Journal of Fusion Energy, Vol. 9, No. 4, 1990

New Cold Nuclear Fusion Theory and Experimental Tests

Yeong E. Kim[1]

A theory of neutron-induced tritium–deuterium fusion at room temperature is developed, based entirely on previously measured cross-sections of known nuclear reactions. The fusion process involves self-sustaining chain reactions: (1) $n + {}^6\mathrm{Li} \rightarrow {}^4\mathrm{He} + \mathrm{T}$ and/or $n + {}^7\mathrm{Li} \rightarrow {}^4\mathrm{He} + \mathrm{T} + n$, and (2) $\mathrm{T} + \mathrm{D} \rightarrow {}^4\mathrm{He} + \mathrm{n}$, in Li—D plasma or pellet surrounded by Li and other blankets and by neutron reflectors. The recent results of cold deuterium fusion reported by Fleischmann, Pons, and Hawkins are described in terms of this fusion process. Experimental evidence and tests of the chain reaction hypothesis are described.

KEY WORDS: Chain reactions with neutron-induced Li fission and T-D fusion; Fleischmann—Pons–Hawkins effect.

1. INTRODUCTION

Recently, it has been suggested[1] that the excess heat generation observed by Fleischmann, Pons, and Hawkins (FPH) in their electrolysis experiment[2] may be due to neutron-induced tritium-deuterium fusion at room temperature. In this paper, the proposed fusion process is first described in a more general context without the use of electrolysis for the purpose of suggesting new designs for large-scale fission-fusion reactors for power generation. Then, the FPH effect[2] is described as a special case of the proposed fusion process which involves electrolysis with a Pd cathode. Some specific experiments are suggested to test the proposed fusion hypothesis for the FPH effect.

2. NEUTRON-INDUCED FISSION-FUSION PROCESS IN LI-D PLASMA AND PELLET

The proposed process consists of self-sustaining chain reactions involving neutron-induced fission of lithium (Li), with the resultant tritium undergoing tritium–deuterium (T-D) fusion in lithium-deuterium (Li—D) plasma or pellet surrounded by Li and other blankets and also by neutron reflectors. The natural abundances of Li are 7.5% ^{6}Li and 92.5% ^{7}Li.

The first stage of the chain reactions is ignited by a continuous or pulsed flux of neutrons from an external source, which produces tritium via the following fission reaction:

$$\mathrm{n} + {}^6\mathrm{Li} \rightarrow {}^4\mathrm{He}\ (2.05\ \mathrm{MeV}) + \mathrm{T}(2.73\ \mathrm{MeV}) \tag{1a}$$

with kinetic energies indicated in parentheses. The cross-section for reaction (1a) is very large at thermal energies (949×10^{24} cm^2).[3] The reaction rate (cross section times velocity, σv) for reaction (1a) is also very large, $\sigma_{n\mathrm{Li}}\, v_n = (2.1 - 1.3) \times 10^{-16}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$, for a range of neutron energies up to 14 MeV.[4] T(2.73 MeV) is produced via reaction (1a) without requiring a heat source to generate extremely high temperatures (1 MeV corresponds to 10^{10} K), in contrast to the conventional nuclear fusion reactor designs in which an enormous electromagnetic energy input is required.

The second stage of the chain reactions is T-D fusion with T (2.73 MeV) generated from the first stage (1a):

---

[1] Purdue Nuclear Theory Group, Department of Physics, Purdue University, West Lafayette, Indiana 47907.

$$\mathrm{T}+\mathrm{D} \rightarrow {}^4\mathrm{He}\ (3.52\ \mathrm{MeV})+\mathrm{n}(14.07\ \mathrm{MeV}) \quad (2)$$

The T-D fusion cross-section is maximum ($\sim 10^{-23}$ cm^2) at a T kinetic energy of ~100 keV and is nearly three orders of magnitude larger than the D-D fusion cross section for the same D kinetic energy. The T-D fusion reaction rate for reaction (2) is large,[5] $\sigma v \gtrsim 10^{-16}$ cm^3 s^{-1}, for T (10 keV ~10 MeV), and is at least 50 orders of magnitude larger than the T-D and D-D fusion reaction rates at room temperature.

The 14.07-MeV neutrons from reaction (2) will be moderated via elastic scattering or the breakup reactions, n + D → n + n + p, etc., producing more neutrons which with the 14.07-MeV neutrons could then feed reaction (1a), thus completing the reaction chain. In addition, the 14.07-MeV neutron from the T-D fusion reaction (2) can also produce excess neutrons via the following reactions:

$$\mathrm{n} + {}^7\mathrm{Li} \rightarrow {}^6\mathrm{Li} + \mathrm{n} + \mathrm{n} - 7.25\ \mathrm{MeV}, \quad (3)$$

and

$$\mathrm{n} + {}^7\mathrm{Li} \rightarrow {}^4\mathrm{He} + \mathrm{T} + \mathrm{n} - 2.46\ \mathrm{MeV} \quad (1b)$$

The reaction rates (σv) for reactions (3) and (1b) are large, 2.9×10^{-16} and 1.6×10^{-15} cm^3 s^{-1}, respectively.[3,4] In particular, reaction (1b) can produce both T and n at a much higher rate than reaction (1a) for T and reactions (2) and (3) for n. Excess neutrons produced via reactions (3) and (1b) by the 14.07-MeV neutron can also feed reactions (1a) and (1b) to complete the reaction chains, (1a, 1b) → (2), thus providing a favorable condition for the self-sustaining stage. The neutron-induced T-D fusion via the chain reactions, (1a, 1b) → (2), is therefore expected to be efficient for producing excess heat once the chain reactions become self-sustaining at some stage.

The feasibility of achieving a controlled self-sustaining state for the chain reactions, (1a, 1b) → (2), in Li-D plasma or pellet will depend on the geometries and the materials for blankets and reflectors used in the design of fission-fusion reactors and will also depend on currently available and/or new fusion reactor technologies.

The same reaction chains, (1a, 1b) → (2), have been considered[6-9] for the conventional magnetic confinement of T-D plasma with a surrounding Li blanket and also for inertial confinement fusion with Li-D pellet driven by pulsed lasers. It has been speculated by Harms et al.[6] that the reaction chain could be maintained for a finite number of cycles in the inertial confinement fusion driven by lasers if the compression/expansion time were sufficiently longer than the tritium recycling time in the reaction chain. The use of an external (continuous or pulsed) neutron flux and Li-D plasma as proposed in this paper is new and is being investigated as to whether it can help to achieve a controlled self-sustaining reaction chain, (1a, 1b) → (2), for specific designs of neutron-induced fission-fusion reactors with optimal conditions and geometries.

It has been argued[6,7] that the chain reactions, (1a, 1b) → (2), could not be sustained in the conventional magnetic confinement fusion of D-T plasma surrounded by a Li-blanket. However, the use of Li-D plasma surrounded by Li and other blankets, and also by neutron reflectors, combined with the use of an external (continuous or pulsed) neutron flux as the initial ignitor of the reaction chain may be able to accomplish this, thus allowing new designs for fission-fusion reactors.

The use of an external neutron flux as the initial ignitor of the chain reactions, (1a, 1b) → (2), has an important practical consequence that the fusion ignition is accomplished by nuclear energy generated from reactions (1a) and (1b), instead of by an enormous electromagnetic energy input as required for the conventional fusion reactor designs. Theoretical reaction-rate estimates for specific reactor designs based on the reaction chain (1a, 1b) → (2) and also on other neutron-induced reaction chains are being investigated using Monte Carlo simulations and will be reported in future publications. For charge particle-induced reaction chains, the use of proton or deuterium flux as an initial ignitor was suggested by McNally.[10]

3. FISSION-FUSION PROCESS IN METAL DEUTERIDES

Recently, it has been reported by Fleischmann, Pons, and Hawkins[2] and Jones et al.[11] that electrochemically induced deuterium–deuterium (D-D) fusion has been observed in a larger palladium cathode immersed in heavy water with 0.1 *M* LiOD (ref. 2) and in a palladium cathode immersed in heavy water with 0.2 g of $Li_2SO_4 \cdot H_2O$ dissolved in 160 g of D_2O ($\sim 0.4 \times 10^{-3}$ *M* Li) (ref. 11). The results of Fleischmann et al.[2] are substantially different from those of Jones et al.[11]

The reported D-D fusion rates of 10^{-9} s^{-1} (ref. 2) and 10^{-23} s^{-1} (ref. 11) are about 50 orders of magnitude larger than the expected cold D-D fusion rate of $\sim 10^{-70}$ s^{-1}.[12] Fleischmann et al.[2] observed a rate of heat output which is about 10 orders of magnitude larger than that expected from the inferred D-D fusion rate (10^{-19} s^{-1}) and state that other nuclear processes must be involved.

In the following, a theoretical explanation of the observed results[2,11] is given in terms of tritium-deuterium (T-D) fusion induced by low-energy neutrons. In the experiments of Fleischmann et al.[2] the background low-energy neutrons (~40/hr) will produce tritium via reaction (1a). ^{6}Li needed for reaction (1a) comes from LiO D in the heavy water solution. Since the positively ionized ^{6}Li concentration is higher near the Pd cathode, T (2.73 MeV) will be produced in greater abundance there via reaction (1a) than elsewhere. Once produced, T (2.73 MeV) will be moderated to lower energies in the heavy water and penetrate the Pd cathode, just as D from the heavy water does. T(10 $\gtrsim$ keV) can now undergo T-D fusion with D in Pd and also in the heavy water through reaction (2). The 14.07-MeV neutron from T-D fusion reaction (2) can produce excess neutrons via reactions (1b) and (3), which can now feed reactions (1a) and (1b) to complete the chain reactions (1a, 1b) → (2). These chain reactions may have occurred in the experiment of Fleischmann et al.,[2] but may not have occurred in the experiment of Jones et al.,[11] who had a much smaller concentration of Li(0.39×10^{-3} *M* Li) in the heavy water.

If n(14.07 MeV) from reaction (2) moves out of the Li-D_2O solution thus terminating the chain reaction, (1a) → (2), it will generate only a small amount of power, which is too small to be detected. However, if the 14.07-MeV neutrons from reaction (2) [starting with the initial density of n_n (0) for reaction (1a)] are moderated in D_2O and in Pd by elastic and inelastic scatterings and also by the break-up reactions {n(14.07 MeV) + D → n + n + p; n(14.07 MeV) + T [thermalized and left over from reaction (2)] → n + n + d or n + n + n + p; reactions (1b) or (3)} to produce excess neutrons, Kn_n $(0)(K > 1)$, then n_n can gradually increase to a self-sustaining value, with an associated increase in the excess power. The amount of T and n present at the self-sustaining stage would be substantially smaller than the amount of ^{4}He, since T and n are being recycled in the chain reaction, (1a) → (2), consistent with the observation reported by Fleischmann et al.[2] The use of electrolysis[2] can help chain reaction, (1a) → (2), to become self-sustaining, since both n_T and n_n will increase in or near the Pd cathode, thus increasing both the reaction rates, R_{nLi} and R_{TD}, for (1a) and (2), respectively.

The above discussions of the chain reactions are based on the assumption that the probability of T-D fusion, P_{TD}, is nearly one, i.e., $P_{TD} = \int dx \sigma_{TD} n_D = \int dE \sigma_{TD} n_D/(dE/dx) \cong \bar{E} \sigma_{TD} n_D/(dE/dx) \approx 1$, where $\bar{E} \approx \int dE$. However, in heavy water, the stopping power, $|dE/dx|$, for a 1.25-MeV T is estimated to be $\sim 10^3$ MeV cm^{-1}, which in turn yields $P_{TD} \approx 10^{-4}$ with $\bar{E} \approx 1.25$ MeV, $n_D \approx 6 \times 10^{22}$ cm^{-3}, and $\sigma_{TD} \approx 10^{-24}$ cm^2, implying that the chain reactions, (1a, 1b) → (2), are unlikely to occur. However, the situation may be quite different with electrolysis,[2] which produces an enormously high concentration (equivalent to pressures of 10^3–10^4 atm[2,13]) of positive ions, D^+, Li^+, and T^+ on and near the Pd cathode. The presence of a high concentration of D on and inside the Pd cathode together with a higher production rate of T and n via reaction (1b) could all help to overcome the difficulty due to $P_{TD} \approx 10^{-4}$ in heavy water and to achieve the self-sustaining state for the chain reactions (1a) → (2) and (1b) → (2) on and/or in the Pd cathode. In addition, the Pd cathode and, also, any stainless-steel containers and sinks used (containing Fe) could act as very efficient reflectors of the 14-MeV neutron, since the reactions, $^{110}_{46}$Pd(n, 2n) and Fe(n, 2n), have sizable cross-sections, (2.57 ± 0.16) and (0.5 ± 0.04) barns, respectively, at $E_n \approx 14$ MeV.[4] In particular, Fe is one of the most efficient reflectors of 14-MeV neutrons since the elastic cross section is also large: (1.14 ± 0.06) barns at $E_n \approx 14$ MeV (the total cross section is 5.3 barns).[4]

4. EXPERIMENTAL EVIDENCE AND TESTS

Support for presence of the self-sustaining chain reactions, (1a, 1b) → (2), comes from the observation reported by Pons and Hawkins[14,15] that in a preliminary experiment, mass spectrometric analysis of evolved gases from a cell operating at 200 mA with an electrode (Pd) volume of 0.0785 cm^3 and delivering 0.5 W cm^{-3} of excess heat, gave a $^4He/D_2$ ratio of 10^{-5}–10^{-6}, a value which is substantially larger than that obtained from a number of blank determinations. This corresponds to a ^{4}He production rate of 8×10^{11} to 8×10^{12} cm^{-3} s^{-1}, which is consistent with the chain reaction, (1a) → (2), whose corresponding power, *P* (chain reaction), would be

$$P(\text{chain reaction}) = R(\text{chain reaction})(E_{nLi} + E_{TD}) \cong 1.4 \sim 14.4 \text{ W cm}^{-3}$$

which is of the same order of magnitude as the observed value of 0.5 W cm^{-3}.[14,15] $E_{nLi} = 0.77 \times 10^{-12}$ J/reaction and $E_{TD} = 2.82 \times 10^{-12}$ J/reaction are the energies generated by reactions (1a) and (2), respectively. In calculating the above values of P (chain reaction), R (chain reaction) $\approx 4 \times 10^{11}$ to 4×10^{12} cm^{-3} s^{-1} is used, since each chain reaction cycle produces two ^{4}He nuclei. These values of R (chain reaction) correspond to $n_T \approx n_n \approx 0.85 \times 10^7$ to 8.5×10^7 cm^{-3}. However, external detection rates of these tritiums and neutrons would be extremely low, since they are being recycled in the self-sustaining chain reactions, (1a, 1b) → (2), while confined in a small volume localized inside or near the Pd cathode which is shielded by the surrounding Li-D_2O solution and by other materials used.

Other support for the self-sustaining chain reactions, (1a) → (2) and (1b) → (2), comes from the recent observations reported by Srinivasan et al.[16] that the use of NaOD or LiOH instead of LiOD does not produce excess heat during electrolysis. The use of NaOD (without Li) will completely break the chain reactions, (1a) → (2) and (1b) → (2), since there are no Li present. The use of LiOH instead of LiOD will also break the chain reactions, (1a) → (2) and (1b) → (2), since H is a very efficient absorber of neutrons and hence will deter the chain reactions from reaching the self-sustaining stage. H will also lower the D^+ concentration on and in the Pd cathode.

It should be noted that reaction (1a) is the first ignition stage in the experiments of Fleischmann et al.[2] and Srinivasan et al.[16] since the background thermal neutrons are utilized in both cases. Therefore, it is expected that the use of ^{7}LiOD instead of natural LiOD (7.5% ^{6}Li and 92.5% ^{7}Li) in their experiments will result in no generation of excess heat, since the absence of ^{6}Li eliminates the possibility of reaction (1a), and also reaction (1b) cannot proceed with thermal energy neutrons because of the threshold neutron energy of 2.46 MeV needed for (1b). The use of ^{6}LiOD instead of natural LiOD is expected to make chain reaction, (1a) → (2), proceed faster but may produce less excess heat since the other chain reaction, (1b) → (2), is absent. In fact, the absence of ^{7}Li and therefore the reaction, (1b) → (2), may prevent the chain reaction, (1a) → (2), from reaching the self-sustaining stage in some cases.

There are many improvements which could provide more favorable conditions for achieving the self-sustaining chain reactions, (1a, 1b) → (2), in the experimental apparatus for the FPH effect. Some are listed below.

(i) Use an intense neutron source.
(ii) Use efficient neutron reflectors in optimal geometrical arrangements.
(iii) Use an optimal current density larger than or equal to the 512 mA/cm^2 Fleischmann et al.[2] used.
(iv) Use an optimal (larger volume and surface) size of the Pd cathode.
(v) Use an optimal concentration of LiOD greater than or equal to the 0.1 M Li concentration Fleischmann et al.[2] used.
(vi) Operate the electrolysis for a sufficient duration to achieve a maximal loading of Li and D on and in the Pd cathode.
(vii) Avoid the use of any electrolytes which contain neutron absorbers, such as H (as in LiOH), Cl (as in LiCl), N (as in $LiNO_3$), etc.

To test the chain reaction hypothesis for the FPH effect, the following signatures should be measured simultaneously after the above-suggested improvements are implemented:

(a) Excess heat generation as a function of the ratio ^{7}Li/^{6}Li for a given concentration of LiOD.
(b) ^{4}He (in Pd, in solution and outside as gas).
(c) T (in Pd, in solution and outside as gas).
(d) n (thermal energies to ~14 MeV).

For (a), the excess heat generation is expected to vary as a function of the ratio ^{7}Li/^{6}Li for a given value of LiOD concentration. This test can be used to distinguish between the chain reaction hypothesis and any chemical reaction hypothesis involving Li, since ^{6}Li and ^{7}Li being chemically identical are expected to produce the same amount of heat from any known or unknown chemical reactions involving Li.

It should be noted that there have been no direct measurements of the 14.07-MeV neutrons (a clear signature of the chain reactions, (1a) → (2) and (1b) → (2)), which can be detected by a specially designed neutron detector. It should be emphasized that the above quantities, (a), (b), (c), and (d), are expected to be detectable only after the self-sustaining stage ($K \geq 1$) for the chain reactions, (1a, 1b) → (2), is achieved. The negative results for (a), (b), (c), or (d) reported by many experimental groups at this workshop may be attributed to the case of the subcritical stage ($K < 1$), since appropriate geometries and other necessary stringent experimental conditions are required for achieving the critical stage ($K \geq 1$).

ACKNOWLEDGMENT

The author wishes to thank Gary Chulick for reading the manuscript and suggesting corrections.

REFERENCES

1. Y. E. Kim, Neutron-induced tritium-deuterium fusion in metal hydrides, Purdue Nuclear Theory Group Report PNTG-89-4 (April 14, 1989); Fission-induced tritium-deuterium in metal deuterides, PNTG-89-5 (June 1989).
2. M. Fleischmann, S. Pons, and M. Hawkins, *J. Electroanal. Chem.* **261**, 301 (1989).
3. T. Lauritsen and F. Ajzenberg-Selove, *Nucl. Phys.* **78**, 39 (1966).
4. H. Goldstein and M. H. Kalos, An Index to the Literature on Microscopic Neutron Data, NDL-SP-10, Nuclear Defense Laboratory, Edgewood Arsenal, MD (1964).
5. D. L. Book, NRL Plasma Formulary, Naval Research Laboratory Publication 0084-4040 (revised 1987).
6. A. A. Harms and E. M. Krenciglowa, *Nucl. Fusion* **20**, 665 (1980).
7. A. A. Harms and M. Heindler, *Acta. Phys. Austria.* **52**, 301 (1980).
8. E. Greenspan and G. H. Miley, *Nucl. Technol./Fusion* **4**, 181 (1983).
9. S. M. Waller, *J. Fusion Energy* **6**, 275 (1987).
10. J. Rand McNally Jr., *Nucl. Fusion* **11**, 187, 189, 191 (1971).
11. S. E. Jones, E. P. Palmer, J. B. Czirr, D. L. Decker, G. L. Jensen, J. M. Thorne, S. F. Taylor, and J. Rafelski, *Nature* **338**, 737 (1989).
12. C. D. Van Siclen and S. E. Jones, *J. Phys. G Nucl. Phys.* **12**, 213 (1986).
13. W. M. Mueller, J. P. Backledge, and G. G. Libowitz, *Metal Hydrides*, Academic Press, New York (1968); G. Bambakadis, ed., *Metal Hydrides*, Plenum Press, New York (1981).
14. S. Pons and M. Hawkins, Private communication to C. Walling and J. Simons, quoted in Ref. 15.
15. C. Walling and J. Simons, Two innocent chemists look at cold fusion, Preprint from Department of Chemistry, University of Utah (April 24, 1989).
16. S. Srinivasan, Y. J. Kim, O. J. Murphy, C. R. Martin, and A. J. Appleby, Evidence for Excess Heat Generation Rates During Electrolysis of D_2O in LiOD Using a Palladium Cathode—A Microcalorimetric Study, a talk presented by Appleby at Workshop on Cold Fusion Phenomena, May 23–25, 1989, Santa Fe, NM.