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Capillary fusion through Coulomb barrier screening in turbulent processes generated by high intensity current pulses

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An experiment performed in Kiel in 1973 paves the way to a possible new model of non-thermonuclear fusion. The process could be pycnonuclear and explain other experiments such as the Z-pinch and cluster fusion. The proposed fusion mechanism is based on quantum tunneling combined with the screening of the Coulomb barrier of two colliding deuterons by electron clouding favoured by chaos. Possible break-even conditions by this mechanism are discussed.

The simple idea of discharging a capacitor bank into a deuterated medium has been used early after the Second World War. In this research field the most popular experiments have been the plasma focus experiments or the Z-pinch experiments. The underlying intent of such experiments was to obtain a sufficiently hot plasma (i.e. the so-called thermonuclear plasma) by using directly electromagnetic energy. The medium density is of first importance for the outcome of such experiments as explained farther in this paper. This density of the deuterated medium does not seem however to have been the most important concern of the people involved, with the sole exception in Kiel, Germany, in the experiments performed by Lochte-Holtgreven [1].

At that time Lochte-Holtgreven performed experiments which were apparently simple. They consisted of discharging a capacitor bank of 5 μF, 200 kV into a liquid thread of metallic conductivity containing deuterium. This liquid consisted of a saturated solution of lithium in heavy ammonia, $Li(ND_3)_4$ which has a good conductivity, comparable to that of mercury. This liquid filled a capillary, typically 7–8 cm long and of 0.5–1.5 mm internal diameter. In this paper were given some very important data (not found in other similar papers) concerning tentative fusion experiments by fast current pulses, i.e. the current in the deuterated medium as a function of time, and the neutron burst time. This current pattern had a shape which was similar to the ones obtained in exploded wire experiments: a relative maximum followed by a relative minimum, and afterwards an absolute maximum. The neutron burst occurred only after the first maximum at a time which depended on the capillary diameter (see fig. 5 of ref. [1] or fig. 5 of ref. [2]) and would last only 30–50 ns. The capillary was broken only after the minimum which occurred also at a time depending on the capillary diameter and before the second maximum (see fig. 1).

This Kiel experiment is exemplary: the phenomenon involved in such so-called "capillary fusion" experiments is hardly thermonuclear. This question is clearly discussed in ref. [1]. Lochte-Holtgreven remarks that the fusible medium, having a volume of about 5.5×10^{-2} cm^3 (density 0.7 g/cm^3), contains 3.85×10^{-2} g of liquid which is heated to 500 J. With a specific heat of 0.6 cal/g deg, he deduces that the upper limit for the temperature in the capillary is about 5500 K, i.e. about 0.5 eV; but he does not take into account the medium ionization energy. This value of 0.5 eV should mostly be regarded as a mean ionization energy per particle, plus the energy due to the acceleration by the action of the flowing current. This hypothesis is in agreement with the fact, observed by Lochte-Holtgreven, that a sufficient voltage threshold was necessary to produce fusion reactions, the lower level being 150 kV, i.e. approx-

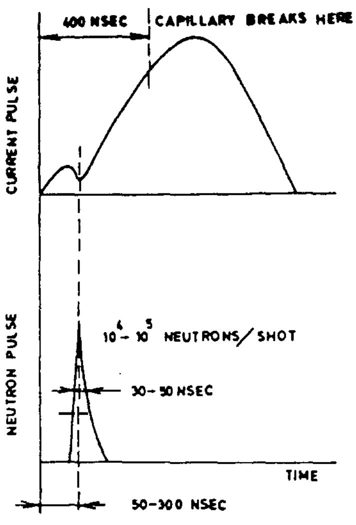

Fig. 1. Figures from ref. [2] showing the most essential elements which describe the capillary fusion experiments performed by Lochte-Holtgreven et al.

imately 20 kV/cm. It is also in agreement with the number of ions per cm^3, estimated by Lochte-Holtgreven as being equal to 8.5×10^{22} ions per cm^3. He obtains this value from the density of the liquid which is 5×10^{21} particles of $Li(ND_3)_4$ per cm^3, and assuming that this molecule is completely turned into ions of lithium, deuterium and nitrogen.

It is interesting to compare the data deduced from the simple heated medium hypothesis with the usual thermonuclear data. For this task it is straightforward to plot the representative point of those experiments in the usual diagram of $\log T$ as a function of $\log E$, T being the nuclear production term, i.e. the mean product of the fusion cross section σ multiplied by the mean ion velocity v ($T=\langle\sigma v\rangle$ in the thermonuclear hypothesis). So the production rate R of the fusion reactions is

$$R=\tfrac{1}{4}N^2T\,, \qquad (1)$$

N being the number of deuterons per unit volume which can be involved in a fusion reaction.

Taking the number of deuterons per unit volume equal to $8.5\times10^{28}/m^3$, the production term T is included between two limits, corresponding to the two recorded rates 10^4 and 10^5 neutrons in 1.5×10^{-7} s in the volume equal to 5.5×10^{-8} m^3. The fusion reaction production rate is thus included between 1.2×10^{14}/s and 1.2×10^{15}/s, and the production term lies between two approximative limits, i.e.

$$10^{-38}<T<10^{-37}\ m^3/s\,.$$

In fig. 2 the thermonuclear production term $\langle\sigma v\rangle$ deduced from D–D and D–T collision experiments is drawn as a solid line. The Kiel representative point, deduced from an equirepartition of energy between the particles, lies completely outside the thermonuclear range. One can thus conclude with Lochte-Holtgreven that the nuclear reactions cannot be caused by thermal heating of the whole volume of the capillary.

As Lochte-Holtgreven emphasizes, the acceleration of some deuterons at certain places up to energies putting them into the thermonuclear range is not more acceptable, since this process is hindered by the very high density. He thus dismissed the process of ion acceleration within the capillary along the external surface of the plasma somewhat compressed by the pinch effect. The process of ion acceleration from the inductive potential at the borders of a single plasma constriction caused by the instability is

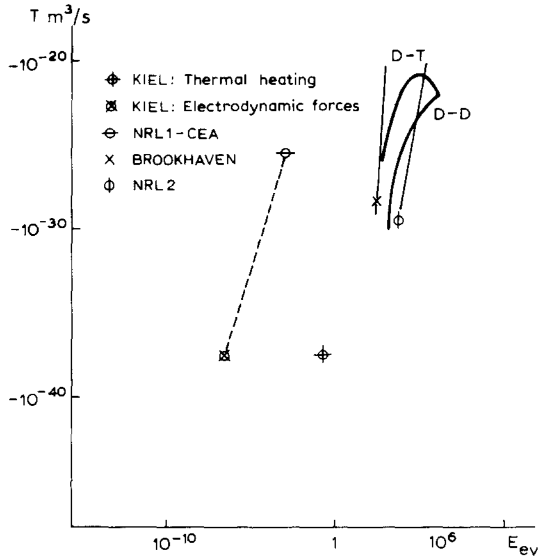

Fig. 2. Fusion production factor (in m^3/s) as a function of the deuteron energy (eV) in logarithmic scale. The thermonuclear curves are drawn as thick solid lines. The T variations for the Brookhaven and the NRL2 points are drawn as thin solid lines. The supposed T variation for capillary fusion is as drawn as a dotted line.

also dismissed [1]. Another interpretation quoted by Händel and Jonsson [2] is that the most probable explanation of the disk formation is related with the MHD instabilities. The sausage type ($m=0$) would develop as soon as the wire itself is liquefied. This would cause the current drop. This hypothesis, however, manifestly contradicts the arguments given by Lochte-Holtgreven himself, since it does not give any explanation about the mechanism (on particle level) which could accelerate the ions involved in nuclear reactions. Nevertheless, this MHD instability point of view leads the authors to make an important remark based only in fact on experimental observation. According to this remark, if a wire is used for fusion research, it is necessary to feed as much energy as possible into the wire before the sausage type instabilities develop [2]. Even if the basic reason is different, this observation is evidently very valuable, since the use of very fast circuit breakers can shape fast pulses and so suppresses the energy wastage like in the Kiel experiments.

If one accepts the hypothesis that the medium is completely ionized, this means in other words that the 500 J energy is mainly used for ionization of the medium, the temperature of 5500 K (or 0.5 eV) does not correspond to any reality. But if one points out the fact that the fusion reaction phenomenon is markedly linked with the current pattern, one has thus to calculate the effects produced by the current acting on the conductor. For this, it is necessary to take into account experimental results obtained principally by Graneau [3]. Those results show that the interaction between current elements is correctly described by the "old" Ampère formula:

$$\Delta F_{m,n} = -\frac{i_m \cdot \mathrm{d}m\, i_n \cdot \mathrm{d}n}{r^2} \times (2\cos\epsilon - 3\cos\alpha_m \cos\alpha_n)\,. \qquad (2)$$

$\Delta F_{m,n}$ is the force between the current elements whose lengths are $\mathrm{d}m$ and $\mathrm{d}n$, with current i_m and i_n. The reference axis joins the two current elements and is oriented from one current element to another, according to Ampère's initial convention; ϵ is the angle between the two oriented current elements, α_m and α_n are the angles between the axis and the current elements [3,4]. This expression satisfies Newton's third principle (equality of action and reaction), a current element being in fact a macroscopic object. The properties of this object are in fact deductible from special relativity by summing all the interactions between the particles inside the conductor [5], and especially the electron acceleration [6]. Expression (2), integrated along one whole circuit, gives the same result as the Biot–Savart force, a reason why they have been considered as indistinguishable since Maxwell [7]. If one considers two current elements which are on the same axis, the force is a repulsion, whereas the Biot–Savart (or Laplace) force would be nil: a collective effect of current elements which does not appear in free charged particle motions.

The Ampère force is thus a new candidate for explaining the current interruption during the capacitor bank discharge into the capillary. If one goes further in this direction, taking into account all electrodynamic forces, one can calculate the pinch effect which is the same in the Biot–Savart hypothesis as in the Ampère hypothesis. A simple calculation can then be made by assuming a uniform current density in the capillary cross section. In the case of the Ampère hypothesis one starts the calculation from the force acting between two current elements contained in the volume $\Delta x\, \Delta y\, \Delta z$ and $\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z$:

$$\Delta F = -\mu_0 (I/S)^2 \frac{\Delta x\, \Delta y\, \Delta z}{r^2} \times [2 - 3(z/r)^2]\, \mathrm{d}x\, \mathrm{d}y\, \mathrm{d}z\,. \qquad (3)$$

At any point in the capillary volume the integration gives one component of the force density along the axis D_ℓ and one component perpendicular to the axis D_t. It is straightforward to obtain for example a simplified expression of the transverse force density D_t, which is good for the case where the capillary tube has a very low radius in comparison with its length:

$$D_t = -\mu_0 (I/S)^2 \int_{y=-R}^{y=R} \log[(A_1/A_2)^2]\, \mathrm{d}y\,. \qquad (4)$$

A_1 and A_2 are expressions which depend on the distance d from the considered point to the axis (R being the capillary radius) and on the integration variable y:

$$A_1^2 = d^2 + R^2 + 2d(R^2 - y^2)^{1/2}\,,$$

$$A_2^2 = d^2 + R^2 - 2d(R^2 - y^2)^{1/2}\,.$$

The result is the same for this transverse density if one starts from the differential expression of the Biot–Savart force:

$$\Delta F = -\mu_0 (I/S)^2 \frac{\Delta x\, \Delta y\, \Delta z}{r^2}\, dx\, dy\, dz\,. \tag{5}$$

The calculation result can be given as a function of a geometrical transverse factor G_t whose dimension is the inverse of a volume:

$$G_t = (1/S)^2 \int_{y=-R}^{y=R} \log[(A_1/A_2)^2]\, dy\,. \tag{6}$$

The ion mean velocity v, at the neutron burst time, is estimated by assuming that the whole medium is ionized and that it is made of the ions Li^+, D^+, N^+ (and also N_2^+, N_3^+, N_4^+); using (3) and (6) one obtains the following simple approximate, but sufficient, relationship,

$$v = \mu_0 I^2 G_t\, \Delta t/m\,, \tag{7}$$

m being the unit volume mass of the fusible medium, Δt the time between the voltage onset and the neutron burst. In fact, the current I is taken equal to its r.m.s. value during this time Δt.

The Ampère force hypothesis is consistent with the observed fact showing that the current path in solid conductors is broken into beads. This has been observed in exploded wire experiments [8] (see fig. 3) and more recently in many experiments like the one of Niffiekeer and McCall [9]. Such a conductor rupture is also shown in fig. 3 of ref. [1] for a tungsten conductor. One can also deduce from (3) the longitudinal force density D_ℓ, acting on the unit volume, which is equal to the sum of the forces due to the current elements situated on the left or on the right of this unit volume,

$$D_\ell = -\mu_0 (I/S)^2 \times \int_{\alpha=-\pi}^{\alpha=\pi} [-l^2 (r^2+l^2)^{-1/2} + l]\, d\alpha\,, \tag{8}$$

with $r = l\cos\alpha + (R^2 - l^2 \sin^2\alpha)^{1/2}$, R being the radius of the cylindrical conductor, l its length on the considered side. In fact the most important contribution is due to the current element which is close to the supposed volume unit. The sum whose origin is in the left side is equal to the one whose origin is in the right side, and those longitudinal forces do not give any effect while their sum is inferior to the maximal strength of the material constituting the conductor. If this force increases, one obtains the conductor's rupture. The conductor's rupture into beads is not completely understood but is probably due to a mechanical standing wave along the conductor turned on by the longitudinal Ampère forces. The stress could thus be increased at the antinode places. This hypothesis still needs to be verified by taking very fast repetitive pictures, in the range of tens of nanosecondes.

Given the assumption of the dependence between the neutron production and the electrodynamic force effect, one obtains the mean velocity at the neutron burst time taking into account the mean current value between the current onset and this burst time. If one assumes moreover that the whole voltage is applied to the capillary, one obtains the r.m.s. current for producing the neutron burst:

$$I_M = W/V\Delta t\,. \tag{9}$$

One obtains for $\Delta t = 150$ ns, $V = 200$ kV, $W = 500$ J: $I_M = 1.25\times10^4$ A. The mean velocity of a medium point, situated on the half of the capillary radius, is a good parameter as one can verify easily that the variation of the geometrical factor G_t is linear between the axis and the conductive cylinder outer part. With these assumptions the mean ion velocity is thus at the neutron burst time $v = 8.37\times10^2$ cm/s, with $R = 0.05$ cm, $G_t = 2.5\times10^3$ cm^{-3} (corresponding to a medium point situated on the half of the capillary radius), $m = 0.7$ g/cm^3. The ion mean displacement is very low: approximately one hundredth of a millimeter. The deuteron mean energy is thus 7.31×10^{-7} eV. At first sight this energy seems surprisingly low, but without this current effect it has been shown that no acceleration could take place

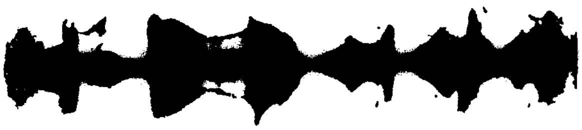

Fig. 3. Figure from ref. [2] showing how a tungsten conductor is cut into pieces called usually "beads". The tungsten wire is photographed during the current pause (Uppsala experiments).

given the high density of the medium. The corresponding representative point is markedly apart from the one deduced from the uniform heating hypothesis [1].

The question which now arises is to understand why the neutron burst begins to come out just when the current begins to decrease as is shown in fig. 4 of ref. [2]. In fact every ion and electron is submitted to two forces: the one is the sum of the Coulomb forces due to the neighbouring charges, the second force is the sum of the electrodynamic forces which are represented by the Ampère formula. After the electromagnetic ionization wave, which lasts only some nanoseconds [10], the medium is strained by the transverse electrodynamic forces. In other terms, the electrodynamic forces impose an order when the current is growing. This order is an ordered motion towards the axis and it could probably collapse when the predominant electrodynamic force is not growing. The ions get the possibility to collide into each other and the electrons get the possibility to mix with them in a random way. This situation can be called chaos. This hypothesis can be submitted to the calculations, but one can remark immediately that it is consistent with the so-called "pycnonuclear" hypothesis.

By definition, a pycnonuclear reaction is a nuclear reaction in a dense medium (from the Greek $\pi\upsilon\kappa\nu o$=dense). A pycnonuclear reaction is one for which the reaction rates are relatively insensitive to temperature [11]. They can occur at sufficiently high densities and low temperatures. According to the ideas developed as early as the fifties, in a dense gas each nucleus attracts neighbouring electrons and repels neighbouring nuclei, thus forming a screening cloud of electrons. At sufficiently high densities and low temperatures the reaction rate is substantially altered. Pycnonuclear reactions hold when the effective thermal energy per nucleus is much less than the Coulomb energy. This is just the case when analysing the Kiel experiment by electrodynamics. In fact Lochte-Holtgreven had the opinion that a pycnonuclear reaction occurred in the capillary experiment [1]. (The term "pycno-thermo-nuclear" is used in this reference.)

As proposed by Vigier and the author one can revisit this concept of the pycnonuclear fusion reaction with the help of the Coulomb screening theory (i.e. reduction of the Coulomb repulsive barrier between deuterons by electrons in their neighbourhood) followed by quantum ion tunneling. It is a matter of going farther and to take into account the great difference of mobility between ions and electrons in a dense ionized medium. It is not sufficient, in this case, to consider electron clouding around an ion, but it is also necessary to take into account the random motion of all charged particles. Two colliding ions are assumed to create in such a medium a more important electron concentration point. The consequence is double: firstly impoverishment of the surrounding ions of their negative charges, and secondly reinforced clouding around the two colliding ions. One has thus two causes for changing the Coulomb barrier: local raising of the mean Coulomb potential (the medium being neutral on the whole, the average Coulomb potential is normally nil) and local lowering of the Coulomb barrier by electron clouding. These two combined effects have been taken into account by Rambaut [12], using some preliminary calculations of Fedorovich [13]. The phenomenon can be called "double screening". It has been necessary to use another production term T (formula (1)) than the usual one in the thermonuclear hypothesis ($T=\langle\sigma v\rangle$). One can show by dimensional analysis that in the double screening case the fusion production rate R is a function of the zero velocity cross section σ, the barrier transmission factor F, the time lag θ, which is necessary for a positive-charge particle to penetrate the screened barrier, and the barrier thickness L:

$$R=\tfrac{1}{4}N^2\sigma FL/\theta\,. \qquad (10)$$

Calculation results have shown that an electron concentration of 10^3 to 2×10^3 around two colliding deuterons gives a fusion production rate not far from the one of the Kiel experiments [12].

As claimed by Lochte-Holtgreven [1] there are other experiments closely related to the capillary experiment but essentially different from the Kiel experiments. For example in the NRL1 experiments from 1973 [14] and quoted by Lochte-Holtgreven in ref. [1] (the addition 1 in NRL1 is given to distinguish those experiments from more recent ones performed in 1987 and designated by NRL2) the current was passing through small diameter deuterated fibers. The direct energy input heated and expanded the thread, while gravity and pinch counteracted. In fact in the Kiel experiments the capillary played the role of containment during some hundreds of nanoseconds, and the great density was maintained till the neutron burst occurred. The velocity due to the pinch effect, calculated in the same way as in the Kiel case but taking into account the exact conductor channel radius during the discharge ($\approx 5\times 10^{-3}$ cm), gives an ion velocity of 4.4×10^4 cm/s and thus an energy of 2×10^{-3} eV. The fusion reaction production term T can be estimated included in a rather large range, between 3×10^{-27} and 3×10^{-25} m^3/s. The representative point is thus largely above the one of Kiel in the logarithmic diagram (fig. 2).

One can also take into account an older experiment performed during the fifties at the CEA [15]. It consisted of discharging a capacitor bank into deuterated tantalum wires. The information is scarce, since at this time people did not have any idea of the importance of the current pattern. With a simple hypothesis about this duration one obtains a T value and an ion energy E which are rather close to the ones of NRL1. This is not surprising, since the medium densities and the r.m.s. current were not very different in both cases.

In the case of the NRL2 experiments [16] the medium was frozen deuterium. Taking into account in this case, like for NRL1, the observed value of the conducting channel, which is at least equal to 2×10^{-2} cm, one obtains an ion velocity equal to 3.3×10^7 cm/s and a deuteron energy equal to 2.6×10^3 eV. In this case the electrodynamic energy is turned predominantly into random motion by collisions. This means that the deuterons are thermalized, since the evaluated fusion reaction production term T is 6.3×10^{-29} m^3/s and the representative point is practically on the $\langle\sigma v\rangle$ thermonuclear curve.

It is also very informative to plot the representative point of a different type of experiment performed in Brookhaven by Beuhler et al. [17]. It consisted of creating clusters with n D_2O molecules (typically $n=150$). Those ionized clusters $(D_2O)_n^+$ were accelerated in a Cockroft–Walton accelerator and directed against a TiD target. The fusion reaction production term was primarily produced by impact of accelerated ion clusters on the TiD target. The value of the fusion cross section σ was estimated to be more than 10 orders of the magnitude larger than that computed from D–D collision data. Another result of those experiments was the value of the fusion reaction production term which was approximately proportional to the eighth power of the energy (see fig. 4). A third experimental result was the dependence of the proton yield on the cluster size at a given accelerating voltage: there was a broad maximum in the reaction rate with a falloff toward both smaller and larger clusters. These experimental results are consistent with the double screening modeling [12]. If the cluster includes too many D_2O molecules, the electron number is insufficient in the cluster so that two D–D couples are screened correctly to insure at least one nuclear reaction. A bigger cluster would be necessary to obtain two nuclear reactions in the same cluster.

In those experiments one can assume that the cluster was completely ionised by impact onto the TiD target. Beuhler et al. evaluate the fusion yield to 10^{-1} s^{-1}/deuteron for a $(D_2O)_{100}$ cluster. The deuteron number per unit volume being approximately $3\times 10^{28}/m^3$, one has for the nuclear production term $T=6.64\times 10^{-30}$ m^3/s.

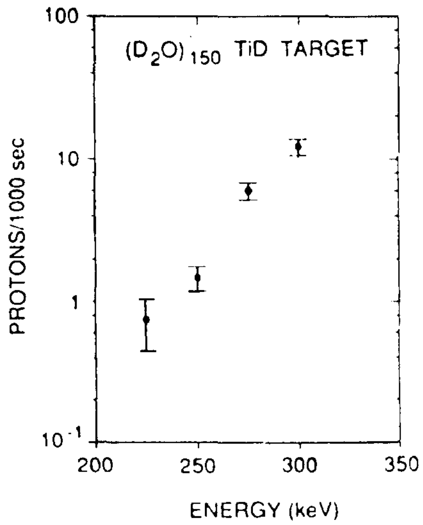

Fig. 4. Figure from ref. [17]. Results of a preliminary study of the energy dependence of the observed D–D reaction using 150 D_2O molecules. The ordinate scale is protons per 1000 s per nA of cluster current. (The protons were the detected particles in the Brookhaven experiments.)

For a typical 300 keV cluster ($n=150$) the energy per deuteron is 0.4 keV. One can thus plot a representative point in the diagram (fig. 2), this point being below the thermonuclear curve. Another similar experiment performed by Fallavier et al. [18] with deuterium clusters has not given any fusion reaction. The modeling by double screening could explain this apparent anomaly, the deuterium cluster medium being not rich enough in electrons for sustaining fusion reactions [#1].

It is worthwhile to notice that the medium of the NRL2 experiment is also rather poor in electrons, whereas the fully ionized $Li(ND_3)_4$ produces more free electrons available for screening, given that the ionization energies of lithium and nitrogen are smaller than the one of deuterium. The fully ionized CH_2 medium of the NRL1 experiments could have a similar richness in electrons. But the difference is the existence of a capillary containment wall in the Kiel experiment and no containment in the NRL1 experiment. One can infer from this remark that the screening conditions, which depend much on the medium components, are perhaps the same in the Kiel and the NRL1 experiments. They could be different in the Brookhaven experiments and also in the NRL2 experiments. In this last case the screening is probably less important but is not non-existent. The computer double screening calculations have also shown that the constant screening variations of T as a function of E were represented by straight lines whose slope was between 1.5 and 2 in the logarithmic diagram. This means that the r.m.s. current would be proportional to a power of the r.m.s. current between I^8 and I^6. In fact the NRL2 experiments have shown a I^{10} dependence (see fig. 5). In cluster experiments as T varies as a function of E like E^8, it would vary like I^{16} if the cause were the electrodynamic forces. It shows that the dynamics of T variations depends drastically on experimental conditions which favour more or less the double screening. But the calculated values for this dynamics (I^8–I^6) appears to be less than the ones measured in cluster experiments and in frozen deuterium experiments. Is there anything to infer concerning the possible dynamics of the capillary experiments? The most pessimistic point of view is to confide in the calculation results (I^8–I^6). An optimistic point of view is to keep in mind the fact that the medium has a high density from the beginning according to the remark of Lochte-Holtgreven [1]. In other words, the dynamics could be at least of the same order as in NRL2 (I^{10}). In fig. 2 the straight lines figuring the measurements of this dynamics are drawn as solid thin lines.

[#1] A more recent experiment, performed by Bae et al. [19], shows that titanium plays no role in the process, as they have replaced TiD targets by deuterated polyethylene targets, and they have confirmed the Brookhaven results.

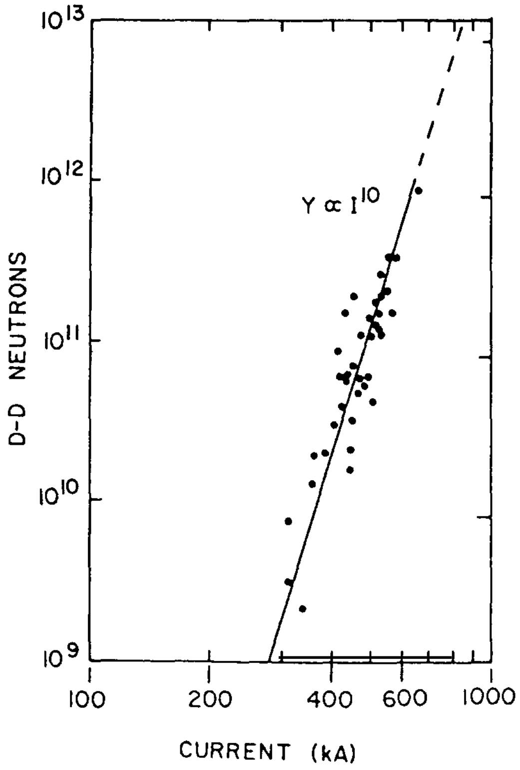

Fig. 5. Figure from ref. [16]. Neutron yield as a function of current in the Z-pinch experiment. The fiber diameter is 80 μm. The yield is well represented by the expression $Y=7.3\times10^{13}I^{10}$, with I in MA.

Considering similar conditions as in the Kiel experiments, the electric energy at the input is approximately $500(I/I_0)$ with $I_0\approx1.25\times10^4$ A. The output can be evaluated taking the two extreme values of the dynamics (I^6 and I^{16}). The energy balance is thus obtained for

$$500(I/I_0)=3.2\times10^{-7}(I/I_0)^q .$$

This equality gives the break-even for $\approx 10^{14}$ fusions, the r.m.s. current being equal to 5.1×10^4 A for $q=16$. For $q=6$ the r.m.s. current would be 8.6×10^5 A. It is interesting to remark the straight line joining the Kiel and NRL1 representative points (dotted line). Its slope could give the good exponent for capillary experiments ($q=12$). The corresponding break-even parameters would be 8.5×10^4 A and 10^{15} fusions.

We conclude that if such a dynamics is possible in capillary experiments the break-even would be attainable for a relatively low r.m.s. current owing to the double screening process even in the most pessimistic case. One has also to notice that this double screening could also explain the so-called "cold fusion reaction". It is now only a matter of performing again experiments (like the ones of Kiel but for higher r.m.s. currents) to verify or invalidate the hypothesis.

This paper reports a common endeavour performed by J.P. Vigier and myself and also summarizes the results obtained by myself on a computer treatment of electron screening [12] in order to understand how fusion reactions could appear under non-thermonuclear conditions. This work has been embodied in two patents [20,21] and summarized in two sealed communications made to the French Academy of Sciences [22,23]. I am grateful to H. Rauch (Kernforschung Institut Wien, Austria) and to P. Graneau (Northeastern University, Boston, MA, USA) for having provided information about the quoted experiments.

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