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NUCLEI
Experiment

Cold Nuclear Fusion*

E. N. Tsyganov**

University of Texas Southwestern Medical Center at Dallas, Texas, USA

Abstract—Recent accelerator experiments on fusion of various elements have clearly demonstrated that the effective cross-sections of these reactions depend on what material the target particle is placed in. In these experiments, there was a significant increase in the probability of interaction when target nuclei are imbedded in a conducting crystal or are a part of it. These experiments open a new perspective on the problem of so-called cold nuclear fusion.

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1. INTRODUCTION

Experiments of Fleischmann and Pons made about 20 years ago [1], raised the question about the possibility of nuclear DD-fusion at "room" temperature. Conflicting results of numerous experiments that followed, dampened the initial euphoria, and the scientific community quickly came to the common belief that the results of [1] are erroneous. One of the convincing arguments of skeptics was the lack in these experiments of evidence of nuclear decay products. It was assumed that "if there are no neutrons, there is no fusion." However, quite a large international group of physicists, currently a total of about 100–150 people, continues to work in this direction. To date, these enthusiasts have accumulated considerable experience in the field. The leading group of physicists working in this direction, in our opinion, is the group led by Dr. M. McKubre [2]. Interesting results were also obtained in the group of Dr. Y. Arata [3]. Despite some setbacks with the repeatability of results, these researchers still believe in the existence of the effect of cold fusion, even though they do not fully understand its nature.

Some time ago we proposed a possible mechanism to explain the results of cold fusion of deuterium [4]. This work considered a possible mechanism of acceleration of deuterium contaminant atoms in crystals through the interaction of atoms with long-wavelength lattice vibrations in deformed parts of the crystal. Estimates have shown that even if a very small portion of the impurity atoms ($\sim 10^{-5}$) gets involved in this process and acquires a few keV of energy, this will be sufficient to describe the energy released in experiments [2].

This work [4] also hypothesized that the lifetime of the intermediate nucleus increases with decreasing energy of its excitation, so that so-called radiationless cooling of the excited nucleus becomes possible. In [5], we set out a more detailed examination of the process.

Quite recently, a sharp increase of the probability of fusion of various elements was found in accelerator experiments for the cases when the target particles are either imbedded in a metal crystal or are a part of the conducting crystal. These experiments have convinced us to look afresh on the problem of cold fusion.

2. RECENT EXPERIMENTS ON FUSION OF ELEMENTS IN ACCELERATORS

In contrast to the collision of "bare" nuclei, in the collision of atoms it is necessary to modify the formula for the probability of penetration through a potential nuclear Coulomb barrier, since the atomic electrons screen the influence of the nuclear charge. In the so-called Born-Oppenheimer static approximation the modification of isolated atomic collision was carried out by Assenbaum and others [6]. Using this approach, it was shown that the so-called "screening potential" acts as an additional energy of collision at the center of mass. It was concluded that the correction to the cross section of the fusion

$$\sigma(E) = S(E)E^{-1}\exp(-2\pi\eta(E))$$

due to the screening effect of atomic electrons could be calculated by introducing a so-called effective energy of interaction

$$E_{\text{eff}} = E + U_e,$$

where

$$U_e = e^2/R_{\text{a}}.$$

*The text was submitted by the author in English.

**E-mail: edward.tsyganov@utsouthwestern.edu

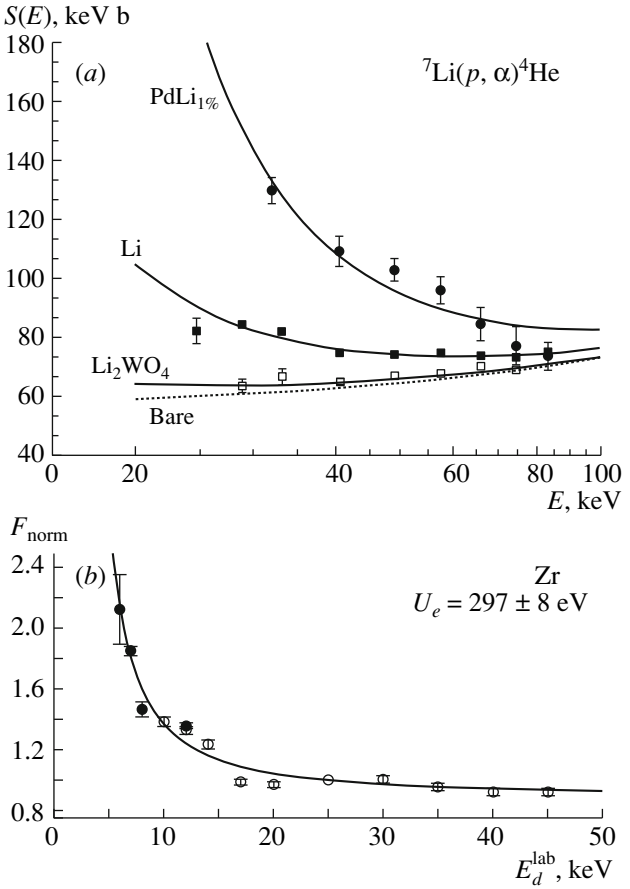

Fig. 1. *a*—experimental data [7], showing the energy dependence of the S-factor for sub-threshold nuclear reaction on the aggregate state of matter that contains the nucleus ^{7}Li. *b*—the same data [8] for the DD reaction, when the target is placed in a crystal of zirconium. F_{norm} value includes the experimental normalization of measured values. The data are well described by the introduction of screening Assenbaum potential of 297 eV.

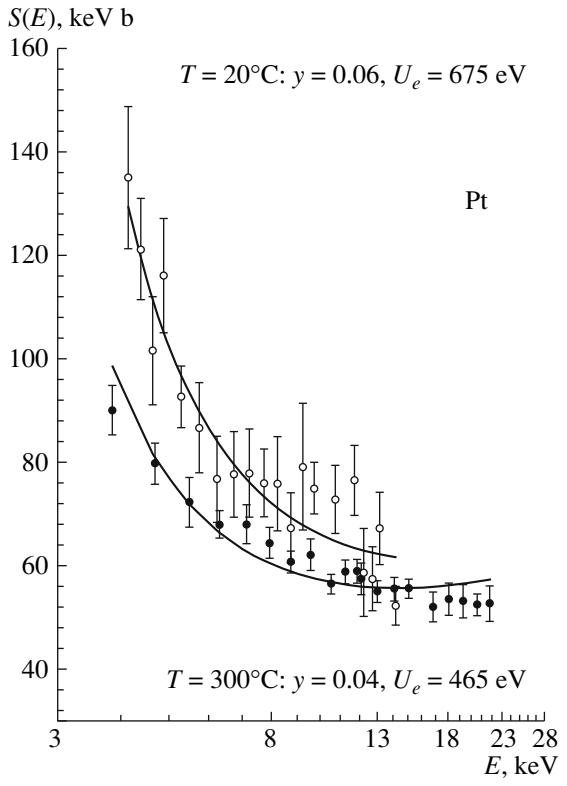

Fig. 2. Data for screening potential for DD fusion in platinum. The horizontal axis shows the kinetic energy of the deuterons, the vertical—the astrophysical factor. At room temperature screening potential of Assenbaum in platinum is 675 ± 50 eV.

Here R_a is the atomic radius. Apparently, this approach is probably equivalent to taking into account the thickness of the potential barrier for calculation of the quantum-mechanical penetration probability through potential barriers developed earlier (Ya.B. Zeldovich and S.S. Gershtein).

The experimental results that shed further light on this problem were obtained in relatively recent works of Rolfs [7], Czerski [8] and Raiola [9]. A review of papers on this subject is given in Bogdanova [10]. A somewhat unusual phenomenon was found in these studies: sub-barrier fusion cross sections of elements depend strongly on the physical state of the matter in which this fusion is taking place. Fig. 1*a* shows the experimental data [7], demonstrating the dependence of the astrophysical factor $S(E)$ for sub-threshold nuclear reaction on the aggregate state of the matter containing a target nucleus ^{7}Li. Fig. 1*b* presents similar data [8] for the reaction of DD, when the target deuterium is embedded in a crystal of zirconium.

Figure 2 shows the experimental data from Raiola et al. [9] of the measurement of the screening potential in platinum. The screening potential for the interaction of deuterium atoms in platinum was found to be 675 ± 50 eV, which is 25 times larger than for free atoms of deuterium. This may mean that in a crystal of platinum, atoms of deuterium do not feel the Coulomb repulsion up to distances of 25 times smaller than the size of the deuterium atoms themselves.

The physical nature of the increase in cross-section of the elements' fusion in the case when this process occurs in the crystal lattice of a conductor has not yet been elucidated fully. Obviously, this phenomenon is caused by the electric fields' anisotropy in the crystal lattice and by the excess of conduction electrons. Under these circumstances, the process of excitation and deformation of electron shells of the impurity atoms becomes possible, and the convergence of these atoms at a distance considerably smaller than the free atom sizes could happen. This process is rather chemical (catalytic) with little expending of energy. In this case the

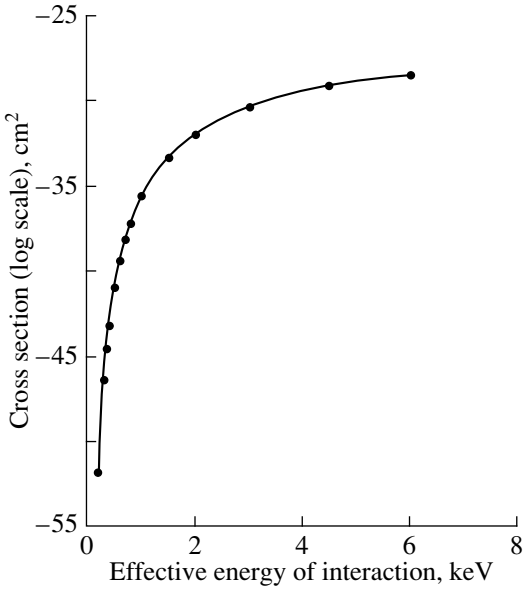

Fig. 3. Cross section of DD-fusion *vs* effective energy of interaction E_{eff}.

thickness of the Coulomb barrier between two nuclei of deuterium (or other contamination nuclei), when they occur in one crystalline cell, decreases, and the probability of penetration through the barrier rises dramatically. The strength of the process is shown in Fig. 3 which presents the cross section of DD-fusion *vs* the effective interaction energy E_{eff}. Here the total value of the astrophysical factor is assumed to be constant and equal to 100 keV b. Fig. 3 shows that the dependence for small values of the screening potential is very sharp. Points in the region of 3–6 keV illustrate the possible value E_{eff} for μ-catalysis, where, apparently, one cannot neglect the residual kinetic energy of deuterons. In the process of μ-catalysis it is necessary to take into account the energy of vibrations of the deuterons, which remains after the "compressing exchange" by the μ-meson.

It is natural to assume that the corresponding convergence distance between two deuterium atoms that are in the same cell of conducting crystal, in the case of the screening potential of 300–600 eV, is much smaller than the size of molecular deuterium. In the case of screening potential 300 eV deuterium atoms this distance would be $\sim 5 \times 10^{-12}$ m, which is about an order of magnitude smaller than the size of a molecule of deuterium, where the screening potential is 27 eV. Figs. 4*a* and 4*b* presents a sketch illustrating the physics of cold DD-fusion in a conducting crystal of palladium. The nuclei of deuterium atoms tend to occupy the center of the crystal cell; electrons are pushed to the periphery by the conduction electrons. Stable orientation of the electron orbit in the deuterium tied to the cell system. Perhaps, the combination shown in the Fig. 4*b* is energy preferable.

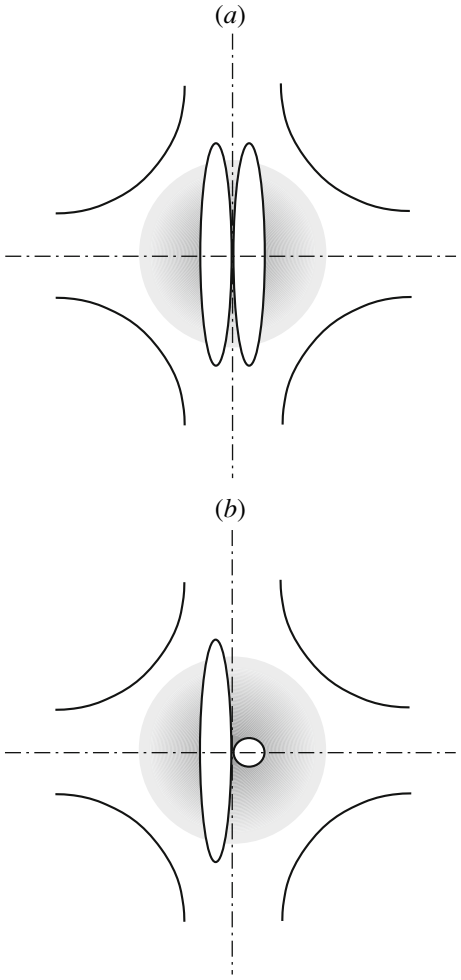

Fig. 4. Scheme of DD-fusion in the conducting crystal.

As it turned out, the rate of DD-fusion in these conditions is quite sufficient to describe the experimental results of McKubre and others [2]. Below is the calculation of the rate of the process which is similar to the μ-catalysis, when instead of μ-meson exchange interaction the factor that causes the two deuterons to converge is the effect of conduction electrons and the lattice of the metal crystal.

3. REACTION RATE CALCULATIONS FOR "METAL-CRYSTALLINE" CATALYSIS OF DD-FUSION

As noted above, the expression for the cross-section of synthesis of the two nuclei can be written as

$$\sigma(E) = \frac{S(E)}{E} e^{-2\pi\eta}, \tag{1}$$

where for DD fusion

$$2\pi\eta = \frac{31.4}{\sqrt{E}}.$$

Here the energy E is shown in the c.m.s. in keV; $S(E)$—astrophysical factor at low energies can be considered constant. The main energy dependence of the synthesis is contained in the expression $e^{-2\pi\eta}$ that determines the probability of penetration of the deuteron through the Coulomb barrier. From these expressions it is clear that in the case of DD-collision and in the case of DDμ-catalysis the physics is the same. We use this fact to determine the probability of DD-fusion in the case of "metal-crystalline" DD-catalysis, using experimental data on the DDμ-catalysis. This way we avoid the uncertainties associated with theoretical calculations.

In the case of DDμ-muon catalysis the size of a molecule of deuterium (+ion) is $\sim 5 \times 10^{-13}$ m. At such a distance deuterium nuclei approach each other at kinetic energy of $\sim$3 keV. After its formation, a μ-molecule keeps significant vibration energy before the nuclear fusion (this time interval is very short) and the intermediate nucleus is significantly excited. Uncertainty in the excitation energy of the intermediate nucleus after DDμ-catalysis currently presents a major uncertainty in the cold fusion rate in conducting crystals with the normalization by DDμ-catalysis. We chose to normalize the effective energy in the case of DDμ-catalysis to 4.5 keV, and we believe that the error in the cold fusion reaction rate obtained with this normalization will be not more than a factor of 10.

Using the expression (1), we found that the ratio of $\sigma(4.5\ \text{keV})/\sigma(0.3\ \text{keV}) = 1.93 \times 10^{17}$. It is interesting to note that the ratio for a free molecule of deuterium $[\sigma(4.5\ \text{keV})/\sigma(0.027\ \text{keV})]$ is about 2.2×10^{74}.

Hale [11] presents experimental estimates of the $(\text{DD}\mu)^+$ fusion rate for P-state (which is significantly lower than the rate of fusion for the S-state—our case.)[1)] Thus, we have:

$$\lambda_{f(4.5\ \text{keV})} \geqslant (4.1 \pm 0.1) \times 10^8\ \text{s}^{-1}.$$

Using the value of $\sigma(4.5\ \text{keV})/\sigma(0.3\ \text{keV})$, we get for "metal-crystalline" rate DD-fusion:

$$\lambda_{f(0.3\ \text{keV})} \geqslant 2.1 \times 10^{-9}\ \text{s}^{-1}.$$

Is this enough to explain McKubre experiments [2] on cold fusion? 1 cm^3 (12.6 g) of palladium contains $6.02 \times 10^{23} \times (12.6/106.4) = 0.7 \times 10^{23}$ atoms. The fraction of crystalline cells with two (or more) deuterium atoms with the ratio of D:Pd $\sim 1:1$, as is the case in the experiments [2], is $\sim$0.25 (e.g., for Poisson distribution). Crystal cells containing fewer than two deuterium atoms, we consider as "passive" in regard to a fusion reaction. Thus, the number of "active" cells of deuterium in 1 cm^3 of palladium is equal to 1.8×10^{22}. As for now, we ignore the fact that the mechanism may happen to be dependent on the orientation of the spin states of electrons of the deuterium atoms. In the 1 cm^3 of palladium the reaction rate will be

$$dN/dt \geqslant 1.8 \times 10^{22} \times 2.1 \times 10^{-9}\ \text{s}^{-1} \geqslant 3.8 \times 10^{13}\ \text{s}^{-1},$$

this corresponds to an energy release of over 150 watts. This is quite sufficient to explain the experimental results of McKubre [2].

The most promising option for practical applications would be to use platinum crystals for DD-fusion, where screening potential at room temperature is 675 eV. In this case the rate of DD-fusion is about eight orders of magnitude greater than in the case of palladium, and is

$$\lambda_{f(0.675\ \text{keV})} \geqslant 1.83 \times 10^{-1}\ \text{s}^{-1}.$$

Note added in proof: The DD fusion process in a cell of a crystal could be considered in terms of a deuterium quasi-molecule trapped in one crystalline cell. The rate of the fusion λ in such a system is a product of the barrier permeability P and the oscillation frequency ν of the quasi-molecule. Calculating the correct oscillation frequency of this quasi-molecule ν in a real crystal cell potential is quite a challenge. As an initial approximation, we considered the estimate $\nu \sim E/h$, where E is the experimentally measured screening potential. The following is based on this approach and provides direct estimates of the DD fusion rate for crystals of palladium, cobalt and platinum.

Crystal type	Screening potential U, eV	Oscillation frequency ν, s^{-1}	Barrier permeability P	Rate of DD fusion λ, s^{-1}
Palladium	300	0.74×10^{17}	1.29×10^{-25}	0.95×10^{-8}
Cobalt	640	1.58×10^{17}	8.99×10^{-18}	1.42
Platinum	675	1.67×10^{17}	2.52×10^{-17}	4.21

[1)] L.N. Bogdanova drew our attention on this circumstance.

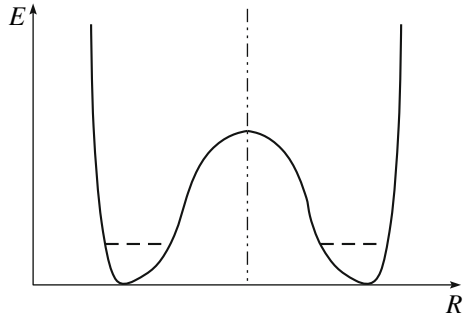

Fig. 5. Schematic illustration of the nuclear transitions frequency dependence in the compound nucleus ^{4}He* on the excitation energy of the fused deuterons. The diagram illustrates the shape of the potential well of the compound nucleus. The edges of the potential well defined by the strong interaction, the behavior at short distances is the Coulomb repulsion.

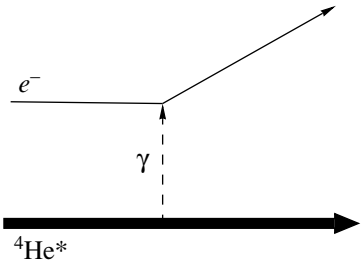

Fig. 6. Diagram of process providing "thermalization" of the DD-fusion in the crystals. Virtual photon is emitted by the compound nucleus ^{4}He*.

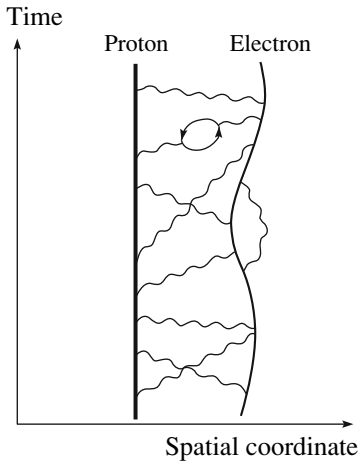

Fig. 7. The original Richard Feynman diagram illustrating the processes in the hydrogen atom.

4. THE PROBLEM OF "NON-RADIATIVE" ALLOCATION OF FUSION ENERGY

As we have noted, one of the paradoxes of DD fusion with the formation of ^{4}He in the experiments [2] was the virtual absence of conventional nuclear decay products of the compound nucleus. We have tried to explain this paradox in [4].

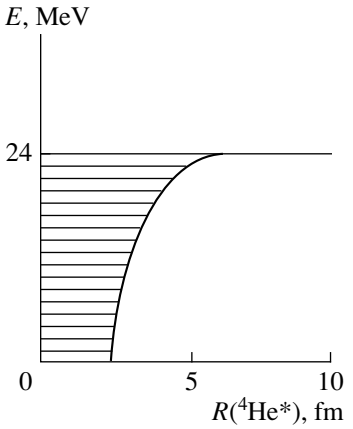

Fig. 8. Possible energy diagram of the excited ^{4}He*.

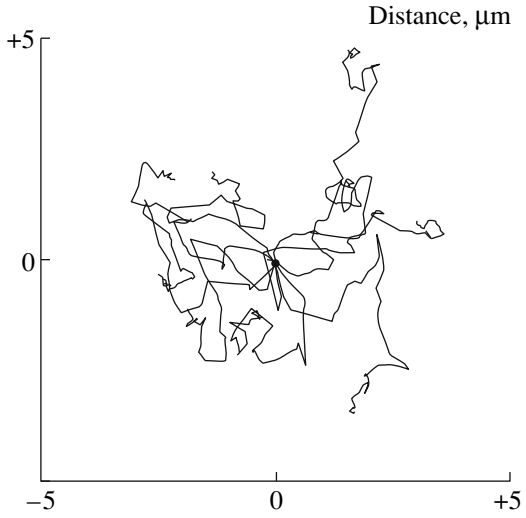

Fig. 9. The trajectories of the electrons, generated in the process of cold DD-fusion in palladium. Dimensions are in micrometers.

We believe, after penetration through the Coulomb barrier at low energies and the materialization of two deuterons in a potential well, these deuterons retain their identity for some time. This time determines the frequency of further nuclear reactions.

Fig. 5 schematically illustrates the mechanism of this process. After the penetration into the compound nucleus at very low initial energies, the deuterons are in a quasi-stable state, while in opposite potential wells. In principle, this system is a double "electro-nuclear" oscillator. In this oscillator, the total kinetic energy of the deuterons transfers to the potential energy of the oscillator, and vice versa. In the case of very low-energy excitation the amplitude of oscil-

lations is small and nucleon exchange reactions are suppressed.

The lifetime of the excited ^{4}He* may be considered in the formalism of the usual radioactive decay. In this case

$$N(t)/N_0 = e^{-t\nu}.$$

Here, ν is the frequency of the decay, i.e., the reciprocal of the decay time. According to our hypothesis, the decay rate ν is a function of the excitation energy of the compound nucleus E. Using only the first two terms approximation in the polynomials, we have:

$$\nu = \nu_0 + aE + \ldots$$

Here ν_0—describes frequency decay at asymptotically low excitation energies. According to quantum-mechanical considerations, the overlap of the deuteron wave function does not vanish completely with decreasing energy, as is illustrated by the introduction of this term. The second term describes the linear dependence of the expansion rate of decay of the excitation energy.

The characteristic nuclear frequency is usually about 10^{22} s^{-1}. As mentioned above, the fusion reactions D + D $\rightarrow$ ^{4}He has a broad resonance at about 8 MeV. Simple estimates of the width of the resonance and the uncertainty relation gives the lifetime of this intermediate state of about 0.8×10^{-22} s. This is an implementation of a "nuclear" reaction rate, which decreases approximately linearly with decreasing energy. This drop in the nuclear reaction rate has little effect on the ratio of output channels of the compound nucleus decay, but it does to a certain limit. After this limit the compound nucleus is no longer an isolated system, since virtual photons from the ^{4}He* can reach the nearest electrons and carry the excitation energy of the compound nucleus. Fig. 6 schematically shows a diagram of the transfer of excitation energy to the electrons of the crystal lattice. Angular momentum carried by the virtual photons can be zero, since it can be directed along the time axis, so this process is not forbidden for ^{4}He* with zero total angular momentum.

It is assumed that after a few exchanges of virtual photons with the electrons of the environment the relatively small excitation energy of the compound nucleus 4He* (the energy of two deuterons before the collision) practically vanishes. In this case, the serial exchange of virtual photons with the electrons of the environment for a time of about 10^{-16} s will lead to the loss of energy of the compound nucleus $\sim$4 MeV (after which decay with emission of nucleons is energetically forbidden). Then the entire energy of the compound nucleus (24 MeV) will be lost through virtual photon exchange, and the ^{4}He nucleus will be in the ground state. In the presence of a large screening potential in a conducting crystal, these processes naturally occur much faster. More information about the process can be provided with the calculations by quantum electrodynamics. Although these calculations are not trivial, they are thought to be an absolute necessity.

Figure 7 shows the original Feynman diagram [12], illustrating the processes providing the parameters of the hydrogen atom. We need to understand what changes will occur, if instead of a stable proton we use ^{4}He*. Similar calculations at the present time are also needed for the explanation of experiments on the anomalous muon electromagnetic form factor of the proton.

The mechanism of energy dissipation of the compound nucleus ^{4}He* with virtual photons naturally raises the question of the electromagnetic nuclear structure of the excited compound nucleus. Figure 8 illustrates a possible energy structure of the excited ^{4}He* and its changes in a spatial configuration of the system in the process of a dissipation of the excitation energy. The study of this process may be of interest in studying the quark-gluon dynamics and structure of the nucleus.

Figure 9 shows the trajectories of electrons produced in the process of energy dissipation of the excited ^{4}He* by virtual photons in a DD-fusion in palladium crystal, computed by the Monte Carlo simulation[2)]. This figure shows the trajectories of ten electrons with energy of 60 keV, resulting from the DD-fusion in palladium. We can see that the direct registration of the process, although difficult because of short ranges of emerging electrons, is not impossible. At present, we are discussing the set-up of this experiment.

5. DISCUSSION

Perhaps, in this long-standing history of cold fusion, finally the mystery of this curious and enigmatic phenomenon is gradually being revealed. Besides possible benefits that the practical application of this discovery will bring, the scientific community should take into account the sociological lessons that we have gained during such a long ordeal of rejection of this brilliant, though largely accidental, scientific discovery. We would like to express special appreciation to the scientists that actively resisted the negative verdict imposed about twenty years ago on this topic by the vast majority of nuclear physicists.

[2)]Figure is a courtesy of S.N. Lobastov

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