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THE COLD FUSION PHENOMENON AND PHYSICS OF NEUTRONS IN SOLIDS

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Abstract

Explanation of some phases of the cold fusion phenomenon (CFP) is given using Quantum Mechanics on the basis of recent development of physics of neutrons in solids. In the explanation, successful application of the TNCF model to various events in CFP has been used as a clue to treat the problems by Quantum Mechanics. Possibility of nuclear reactions between nuclei in solids is investigated. Physics of neutrons developed recently justifies the Premises in the TNCF model and gives a whole perspective of CFP.

1. Introduction

After the discovery of the neutron as a component of the nucleus by J. Chadwick in 1932, neutrons have been used in many ways as a tool to bombard nuclei in experiments of nuclear physics, as a catalyst to induce nuclear chain reactions of $^{235}_{92}U$ in atomic pile, as a wave for structural analysis of materials and so on. The source of neutrons for these applications has been nuclei emitting neutrons spontaneously or by stimulation. The ambient neutrons generated in the outer atmosphere by cosmic ray have not been utilized with purpose even if tritium on the earth is produced mainly by them through collisions with deuterons in heavy water, minor component of water on the earth with a relative concentration of 0.015 %.

Recently, it has become common knowledge in nuclear physics that atomic nuclei have rather wide variation of Z/A ratio than known 20 years ago. The so-called exotic nuclei as $^{10}_{2}He$, $^{11}_{3}Li$, $^{32}_{11}Na$ and so on [1] have been observed in free space by collision experiments in these 10 years. This fact gives us a hint to investigate physics of neutrons in solids which is not touched by physicists before due to the short life time of a free neutron of 886.7 $\pm$ 1.9 s.

The investigation of physics of neutrons in solids was performed by the present author[2 $\sim$ 5] and revealed their interesting features in solids with characteristic structure and composition which can be realized in experimental procedure in researches of the cold fusion phenomenon (CFP). The essential points of neutron physics in solids are explained in the next section.

Importance of behavior of neutrons in solids for physics of CFP should be emphasized here. The cold fusion phenomenon occurs in solids at near room temperature surrounded by ambient neutrons. By conventional logic of physics as discussed in Section 3, it is clear that Quantum Mechanics established in these more than 80 years is completely applicable to CFP which occurs in solids composed of atoms with the thermal energy of about 25 meV and mutual distance of 10^{-8} cm and of nuclear interactions taking place with an energy of about 1 MeV at a distance of about 10^{-13} cm . Then, it is also clear that CFP is most easily explained by reactions catalyzed by some neutral particle(s) in solids. The neutron should be a most hopeful candidate to it.

2. Neutrons in Solids

As pointed out in the preceding section, neutron is used widely as a tool of structural analysis in the neutron diffraction. In this case, neutron is wholly parallel to photon and electron as showing the wave nature of a quantum mechanical object. It should be noticed here that the particle nature of a quantum mechanical object will be revealed in which a position measurement is performed, or in such a corresponding event like an absorption by an atom or by a nucleus, as known in Quantum Mechanics as the contraction of wave packet. The frequency of the contraction is determined by a quantum mechanical probability depending on the wave functions of pertinent particles and their interaction.

2-1 Neutron Band and Local Coherence of Neutron Bloch Waves at Boundary Region

A phase of behavior of a neutron in a crystal lattice not noticed clearly until now is formation of a band structure in the energy spectrum of the neutron.[5] A neutron in a crystal interacts with nuclei in the crystal lattice (lattice nuclei) by the nuclear force. In a periodic potential of a lattice, the wave function of a neutron, expressed by a plane wave in free space, are modified by a factor with the same periods to those of the lattice and the energy spectrum becomes stratified to be a band structure.

Due to the strong interaction with very short range $\sim 10^{-13}$ cm of the nuclear force, a neutron band in the crystal lattice of attractive interaction becomes peculiar compared with the electron band popular in solid state physics. For an appropriate strength of the interaction constant, the lowest band above zero by a standard of free space has the energy minimum at a Brillouin zone boundary. The lowest band in the free space, in this case, is pulled into the negative energy region and represents trapped states. The concept of *the neutron affinity* of a nucleus defined to treat material aptitude for CFP[2] seems to reflect this property of nuclear interaction between a neutron and a lattice nucleus.

The larger the neutron affinity with a positive sign of a nucleus is, the stronger the attractive interaction potential of the nucleus for a neutron is, and the whole band structure of the energy spectrum of the neutron becomes lower in energy. We have noticed that all nuclei used in CF experiments have positive neutron affinities if they have shown positive results of CFP. This fact suggests strong correlation between the structure of the neutron band of a solid and occurrence of CFP in its.

If the energy minimum of a band above zero is at Brillouin zone edge, there appears *the local coherence* of wave functions of neutrons in the band. The local coherence makes the density of neutrons at the boundary region very high. The one-body approximation used to calculate the band structure of the energy spectrum fails here where we must take into our consideration the strong mutual nuclear interaction between neutrons.

The characteristics of the trapped neutron assumed in the Premises 1 and 2 of the TNCF model[2,10] may be interpreted as demonstration of the feature revealed by the occurrence of the local coherence and such related phenomena as the neutron drop investigated in the next subsection.

2-2 Neutron Drop $n_{A-Z}p_Z$

If the crystal contains many nuclei of hydrogen isotopes as metal hydrides or deuterides used in CF experiments, the high density neutrons in the boundary region can form a neutron drop $n_{A-Z}p_Z$ ($Z \ll A$) grown up from one of lattice nuclei or from a n-p or n-d cluster.

Some properties of the neutron drop can be investigated on the evaporation model of nuclear reaction.[6] In an equilibrium state, evaporation and condensation are reverse processes in balance and the same situation is also in quasi-equilibrium state we consider hereafter.

In the evaporation model, the evaporated neutron from a nucleus has the Maxwell energy distribution characterized by a temperature Θ defined by the level density of the residual nucleus. The thermal energy of $\sim 1/40$ eV in CF experiments is very small in the scale of that in nuclear reaction and the temperature Θ is almost constant for a neutron drop, a group of many neutrons and a few protons or deuterons, supposed to be in the boundary region. The evaporation channel of the neutron drop is not known at present and we have to guess it from experimental data obtained in CF experiments if possible.

The formation of the neutron drop $n_{A-Z}p_Z$ ($N_p \equiv Z \ll N_n \equiv N = A - Z$), or the neutron cluster including several protons, is considered as follows. As the exotic nuclei are formed from ordinary nuclei in solids at crystal boundary where high density neutrons are, the neutron drops can be formed there from p or d as a seed when sufficient neutrons be supplied to increase neutron number N_n in the drop. One-body approximation which concluded local coherence of neutron waves in a band loses its validity if the strong interaction between nucleons is taken in.

To consider growth of the neutron drop as a result of condensation and evaporation processes of neutrons in a quasi-equilibrium state, we assume a situation where is a neutron drop with a number density of neutrons in it n_d and a radius R ($(4\pi/3)R^3 n_d = N_n$) in a boundary region of a solid where the neutron density is n_n. Motion of neutrons in and out of the drop is treated classically in this calculation and motion of N_p protons in it is neglected. Then, rate P_c of condensation of neutrons from outside is expressed as follows:

$$P_c = 0.35 n_n v_n 4\pi R^2 \eta. \tag{1}$$

where $0.35 n_n v_n$ is the neutron flux (cm^{-2}s^{-1}) onto the drop in the boundary region and η is a factor between 0 and 1 characterizing rate of capture by the drop.

On the other hand, the rate P_e of evaporation from the neutron drop in the evaporation model is written down as follows;[6]

$$P_e = \sum_b \int G_b(\varepsilon) d\varepsilon, \tag{2}$$

where the distribution function $G_b(\varepsilon)$ is the number of neutrons emitted through a channel b with an energy between ε and $\varepsilon + d\varepsilon$. The sum is extended over all channel b and the integration is over the energy ε of the particle in the channel b . We do not have any information about the function $G_b(\varepsilon)$ at present and have to take an approximate form for P_e. Considering the complex energy dependence of neutron capture cross section of many nuclei in the thermal energy region and reciprocity theorem of nuclear reactions, we can only guess strong dependence of $G_b(\varepsilon)$ on ε.

It is natural, then, to assume that the neutron drop becomes less stable with increase of the radius R or of the number of neutrons N_n in it. We, therefore, assume that P_e measures stability of the neutron drop and reaches the limit at a definite maximum value R_M of R depending probably on the number of protons N_p in the drop. We assume following dependence of P_e on R ;

$$P_e = 0.35 n_d v_d 4\pi R^2 (\frac{R}{R_M})^\beta \quad (R \leq R_M), \tag{3}$$

where β is a constant depending probably on N_p to be determined later using experimental data and n_d and v_d are density and velocity of neutrons in the neutron drop, respectively ($4\pi\ R^3 n_d/3 = N_n$).

Putting $P_c = P_e$ in the quasi-equilibrium state, we obtain a relation between characteristic quantities of the neutron drop in the boundary layer with a neutron density n_n:

$$n_n v_n \eta = n_d v_d (\frac{R}{R_M})^\beta. \tag{4}$$

If the temperature in the drop is the same as that of neutrons in solids, i.e. $v_n = v_d$, the radius of the drop is given as

$$R \ = \ (\frac{\eta n_n}{n_d})^{1/\beta} R_M \ = \ (\frac{\eta n_n}{n_d})^{1/\beta} N_0^{1/3} r_0. \tag{5}$$

Here, N_0 is the maximum number of N_n or the number of neutrons in the largest drop with a radius R_M and r_0 is a constant with a value 1.5×10^{-13} cm = 1.5 fm;

$$R_M \ = \ r_0 N_0^{1/3} \tag{6}$$

if we assume the same density for the drop as the ordinary nuclei. R_M and β depend naturally on the number of protons N_p in the drop as explained already.

Then, we can express R as follows;

$$R \ = \ \frac{3}{4\pi}(\eta n_n)^{1/\beta} r_0^{(\beta-1)/\beta} N_0^{1/3} \quad (R \leq R_M). \tag{7}$$

It is probable that $N_0 \sim 27$ or $N_0{}^{1/3} \sim 3$ when $N_p = 1$ and then we have

$$R \ \sim \ \frac{9}{4\pi}(\eta n_n)^{1/\beta} r_0^{(\beta-1)/\beta} \quad (R \leq R_M). \tag{8}$$

R is insensitive to N_0. If we take $N_0 = 8$, then the factor of this relation shifts by a factor 2/3 and becomes $(6/4\pi)$.

On the other hand, the neutron drop reduces to an ordinary nucleus when $A - Z \geq Z$, or $N_n \geq N_p$, and R should be larger than r_0;

$$(\frac{\eta n_n}{n_d})^{1/\beta} N_0^{1/3} r_0 \ > \ r_0, \tag{9}$$

or

$$n_n > \frac{1}{\eta}\frac{n_d}{N_0^{\beta/3}} \sim \frac{3}{4\pi\eta} r_0^3 N_0{}^{-\beta/3}. \tag{10}$$

From our analysis of experimental data in CF phenomenon, we can take the maximum value of n_n in the boundary regions as 10^{31} cm^{-3} [3] and from empirical formula in nuclear physics $n_d \sim 10^{38}$ cm^{-3}, and then the above relation gives a relation of N_0 and β ;

$$N_0^{\beta/3} \sim 10^7 \eta^{-1}. \tag{11}$$

If we take the maximum number N_0 of the neutrons in a drop with $N_p = 1$ as 27 as assumed above, Eq.(11) gives $3^\beta \sim 10^7 \eta^{-1}$ or β log3 $\sim 7 -$ logη :

$$\beta \sim 14.7 \quad (\text{when} \ \ \eta = 1). \tag{12}$$

It is interesting to notice that the average distance of about 0.5 pm (picometers) suggested by the maximum value 10^{31} cm^{-3} of n_n in the TNCF model is very close to the characteristic distances of 1 pm obtained in the heterogeneous models of Hora et al.[8] and X.Z. Li.[9]

3. Difficulty of a Nuclear Reaction between Charged Particles in Solids

After the discovery of the cold fusion phenomenon (CFP), or "nuclear reactions and accompanied events in solids with high density hydrogen isotopes", in 1989, there have been many works trying to show possibility of nuclear reactions between charged particles in the solids.

Almost all works of them are used to take up one (or several) experimental results as a goal to be proved assuming a special mechanism not noticed before as *a missing factor* in the conventional physics. Due to the situation where occurs CFP, the assumed missing factors are related with phonons or electrons in the crystal lattice or are effects of the periodic potential on the deuteron in the sample solids.

As was pointed out in the Introduction, CFP occurs in solids composed of atoms with the thermal energy of about 25 meV and mutual distance of 10^{-8} cm while the nuclear interactions between a nucleus and a particle takes place with an energy of about 1 MeV at a distance of about 10^{-13} cm.

We would like to suggest here only difficulty of nuclear reactions between charged particles in solids because it is impossible to prove absence of a process or an effect to occur unless we know everything relevant to it and also the method to treat them.

First of all, the average energy of phonons excited in the solids is about an order of 25 meV and it is not possible to have their accumulation up to $\sim$ 1 MeV with a finite probability. The difference is about 10^8 or eight orders of magnitude as easily estimated by a common sense of physics. Therefore, a nuclear reaction of charged particles in solids is not catalyzed by phonons.

Second, an electron confined in a small space with a linear dimension of $\delta x \sim 10^{-13}$ cm has a momentum of $\delta p \sim \hbar/\delta x$ and therefore a relevant energy $\delta E \sim (\delta p)^2/2m_e \sim 10$ GeV. Thus an electron and also a group of electrons can not screen the repulsive Coulomb interaction between two nuclei down to a distance where works the strong nuclear interaction.

Third, a proton (or a deuteron) in the lattice of a metal hydride is known to behave as a charged particle hopping around from an interstitial site to another even if it is possible to consider a band structure for the energy spectrum of a proton in a crystal. When two deuterons in the lattice interact with nuclear force, the situation considered in the above paragraph is applied to them and particle nature, one phase of duality of a quantum mechanical particle, appears and the wave nature disappears.

Thus, it is very difficult to find out an escape route for a nuclear reaction of two charged particles in solids even if its impossibility is not proved. The complicated nature of CFP

4. Conclusion

As is shown in the paper,[10] a phenomenological approach to CFP is effective in the present stage of investigation. The nuclear transmutation observed in CFP have been explained in consistent with other data with an adjustable parameter n_n of values 10^8 to 10^{12} cm^{-3}.[2,3,11]

By the success of the TNCF model and the liquid-drop model[7] in the analysis of data in CF phenomenon (CFP), it is probable that there are high density neutrons in the samples with positive results of CFP. We could give some information about a possible state of neutrons in the metal hydrides or deuterides, the neutron drop with radius R determined by parameters of the system as Eq.(7). The numerical factor β defined in Eq.(3) was determined by experimental facts as in Eq.(12) showing very strong dependence of evaporation rate on the radius of the drop. These conclusions depend strongly on the assumption made about nature of the neutron drop and should be considered as tentative ones.

With these reservations on the quantitative conclusions, we may be able to discuss qualitative nature of the neutron drop. The neutron drop $n_{A-Z}p_Z$ $(Z \ll A - Z)$ and the exotic nuclei (extremely neutron-rich nuclei) are states of neutrons in the boundary region of metal hydrides (deuterides) formed through their interaction with protons and ordinary nuclei, respectively. It might be rather probable to form an exotic nucleus than a neutron drop if we consider probability of neutron capture by a deuteron (cross section = 5.5×10^{-4} barns) with that by appropriate nuclei in the material, i.e. $^{48}_{22}$Ti, $^{58}_{26}$Ni and $^{104}_{46}$Pd with cross sections of 7.8, 4.5 and 8.5 barns, respectively. This tendency is, probably, the cause of frequent observations of products of NT compared with tritium (and helium-4) in systems without

${}^{9}_{3}$Li in recent experiments. Further, interaction of the neutron drop with the exotic nucleus should be taken in our consideration to understand CFP as a whole as Fisher[7] did in the explanation of NT_F.

The estimation given in this paper is based on the assumption that the CFP is real and indicate some states of matter described by Quantum Mechanics. A new phenomenon, if it is really new, should includes one or more factor not noticed before related with the phenomenon. This factor is not known or missing in past and may be called *a missing factor* as noticed already. The CFP should be resolved by a missing factor if it is a real one, according to the author's viewpoint. The missing factor of the CFP is trapped neutrons from the viewpoint of the TNCF model[2,10] and it is the polyneutron in Fisher's liquid-drop model[7] for NT_F.

The tentative estimation of several properties of the neutron drop in metal hydrides and deuterides based on experimental data in CFP and given in the preceding section should be revised by more elaborate calculations of many-body system with neutrons, hydrogen isotopes and lattice nuclei distributed heterogeneously in a solid.

There are plenty of space for developing new solid state-nuclear physics if existence of the neutron drop and the extremely neutron-rich nuclei (exotic nuclei) is confirmed in the boundary region of CF materials with positive results. The application of this science will produce great possibility of new energy and material sources.

One of effective methods to verify the existence of the neutron drop is, in the author's point of view, neutron diffraction investigation of CF materials which showed positive results. Another will be NMR investigation of trapped neutrons in the boundary region. Any method other than used in CF experiments will substantiate the results obtained hitherto in this field.

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