COMMENT

COLD FUSION: IS THERE A SOLID STATE EFFECT?

RECENTLY Fleischmann and Pons[1] have reported experimental observation of an 'excess' heat production accompanied by emissions of gamma rays and neutrons when isotopic hydrogen (D_2) was infused electrolytically into a palladium cathode to near saturation level ($\sim 1 D_2/Pd$). Independently, Jones and coworkers[2], using a somewhat similar electrolytic cell and Ti as well as Pd as cathode, have reported details of observation of neutron emission peaking at ~ 2.4 MeV and significantly above the broad-spectrum background neutron count. Both groups have claimed this as evidence for a cold fusion occurring in the deuterated cathodes.

The diagnostic 2.4 MeV neutron emission is strongly suggestive of the allowed fusion reactions

$$\begin{aligned} d + d &\rightarrow {}^3He\,(0.82\ MeV) + n\,(2.45\ MeV) \\ &\rightarrow t\,(1.01\ MeV) + p\,(3.03\ MeV) \end{aligned}$$

(with 1:1 branching ratio). The neutron flux detected by Jones *et al.* was, however, much smaller ($\sim 0.41\ s^{-1}$ for a 3 g electrode of Ti) than that of Fleischmann and Pons ($\sim 4 \times 10^4\ s^{-1}$ for a 15 g Pd electrode). Moreover, the latter was at least nine orders of magnitude much too small to be consistent with the observed rate of 'excess' heat production (~ 10 W per cm^3 of electrode volume). This large discrepancy indicates that (i) alternative aneutronic channels may be operative, (ii) the 'excess' heat may after all be of chemical origin, not altogether unexpected from the known chemistry of these transition metal hydrides, or (iii) the experimental results are simply wrong in terms of the heat balance reckoning or the neutron flux detection. Absence of contemporaneous control experiments in order to properly subtract for the varying cosmic ray neutron and gamma ray backgrounds, and inadequate ^3He and tritium assays are the obvious worrying points. While initially several laboratories around the world corroborated—some informally—the original findings of these two groups, negative results were soon reported, notably by major laboratories[3], questioning this claim of cold fusion. There is now no compelling reason to believe cold fusion, at least as a commercial source of energy[4].

Be that as it may, these experiments and the extensive discussion that followed have successfully focused attention on the single most important and as yet unresolved basic question, namely whether or not solid state effects can affect the fusion rate appreciably[5]. The question is not entirely devoid of practical importance, for, if the answer is affirmative, the solid state effects can be tuned to advantage. In the following we will address this problem in physical terms.

Consider first the simplest case of d–d fusion in a deuterium molecule D_2. The nuclear interaction causing fusion is strong but of short range ~ 2–3 fm $\ll$ bond length $\sim$ closest distance of approach, classically $R_0 \simeq 0.7$ Å in the deuterium molecule D_2. The latter is essentially the internuclear separation (screening length), below which the charged nuclei are exposed to the bare Coulomb repulsion. The resulting so-called Coulomb barrier must be tunnelled through quantum-mechanically. The fusion rate is then limited by the barrier penetrability (Gamov) factor, which, for free d–d collision, as in the case of plasma fusion, is given by

$$\exp(-2\pi e^2 \sqrt{M/\hbar}\sqrt{2E}).$$

This has a sensitive (exponential) dependence on the centre-of-mass energy E, which in turn determines the tunnelling distance ($\simeq R_0$ under the barrier). For the case of molecular fusion in D_2, E is effectively $\sim e^2/R_0$. The sensitive dependence on the tunnelling distance R_0 is, of course, well demonstrated by the known muon-catalysed fusion in muomolecular deuterium ion $(dd\mu)^+$. Here the electron is replaced by a negative muon (heavy electron), which is about 200 times as massive. This leads to a contraction of the Bohr radius (and, therefore, of the screening length R_0) by the same factor, leading to a fusion time in D^+ of $\sim 10^{-11}$ s, which is an 85 orders of magnitude enhancement over the fusion rate of $\sim 10^{-74}$ fusions per deuteron pair per second for the electronic deuterium molecular ion $(dde)^+$. (Indeed, there has been a suggestion that cosmic muons may have catalysed the reported fusion in deuterated palladium/titanium. However, realistic estimates based on the observed muon flux, their tendency to get stopped and captured by high-Z nuclei, and their short lifetime of $\sim 2.2\ \mu$s rule this out.) From the Gamov factor one can readily see that to get the

inferred fusion rate of $\sim 10^{-23}$ per d–d pair per second, all that is necessary is to make the electronic effective mass just about 6 times its bare mass, thus reducing the bond length from 0.7 Å to 0.1 Å and effectively increasing E from 20 eV to $\sim 10^2$ eV. Naively one could hope for such an effective mass enhancement from the band structure and the Fermi-liquid renormalization effects in deuterated Pd/Ti. Transition metals do have large effective masses and in heavy fermion systems $m_{\text{eff}}/m \sim 10^2$ is common. When a D_2 molecule is introduced into metallic palladium, the covalent bond in D_2, which may be regarded as a highly nonlinear screening of d–d Coulomb repulsion by the bound valence electrons, is expected to be replaced by a metallized bond (electron gas screening), giving D^+ ions. For a simple electron gas model of the host metal, the condition for this ionization is

$$K_c \hbar^2 / Zme^2 > \sqrt{2},$$

where Z (= 1) is the charge on D^+, and

$$K_c^2 = 4\left(\frac{me^2}{\hbar^2}\right)\left(\frac{3n}{\pi}\right)^{1/3},$$

the reciprocal of Thomas–Fermi screening length squared for the electron concentration n. For deuterated Pd/Ti this condition is satisfied. It is clear that the screening length and, therefore, the closest d–d separation for free encounter can be reduced by enhancing the electron mass effectively by the above-mentioned solid state effects. Unfortunately, the solid-state effective mass and the associated screening is meaningful only for electronic motion on the length scale $> a$ (lattice constant) $\simeq$ 2–3 Å. For the local motion on the length scale ~ 0.1 Å $\ll a$, it is the bare inertial mass that is relevant. Since the metallic screening length $1/K_s$ is typically $\sim a >$ covalent bond length R_0, metallization of the D_2 bond as in deuterated Pd/Ti is detrimental to fusion. The above electron gas-based arguments may not apply realistically to the actual lattice-bound deuterons that occupy octahedral (tetrahedral) sites in the Pd(Ti) host. There is, however, a global argument[6] that rules out formation of compact d–d pairs in Pd/Ti host.

The point of the argument is that when the d–d distance is $\ll$ lattice spacing (i.e. both deuterons occupy the octahedral/tetrahedral sites in the host Pd/Ti), the intimate pair should act as an alpha particle (helium nucleus), except for the large positive Coulomb energy of d–d repulsion. Now, since helium is known to spontaneously desorb from the host Pd/Ti, the assumed compact d–d pairs can only do worse energetically and will simply not form. This is essentially the 'helium trick' recently formalized by Leggett and Baym[7] in the Born–Oppenheimer approximation.

Finally, we turn to a nonelectronic and nonequilibrium solid state effect that seems plausible. First let us note that the electrolytic infusion is not essential to 'cold fusion'. Similar effects have been reported by the Italian group[8] who deuterated titanium under pressure/temperature instead, and neutron bursts were detected during absorption and desorption due to change of thermodynamic conditions. Thus what is essential is a condition of nonequilibrium. Well-equilibrated deuterated samples do not emit neutrons. After all deuterated compounds such as d_4-ammonium halides with comparable d–d distances do not emit neutrons. Under the nonequilibrium conditions it seems possible to pump energy associated with motion/relaxation of macroscopic defects into a microscopic degree of freedom, e.g. accelerate deuterons to kinetic energy of $\sim 10^2$–10^3 eV, far in excess of the equipartition value. An example would be a propagating crack in embrittled Pd/Ti with deuterons trapped in the tip. (Deuterons, like water molecules, are expected to lubricate crack propagation.) Such nonthermodynamic defects are 'intelligent heat engines' driven by extended random stress fields due to conditions far from equilibrium, and funnel energy into the microscopic propagating tip. Neutron emission accompanying fracture in LiD crystals is understood in these terms[9]. It should be interesting to study neutron emission from a vibrating reed mode from deuterated Pd/Ti (Gorsky effect-induced). It should be remarked here that the Born–Oppenheimer potential for deuterons in metallic Pd/Ti may have relatively large three-body and many-body components in addition to the two-body component. On the one hand this makes quantum tunnelling multidimensional with preferred reaction coordinates having low barrier, and on the other it helps pumping of energy into a certain degree of freedom as in a driven system of nonlinearly coupled modes. This calls for further study.

11 July 1989

1. Fleischmann, M. and Pons, S. J., *J. Electroanal. Chem.*, 1989, **261**, 301.
2. Jones, S. E. *et al.*, *Nature* (*London*), 1989, **338**, 737.

3. Gai, M. *et al.*, *Nature* (*London*), 1989, **340**, 29.
4. Maddox, John, *Nature* (*London*), 1989, **340**, 15, and references therein.
5. For a critical discussion of related questions, see Cohen, J. S. and Davies J. D., *Nature* (*London*), 1989, **338**, 705.
6. Tossatti, Erio (private communication).
7. Leggett, A. J. and Baym, G., *Nature* (*London*), 1989, **340**, 45.
8. De Ninno. A. *et al.*, 1989 (preprint).
9. Klyuev, V. A. *et al.*, *Sov. Tech. Phys. Lett.*, 1986, **12**, 55.

N. KUMAR

Department of Physics
Indian Institute of Science
Bangalore 560 012