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Thermal Neutrons and Hydrogen Isotopes in Solids Responsible to the Cold Fusion Phenomenon

Hideo KOZIMA
Cold Fusion Research Laboratory
Yatsu 597-16, Shizuoka 421-1202, Japan
Tel/Fax. +81-54-278-0327
E-mail cf-lab.kozima@nifty.ne.jp

Abstract

Using the concept of the neutron Bloch wave in the one-body approximation presented in a preceding paper, following predictions are given: occurrence of local coherence of neutron waves, formations of neutron Cooper pair, neutron-proton (deuteron) cluster and neutron drops, possibilities of an effective nuclear reactions of a nucleus with thermal neutrons in boundary regions of crystals containing hydrogen isotopes. Possible effects of this new states and the reactions on solid state-nuclear physics in metal hydrides (deuterides) are discussed. Occurrence of localized nuclear reactions observed in CF experiments is explained by these properties of the trapped neutrons.

KEYWORDS: nuclear reaction, neutron band, neutron Bloch wave, neutron-nucleus reaction, neutron drop, neutron-proton (deuteron) cluster, local coherence, cold fusion phenomenon.

1. Introduction

In the preceding paper[1], it was pointed out that a thermal neutron in appropriate crystals can have an energy spectrum with a band structure in the one-body approximation. This is a natural conclusion from the wave nature of quantum mechanical objects common to electron, photon, neutron and others but has been overlooked for a long period about neutron due to its short life time in free space of 887.4 ± 1.7 s.

In these 30 years, various aspects concerning diffraction patterns of neutron have been developed after the work of C.G. Shull[2] on the Pendellösung fringe structure in neutron diffraction. The dynamical theory of diffraction was applied to such cases of neutron scattering as neutron interferometry[3], the change of sign of the neutron wave function in a 2π precession[4], the effect of Earth's rotation on the quantum-mechanical phase of the neutron[5] and the effect of gravity (or of a magnetic field) on the propagation of neutrons within the perfect, single-crystal silicon slabs.[6]

On the same line of investigation, properties of the cold neutron in solids with artificial potential wells have been used[7] to investigate external effects on the phase of neutrons using such quantum mechanical characteristics of neutrons as trapping and tunneling in and through potential walls similar to those of electron and photon.

In the case of thermal neutrons, periodic potential on them is provided by natural crystal lattice instead of artificial one for the cold neutron and band structure in the energy spectrum of neutrons is realized as illustrated by a simple calculation in the one-dimensional Kronig-Penny model.[1)]

On the other hand, neutrons in the nucleus have shown exotic features revealed by scattering experiments.[8~11)] Existence of exotic nuclei far from the stability line, like ^{10}He, ^{11}Li, ^{32}Na, and so on, were observed in free space and its explanation[12)] has been tried.

In contrast to the dynamical characteristics[2~7)] of the neutron-lattice system investigated hitherto, its quantum-mechanical state has been left little noticed until now. Interaction of neutrons in lower density than that in nucleus is also left untouched due to its vague reality.

The purpose of this paper is to present a microscopic treatment of neutrons in an allowed band of a crystal by physical investigation of simplified situations of neutron-crystal lattice system using the ordinary Quantum Mechanics. Realization of optimum condition for CF phenomenon in metal hydrides (deuterides) is discussed. Experimental facts concerning localization of reaction products in CF phenomenon have been explained using these concepts.

2. Local Coherence of Neutron Bloch Waves in Boundary Layer

A simplified calculation of neutron energy in solids[1)] showed a band structure in the one-body approximation similar to that of electron energy in solids. In a case where bands above zero energy level (in terms of a scale where a neutron rest far away from the solid has an energy zero) are empty and below it are fully occupied, extra neutrons from outside and those generated by nuclear reactions enter into one of the empty bands. Properties of the band neutron are governed by the band with vacancy of the lowest energy. Thus, the band structure of the neutron energy (neutron band) in solids has important influences on the properties of the neutron interacting each other and with nuclei in the crystal.

When a solid (say A) with empty bands above zero and with fully occupied bands below zero is surrounded by another solid (say B), neutrons in A may be trapped in A if the lowest allowed band of A corresponds in energy to a forbidden band of B and if its thickness is enough to prevent substantially tunneling of the neutron.[13,14)]

The trapped neutrons in A has a large probability density at the boundary region between A and B as shown numerically below.

To investigate characteristics of the trapped neutron at a boundary between two crystals A and B mentioned above, we approximate the Bloch wave in A by a plane wave and the boundary by a potential wall linearly increasing with decrease of the coordinate (say x) perpendicular to the boundary (at $x = x_0$) as a zeroth approximation:

$$V(x) = \alpha(x_0 - x), \quad (x_0 \geq x) \tag{1}$$

$$= 0. \quad (x > x_0) \tag{2}$$

Classically, a particle with a mass m_n and an energy E moving leftward to the boundary wall loses kinetic energy gradually from $x = x_0$ and reaches 0 determined by a relation $E = V(0)$ to be reflected there. The classical probability of existence[13) at x ($\propto 1/v(x)$) is proportional to a quantity $\sqrt{m_n/E - V(x)}$ which is shown with a dotted line in Fig.1.

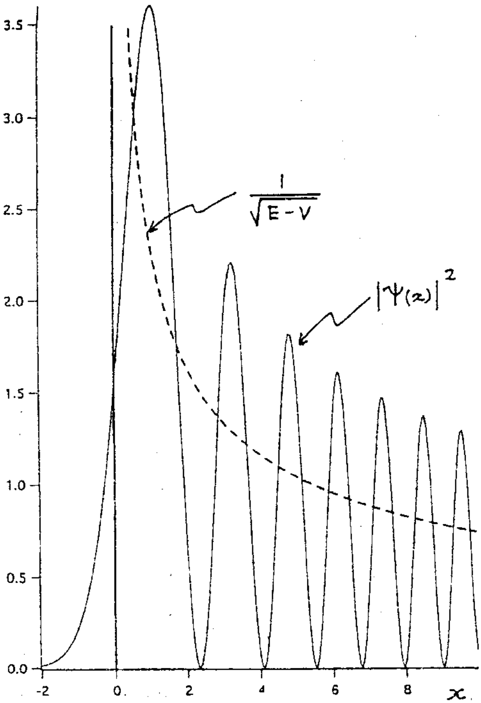

Figure 1: Classical probability of existence (dotted line) and quantum mechanical probability density (solid line) of a particle with a mass m_n and an energy E (in arbitrary units) in the boundary region $x \sim 0$ determined by a condition $E = V(0)$ with a potential $V(x) = 0$ $(x_0 \leq x)$, $= \alpha(x_0 - x)$ $(x \leq x_0)$ for $\alpha = 1$.

Quantum mechanically, the corresponding quantity, the probability density $\rho(x)$ $\equiv |\psi(x)|^2$, is calculated numerically with the Airy function[13) for the wave function $\psi(x)$ and shown with a solid line in Fig.1. As is well known in quantum mechanics, e.g. for a case of harmonic oscillator, quantum behavior of a microscopic object approaches to classical one with increase of the quantum number and the similarity of two curves in Fig.1 is an example of this nature. Qualitative investigation of a quantum object at boundary is therefore partly given by behavior of a classical particle.

The neutron Bloch waves in a band above zero with energy minimum at Brillouin zone boundary have almost the same energy and their behavior in the classical forbidden region ($x \leq 0$) is expressed by similar exponential functions with almost the same decay constant. Therefore, the behavior of the Bloch functions in the classical allowed region ($0 \leq x$) determined by the shape of the function in the forbidden region is coherent for a finite length determined by the difference of their wave number vectors. Range of this local coherence in phase factor of wave functions is longer for two waves with smaller difference of the wave number vectors.

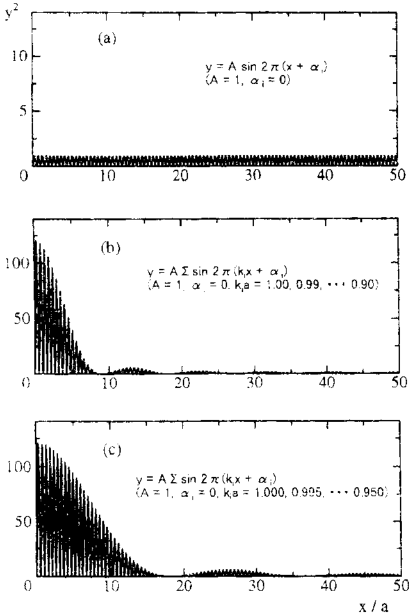

Figure 2: Illustration of local coherence of neutron Bloch waves near the boundary region by sinusoidal waves in phase at $x = 0$. Probability amplitudes of (a) a single sinusoidal wave with $k = k_0 \equiv \pi/a$, (b) eleven sinusoidal waves with different wave numbers between $k = 0.90\pi/a$ and $k_0 \equiv 1.00\pi/a$ and (c) eleven sinusoidal waves with different wave numbers between $k = 0.95\pi/a$ and $k_0 \equiv 1.00\pi/a$ where a is the period of the Kronig-Penny potential.

In the case of the model calculation of the Kronig-Penny potential,[1] the energy of the lowest band above zero does not change much from $k_0 = \pi/a$ to $k' = 3\pi/4a$ and the local coherence of the Bloch waves exists at least for a region with a length ℓ_{coh} from the turning point determined by $(\pi/a - 3\pi/4a)\ell_{coh} = \pi$, or ℓ_{coh} = 4a for $N/4$ neutrons in the band where a = lattice constant as shown numerically in Fig. 2.

3. Formation of Neutron Cooper Pair, Neutron-Proton (Deuteron) Clusters and Neutron Drops in a Boundary Region

There are two remarkable possibilities to have new quantum states of neutrons in solids due to the existence of the empty bands above zero.

First, in the situation where there is an empty band with energy minimum at $k = \pi/a$, it is conceivable to have a neutron Cooper pair of two neutrons with opposite spins and quasi-momenta $\boldsymbol{k}$ and $-\boldsymbol{k}$ due to the interaction through photons just as in the case of electrons shown in the BCS theory of superconductivity. If this is the case, the whole system will be in a more stable state with a lower energy than the state without them even though mutual interaction of neutrons are ignored.

Second, in the situation where the trapped neutrons are in a band above zero of a crystal surrounded by another satisfying the condition described in Section 2, it was shown there that neutron density in the boundary region becomes extremely large in the one-body approximation. Neutrons interact each other through the strong interaction (attractive nuclear force) and therefore the one-body approximation lose its applicability as shown drastically by the existence of superconductivity in metals. It might be possible to form a drop of neutrons with several protons in it which has not been treated appropriately in neutron physics in solids and also not observed by now. Reality of this speculation is shown as follows.

The density of the nuclear matter in the nucleus, or number density n_A (cm^{-3}) of nucleons in the nucleus. is well defined quantity in nuclear physics[15] and is given as follows:

$$R = 1.5 \times 10^{-13} A^{1/3} \quad \text{cm}, \tag{3}$$

$$n_A = \frac{A}{(4\pi/3)R^3} = 7.07 \times 10^{37} \quad \text{cm}^{-3}. \tag{4}$$

The nucleons in the nucleus with this density are interacting each other with the nuclear force, the so-called strong interaction. Existence of the exotic nuclei, ^{10}He, ^{11}Li, ^{12}Be, ^{32}Na, and so on in free space, is a clear evidence of the nuclear force between neutrons in a state with a density of this order.

Local coherence of the trapped neutrons in the boundary layer illustrated in the preceding section makes the neutron density in this region very high; if the density of the trapped neutron in a crystal is such a high value 10^{12} cm^{-3} as determined in several situations observed in CF experiment, the local coherence makes the probability amplitude of whole neutron as high as 10^{12} times that of a single neutron in the coherent region of a thickness 10 a, or ~ 30 Å = 3×10^{-7} cm as shown in Fig. 2.

If we assume whole neutrons in a unit volume accumulate in this region, the effective density in coherence becomes very high as $(10^{12})^2/3 \times 10^{-7}\ \mathrm{cm}^{-3} = 10^{31}\ \mathrm{cm}^{-3}$. This is fairly large value expected in the outer region of the neutron halo of exotic nuclei and we can expect effect of neutron-neutron interaction result in condensation of neutrons to form neutron drops[16] in the boundary layer like condensation of vapor from gas into liquid or solid phase.

This possibility will be enhanced by formation of the neutron Cooper pair, a boson, which be favorable to form a cluster because of probable Bose-Einstein condensation.

It is necessary, here, to spend several words on one of the necessary conditions for the CF phenomenon – existence of hydrogen isotopes. In the TNCF model, we have only used hydrogen isotopes as components relevant with the trapping condition for thermal neutrons and participating in nuclear reactions with a neutron and each other. Considering the existence of the exotic nuclei, where proton and neutron are interacting together to realize a stable state, it is definitely necessary to take hydrogen isotopes into consideration of the state of neutrons in the boundary region where the neutron drop could be formed.

Thus, hydrogen isotopes in metal hydrides used in CF experiments may be an inevitable component to form a stable neutron state with high density at crystal boundary through formation of neutron-proton or neutron-deuteron cluster: $n_x p_y$ or $n_x d_y$.

In the process of neutron drop formation, or neutron condensation, it is probable that the neutron-proton and/or neutron-deuteron cluster play a key role as, for instance, a seed of condensation. It is possible to form neutrons-protons (deuterons) cluster first and then the cluster emerges into a neutron drop instead of a polyneutron. This is only an idea and has not been investigated quantum-mechanically yet.

These problems should be treated quantum mechanically taking the strong interaction between neutrons and between neutron and proton (deuteron) and the neutron-nucleus interaction into consideration which have been ignored in neutron physics in crystal by now. This is a new phase of neutron physics in solids, similar to the exotic nucleus in nuclear physics as treated recently by the relativistic Hartree theory[12] to explain existence of the neutron skin and the neutron halo. This phase of properties of neutrons in solids in relation with the TNCF model is left as future work.

4. Interaction of Neutron Bloch Waves with a Nucleus in a Boundary Region of Metal Hydrides (Deuterides)

In many metal hydrides and deuterides used in the cold fusion experiments, structure of the samples is generally complex. Metals are usually composed of several components, e.g. Pd-Li, Ni-K, Cu-Ti-Pd-Ti, C-Pd, and so on, In the process of hydrogenation, there is usually formed density gradient of the relevant hydrogen isotope in the sample crystal. The resultant material should be accepted as multilayer even if the original sample is of single component. The inhomogeneity between regions of different components or compositions works as crystal boundary to reflect neutrons as treated in previous sections.

As shown in the preceding section, the trapped neutrons in the lowest band above zero in a crystal A surrounded by another B has a large probability density at the boundary region of the two crystals if the boundary is expressed by a potential wall $V(x)$ in Eq.(1). In the boundary region between A and B, the atomic arrangement and composition vary gradually from that of A to that of B, in reality. If thickness of the crystal B is thick enough to prevent tunneling of the neutron in an allowed band in A which corresponds energetically to a forbidden band in B, the potential wall against the neutron may be approximated by an increasing function of x and the potential of Eq.(1) is considered as its zeroth order approximation.

The fusion probability of a neutron and a nucleus is known to be proportional to an interaction time, i.e. a time they stay in a range where the nuclear force is working. This property results in the well-known general energy dependence of the fusion cross section of $1/\sqrt{E}$ for the reaction of a neutron with a target nucleus. In the case of interaction of the trapped neutrons with a lattice nuclei in a surface layer, the reaction time is reduced to the probability density of the neutrons in the surface layer.

Therefore, the trapped neutrons in the band above zero, which is quasi-stable unless it suffers large perturbation, fuse with a heterogeneous nucleus at an aperiodic site seen from the periodic lattice, where the neutron is trapped, and in the boundary region with a large cross section.

In three dimensional crystal with a volume of 1 cm^3, there are about 10^{22} atoms and therefore there are $\sim 10^{22}$ states in a band. In one dimensional scheme, this corresponds to 10^7 states in such a band as calculated by one-dimensional Kronig-Penny potential.

If the number of the trapped neutron in the band is as large as 10^6, the local coherence discussed in the previous section make the fusion probability 10^6 times that of single neutron in the boundary region fairly deep (ℓ_{coh}) into the crystal A determined by a relation $(\pi/a - 9\pi/10a)\ell_{coh} = \pi$, or $\ell_{coh} = 10a$. This coherence last partially further into the crystal decreasing its multiplicity 1/10 (10^5) at $100a$. The amplification of the fusion probability becomes larger in the surface region if there is formation of neutron-cluster, or neutron condensation, considered in Section 3.

5. Stabilization of Neutrons Trapped in Solids

In such a situation where the highest band below zero is partially filled in the solid A discussed in Section 2, the extra neutrons entered into the band from outside are in lower energy states to prevent their spontaneous transmutation into proton by β-decay. In this case, the neutrons trapped in the solid accumulate to a high density where the mutual interaction of neutrons through such a strong interaction as that exhibited by the exotic nucleus enforces stability of the system. It is, of course, necessary to take into consideration of the neutron-lattice nucleus interaction in this case which introduce much complexity to the state of the system, neutrons and crystal lattice, than in the case of the exotic nucleus.

Anyway, there is a large possibility the trapped neutrons stabilize in optimum situation conditioned by combination of structure and components of the system, a concrete treatment of this problem will be given elsewhere.

6. Discussion

The duality of a microscopic object, a characteristic of quantum mechanical point of view, has been an interesting property sometimes attracted and sometimes confused people. An example clearly expressed beauty of quantum mechanical logic is production of a cloud-chamber track by a fast electron.[17] The same will be said about the nuclear reaction of the trapped neutrons and a nucleus in a boundary region investigated above. The local coherence due to behavior of the neutron Bloch waves in the boundary region and perhaps due to the Cooper pair and/or neutron-proton (deuteron) cluster formations should be responsible to tremendous nuclear reactions in the region not noticed before.

Neutron has been an object difficult to control due to its weak interaction with other particles except in the nucleus, where neutron density is very high, although there are recent advanced treatment of the cold neutron.[7] As a natural conclusion from its wave nature, the concept of neutron band in the one-body approximation has been deduced and an energy spectrum with a band structure above zero is shown for one-dimensional Kronig-Penny model with appropriate parameters which is applicable to a real situation with two-dimensional homogeneity by a simplified numerical calculation.

The neutron band structure, a result of its wave nature, brings in the trapping of the neutron in a crystal with an appropriate boundary condition. In the case of the lowest allowed band with vacant level below zero, it is expected stabilization of neutrons trapped in the solid occurs. In the case where the level is above zero, accumulation of neutron density in the one-body approximation is expected resulting in formations of the neutron cluster and/or neutron-proton (deuteron) cluster.

The particle nature of neutron, however, appears in the absorption of the neutron by a nucleus which gives a strong perturbation on the neutron Bloch wave. The interaction in the boundary region treated above is just such a perturbation due to the large probability density of neutrons in it and reveals particle nature of the neutron in the nuclear reaction with a nucleus in it.

When the number of the trapped thermal neutrons in an allowed band above zero is very large, the interaction of a nucleus with trapped neutrons with almost the same energy in the boundary region can induce a drastic change of properties of the nucleus, e.g. change of its decay characteristics, by summation of the individual interaction due to almost the same phases of the wave functions at the classical turning point $x = 0$.

Thus, the thermal neutrons in solids expressed by neutron Bloch waves in one-body approximation can induce qualitatively new phases of mutual interaction of neutrons each other and with hydrogen isotopes and nuclear reactions between neutrons and a nucleus in solids not noticed before and could be a basis of a new science in solid state-nuclear physics. The idea of the poly-neutron used to explain the mass spectrum of nuclear products[18] might be a result of the neutron cluster discussed above in Section 3.

A part of this new feature of the trapped neutron-lattice nucleus system in the boundary region is exhibited by the occurrence of localized nuclear products observed in CF experiments.[19~29] There are various events showing production of new elements in materials, mainly in electrodes electrolyzing water or heavy water, observed in CF experiments.

The first confirmation of the localized existence of reaction products is, as far as the author knows, the detection of ^{4}He in the surface layer of a thickness of 40 μm by Morrey et al.[19] and of less than 1 mm by Bockris et al.[20].

The occurrence and the amount of ^{4}He observed in these experiments have been explained by the so-called TNCF model[30~32] using a single parameter n_n and premises related with effective nuclear reactions in the boundary layer justified in this paper.

The origin of ^{4}He is supposed to be due to the first reaction of those neutron reactions expected in Pd/D(H)/Li system:

$$n + {}^6_3\text{Li} = {}^4_2\text{He}\,(2.1\text{ MeV}) + t\,(2.7\text{ MeV}), \quad (5)$$
$$n + p = d\ (1.33\text{ keV}) + \gamma\ (2.22\text{ MeV}), \quad (6)$$
$$n + d = t\ (6.98\text{ keV}) + \gamma\ (6.25\text{ MeV}). \quad (7)$$

Assuming the ^{4}He detected in the surface layer of the Pd cathodes to be few% of produced in it, the data were shown to be consistent with ^{4}He detected in the gas phase of the system later by others.[33,34]

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