COLD FUSION-RECENT STATUS AND A NEW DOOR FOR SCIENCE

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I. Nature of the Experiments

In the original report of "cold fusion" (CF) by Pons, Fleischmann, and Hawkins[1] (PF), excess heat generation of up to 26.8 Watts was reported for an experiment in which the input electric power was 55.3 Watts. This result was obtained within a Pd electrode of volume 4 cm^3. Similar energy production rates per cm^3 of metal electrode were subsequently observed by workers[2] at Texas A&M. Other groups[2] at Utah, Stanford, Florida, Case Western Reserve, and Minnesota have also observed excess heat. In many cases, excess heat generation has persisted for weeks and even months at "low levels" (e.g., 10^{-3} - 10^{-1} Wcm^{-3}) and has undergone "bursts" lasting for minutes to many hours at "high" levels (e.g., >10 Wcm^{-3}). Clearly, the hope that these energy production rates could be scaled up and even improved (e.g., a 1.0 meter cube of Pd promises to produce 10 Megawatts of power at the 10 Wcm^{-3} level) through scientific study has generated tremendous interest. Thus far, a firm scientific of understanding of what processes are causing the excess heat and of how to controll these processes has not been achieved.

In the PF experiments[1], liquid heavy water D_2O is electrolyzed, with LiOD acting as the solution electrolyte, to produce D_2 gas and O_2 gas. Although the vast majority of these gases bubble through the liquid and escape to "outside" (where they may or may not be catalytically recombined to permit quantitative analysis), it is thought that a fraction of the D or D_2 species is forced into the Pd

or Pt metal electrode during this electrolysis, and that some form of fusion then occurs inside the electrode metal lattice. The hypothesis[1] that D or D_2 is absorbed into the electrode lattice in high concentration (e.g., 0,5-1.0 part D to 1.0 part Pd) is based on a long history of experimental knowledge. The proposal that fusion of D+D occurs inside the electrode to produce t (tritium) + p (proton) + 4.03 MeV, or n (neutron) + ^{3}He (an isotope of helium) + 3.27 MeV, or ^{4}He (the most stable isotope of helium) + 23.85 MeV was the most controversial part of the original data interpretation by PF. As any or all of the above fusion products are formed, the 3.27-23.85 MeV of energy released per event would, at least partially, be converted to heat as the translationally hot particles become thermalized.

The PF experiments are based on well established and widely used calorimetric measurements. The temperature of the cell that contains the electrodes, electrolyte, D_2O liquid, and all other materials that are invloved in the CF process is monitored and compared to the temperature of a "bath" with which the cell is in thermal contact. The bath consists of a very large surrounding water container plus the laboratory air and contents in the PF case. As heat is generated within the cell, a temperature difference ΔT arises between the cell and the surrounding bath. The steady-state value of ΔT is proportional to the total rate of energy production within the cell. Calibrating each cell, both before it is used and periodically throughout its use in CF experiments, is performed by producing known amounts of electrical resistive heating $Q_{res.}$ (through a separate electrical circuit that remains part of the cell at all times) and monitoring the resulting temperature increase ΔT_{res}. The so-called cell constant $K=\Delta T_{res}/Q_{res}$ is then used to determine how much heat Q_{tot} is produced as the operating cell yields a temperature difference of ΔT_{tot}.

Using the caorimetrically determined total heat output of a given cell Q_{tot} , and knowing the electrical input power

Q_{el} that is used in the electrolysis in terms of the measured current i passing through the cell and the measured voltage drop V over the cell (Q_{el} = i V), one can determine the excess power Q_{ex}. If the D_2 and O_2 gases produced in the electrolysis are subsequently recombined via catalysis, the excess heat is given as: $Q_{ex} = Q_{tot}$ - iV. If the D_2 and O_2 gases are allowed to escape without undergoing (exothermic) recombination, the excess power is calculated as $Q_{ex} = Q_{tot}$ - (iV - iV_{chem}). The iV_{chem} term gives the amount of energy needed to electrolyze the D_2O into D_2 + O_2; it is non-resistive energy that can be regained if the D_2 and O_2 were subsequently recombined. For D_2O at the operating temperatures of PF, V_{chem} = 1.54 volts.

Although most of the attention surrounding CF has been focused on experiments based on electrochemical loading of Pd, Pt, or Ti metal electrodes, there have appeared "surprises" from more conventional experiments that may relate to the PF type of CF. For example, Beuhler, Friedlander, and Friedman at Brookhaven Labs have observed[3] protons and tritium when translationally hot D-containing molecules impinge on a metal consisting of Ti loaded with deuterium. More specifically, $D^+(D_2O)_n$ (n=25 to 1300) cluster ions are accelerated to speeds at which each D atom strikes the TiD target with 30 eV to 1,000 eV of kinetic energy. The yield of tritium and protons observed by these workers is[3] "more than 10 orders of magnitude larger than that computed for 300 eV impacts using the standard value of S(E) = 5.5 $x10^{-24}$ cm^2 keV". The relevance of results obtained at collision energies of even 30 eV to PF room temperature experiments is certainly questionable. However, Bockris et al have taken the position[4] that the electrochemical CF may occur near the electrode surface where dendrites form; at such dendrites, strong local electric fields may indeed accelerate D^+ ions to higher kinetic energies. Even if Bockris' conjecture is wrong, the fact that the Brookhaven yield of tritium and protons is 10^{10} larger than conventional physics expectations indicates that the TiD

lattice may indeed be able to influence the rate of fusion reactions.

II. Why the Findings are Inconsistent With "Normal" Physics

To yield an excess heat generation of 1.0 Wcm^{-3} (which is equal to 6.24 $x10^{12}$ $MeVcm^{-3}sec^{-1}$) would require that between 0.26 $x10^{12}$ and 1.9 $x10^{12}$ fusion events occur in 1.0 cm^3 of electrode each second. If the concentration of D nuclei in the Pd lattice is as high as is widely believed (nearly 1:1 atom ratio with Pd), there are approximately 4 $x10^{22}$ D nuclei in the 1.0 cm^3 electrode. These facts imply that the rate of fusion per D nucleus would have to be between
0.06 $x10^{-10}$ and 0.5 $x10^{-10}$ in each second. Using experimental data collected over many years at D + D collision energies from 1.0 KeV to more than 100 MeV, and extrapolating[5] said data down to room temperature using well established models[6] of nuclear physics, one arrives at expected fusion rates of 3 $x10^{-64}$ per second!

Not only is there a factor of 10^{53} discrepancy between the fusion rates expected from conventional nuclear physics and those inferred from the PF heat data, but the large amounts of the fusion products (neutrons or tritium or protons or helium) that should accompany[6] the PF heat have not been observed in most of the laboratories that claim excess heat via CF. At Texas A&M, Wolf, Bockris, and Appleby have detected moderate levels[4] of tritium in the liquid solution within the cell and levels in the "off gases" that approach being consistent with the heat production they observe. In most other laboratories performing electrochemically induced CF, it appears that substantially lower, yet significant, rates of tritium formation are observed. As mentioned earlier, the Brookhaven group[3] also detects tritium and protons in unexpected amounts.

In none of the laboratories that observe excess heat are neutrons, protons, ^3He, or ^4He observed in amounts that even approach the heat or tritium production rates. Salamon and coworkers[7] have searched for γ-rays, electrons, and protons in the vicinity of cells in Pons' labs at Utah and have not detected signals in line with the excess heat; these workers did not quantitate tritium. The fact that neutrons are not seen in numbers close to the amount of tritium is especially troubling, because the present theories of nuclear structure predict that the "branching ratios" for formation of t + p and n + ^3He should be nearly equal. That is, there should be approximately the same number of neutrons as tritium atoms.

In summary, the PF data and data subsequently gathered in numerous other laboratories is inconsistent with expectations of conventional nuclear physics because: (i) the inferred rates of D + D fusion are much larger than experimental data on higher energy D + D collisions predict, (ii) there seems not to be enough fusion products to be consistent with the inferred fusion rate, and (iii) the t + p to
^3He + n branching ratio seems to be violated.

III. Possible Sources of Error

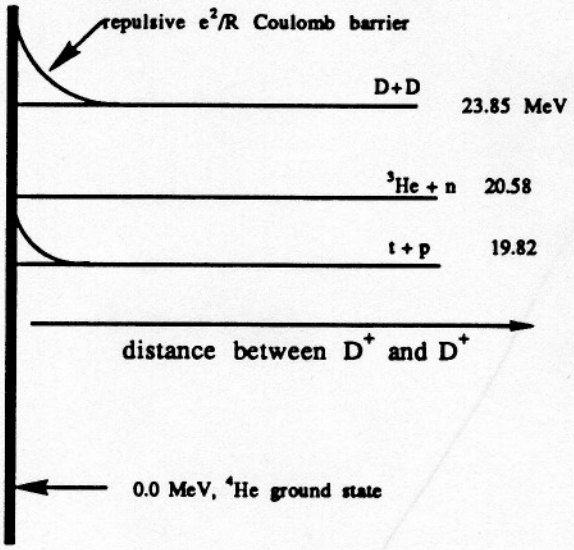
The most likely source of error involves the calorimetric techniques and resulting data of PF and of other workers who claim excess heat. The National Cold Fusion Institute in Utah continues to examine the calorimetric measurements but has, to date, not found errors that would negate the claims that heat output rates exceed input. These workers and researchers at numerous other laboratories are constructing fully isolated cells that recombine all off gases so the input and output energies can be even more accurately quantitated. It is these heat measurements that must be verified beyond any doubt if CF is to be widely accepted as an important discovery. For

this reason, it is proper that the majority of the efforts in the Utah labs and elsewhere emphasizes calorimetry experiments.

Although early measurements of fusion products (i.e., neutrons, ^4He, and tritium) performed by workers who detected excess heat may have been inaccurate, subsequent more detailed and careful studies of tritium yields, especially by Wolf at Texas A&M, have not been proven suspect. The Brookhaven data on tritium and protons has also not been questioned as of this date. Most measurements have focused on neutrons and tritium because they are more straightforward to detect and because they are expected to escape the Pd lattice with appreciable probability. Helium, even if formed, remains difficult to quantitate both because it is thought to remain trapped within the Pt or Pd lattice and because its mass spectrometric detection is difficult (^3He is difficult to separate from HD, and ^4He occurs naturally in concentrations of a few ppm and has a mass close to that of D_2).

IV. Possible Mechanistic Models

Frankly, if the PF data and similar data from other groups are correct, one is faced with explaining how the environment within the Pd (or TiD or Pt) lattice can (i) cause fusion to occur at "room temperature" many orders of magnitude faster than present theory would have it and (ii) cause tritium to be formed at far greater rates than neutrons. As depicted in the Figure shown below, the fusion reaction thought to be operative involves combining two positively charged D nuclei (each with one proton and one neutron) to form an intermediate short-lived "complex" which can either fragment or eject a high energy photon (a γ-ray) to stabilize itself.

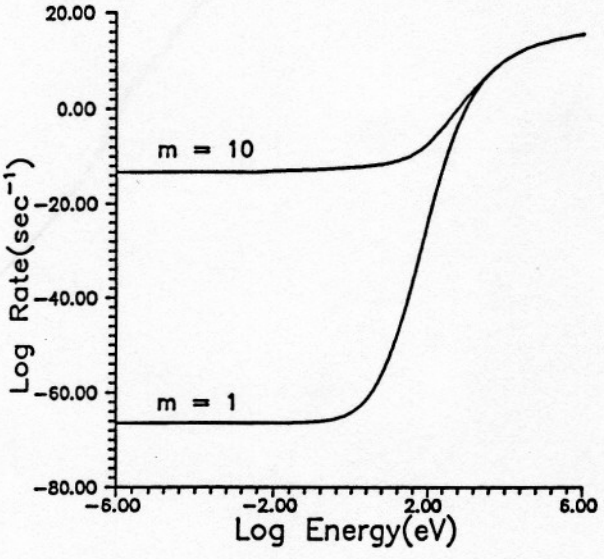


Fragmentation can occur either to produce tritium (containing one proton and two neutrons) and a proton with a release of 4.03 MeV of energy or to produce ^{3}He (containing one neutron and two protons) and a neutron with a release of 3.27 MeV. Alternatively, emission of 23.85 MeV γ-rays could occur to form stable ^{4}He.

The question of how the metal lattice could affect the fusion rate has been examined by many workers. There are two qualitatively different working hypotheses that have been put forth:
(i) Some form[8] of "screening" (i.e., reduction of the coulombic repulsion between pairs of D^+ nuclei) allows D nuclei that encounter other D nuclei within the lattice to approach more closely, at any given collision energy, than they would in the absence of the lattice. Closer encounters lead to greatly enhanced probabilities of tunnelling through the coulomb barrier (see the Figure above) and hence much greater fusion rates.
(ii) Locally strong electric fields[4] exist within the electrode (probably at or near the surface where dendrites form). These fields accelerate the surrounding D^+ particles to

high kinetic energy, thereby greatly enhancing the tunnelling probability and hence the fusion rate.

The Figure shown below depicts the results of model calculations[9] carried out to examine the effects of screening and of locally high kinetic energy on the rate of D + D fusion. The generally accepted[5] intrinsic cross-section for D + D fusion was used in these calculations, but the potential energy of interaction between the two positive D^+ nuclei was parameterized in terms of an attractive component characteristic of binding together by an electron (from the lattice's bands) plus a repulsive coulomb component e^2/mR that is screened by a factor $1/m$. The parameter m is to be viewed[8] as a measure of the screening strength, whatever its cause. The collision energy between the pairs of D nuclei was also varied from very low energies characteristic of room temperature (0.026 eV) to energies in the MeV range.



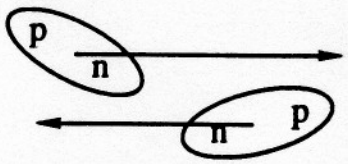
The results of these calculations indicate that fusion rates consistent with the PF heat data (ca, 10^{-11} sec^{-1}) could be realized if either (i) the lattice were able to produce screening of the coulombic repulsions among D nuclei of a factor near 10 (for distances down to approximately 0.07 Å) or (ii) an appreciable fraction of the D^+ species were

accellerated within the lattice to local kinetic energies near 100 eV. Of course, a combination of the two effects could also account for the PF data. Both of these proposals have been met with skepticism because it is difficult to imagine the origin of such strong screening or local fields, given current understanding of the physical, chemical, and material properties of the Pt, Ti, and Pd electrodes.

The second issue mentioned above, that dealing with the aparently anomolous branching ratio, has not been addressed satisfactorially. The problem remains to explain how D + D fusion could yield predominantly tritium and protons with very little, if any, neutrons or γ-emission <u>in the lattice</u> although D + D fusion yields nearly equal quantities of tritium and neutrons when carried out at higher energies in the absence of the lattice.

Two alternatives have been mentioned as scientists have attempted to rationalize the branching ratio data. From the energy level diagram shown in the first Figure above, it is clear that <u>if</u> the fusing D + D nuclei were able to transfer to the surrounding lattice[9] at least 3.27 MeV of energy, the short-lived complex would no longer possess enough internal energy to fragment to the n + ^{3}He channel; only t + p or γ-ray emission would be possible. It is believed that γ-emission occurs several orders of magnitude more slowly than fragmentation, so t + p formation should dominate under such circumstances. Unfortunately, no one has yet thought of a <u>mechanism</u> by which 3.27 MeV of energy could be so dissipated to the metal lattice.

In the alternative proposal[10], the internal structures of the two colliding D^+ species are altered, at the low collision energies (0.026-100 eV) that exist inside the metal lattice, in a manner that places the protons within each D^+ further apart than the two neutrons. The Figure shown below depicts such a collision arrangement.



Oriented Collision of Two D^+ Nuclei

Collisions that occur with such oriented nuclei are then more likely to give rise to neutron transfer, thus yielding p + t, than proton transfer to yield n + ^{3}He. As with the first proposal, no one has thought of a plausible mechanism which could so orient the colliding D^+ nuclei.

In summary, there are, to date, no sound theoretical models in terms of which ananomolous branching ratios could be understood.

V. The Future

It is difficult to forsee the future of CF. As long as several research groups observe excess heat, it is certain to attract considerable attention even if many scientists doubt that fusion can be the source of the energy. In the short term, research is being focused on (i) verifying the calorimetric data beyond any possible doubt, (ii) monitoring all expected fusion products (t, p, n, He, γ) and trying to correlate the appearance of these products with the excess heat, (iii) varying materials and experimental conditions in hopes of discovering how higher levels of excess heat can be achieved and how this heat can be reliably and reproducibly obtained, and (iv) searching for physical or chemical mechanisms that could explain the observed data.

References

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9. J. Nichols, M. Gutowski, and J. Simons (preprint submitted to Phys. Rev. C)
10. This model was mentioned by J. O'M Bockris at a panel discussion held in connection with a symposium on energy production held on Sept. 8, 1989 at the University of Utah.