 $\times10^8$	N_Q/N_{He}~5.4 (If 3% ^{4}He in Pd)
Packham[43)]	Pd/D/Li	40	t in solution	3.6 $\times10^7$	
Chien et al.[43')]	Pd/D/Li	4	^{4}He in surf. layer and t , no ^{3}He	1.8 $\times10^6$	N_t/N_{He}~1(If few % ^{4}He in Pd)
Roulette[1''')]	Pd/D/Li	63	Q	~10^{12}	
Storms[4)]	Pd/D/Li	9	t(1.8$\times10^2$Bq/mℓ)	2.2$\times10^7$	(τ=250h)
Storms[4')]	Pd/D/Li	22	Q (Q_{max}=7W)	5.5$\times10^{10}$	(τ=120h)
Takahashi et al.[5')]	Pd/D/Li	2.7	t, n N_t/N_n~6.7×10^4	3$\times10^5$	N_t/N_n~ 5.3$\times10^5$
Miles et al.[18')]	Pd/D/Li	5	Q, ^{4}He (N_Q/N_{He}=1~10)	~10^{10}	N_Q/N_{He}~5
Okamoto et al.[12')]	Pd/D/Li	23	Q, NT$_D$ ℓ_0 ~1 μm	~10^{10}	N_Q/N_{NT}~1.4 (^{27}Al→^{28}Si)
Oya[12−5)]	Pd/D/Li	41	Q, γ spectrum	3.0$\times10^9$	(with^{252}Cf)
Arata. et al.[14)]	Pd/D/Li	7.5 $\times10^4$	Q, ^{4}He (10^{20}~10^{21} cm^{-3}) N_Q/N_{He}~6	~10^{12}	(Assume t channeling in Pd wall)
McKubre[3)]	Pd/D/Li	125	Q (& Formula)	~10^{10}	Qualit.explan.
Passell[3''')]	Pd/D/Li	400	NT$_D$	1.1$\times10^9$	N_{NT}/N_Q=2
Cravens[24'')]	Pd/H/Li	4000	Q (Q_{out}/Q_{in}=3.8)	8.5$\times10^9$	(If PdD exists)
Bockris[43)]	Pd/D/Li	5.3	t,^{4}He;N_t/N_{He}~240	3.2$\times10^6$	N_t/N_{He}~8
Lipson[15−4)]	Pd/D/Na	200	γ (E_γ=6.25MeV)	4$\times10^5$	If effic. =1%
Will[45)]	Pd/D_2SO_4	21	t(1.8$\times10^5$/cm^2s)	3.5$\times10^7$	(If ℓ_0~10μm)
Cellucci et al.[51''')]	Pd/D/Li	40	Q, ^{4}He N_Q/N_{He}=1~5	2.2$\times10^9$	(IfQ=5W) N_Q/N_{He}=1
Celani[32''')]	Pd/D/Li	400	Q (Q_{max}=7 W)	1.0$\times10^{12}$	(If200%output)
Ota[53)]	Pd/D/Li	10	Q (113%)	3.5$\times10^{10}$	(τ=220 h)
Gozzi[51'')]	Pd/D/Li	14	Q, t, ^{4}He	~10^{11}	(τ~10^3h)
Bush[27')]	Ag/PdD/Li	2000	Q (Q_{max}=6W)	1.1$\times10^9$	(τ=54d,Film)
Mizuno [26−4)]	Pd/D/Li (If Cr in Pd)	3.4	Q, NT$_D$ $\ell \le$ 2 μm)	2.6$\times10^8$	τ=30d,Pd 1cm$\phi\times$10cm
Iwamura[17)]	PdD$_x$	20	n (400/s),t	3.9 $\times10^8$	4.4 $\times10^6 t$/s
Itoh[17')]	PdD$_x$	13.3	n (22/m),t	8.7 $\times10^7$	7.3 $\times10^{10} t$/s
Itoh[17'')]	PdD$_x$	13.3	n (2.1 $\times10^3$/s)	3.9 $\times10^8$	
Iwamura [17''')]	PdD$_x$	20	Q (4 W) NT$_F$(Ti, Cr etc.)	3.3 $\times10^{10}$	(NT$_F$? unexplained)
Miley[65)]	Pd/H/Li	150	NT$_F$(Ni,Zn,……)	4.5 $\times10^{12}$	
Dash[59)]	Pd/D,H_2SO_4	57	Q, NT$_D$	~10^{12}	Pt→Au
Szpak et al.[79−9)]	Pd/D/Li	10^3(?)	t	~10^2	Electroplated Pd
Clarke et al.[80')]	Pd/D/Li	0.26(?)	(Q), t	~10^{10}	Pd black[14)]
Kozima[203)]	Pd/D,H/Li	200	n (2.5$\times10^{-4}$/s)	2.5 $\times10^2$	Effic. =0.44%

Table C-2 Ni/H/K System and Others. Neutron Density n_n and Relations between the Numbers N_x of Event x Obtained by Theoretical Analysis of Experimental Data on TNCF Model ($N_Q \equiv Q$ (MeV)/5 (MeV)). Typical value of the surface vs. volume ratio S/V (cm^{-1}) of the sample is tabulated, also. Reference numbers are those of the original book. [Kozima 1998a] (Revised May, 2002) and the References is posted at CFRL website;
http://www.kozima^cfrl/Books/bookse/bookse01.html

Authors	System	S/V cm^{-1}	Measured Quantities	n_n cm^{-3}	Other Results (Remarks)
Jones[2]	Ti/D/Li	8.1	n (2.45 MeV)	3.1×10^{11}	
Mills[25]	Ni/H/K	160	Q (0.13 W)	3.4×10^{10}	
Bush[27′]	Ni/H/K Ni/H/Na	~160 ~160	NT$_D$(Ca) NT$_D$(Mg)	5.3×10^{10} 5.3×10^{11}	N_Q/N_{NT}~3.5 if τ=0 for ^{40}K)
Bush[27″]	Ni/H/Rb	~10^4	NT$_D$(Sr)	1.6×10^7	N_Q/N_{NT}~3
Savvatimova et al.[34″]	Pd/D_2	100	NT$_D$(Ag)	9×10^{10}	
Bockris et al.[43−6]	Pd/H/		NT$_F$(Mg,Si,Cs,Fe, etc. in 1μm layer)	3.0×10^{11}	Only Fe(10%of Pd) is taken up.
Alekseev[44′]	Mo/D_2	4.1	t (~10^7/s)	1.8×10^7	(If MoD)
Romodanov et al.[44‴]	TiC/D	4.1	t (~10^6/s)	~10^6	(D/Ti~ 0.5assumed)
Reifensch-weiler[38′]	$TiT_{0.0035}$	7×10^5	β decay reduction	1.1×10^9	(T=0~450°C)
Dufour[7]	Pd,SS/D_2 Pd,SS/H_2	48	Q, t, n	9.2×10^{11} 4.0×10^9	(D(H)/Pd~1 is assumed)
Claytor[9]	Pd/D_2	400	t (12.5 nCi/h)	1.6×10^{13}	(If D/Pd~0.5)
Srinivasan[16]	Ti/D_2	1500	t (t/d ~10^{-5})	1.9×10^8	(Aged plate)
De Ninno[6′]	Ti/D_2	440	n , t	1.2×10^6	(D/Ti=1,1w)
Focardi[23]	Ni/H_2	8.2	Q	3.0×10^{12}	(IfN_p=10^{21})
Oriani[52]	$SrCeO_3/D_2$	22	Q ~ 0.7W	4.0×10^{10}	V=0.31cm^3
Notoya[35″]	Ni/D,H/K	3.4 $\times10^4$	Q (0.9 W), t	2.4×10^{13}	(If 1/2 t is in liquid)
Notoya[35−4]	Ni/D,H/K	same	NT$_D$(Ca)	1.4×10^9	(Sintered Ni)
Yamada[54]	Pd/D_2	185	n , NT$_D$(C)	2.0×10^{12}	
Cuevas[55]	$TiD_{1.5}$	134	n (102 n/s)	5.4×10^{11}	
Niedra[56]	Ni/H/K	80	Q (11.4 W)	1.4×10^9	5km×0.5mmϕ
Ohmori[22″]	Au/H/K	200	Q, NT$_F$(Fe)	~10^{11}	(Au plate)
Li[57]	Pd/D_2	185	Q	1.6×10^{12}	(Pd wire)
Qiao[57′]	Pd/H_2	185	NT$_F$(Zn)	3.8×10^{10}	(40%NTin 1y)
Bressani[58′]	Ti/D_2	$\leq 10^3$?	n (ε)	10^4 – 10^7	(Ti shaving)
Miley[65′]	Ni/H/Li	50	NT$_D$(Fe,Cr,$\cdots$)	1.7×10^{12}	
Botta[58″]	Pd/D_2	$\leq 10^3$?	^{4}He	7×10^{12}	(0.1 mm Pd sheet)
Coupland et al[81]	Pd/H,D	~4	$\Delta(^7Li/^6Li)$=60-90% if $(^7Li/^6Li)_0$=12.5	3.5-4.1$\times10^8$	Pd rod returned by F. and P.[1]
Passell[3−6]	Pd/H_2	185(?)	$\Delta(^7Li/^6Li)$=100%	4.4×10^8	Pd wire[57−3]

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