THEORETICAL IDEAS ON COLD FUSION

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ABSTRACT: The rapidly expanding experimental body of information on the phenomena attributed to cold nuclear fusion poses several fundamental challenges to the generally accepted physical picture of both condensed matter and nuclear physics. In this presentation I will show how a recently proposed approach to the coherent electrodynamic processes in condensed matter, in terms of the so called "superradiant" behavior, can be used to provide for explicit coherent mechanisms for: (a) greatly enhancing the tunneling probability in the DD fusion process; (b) ultrarapid electron cooling of the excited compound nucleus, thus strongly suppressing the usual n-^{3}He and p-T channels of DD fusion in vacuum.

INTRODUCTION

In the year that has elapsed since the Fleischmann-Pons announcement of anomalous heat production in the electrolysis of heavy water with a Pd cathode, the experimental activity in the field of "cold" nuclear fusion has been steadily going on, so that today we can identify roughly 5 distinct lines, or broad categories of experimental results, with which present day theoretical efforts must confront themselves; namely

(1) The Fleischmann-Pons (FP) line[1], where an excess heat of the order of a few tens of $\frac{W}{cm^3}$ (corresponding to $\sim 10^{12}$ fusion $sec^{-1}cm^{-3}$) is produced over periods of time of a few days. The observed excess heat is at least 9 orders of magnitude larger than the rate of production of both neutrons and tritium;

(2) The Jones (J) line [2], where the electrolysis of heavy water is performed with both Pd and Ti cathodes, but with a very different choice for the electrolytes (in FP case LiOD 0.1 molar). The 2.45 MeV neutrons of DD fusion have been observed significantly above background, with rates typically 9-10 orders of magnitude smaller than those implied by FP excess heat. We may attribute to this line, due to the similarity in the fusion rates, also absorption experiments of gaseous D_2, such as Scaramuzzi's[3];

(3) The Texas A& M (TAM) line [4], where the excess heat production in similar electrolysis setups has been observed, accompanied by the occasional large release of tritium (with rate only a few orders of magnitude smaller than the FP rate) and of a much smaller numbers of neutrons (compatible with Jones' rate $\sim 10^2 \div 10^3$ fusions $sec^{-1}cm^{-3}$)

(4) The Brookhaven (B) line [5], where Titanium deuteride is bombarded with very small clusters of heavy water (of the typical size of a few hundred molecules) with average D energy of the order of few hundred eV. DD fusion is detected in the p-T channel with a cross section about 10^{10} times bigger than expected;

(5) The Caltech-Harwell-Yale (CHY) line[6], where FP types of experiment were conducted with sophisticated equipment to detect nuclear fusion products. No significant effects of any type have been observed.

Three of the four positive lines have received rather significant confirmation; here is a very incomplete and rather arbitrary selection:

(FP) The Minnesota group [7] experiment

(J) The Gran Sasso [8] and Los Alamos [9] experiments;

(TAM) The Oak Ridge [10] and Rome [11] experiments;

The most remarkable aspect, however, of the four positive lines is their general lack of reproducibility that, in a sense, makes them not totally incompatible with the CHY line.

Thus if we accept that, as J. Schwinger puts it, nuclear energy appears in an atomic lattice, we must face the hard and heavy task to understand theoretically how MeV physics (nuclear energy) can arise from eV physics (the energy that is at play in an atomic lattice). In other words we must address two basic problems:

i) how does the Coulomb barrier, that inhibits DD fusion in the D_2 molecule, get suppressed in a metal (Pd, Ti) matrix so as to enhance the tunneling probability by more than 50 orders of magnitude ($\sim 10^{-40}$ to account for J-line rates);

ii) how can DD fusion take place in a Pd lattice differently than in vacuum, and with a gain in rate of an extra ten orders of magnitude (to explain the FP rate).

Needless to say, the answer to both questions appears desperate within the generally accepted physical picture of condensed matter, where the elementary matter systems (nuclei, electrons, atoms) are held together by electrostatic and magnetostatic short-range forces. Indeed, as for i) the diffuse conduction electrons' cloud cannot substantially lower the DD Coulomb barrier, nor can the electrons' enhanced effective mass, that sometimes characterizes their propagation through the lattice, be invoked at the small distances ($\leq .5$Å) where tunneling takes place. As for ii) it appears sheer science fiction that for the times ($\sim 10^{-21}$ sec) and the distances ($\sim 10^{-12}$ cm) involved in DD fusion the lattice may be any different from the perturbative QED vacuum.

In this presentation I shall illustrate how a recent approach to the coherent interaction between the matter constituents and the electromagnetic radiation field [12] in condensed matter ("Superradiance") can provide natural mechanisms to give a solution to both problems i) and ii). Much of the material that I shall present has already appeared in print [13,14].

THE "PLASMAS" OF COLD FUSION

Let me first briefly illustrate the ideas and the main results of the application of "Superradiance" to plasmas [12].

A plasma is, as usual, a system of N charged particles, of charge Q and mass M, in a volume V oscillating around their equilibrium positions, immersed in a fluid of opposite charge that insures overall neutrality. Such a system is characterized, as well known, by a plasma frequency (I shall use throughout the natural units $\hbar = c = 1$)

$$\omega_p = \frac{Q}{(M)^{1/2}}\left(\frac{N}{V}\right)^{1/2}, \tag{1}$$

the frequency of small amplitude oscillations of the charged particles around their equilibrium positions. The "Superradiant" program describes a plasma by a quantum wave field $\Psi(\vec{x}, \vec{\xi}, t)$, $\vec{x}$ denoting the equilibrium position and $\vec{\xi}$ the small deviation therefrom (obviously the particle position is $\vec{X} = \vec{x} + \vec{\xi}$). For large N it is possible to show that:

(a) the wave field can be written as

$$\Psi(\vec{x}, \vec{\xi}, t) = \Psi_0(\vec{x}, \vec{\xi}, t) + \eta(\vec{x}, \vec{\xi}, t), \tag{2}$$

where $\Psi_0(\vec{x}, \vec{\xi}, t)$ is a complex c-number wave function such that

$$|\Psi_0(\vec{x}, \vec{\xi}, t)|^2 \sim O\left(\frac{N}{V}\right), \tag{3}$$

while $\eta(\vec{x}, \vec{\xi}, t)$, the field of quantum fluctuations, is in general $O[\frac{|\Psi_0(\vec{x}, \vec{\xi}, t)|}{\sqrt{N}}]$;

(b) the wave function $\Psi_0(\vec{x}, \vec{\xi}, t)$ is $\vec{x}$ independent within space domains of at least the size of the e.m. field wave length λ_p associated with the plasma frequency ω_p,

$$\lambda_p = \frac{2\pi}{\omega_p}, \tag{4}$$

such space regions shall be called "coherence domains";

(c) at temperature T=0, within a coherence domain all charges oscillate in phase performing oscillations of well defined amplitude, depending on the anharmonicities of the real system. These coherent charge oscillations are also in phase with a peculiar coherent mode of the e.m. field, of wave length λ_p and frequency $\omega < \omega_p$, that remains trapped in matter;

(d) the coherent e.m. field interacts also with the quantum fluctuations $\eta(\vec{x}, \vec{\xi}, t)$, creating energy gaps in their spectrum. When T increases the quantum fluctuations get excited with a Boltzmann spectrum up to the point when the condensed phase described by $\Psi_0(\vec{x}, \vec{\xi}, t)$ is totally depleted, thus leading to a phase transition.

In the following these results shall be applied to the three plasmas of a Pd deuteride:

(α) the electron plasma of the 10 peripheral d electrons, with plasma frequency

$$\omega_{ep} \simeq 30\ eV, \tag{5}$$

implying that the minimum size of coherence domains is

$$\lambda_{ep} = \frac{2\pi}{\omega_{ep}} \simeq 400 Å; \tag{6}$$

(β) the Pd nuclei plasma(*) whose plasma frequency is

$$\omega_{Np} \simeq .85\ eV, \tag{7}$$

with coherence length

$$\lambda_{Np} = 1.5\mu; \tag{8}$$

(γ) the D plasma with

$$\omega_{Dp} = x^{1/2}.13\ eV, \tag{9}$$

and

$$\lambda_{Dp} \simeq 10\ x^{-1/2}\mu; \tag{10}$$

where x denotes the ratio D/Pd.

Before proceeding I should sound the warning that in real life $T \neq 0$, and the different systems may considerably deviate from the behavior of an ideal plasma. However I shall assume that these factors do not qualitatively change the picture.

(*)Actually in the analysis of this paper, this plasma does not play any important role.

THE COHERENT ELECTRON PLASMA AND THE ENHANCED TUNNELING

Let's consider a plane of the Pd lattice (see Fig.1). Suppose that the d electrons oscillate coherently in one of the direction connecting nearest Pd neighbors (say ξ);

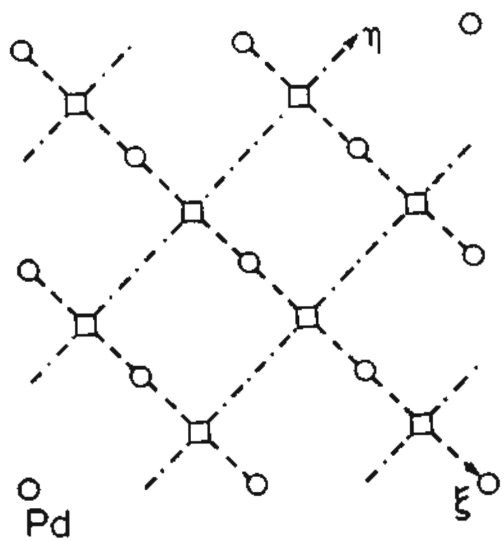

Fig.1 A plane of the Pd-lattice. The sites denoted by a circle are occupied by the Pd-nuclei, while those denoted by a square are occupied by D-nuclei. ξ and η are the two orthogonal directions linking nearest Pd neighbors. The dashed lines shall be called ξ-lines, the dash-dotted η-lines.

then from Thomas-Fermi theory we have approximately the situation depicted in fig.2. We can imagine in fact the d-electrons concentrated in a spherical shell at about 1.5 a_o (a_o = .57 Åis the Bohr radius) from the Pd nucleus, performing coherent oscillations of amplitude approximatively a_o in the ξ-direction. It is clear that in the hatched region of fig.2 a static negative charge distribution will be seen by any D nucleus moving along the orthogonal direction η . A simple application of the Gauss theorem to the disc-like region around the positions denoted by squares in fig.1, of height (in the ξ direction) a_o and radius R, together with symmetry considerations [the electric field in the ξ-direction vanishes for symmetry reasons on the circles at $\xi = \pm a_o/2$ (fig.2)], yields (e is the electron charge; $\alpha = \frac{e^2}{4\pi} \simeq \frac{1}{137}$)

$$e\,V(R) \simeq Z_d \frac{\alpha}{a_o} \frac{R^2}{R_o^2} \qquad (11)$$

where $R_o \simeq \sqrt{2}a_o$ (the maximum radius of the disc within which the stationary electron plasma is contained) and $Z_d \simeq \frac{10}{3}$ is the charge contained in the disc. Thus along any η-line we have the potential profile reported in fig.3(a).

Suppose a D_2 molecule of the approximate size of $\simeq 2a_0$ enters the lattice, the electrostatic forces will be strong enough to tear it apart and send the deuterons into contiguous minima, thus modifying the potential profile as depicted in figure 3(b). The modification of the nearest wells (by about 10 eV at the bottom) is then, presumably, strong enough that molecular D_2 cannot be dissociated there. This would explain easily and naturally why the β-phase of D_2 absorbed in Pd, in a wide span of p and T, is at $x \simeq 2/3$. This physical situation does not apply to the D nucleus (which is presumably the form in which deuterium enters the lattice in appropriate electrolytical conditions), and its wandering around will bring it to fill one of the vacant deep holes. In the process it may be trapped in one of the shallow holes(fig.3(b)), but it will have no chance to tunnel toward the D nucleus sitting close, for there are around empty deep holes that are better accessible. The situation will clearly change when all the deep holes are filled, i.e. when

$$x \simeq 1, \qquad (12)$$

for then the D nucleus trapped inside the lattice will evolve to a stationary state, and its tunneling amplitude can be computed by the well known semiclassical formula:

$$D_T^{1/2} \sim exp - (2\mu)^{1/2} \int_{r_n}^{r_0} dr\sqrt{V(r) - E}, \qquad (13)$$

where $\mu = \frac{m_D}{2}$, $E \simeq 0$,

$$V(r) \simeq \frac{\alpha}{r} - V_0 \qquad (V_0 \simeq 100\ eV), \qquad (14)$$

the classical turning point r_o is given by

$$r_0 = \frac{\alpha}{V_0} \simeq 1.4 \cdot 10^{-9} cm,$$

and r_n is the distance between the two protons ($\sim 10^{-12}$) where Yukawa attraction overtakes Coulomb repulsion. A simple calculation yields:

$$D_T^{1/2} \simeq exp\{-(2\mu\alpha r_0)^{1/2}[\frac{\pi}{2} - 2(\frac{r_n}{r_0})^{1/2}]\} =$$

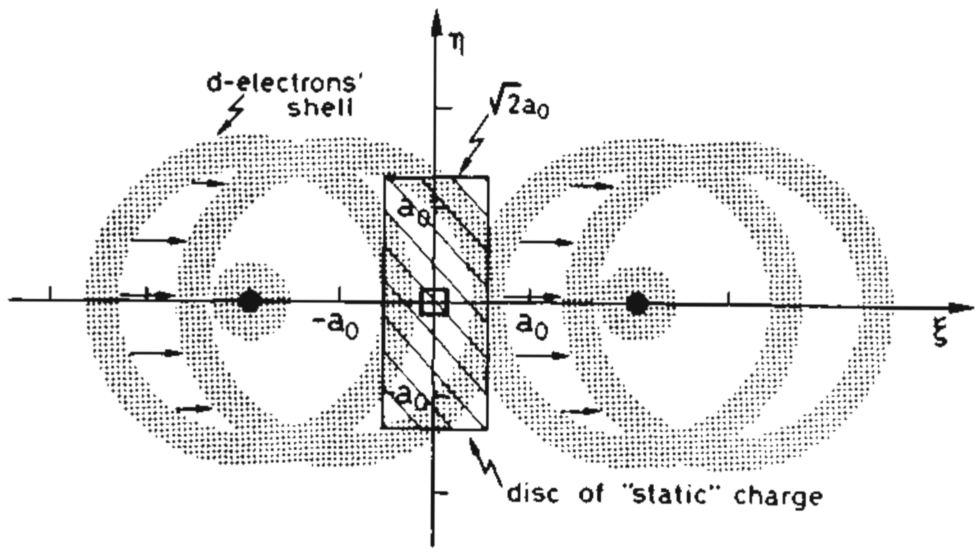

Fig.2 The d-electrons' plasma oscillations between nearest Pd-neighbors. a_o is the Bohr radius (.57Å)

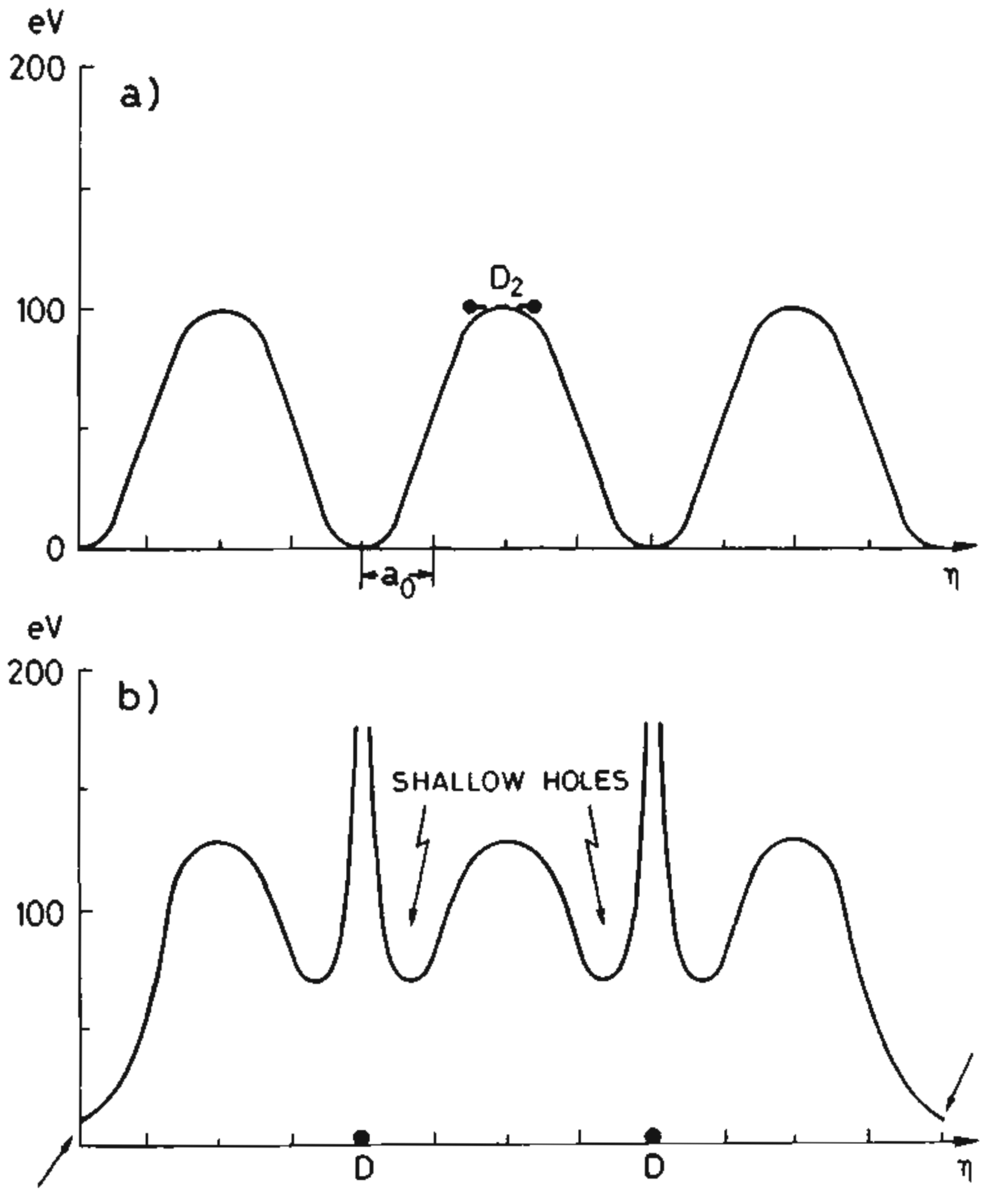

Fig.3

(a) The potential profile along η that a D_2 molecule sees in an empty Pd-lattice.

(b) Same, when two contiguous square-sites are occupied by a D-nuclei. The arrows indicate the modification of the deep holes close to the D's.

$$= 10^{-21.5} \cdot 10^{.3(r_n)^{1/2}} \sim \quad (r_n \; in \; fermis)$$
$$\sim \; 10^{-20} \quad for \; r_n \simeq 20F, \qquad (15)$$

thus realising an enhancement of some 30 orders of magnitude over the tunneling amplitude for molecular deuterium. For titanium deuteride similar mechanisms can be envisaged, but an explicit analysis has still to be performed.

COHERENT vs. INCOHERENT FUSION

If the coherent electron plasma oscillations, just described, were the whole story, that part (10^{-40}) of all the D nuclei in excess of $x_0N(x_0 \simeq 1)$ that tunnels beyond r_n would undergo usual (in vacuo) DD fusion with an incoherent fusion rate ($\Gamma \sim 10^{21} sec^{-1}$)

$$R_{inc} = D_T(x - x_0)N\Gamma \simeq$$
$$\simeq 5 \cdot 10^3(x - x_0)sec^{-1}cm^{-3} \qquad (16)$$

some ten orders of magnitude smaller than the rate of excess heat production. This, however, may explain the results belonging to the J-line. Furthermore, the incoherent fusion will yield the same fusion products as hot fusion, namely p-T and n-^{3}He in an approximately fifty-fifty proportion.

Where then can one find the factor of about ten billion that we need to account for the observed excess heat? Let's suppose that x_0 has been reached and therefore no "deep hole" is accessible to the extra $(x - x_0)$N deuterons that are jammed into the lattice. Then the plasma of deuterons in the deep holes within a coherence domain (10μ across) will be in a collective state and will be "seen" by the incoming excess deuteron as **a single quantum mechanical system**, described by **a single quantum mechanical wave function.** This simply means that the DD fusion amplitude will be constructed coherently by summing over all N_{cd} (N_{cd} is the number of D's in a coherence domain) "classical paths of fusion". However in order for coherence to hold up we must require that very little or no energy be transferred to the D plasma. As a consequence we must have somebody else in the metal to carry away the several MeV involved in a fusion process.

We shall now see how the electron plasma can do this job most efficiently. By applying perturbation theory, we need compute the diagram in fig.4, according to which the fusion amplitude at the time T, for an energy release E to the plasma, is given by

$$A_n(E,T) = -i\int_0^T dt \langle e_p'n|\vec{d}\cdot\vec{E}(t)|e_p\rangle, \qquad (17)$$

where $\vec{d}$ is the electric dipole operator for the electron plasma [12],

$$\vec{d} = e\left(\frac{1}{2m_e\omega_{ep}}\right)^{1/2}(\vec{a}^\dagger + \vec{a}),$$

and the electric field $\vec{E}(t)$ is given by the matrix element

$$\langle final\; state, -E|\vec{E}(t)|DD_p\rangle =$$

$$= \frac{ie^{-iEt}}{E}\langle final\; state, -E|\vec{J}_{em}(0)|DD_p\rangle, \qquad (18)$$

where use has been made of the Maxwell equations and the fact that, due to the condensation of the plasma of deuterons D_p, no substantial $\vec{x}$-dependence can arise in the problem. Thus in order for the matrix element (18) to be non zero beyond r_n we must have nuclear configurations that allow for the large e.m. current needed in the cooling process.

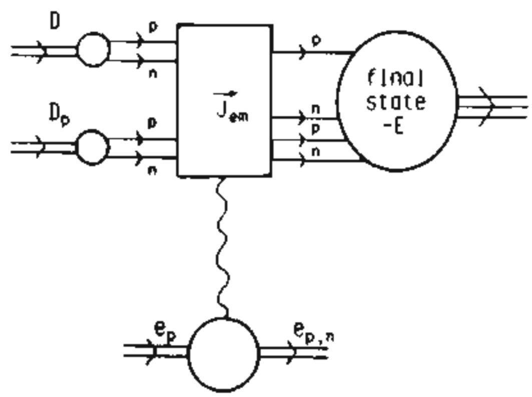

Fig.4 The perturbative amplitude for the electromagnetic cooling of the initial DD_p-state by the electron plasma.

A look at fig.5 immediately shows that the most favorable configuration for the long range Yukawa interaction (that requires a neutron and a proton to "face" each other) in order to give rise to large e.m. currents (through the rapid motion of the peripheral proton) must evolve into a p-T^* configuration.

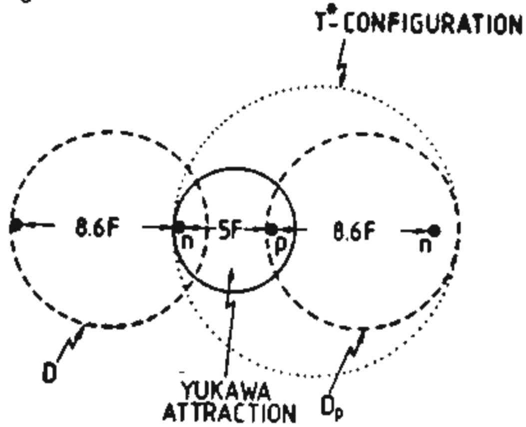

Fig.5 The preferred configuration for DD_p-tunneling (p n facing each other) evolves toward a p-T* state in order to maximise the e.m. current, necessary to the couple the electron plasma.

The n-^{3}He* configuration being clearly suppressed for in this case it is the neutron that is rapidly moving. Thus we can write

$$\vec{E}(t) \sim \frac{e^{-iEt}}{E} e\vec{v}_p(E) D_T^{1/2} (\frac{N}{V}) =$$

$$= ie^{-iEt} \vec{E}_0 D_T^{1/2}, \qquad (19)$$

where $|\vec{v}_p| \simeq .1$ for $E \simeq 5MeV$. The probability for an energy release E after the time T can be easily calculated from (17). We obtain:

$$P(E,T) = \sum_n |A_n(E,T)|^2 =$$

$$= \frac{4e^2}{E^2} |\vec{E}_0|^2 \frac{D_T N_e^2}{2m_e\omega_{ep}} \sin^2(\frac{ET}{2}), \qquad (20)$$

where N_e is the number of "condensed " electrons contained in a coherence domain of the D plasma (with volume $V_{cd} \simeq \lambda_p^3$):

$$N_e \simeq 10 \frac{N}{V} V_{cd} \cdot f \simeq 6 \cdot 10^{14} f, \qquad (21)$$

$f \leq 1$ being the fraction of the correlated component of the electron plasma. In order to determine the " coherent" fusion rate we must evaluate the energy E that the electron plasma can absorb in a cycle $ET = \pi$. From the classical equation ($\vec{v}_e$ is the velocity of the electron plasma)

$$\frac{dE}{dt} = e\vec{E}_0 \cdot \vec{v}_e N_e \sin(Et), \qquad (22)$$

and Eq.(19) one obtains

$$E^3 = 2e^2 (\vec{v}_p \cdot \vec{v}_e) \frac{N}{V} N_e, \qquad (23)$$

and putting numbers in one gets

$$E \simeq 3.6 \ f^{1/3} MeV. \qquad (24)$$

The time in which this energy is released is given by

$$T = \frac{\pi}{E} \simeq f^{-1/3} .5 \cdot 10^{-21} sec, \qquad (25)$$

very short indeed! We can now estimate the coherent fusion rate

$$R_{coh} = (x - x_0) N \Gamma_{coh} \simeq$$

$$\simeq f(x - x_0) 3.5 \cdot 10^{13} sec^{-1} cm^{-3}, \qquad (26)$$

$$\Gamma_{coh} = \frac{P(E,T)}{T} = f \ .7 \cdot 10^{-9} sec^{-1}, \qquad (27)$$

some ten orders of magnitude larger than R_{inc}. For $x - x_0 \simeq .1$ and $f \simeq 1$, we obtain a power output

$$W \simeq 20 \ Watt/cm^3. \qquad (28)$$

In spite of the definite crudeness of the calculation reported here, we seem to obtain rather naturally numbers in the right ball park.

HAS A COHERENT PICTURE EMERGED?

I shall address this question by assuming that superradiant behavior sets in in all plasmas of the metal-deuteride under consideration. Then for the various lines, sketched in the Introduction, the following is a possible scenario arising from the previous discussion:

(a) The CHY line, that reports consistently negative results can be explained by the failure of the groups involved to reach the obligatory threshold value $x_0 \simeq 1$ (*).

(*) From a discussion with Dr. F.G.Will, this possibility seems strongly suggested by his survey of all negative and positive results so far reported.

The threshold condition may also be a convincing explanation for the universally observed erratic reproducibility of the cold fusion phenomena.

(b) The B line: if the kind of potential wells ($\sim 100\ eV$) that surround D in the Pd lattice also hold in the Ti lattice (we have not been able to work it out yet, however) then the enhancement by 10 orders of magnitude of the DD fusion cross-section, observed in [4], can be easily explained.

(c) The J line: the conditions prevailing in this line of experiment are most likely non-stationary, so that the incoherent fusion processes with rate (16) is the only possible. This agrees with observation.

(d) The FP line: the substantial excess heat of the order of a few tens of $Watts/cm^3$ observed by Fleischmann and Pons is just in agreement with (28). The lack of observation of both neutrons and tritium can be understood if we make the hypothesis that they have reached almost ideal conditions ($f \simeq 1$). In this case, after the coherent interaction with the electron plasma has cooled the DD system, according to (24) by about $3.6\ MeV$, the successive cooling steps will occur with rates

$$\Gamma \simeq \frac{1}{T} = \frac{E}{\pi} \simeq 1.2\ MeV,$$

[see Eq. (25)], competing in principle with the rate of a p-T^* configuration to turn into a p T state with a Q value of about $400\ KeV$. It is reasonable that in this condition the latter rate will be much smaller than 1 MeV (or $1.5 \cdot 10^{21} sec^{-1}$).

(e) The TAM line: abundant production of tritium in a late stage of excess heat yield may be attributed to some ageing effect of the electron plasma, which substantially lowers f by the presumable creation of vortices in the cooling processes. If this is the case, for, say, $f \simeq 10^{-2}$ according to (24) the cooling steps carry away about $800\ KeV$ each, and their rate is [see Eq.(25)] about $0.5 \cdot 10^{21} sec^{-1}$ (or $250\ KeV$). This means that after about 5 steps the system p-T^*, having consumed all its Q($\sim 4MeV$), will be close to a p-T configuration where both nuclei are at rest, thus decoupling from the electrons' plasma. Coulomb repulsion will then succeed in producing, some of the times, a (almost) zero-energy p-T final state at a rate between two and three orders of magnitude smaller than the FP-rate, as observed. Obviously much more theoretical work is needed to turn this plausible arguments into a quantitative description. We hope to get back to this important problem soon.

Finally, about the question of the main fusion product in the FP and TAM lines the inevitable conclusion is that ^4He is produced. It is very unlikely, however, that in the condition prevailing in a "successful" electrolysis atomic He, which most probably gets formed, lingers on in the Pd lattice, being expelled by the flux of incoming D nuclei that strenuously compete to occupy the shallow holes available to them.

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