Review of the Current Theoretical Status of Cold Fusion

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ABSTRACT: We review conventional models of neutron production in metal deuterides, concentrating particularly on speculations that the fusion neutrons are resulting from a small population of deuterium nuclei at high energy. We show that the neutron production resulting from the formation of thermalized pockets of deuterium plasma, or from collisions between high energy deuterons during the fracturing of hydrides, is insufficient to explain the rates reported by Jones *et al* and others.

1 Introduction and overview

Following the first major workshop devoted to Cold Fusion, held in Santa Fe, New Mexico on May 23-25, it appears that the observation of 2.5 MeV neutrons by Jones *et al* [1] has been tentatively confirmed by experiments performed at Los Alamos [2] and Grand Sasso [3]. The Los Alamos experiment in particular also observe neutron 'bursts', as suggested by an earlier report from Frascati [4]. Theorists now face the challenge of understanding these extraordinary observations.

Fusion rates of heavy *molecules* have been known to be exceedingly small. However, the new idea pursued in the experiments of Jones *et al* has been the possibility that the key quantity η, essentially the exponent of the coulomb barrier tunnelling probability, will be substantially altered when hydrogen is implanted into a metallic lattice. Several metals were identified as particularly suitable, based on the known absorption and mobility of hydrogen. η is sensitive to the integrated strength of the (Coulomb) repulsion in the classically forbidden domain:

$$\eta = \frac{1}{\pi}\int_{forbidden} dR\sqrt{2\mu(E_{eff}-V_{eff})}$$

In a metallic environment, V_{eff} is governed by the presence of conduction electrons, whilst E_{eff} can be influenced by nonequilibrium processes. Since the reduced mass μ is most favorable for the *pd* reaction, this reaction was initially regarded as more promising than the *dd* reaction. In either *pd* or *dd* fusion reactions,

$$\begin{aligned} d+d &\rightarrow {}^3\text{He}\ (0.82\text{MeV}) + n\ (2.45\ \text{MeV}), \\ &\rightarrow {}^3\text{H}\ (1.01\text{MeV}) + p\ (3.02\ \text{MeV}),\ \text{ and} \\ &\rightarrow {}^4\text{He} + \gamma\ (23.8\ \text{MeV});\ \text{ or} \\ p+d &\rightarrow {}^3\text{He} + \gamma\ (5.4\ \text{MeV}), \end{aligned}$$

the final ash of the reaction is ^{3}He, while γ's and neutrons are produced at a specific energy, and can easily penetrate out of the experimental cell. A significant branch of the *dd* reaction produces tritium (t), which is easily detectible by the emission of an e^- during its decay into ^{3}He.

In normal low-level fusion activity, one would expect a random ('singles') fusion signal in the form of a γ (*pd* reaction) or an n (*dd* reaction). Tritium is much less likely to be produced for detection, without a dangerously high level of neutron activity, while neutron 'bursts' were not foreseen unless a chain-reaction of fusions were to develop, or some catastrophic event such as the collapse of an interstitial cavity occurs resulting in a sudden enhancement of the fusion rate for many deuterons. In the next section we discuss some of the theoretical limits on cold fusion neutron production rates imposed by the conventional view, and look at some specific physical models that have been proposed recently. We find ourselves forced to the conclusion that any realistic approach based on conventional two body nuclear and molecular physics is unlikely to explain even the cold fusion neutrons. The excess heat reported by Fleischmann and Pons [6], if correctly attributed to nuclear fusion, demands not only a vastly accelerated fusion rate but also an exotic mechanism to transform nuclear energies into heat without any accompanying radiation.

2 Status of Cold Fusion Theory

2.1 Perspective

One of the critical elements in understanding the "background" rate of fusions in a hydride is the understanding of the interaction potential between the hydrogen nuclei in metals such as palladium or titanium. It was quickly realized that diverse solid state effects can greatly influence the interaction potential and hence the fusion rate [7,8]. One particularly important mechanism is electron screening, in which the high electron densities lead to a substantial softening of the Coulomb barrier between the fusion nuclei in the region of half an electronic Bohr radius, or about 0.25 Å. Due to many other subtle (and perhaps as yet un-thought of) collective interactions, the long-range coulomb potential may be further modified. One of the conclusions arising from these quantitative studies is that even a very substantial modification of the Coulomb barrier will result in fusion rates that are many orders of magnitude smaller than the Jones rate. This conclusion has also been reached by other authors arguing on more general grounds [9].

A second effect that has been given much attention very recently is the confinement of two hydrogen nuclei within a lattice site. The primary motivation for this interest are the recent experimental indications that a stoichiometric ratio of greater than 1 is required [10] in order to obtain the heat production as reported by Fleischmann and Pons [6]. It is easy to obtain an order of magnitude estimate of the effect of confinement simply by placing two hydrogen nuclei in a box and by squeezing. This exercise again leads to the conclusion that the hydrogen fusion rates that can be realistically achieved are far too small to explain even the Jones rate [11].

The final item completing the list of "conventional" ingredients is energy or temperature. Two specific mechanisms have been discussed in this context. The first is the formation of thermalized "hot-spots" in the metal, formed for example during the collapse cavities when stress within the material is suddenly relieved, or during the fracture of the material which could result in the acceleration of deuterons to high energies. The second is the acceleration of deuterons across keV potentials caused by charge separation as a material fractures. These particular mechanisms could conceivably explain the neutron bursts that have been reported, if the required peak rates can be achieved. In addition, such high-temperature phenomena would have distinct energy or temperature dependent signatures in terms of the relative fusion rates between different hydrogen isotopes, making the verification of such mechanisms an attractive experimental target.

2.2 Fusion rates of Hydrogen isotopes

2.2.1 Standard fusion rates and tunnelling

The nuclear reaction rate in a static system consisting of two fusion nuclei described by a relative wavefunction $\Psi(R)$ is simply proportional to the probability amplitude of the nuclei being close enough to fuse. Generally, when the amplitude is small the wavefunction does not vary significantly within the nuclear region and we may express the fusion rate as:

$$\lambda = K_0 |\Psi(0)|^2 \tag{1}$$

$|\Psi(0)|^2$ is the probability amplitude that the two hydrogen nuclei come together, and K_0 is the fusion constant when the fusing nuclei are in a relative S-wave. Fusion from states of higher angular momentum are strongly suppressed due to the centrifugal barrier, and is important only under very special circumstances. For the d(d,n) ^{3}He reaction, generally considered the best candidate reaction for neutron production, $K_0 = 0.75 \times 10^{-16}$ cm^{-3}s^{-1} . This implies that in order to achieve the fusion rate of $\lambda = 10^{-24}\text{s}^{-1}$ per deuteron pair reported by Jones, we require a probability amplitude of $|\Psi(0)|^2 \sim 10^{-22}$ in natural units, an exceedingly small number indeed. The fusion constant K_0 in eq. (1) is usually obtained from scattering experiments at $E \geq 10$ keV, in which the fusion cross section can be measured. In this context, it is customary in literature to refer to the so called astrophysical function $S(E)$, which plays a very similar role as K_0 and which is also a slowly varying function of energy and is related to the fusion cross section (in free space, for the Coulomb potential) by:

$$\sigma(E) = \frac{S(E)}{E} e^{-2\pi\eta_0} \tag{2}$$

where $\eta_0 = \alpha/v$ is the Sommerfeld parameter, $\alpha \simeq 1/137$ being the fine-structure constant. (All units used from here on and above are with $c = \hbar = k_B = 1$.) The link between equations (1) and (2) is straight forward in the regime in which the WKB approximation is valid. In this semi- classical approximation, the amplitude of the wavefunction at the origin is given by:

$$|\Psi(0)|^2 \simeq \frac{1}{\Omega} 2\pi\eta e^{-2\pi\eta} \tag{3}$$

where Ω is the volume, and

$$\eta = \frac{1}{\pi} \int_{r_{min}}^{r_{max}} \sqrt{2\mu(V(r) - E)}dr \tag{4}$$

μ is the reduced mass of the reacting bodies, $V(r)$ the barrier potential and E the relative energy. For the Coulomb potential, η reduces to the usual Sommerfeld parameter. The range of the integral is in the classically forbidden region of motion. For the small rates considered here the fusion rate is relatively insensitive to the nuclear channel radius r_{min}, of order fm, and we have set $r_{min} = 0$ for simplicity. For larger rates the finite size could become significant, as for example in the muonic molecular systems [12].

By comparing the equations (1) and (2) in the context of a coulomb scattering experiment in which the fusion rate is given by the usual expression $\lambda = \sigma\rho v$, we obtain the correspondence between K_0, the fusion constant at low energies, and the astrophysical S-factor obtained from scattering experiments:

$$K_0 = \lim_{E \to 0} \frac{S(E)}{\pi\alpha\mu} \tag{5}$$

The values of K_0 vary by several orders of magnitude for the different hydrogen isotopes, depending upon whether the fusion rate is mediated by the strong or electromagnetic interactions. The important physical parameters governing the fusion rate are gathered together in table 1.

The reactions of primary interest here are those involving deuterons. Inserting the values from table 1 into equations (1) and (4), we find that for the different reactions, the two effects of reduced mass and the fusion rate constant vie with one another as the parameter dominating the fusion rate. For low energies, the root of the reduced mass factors out in eq. (4) and it is the reduced mass that dominates the fusion rate. For higher energies, the barrier is reduced to a level of insignificance and it is the K-factor which dominates. In between, there is a cross-over in which the different fusion rates correspond. For the bare pd, pt, dd and *dt* reactions this occurs in the vicinity of 220 eV (CM energy), in which the different effects, each influencing the fusion rate by many orders of magnitude, conspire to cancel and bring the fusion rates to within an order of magnitude of one another. Although 220 eV is much above the energies one might believe to be present in the environment of the palladium, it is important to note that in thermalized systems the primary contribution for the fusion rate comes from the high energy tail of the energy distribution function. We shall return to this point in a following section.

Table 1

Reaction	μ (MeV)	$S(0)$ (MeVb)	K_0 (cm^3s^{-1})
$p+d \rightarrow {}^3$He $+\gamma$	625.411	2.5×10^{-7}	5.2×10^{-22}
$p+t \rightarrow {}^4$He $+\gamma$	703.336	2.6×10^{-6}	4.8×10^{-21}
$d+d \rightarrow {}^3$He $+n$	937.807	5.36×10^{-2}	7.48×10^{-17}
$d+d \rightarrow {}^3$H $+p$	937.807	5.58×10^{-2}	7.80×10^{-17}
$d+d \rightarrow {}^4$He $+\gamma$	937.807	2.2×10^{-10}	3.1×10^{-25}
$d+t \rightarrow {}^4$He $+n$	1124.65	1.16×10^{1}	1.35×10^{-14}

2.2.2 The effective Coulomb Interaction

The effective interaction between deuterons in a hydride is considerably modified by the presence of conduction electrons and metallic ions in the lattice. One of the simplest and most well-known effects is screening of charges by the conduction electrons, so that the usual Coulomb potential between two hydrogen ions is modified to a Yukawa-like potential with an exponentially falling repulsion at intermediate distances, of the form [13]:

$$V(R) = -\alpha \frac{e^{-R/R_s}}{R} \tag{6}$$

R_s is the screening length, and introduces a new length scale into the usual Coulomb potential. For distances much smaller than R_s the potential returns to the usual Coulomb potential. The behavior at larger distances is more complex, but is so small that it is not of much relevance to us here.

The actual value of R_s depends upon the density of electrons at the particular location within the material. A generally acceptable value is of the order of 0.25 Å [8]. Actually the screening length is not uniform throughout the material, but varies according to the presence of local crystal defects, grain boundaries etc. Since it is from these regions that most of the fusion will occur, we shall treat the screening length as a parameter in this analysis and take values ranging from the vacuum value of $R_s = \infty$, to a very optimistic $R_s = 0.1$ Å. In figure 1 we present the fusion cross section for the reaction $d + d \rightarrow {}^3$H$+n$, as computed from equation (2) for the screened potential (6). Figure 1 illustrates the impact screening has on the cross section. At low energies, below 100 eV, the impact is of several orders of magnitude and increases considerably towards the eV range (not shown).

At energies above 100 eV, however, the screening becomes increasingly irrelevant. This is a point worth

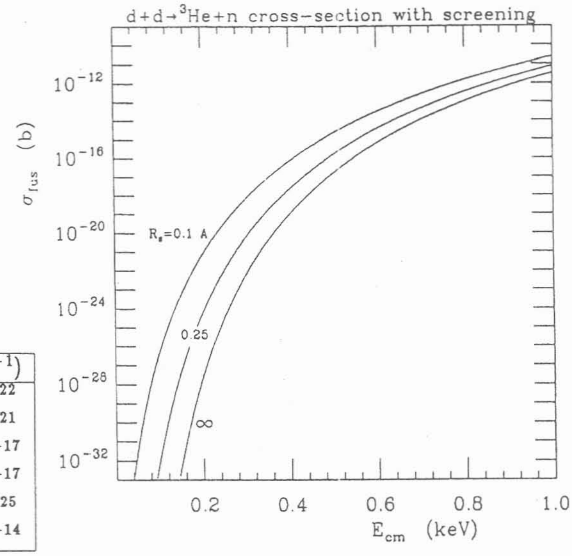

Figure 1: The screened fusion cross-section for the neutron reaction $d + d \rightarrow {}^3$H$+n$ for different screening lengths in Å.

noting when computing the fusion rates within a thermalized system, as the largest contribution to the fusion rate comes from the high energy tail of the energy distribution function. As for the low energy regime, where screening *does* have a significant impact on the fusion rate, it has been found that the fusion rates are simply too small to explain the Jones rate, unless screening lengths of less than 0.04 Å can be achieved [8]. Even 0.1 Å is on the borders of credibility, and for this reason, we turn next to the 'high energy' domain of cold fusion.

2.2.3 'Hot' Cold Fusion?

Cold fusion neutron production requires a mechanism that is able to produce of the order of 0.01 neutrons s^{-1} cm^{-3} of deuterated metal. When considering the number of deuterons within the sample, of the order of $10^{22}cm^{-3}$, it is clear that only a few deuterons need actually be responsible for the production of such a small number of neutrons, and suggests that perhaps some mechanism exists that accelerates a small number of deuterons to higher energies which then have a substantially enhanced fusion rate. The simplest model is that of a thermalized hot-spot consisting entirely of deuterium, heated perhaps by the collapse of a cavity within the lattice. The exact temperature of the hot-spots depends upon the specific model chosen, but we can estimate the order of magnitude by considering the energy densities within a stressed palladium crystal. The stiffness constants of metals are typically of the order of $C = 10^{11}$N/m^2, and the energy density of a stressed sample is $E/V = \frac{1}{2}C\sigma$ where $\sigma = \Delta L/L$ is the strain. Hydrides are known to distort by as much as 10% during the infusion of the hydrogen, so a strain of $\sigma = 0.1$ is reasonable. This results in energy densities of the order of 10^{11}J/m^3, or about 1 eV/Å^3, as being available for compressing and heating pockets of deuterons within the crystal. It is not possible to estimate the final temperature and lifetime of the resulting plasma without specifying the initial density, geometry and volume of the deuterium pocket, details which are beyond the scope of this paper, but a simple and realistic model places an upper limit on the attainable temperature of $T = 10$ eV.

Within a thermalized plasma, the cross section in eq. (2) must be folded with the thermal distribution in energies, which is simply the Maxwell-Boltzmann distribution:

$$f_{B_i}(E;T) = N(T, m_i)\, e^{-E/T} \tag{7}$$

where $N(T, m_i) = (m_i/2\pi T)^{\frac{3}{2}}$, and m_i is the mass of the thermalized particle of species i at temperature T. The net fusion rate between two species of nuclei i and j, of density ρ_i and ρ_j, is then:

$$\lambda_{fus}(T) = \rho_i \rho_j \int d^3v_1 d^3v_2 f_{B_i}(v_1) f_{B_j}(v_2) |v_1 - v_2| \sigma_{fus}(|v_1 - v_2|) \tag{8}$$

The velocity of the particles v is related to their energy E by the usual $v = \sqrt{2Em}$. Once the center of mass motion has been removed, eq. (8) becomes:

$$\lambda_{fus} = \rho_i \rho_j N(T, \mu_{i,j})\, \frac{1}{2}(2\mu_{i,j})^2 \times \int_0^\infty dEE\, e^{-E/T}\, \sigma_{fus}(E) \tag{9}$$

where $\mu_{i,j} = (1/m_i + 1/m_j)^{-1}$ is the reduced mass of the fusing nuclei. We see from eq. (9) that the fusion rate in such a system is thus a product of a steeply decreasing probability of occupying a state of high energy, here $E\, e^{-E/T}$, and a steeply increasing fusion cross-section $\sigma_{fus}(E)$. Generally, the product peaks at an energy very much above the temperature, depending on the penetration barrier determining the fusion cross section. Almost the entire contribution to the fusion rate therefore comes from a narrow region of energy far above the mean energy of particles in the system; this is the well-known Gamow-Teller peak. This fact implies that the relatively long-range modifications to the barrier potential, such as the screening discussed above, are relatively ineffective in increasing the fusion rates of thermalized systems of even very moderate energies of the order of eV. For example, if the temperature is only 5 eV, the Gamow peak is found to lie at about 190 eV.

In figure 2 we plot the fusion rate per particle in a plasma for a 50:50 mixture of hydrogen isotopes, at an overall density of 4×10^{22}/cc, for no screening and an extreme screening of 0.1 Å. For the extreme screening case $R_s = 0.1$ Å we can indeed reach 10^{-24} fusions per particle pair when the temperature is between 8 and 10 eV. However, remembering that only a small fraction of the deuterons within an electrode can possibly be in such an extreme state, it is clear that high temperatures are not going to come even close to explaining the neutron flux reported by Jones and others.

This result does not yet exclude high-energy fusion as being responsible for cold fusion. As noted

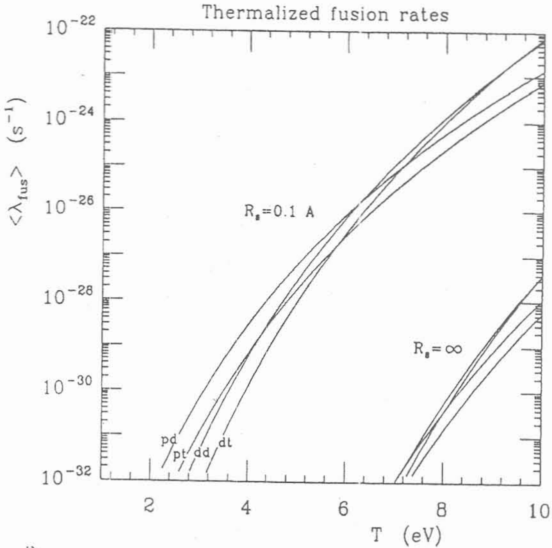

Figure 2: The fusion rate per particle in a plasma containing two hydrogen isotopes (dt,dd,pt or dp) of equal concentration, at an overall density of 4×10^{22}/cc, for no screening and an extreme screening of 0.1 Å

above, only a small fraction of the deuterons within the Gamow-Teller peak actually contribute to the fusion rate. It is not impossible that a mechanism exists that produces only high energy deuterons with energies in the keV region. There are several experiments that have been performed in which materials have been fractured or adhesive bonds broken in which the emission of x-rays in the keV region has been reported [14]. In addition, experiments have been performed in which LiD or D_2O have been fractured, and neutron emission have been reported, although the statistical significance of the neutron emission is only of the 2σ level and therefore cannot be taken as strong evidence for nuclear reactions [15]. Given that there is a source of high energy deuterons it is possible to compute the fraction of deuterons likely to yield neutrons, when incident upon a deuterated metal. This situation is somewhat different to that of the thermalized region of deuterons, in that the fusion occurs within the lattice itself and the high-energy deuteron rapidly looses energy as it passes through the lattice. Most of the energy is lost to electron ionization at energies below 1 keV, but for higher energies recoil against the lattice nuclei and deuteron nuclei within the lattice becomes increasingly important. The rate of energy loss is generally expressed in terms of the stopping powers S_i of each particle species i making up the target. When the ratio of fusing particles to incident particles N_{fus}/N_{inc} is small, the stopping powers are approximately related to the incident particle's energy loss rate by

$$\frac{dE}{dt} \simeq -\sum_i v \rho_i S_i(E), \tag{10}$$

E is the instantaneous energy of the incident particle slowing down in the material, and $v = \sqrt{2mE}$ is its velocity. ρ_i is the number density of each species of particle in the target. The stopping power is typically of the order of $10^6 - 10^7$ keV-barn and varies from material to material, generally increasing dramatically from below 100 eV, but then levelling off and becoming almost flat up to energies of 10 keV [16].

When the energy loss in (10) is taken into account, the fraction of incident particles of energy E_{inc} that will actually fuse when incident upon a metal deuteride AD_x of stoichiometric ratio x is:

$$\frac{N_{fus}}{N_{inc}} = x \int_0^{E_{inc}} dE \, \frac{\sigma_{fus}(E)}{S_{AD_x}(E)} \qquad (11)$$

with

$$S_{AD_x}(E) \simeq S_A(E) + xS_D(E) \qquad (12)$$

being the stopping power of the deuteride for the incident deuterium. E_{inc} is the energy of the incident particles. The ratio in eq. (11) is an expression of the efficiency of the target in allowing the incident deuterons to collide with and fuse with deuterons in the target, before the incident deuterons are slowed to a stop. This ratio is presented in figure 3. For ener-

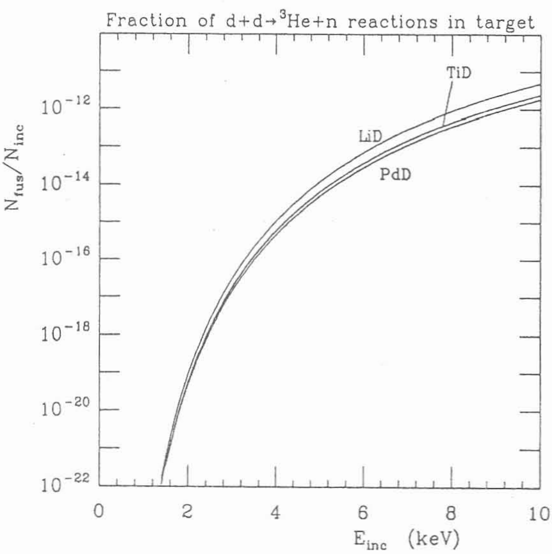

Figure 3: The fusion ratio for PdD, TiD, and LiD as a function of the incident particle energy.

gies in the region of 5-10 keV, the fusion ratio is of the order of 10^{-14}-10^{-11}. Thus, in order to induce 0.01 fusions per second one requires an incident flux of 10^{12} 5 keV deuterons or 10^{10}-10^{11} 10 keV deuterons per second. Numbers of this magnitude are comparable to the estimated number of keV electrons per square cm produced when an adhesive bond is broken as a material is torn from a metallic surface [17], although the great majority of these electrons are considerably below 5 keV in energy and some efficient mechanism would have to be found to transfer the kinetic energy from electrons to the heavier deuterons.

The number of required deuterons at a given energy may be re-expressed in terms of the *power* required to induce a neutron event rate of $0.01 s^{-1}$; the power required is simply:

$$P = \frac{0.01\,\mathrm{s}^{-1}}{(N_{fus}/N_{inc})} \times E_{inc} \qquad (13)$$

This quantity is plotted in figure 4. The fusion rate

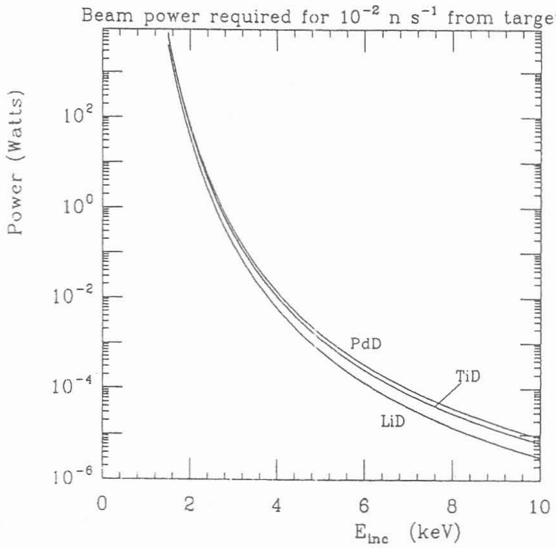

Figure 4: The deuteron beam power required to produce a neutron event rate of $0.01 s^{-1}$ from PdD, TiD, and LiD targets, as a function of the incident beam energy.

increases exponentially with incident energy, and consequently the power required to produce the desired neutron event rate decreases dramatically with increasing energy. The deuteron beam power at 2.8 keV is about 1 W, and decreases to about 10^{-5}-10^{-6} W for a beam energy of 10 keV. As the electrical power being passed trough a typical electrolytic cell is of the order of 1 W, we can conclude that if the electrical current in the cell is indeed driving the fusion, we are faced with an almost insurmountable problem of finding a mechanism to accelerate of the order of 10^{10} deuterons to keV energies.

We conclude that 'hot' cold fusion is unlikely to be responsible for the neutrons that have been observed by Jones and others. Thermalized hot spots are unable to reach the required temperature for the required periods of time. A monoenergetic mechanism requires such high energies for the particles that it is difficult to imagine a mechanism capable of accelerating them against the ever-present stopping power of the crystal. This induces us to believe that a truly unusual mechanism is required, such as the presence of a catalytic third body, or some fundamentally new effect that has up to now been overlooked.

3 Closing Remarks

The most significant problem facing cold fusion is the inability of some competent experimentalist to observe it. This could indicate that the important parameters have not yet been identified, and that some crucial element governing the effect differs from laboratory to laboratory. This uncertainty has had a very negative impact on many experimentalist and theorists, many of whom have chosen to discount those few experiments supporting cold fusion as a matter of personal preference. Nevertheless, there *is* a definite problem facing us; how to accommodate the—albeit few—experiments that *do* see the 'cold fusion effect' by confirming and explaining cold fusion theoretically and discovering the omissions in the failed experiments, or by discovering the errors in the experimental procedure of those experiments the now support the existence of cold fusion. When considering the experimental evidence that has already been accumulated, it appears that attaining either objective will be equally difficult.

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