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Solid state modified nuclear processes

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Abstract. It is theoretically shown that an attractive effective potential is generated via optical phonon exchange between two quasi-free, different particles in deuterated Pd which, in turn, enhances the probability of their nuclear fusion reaction. Mechanisms, that may be responsible for extra heat production and nuclear isomer formation, are also discussed. Creation of ^{4}He pairs due to the significantly increased probability of the p $+^7$Li $\rightarrow 2\,^4$He + 17.35 MeV and d $+^6$Li $\rightarrow 2\,^4$He + 22.37 MeV nuclear reactions is predicted. Some of the basic questions of fusion reactions in solids seem to be successfully explained.

PACS. 63.90.+t Other topics in lattice dynamics – 25.60.Pj Fusion reactions – 23.20.Nx Internal conversion and extranuclear effects

1 Introduction

At the beginning of this decade in several experimental works [1,2] solid state environment dependent increment of the cross section of low energy fusion reactions was observed. The full, theoretical explanation of this so-called "screening effect" still seems to be missing. Also, it was about two decades ago that Fleishmann and Pons [3] first published observation of a phenomenon that is today called "cold fusion". The experimental situation seemed rather controversial and the observations were considered contradictory to basic features of nuclear processes that are thought to be related to the effect [4,5]. Recently, however, in a sequence of experimental works [6,7] evidence of tracks of fast charged particles was found, that were emitted from nuclear fusion events in Pd/D during electrolysis and it seems experimentally proved [6] that alpha particles of energy between 11–16 MeV and protons of energy of 1.6 MeV were emitted from palladium chatode.

Parallel with the experimental efforts we have got two theoretical findings of possible importance in understanding the influence of dense (e.g. solid state) matter environment on low energy nuclear fusion reactions. In [8] we found that in a solid (deuterized Pd) optical phonon exchange leads to an attractive potential between quasi-free fusionable particles (between two quasi-free deuterons). The attraction increases with the increase of the relative deuteron content in the host material and it may have a dramatic effect on the low nuclear fusion rate mainly determined by the strong Coulomb-repulsion. In [9] it was shown that in a solid material nuclear fusion reactions can take place in the so-called solid state internal conversion process (SS-ICP) generating (in general a bound-free) transition of any charged particle by electromagnetic interaction. In this process some ordinary products (such e.g. γ particles) of the fusion reaction are missing and some energy is taken off by the accelerated particle (e.g. electron or in case of d–d reaction a third deuteron).

Applying and extending our results we address here a number of the basic questions and contradictory observations of solid state modified nuclear fusion phenomena and show that some of them may now be successfully explained. As a result, hopefully more informative and decisive experiments can be devised.

2 Nuclear fusion rate in solids

In a solid the nuclear reaction rate $\lambda_f = A\left|\Psi\left(0\right)\right|^2$ [10] where A is the nuclear reaction constant, (e.g. for the $\mathrm{d}+\mathrm{d} \rightarrow \mathrm{He}+\gamma$ reaction its value $A_{d-d} = 1.48 \times 10^{-16}$ cm^3 s^{-1} [11]) and $\Psi\left(0\right) = Be^{-G_w/2}$ is the value of the wave function of the two fusing particles in relative coordinate at zero separation (at $r = 0$) with B as normalization constant. Accordingly the rate of the nuclear fusion of two charged nuclei is proportional to the Gamow-factor $\exp\left(-G_W\right)$ [12], the characteristic quantity of tunneling through the Coulomb-barrier with

$$G_W = \sqrt{\frac{8\mu}{\hbar^2}} \int_R^{b_W} dr \sqrt{V(r) - E_{rel}}, \tag{1}$$

where $V(r)$ is the interaction potential between and μ is the reduced mass of the two fusing particles. E_{rel} is the

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energy of their relative motion, r is their distance, R is the radius of the nucleus of higher nucleon number and b_W is the other classical turning point.

In [13] and [14] it was shown for deuterons localized in interstitial sites that the probability of getting close enough to be able to fuse is too small. This result was tacitly extended to all deuterons contained in metals. We however found [8] that phonon exchange of each branch between quasi-free deuterons moving in a Pd crystal lattice partly filled with deuterons leads to an interaction potential $V_{ph}(r)$ that can become attractive for small distances with increasing $u = n_d/n_{ion}$, the deuteron-density fraction i.e. deuteron number density n_d over metal ion number density n_{ion}. Thus the interaction potential $V(r) = V_{Coul} + V_{ph}(r)$, that has to be substituted into G_W, where $V_{Coul} = z_1 z_2 e^2/r$ is the repulsive Coulomb-potential and $V_{ph}(r)$ is the spherically symmetric part of the phonon exchange induced potential. z_1 and z_2 are the charge numbers of the fusing nuclei. For deuterons $z_1 = z_2 = 1$. In [8] $V_{ph}(r) = U_O(r)$ is supposed, where $U_O(r)$ is the spherically symmetric part of the attractive potential created by optical phonon exchange as, according to the calculations, the dominant contribution to the potential is made by optical phonons. The shape and depth of $U_O(r)$ is very sensitive to the change of parameters u and $N(E_F)$, that is the density of electron states at the Fermi energy. As $b_W \gg R$ the well known approximation [12] of G_W can be applied that gives

$$G_W = 2\pi z_1 z_2 \sqrt{\frac{\mu}{m}\frac{R_y}{|U|}}. \tag{2}$$

In obtaining (2) the following approximations were used. The attractive potential is effective for $E_{rel} = 0$. Furthermore for $r < b_W$ $U_O(r) \simeq U_O(0) \equiv U$. If we neglect the u dependence of B then the u dependence of λ_f reduces to the u dependence of the Gamow-factor. The Gamow-factor strongly increases with the increasing concentration (u) of bound deuterons in the essential range. It can reach unexpectedly high values, and above $u = 1$ its hindering effect may practically disappear for particles of the same $E = \hbar\omega_O$ (where $\hbar\omega_O$ is the optical phonon energy and E is the kinetic energy of the quasi-free particles in the band. For the optical modes of PdD_u the $\hbar\omega_{\mathbf{q},\lambda} = \hbar\omega_O$ is an acceptable approximation, where $\hbar\omega_{\mathbf{q},\lambda}$ is the energy of a phonon with wave number vector $\mathbf{q}$ in the first Brillouin zone and λ is the branch index [15]). Figure 7 of [8] depicts the function $-G_W/\ln(10)$ vs. u at $E = \hbar\omega_O$ [16]. So with increasing u the hindering in the nuclear fusion by the Gamow-factor diminishes.

The calculated huge increase of the Gamow-factor with increasing u may solve the puzzle how (quasi-free) deuterons could be able to fuse getting through by tunneling the potential barrier the width of which is decreasing as u increases. As a consequence, the alleged high rate of nuclear fusion at near room temperature at about $u = 2$ in Pd (reported in [3]) does not seem impossible and the statement that their fusion reaction is impossible is in doubt. Also, the seemingly negative observation of [17], that earlier seemed to strengthen the rejection of the possibility of cold fusion, tallies with our results as the experiment was carried out at $u = 0.6$ where the Gamow-factor is still so small that no effect was to be expected. (The value of u is missing from most of the experimental reports, a fact that can be partly responsible for the confused situation.)

The formula (2) of G_W can be compared to

$$G_W = 2\pi z_1 z_2 \sqrt{\frac{\mu}{m}\frac{R_y}{E_{rel}}}, \tag{3}$$

that is applicable in a hot plasma of temperature $kT = \langle E_{rel} \rangle$ for particles colliding with relative energy E_{rel}. Accordingly an equivalent temperature $kT_{eq} = |U|$ may be introduced. For the d–d fusion reaction of particles of the same $E = \hbar\omega_O$, at $u = 1$ the equivalent temperature $T_{eq} = 3.7 \times 10^6$ K and at $u = 2$ the equivalent temperature $T_{eq} = 8.3 \times 10^7$ K. Thus we can conclude that a PdD_u solid at near room temperature may be equivalent in its effect on nuclear fusion reactions with a very hot plasma.

3 Optical phonon exchange induced attraction between different particles: p–d, ^{7}Li–p and ^{6}Li–d fusion reactions

Our model for the attractive interaction potential produced by phonon exchange [8] may be extended to the case of the interaction of two different quasi-free particles of wave vector $\mathbf{k}_1$ and $\mathbf{k}_2$, respectively. Following standard methods [18], one can obtain the interaction potential due to phonon exchange in the λth branch in $\mathbf{K}$ space as

$$V_{ph}(\mathbf{K},\lambda) = |g(\mathbf{K},\lambda)|^2 \hbar\omega_{\mathbf{q},\lambda} \left(D_1(\mathbf{k}_1) + D_2(\mathbf{k}_2)\right), \tag{4}$$

where $\mathbf{q}$ is the wave number vector in the first Brillouin zone ($\mathbf{K} = \mathbf{q} + \mathbf{G}$ outside the first Brillouin zone, where $\mathbf{G}$ is a vector of the reciprocal lattice). $g(\mathbf{K},\lambda)$ is the particle-phonon coupling function, as given in [8]. $\lambda = 4, 5, 6$ for the optical branches, and

$$D_j(\mathbf{k}_j) = \frac{1}{\Delta E_j(\mathbf{k}_j, \mathbf{K})^2 - (\hbar\omega_{\mathbf{q},\lambda})^2}, \tag{5}$$

for $j = 1, 2$ with $\Delta E_j(\mathbf{k}_j, \mathbf{K}) = E_j(\mathbf{k}_j) - E_j(\mathbf{k}_j + \mathbf{K})$. Here $E_j = \hbar^2\mathbf{k}_j^2/(2M_j)$ is the kinetic energy in the corresponding band and M_j is the rest mass of the particle. The effect of electrons are taken into account in an indirect way through the dependence of $g(\mathbf{K},\lambda)$ on the static dielectric function $\epsilon(K) = 1 + L_0^2/K^2$, where $L_0 = \sqrt{4\pi e^2 N(E_F)}$ is the shielding parameter [19,20]. The interaction is attractive if $|\Delta E_j(\mathbf{k}_j, \mathbf{K})| < \hbar\omega_{\mathbf{q},\lambda}$. Similar attractive potential due to phonon exchange between electrons is known to be responsible for superconductivity [21]. For heavier particles, because of their much larger rest mass, the inequality is fulfilled in a much larger range of $\mathbf{K}$, therefore the attraction is expected to be much stronger than in the case of electrons.

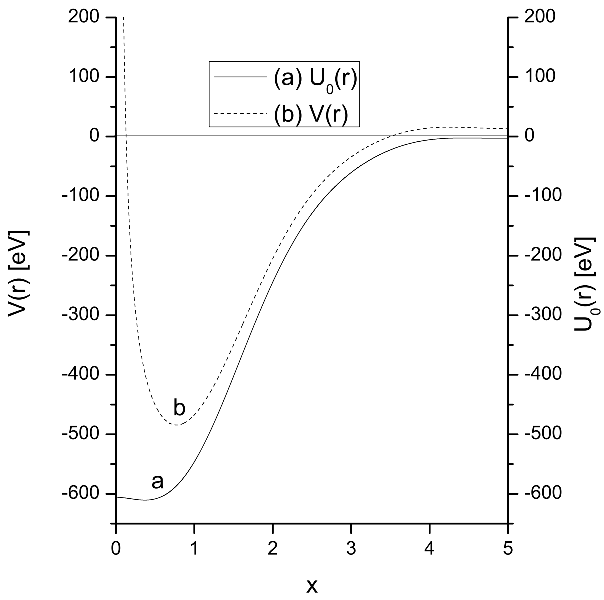

Fig. 1. (a) Spherically symmetric part $U_O(r)$ of the attractive potential created by optical phonon exchange between quasi-free deuteron and proton in deuterated Pd in eV units at $E_1 = E_2 = \hbar\omega_O$, $u = 1$ (u is the deuteron-density fraction, $u = n_d/n_{ion}$ the deuteron over metal ion number density), and $N(E_F) = 5.67$ states/rydberg/elementary cell. $N(E_F)$ is the density of the electron states at the Fermi energy, $E_1 = E_2$ is the kinetic energy of the particles in the band ($\hbar\omega_O = 0.0311$ eV is the energy of the optical phonon exchanged, [15]. $x = r/(s_0 a_0)$, a_0 is the Bohr radius, r is the radial distance and $s_0 = 0.345$). (b) The spherically symmetric, total potential $V(r) = V_{Coul} + U_O(r)$ in eV units. The shielding in the Coulomb potential is neglected. (For more details see the text and [8].)

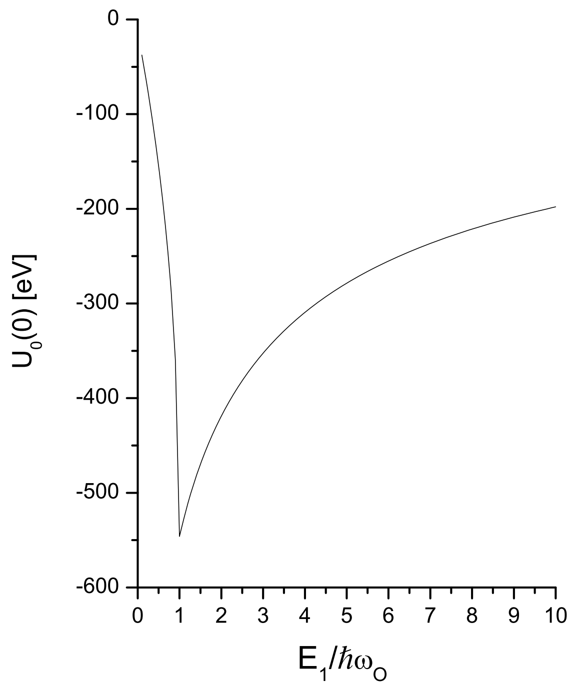

Fig. 2. The $E_1(= E_2)$ dependence of the depth $U_O(0)$ of the optical phonon exchange induced interaction potential in eV units in the case of the p–d process at $u = 1$. $E_{ph} = \hbar\omega_O$ is the energy of the optical phonon. For other parameters see Figure 1.

We demonstrate the basic features of our result in Figure 1 (curve (a)) that shows the spherically symmetric part of the attractive p–d potential $U_O(r)$ created by optical phonon exchange at $u = 1$ with $E_1 = E_2 = \hbar\omega_O$ [16]. If one compares Figure 1 (curve (a)) with Figure 3 of [8] one can recognize that the p–d interaction potential is significantly deeper than the d–d interaction potential. We depict the shape of $V(r)$ in the case of $u = 1$ for p–d interaction in Figure 1 (curve (b)). (It has to be compared with Fig. 6 of [8].) The deeper potential well decreases the upper turning point compared with the case of d–d process. It should be stressed here again that the repulsive Coulomb-interaction is still present and it is dominant for $r < b_W$ as it can be seen from Figure 1 (curve (b)).

Figure 2 shows the $E_1(= E_2)$ dependence of the depth $U_O(0)$ of the optical phonon exchange induced interaction potential in the case of the p–d process. The deep, narrow negative peak at $E_1 = E_2 = \hbar\omega_O$ indicate that nuclear fusion reactions will be probable with initial states near $E_1 = E_2 = \hbar\omega_O$.

Figure 3 depicts the function $-G_W/\ln(10)$ vs. u modified by the optical phonon exchanged potential in the case of (a) d–d, (b) p–d, (c) p–^{7}Li and (d) d–^{6}Li interaction at $E_1 = E_2 = \hbar\omega_O$. One can see that with increasing u the hindering effect in the nuclear fusion by the Gamow-factor can practically diminish. The Gamow-factor of the p–d process is the highest one.

Curves (c) and (d) in Figure 3 show the u dependence of Gamow-factors modified by optical phonon exchange produced potentials in the case of p–^{7}Li and d–^{6}Li interactions. The increase of the corresponding Gamow-factors indicates that the

$$A + B \to 2\,^4\mathrm{He} + \mathrm{Q} \tag{6}$$

nuclear fusion reactions may also be possible. Here $A = \mathrm{p}$, $B = {}^7\mathrm{Li}(92.5\%)$, $Q = 17.35$ MeV, or $A = \mathrm{d}$, $B = {}^6\mathrm{Li}(7.5\%)$, $Q = 22.37$ MeV, corresponding to the two reactions, respectively. The natural isotopic abundance is given in the parenthesis. In these fusion reactions half the reaction-energy $(Q/2)$ is carried away by α particles, as their wave vectors ($\mathbf{k}_j$ and $-\mathbf{k}_j$) are opposite in the center of mass system. If these energetic α particles are created then they will be decelerated in a few μm distance converting their energy of nuclear origin into heat.

If the sample has some proton content, that was about 0.5% in the case of [3], then not only the rate of nuclear fusion but the type of the reaction can strongly depend on u. In order to show this, it is useful to introduce the ratio $\eta = \lambda_{f,\ p-d}/\lambda_{f,\ d-d}$ of the rates of the p–d and d–d reactions. If we use $\Psi(0) = Be^{-G_w/2}$ and neglect the u dependence of B then η can be estimated as $\eta = \eta_A \rho$ with $\eta_A = A_{p-d}/A_{d-d}$ and $\rho = \exp(-G_{W,\ p-d})/\exp(-G_{W,\ d-d})$. From [11] $A_{p-d} = 5.2 \times 10^{-22}\ \mathrm{cm^3\,s^{-1}}$ and $A_{d-d} =$

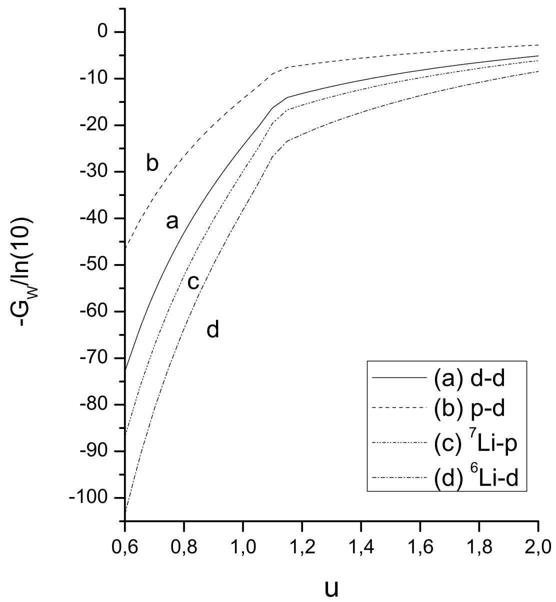

Fig. 3. Function $-G_W/\ln(10)$ vs. u at $E_1 = E_2 = \hbar\omega_O$ in the case of the (a) d–d, (b) p–d, (c) $^7\mathrm{Li} + \mathrm{p} \rightarrow 2\ ^4\mathrm{He}$, and (d) $^6\mathrm{Li} + \mathrm{d} \rightarrow 2\ ^4\mathrm{He}$ nuclear fusion processes. u is the deuteron-density fraction. (For other notation see Fig. 1.)

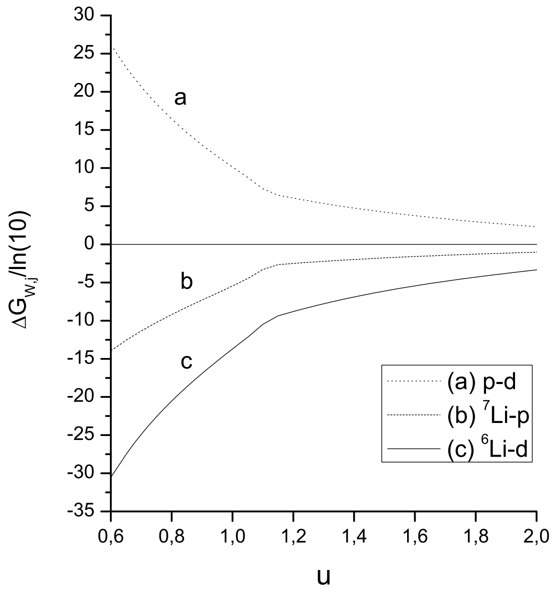

Fig. 4. Function $\Delta G_{W,j}/\ln(10)$ vs. u at $E_1 = E_2 = \hbar\omega_O$ in the case of the (a) p–d, (b) $^7\mathrm{Li} + \mathrm{p} \rightarrow 2\ ^4\mathrm{He}$, and (c) $^6\mathrm{Li} + \mathrm{d} \rightarrow 2\ ^4\mathrm{He}$ nuclear fusion processes. u is the deuteron-density fraction. (For other notation see Fig. 1.)

1.48×10^{-16} cm^3 s^{-1} that yields $\eta_A = 3.5 \times 10^{-6}$. In Figure 4 the u dependence of $\Delta G_{W,\ j}/\ln(10)$ is given, where $\Delta G_{W,\ j} = G_{W,\ d} - G_{W,\ j}$ with $G_{W,\ j}$ corresponding to the G_W of the jth process. We have found that $\Delta G_{W,\ j}/\ln(10) > 6$ for $u < 1.2$, thus the ratio $\rho > 10^6$ and therefore $\eta > 1$, i.e. in this range the p–d reaction is dominant, while for $u > 1.2$ the d–d reaction is the leading one. Thus we can conclude that at different values of u, if the sample has some proton content, different nuclear reactions can be dominant.

Although in [6] it is concluded "that LiCl is not essential for the production of pits" (for the production of traces of energetic charged particles) the curves (b) and (c) of Figure 4 indicate that in certain conditions the Li concentration may be essential.

Thus, generally the answer to the most essential question of how the particles can get through the Coulomb-barrier lies in the existence of the phonon exchange induced attractive potential. It causes a decrease in the width of the Coulomb-barrier and a corresponding exponentially large increase in the Gamow-factor that can allow for fusion reactions, if the deuteron concentration u is suitably high. This statement seems to be in agreement with the observation that the excess power increases with u in the $0.88 < u < 0.98$ range (see Fig. 2 in [22]) and also with the positive results of experiments of [6] for $u > 1$.

4 Solid state internal conversion process (SS-ICP): another key to excess heat and extra nuclear reactions

In [9] it was shown that if nuclear reactions take place in solids then they can also happen in the channel of the so-called SS-ICP. The graph of the SS-ICP is given in Figure 5. It shows that the nuclei A and B fuse into the nucleus C meanwhile they interact through the Coulomb interaction with any charged particle denoted by q(in) in the figure and induce its scattering to a state denoted by q(out). As a consequence the charged particle can take off energy and can help to fulfil energy and momentum conservation laws in the process. If fusion takes place in the SS-ICP channel then some of ordinary fusion products (such as e.g. γ particles) are missing.

We demonstrated the SS-ICP on the $\mathrm{p} + \mathrm{d} \rightarrow\ ^3\mathrm{He}\,(5\ \mathrm{keV})\ +\ \gamma\,(5.483\ \mathrm{MeV})$ nuclear reaction ($Q = 5.49$ MeV) [9]. We calculated the nuclear reaction constant of the SS-ICP of the reaction containing e.g. a bound-free deuteron transition $\left(\mathrm{p} + \mathrm{d} + (\mathrm{d}) \rightarrow {}^3\mathrm{He} + (\mathrm{d})\right)$. In this case the reaction energy Q is distributed among the outcoming $\mathrm{d}\left(\frac{3}{5}Q\right)$ and $^3\mathrm{He}\left(\frac{2}{5}Q\right)$ particles, so deuterons and ^{3}He particles of energy about 3.3 MeV and 2.2 MeV, respectively, are created. Comparing the obtained value of the reaction constant with the value of $A_{p-d,\ \gamma}$ in [11] one can conclude that even the reaction rate of this process is not to be neglected.

The SS-ICP of cold fusion channels may produce fast charged particles (deuterons, ^{3}He, α particles, Pd ions, electrons, etc.) that can partly take off the energy of the nuclear reaction and in their decelerating process they lose energy and transform it in several steps to heat. Radioactive isotopes [23] and ordinary fusion events may be produced in customary nuclear reactions by the energetic particles (e.g. by deuterons of energy 3.29 MeV produced in the above process if the sample has some proton contents). Moreover, repeating our train of thought for the case of $\mathrm{d} + \mathrm{d} \rightarrow\ ^4\mathrm{He}$ reaction α particles of energy up to

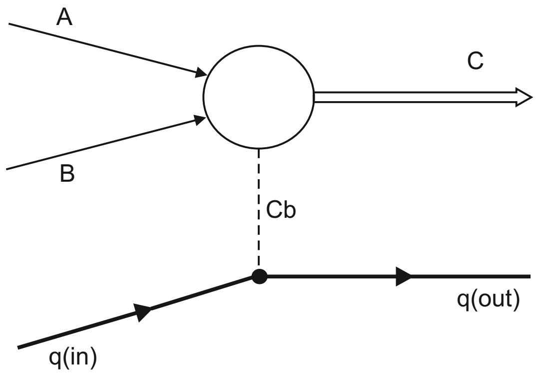

Fig. 5. Graph of SS-ICP. For the explanation see the text.

23.8 MeV may be expected if a Pd^{+2} ion participates in the bound-free transition of the SS-ICP. Moreover a decelerating, energetic charged particle created in SS-ICP may be the source of quasi-free (hot) deuterons, that can lead to further nuclear fusion events.

Observation of hot spots that erupt and then die on the surface of electrode can be explained as follows. The initial source of quasi-free particles, that reach the surface from the heavy water solution, is electrolysis. The flux of incoming free, fusionable particles creates the initial (cold) fusion event. It is accompanied by fast charged particles, that create further quasi-free (hot) particles in the decelerating process that can normally fuse too. A chain of fusion events is formed in this manner. The deceleration process of fast, charged particles, that heats the sample, takes place in a limited volume (the stopping length of energetic α particles is about 10^{-6} m) and it may accompanied by a great number of fusion events [24].

The cross section of the low-energy fusion reaction has energy dependence $\sigma(E) = S(E) \exp(-2\pi\eta)/E$, where $S(E)$ is the astrophysical factor and $\eta = e^2/\hbar v$ with v as the relative velocity of the particles (see e.g. [1]). In deuterated metals the cross section is influenced by electron screening since electron clouds surrounding the nuclei reduce the Coulomb-barrier decreasing the pure Coulomb-repulsion by an additional attractive potential U_e. Its effect can be taken into account adding it to the energy in the last two factors of σ. Thus U_e is characteristic of the surroundings (in our case the deuterated metal) of the fusion reaction. However measurements lead to so large experimentally fitted U_e values (e.g. $U_e \simeq 800 \pm 90$ eV for deuterated Pd. [1]) that can not be explained by electron screening.

The SS-ICP gives us a chance to explain some part of the enhancement of the fusion reaction rates obtained in the above mentioned experiments [1,2]. The qualitative explanation of this effect is the following. Fast deuterons (of energy of a few MeV), that were created in normal SS-ICP, are able to cause additional fusion events. Moreover, during deceleration the fast charged particles created in SS-ICP can transfer a part of their energy to deuterons located in the crystal creating additional fusionable particles of necessary kinetic energy and yielding further fusion events. Thus all these extra fusion events may responsible for the so called anomalous screening [1,2].

5 Summary

There is reason to believe that in solids at near room temperature particles are able to get through the Coulomb-barrier because of a phonon exchange induced attractive potential. It causes, if the deuteron concentration (u) reaches appropriately high value, a decrease in the width of the Coulomb-barrier resulting so large increase in the Gamow-factor that can bring the rate of fusion reactions up to observable magnitudes.

In the SS-ICP fast, charged particles are created that take off the energy of the fusion reaction and convert it to heat in their decelerating process. This may explain the observed correlation between He and excess heat production (see Fig. 6 of [22]).

Some of the charged particles created may have enough energy (e.g. of some 10 keV up to MeV order of magnitude) to enter an ordinary nuclear reaction including ordinary fusion reactions. Nuclear isomers found can also be created in that manner.

In order to induce low energetic fusion events and heat production the following should be considered.

(a) Deuterons of appropriately high concentration ($u > 1$) must be solved in metals and u should be well controlled in the experiments to come.
(b) Fusionable nuclei, e.g. a fraction of deuterons, introduced with electrolysis [3], by an accelerator [2] or from a gas discharge [25] must move quasi-freely (sometimes after some scatterings or deceleration) with kinetic energy E near to the appropriate value $E \sim \hbar\omega_O$, i.e. the distribution and change of E should also be under good control.
(c) The excess heat is thought to be produced in SS-ICP or sometimes in $p-{}^7Li$ and $d-{}^6Li$ fusion reactions.
(d) The proton and the Li ion concentration in the electrolyte may also have an essential role.

The two basic effects, the phonon exchange induced attractive potentials and the SS-ICP, that helped to understand some essential features of condensed matter modified nuclear fusion reactions, are based on standard solid state physics ideas, and no “exotic” mechanisms were called in throughout the paper at all. Although our work was partly motivated by the papers of [1–3,6] and [7] some of the reported phenomena of which we seemed to able to explain, our results themselves may have general importance of their own right.

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