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George Chapline

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Lawrence Livermore National Laboratory

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George Chapline

Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

INTRODUCTION

On March 23 two chemists, Martin Fleischmann and Stanley Pons startled the world with a press conference at the University of Utah where they announced that they had achieved nuclear fusion at room temperatures. As evidence they cited the production of "excess" amounts of heat in an electrochemical apparatus and observation of neutron production. While the production of heat in a chemical apparatus is not in itself unusual the observation of neutrons is certainly extraordinary. As it turned out, though, careful measurements of the neutron production in electrochemical apparatus similar to that used by Fleischmann and Pons carried out at dozens of other laboratories has shown that the neutron production fails by many orders of magnitude to support the assertion by Fleischmann and Pons that their discovery represents a new and cheap source of fusion power. In particular, independent measurements of the neutron production rate suggest that the actual rate of fusion energy production probably does not exceed 1 trillionth of a watt.

Actually Fleischmann and Pons acknowledged in even their first press conference that there was a serious discrepancy between the observed number of neutrons and their claim that they were producing useful amounts of fusion energy. They explained this discrepancy by suggesting that the excess heat they were observing was due to a new kind of fusion reaction. However, to date Fleischmann and Pons have presented absolutely no evidence that any of the heat being produced is due to fusion reactions.

In fact, apart from the entertainment value of various remarks by Fleischmann and Pons it does not appear that their work has produced much of value. It is clear that they, and apparently also the group at Brigham Young University led by Steve Jones, deluded themselves into believing they had discovered way of producing fusion reactions by compressing deuterium inside the electrodes of an electrochemical cell.

Historically the possibility of producing fusion reactions by compressing cold hydrogen has been of interest to astrophysicists for some time. In 1959 Alistar Cameron named such fusion reactions pycnonuclear reactions.[1] The rate of such reactions depends sensitively on electron screening; however, by 1969 the effect of electron screening was well enough understood,[2] so that one could make fairly accurate estimates of how the fusion rate depends on compression. The results of these calculations show that even if one could produce pressures as high as 10 million atmospheres, i.e., on the order of the central pressure in Jupiter, the rate of pycnonuclear fusion would still be much too low to explain the "fusion" neutrons reported by Steve Jones and his collaborators.[3] This theoretical remark is bolstered by the observation that the heat radiated by Jupiter can be entirely explained as the heat generated by gravitational contraction[4] - leaving no room for fusion energy production at the level reported by Jones.

As for the possibility of using pycnonuclear fusion to produce energy here on earth one can prove the following:

Theorem: It is impossible to produce energy by compressing small amounts of deuterium.

The point is that to get a useful fusion rate one would first of all have to produce a much higher pressure than could be contained by any real material. One could imagine transiently producing very high densities in deuterium, e.g., using explosives to produce a spherical implosion, but then the question arises whether the fusion energy gain exceeds the energy used to compress the deuterium. Using reasonable estimates of the energies involved one finds that the compressional energy always exceeds the fusion energy (see Appendix).

10^{23} ATMOSPHERES

Of course, if one had some magical way of producing extremely dense deuterium in a laboratory apparatus then cold fusion might be possible. In their appearance before the U.S. House of Representatives Committee on Science and Technology Fleischmann and Pons claimed that they were producing an effective pressure in their electrochemical apparatus of 10^{23} atmospheres! They based their claim on the well known formula for the free energy per particle of an ideal gas

$$\mu = kT \ln(\lambda^3 p/kT) \qquad (1)$$

where λ is the thermal DeBroglie wavelength and p is the pressure. For the left side of this equation Fleischmann and Pons apparently took μ equal to 0.8 eV, the chemical potential of D^+ ions in the palladium electrode, even though the physical origin of this free energy is obscure. With T equal to 300° Eq. (1) yields something like 10^{23} atm (I don't get exactly 10^{23} atm). Needless to say, this is an absurd conclusion. In his presentation Professor Pons did not explain why an activity of unknown origin should be identified with the entropy of an ideal gas. In any case hydrogen does not behave like an ideal gas at high pressures, and it is easy to check that a free energy per atom of 0.8 eV corresponds to a pressure on the order of 10^3 atmospheres - a much more reasonable number.

The next question is whether a few thousand atmospheres would be sufficient to give an observable pycnonuclear fusion rate.

In pure deuterium at a pressure of a few thousand atmospheres, the deuterium atoms are still bound in molecules, so the smallest separation between deuterons is essentially the same as it is in isolated molecules; i.e., about 0.7 Å. The fusion rate in an isolated deuterium molecule has recently been calculated by Steven Koonin and Michael Nauenberg,[5] using the by now very accurately known wavefunctions for a hydrogen molecule. Their result is 10^{-64} per second. To visualize the magnitude of this result image a mass of molecular euterium equal to the mass of the sun. The calculated rate corresponds to one cold fusion event per year!

Of course, the hope for palladium mediated cold fusion is that the deuterons in saturated palladium deuteride are somehow closer together than they are in a deuterium molecule. let's think about that for a moment. If solid hydrogen is compressed with a pressure greater than about 3 million atmospheres the molecules of hydrogen in the solid dissolve[6] and hydrogen (or deuterium) exists in a metallic form where the electrons are no longer localized in molecules, but instead form a conduction band. In first approximation the electrons form a uniform background in which the bare ions move. It is amusing that something similar apparently happens in saturated palladium hydride. In pure palladium the palladium atoms have a $(4d)^8(5s)^2$ configuration, where the 5s electrons form a conduction band. However, in saturated palladium hydride, i.e., Pd H_x where $x \geq 0.6$, the 5s electrons recombine with the palladium ions to form neutral atoms with a $(4d)^{10}$ configuration.[7] The electrons in the s-wave conduction band in the saturated hydride are contributed by the hydrogen atoms. Thus saturated palladium hydride can be thought of as "metallic hydrogen" which is stablized by the palladium atoms. The important point for us is that in first approximation the probability of cold fusion in saturated palladium deuteride will be no different than that in metallic deuterium, which as noted in the introduction is a problem that has long been studied in astrophysics. Even without referring to the astrophysical literature though it is easy to see that the pycnonuclear fusion rate in palladium deuteride will be negligible.

The lattice spacing in palladium deuteride is about 2 Å. Therefore even for a stochiometric composition Pd D_2 the average separation at the deuterons is $2^{-1/3} \cdot 2$ Å, which is more than twice the spacing in a deuterium molecule. Because of the larger deuteron separation and smaller electron screening in the palladium hydride the cold fusion rate in palladium deuteride should be much smaller than it is molecular deuterium, where according to the calculation of Koonin and Nauenberg it is already much too small to be detectable.

It is perhaps worth noting[6] that in the center of Jupiter the interhydrogen separation is about the same as in a deuterium molecule. As mentioned in the introduction we have direct evidence in the case of Jupiter that the fusion rate is smaller than that claimed to have been observed by Steven Jones. Of course, one must take into account that only a small fraction of the hydrogen in Jupiter is deuterium. However, one of the interesting features of cold pycnonuclear fusion is that proton-deuteron fusion should be much faster than deuteron-deuteron fusion.[5]

CAN ONE LOSE WEIGHT BY EXERCISE?

Even if one accepts that the neutrons being reported by various laboratories are not due to pycnonuclear reactions what about Fleischmann's and Pons' claims that some of the heat being produced in their apparatus cannot be accounted for by chemical reactions? A notable statement in this connection is the claim by Professor Fleischmann that (as I recall goes something like) "it is inconceivable that one could store 4 MJ cm^{-3} in the electrodes of the apparatus by chemical means." Indeed, if it were literally true that 4 MJ cm^{-3} were being stored in the electrodes of their apparatus, then that would be difficult to explain. On the other hand, an energy like 4 MJ (10 watts for 120 hours) is not totally beyond the realm of chemistry. For example, the calories in the food one eats during a single day normally exceeds 4 MJ. Although it may be rather arrogant for a physicist to assert that two professors of chemistry don't know how to do chemistry, the assertion of Professor Fleischmann that 0.8 MJ per day cannot be accounted for does invite scepticism.

I'm sure that many if not most of you have had some experience with attempting to lose weight by exercise. Vigorous exercise for an hour or more will dissipate at least a megajoule. In addition, one may vary one's diet. For example, instead of a knockwurst in the morning one might eat an orange. Unfortunately, too often the result of such an experiment is that one doesn't lose weight. One may even gain weight. I suppose that under these circumstances Professor Fleischmann would conclude that when orange juice is in your guts nuclear fusion reactions are occurring.

What this illustrates, of course, is that the law of conservation of energy can be experimentally elusive.

Incidently, in 1832 a German chemist, Johan Dobereiner, discovered that palladium will spontaneously catalyze the oxidation of hydrogen. This discovery led to an invention, the Feuerzeug, which has been commercially marketed in Germany as a cigarette lighter. The working fluid in a Feuerzeug is called Columbian Spirits. I haven't been able to ascertain the chemical composition of Columbian Spirits; however, cold fusion enthusiasts may want to delve into this as this liquid may work better than Canadian heavy water.

CONCLUSION

Despite the attention Fleischmann and Pons have drawn to their work they have produced no credible evidence that a portion of the heat being produced in their apparatus is due to nuclear fusion reactions. This is all the more remarkable because they could have easily produced credible evidence if nuclear fusion reactions were really occurring. For example, they could have submitted the electrodes of their apparatus for independent analysis of their helium content.

What about the possibility that under some circumstances palladium or titanium saturated with deuterium will emit neutrons? If these neutrons are real, their origin may or may not be interesting. It should be kept in mind though that a few neutrons don't represent an immediate and cheap source of electrical power. The most likely resting place for the discovery of neutrons coming from an electrochemical apparatus is as a footnote in a future history.

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APPENDIX

Assuming no losses the energy required to compress deuterium to high densities is 0.2 $\rho^{2/3}$ MJ/gm, where ρ is the density in units of gm cm^{-3}. The theoretical fusion energy yield for deuterium is about 10^5 MJ/gm. However, in practice the yield will be substantially less because of depletion and hydrodynamic expansion of the compressed deuterium. A more practical number would be about 10^4 MJ/gm. Thus the maximum density allowed is about 10^7 gm cm^{-3}.

Using the formula [2]

$$\text{Rate} = 9 \cdot 10^{45} \rho\lambda^{7/4} \exp(-2.638\ \lambda^{-1/2})\ cm^{-3}\ s^{-1} \qquad \text{(A)}$$

where $\lambda = 7.7 \cdot 10^{-5} \rho^{1/3}$, one finds that at a density of 10^7 gm cm^{-3} the cold fusion rate is 10^{40} cm^{-3} s^{-1}. This means that at a density of 10^7 gm cm^{-3} the deuterium will be consumed in $3 \cdot 10^{-10}$ sec. Sounds good? Unfortunately though the speed of sound in deuterium at a density of 10^7 gm cm^{-3} is about 200 times that in normal metals, so that the compressed sample of deuterium would have to be at least 1 mm in radius. In other words in order to achieve fusion energy breakeven we would have to compress more than 40 kg of deuterium to a density 10^8 times normal solid density. Needless to say this is not very practical, and examination of formula (A) reveals that as the density is lowered the amount of deuterium required for fusion breakeven increases very rapidly.

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