NEUTRON DROP: CONDENSATION OF NEUTRONS IN METAL HYDRIDES AND DEUTERIDES

NUCLEAR REACTIONS IN SOLIDS

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HIDEO KOZIMA* *Cold Fusion Research Laboratory*
Yatsu 597-16, Shizuoka 421-1202, Japan

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The possible formation of the neutron drop $n_{A-Z}p_Z$ *composed of* $N_n = A - Z$ *neutrons and* $N_p = Z$ *protons in metal hydrides and deuterides is discussed on the basis of experimental facts using the evaporation model of the decay of the compound nucleus. Exotic nuclei and the neutron drop will be formed at a region with a high neutron density in crystals including hydrogen isotopes. Successful explanation of the anomalous nuclear reaction phenomenon in solids by models assuming neutrons in a solid lattice is legitimated.*

I. INTRODUCTION

As is well known in nuclear physics,[1] several features of nuclear reactions at an intermediate-energy range are explained using an evaporation model analogous to the evaporation of molecules from a condensed phase.

It is natural to consider the reverse process, condensation, in the case of molecules that balance the evaporation in equilibrium of two phases on the earth. The nuclear matter, however, has been a special state on the earth, with a high number density of nucleons of an order 10^{38} cm^{-3} higher by a factor 10^{16} than those of atoms and molecules of $\sim 10^{22}$ cm^{-3} in condensed matters. In the present state of the earth, evaporation of the nuclear matter is realizable only in nuclei excited by an incident particle, but condensation has been considered unrealistic, beyond our access.

In the course of investigating various events in the nuclear reactions in solids, i.e., in the anomalous nuclear reaction so-called cold fusion phenomenon (CFP), it has been noticed that an assumption of high-density neutrons in metal hydrides or deuterides is effective as a cause of these events to give consistent and unified explanation.[2] The assumption of high-density neutrons in metal hydrides (deuterides) used to explain the experimental data of the CFP is beyond our common sense in physics: A neutron in free space decays into a proton with a time constant of 887.4 ± 1.7 s even if there are many ambient neutrons on the earth both with thermal and epithermal energies and a flux density of $\sim 10^2$ m$^{-2}\cdot$s^{-1} each.[3]

After the discovery of the neutron by Chadwick in 1932, neutrons have been used in many ways: as a tool to bombard nuclei, as a catalyst to induce nuclear chain reactions of ^{235}U, as a wave for structure analysis of materials, and so on. The source of neutrons for these applications has been nuclei-emitting neutrons spontaneously or by activation. The ambient neutrons have not been purposefully utilized even though tritium on the earth is produced mainly by them through collisions with deuterons in heavy water—a minor component of water on the earth, with a relative concentration of 0.015%.

There are two successful explanations of the anomalous nuclear reaction phenomenon using neutrons in solids. One is the TNCF for various events in the CFP, assuming many stable trapped neutrons in solids but the possibility of making reactions with nuclei in the boundary region. The reactions in this model have been limited to those initiated by single neutron absorption followed by disintegration or fission of the compound nucleus. Various events measured with qualitative reproducibility have been explained consistently with values of the single adjustable parameter n_n of the model in the range of 10^6 to 10^{12} cm^{-3} depending on the experimental condition. The source of the trapped neutron, although it is not relevant to the explanation of events by the model, is supposed to be ambient neutrons[3] and neutrons emitted by induced nuclear reactions in solids.[4,5]

The other is the liquid-drop model for the mass spectrum[6] of nuclei produced by nuclear transmutation (NT) in electrolytic systems. In explaining the observed mass

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*E-mail: cf-lab.kozima@nifty.ne.jp

spectrum, Fisher[7] assumed the existence of the polyneutron and also extremely neutron rich nuclei, i.e., exotic nuclei, in the system. The observed mass spectrum was qualitatively explained by these assumptions as a result of nuclear transmutation by a fission (NT_F), i.e., of fission reactions of transmuted nuclei formed of exotic nuclei absorbing several neutrons from a polyneutron.

The assumption of the exotic isotopes of matrix nuclei in Fisher's model is based on the recent observation of exotic nuclei, ^{10}He, ^{11}Li, ^{32}Na (Refs. 8, 9, and 10, respectively), etc., in free space, by collision experiments in these 10 yr, while the neutron drop has not been detected. Existence of these exotic nuclei in free space will give a rather wide possible variety of them in specific regions of materials where there are high-density neutrons.

The success of the two models to explain the CFP suggests that neutrons play a key role in the anomalous phenomenon in solids, called the CFP, which is difficult to understand from conventional solid-state physics and nuclear physics without a new factor(s) not noticed until now, i.e., without *a missing factor*. In this context, neutrons in solids are the missing factor for the CFP in these models.

It should be mentioned that there are other approaches to the CFP with mechanisms using lattice effects to overcome the Coulomb repulsion between charged nuclei. Two examples cited here are by the authors of Refs. 11 through 15.

In the paper by Hora et al.,[11] a model of field-screened, long-range nuclear reactions has been confirmed from the isotopes produced by nuclear reactions in a film-excited complex using Ni and Ni/Pd films. On the other hand, the papers by Hora et al.,[12] Hora and Miley,[13] and Hora et al.[14] have explained a large number of nuclides observed in cold fusion experiments based on data, i.e., a sequence of nuclear reactions including virtual states (compound nuclei) in a $d + d$ endothermic branch with final exothermic sums of reaction energy.

Li[15] has discussed possible fusion without strong nuclear radiations using a concept of the long lifetime nuclear active state created after the resonance penetration of the Coulomb barrier in the $d + d$ system in terms of the lattice-confined deuterons.

It is a main theme of this paper to show a possible state of neutrons in metal hydrides or deuterides, the neutron drop $n_{A-Z}p_Z$ composed of $(A - Z)$ neutrons and Z protons $(Z \ll A - Z)$, using ordinary quantum mechanics and to verify the CFP by these models with the assumed existence of neutron-rich particles in specific solids consistent with experimental results.

II. CHARACTERISTICS OF THE ANOMALOUS NUCLEAR REACTION IN SOLIDS (OR CFP)

Several characteristics of the CFP are related to the assumed existence of neutrons in the CFP materials. First, there is a consistent explanation of several events (the excess heat Q, tritium t, neutron n, and ^{4}He) observed in a system. Several of the data by Fleischmann et al.[16] (Q, t, n), Morrey et al.[17] (Q, ^{4}He), Chien et al.[18] (^{4}He, t), Takahashi et al.[19] (t, n), Miles et al.[20] (Q, ^{4}He), Okamoto et al.[21] (Q, NT), and Cellucci et al.[22] (Q, ^{4}He) are explained by the TNCF model.[2] Second, the widespread mass spectrum of nuclear products in electrolytic experiments[6] is explained as results of nuclear fission (NT_F) of nuclei formed from exotic nuclei by absorption of several neutrons in the polyneutron[7] using the liquid-drop model. Third, there is some decisive evidence of null results in situations without background neutrons.[23,24] Fourth, there are several data showing a decrease of background neutrons when there are CFP (Refs. 25 and 26).

In addition to the data showing the participation of neutrons in the CFP, there is an important characteristic in this phenomenon: irreproducibility of events. Even though one carries out procedures that seem to be the same every time, the result is different: null or positive with a difference in values obtained. This characteristic may be called *the qualitative reproducibility*[2,4] resulting from the stochastic nature of the atomic processes in materials during the experiments.

The missing factor responsible for the CFP should be related to the stochastic process if the qualitative reproducibility is essential to the CFP, as is considered at present. Then, formations of the trapped neutrons in the TNCF model[2,4,5] and of the polyneutron and exotic nuclei (extremely neutron rich nuclei) in the liquid-drop model explanation of the mass spectrum[7] should be results of atomic processes in CFP materials during experiments. The variations of the time needed to realize the CFP seem to be an evidence of this nature.

Another important characteristic of the CFP, observed especially in NT, is locality of the cold fusion reaction. Nuclear products have been detected in a narrow surface layer with an ~1-μm width[6,17,27–32] [at most up to 40 μm (Ref. 17)]. Also, several data show localization of nuclear reactions in a definite area of the sample surface.[28,30,31]

These data showing localized nuclear reactions and the success of theories using neutrons participating in the CFP should be combined to form a unified system of explanation based on the present knowledge of nuclear physics and solid-state physics using quantum mechanics.

III. CONDENSATION OF NEUTRONS IN BOUNDARY REGIONS OF METAL HYDRIDES (DEUTERIDES)

In this section, we give a qualitative explanation of condensation of the trapped neutrons in the boundary region of metal hydrides and deuterides responsible for the experimental data explained in Sec. II.

The thermal neutron in solids has an energy spectrum with a band structure,[33] and the local coherence[5] of wave functions, therefore, exists in the boundary layer where the neutron wave is reflected. If the crystal contains many nuclei of hydrogen isotopes as metal hydrides or deuterides used in the CFP experiments, the high-density neutrons in the boundary region can form exotic nuclei grown up from one of lattice nuclei or neutron drops $n_{A-Z}p_Z$ grown up from a *n-p* or *n-d* cluster.

Some properties of the neutron drop can be investigated with the evaporation model of nuclear reactions.[1] In an equilibrium state, evaporation and condensation are reverse processes in balance, and the same situation is also in the 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 $\sim \frac{1}{40}$ eV in CFP experiments is very small, on a scale of that in nuclear reactions, 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 cold fusion experiments if possible.

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

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 in which there 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. The motion of neutrons in and out of the drop is treated classically in this calculation, and the motion of N_p protons in it is neglected. Then, the rate P_c of condensation of neutrons from outside is expressed as follows:

$$P_c = 0.35 n_n v_n 4\pi R^2 \eta \ , \qquad (1)$$

where $0.35 n_n v_n$ is the neutron flux ($\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$) onto the drop in the boundary region and η is a factor between 0 and 1 characterizing the 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 as follows[1]:

$$P_e = \sum_b \int G_b(\epsilon)\, d\epsilon \ , \qquad (2)$$

where the distribution function $G_b(\epsilon)$ is the number of neutrons emitted through a channel *b* with an energy between ϵ and $\epsilon + d\epsilon$. 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 $G_b(\epsilon)$ at present and have to take an approximate form for P_e. Considering the complex energy dependence of the neutron capture cross section of many nuclei[34] in the thermal energy region and the reciprocity theorem of nuclear reactions, we can only guess a strong dependence of $G_b(\epsilon)$ on ϵ.

It is natural, then, to assume that the neutron drop becomes less stable with an increase of the radius *R* or of the number of neutrons N_n in it. We, therefore, assume that P_e measures the 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 the following dependence of P_e on *R*:

$$P_e = 0.35 n_d v_d 4\pi R^2 \left(\frac{R}{R_M}\right)^{\beta} \quad (R \le R_M) \ , \qquad (3)$$

where β is a constant depending probably on N_p, to be determined later using experimental data, and n_d and v_d are the 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:

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

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

$$R = \left(\frac{\eta n_n}{n_d}\right)^{1/\beta} R_M = \left(\frac{\eta n_n}{n_d}\right)^{1/\beta} N_0^{1/3} r_0 \ , \qquad (5)$$

where 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,

$$R_M = r_0 N_0^{1/3} \ , \qquad (6)$$

if we assume the same density for the drop as the ordinary nuclei, and 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:

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

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

$$R \sim \frac{9}{4\pi} (\eta n_n)^{1/\beta} r_0^{(\beta-1)/\beta} \quad (R \le R_M) \ , \qquad (8)$$

where R is insensitive to N_0. If we take $N_0 = 8$, then the factor of this relation shifts by a factor of $\frac{2}{3}$ 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:

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

or

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

From our analysis of the experimental data[5] in the CFP, we can take the maximum value of n_n as 10^{31} cm^{-3}, and from empirical formula in nuclear physics, $n_d \sim 10^{38}$ cm^{-3}, and then the foregoing relation gives a relation of N_0 and β:

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

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

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

It is interesting to note that the average distance of ~0.5 pm suggested by the maximum value 10^{31} cm^{-3} of n_n is very close to the characteristic distances of 1 pm obtained in the models of Hora and Miley[13] and Li.

IV. CONCLUSION

By the success of the TNCF and the liquid-drop models in the analysis of the data in the CFP, it is probable that there are high-density neutrons in the samples with positive results if we confine our consideration to models with neutral particle assisted reactions. 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 a very strong dependence of the evaporation rate on the radius of the drop. These conclusions depend strongly on the assumption made about the nature of the neutron drop and should be considered tentative.

With these reservations of the quantitative conclusions, we may be able to discuss the 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 the probability of neutron capture by a deuteron (cross section = 5.5×10^{-4} b) 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 b, respectively. This tendency is, probably, the cause of frequent observations of products of NT compared with tritium (and ^{4}He) in systems without $^6_3$Li in recent experiments. Further, interaction of the neutron drop with the exotic nucleus should be taken into our consideration to understand the 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 indicates some states of matter described by quantum mechanics. A new phenomenon, if it is really new, should include one or more factors not previously noticed related to the phenomenon. This factor is not known or missing in the past and may be called *a missing factor*, as noted 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,[2,4,5] and it is the polyneutron in Fisher's liquid-drop model[7] for NT$_F$.

The existence of the trapped neutrons has been investigated from a microscopic viewpoint[2,4,5] using such concepts in solid-state physics and nuclear physics as the neutron band; neutron Cooper pair; the neutron affinity; and the neutron drop, which is explained in this paper. The neutron drop is a combination of two concepts: trapped neutrons in the TNCF and the polyneutron used by Fisher.[7] It should be mentioned here that a similar idea, a superhydrogen isotope $^n_1$H $(n > 4)$, has been used by Yabuuchi in the construction of his philosophical model[35] for the CFP.

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

There is much room to develop new solid-state nuclear physics if the existence of the neutron drop and the extremely neutron rich nuclei (exotic nuclei) is confirmed in the boundary region of CFP materials, with positive results. The application of this science raises the great possibility of new energy and material sources.

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

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Hideo Kozima (BSc, physics, Tokyo College of Science, Japan, 1958; MSc, physics, Tokyo University, Japan, 1960; PhD, physics, Tokyo University of Education, Japan, 1976) has been a professor emeritus at Shizuoka University, Japan, from April 1999 and is the director of the Cold Fusion Research Laboratory. He worked on solid-state physics and plasma physics, and he has been working on solid-state nuclear physics for the last 10 years.