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Superfluidity of Deuterons in Metal-Deuterium Solid Solutionsand Cold Fusion

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Abstract: It is shown that the formation of a Bose-condensate of delocalized deuterons in solid solutions of metals and deuterium leads to the possibility of a d-d-fusion reaction in which one superfluid deuteron and one deuteron that does not participate in superfluid motion participate. Overcoming the Coulomb barrier is due to the large kinetic energy of macroscopic superfluid motion. It is shown that the intensity of the nuclear reaction depends on the velocity of the superfluid motion and, as a consequence, on the magnitude of the vector $\mathbf{B}$ of the external magnetic field. In the London Electrodynamics approximation, a linear dependence of the power released during the nuclear reaction on the magnitude of the vector $\mathbf{B}$ of the external magnetic field is obtained.

Keywords: Superfluidity, deuteron, cold fusion, energy release, magnetic field.

The idea of cold fusion (CF) was proposed in 1989 [1]. The idea is to use solid solutions of metals and deuterium to initiate the nuclear reaction of d-d-synthesis. There are a rather large number of publications (for example, [2-10]), in which it is reported on the observation of energy release and releasation of nuclear reaction products in solid solutions of titanium (palladium) and deuterium. Despite a large number of theoretical works (for example, [8, 11-16]), there is still no understanding of exactly how the Coulomb barrier between the two deuterons is overcome. In the sequel, other ideas of the CF were proposed, but in this paper we will refer to the processes of CF as the reaction of d-d-synthesis.

In this paper, it is proposed to consider the superfluidity of a part of delocalized deuterons in solid solutions of metals and deuterium as a cause for overcoming the Coulomb barrier. With this consideration, a nuclear reaction is possible between one of the deuterons participating in the superfluid motion and one of the deuterons that do not take part in the superfluid motion. Overcoming the Coulomb barrier between deuterons is due to the fact that a macroscopically large number of deuterons participate in superfluid motion,

At high velocities of colliding deuterons, the following d-d-synthesis reactions occur:

$$d + d \to t + p + 4.03 \text{ MeV} \tag{1}$$

$$d + d \to {}^{3}He + n + 3.27 \text{ MeV} \tag{2}$$

$$d + d \to {}^{4}He + \gamma + 23.8 \text{ MeV} \tag{3}$$

Reactions (1) and (2) occur approximately at the same frequency. Reaction (3) occurs very rarely.

CF processes consist in d-d-synthesis reactions (1), (2) and

$$B_d + d + d \to {}^{4}He + B_d^{'} + 23.8 \text{ MeV}, \tag{4}$$

where B_d and $B_d^{'}$ are states of the Bose condensate of delocalized deuterons before and after collision with a deuteron not participating in superfluid motion. A deuteron, which participates in the collision, is separated from the Bose condensate. The processes of CF occur in solid solutions of titanium and deuterium and palladium and deuterium at a deuterium concentration comparable with the concentration of metal ions [2].

There are a number of ways to determine whether the d-d-fusion reaction occurs in a solid solution of

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metal and deuterium. First, it is the observation of energy release, which is measured by a calorimeter. In the works analyzed in the review [2], the releasation of energy in a solid solution of metal and deuterium with a specific power of several W/sm^3 was recorded. Secondly, it is the observation of the products of a nuclear reaction. In most of the works on CF, a large amountof ^4He is reported in the processes of CF[2]. It is reported that the fluxes of reaction products (1) and (2) are very small. This can be explained from the standpoint of the concept of the superfluidity of a part of deuterons. ^4He can be intensively formed in a reaction proceeding at low velocities. In this case, the laws of conservation of energy and momentum are fulfilled due to the participation of the Bose-condensate of delocalized deuterons in reaction (4). However, in Ref. [3] only the 3 MeV protons releasation are reported. It can be noted that the size of the samples studied in Ref. [3] are much smaller than the size of the electrodes in the experiments discussed in Ref. [2]. At the same time, it may well be assumed that there is a criterion for the stability of the Bose condensate, in which the reaction (4) is still possible, and into which the total number of Bose condensate particles enters. A somewhat more detailed analysis of this situation is given at the end of the article.

The problem of the formation of γ-radiation in nuclear reactions is discussed separately. On the one hand, the release of ^4He unlike the reactions at high velocities is not accompanied by the emission of γ-quanta. This can also be explained by the fact that a reaction (4) occurs in solid solutions of metals and deuterium, at which theγ-quantum is not released. On the other hand, in a number of papers [2], the emission ofγ-quanta is reported. Apparently, these γ-quanta are formed in secondary reactions involving nuclear reaction products.

It is known that in solid solutions of metals and deuterium deuterons are in some positions in the crystal lattice of a metal [17]. Diffusion of deuterons in a solid solution is the tunneling of deuterons between different minima of the crystalline potential. However, under certain external conditions, one can expect the appearance of delocalized deuterons in a solid solution. In particular, the appearance of delocalized deuterons can occur in the situation when a solid solution of metal and deuterium is an electrode in the electrolysis of heavy water. A large flux of deuterons across the surface of the electrode under the conditions of electrolysis creates an excess of the deuteron concentration near the surface, as a result of which deuterons do not have time to occupy positions in the crystal lattice and become delocalized.

In Ref. [3], as a method of excitation of the deuteron subsystem, X-ray radiation and a beam of electrons with an energy of 30 keV are used. Both the first and second effects can lead to the excitation of deuterons in the minima of the crystalline potential and their transition to a delocalized state. Obviously, both the energy of the X-ray quantum and the energy of electron of 30 keV exceed the potential barrier between the different minima in the potential energy of deuterons. The fact that under the action of X-rays and electron beams delocalized deuterons are formed, is confirmed by intensive migration and the yield of deuterons from solid solutions,which have been observed in a number of works [3].

Delocalized deuterons in solid solutions of metals and deuterium will be described by Bloch wave functions, and by analogy with electronic states in a solid, the state spectrum of delocalized deuterons will be described by a certain $\varepsilon(\boldsymbol{k})$ dependence. We shall assume that near the minimum of the $\varepsilon(\boldsymbol{k})$ dependence, the energy of delocalized deuterons is described by a parabolic law

$$\varepsilon(\mathbf{k}) = \frac{\hbar^2}{2m^*}(k_x^2 + k_y^2 + k_z^2) \qquad (5)$$

The problem of Bose condensation of delocalized deuterons with energy described by the dependence (5) reduces to the problem of Bose condensation of an ideal boson gas. As is well known, the phenomenon of

Bose condensation of an ideal gas of bosons is that at a temperature

$$T < \frac{3.3}{(2S+1)^{2/3}} \frac{\hbar^2}{km^*} n^{2/3} \qquad (6)$$

part of the bosons will be in a state with zero momentum. In formula (6), S is the particle spin, and n is concentration of the particles. Thus, the Bose condensation of delocalized deuterons ($S = 1$) will occur at a temperature T_0 if the effective mass of delocalized deuterons satisfies the condition

$$m^* < 1.5 \frac{\hbar^2}{kT_0} n^{2/3} \qquad (7)$$

Using the magnetudies of $T_0 = 300\,K$, $n = n_d^{del} + n_s = 10^{22} sm^{-3}$, where n_d^{del} is the concentration of delocalized deuterons not participating in superfluid motion, n_s is the Bose-condensate deuterons (superfluid deuterons) concentration, we obtain the estimate

$$m^* < 2 \cdot 10^{-26} g \approx 0.006\, m_d \qquad (8)$$

As is well known, delocalized electrons and holes in solids can have effective masses on the order of one-hundredth of the electron mass. Consequently, the conclusion about the possibility of formation of Bose condensate of delocalized deuterons at room temperature in principle does not contradict the basic ideas of solid state physics.

The Bose condensate of delocalized deuterons can be considered by analogy with the Bose condensate of atoms ^4He and other similar systems. In the framework of the two-fluid model, the total deuteron concentration in a solid solution of metal and deuterium will be represented in the form

$$n_d = n_d^{lat} + n_d^{del} + n_s \qquad (9)$$

where n_d^{lat} is the concentration of deuterons in some positions in the crystal lattice.

The wave function of the Bose condensate of delocalized deuterons can be written the standard way:

$$\Psi = \sqrt{n_s} e^{i\Phi(\mathbf{r})} \qquad (10)$$

When calculating the properties of the Bose condensate in a magnetic field, we will assume that $\Phi(\mathbf{r}) = \mathbf{\Phi_0} = \mathrm{const}$. Then in an external magnetic field with a vector potential $\mathbf{A}(\mathbf{r})$, the Bose condensate particles will move with the velocity $\mathbf{v}_s$ determined by the integral equation

$$en_s v_{si}(\mathbf{r}) = -\int Q_{ik}(\mathbf{r}-\mathbf{r}') A_k(\mathbf{r}') d^3r' \qquad (11)$$

The kernel $Q_{ik}(\mathbf{r}-\mathbf{r}')$ of the integral operator is determined from the microscopic analysis of the Bose-condensed state.

The nuclear reaction of d-d-synthesis occurs when one of superfluid deuterons collides with a deuteron that does not participate in superfluid motion. The problem of overcoming the Coulomb barrier is solved by the fact that the superfluid deuteron belongs to the Bose condensate, whose wave function is coherent. Bose condensate particles move in phase, and the kinetic energy of the Bose condensate is much greater than the energy of the Coulomb repulsion of two deuterons.

The probability of d-d-reaction in the collision of a superfluid deuteron and a deuteron not participating in superfluid motion is determined by nuclear factors. At the moment, the theory of the interaction of nuclei in collisions occurring at low velocities is not developed. Therefore, it will be assumed that the probability of a nuclear reaction in the collision of two deuterons does not depend on the relative velocity of the colliding particles. Then the intensity of the nuclear reaction will be determined by the velocity of the superfluid motion.

The intensity of the nuclear reaction will be determined by the relative velocity of the colliding deuterons. We assume that deuterons that do not participate in superfluid motion are immobile in the lattice. Then the intensity of the nuclear reaction will be determined by the velocity $\mathbf{v_s}$ of the superfluid motion. The velocity of superfluid motion, as is well known, is determined by the integral dependence (11).

Obviously, the velocity of superfluid motion is determined by the vector potential $\mathbf{A}$ of the external magnetic field, and, as a consequence, the intensity of the nuclear reaction will depend on the external magnetic field. Then the dependence of the power released during the nuclear reaction on the magnitude of the vector **B** of the external magnetic field $W(B)$can be represented as a series of B. Below we show how one can obtain a linear term in this dependence.

Proceeding from the proposed picture of the course of the nuclear reaction, it is possible to understand why reactions (4) predominate in CF. At low relative velocities of deuterons, it is more advantageous for them to combine precisely into the nucleus ^4He. In addition, the relative probabilities of reactions (1) - (3) at high speeds are determined by the laws of conservation of energy and momentum. In a collision at a low velocity, the conservation laws of energy and momentum can be satisfied by taking into account the motion of one nucleus ^4He and participation of the Bose-condensate in collision process. Also, due to these considerations, one can understand the fact that the γ-quantum is not released during the course of the reaction (4).

The power released during the nuclear reaction is

$$W = \int_{V_0} P(\mathbf{r}) \cdot \nu(\mathbf{r}) \cdot E_{\mathbf{0}} \cdot d\mathbf{r} \qquad (12)$$

where $P(\mathbf{r})$ is the probability of a nuclear reaction in the collision of one superfluid deuteron and deuteron not participating in superfluid motion, $\nu(\mathbf{r})$ is the collision frequency of such deuterons per unit volume, E_0 is the energy release in the nuclear reaction. When estimating the released power in order of magnitude, we will not be interested in what channel the $d-d$-reaction goes by. In a more detailed analysis, in formula (12) it is necessary to carry out summation over all reaction channels. The integration in (12) is carried out over the entire volume of the sample in which the nuclear reaction proceeds. Both the probability of the nuclear reaction $P(\mathbf{r})$ and the collision frequency $\nu(\mathbf{r})$ will depend on the velocity of the superfluid motion, and hence on the coordinates.

The quantity ν is computed in the classical approximation. We will assume that $n_s \ll n_d$. We represent ν as the collision frequency per unit volume of particles of two ideal gases.

$$\nu = n_s n_d \sigma \bar{v}_{rel} \qquad (13)$$

Here, $\sigma = 4\pi r_d^2$ is the effective collision cross section of two deuterons, $\bar{v}_{rel}$ is their relative velocity, which we will consider equal to the velocity modulus of the superfluid motion v_s. We assume that $P(\mathbf{r}) = P_0$. Then the integral (12) is represented in the form

$$W = P_0 n_s n_d \sigma E_0 \int_{V_0} \bar{v}_{rel}\, dV \qquad (14)$$

The quantity $\bar{v}_{rel} = v_s$ is obtained from the London electrodynamics equation for superconductors:

$$rot\mathbf{j} = -\frac{n_s e^2}{m^* c}\mathbf{B} \qquad (15)$$

As is known, London electrodynamics is the limiting case of the dependence (11) for

$$Q_{ik}(\mathbf{r} - \mathbf{r}') = \frac{n_s e^2}{mc}\delta(\mathbf{r} - \mathbf{r}')\delta_{ik} \qquad (16)$$

In this calculation, the kernel (16) is chosen for reasons of simplicity. It is fairly obvious that in the investigated case the dependence $Q_{ik}(\mathrm{r} - \mathrm{r}')$ will be more complicated than (16), however, at the present moment of the development of the research on CF it is impossible to make any statements about the form of the function $Q_{ik}(\mathbf{r} - \mathbf{r}')$. Meanwhile, as will be seen below, the approximation of London's electrodynamics makes it possible to obtain a linear term in the dependence $W(B)$.

Let us consider the energy release in a sample of cylindrical shape with a base radius r_0 and height h placed in a magnetic field $\mathbf{B}_0$ perpendicular to its base. Under these conditions, the non-zero projection **j** in cylindrical coordinates is j_θ, where θ is the angular coordinate. The solution (15) for j_θ is given in the form:

$$j_\theta = -\frac{n_s e^2}{m^* c} B_0 \lambda \exp\left(-\frac{r_0}{\lambda}\right) \exp\left(\frac{r}{\lambda}\right) \qquad (17)$$

Here $\lambda = \sqrt{m^* c^2 / 4\pi e^2 n_s}$ is the penetration depth of the magnetic field in the sample.

Current density

$$|j_\theta| = n_s e v_s \quad (18)$$

Then, using (14), we obtain

$$W = P_0 n_d \sigma E_0 \frac{1}{e} \int_{V_0} |j_\theta| dV \quad (19)$$

Using j_θ (17), we obtain finally the expression for the emitted power

$$W = P_0 n_d \sigma E_0 \frac{B_0 c}{2e} h \left(r_0 + \lambda \left(\exp\left(-\frac{r_0}{\lambda}\right) - 1 \right) \right) \quad (20)$$

Let us consider the case $h \gg r_0 \gg \lambda$. Then

$$W = 2\pi r_d^2 \frac{B_0 c}{e} h r_0 P_0 n_d E_0 \quad (21)$$

Thus, the power released in a cylindrical sample placed in a constant magnetic field is directly proportional to the magnitude B_0 of the magnetic field vector **B**. We can estimate the value of P_0 for the reaction (4) in order of magnitude from the results presented in the review [2]. We will assume that the motion occurs in the earth's magnetic field. We will assume that $E_0 \approx 23.4\, MeV$. We will assume that $B_0 \approx 0.5\, Gs$, $n_d \sim 10^{23} sm^{-3}, h = 10\, sm r_0 = 1\, sm$, $W \sim 10^9 erg/c$. Then we obtain the estimate

$$P_0 \sim 10^{-5} \quad (22)$$

It can be seen that for $n_s \sim 10^{22} sm^{-3}$ and $m^* = 0.006 m_d$, the approximation $r_0 \gg \lambda$ for the specified sample sizes is satisfied. Also, from formula (20) it is obvious that for $r_0 \sim \lambda$, formula (21) and estimate (22) change insignificantly.

The intensity of the reaction is obtained from formula (20) by dividing by E_0:

$$I = P_0 n_d \sigma \frac{B_0 c}{2e} h \left(r_0 + \lambda \left(\exp\left(-\frac{r_0}{\lambda}\right) - 1 \right) \right) \quad (23)$$

Accordingly, for $h \gg r_0 \gg \lambda$

$$I = 2\pi r_d^2 \frac{B_0 c}{e} h r_0 P_0 n_d \quad (24)$$

We estimate P_0 of the reaction (1) according to the results of [3]. We substitute in (24) the values of the quantities $B_0 \approx 0.5\, Gs$, $n_d \sim 10^{23} sm^{-3}$, $h = 10\, sm$, $r_0 = 5 \cdot 10^{-3} sm, I \sim 10^{-1}\, s^{-1}$. We obtain the estimate.

$$P_0 \sim 5 \cdot 10^{-18} \quad (25)$$

This estimate together with the estimate (22) shows that the products of reactions (1) and (2) are not observed in solid solutions in which reaction (4) can occur.

Let us dwell on the possibility of the reaction (4) proceeding in solid solutions of metals and deuterium. The laws of conservation of momentum and energy under the conditions of the flow of this reaction are as follows:

$$\sum_i \boldsymbol{p_i} = \boldsymbol{p} + \sum_{\boldsymbol{i}} (\boldsymbol{p_i} + m^* \Delta \boldsymbol{v_i}) \quad (26)$$

$$\sum_i \frac{p_i^2}{2m^*} + Q = \frac{p^2}{2m_{He}} + \sum_i \frac{(\boldsymbol{p_i} + m^* \Delta \boldsymbol{v_i})^2}{2m^*} \quad (27)$$

Here $\boldsymbol{p_i}$ are the momenta of the Bose condensate particles before the collision, $\Delta \boldsymbol{v_i}$ is the change in the velocities of the Bose condensate particles after the collision, $\boldsymbol{p}$ is the momentum of the nucleus ^4He, Q is the energy released during the nuclear reaction.

Laws (26) and (27) can be rewritten as:

$$\boldsymbol{p} + m^* \sum_i \Delta \boldsymbol{v_i} = \boldsymbol{0} \quad (28)$$

$$Q = \frac{p^2}{2m_{He}} + \sum_i (\boldsymbol{p_i} \cdot \boldsymbol{\Delta v_i}) + \frac{m^*}{2} \sum_i (\Delta \boldsymbol{v_i})^2 \quad (29)$$

The law of conservation of momentum (28) can be fulfilled only if a large number of Bose condensate particles has changed its velocity. It can be seen that, in this case, in the law of conservation of energy (29), the second and third terms in the right-hand side will be small in comparison with the first.

Thus, reaction (4) is possible in solid solutions of metals and deuterium.

It can be expected that the criterion for the reaction (4) takes the form of inequality

$$N > N_{crit} \quad (30)$$

where N is the total number of Bose condensate particles. Accordingly, it can be expected that, under the experimental conditions considered in the review [2] and in other papers on CF [4-7], criterion (30) is satisfied, and under the experimental conditions described in [3] this criterion is not satisfied.

The assumption made in the work about the transition of a part of the deuterons in a solid solution of a metal and deuterium to a superfluid state can explained in principle the very nature of the Coulomb barrier overcoming between two deuterons and such features of the experiments on CF as the predominance of ^4He among nuclear reaction products. It also is important to note that the obtained estimate of the power released in the earth's magnetic field coincides in order of magnitude with the results of calorimetric measurements under the conditions of the processes of the CF. Proceeding from the assumption about the small effective mass of delocalized deuterons, made in the work one can understand why the course of d-d-reactions is observed only in palladium and titanium. Apparently, the effective mass of delocalized deuterons in them is small.

The description of the properties of delocalized deuterons certainly faces a number of difficulties.In contrast to the case of electrons, an adiabatic approximation is not applicable to delocalized deuterons. Calculation of the function ε(k) of delocalized deuterons involves great difficulties, since it is required to take into account the interaction of delocalized deuterons with metal nuclei, deuterons in positions in the crystal lattice, and electrons.

It can be noted that the dependence of the energy release on the external magnetic field obtained in the work gives an unambiguous method for the experimental determination of the truth of the proposed mechanism of the nuclear reaction. Obviously, in addition to the output power, the fluxes of nuclear reaction products will also depend on the magnitude of the external magnetic field. It can also be assumed that in sufficiently strong magnetic fields one can observe the levitation of a sample in which a nuclear reaction proceeds.

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