Cold fusion results still unexplained

SIR—In the experiments which purport to demonstrate cold fusion of deuterons, neutron fluxes are low[1] but the heat output is high[2], which has led to suggestions that deuterium fusion leading directly to ^{4}He somehow dominates over the more usual reactions. To consider a possible but improbable mechanism, I have calculated the rate of the reaction

$$\mathrm{d} + \mathrm{d} \rightarrow {}^4\mathrm{He} + \mathrm{e}^+\mathrm{e}^- \qquad (1)$$

in comparison with the reaction

$$\mathrm{d} + \mathrm{d} \rightarrow {}^4\mathrm{He} + \gamma \qquad (2)$$

on which extensive low-energy measurements have been made[3]. The rate of reaction (2) is known[4] to be about 10^{-7} times that of the d+d→n+^{3}He and d+d→p+t reactions at temperatures below 10^9 K. I conclude that the rate of reaction (1) is lower still, by an additional factor of 1.5×10^{-2}, so cannot account for the claimed cold fusion.

Reaction (2) is a radiative-capture reaction, the theory of which has been treated in detail[5]. Resonance is not involved. Nevertheless, I prefer to express my results in terms of transition or $\hbar$ times the transition probability per second. I find the γ-ray width in reaction (2) to be[6]

$$\Gamma_\gamma = \frac{\pi}{675}\alpha Z^2 \frac{E_\gamma^5}{(\hbar c)^4} a_\gamma^4 f_\gamma \qquad (3)$$

where α is the fine-structure constant, E_γ = 23.847 MeV is the γ-ray energy (neglecting kinetic energy of the deuterons at low temperature), a_γ is a suitably defined radius for quadrupole transitions, $^5S_2 \rightarrow {}^5D_0$, of the electronic states (see equations (3) and (4) in ref. 6) and f_γ = 0.068 is the D-state admixture[6] in the ground state of ^{4}He. Equation (3) is consistent with results obtained by others[5,7].

Reaction (1) can be considered to be a capture reaction similar to reaction (2) but with different products. I find the pair-emission (π) width in reaction (1) to be[8]

$$\Gamma_\pi = \frac{1}{375\pi}\alpha^2 Z^2 \frac{E_\pi^5}{\hbar c^4} a_\pi^4 f_\pi \qquad (4)$$

where $E_\pi = E_\gamma - 2m_ec^2 = E_\gamma - 1.022$ MeV is the pair-emission kinetic energy, a_π is a suitably defined radius for electric monopole transitions, $^1S_0 \rightarrow {}^1S_0$, and $f_\pi = 0.932$ is the S-state admixture[6] in the ground state of ^{4}He.

The ratio of equations (4) and (3) yields

$$\frac{\Gamma_\pi}{\Gamma_\gamma} = \frac{9}{5\pi^2}\alpha\left(\frac{f_\pi}{f_\gamma}\right)(1-2m_ec^2/E_\gamma)^5 = 1.465 \times 10^{-2} \qquad (5)$$

In computing this ratio I have set $a_\pi = a_\gamma$ and I estimate an uncertainty of no more than 20 per cent in this equality. Thus equation (5) holds to within a factor of about 2 and reaction (1) as well as all other d + d reactions cannot be the source of the claimed cold fusion of deuterons.

My conclusion is reinforced by experimental measurements[9] in ^{16}O; these indicate that the 0^+ pair-emitting state at 6.0494 MeV has a mean lifetime $\tau_m = 96 \pm 7$ ps, whereas the 2^+ quadrupole γ-ray-emitting state at 6.9171 MeV has a mean lifetime $\tau_m = 6.78 \pm 0.19$ fs. The inverse ratio $\tau_m(2^+)/\tau_m(0^+) = \Gamma_\pi/\Gamma_\gamma = 7.06 \times 10^{-5}$. In this case equation (5) can be used with $f_\pi = f_\gamma$ and the last term in brackets replaced by $(5.0274/6.9171)^5$. The result is $\Gamma_\pi/\Gamma_\gamma = 2.70 \times 10^{-4}$, which is high by a factor of 3.8. However, in this case it is reasonable to expect $a_\gamma > a_\pi$, because of the higher angular momentum of the γ-ray-emitting state, and a ratio $a_\gamma/a_\pi = 1.4$ removes the discrepancy with experiment.

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1. Jones, S.E. *et al. Nature* **338**, 737–740 (1989).
2. Fleischmann, M. & Pons, S. *J. electroanalyt. Chem.* **261**, 301–308 (1989).
3. Barnes, C.A., *et al. Phys. Lett.* B **197**, 315 (1987).
4. Caughlan, G.R. & Fowler, W.A. *Atomic Data and Nuclear Data Tables* **40**, 283–334 (1988).
5. Christy, R.F. & Duck, I. *Nucl. Phys.* **24**, 89–101 (1961).
6. Assenbaum, H.-J. & Langanke, K. *Phys. Rev.* C **36**, 17 (1987).
7. Moszkowski, S.A. *Beta- and Gamma-Ray Spectroscopy* (ed. Siegbahn, K.) 373–395 (North-Holland, Amsterdam, 1955).
8. Oppenheimer, J.R. & Schwinger, J.S. *Phys. Rev.* **56**, 1066–1067 (1939).
9. Ajzenberg-Selove, F. *Nucl. Phys.* A**460**, 22 (1986).

SIR—Excessive energy release has been cited as part of the evidence for cold fusion of deuterium dissolved in palladium[1,2]. I propose that the energy release, although nuclear in origin, is not due to fusion of deuterium but rather to a chain reaction involving radiative capture, by palladium nuclei, of neutrons produced by photodisintegration of deuterons.

Consider as a model situation an atomic pile comprising thin sheets of metallic palladium embedded in a moderator of solid deuterium. What would be the fate of a (possibly energetic) neutron in such an environment? Apart from elastic collisions in the moderator, the most likely event would be radiative capture by Pd nuclei; for example

$$\mathrm{n} + {}^{104}\mathrm{Pd} \rightarrow {}^{105}\mathrm{Pd} + \gamma \qquad (1)$$

where the γ-ray energy is 9.95 MeV, a typical neutron-binding energy. The cross-section of this reaction, for neutron energies in the MeV range, is typically ~ 100 millibarns, corresponding to a mean free path of the order of 10 cm in the metal. At lower energies the mean cross-section averaged over resonances is of the order of tens of barns (ref. 3). What happens to the γ-ray? As its energy is well above the relevant threshold (2.22 MeV), a significant reaction in this context would be photodisintegration of the deuterons:

$$\mathrm{D} + \gamma \rightarrow \mathrm{p} + \mathrm{n} \qquad (2)$$

followed by neutron-induced disintegration:

$$\mathrm{D} + \mathrm{n} \rightarrow \mathrm{p} + 2\mathrm{n} \qquad (3)$$

for which sequence the total threshold energy is 5.55 MeV. Clearly in reactions (2) and (3) there are the makings of a chain reaction, in which each liberated neutron creates several more.

The cross-section for reaction (2) is of the order of several millibarns, and that for (3) is of the order of hundreds of millibarns[4,5]. The corresponding mean free path would be of the order of several metres at normal densities, which would be the required scale of the assembly if the reactions are to be self-sustaining. Elastic (Compton) scattering of electrons would compete with reaction (2), particularly as its cross-section at these photon energies is an order of magnitude higher than that for (2). This is not to say that the photon energy would be lost; energetic electrons so created would regenerate energetic photons via *bremsstrahlung*, resulting in a photon/electron cascade. A detailed mathematical model of this degradation process would be required to settle the question of net neutron yield on the basis of reactions (2) and (3); one suspects that they would fail to be self-sustaining, but not by a large factor.

My highly speculative scheme was motivated by the recent reports[1,2] of cold fusion in electrochemical cells comprising elements similar to those described above. I suggest that conditions within the palladium lattice, for example enhanced deuteron density, might be sufficient to initiate the chain reaction. An attractive feature of the proposed scheme, in comparison with fusion proper, is that of energy generation without commensurate neutron emission, which is what seems to be observed; energy is generated here as neutrons are captured, rather than released. The overall picture is that neutrons weakly bound to protons in deuterium are transferred to palladium nuclei, where they are much more strongly bound. In this context beryllium is similar to deuterium, undergoing a photonuclear reaction similar to reaction (2) with an even lower threshold (1.71 MeV), and electrochemical experiments involving beryllium might be instructive.

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1. Fleischmann, M. & Pons, S. *J. electroanalyt. Chem.* **261**, 301–308 (1989).
2. Jones, S. E. *et al. Nature* **338**, 737–740 (1989).
3. Goldberg, M. D. & Harvey, J. A. *American Institute of Physics Handbook* 3rd edn (McGraw Hill, New York, 1972).
4. Allred, J. C., Armstrong, A. H. & Rosen, L. *Phys. Rev.* **91**, 90–99 (1953).
5. Seagrave, J. D. *Phys. Rev.* **97**, 757–765 (1955).