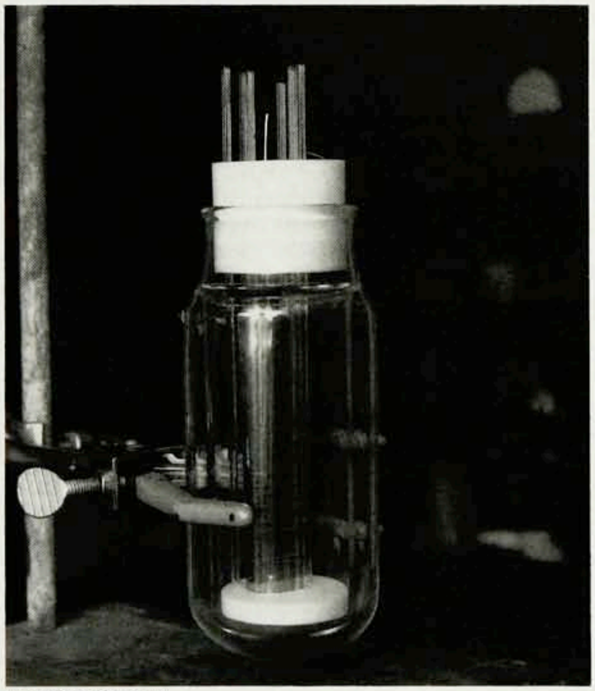
DOUBTS GROW AS MANY ATTEMPTS AT COLD FUSION FAIL

All the world has been hoping for evidence that Martin Fleischmann of the University of Southampton, England, and Stanley Pons of the University of Utah are right. The pair claimed on 23 March that, inside a small cell containing a palladium cathode immersed in heavy water at room temperature, deuterium nuclei were fusing and producing heat at a rate four times higher than the input power. Two hectic months later scores of research groups were ready to confirm or deny that claim. Many reported at special sessions of the APS meeting in Baltimore and of the Electrochemical Society meeting in Los Angeles in early May. At the time of this writing the "nays" were outnumbering the "yeas." Although the final tally will not be taken until more experiments are done and all papers are published in peer-reviewed journals, the euphoria is quickly fading.

Still the variety of experimental results suggests some mystery regarding events—nuclear or otherwise—in systems with deuterium embedded in palladium. Fleischmann, Pons and graduate student Marvin Hawkins estimated in their paper[1] that neutrons and tritium were being released at rates that are a billion times slower than the fusion rate expected from the heat generated. In Los Angeles, Pons admitted to errors in the neutron results but still stands behind the heat measurements. In a cell with different materials, Steven Jones and his colleagues from Brigham Young University and the University of Arizona claim to see neutrons but not heat. The neutron count implies a fusion rate about ten thousand times smaller than the rate consistent with the neutron data reported by Fleischmann, Pons and Hawkins.



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Electrolytic cell, originally used in experiments at the University of Utah. Similar cells have now been studied in many labs around the world. In the cell a palladium cathode is surrounded by a platinum wire anode. The whole cell is then filled with heavy water and lithium deuteroxide salts. In such a simple device Fleischmann, Pons and Hawkins claimed in March to see signs of fusion—neutrons, tritium and excess heat.

Fusion in an electrolytic cell

The techniques for possibly achieving fusion borrow from extensive research over the years on metal hydride systems. It has long been known that certain metals such as palladium and titanium have a particularly large capacity for storing hydrogen: The lattice spacing is large enough and the atomic size small enough that there are regions of low electron density where hydrogen atoms can readily sit. The hydrogen can be attracted into the lattice either by high pressures or by the electric fields in an electrochemical cell. One can get a ratio of somewhat less than one hydrogen to every palladium or nearly two hydrogens to every atom of titanium.

Fleischmann, Pons and Hawkins filled a small cell with a solution of lithium deuteroxide salts and 99.5% deuterium oxide, or heavy water.[1] (See the photo above.) They surrounded a 10-cm-long palladium cathode with a platinum wire anode and ran the cell with current densities as high as 516 mA/cm^2. They studied the cell behavior with cathodes ranging in diameter from 1 to 4 mm, and found that the heat released increased markedly as a function of both cathode volume and current density.

Fleischmann, Pons and Hawkins report that they generated heat in excess of their input energy at a rate of more than 10 watts per cm^3 of Pd for longer than 120 hours. During another trial, the experimenters came in one morning to find the cathode melted and part of the experiment housing destroyed. They calculated the heat output from temperature differences between the cell and a surrounding water bath. They used three different methods for calculating the power output as a percentage of the breakeven, where breakeven is the point at which power in just equals power out. The excess heat ratios are significantly greater than 100% only for one of these methods.

The heat output reported by Fleischmann and Pons is so large that it is hard to imagine what besides nuclear processes could be the source. Cheves Walling of the University of Utah told us that the heat released is larger than what one would get if all the hydrogen in a fully saturated palladium cathode recombined with oxygen. However, heat generation alone does not prove that fusion has occurred. Confirmation requires evidence for at least one of the two common modes of deuterium–deuterium fusion:

$$H^2 + H^2 \rightarrow He^3 + n\ (3.3\ \text{MeV})$$
$$H^2 + H^2 \rightarrow H^3 + p\ (4.2\ \text{MeV})$$

These two modes have been found to occur with roughly equal probability; the branching ratio for a third mode—involving helium-4 and a gamma ray—is about a million times lower.

Seeking evidence for these reactions, the University of Utah group measured the tritium generated, the direct neutron flux and the spectrum of gamma rays. (The capture of the 2.45-MeV neutrons from fusion in the surrounding water bath yields 2.22-MeV gamma rays.) The experimenters claimed evidence for each of these particles (see the figure below). The 2.22-MeV gamma ray spectrum, when corrected for a low counter efficiency, implied a neutron production rate of about $10^4/\text{cm}^3$-sec, corresponding to a fusion rate of 10^{-20} fusions per deuteron pair per second. At the Los Angeles meeting, however, Fleischmann and Pons said they no longer have confidence in these measurements.

The initial puzzle of this experiment was that the heat flux was greatly out of proportion to the neutron flux. If fusion were responsible for the heat production, and if half the fusions produced neutrons, one would expect a neutron flux on the order of $10^{13}/\text{cm}^3$-sec rather than the $10^4/\text{cm}^3$-sec originally reported. The heat flux corresponds to a rate of 10^{-10} fusions per deuteron pair per second.

For the experiment at Brigham Young University, Jones collaborated with E. Paul Palmer, J. Burt Czirr, Daniel L. Decker, Gary L. Jensen, James M. Thorne and Stuart F. Taylor, all of Brigham Young University, and Johann Rafelski of the University of Arizona.[2] Into cells about 4 cm high by 4 cm in diameter, they put cathodes typically made of about 3 g of fused titanium crystals. Thus the cells were much smaller than those in the University of Utah experiment, and the cathodes had a higher ratio of surface area to volume. The Brigham Young–Arizona group often ran the experiment with four to eight cells simultaneously. They added a variety of salts to their heavy water.

Jones and his colleagues measured neutrons at the expected energy of 2.5 MeV and estimated the signal to be about five standard deviations above background (see the figure on page 19). No neutrons appeared when the experiment was repeated with ordinary water. The average neutron source rate of 0.06/sec from heavy-water runs is consistent with an event rate of 10^{-24} fusions per deuteron pair per second, 14 orders of magnitude below the rate inferred from the heat production reported by Fleischmann, Pons and Hawkins. This rate has no potential as a possible energy source, but would elicit considerable interest in the physics community. Jones and his colleagues hypothesize that such fusion might account for some heat generation in the Earth's interior. Indeed, anomalous amounts of helium-3 have been found in the rocks, liquids and gases from volcanoes and other active tectonic regions.

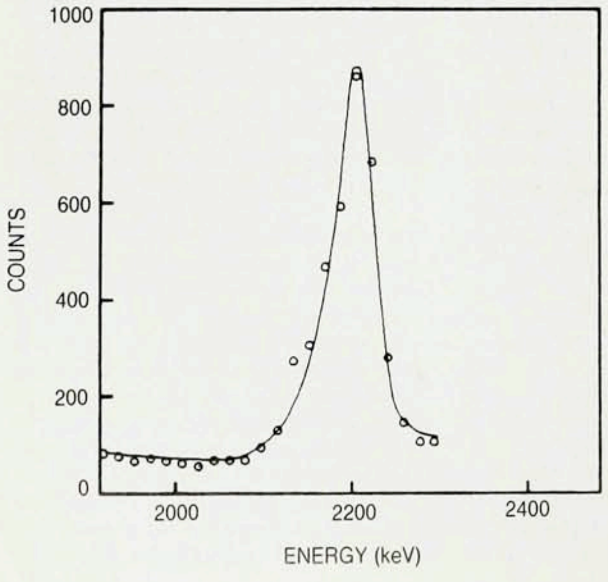
Confirmations and refutations

Several groups have so far reported seeing net heat production from a palladium electrode immersed in a heavy water electrolytic cell. They include two groups from Texas A&M, which are both measuring 10–25% more heat out than energy in, as well as Robert Huggins and his students at Stanford University. All of these see heat only when their cells are filled with heavy water and not with ordinary water.

Other researchers have looked for heat but have not found it. Speaking at the Baltimore meeting, Nathan Lewis, a chemist from Caltech, described an extensive series of experiments he and his colleagues had done, looking for both heat and nuclear radiations in a variety of cells. They did not find either but did encounter several factors that could mislead experimenters into concluding that excess heat was generated. These factors include the placement of the thermometer and the failure to stir the solution. Walter Meyerhof of Stanford came to the same conclusion after constructing an analytical model of an electrolytic cell. Moreover, Lewis analyzed the method used by Fleischmann and Pons to calculate breakeven values greater than 100% and found that they base these results on an assumed cell potential of 0.5 volts—which Lewis feels is about six times too low.

Measurements of neutron fluxes have been reported by scientists in places as farflung as the Soviet Union, Eastern Europe, India and Argentina. A team from Georgia Tech retracted a claim of neutron flux after discovering that its neutron detector gave false readings when the temperature varied. From Italy came a report of a rather different experiment that nevertheless appeared to yield neutrons characteristic of fusion. Physicists led by F. Scaramuzzi from the National Agency for Alternative Energy in Frascati forced deuterium gas at high pressure into a cell containing slivers of titanium. In three trials, this team has seen bursts of neutrons lasting for a short time after the experimenters abruptly changed the pressure and temperature. Physicists at both the University of Genoa and the National Council for Research, Frascati, have also reported bursts of neutrons with a similar arrangement.

On the negative side, physicists from many institutions have searched unsuccessfully for particles that would signal fusion. A collaboration headed by Moshe Gai of Yale University and Kelvin Lynn of Brookhaven National Laboratory placed a very-sensitive upper limit on neutron rates that corresponds to 10^{-25} fusions per deuteron pair per second, ten times lower than the average value reported by Jones. They used an experimental setup as similar as possible to



Spectrum of gamma rays that Fleischmann, Pons and Hawkins measured for their electrolytic cell. They asserted that the gammas resulted from neutron capture in water and hence signaled a fusion reaction. An MIT group has presented evidence that this curve does not have the right shape and intensity to come from that source. (From an erratum sheet for reference 1.)

that of Jones and his colleagues, and eliminated any events that were in coincidence with cosmic rays. Their background was 1.4 counts per hour. A group using a well-shielded neutron counter at Bugey, France, also measured a neutron flux lower than that reported by the Brigham Young–Arizona team. David Williams of the Atomic Energy Research Establishment in Harwell, England, has stated that the lab's efforts to confirm cold fusion, while still underway, have so far proved disappointingly negative. Jones said in Baltimore that further experiments he and his team are doing at Gran Sasso, Italy, in collaboration with scientists from the University of Bologna, continue to support his results.

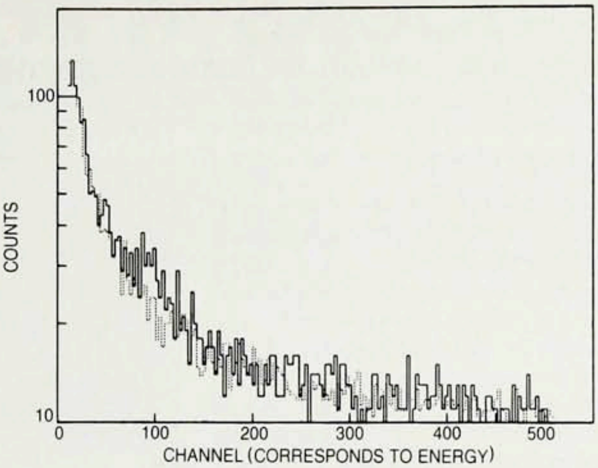
Ron Parker, director of MIT's Plasma Fusion Center, together with Richard Petrasso and their coworkers have measured the gamma-ray spectrum from neutron capture in water and have found considerable discrepancies in shape and intensity between their measured spectrum and that published by Fleischmann, Pons and Hawkins. Lewis noted that the light signaling tritium production can easily be confused with chemiluminescence.

Others weighing in with null results include researchers from IBM's Thomas J. Watson Research Center, AT&T Bell Labs, Ohio State University, the University of Rochester, Oak Ridge, the University of Toronto, Lawrence Berkeley Laboratory, Florida State University, Chalk River Nuclear Labs in Canada and the Ecole Polytechnique in Lausanne, Switzerland. None see neutron rates at the levels seen by Fleischmann, Pons and Hawkins, but many are not sensitive enough to rule out the neutron flux reported by Jones and his colleagues.

In the past palladium has produced false alarms. In 1926, Fritz Panath and Kurt Peters of the Chemical Institute of Berlin University reported the conversion of hydrogen to helium in palladium, only to retract the next year.[3]

Efforts to explain

If cold fusion does occur, how could it happen? Hydrogen atoms would have to get much closer than the typical lattice separations of a few angstroms to enhance the probability of tunneling through the Coulomb barrier between them. Even in a deuterium molecule, where the internuclear spacing is 0.74 angstroms, the tunneling probability is extremely small. Clinton DeW. Van Siclen (Idaho National Engineering Lab) and Jones have calculated this probability to be 10^{-70}/molecule-sec.[4] Steven Koonin (Caltech) and Michael Nauenberg (University of California, Santa Cruz) recently refined this calculation and found a value of 10^{-64}/molecule-sec. If the electron in a deuterium molecule ion is replaced with a muon, which is about 200 times heavier, the distance between the deuterium nuclei would be reduced by the same factor. The tunneling probability is so sensitive to this distance that it would then increase by 80 orders of magnitude.



Neutron spectrum reported by Steven Jones and his colleagues at Brigham Young University and the University of Arizona. Foreground counts (solid) appear to peak near channel 100, corresponding to the energy expected for fusion neutrons. Background counts (dotted) show no such peak. (From reference 2.)

Perhaps then cosmic-ray muons might be catalyzing fusion in the metal hydrides. Muons cannot fuse many deuterons in gases and liquids, but some theorists have speculated that conditions within the lattice may speed up the fusion enough that a single muon could catalyze many fusions. Still, roughly 700 fusions per muon would be required to produce the event rate claimed by Jones and his colleagues. Furthermore, many feel that the muons would be absorbed by the metal atoms.

Might some other heavy particle be catalyzing fusion in the metal hydrides? The fusion rate observed in the Brigham Young–Arizona experiment is what one would expect if the electron around the deuterium nuclei were replaced with a hypothetical particle of about 5 times the electron mass, and that seen at the University of Utah requires 10 times the electron mass. But there does not appear to be a mechanism for producing a heavy effective electron mass. The concept of effective mass defined in condensed matter physics is not thought to be relevant.

The fusion rate reported by Jones and his team is the same as if the usual internuclear distance were cut by a factor of three to five—a distance much smaller than one would expect for the equilibrium separation of deuterons in metal hydrides. It is true that at least six deuterons can accumulate at a single lattice vacancy, but even then the internuclear spacing is more than twice what it is in the deuterium molecule.

If the deuterons are in constant motion within the lattice, partly due to lattice vibrations, their probability of interaction might increase. Koonin has speculated that nonequilibrium conditions could conceivably enhance the fusion rate. Jones and his colleagues were specifically trying to create nonequilibrium conditions, and Scaramuzzi also feels that dynamic conditions were critical to the behavior his group observed.

Could the fusion be caused by acceleration of deuterons in high electric fields? A 1986 Soviet experiment indicated that very high fields created at places where crystals fractured might accelerate deuterons to high enough speeds to facilitate fusion.

If the University of Utah investigators really were generating the quantities of heat they report, theorists would have to explain why fusion particles were not appearing in the same proportion. University of Utah chemists propose that the deuterons fuse into helium-4 and that the lattice absorbs the excess energy. An MIT theorist has withdrawn a paper suggesting how this might occur. Walling of Utah told us that they had detected helium-4 but did not yet have a quantitative measure of it.

—Barbara G. Levi

References

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2. S. E. Jones, E. P. Palmer, J. B. Czirr, D. L. Decker, G. L. Jensen, J. M. Thorne, S. F. Taylor, J. Rafelski, Nature **338**, 737 (1989).
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4. C. DeW. Van Siclen, S. E. Jones, J. Phys. G, **12**, 213 (1986).