Catalitically Induced D-D Fusion in Ferroelectrics

V.D. Dougar Jabon[1], G.V. Fedorovich[2] and N.V. Samsonenko[3]
[1] *Escuela de Fisica, Universidad Industrial de Santander,*
Bucaramanga, A.A.678, Colombia
[2] *Theoretical Problem Department, Russian Academy of Sciences,*
Moscow, 121002, Russia
[3] *Department of Theoretical Physics, Russian Friendship University,*
Moscow, 117198, Russia

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A model of deuteron acceleration in ferroelectrical crystals under the process of domain polarization reversal is proposed. Experimental verification of the model with $LiTaO_3$ crystals saturated with deuterium was fulfilled. It was shown that in the 75 kV/cm a.c. field the neutron emission attributed to D-D fusion is two order magnitude higher the Jones level.

I. Introduction

There are strong grounds (both theoretical [1,2] and experimental [3]) to believe that the phenomenon of enhancement of the D-D fusion rate during electrolytic infusion of deuterons into metallic Ti or Pd electrodes connected with the crack and break formations in the cathode material. Also, a neutron emission from a crushing process of Lithium Niobate crystal in deuterium gas atmosphere was observed [4].

To put this another way, the physical mechanism of cold fusion in electrolytic cells [5,6] is the same as the one in the case of a destruction of deutered crystals [7,8]. A model of that mechanism (the stochastic acceleration of particles in the field of intensive oscillations that are generated at the crack boundary) has been proposed in [8,9]. The analysis of the model allows to make some conclusions which are of interest for following investigations. It has been found that, for deuterium contained crystals, the emissions of high energy electrons and electromagnetic radiation (in the range from visual light to X-rays) are that indicator of creating conditions for enhancement of the nuclear fusion rate. It was noted [9] in connection with this that the phenomenon of light [10] and high energy electron [11,12] emission are involved in the process of polarization reversal of ferroelectrics. The direct evidence are found for the nuclear fusion in deuterated ferroelectrics during changes of their crystalline structure in the process of phase transition [13] and polarization reversal [14,23,24].

The foregoing is a good reason to consider the phenomenon of the stochastic acceleration of d-ions in the field of dominant mode oscillations, which are generated during the polarization reversal, more closely. This will allow an revealing the parameters of crystals that determine the D-D fusion rate. An understanding of the effect will guide the way to improvements in the design of experiments. This is the main purpose of the paper.

II. Model of a domain wall motion

Let us assume that for every polarization of the individual cell we can introduce certain quantitative characteristics, coordinate s, which is defined in such a manner that it is equal zero in a non-polarized cell and it has positive or negative in variously polarized cells. It will be reasonable to assume that temporal variations of s are described by the Hamiltonian (see also [15])

$$H = (1/2)M\dot{s}^2 + (1/2)\sum_n g(s_{n+1} - S_n)^2 + U(s) - eEs \tag{1}$$

where M and $U(s)$ are effective mass and potential, g is the forced constant. In order to describe the possibility of the crystal polarization reversal, let us define the double-minimum potential energy function by the formula: $U(s) = -(a/2)s^2 + (b/4)s^4$. This potential is minimal when $s = s_{eq} \equiv \pm(a/b)^{1/2}$. One can see that if $E = 0$ the system is in a symmetric potential well. As the field E increases to the critical value $E_0 = (2a/3e)(a/3b)^{1/2}$, the left hand part of the well disappears. The summary potential transforms into the broad asymmetric well in which the system can oscillate near the right hand equilibrium position.

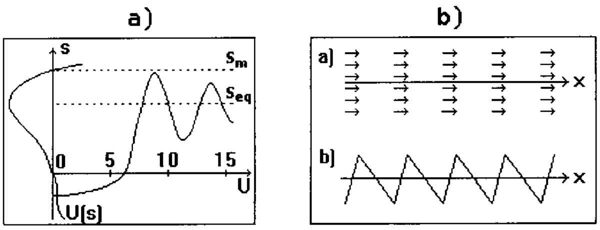

Figure 1. Left side (a) represents the results of numerical solution for $U(s)$.The characteristic points: $S_m = 1,66$ and $S_{eq} = 1,15$; right side (b) is the illustration of the D-ion acceleration area.

To get an equation for the dominant mode oscillations, which are generated during the polarization reversal of ferroelectrics, it is convenient to use a continuum approximation. Then by defining $k \equiv gd^2$ and introducing the co-ordinate x along the crystal, we obtain

$$M\partial^2/\partial t^2 - k\partial^2 s/\partial x^2 = eE + as - bs^3. \qquad (2)$$

The eq.(2) is classed as a quasi-linear hyperbolic equation. All of the perturbations, described by this equation, extend with the velocity $C = (k/M)^{1/2}$ in both directions of the x-axis. In order to determine the dependence $s(x,t)$ it is necessary to add the corresponding initial and boundary conditions to the eq.(2). Let us suppose that the field $E = E_0 - 0$ is applied to the crystal. The system of each cell is characterised by the s-value near the left equilibrium (unstable) position. For turning the system out of this state, the disturbing force $f \cong f_o\delta(x)\delta(t)$ is added in the right-hand side of the eq.(2). As a result, the breaks of the function $s(x,t)$ will extend along both directions $x = \pm Ct$. The magnitude of $s(x,t)$ varies from $s_0 = -(a/3b)^{1/2}$ (before a break) to $s_1 = s_0 + Cf_0/2$ (immediately behind a break). Let us consider variations of s in the area $-Ct < x < +Ct$. The boundary conditions

$$s(x = \pm Ct) = s_1; s'(x = \pm Ct) = 0 \qquad (3)$$

is sufficient for the definition of $s(x,t)$ over the whole area.

The solution of the problems (1)-(3) was obtained numerically. It brings us to the description of the domain polarization by the following function

$$P(x,T) = P_s(\sqrt{(a/k)[(Ct)^2 - x^2)]}) \qquad (4)$$

where the function $S(\nu)$ is shown in Fig. 1a (characteristic points of the diagram are $S_m \cong 1,66$, $S_{eq} \cong 1,16$) and P_s is the value of the spontaneous polarization of ferroelectrics. The amplitude and the frequency of the oscillations relative to the equilibrium value are

$$\delta S = S_m - S_{eq} \approx 0.5 \quad \text{and} \quad \omega = (a/M)^{1/2}.$$

III. Fermi acceleration of deuterons

A model of a ferroelectrical crystal consisted of a sequence of layers of electrical dipoles p_j (arrows in Fig.1b) which are spaced d apart is studied. The integral index j enumerates layers of dipoles. We suppose that a deuteron moves along the domain axis. The straight line represents the deuteron parth. It crosses sequential layers of dipoles. If the crystal is found between electrodes then the depolarization field $E = 4\pi p/d^3$ exist in the crystal (here p is the average value of cell dipoles p_j). The field compensates the summary potential difference on the bounds of the crystal.

The variation of the potential energy along the path of the movement of the D-ion is represent in Fig. 1b (here Δ is the effective size of dipoles). The oscillations of atoms forming dipoles bring to variation of the dipole moments with respect to the average value p. In general, the value of difference $p'_j = p_j - p$ can be represented as the sum of the normal waves. However, we assume that the dominating oscillation exists in the crystal (see above). It can be described by the function $p'(t) = p_0\cos\omega t$. It is convenient to consider the limiting case where dipole sizes are sufficiently small ($\Delta << d$). In this case the D-ion trajectory $x(t)$ can be determined from the equation

$$Mx''_{tt} = eE - e\sum_j p_j(t)\delta(x - jd)$$

where M is the deuteron mass. This equation describes the uniformly accelerated movement of the D-ion on intervals $jd < x < (j+1)d$ and the dampening shocks on the interval boundaries.

Let at $t = t_n$ the D-ion is in the point $x = jd - 0$, it has the kinetic energy $T_n > 4\pi e p_j/d^2$ its velocity is oriented in the positive direction of the x-axis. At $t = t_{n+1}$, where t_{n+1} is determined by the relation

$$t_{n+1} = t_n + [d^3(2M)^{1/2}/4\pi e p][T_{n+1}^{1/2} - (T_{n+1} - 4\pi e p/d^2)^{1/2}], \tag{5}$$

the D-ion will be in the point $x = dj_{n+1} - 0$ (where $j_{n+1} = j_n + 1$) with the kinetic energy $T = T_{n+1}$ determined by the relation

$$T_{n+1} = T_n - 4\pi e p_j(t)/d^2 \tag{6}$$

The set of relations (5),(6) represents a mapping [16] which defines the D-ion dynamics with a sufficiently large positive velocity. Similar relations can be determined for the case of a small positive velocity (if $T_n < 4\pi e p_j/d^2$) and also for the case of a negative velocity. For dimensionless variables $W = T/T_o$, ($T_o \equiv 4\pi e p/d^2$) and $y = \omega t$ the set of mappings, which entirely defines the dynamics of the D-ion, has the form

$$W_{n+1} = W_n - q(y_n)$$

$$y_{n+1} = y_n + Q[W_{n+1}^{1/2} - (W_{n+1} - 1)^{1/2}] \text{ if } W_n > 1 + q(y_n) \tag{7a}$$

If $W_n < 1 + q(y_n)$ then at $t = t_n + 0$ the D-ion velocity becomes negative. Two possibilities exist in this case:

$$y_{n+1} = y_n + Q[W_n^{1/2} - (W_n - 1)^{1/2}]$$

$$W_{n+1} = W_n + q(y_{n+1}) \quad \text{if} \quad W_n > 1, \tag{7b}$$

$$y_{n+1} = y_n + QW_n^{1/2}$$

$$W_{n+1} = W_n \qquad \text{if} \;\; W_n < 1 \tag{7c}$$

where

$$q(y) \equiv p'(t)/p \;;\; Q \equiv \omega d^2(M/2\pi e p)^{1/2} \;.$$

If the value p_j depends arbitrarily on t, the mapping (7) has the form of a radial twist mapping. For $q \propto \cos(y)$ eqs.(7) becomes the standard mapping (also known as Chirikov-Taylor mapping). This mapping has been well investigated lately in connection with the problem of the Fermi acceleration (see [16-18]). It was shown, in particular, that a stochastic acceleration regime exists if $P_j(t)$ is an oscillating function. Then it results that the particle energy W can noticeably exceed the value $1 + Amp\{q(y)\}$.

For $W >> 1$ stochastic motion of the deuteron (at least strong stochastic motion) disappears. In this case the inequality $Amp\{q(y)\} < 1$ seems to be reasonable so that variations of W are small ($\Delta W << W$) for each steps of mapping. By assuming that Q is small too, we obtain that the phase y of a deuteron movement varies only slightly ($\Delta y << 1$).

The fulfilment of these conditions makes possible the transformation of difference equations (7) into differential ones and we can turn to the continuous variations of n. For definiteness we consider particles which move in the positive direction of x-axis. The equations

$$dW/dn = -q\cos(y); \quad dy/dn = Q[W^{1/2} - (W - 1)^{1/2}] \tag{8}$$

follows from (7a) after this transformation. The system (8) has the first integral

$$(2/3)Q[W^{3/2} - (W - 1)^{3/2}]q\sin(y) = const.$$

Let the energy W exceeds 1 at some moment when the phase of its movement is y_0. Then the variations of W in the course of moving are described by the implicit function $W^{3/2} - 1 - (W - 1)^{3/2} = \Gamma[\sin y_0 - \sin y]$ where $\Gamma \equiv 3q/2Q$. Since the value of Q is small, the value of Γ is great.

Under appropriate choice of the initial phase y_0, the value of W may be as $MaxW = (4\Gamma/3)^2 >> 1$. It suggests that the effect of the deuteron acceleration in ferroelectrical crystals is quite actual. It is interesting to note that the considered phenomenon is the combination of the two radically different mechanisms of acceleration: when the energy is small ($W < 1$), the stochastic acceleration takes place, this mechanism is similar to the Fermi acceleration. In the region $W > 1$ the D-ion energy increases (if particles enter into this region with the appropriate phase) at the expense of the resonance acceleration in the field of the dominate mode oscillations.

IV. Energy losses and limiting energy accelerated deutrons

The energy losses of accelerated deuterons are determined by a combination of individual collision processes. The systematic description of the processes is given in [19] (the quantitative data see in [20]). Stopping power is maximal at velocities of approximately $V_0 Z_A^{2/3}$, where V_0 is the Bohr velocity and Z_A is the charge of the incident particle, corresponding to 25 keV/nucleon. At lower energies the inelastic electronic interactions and elastic recoils can completely dominate the stopping process.

The theoretical treatment in this low velocity region is largely due to Lindhard and his collaborators [21]. They give simple expressions for electronic stopping power $S(S \equiv n^{-1}(dT/dx)$, where n is the density of absorber material) based on the Thomas-Fermi model of the atom. The stopping power is the function of the velocity of the incident particle **A** and the absorber material consisting of particles **B** with charge Z_B. For $V < V_0$ the expression for S has the form

$$S = 8\pi\chi e^2 a_0 (Z_A Z_B / Z)(V/V_0). \tag{9}$$

In this expression $\chi = Z_A^{1/6}$, $Z = (Z_A^{2/3} + Z_B^{2/3})^{3/2}$, a_0 is the Bohr radius. The molecular effects are small in the total energy loss process.

Using eq.(9), the value of the dimensionless (see Sec.III) energy loss ΔW at one collision can be estimated by the formula

$$\Delta W \cong \alpha W^{1/2}; \alpha = 8\pi < n >^{5/6} e^2 a_0 < Z_B/Z > (2\pi e P_s M V_0^2)^{-1/2} \tag{10}$$

The accounting of the energy losses brings to the variation of the form of the mapping (7). We have $W_{n+1} = W_n - q(y_n) - \alpha W_n^{1/2}$ instead of the first relation of eq.(7a). The other relations of the mapping (7) must be changed similarly. The modified system (8) has the form (for $W >> 1$)

$$dW/dn = -q \cos y - \alpha W^{1/2}; \; dy/dn = Q/2W^{1/2}. \tag{11}$$

The system (11) has the first integral

$$W = Max\{W\}(\cos(y - y^*) + O\{\exp[-\alpha(y - y_0)/Q]\})^2. \tag{12}$$

where

$$Max\{W\} \equiv q^2/(Q^2 + \alpha^2), \quad \cos y^* \equiv \alpha/(Q^2 + \alpha^2)^{1/2} \tag{13}$$

The second term in eq.(12) is the exponentially damped contribution of the initial condition.

To make a quantitative estimate of the maximal energy, we use parameters of some ferroelectrics listed in [22,23]. The results are collected in the Table 1.

Ferroelectrics	P_s, μC/cm^2	T_0, eV	α	Q	max(W)	max(T), eV
KD_2PO_4 (DKDP)	4,5	2,4	0,085	0,62	0,65	1,5
$(ND_2CD_2COOH)_3D_2SO_4$	4,5	3,5	0,12	0,76	0,43	1,5
$LiNbO_3$	75	32,3	0,023	0,14	13,0	420
$LiTaO_3$	50	21,2	0,03	0,17	8,7	185
$PbTiO_3$	50	31,6	0,023	0,15	11,6	365
$BaTiO_3$	25	11,3	0,038	0,24	4,1	47
$Ba_2NaNb_5O_{15}$ (BNN)	40	30,6	0,037	0,25	3,9	119
$Ba_{0.4}Sr_{0.6}Nb_2O_6$ (SBN)	35	24,6	0,038	0,26	3,7	92

Table 1. Parameters of some ferroelectrics and the maximum deutron energies.

One can see that some oxide ferroelectrics with the large magnitude of the spontaneous polarization have turned out to be interesting from the viewpoint of D-D fusion in cold samples, so that it may be worth devoting some space to them.

V. Experiment on polarization reversal

To check the theoretical prognosis of catalytic enhancement of the D-D fusion reactions in ferroelectrics, experiments on warming up of D-dopant subsystem in a field of the dominant mode oscillations are performed. Possible evidence of D-D catalysis under the domain polarization reversal of some ferroelectrics in an a.c. field was looked for.

Choice of ferroelectrics

The advantage of this experimental program is available theoretical model of the catalytic induced fusion reactions. The model dictate ways of the expected effect intensification by choosing ferroelectric with the next properties:

(1) large value of spontaneous plarization P_s,

(2) low energy losses of D-ions at movement in a crystal,

(3) coercive force less than the dielectric strength of a crystal,

(4) capability of dissolving of a sufficient number of deuterium.

There are no ferroelectrics which are fit completely all of these requirements.

For $LiNbO_3$, as example, a large value of the spontaneous polarization P_s is a characteristic property. This ferroelectric satisfies the condition (2) but not (3). It is common knowledge that the problem (4) is not exist for some ferroelectrics as the deuterium forms part of its chemical composition. An example is KD_2PO_4 which answers the requirement (3) but has moderate spontaneous polarization ($P_s = 5\mu C/cm^2$) and does not meet the demand (2).

To perform experiments, $LiTaO_3$ (LT) and $Ba_{0.4}Sr_{0.6}Nb_2O_6$ (SNB) of perovskite-like structure were used. This choice is a certain compromise between the requirements (1)-(4). The polarization reversal takes place at actual electric fields $E_c \cong 50$ kV/cm for LT and at $E_c = 5$ kV/cm for SNB [23]. The additional point to be emphasised is that the both ferroeiectrics dissolve a great number N_D of deuterium ($N_D \approx 10^{22}$ cm^{-3} for LT, $N_D \approx 10^{21}$ cm^{-3} for SNB) without the ferroelectric properties degradation.

Samples of LT cut from a monocrystal were annealed at temperature of 1200°C and were subjected to monodominization process in an electric field. The crystal samples to be used are of two types. Ones have a form of parallelepiped with dimensions of 10 × 10 mm in a plane perpendicular to the ferroelectrical axis and 5 mm along this axis (thick samples). The other ones are discs of 5 mm in diameter and 1 mm of thickness (thin samples). The axis of the discs coincides with the ferroelectrical one. The opposite wide sides of samples were covered with nickel thin films by a method of vacuum deposition in order to use them as electrodes. Samples of SBN crystals were prepared essentially similar to LT ones with the only difference that the thickness of these samples along the ferroelectrical axis was 2 mm.

Experimental device

Experiments were performed on a device which is shown schematically in Fig.2. The main part of the device is a processing ss chamber which is equipped with a pipe for pumping and a pipe for gas injection from a container with deuterium under pressure of 2,5 at. The chamber is evacuated up to pressure of 1.10^{-9} at by a turbomolecular pump. A pressure in the chamber is controlled by a manometer. The lower part of the chamber is a quartz cylindrical vessel 39 cm in long and 4 cm in diameter. A crystal samples are placed between two plate nickel electrodes connected through two high voltage lead-in with the oscillator generating sinusoidal voltage 50 Hz and regulated up to 10 kV amplitude. The samples are oriented in such a way that the electric field is directed along the ferroelectric axis.. From the outer side of the quartz tube there is an electric heater to raise a sample temperature to 600°C which is controlled by a thermocouple.

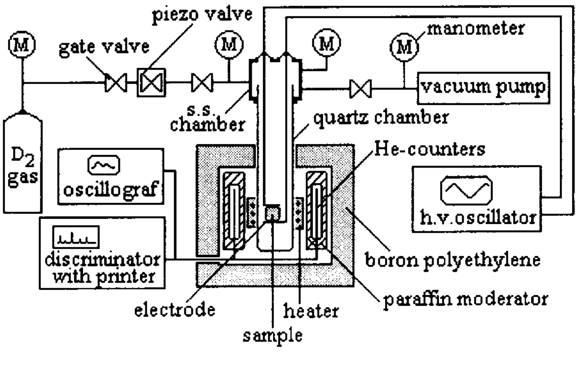

Figure 2. Scheme of experimental device.

It seems reasonable to say that the most adequate manner of searching the D-D reactions is a record of neutrons. This is at least under assumption of classical channels of D-D fusion with a low rate. A block consisting of 10 proportional He^3 counters surrounded by paraffin moderator is used for neutron registration. In order to diminish the neutron background, the processing chamber is surrounded by a Boron polyethylene wall of 20 cm in thickness. Detector signals were registered by a 1024 channel pulse-in-height discriminator and a digital type. The total efficiency on neutron registration is estimated as 3% in accordance with measurements made with a 600 neutron/s Cf^{252} calibrated source. The registration system is equipped with a special earth contour to suppress an electrical interference.

Preparation of crystals

Preparation of selected samples for experiments was consisted in degassing of the samples by a method of annealing at temperature of 400-450^{o}C under a vacuum of 10^{-6} at. This process was followed by saturation of the samples with deuterium at an initial pressure of 0,6-1,2 at during time intervals from a few hours to 5 days. A quantitative characteristic of deuterium absorption was reduction of pressure in the chamber [25].

It was found that a LT sample absorbs detachable quantity of deuterium during the first 10 hours leading to pressure drop in the chamber from 0,7 at to 0,5 at. After 30 hours of a saturation procedure the pressure decreased to 0,3 at. By this meant that each lattice of LT crystal absorbed one atom of deuterium. For the SNB samples the limiting density of absorbed deuterium was slightly below, approximately 5.10^{20} cm^{-3}, that was reached after the exposure time of 25-30 hours.

Experimental results

As mentioned above the experiments was fulfilled with the samples subjected to an alternating electric field. Each experimental cycle was divided into 10 min intervals during which total neutron yield was recorded. The control experiments were consisted in a neutron registration at absence of a sample in the chamber but an electric field between the electrode was left to be switched on. The neutron background was registered during 70 hours.

Based on this experiments, a mean background level **M** of $12,0 \pm 3,4$ neutrons per 10 minutes interval and the 90% confidence level **H** and **L** were found (see. Fig.3). It is necessary to note that during 5-8 cycles a tendency for sequential weakening of the neutron emission of LT samples was observed. This peculiarity can be attributed to depletion of deuterium in the active zones where the domain walls propagates (see above Sec.II). In this zones an intensive warming of D-dopant sublattice takes place which followed by the diffusion of deuterium atoms into neighbouring regions of crystal as well as releasing them from a sample. So, the diffusion of deuterium is responsible for a reduction of the total neutron emission from samples.

In order to equalise the deuterium density in a crystal body, an additional annealing of the samples in the deuterium atmosphere at the temperature of 450-500^{o}C was made. Then the crystal activity partly reestablished. On the other hand after 5-7 experimental cycles the samples lost their capability to produce excess of neutrons in comparison with the background data.

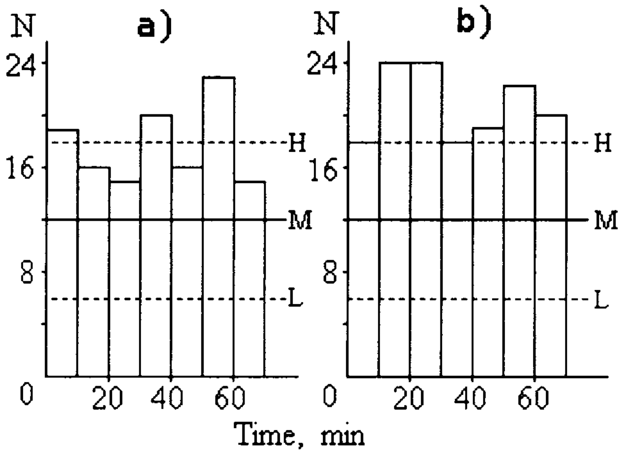

Figure 3. An example of experiments with a thick (a) and a thin (b) samples.

Typical results on neutron detection taken with the LT samples is shown in Fig.3. Each column shows a number of neutrons detected during the 6.10^4 polarization reversals. As it is easy see, there is essential difference between the distribution which was obtained for a thick sample (Fig.3a) at the electric field of 25 kV/cm and the thin ones (Fig.3b) at 75 kV/cm. It must be emphasised that the number of neutrons recorded during all operating intervals for case B is above the middle level for the case A although the volume of the thick samples is approximately seven times larger. But it is reasonable to note that the value of electric field was insufficient for the effective domain reversal polarization of the thick ferroelectrics so as the field of 25 kV/cm is less than the coercive force.

The differences between the background level and the average level through exposures are $(0,53 \pm 0,21)$ neutrons/min for the thick sample and $(0,89 \pm 0,32)$ neutrons/min for the thin one. On the assumption that this difference is due to a neutron emission owing to D-D fusion reactions, the activity of a LT sample to be used can be estimated as $Q = (0,30 \pm 0,12)$ neutrons/s for the thick sample and $(0,49 \pm 0,17)$ neutrons/s for the thin one. This gives the fusion rate $(6,0 \pm 2,4)10^{-22}$ s^{-1} per deuteron pair for the thick crystal and $(7,8 \pm 1,4)10^{-21}$ s^{-1} for the thin one. The last value is practically two orders of magnitude higher the Jones level. This results permit us to suppose that the process of the reversal polarization of domains results the acceleration of the deuterium nuclei to energy of 200 eV (which corresponds to a temperature of 10^6 K) and larger in an cold crystal sample.

For SNB samples, any excess of neutron emission above the background level was not found in our experiments. There are some reason which can explain this negative result.

Conclusing remarks

From the experimental results it is possible conclude that the mechanism of Fermi acceleration in the field of the wave generated during the domain polarization reversal of LT crystals can raise the D-nuclei energy up to value enough to realise the fusion reactions in ferroelectrics with the rate which is significantly higher the one determined through the Jones level.

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