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The mechanism of DD fusion in crystals

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Summary. — This paper discusses the mechanism of DD fusion and the so-called nonradiative thermalization of the reaction in palladium crystals. Possible dynamics of this process are considered. The assumption that the decay time of the compound nucleus depends on its excitation energy makes experiments in crystals well compatible with the accelerator data.

PACS 25.45.-z – ^{2}H-induced reactions.

1. – Introduction

In 1989, Fleischmann and Pons reported observing the production of heat of non-chemical origin in a palladium electrochemical cell, saturated with deuterium [1]. The most complete data on this subject is given in the report of McKubre *et al.* [2]. Results of experiments on cold fusion in the past 20 years have been severely criticized by the nuclear physics community as non-scientific and contradictory to fundamental scientific facts. The main objections of the scientists focused on the apparent contradiction of the experiments on cold fusion to the absence of nuclear radiation in these experiments.

Recently, we described the hypothetical mechanism of DD fusion in crystals [3].

2. – DD fusion at low energies

Fusion of two ^{2}H nucleus into ^{4}He releases 24 MeV. This is the most efficient nuclear reaction.

A good overview of the fusion problem has been done by Fowler [4]. Salpeter [5] and Bethe [6] proposed to extrapolate the cross-sections for the fusion of two nuclei at low energies using the so-called astrophysical S-factor equal to the product of the reaction cross-section σ and the energy E of a particle in the center of mass, in order to avoid the singularity in the cross-section at low energies. Taking into account the probability

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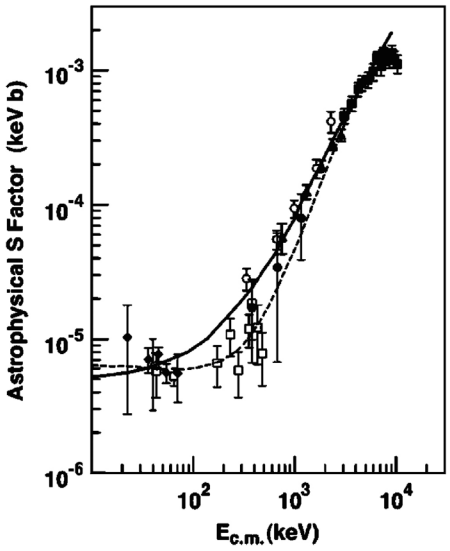

Fig. 1. – Data on DD-fusion with the formation of ^{4}He from Sabourov *et al.* [8]. The solid line shows the fit of all known data for the reaction $^2\mathrm{H}(\mathrm{d},\gamma)^4\mathrm{He}$, taking into account the radiative transitions $E2$, $E1$ and $M2$ by the model RRGM. The dotted line shows the fit when accounting only for the $E2$ transition.

of penetration of a particle through the Coulomb barrier (Gamow's factor), in the case of DD interaction

$$S(E) = E\sigma \cdot \exp\left[\pi \frac{e^2}{\hbar c}\sqrt{\frac{M_\mathrm{d}c^2}{E}}\right] = E\sigma \cdot \exp[31.41/\sqrt{E}]. \tag{1}$$

Here E is in keV. The main uncertainty in this lies in the choice of the M_d parameter, which depends on the radius of the compound nucleus, but this parameter is well defined by measurements made at accessible energies. $S(E)$ allows a more accurate extrapolation of experimental data to the region of very low energy, where direct measurement is impossible. In the case of pure S-wave the astrophysical function $S(E)$ must be constant.

The cross-section of DD interaction with ^{4}He production has a so-called broad resonance at energy of about 8 MeV [7]. The most complete data for the reaction $^2\mathrm{H}(\mathrm{d},\gamma)^4\mathrm{He}$ are given in Sabourov *et al.* [8]. Figure 1 show the data presented in [8]. This work also provides an analysis of all known data for the reaction $^2\mathrm{H}(\mathrm{d},\gamma)^4\mathrm{He}$. The Refined Resonating Group Model (RRGM) properly takes into account the scattering in the system of ^{4}He, using the variational principle with the inclusion of some specific models. The results are supported by good agreement between the calculated binding energies of deuteron and ^{3}H and the experimental values. One of the interesting results of this work is the evaluation of the astrophysical factor $\mathrm{D} + \mathrm{D} \to {}^4\mathrm{He}$ at zero energy, which is found to be $S(0) = 4.8 \times 10^{-6}$ keV b.

It seems interesting to compare the data obtained using particle beams with the experiments of McKubre *et al.* [2].

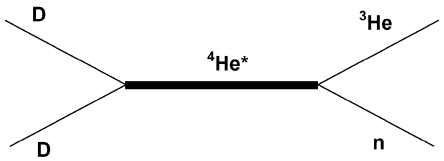

Fig. 2. – This diagram of the reaction $D + D \rightarrow {}^3He + n$ depicts the time involved in the process of ${}^4He^*$ decay.

3. – Decay of compound nucleus via nuclear channels

One of the paradoxes of DD fusion with the production of ^{4}He in crystals in experiments [2] is the apparent absence of the usual nuclear decay products of the compound nucleus.

Figure 2 of the $D + D \rightarrow {}^3He + n$ shows the process in a form that emphasizes the duration of the element ${}^4He^*$. This diagram was inspired by the Schrödinger equation containing the space-time coordinates in an explicit form.

It seems that in this process, a certain hierarchy of strong interactions is manifested. The peripheral nuclear field (pion exchange and so on) is strong enough to hold the two deuterons in the well of the strong interactions.

Figure 3 schematically illustrates the mechanism of this process. The dash-dotted line shows the boundary of the potential well. In principle, this system is a dual electromagnetic-nuclear oscillator. In the case of very low excitation energy, the amplitude of the oscillation of the deuterons is small, and the reaction of nucleon exchange is suppressed.

The stability of the excited compound nucleus ${}^4He^*$ can be considered in the formalism of the usual radioactive decay. In this case,

$$N(t)/N_0 = e^{-t\nu}. \tag{2}$$

Here ν is the decay rate, *i.e.* the reciprocal of average decay time τ. According to our hypothesis, the decay rate ν is a function of excitation energy of the compound nucleus E. Approximating with the first two terms of the polynomial expansion, we have

$$\nu = \nu_0 + aE + \ldots, \tag{3}$$

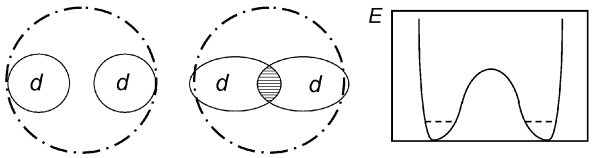

Fig. 3. – The dependence of the nuclear decay rate on the excitation energy for compound nucleus ${}^4He^*$ is illustrated. Left: dash-dotted lines show the boundaries of the potential wells. One diagram depicts the state of the compound nucleus for low excitation, and another diagram depicts the compound nucleus for higher energy. Right: a schematic illustration of the potential well of the compound nucleus ${}^4He^*$, the dashed lines represent the excitation energy.

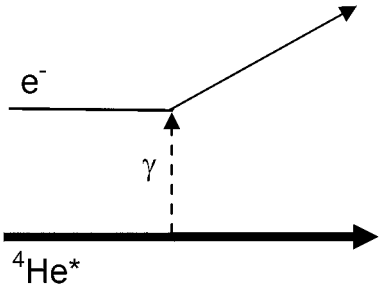

Fig. 4. – The diagram of the processes that provide thermalization of DD fusion reactions in crystals presented. Virtual photons are emitted by compound nucleus ^{4}He*.

where ν_0 is the decay rate at asymptotically low energy excitation. According to quantum-mechanical considerations, the overlap of the wave functions of the deuterons does not disappear completely with a decrease in energy, and this is illustrated by the presence of the ν_0 term. The second term characterizes the decay rate that depends on energy.

Characteristic nuclear rates are usually about 10^{22} per second. As mentioned above, the fusion reactions D + D $\rightarrow$ ^{4}He has the so-called "broad resonance" at the energy of about 8 MeV. In our approximation the rate of nuclear decays in our case is less than that at the resonance, and the corresponding decay time is about 0.2×10^{-18} s. Then the compound nucleus is no longer an isolated system, since virtual photons from ^{4}He* can reach the nearest electron and carry out some excitation energy of the compound nucleus. From the uncertainty relationship, the time of these processes is about 10^{-19} s. The process of the exchange by virtual photons without changing the total angular momentum, namely $E0$, known in nuclear spectroscopy and sometimes called photonless exchange [9]. We believe that after a few exchanges of virtual photons with the electrons of the environment, the decay rate of the compound nucleus with the emission of nucleons is determined only by the ν_0 term. We assume, for convenience, that this term is not more than 10^{12}–10^{14} per second. In this case, in about 10^{-16} seconds the virtual photons carry off $\sim$ 4 MeV, and then the remaining energy of the compound nucleus (20 MeV). After that, the nucleus ^{4}He is in the ground state. Full discharge can be completed in approximately 10^{-15} s.

Figure 4 illustrates the processes that provide thermalization of DD fusion reactions in crystals.

The mechanism of energy dissipation of the compound nucleus ^{4}He* with virtual photons, discussed above, naturally raises the question of the electromagnetic-nuclear structure of the excited compound nucleus. Figure 5 presents a possible energy structure of ^{4}He*. This figure illustrates schematically how the compound nucleus is compacted during the loss of excitation energy. This process could shed light on quark-gluon dynamics and nuclear structure.

4. – Estimates of the fusion reaction rate of deuterons in the crystals

As we pointed out earlier [3], our hypothesis is that at least some of the deuterium atoms which are impurities in the crystal lattice are not "settled" in certain niches of the lattice. Instead, these deuterium atoms travel almost freely along the axes of the crystal lattice.

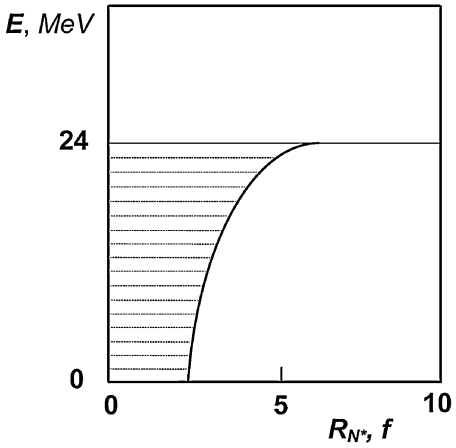

Fig. 5. – Presumable energy diagram of $^4He^*$.

A very unusual situation arises when atoms of deuterium are moving in a bent channel. When the crystal lattice experiences collective thermal vibrations, the particle moving in the bent channel experiences successive transverse kicks from a group of atoms of the lattice, and therefore absorbs momentum and energy from the lattice. This small "thermal acceleration" of the deuterium atoms, in our view, is one of the origins of deuterium fusion in crystals. Beginning of the ionization process puts limits on the energy gain in this course, and this occurs at about 50 keV.

The mechanism of possible thermal acceleration of moving deuterium contaminants is illustrated in fig. 6.

Based on the evaluation of the cross-section of the $D + D \rightarrow {}^4He$ reaction at low energies, given in Sabourov *et al.* [8], our calculations [3] give a value of about 2.5×10^{13} $D + D \rightarrow {}^4He$ reactions per second per $1\,cm^3$ of palladium in the experiments [2]. We assumed the effective energy of fast deuterons to be about 2 keV in the center of mass. Taking into account the fact that the parameters of the process are still largely uncertain, these estimates are considered very encouraging.

5. – Problem of electron shielding in fusion process and fusion in crystal conductors

For atom-atom collisions there is a shielding effect due to presence atomic electrons. A calculation of this effect has been done in a paper by Assenbaum *et al.* [10]. They

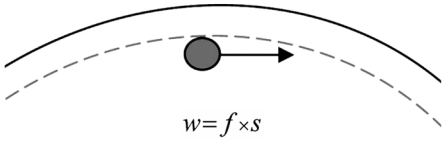

Fig. 6. – Swing effect. The energy gain is proportional to the average electrical field of a lattice and the transverse distance traveled by the atom.

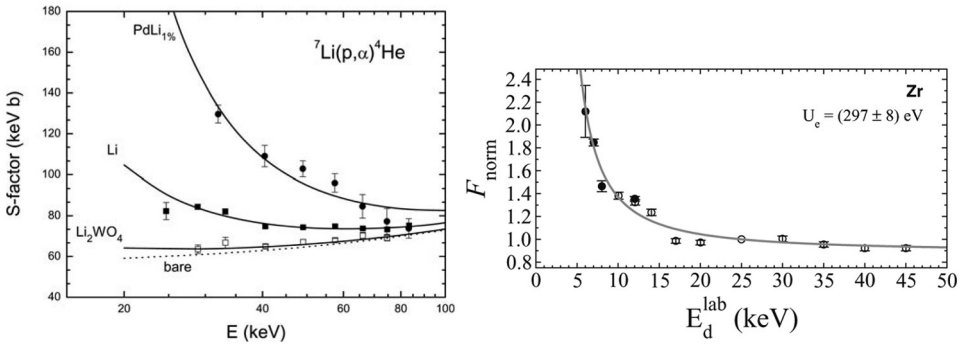

Fig. 7. – Left—experimental data [11], showing the energy dependence of the S-factor for sub-threshold nuclear reaction on the aggregate state of matter that contains the nucleus ^{7}Li. Right—similar data [12] for the reaction DD, when the target D is placed in a crystal of zirconium. The data are well described by the introduction of the single screening potential of about 300 eV.

studied the effect of electron shielding on the low energy cross-sections of nuclear fusion reactions within the Born-Oppenheimer approximation using a simplified static model. They supposed that the penetration through a shielded Coulomb barrier at projectile energy E is equivalent to that of bare nucley at energy $E_{\text{eff}} = E + U_e$. For reaction D + D and the energy of 27 eV the correction factor in a static model already reaches 1.7×10^{24}.

The experimental results that shed further light on this problem are presented in relatively recent works by Rolfs [11] and Czerski [12]. It was shown in these studies that sub-barrier cross-sections of fusion process for different elements strongly depend on the physical state of the matter in which these elements are embedded, and the static model definitely does not work. Figure 7, left, shows the experimental data [11], demonstrating the dependence of the astrophysical factor $S(E)$ of elements for sub-threshold nuclear reaction on the aggregate state of matter that contains the target nucleus ^{7}Li. Figure 7, right, shows the experimental data [12], demonstrating a similar dependence for DD fusion when the D-target is embedded in zirconium crystal.

We must note that the physical nature of the phenomenon of increasing cross-section of synthesis of elements placed in a conducting crystal lattice is not fully known yet. However, the data can be well described by the introduction of the single screening potential, which for DD interactions in metals is by about an order of magnitude greater than is the case of collisions of free atoms [10]. At present, we consider a process for the fusion enhancement that is analogous to the well-known process of muon catalysis, when instead of a muon exchange process, the contraction of two deuterons is the effect of conduction electrons together with the influence of the crystal lattice. Anyway, these experiments suggest that the distance of junction of two deuterium atoms in these circumstances is an order of magnitude smaller than the size of two deuterium atoms, and the reaction rate of DD fusion may be sufficient to describe the experimental results of McKubre [2]. Although in the case of muon catalysis the junction of two deuterium atoms is still at least an order of magnitude less than in experiments [11,12], in the latter case there is no limitation of the carrier population in the media, and their lifetime is not limited. The calculations of the reaction rate of the DD fusion through this mechanism are presently being carried out by us.

Finally, the hypothesis of a decrease in the rate of nuclear decay of the compound nucleus $^4He^*$ at low excitation energies opens up the possibility of "nonradioactive" energy released. Experiments [2] support this hypothesis and provide evidence for this new phenomenon in nuclear physics.

6. – Discussion

Peculiarities of the behavior of deuterium atoms in a crystalline environment provide a gross increase in the probability of deuteron fusion and open up the possibility of practical application of this process. Especially interesting is the novel experimental evidence of the enhancement of the fusion processes in conducting crystals.

The assumption that decay time of the compound nucleus depends on its excitation energy makes experiments in crystals compatible with all the acceleration data and explains the practical absence of unwanted nuclear products in this reaction.

New physics of the energy discharge of excited nuclei to the electronic environment through the processes with virtual photons could open a new possibility to study the nature of nuclear forces. Deuterium fusion in semiconductor detectors could be a good tool for this new physics.

The new nuclear physics at low energies could have unexpected implications for the customary practice with nuclear reactions. For example, the rate of certain nuclear reactions excited by thermal neutrons may happen to be environmentally dependent.

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REFERENCES

[1] Fleischmann M., Pons S., Anderson M. W., Li L. J. and Hawkins M., *J. Electroanal. Chem.*, **287** (1990) 293.
[2] McKubre M. C. H., Tanzella F., Tripodi P. and Haglestein P., in *Proceedings of the 8th International Conference on Cold Fusion, 2000, Lerici (La Spezia)*, edited by Scaramuzzi F. (SIF, Italian Physical Society, Bologna, Italy) 2001, p. 3; McKubre M. C. H., in *Condensed Matter Nuclear Science: Proceedings of the 10th International Conference On Cold Fusion, Cambridge, Massachusetts, USA 21-29 August, 2003*, edited by Hagelstein P. L. and Chubb S. R. (World Scientific, Singapore) 2006; McKubre M. C. H., *Review of experimental measurements involving dd reactions*, presented at the Short Course on LENR for ICCF-10, August 25, 2003.
[3] Tsyganov E., *Phys. At. Nuclei*, **73** (2010) 1981; *Yad. Fiz.*, **73** (2010) 2036 (in Russian).
[4] Fowler W. A., *Rev. Mod. Phys.*, **56** (1984) 149.
[5] Salpeter E. E., *Phys. Rev.*, **88** (1952) 547.
[6] Bethe H. A., *Les Prix Nobel* 1967 (Almquist and Wiksells, Stockholm) 1968.
[7] Barnes C. A., Chang K. H., Donoghue T. R., Rolfs C. and Kammeraad J., *Phys. Lett. B*, **197** (1987) 315.
[8] Sabourov K., Ahmed M. W., Canon S. R., Crowley B., Joshi K., Kelley J. H., Nelson S. O., Perdue B. A., Schreiber E. C., Sabourov A., Tonchev A., Weller H. R., Wulf E. A., Prior R. M., Spraker M. C., Hofmann H. M. and Trini M., *Phys. Rev. C*, **70** (2004) 064601.
[9] Pauli H. C., Adler K. and Steffen R. M., *The Electromagnetic Interaction in Nuclear Spectroscopy*, edited by Hamilton W. D. (North Holland Pub. Co., Amsterdam, Oxford) 1975, p. 341.

[10] Assenbaum H. J., Langanke K. and Rolfs C., *Z. Phys. A - At. Nucl.*, **327** (1987) 461.
[11] Rolfs C., *Nucl. Phys. News*, **16** (2006) 9.
[12] Huke A., Czerski K., Heide P., Ruprecht G., Targosz N. and Zebrowski W., *Phys. Rev. C*, **78** (2008) 015803.