In: Developments in Quantum Physics ISBN 1-59454-003-9
Editor: F. Columbus and V. Krasnoholovets, pp. 167-196

Quantum Physics of Cold Fusion Phenomenon

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"... From this natural phenomenon which previously seemed impossible to you, you should realize that there may be others which you do not yet know. Do not conclude from your apprenticeship that there is nothing left for you to learn, but that you still have an infinite amount to learn." (Pascal *Pansées* [420] Translated by A.J. Krailsheimer, Penguin Classics, p.126)

ABSTRACT

First of all, it should be mentioned that the term "the Cold Fusion Phenomenon" (CFP) includes nuclear reactions and accompanying events occurring in solids with high densities of hydrogen isotopes (H and/or D) in ambient radiation.

Investigation of the cold fusion phenomenon (CFP) during the past 14 years revealed that CFP occurs in localized regions at boundaries (and surfaces) in solids containing a high concentration of either deuterium or protium or both. The occurrence is characterized by sporadicity and only qualitative reproducibility. The former means unpredictability and the latter different effects for the same macroscopic initial conditions.

Success of a phenomenological model (the TNCF model) assuming the existence of thermal neutrons in solids to explain CFP as a whole both in deuterium and protium systems suggests the existence of an unexplored field between nuclear physics and solid state physics related to neutrons in solids. Examining excited states of neutrons near the separation level of a nucleus and also excited states of protons (deuterons) in solids, we show the existence of new states of neutrons (the cf-matter) in transition-metal deuterides and hydrides, typical materials for CFP, which are responsible for exotic nuclear reactions in solids including CFP.

An excited state of a neutron in a lattice nucleus (nucleus at each lattice point) interacts with another in adjacent lattice nuclei mediated by protons (deuterons) at interstices. The result is a corresponding neutron band. Neutrons in this band form a high-density neutron matter (cf-matter) at boundary/surface regions with neutron drops (clusters of neutrons and protons) that makes nuclear reactions in solids so different from those in free space.

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1. INTRODUCTION

In 1989, Fleischmann and Pons published the first paper on CFP (Fleischmann 1989). In an electrolytic system, Pd/D_2O + LiOD/Pt, they measured excess heat, tritium and neutrons and concluded that the observed data resulted from *d-d* fusion reactions, which are improbable to occur in solids. Succeeding investigations revealed, however, that the experimentally observed variables are also observed in systems containing only protium without deuterium. Furthermore, it became clear that there are no positive results without background thermal neutrons thus showing the essential role of thermal neutrons in CFP. More puzzling factors in CFP are poor reproducibility and the sporadic occurrence of events. In addition to these qualitative discoveries, there is an enormous amount of data of various kinds of events showing facts peculiar to CFP, which are inexplicable without invoking various nuclear reactions in materials used in the CF experiments.

A phenomenological approach was tried as an orthodox procedure to attack theoretically difficult problems with unknown variables (Kozima 1994a). We were able to obtain a consistent explanation of various experimental data sets obtained in both protium and deuterium systems. Puzzles of CFP pointed out above were explained consistently (Kozima 1998a). The key postulate of the phenomenological model (the TNCDF model) is the existence of thermal neutrons in CF materials, where positive data have been obtained. The TNCF model using an adjustable parameter has been successful in explaining many quantitative relations between CF products. Also, progress has been on the neutron drop model to explain nuclear transmutations where a multi-neutron absorption by a nuclide is needed (Kozima 2000a, 2003).

In an attempt to explain quantum mechanically the several postulates assumed in the successful models, it has been shown that there are previously unknown, important new fields in nuclear physics and solid-state physics. These fields are closely related to CFP and are not explained by conventional knowledge of physics. The excited state of neutrons around the separation level (zero energy) in a nucleus is a concept not recognized to have any importance in nuclear physics. The quantum mechanical state of hydrogen isotopes in *fcc* (*hcp*) transition-metal hydrides and deuterides is another concept not recognized to have an important connection with nuclear physics in solids. Surface layers on the cathodes in electrolytic systems play important role in realization of CFP. These problems are investigated quantum mechanically in this paper and show peculiarity of nuclear reactions in *fcc* (*hcp*) transition-metal hydrides and deuterides (proton conductors) completely different from those in free space.

The presumption of *d-d* fusion reactions in solids is assumed by Fleischmann et al. (Fleischmann 1989) and many of the following researchers and also by critics opposing CFP. These reactions in free space are written as follows:

$$d + d = t\ (1.01\ \mathrm{MeV}) + p\ (3.02\ \mathrm{MeV}), \quad (1)$$

$$= {}^{3}_{2}\mathrm{He}\ (0.82\ \mathrm{MeV}) + n\ (2.45\ \mathrm{MeV}), \quad (2)$$

$$= \ {}^4_2\text{He (76.0 keV)} + \gamma \text{ (23.8 MeV)}. \qquad (3)$$

Branching ratios of these reactions in free space are, as is well known, $1 : 1 : \sim 10^{-7}$ and it is known that they occur effectively only if the mutual energy is above about 100 keV.

Some researchers assumed the *d-d* fusion reactions as causes of products measured in CF experiments with materials where deuterium was occluded (Fleischmann 1989, Jones 1989). It was pointed out, however, that the *d-d* fusion reactions in solids are not realistic from physical point of view (Leggett 1989, Ichimaru 1993) even if there are limitations of the calculation by Leggett et al. (Kim 1996b).

Simple reasoning for difficulty of the *d-d* fusion reactions in crystals without additional accelerations can be given as follows:

Phonons have minimum wavelength about a lattice constant a; $\lambda_{min} \sim a$. Therefore, they cannot distinguish two deuterons approached to less than a and can not do anything to make them approach to a distance about 1 fm where nuclear force works by overcoming the Coulomb barrier between them.

The electrons has a light mass $m_e = 9.11 \times 10^{-31}$ kg and the uncertainty principle makes the energy of an electron large when its position is confined in a small range; $\delta x \cdot \delta p \sim \hbar$: In a hydrogen atom, an electron with a classical Bohr orbit with a radius $a_H \sim a$ $(= \delta x)$ has a kinetic energy E_e as given by

$E_e \sim \delta p^2/2m \sim \hbar^2/ma_H^2 \sim 10$ eV $(\sim e^2/2a_H = E_H)$.

If an electron works to lower the Coulomb barrier between two deuterons to make them fuse together, the electron has to remain between them at a distance about $r_{n.f.} \sim 1$ fm $\sim 10^{-5}a_H$ $(= \delta x)$ where works the nuclear force. Then, the energy of the electron becomes very large showing inability of electron effect for the fusion reaction:

$E_e \sim \delta p^2/2m \sim 10^{10}\hbar^2/ma_H^2 \sim 10^{10}E_H$.

Dielectric constants ε's cannot work for this object, too. Dielectric constants are concepts averaged over ions on lattice with lattice constants a's and cannot be used for problems between two deuterons approached closer than a lattice constant a.

This simple calculation and also more elaborate reasoning (Leggett 1989, Ichimaru 1993), of course, do not exclude the possibility that there may be some mechanism to realize *d-d* fusion reactions in solids by overcoming the Coulomb barrier between charged nuclei.

Experimental data sets obtained thenceforth themselves have shown that *d-d* fusion reactions are not fundamentally responsible for observed products in both deuterium and protium systems, first of all. Variety of these products also has told that fundamental causes of nuclear reactions in solids producing them should be others not noticed by researchers and critics. For convenience sake, le us use a working concept *the cf-matter* to specify a state of particles (lattice nuclei and occluded hydrogen isotopes) in a part of CF samples where occurs CFP, nature of which we investigate in the course of this paper.

As was experimentally shown, CFP includes various events (phenomena) in various kinds of crystals as shown in Table 1.

Table 1: Matrix Substances, Agent nuclei, Direct and Indirect Evidence of nuclear reactions in cold fusion phenomenon (CFP). Q is for the excess heat and NT for the nuclear transmutation. Dependences of products on energy ε and position $\boldsymbol{r}$, decay time shortening of radioactive nuclides, and fission-barrier lowering of compound nuclides give direct information of nuclear reactions in CFP.

Matrix Substances	Transition metals (Ti, Ni, Mo, Pd, Pt, etc.) Proton conductors ($SrCeO_3$, $REBa_2Cu_3O_7$, $AlLaO_3$ etc.) Ferroelectrics (KD_2PO_4, TGS, etc.) Others (C, Na_xWO_3, Stainless steel, etc.)
Agents	${}^1_0n$, ${}^1_1$H, ${}^2_1$H , (${}^{16}_8$O) ${}^6_3$Li, ${}^{10}_5$B, ${}^{23}_{11}$Na, ${}^{39}_{19}$K, ${}^{85}_{37}$Rb, ${}^{87}_{37}$Rb, SO_4^{2-}, etc.
Direct Evidences	Neutron energy spectra $n(\varepsilon)$, Gamma rays $\gamma(\varepsilon)$ Spatial distribution of NT products (${}^{A'}_{Z'}X(\boldsymbol{r})$) Decay time shortening, Fission-barrier decrease
Indirect Evidences	Excess heat Q, Number of Neutrons N_n , Number of Tritium T_t, Number of ${}^4_2$He N_{He4} Number of NT products N_{NT} X-ray spectra $X(\varepsilon)$

We can see in this table that the CF materials where the cf-matter is formed include various substances. We, however, concentrate our discussion on *fcc* transition metals in this paper to investigate characteristics of CFP because of rich data in them.

Observations of neutrons in CFP (Jones 1989, De Ninno 1989, and others) can be taken as an opening of a new era of solid state-nuclear physics. In the process of development of CF research, there are several signals showing importance of the role of neutrons in CFP. The first signal was the experiment by Shani et al. (Shani 1989) showing several orders of magnitude larger effect of thermal neutrons on neutron emission from PdD_x compared with those from deuterium gas. Several succeeded works have shown enhancement of CFP by thermal neutron irradiation to CF materials (Yuhimchuk 1992, Celani 1992, Stella 1993, Lipson 1995, 1996, Oya 1996, Notoya 1998). The second was absence of CFP in experiments without background neutrons (Ishida 1992, Jones 1994, Taylor 1994, Forsley 1998). There are also peculiar experimental data showing trapping and later release of neutrons perhaps related to the effects just mentioned (Cerofolini 1993, Samgin 1996, Lipson 2002, and others).

The background neutron is abundant around us (Carpenter 1989) and should be considered its role in CFP seriously as we done in the TNCF model (Kozima 1998a). Furthermore, observations of a lot of neutrons with energies up to about 10 MeV (upper limits of measurements) (Sato 1991, Botta 1999, and others) indicate experimentally occurrence of other nuclear reactions than Eq.(2) in solids (Kozima 1999b).

Interesting works related to neutrons in solids were performed about 30 years ago in relation to the problem of theoretical verification of the neutron star by simulation (Baym 1971, Negele 1973). When there is a neutron liquid with densities more than 10^{35} cm^{-3}, there appears a so-called Coulomb lattice of clusters of neutrons and protons (and electrons) with a definite lattice constant. The lattice constant and proton to neutron ratio in a cluster decrease with increase of the average neutron density and finally stable homogeneous distribution of pure neutrons are realized as a neutron star at densities more than about 10^{38} cm^{-3}. If we extrapolate the result of their simulation to lower density region of about 10^{30} cm^{-3} attainable in surface layers (Kozima 2000a), we obtain a Coulomb lattice with a lattice constant about 10^{-3} Å and almost the same proton to neutron ratio to that of Pd nuclei (Kozima 2002) (cf. Section 3.3).

There are recent developments in neutron physics in solids. We will give some examples in relation to our TNCF model (Kozima 1998a): Multi-layer structures of crystals, for instance Ti (100 Å)/ Ni (100 Å)/ $\cdots$ and Permalloy (100 Å)/ Ge (800 Å)/ Permalloy (100 Å), have been used to reflect cold neutrons (Ebisawa 1998) and to investigate trapping and tunneling characteristics of cold neutrons (Achiwa 1998, Hino 1998). Here is a new direction of low energy neutron physics where the property of a neutron in a potential is an object of research instead of the external effect of a crystal or a potential structure on the neutron investigated hitherto (Shull 1956, Williams 1988).

The cold fusion matter (*the cf-matter*) is, as defined above, a working concept used in the following chapters to specify a state of composite particles in a part of CF materials where occurs CFP. The part of CF materials where the cf-matter is formed, is usually localized at boundary/surface regions of samples used in CF researches (CF samples) but sometimes it should be considered to be a whole volume of the CF materials. The size of the localized region is known to be measured by micrometers (μm).

Standard of energy for nucleons in a nucleus is taken at the threshold energy of neutron emission or the separation level except otherwise stated. This means that *the zero of energy* is about 8 MeV higher than the ground level of nuclides with a medium nucleon number while it corresponds to the energy scale of thermal neutrons in free space.

2. QUANTUM MECHANICAL INVESTIGATION OF INTERDISCIPLINARY FIELD BETWEEN NUCLEAR PHYSICS AND SOLID-STATE PHYSICS USING DATA OF CFP

The cold fusion phenomenon (CFP) could not be independent of physical properties of CF materials and also of properties of nuclides included in them. In this Chapter, therefore, we survey these properties of nuclides and occluded hydrogen