Department of Energy
Office of Scientific and Technical Information
Post Office Box 62
Oak Ridge, Tennessee 37831

August 10, 2016

Re: OSTI-2016-01064-F

Dear Mr. Ravnitzky:
This is in final response to the request for information you sent to the Department of Energy (DOE), Office of Scientific and Technical Information (OSTI) under the Freedom of Information Act (FOIA), 5 U.S.C. 552 on June 22, 2016.

You requested a "copy of records, electronic, or otherwise, of each letter TO and FROM universities, companies, and organizations, from the OSTI 'cold fusion' documents collection." On July 11, 2016, you were emailed an interim response letter informing you of the need for OSTI to obtain release authorization from the Department of Energy. OSTI received notification to release the letters to you in their entirety on August 8, 2016. As a result, OSTI is releasing 72 cold fusion letters in this mailing on a CD-ROM because of the volume and file size of the PDFs.

In addition, there are approximately 13 letters that are currently being reviewed by the DOE's General Counsel Office (GC) for release or redaction. Upon receipt of guidance from GC, OSTI will release in whole or in part.

This decision, as well as the adequacy of the search, may be appealed within **90** calendar days from your receipt of this letter pursuant to 10 C.F.R. § 1004.8. Appeals should be addressed to Director, Office of Hearings and Appeals, HG-1, L'Enfant Plaza, U.S. Department of Energy, 1000 Independence Avenue, S.W., Washington, D.C. 20585-1615. The written appeal, including the envelope, must clearly indicate that a FOIA appeal is being made. You may also submit your appeal to OHA.filings@hq.doe.gov, including the phrase "Freedom of Information Appeal" in the subject line. The appeal must contain all of the elements required by 10 C.F.R. § 1004.8, including a copy of the determination letter. Thereafter, judicial review will be available to you in the Federal District Court either: 1) in the district where you reside; 2) where you have your principal place of business; 3) where DOE's records are situated; or 4) in the District of Columbia.

You may contact OSTI's FOIA Public Liaison, Charlene Luther, Office of Preservation and Technology at 865.576.1138 or by mail at the Department of Energy, Office of Scientific and Technical Information, 1 Science.gov Way, Oak Ridge, TN 37830 for any further assistance and to discuss any aspect of your request. Additionally, you may contact the Office of Government Information Services (OGIS) at the National Archives and Records Administration to inquire about the FOIA mediation services they offer.

The contact information for OGIS is as follows: Office of Government Information Services, National Archives and Records Administration, 8601 Adelphi Road-OGIS, College Park, Maryland 20740-6001, e-mail at ogis@nara.gov; telephone at 202-741-5770; toll free at 1-877-684-6448; or facsimile at 202-741-5769.

If you have any questions about the processing of the request or about this letter, please contact Madelyn M. Wilson at

Sincerely,

Madelyn M. Wilson
FOIA Officer
DOE OSTI
1 Science.gov Way
Oak Ridge, TN 37830

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REMARKS: THIS IS THE SECRETARY'S COPY OF A LETTER TO THE COLD FUSION PANEL, JOHN R. HUIZENGA.

SUBJ: NUCLEAR FUSION
ENCLOSES "SHORT SUMMARY OF RESEARCH ON NEUTRON-INDUCED CHAIN-REACTION PROCESSES FOR LARGE-SCALE POWER ..."

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PURDUE UNIVERSITY

DEPARTMENT OF PHYSICS

August 10, 1989

Dr. John R. Huizenga
Co-Chairman, Cold Fusion Panel
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, D.C. 20585

Dear Dr. Huizenga:

As you requested in your letter of July 20, 1989, I am sending you a short summary of my past and present research on nuclear fusion.

Enclosed are one copy each of (1) "Short Summary", (2) a preprint (reference 5) entitled "New Cold Nuclear Fusion Theory and Experimental Tests", and (3) a preprint (reference 6) entitled "Neutron-Induced Photonuclear Chain-Reaction Process in Palladium Deuteride".

In my summary, two aspects of my fusion research are emphasized: (a) neutron-induced chain-reaction processes as a possible explanation of the effect reported by Fleischmann et al. and others, and (b) importance of and urgent need for designing and building new neutron-induced fission-fusion reactors for large-scale power generation, utilizing existing and/or new fission and fusion reactor technologies, **regardless** of whether the final outcome and results of "cold fusion" reported by Fleischmann et al. and others turn out to be valid or not.

Sincerely,

Yeong E. Kim

Yeong E. Kim
Professor of Physics
Phone: (317)494-3042
FAX: (317)494-0706

Enclosures

cc:

Mr. John H. Schoettler, Chairman, DOE Energy Research Advisory Board
Admiral James D. Watkins, Secretary of DOE
Dr. D. Allan Bromley, White House Science Advisor

Short Summary of Research*

on

Neutron-Induced Chain-Reaction Processes for Large-Scale Power Generation and for Electrolysis with Palladium Deuteride

Y.E. Kim

Department of Physics
Purdue University
West Lafayette, Indiana 47907

August, 1989

*Submitted to Dr. John R. Huizenga, Co-Chairman, Cold Fusion Panel to the DOE Energy Research Advisory Committee.

Neutron-induced chain-reaction processes for large-scale power generation and for electrolysis with palladium deuteride

Y.E. Kim

Department of Physics, Purdue University, West Lafayette, Indiana 47907, USA

Tritium production and excess heat generation above that due to the electrode reaction observed by Fleischman, Pons, and Hawkins (FPH)[1] and others[2,3,4] in their electrolysis experiments with a palladium cathode immersed in heavy water (with 0.1M LiOD) can not be explained by known single-step nuclear reactions such as deuterium-deuterium fusion, since the reaction cross-sections and rates are too small at room temperature. However, a combination of known nuclear reactions can form a set of closed chain reactions which can become self-sustaining at a critical stage under favorable conditions and geometries, as in the well-known case of neutron-induced fission chain reactions. The FPH effect is described in terms of chain-reaction processes involving (a) neutron-induced fission-fusion chain reactions[5] and (b) neutron-induced photonuclear chain reactions in palladium deuteride.[6]

The process (a) involves neutron-induced fission of lithium with the resultant tritium (2.73 MeV) participating in tritium-deuterium fusion. The process (b) involves radiative neutron capture by ^{108}Pd with the resultant γ-rays ($\lesssim$ 6.15 MeV) breaking up deuterium by photodisintegration. Each hypothesis for the FPH effect leads a set of predictions which can be tested experimentally. Experimental evidence and suggested tests for each hypothesis are given.[5,6]

The chain-reaction process (a) can be used **without** the use of electrolysis

to design new fission-fusion reactors for large-scale power generation, when an external (continuous or pulsed) neutron flux is included.[5] The process involves self-sustaining chain reactions: (1) $n + {}^{6}Li \rightarrow {}^{4}He + T$ and/or $n + {}^{7}Li \rightarrow {}^{4}He + T + n$, and (2) T + D $\rightarrow {}^{4}He + n$, in $Li - D$ plasma or pellet surrounded by Li and other blankets and by neutron reflectors. The use of an external neutron flux as the initial ignitor of the chain reactions, (1) $\rightarrow$ (2), has an important practical consequence in that the fusion ignition is accomplished by nuclear energy generated from reactions, (1), instead of by an enormous electromagnetic energy input as required for the conventional fusion reactor designs. The feasibility of achieving a controlled self-sustaining state for the chain reactions, (1) $\rightarrow$ (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 fission and fusion reactor technologies.

Prototype fusion reactors, based on the conventional designs for both plasma and inertial confinement fusions, have not yet achieved a break-even stage for a sufficient time duration in spite of enormous scientific and engineering efforts invested during the last two decades. Therefore it is important and urgent to investigate the feasibility of achieving a controlled self-sustaining stage in new prototype fission-fusion reactors based on the above chain-reaction process (a) with the use of an external neutron flux.

Theoretical reaction-rate estimates for specific reactor designs based on the reaction chain, (1) $\rightarrow$ (2), and also on other neutron-induced reaction chains are being investigated using Monte Carlo simulations.

REFERENCES

1. Fleischmann, M., Pons, S., and Hawkins, M., Journal of Electroanalytic Chemistry, **261**, 301 (1989); and errata, **263**, 187 (1989).

2. Appleby, A.J., Srinivasan, S., Kim, Y.J., Murphy, O.J., and Martin, C.R., "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, New Mexico; "Anomalous calorimetric results during long-term evolution of deuterium on palladium from lithium deuteroxide electrolyte" to be published in Nature; Appleby, A.J., Kim, Y.J., Murphy, O.J., and Srinavasan, S., "Specific effect of lithium ion on anomalous calorimetric results during long-term evolution of deuterium on palladium electrodes", submitted to Nature.

3. Wolf, K.L., Packham, N.J.C., Lawson, D.R., Shoemaker, J., Cheng, F., and Wass, J.C., "Neutron emission and the tritium content associated with deuterium loaded palladium and titanium metals", in the Proceedings of Workshop on Cold Fusion Phenomena, May 23-25, 1989, Santa Fe, New Mexico, to be published in J. Fusion Energy.

4. Huggins, R.A. in the Proceedings of Workshop on Cold Fusion Phenomena, May 23-25, 1989, Santa Fe, New Mexico, to be published in J. Fusion Energy.

5. Kim, Y.E., "New cold nuclear fusion theory and experimental tests", in the Proceedings of Workshop on Cold Fusion Phenomena, May 23-25, 1989, Santa Fe, New Mexico, to be published in J. Fusion Energy.

6. Kim, Y.E., "Neutron-induced photonuclear chain-reaction process in palladium deuteride", Purdue Nuclear Theory Group Report PNTG-89-7 (July, 1989).

PNTG-89-6
June 1989

New Cold Nuclear Fusion Theory and Experimental Tests*

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Abstract

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) $n + {}^6Li \rightarrow {}^4He + T$ and/or $n + {}^7Li \rightarrow {}^4He + T + n$, and (2) $T + D \rightarrow {}^4He + n$, 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.

*An extended summary of a talk presented at the Workshop on Cold Fusion Phenomena, Santa Fe, New Mexico, May 23-25, 1989; to be published in the workshop proceedings.

+Patent applications pending.

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) $n + {}^6Li \rightarrow {}^4He + T$ and/or $n + {}^7Li \rightarrow {}^4He + T + n$, and (2) $T + D \rightarrow {}^4He + n$, 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.

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 will be 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] will be 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.

[1]Purdue Nuclear Theory Group, Department of Physics, Purdue University, West Lafayette, IN 47907, U.S.A.

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% ^6Li and 92.5% ^7Li.

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:

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

with kinetic energies indicated in parentheses. The cross-section for the reaction (1a) is very large at thermal energies ($949 \times 10^{24} cm^2$)[3]. The reaction rate (cross-section times velocity, σv) for reaction (1a) is also very large, $\sigma_{nLi}\ v_n = (2.1 - 1.3) \times 10^{-16} cm^3 s^{-1}$, for a range of neutron energies up to 14 MeV[4]. T(2.73 MeV) is produced via the reaction (1a) without requiring a heat source to generate extremely high temperatures (1 MeV corresponds to $10^{10}\ ^\circ K$) 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):

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

The T-D fusion cross-section is maximum ($\sim 10^{-23} cm^2$) at a T kinetic energy of $\sim 100\ keV$ 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 $T(10keV \sim 10MeV)$, and is at least fifty 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, $n + D \rightarrow n + n + p$, etc., producing more neutrons which with the 14.07 MeV neutrons could then feed the 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:

$$n + {}^{7}Li \rightarrow {}^{6}Li + n + n - 7.25MeV, \tag{3}$$

and

$$n + {}^{7}Li \rightarrow {}^{4}He + T + n - 2.46MeV. \tag{1b}$$

The reaction rates (σv) for reactions (3) and (1b) are large, $2.9 \times 10^{-16} cm^3 s^{-1}$ and $1.6 \times 10^{-15} cm^3 s^{-1}$, 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) $\rightarrow$ (2), thus providing a favorable condition for the self-sustaining stage. The neutron-induced T-D fusion via the chain reactions, $(1a, 1b) \rightarrow (2)$, 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, $(1a, 1b) \rightarrow (2)$, 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, $(1a, 1b) \rightarrow (2)$, 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, $(1a, 1b) \rightarrow (2)$, for specific designs of neutron-induced fission-fusion reactors with optimal conditions and geometries.

It has been argued[6,7] that the chain reactions, $(1a, 1b) \rightarrow (2)$, 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, $(1a, 1b) \rightarrow (2)$, 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, $(1a, 1b) \rightarrow (2)$ 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].

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 $0.1 M LiOD$[2], and in a palladium cathode immersed in heavy water with $0.2g$ of $Li_2SO_4 \cdot H_2O$ dissolved in 160 g of D_2O[11]($\sim 0.4 \times 10^{-3} M Li$). The results of Fleischmann et al.[2] are substantially different from those of Jones et al.[11]

The reported D-D fusion rates of $10^{-19} s^{-2}$ [2] and $10^{-23} s^{-1}$ [11] are about fifty 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 twenty 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 ($\sim 40/hour$) will produce tritium via the reaction (1a). ^6Li needed for the reaction (1a) comes from $LiOD$ in the heavy water solution.

Since the positively ionized ^6Li concentration is higher near the Pd cathode, $T(2.73MeV)$ will be produced in greater abundance there via the reaction (1a) than elsewhere. Once produced, $T(2.73MeV)$ 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 the reaction (2). The 14.07 Mev neutron from the T-D fusion reaction (2) can produce excess neutrons via the reactions (1b) and (3), which can now feed reactions (1a) and (1b) to complete the chain reactions $(1a, 1b) \rightarrow (2)$. 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 $Li(0.39 \times 10^{-3} MLi)$ in the heavy water.

If n(14.07 MeV) from the reaction (2) moves out of the $Li - D_2O$ solution thus terminating the chain reaction, $(1a) \rightarrow (2)$, it will generate only a small amount of power, which is too small to be detected. However, if the 14.07MeV neutrons from the reaction (2) (starting with the initial density of $n_n(0)$ for the reaction (1a)) are moderated in D_2O and in Pd by elastic and inelastic scatterings and also by the break-up reactions $(n(14.07MeV) + D \rightarrow n + n + p$; $n(14.07MeV) + T$ (thermalized and left over from the reaction (2)) $\rightarrow n + n + d$ 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 ^4He, since T and n are being recycled in the chain reaction, $(1a) \rightarrow (2)$, consistent with the observation reported by Fleischmann et al.[2]. The use of electrolysis[2] can help chain reaction, $(1a) \rightarrow (2)$, 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, $(1a, 1b) \rightarrow (2)$, are unlikely to occur. However, the situation may be quite different with electrolysis[2] which produces an enormously high concentration (equivalent to pressures of $10^3 - 10^4$ atmospheres[2,13]) of positive ions, D^+, Li^+, and T^+ on and near the Pd cathode, thus diminishing the electron density, ρ_e, and hence $|dE/dx|$, near the Pd cathode. A reduction of ρ_e on and near the surface of the Pd cathode and 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 $(1a) \rightarrow (2)$ and $(1b) \rightarrow (2)$ 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) barns 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].

EXPERIMENTAL EVIDENCE AND TESTS

Support for presence of the self-sustaining chain reactions, $(1a, 1b) \rightarrow (2)$, 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 milliamps with an electrode (Pd) volume of 0.0785 cm^3 and delivering 0.5 watts 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 ^4He production rate of 8×10^{11} to $8 \times 10^{12} cm^{-3} s^{-1}$ which is consistent with the chain reaction, $(1a) \rightarrow (2)$, whose corresponding power, P (chain reaction), would be

$$\begin{aligned} P(chain\ reaction) &= R(chain\ reaction)(E_{nLi} + E_{TD}) \\ &\cong 1.4 \sim 14.4\ watts\ cm^{-3}, \end{aligned}$$

which is of the same order of magnitude as the observed value of 0.5 watts

cm^{-3} [14,15]. $E_{nLi} = 0.77 \times 10^{-12}$ joules/reaction and $E_{TD} = 2.82 \times 10^{-12}$ joules/reaction are the energies generated by the reactions, (1a) and (2), respectively. In calculating the above values of P (chain reaction), R (chain reaction) $\approx 4 \times 10^{11}$ to $4 \times 10^{12} cm^{-3} s^{-1}$ is used, since each chain reaction cycle produces two ^4He 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, $(1a, 1b) \rightarrow (2)$, 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, $(1a) \rightarrow (2)$ and $(1b) \rightarrow (2)$, 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, $(1a) \rightarrow (2)$ and $(1b) \rightarrow (2)$, since there are no Li present. The use of $LiOH$ instead of $LiOD$ will also break the chain reactions, $(1a) \rightarrow (2)$ and $(1b) \rightarrow (2)$, 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 ^7LiOD instead of natural $LiOD$(7.5% ^6Li and 92.5% ^7Li) in their experiments will result in no generation of excess heat, since the absence of ^6Li eliminates the possibility of reaction (1a) and also the reaction (1b) cannot proceed with thermal energy neutrons because of the threshold neutron energy of 2.46 MeV needed for (1b). The use of ^6LiOD instead of natural LiOD is expected to make chain reaction, $(1a) \rightarrow (2)$, proceed faster but may produce less excess heat since the other chain reaction, $(1b) \rightarrow (2)$, is absent. In fact, the absence of ^7Li and therefore the reaction, $(1b) \rightarrow (2)$, may prevent the chain reaction, $(1a) \rightarrow (2)$, 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, $(1a, 1b) \rightarrow (2)$, 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 $^7Li/^6Li$ for a given concentration of $LiOD$.

(b) ^4He (in Pd, in solution and outside as gas).

(c) T (in Pd, in solution and outside as gas).

(d) n (thermal energies to $\sim 14MeV$).

For (a), the excess heat generation is expected to vary as a function of the ratio $^7Li/^6Li$ 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 ^6Li and ^7Li 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, $(1a) \rightarrow (2)$ and $(1b) \rightarrow (2)$), which can be detected only 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, $(1a, 1b) \rightarrow (2)$, 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 ($K \geq 1$).

More detailed analyses of the required conditions for the critical stage and quantitative estimates for the rates of the chain reactions, $(1a, 1b) \rightarrow (2)$, are currently being carried out using Monte Carlo simulations for specific cases of the electrolysis experiments and will be reported in a separate publication.[17]

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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, Journal of Electroanalytic Chemistry **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. Austriaca **52**, 301 (1980).

8. E. Greenspan and G. H. Miley, Nucl. Technology/Fusion 4, 181 (1983).

9. S. M. Waller, J. Fusion Energy **6**, 275 (1987).

10. J. Rand McNally Jr., Nucl. Fusion **11**, 187, 189, and 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 (27 April 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, 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 reference 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, New Mexico.

17. Y. E. Kim, G. S. Chulick, R. A. Rice, A. Tubis, M. V. Hynes, and A. Picklesimer, "Theoretical estimates of conditions and rates of controlled t-d fusion induced by neutrons", in preparation.

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Neutron-Induced Photonuclear Chain-Reaction Process in Palladium Deuteride

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ABSTRACT

Recently, it has been reported by Fleischmann, Pons, and Hawkins (FPH) that tritium production and excess heat generation above that due to the electrode reaction have been observed in their electrolysis experiments with a palladium cathode immersed in heavy water with 0.1M LiOD. The FPH effect cannot be explained by known single-step nuclear reactions such as deuterium-deuterium fusion, since the reaction cross-sections and rates are too small at room temperature. However, a combination of known nuclear reactions can form a set of closed chain reactions which can become self-sustaining at a critical stage under favorable conditions and geometries, as in the well-known case of neutron-induced fission chain reactions. In this paper, the FPH effect is described in terms of a chain-reaction process involving neutron-induced photonuclear chain reactions in palladium deuteride. Experimental evidence and tests of this chain-reaction hypothesis for the FPH are described.

Neutron-induced photonuclear chain-reaction process in palladium deuteride

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Recently, it has been reported by Fleischmann, Pons, and Hawkins (FPH) that tritium production and excess heat generation above that due to the electrode reaction have been observed in their electrolysis experiments with a palladium cathode immersed in heavy water with 0.1M LiOD. The FPH effect cannot be explained by known single-step nuclear reactions such as deuterium-deuterium fusion, since the reaction cross-sections and rates are too small at room temperature. However, a combination of known nuclear reactions can form a set of closed chain reactions which can become self-sustaining at a critical stage under favorable conditions and geometries, as in the well-known case of neutron-induced fission chain reactions. In this paper, the FPH effect is described in terms of a chain-reaction process involving neutron-induced photonuclear chain reactions in palladium deuteride. Experimental evidence and tests of this chain-reaction hypothesis for the FPH are described.

Recently it has been suggested[1,2] that the excess heat generation observed by Fleischmann, Pons, and Hawkins (FPH) in their electrolysis experiment[3] may be due to self-sustaining chain reactions involving neutron-induced tritium-deuterium (T-D) fusion at room temperature. In this paper, an alternative chain-reaction hypothesis is proposed, which is consistent with both the excess heat generation and the tritium production reported by Fleischmann et al.[3] and more recently by other groups[4,5,6].

In addition to the excess heat generation, Fleischmann et al.[3] reported tritium and neutron production. An attempt to interpret their data and that of other's[4-6] in terms of the cold D-D fusion presents the following difficulties:

(I) The D-D fusion rate inferred by Fleischmann et al.[3] from measurements of tritium and neutron production ($10^{-19}s^{-1}$) is about fifty orders of magnitude larger than the expected D-D fusion rate[7] of $\sim 10^{-70}s^{-1}$.

(II) The rate of excess heat output observed by Fleischmann et al.[3] is about twenty orders of magnitude larger than that expected from the inferred D-D fusion rate ($10^{-19}s^{-1}$). Similar rates of excess heat generation have been reported by Appleby et al.[4] and Huggins[6].

(III) The rate of neutron production ($10^{-19}s^{-1}$) reported by Fleischmann et al.[3] is now uncertain and may be substantially less due to a misinterpretation[8,9,10] of their data. The energy of the observed γ-ray appears to be $\sim 2.8MeV$ which cannot be attributed to radiative capture, $n + p \rightarrow D + \gamma$ (2.22 MeV), of neutrons produced in their experiments.

(IV) Wolf et al.[5] reported excess tritium production with a rate comparable to that inferred from the excess heat generation observed by of Fleischmann et al.[3], but did not observe excess neutron production for neutron energies larger than $\sim 1MeV$.

The reaction rates for other known single-step nuclear reactions are also too low at room temperature and hence cannot explain the observed experimental data[3-6] and the above difficulties, for the FPH effect. Therefore, it is reasonable to consider other possible nuclear processes based on self-sustaining neutron-induced chain reactions, which can achieve a critical or supercritical stage in electrolysis experiments. One such chain-reaction hypothesis[1,2] for the FPH effect has been suggested and involves neutron-induced fission of lithium with the resultant high-energy tritium participating in tritium-deuterium fusion. In the following, another possible chain reaction hypothesis is considered, based on a neutron-induced photonuclear chain-reaction process which is capable of resolving the difficulties (I)-(IV). A set of predictions for the new chain-reaction hypothesis, to be tested experimentally, are given at the end.

In the electrolysis experiments of Fleischmann et al.[3], Appleby et al.[4], Wolf et al.[5], and Huggins[6], the background low energy neutrons (~ 40/hour) will produce photons via radiative capture in the Pd cathode,

$$n + {}^{108}Pd \hookrightarrow {}^{109}Pd(\text{excite states}) + \gamma(\lesssim 6.15MeV) \qquad (1)$$

with photon energies[11] indicated in parenthesis. The cross-section for reaction (1) is large at thermal energies, $\sigma = (12 \pm 2)b$ ($b = barn = 10^{-24}cm^2$).[12] The reaction rate (cross-section times velocity, σv) for reaction (1) is also large, $\sigma_{nPd}v_n \approx 2.64 \times 10^{-18}cm^3s^{-1}$. ${}^{109}_{46}Pd$ in its ground state (g.s.) has a spin-parity ($J\pi$) of $(5/2\ +)$ with a half-life of 13.4 hours, and decays by β-decay into excited states of ${}^{109}Ag$ which subsequently de-excite to the ground state $(\frac{1}{2}-)$ of ${}^{109}Ag$ by gamma-ray emissions.[13] There are additional neutron radiative capture processes by other Pd isotopes but their cross-sections are much smaller than that of reaction (1): $\sigma_{n,\gamma} \approx (0.36 \pm 0.05)$b for ${}^{110}Pd(n,\gamma)$

^{111}Pd(g.s.), and $\sigma_{n,\gamma} \approx (13 \pm 2)mb$ for $^{106}Pd(n,\gamma)^{107}Pd$ (isomeric s.).[12] The natural abundances[13] of Pd are 1% ^{102}Pd, 11% ^{104}Pd, 22.2% ^{105}Pd, 27.3% ^{106}Pd, 26.7% ^{108}Pd, and 11.8% ^{110}Pd.

Once the $\gamma(\lesssim 6.15MeV)$ is produced in the Pd cathode, it will lose its energy or be absorbed as it passes through the deuterated Pd and then through the $Li - D_2O$ solution outside the Pd cathode. However, the atomic photo-absorption coefficient[14], $\tau(E_\gamma)$, for Pd has a minimum near $E_\gamma \approx 3 \sim 5MeV$ as do most other elements with atomic number $Z \gtrsim 20$. Therefore, if $\gamma(\lesssim 6.15MeV)$ from reaction (1) is not absorbed, it can participate in nuclear absorption processes by breaking up deuterium in Pd and D_2O via the photonuclear reaction

$$\gamma(\lesssim 6.15MeV) + D \rightarrow p + n - 2.225MeV \qquad (2)$$

which generates neutrons with kinetic energies $\lesssim$ 2 MeV. The cross-section for (2) has a maximum value of $\sigma \approx 2.5$ mb at $E_\gamma \approx 4$ MeV, and a value of $\sigma \approx 2$mb at $E_\gamma \approx 6$MeV[15]. Hence the reaction rate is $(\sigma c) \sim 7 \times 10^{-17} cm^3 s^{-1}$. These neutrons can then feed back into reaction (1) thereby establishing a chain reaction which is designated as (1) $\rightarrow$ (2).

If most of $\gamma(\lesssim 6.15MeV)$ from (1) and/or $n(\lesssim 2MeV)$ from (2) move out of the Pd cathode, the electrolysis cell, and the surrounding shielding, and are lost, then the chain reaction (1) $\rightarrow$ (2) cannot occur and will generate only a small amount of excess heat which is too small to be detected. However, if both $\gamma(\lesssim 6.15MeV)$ from reaction (1) and $n(\lesssim 2MeV)$ from reaction (2) can be kept inside and/or near the Pd cathode, the photon flux inside will increase to a favorable value for the self-sustaining stage, producing enough photons and neutrons to be recycled continuously in the chain reaction, (1) $\rightarrow$ (2) with an associated increase in the excess heat generation. The neutron-induced

photonuclear chain reaction, (1) → (2), is therefore expected to be efficient for producing excess heat once the chain reaction becomes self-sustaining at some stage, thus resolving the difficulties (I) and (II).

When the positively charged Li^+ ions migrate to the Pd cathode during electrolysis, they may form a thin surface layer of Li metal, deuteride and/or alloy crystal,[4] which can act as a reflector of γ-rays. If $\gamma(\lesssim 6.15 MeV)$ are moderated and stay in the Pd cathode by reflecting off the enclosing Li surface layer, they can generate neutrons efficiently via reaction (2) inside the Pd cathode. If most of these neutrons can also stay inside the Pd cathode by moderation through the deuterated Pd cathode and reflections from the Li surface layer, they will feed reaction (1), thus completing the chain reaction, (1) → (2). When the above chain reaction becomes self-sustaining, excess heat of 3.93 MeV (= 6.15 MeV - 2.22 MeV) per chain cycle will be generated along with smaller amounts of other single-step nuclear reaction products (such as tritium). Also the external detection rates of neutrons and γ-rays from this reaction are expected to be substantially smaller than those inferred from the production rates of excess heat and tritium assuming single-step reactions, since these products are being recycled and also shielded by the $Li - D_2O$ solution. Experimental results of Appleby et al.[4] (excess heat generation with some possible tritium gas production) may correspond to the above situation.

If the chain reaction, (1) → (2), is occurring at a self-sustaining stage within the deuterated Pd cathode enclosed by the Li surface layer, the amount of neutrons and photons leaking out into the heavy water solution would thus be minimal. However, if the chain-reaction becomes critical or supercritical, a large excess of neutrons and photons may leak out into the

$Li - D_2O$ solution. Excess neutrons produced by reaction (2) that do not feed reaction (1) will be absorbed by Li to produce tritium and ^4He through the following fission process

$$n + {}^6Li \rightarrow T(2.73MeV) + {}^4He(2.05MeV) \qquad (3)$$

with kinetic energies indicated in parenthesis. The cross-section for reaction (3) is large at thermal energies (949 b),[16] and so is the reaction rate, $\sigma_{nLi}\upsilon_n = 2.1 \times 10^{-16} cm^3 s^{-1}$. ^6Li in reaction (3) comes from LiOD dissolved in the heavy water solution. The natural abundances of ^6Li and ^7Li are 7.5% and 92.5% , respectively. T and ^4He are mostly produced outside the Pd cathode in the solution, since Li ions do not penetrate deeply into the Pd cathode through electrolysis. Thus, the external detection rate of any excess neutrons is expected to be substantially smaller than that of tritium, since most of the neutrons are thermalized in the $Li - D_2O$ solution and absorbed by ^6Li via reaction (3). The experimental results of Wolf et al.[6] (excess tritium production in a few-hour burst with no detection of neutrons with energies greater than $\sim$ 1 MeV) may correspond to this situation, thus qualitatively resolving difficulties (III) and (IV).

The chain-reaction, (1) $\rightarrow$ (2), may be sustained for long periods if favorable geometries and conditions are maintained thereby producing excess heat and tritium in a steady flow. It may terminate abruptly if unfavorable conditions develop (such as reaching its supercritical stage), thus producing the excess heat and tritium as short bursts.

The 2.8 MeV photon observed by Fleischmann et al.[8,9,10] (see difficulty (III)) cannot be attributed to those[11] from to the reaction $^{108}Pd(n,\gamma)\,^{109}Pd$ but may be to the reaction $T(^4He,\gamma)^7Li$. The 2.05 MeV ^4He and thermal-

ized T produced from reaction (3) can interact via

$$^4He(2.05MeV) + T \rightarrow {}^7Li + \gamma \qquad (4)$$

For reaction (4), γ-rays with three different energies, $E_\gamma^{(1)} = E_\gamma^{(2)} + E_\gamma^{(3)} = 3.34MeV$, $E_\gamma^{(2)} = 2.86MeV$, and $E_\gamma^{(3)} = 0.48MeV$, are expected[16,17] since reaction (4) populates a continuum state of ^7Li at $E \approx 3.34MeV$ which decays to the ground state (E = 0 MeV $J\pi = \frac{3}{2}-$, and isospin $I = \frac{1}{2}$) or to the first excited state (E = 0.48 MeV, $J\pi = \frac{1}{2}-$, and $I = \frac{1}{2}$).[16] $E_\gamma^{(1)}$ and $E_\gamma^{(3)}$ may not have been detected by their γ-ray (NaI) detector, since $E_\gamma^{(1)} = 3.34$MeV is out of the energy range of their detector and $E_\gamma^{(3)} = 0.48$MeV will be buried under the background γ-ray spectrum. The 2.8 MeV γ-ray observed by Fleischmann et al. may be identified as $E_\gamma^{(2)} = 2.86MeV$.

The self-sustaining chain reaction, (1) $\rightarrow$ (2), is consistent with the recent observations reported by Appelby et al.[4] that the use of LiOH or NaOD produces a smaller amount of excess heat than does the use of LiOD. The use of LiOH will deter the chain reaction from reaching the self-sustaining stage since H will lower D^+ concentration near and in the Pd cathode and is also a very efficient absorber of neutrons. The use of NaOD or other heavier salts with larger atomic numbers will also deter the self-sustaining chain reaction, since heavier ions (such as Na^+) have larger atomic photoabsorption coefficients than lighter ions (such as Li^+).[14] Furthermore, Na may not form a surface crystal layer on the Pd cathode during electrolysis, since Na may not be loaded into the Pd cathode to form deuteride or alloy while Li may do so.[4]

The self-sustaining chain reaction is also consistent with another observation by Appleby et al.[4] that the use of a platinum (Pt) cathode does not produce excess heat during electrolysis. The radiative neutron capture cross

section, $\sigma_{n,\gamma}$, for Pt isotopes is largest for ^{198}Pt (7.21% abundance), where $\sigma_{n,\gamma} = 3.7 \pm 0.2b$.[12]. However, the rate of photon production will be much smaller for comparable amounts of Pt to Pd, since $\sigma_{n,\gamma}(12 \pm 2b)$ and relative abundance (26.7%) are larger for ^{108}Pd in reaction (1). Furthermore, a Pt cathode does not absorb D to become deuterated during electrolysis.

One way to check the chain reaction hypothesis for the FPH effect and to improve experimental conditions for achieving the self-sustaining chain-reaction, (1) $\rightarrow$ (2), is to use pure ^{108}Pd ($\sim$ 100%) as the cathode in electrolysis. Another possibility is to use a cathode metal which (i) can load deuterium as efficiently as or better than Pd, (ii) has a larger radiative neutron capture cross-section than Pd does, and (iii) produces photons with energies comparable with the minimum atomic photoabsorption coefficients (photon energies of $\sim$ 3 *to* $5MeV$).[14] Titanium is not a good candidate; the largest $\sigma_{n,\gamma}$ for Ti isotopes is that of ^{50}Ti (5.34% abundance) with $\sigma_{n,\gamma} = 0.179 \pm 0.003\ b$ [12], which is substantially smaller than $\sigma_{n,\gamma} = 12 \pm 2b$ for ^{108}Pd (26.7% abundance). This is consistent with the observation reported by Wolf et al.[5] that their electrolysis experiments with titanium cathodes yielded negative results.

There are many improvements which could provide more favorable conditions for achieving the self-sustaining chain reaction, (1) $\rightarrow$ (2), in the experimental apparatus for the FPH effect. Some suggested improvements are: use an intense neutron source; use efficient neutron and photon reflectors in optimal geometrical arrangements; use an optimal current density larger than or equal to the 512 mA/cm^2 Fleischmann et al. used; use an optimal (larger volume and surface) size of the Pd cathode; use an optimal concentration of LiOD greater than or equal to the 0.1 M Li concentration

Fleischmann et al. used; operate the electrolysis for a sufficient duration to achieve a maximal coating of Li^+ on and loading of D^+ in the Pd cathode; and avoid the use of any electrolytes which contain strong photon absorbers such as Na (as in NaOD), 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 isotope ratio $^{108}Pd/Pd$.

(b) ^4He generation (in solution and outside as a gas) as a function of the ratio $^6Li/^7Li$ for a given concentration of LiOD.

(c) T generation (in solution and outside as a gas) as a function of the ratio $^6Li/^7Li$ for a given concentration of LiOD.

(d) n production (thermal energies to ~ 2 MeV).

(e) γ production (energy spectrum $\lesssim 6.15MeV$ from $^{108}Pd(n,\gamma)\,^{109}Pd$).[11]

For (a), the excess heat generation is expected to vary as a function of the isotope ratio $^{108}Pd/Pd$. This test can be used to distinguish between the chain reaction hypothesis and any chemical reaction hypothesis involving Pd since Pd isotopes being chemically identical are expected to produce the same amount of heat from any known or unknown chemical reactions involving Pd.

It should be emphasized that the above quantities, (a)-(e), are expected to be detectable only after the self-sustaining stage for the chain reaction, (1) $\rightarrow$ (2), is achieved. The negative results for (a),(b),(c),(d), and/or (e) reported by many experimental groups may be attributed to the case of the subcritical stage since appropriate geometries and other necessary stringent experimental conditions are required for achieving the critical stage. The chain-reaction hypothesis described above or other chain-reaction hypotheses

such as the one proposed in references 1 and 2 for the FPH effect can be tested experimentally, since each of these hypotheses leads to a set of specific predictions.

Detailed analysis of the required conditions for the critical stage and quantitative estimates for the rates of the chain reaction, (1) $\rightarrow$ (2), are currently being carried out using Monte Carlo simulations for specific cases of the electrolysis experiments and will be reported in a separate publication.

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The author wishes to thank Gary Chulick for helpful discussions and suggesting corrections.

REFERENCES

1. Kim, Y.E., "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. Kim, Y.E., "New cold nuclear fusion theory and experimental tests", in the Proceedings of Workshop on Cold Fusion Phenomena, May 23-25, 1989, Santa Fe, New Mexico, to be published in J. Fusion Energy.

3. Fleischmann, M., Pons, S., and Hawkins, M., Journal of Electroanalytic Chemistry, **261**, 301 (1989); and errata, **263**, 187 (1989).

4. Appleby, A.J., Srinivasan, S., Kim, Y.J., Murphy, O.J., and Martin, C.R., "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, New Mexico; "Anomalous calorimetric results during long-term evolution of deuterium on palladium from lithium deuteroxide electrolyte" to be published in Nature; Appleby, A.J., Kim, Y.J., Murphy, O.J., and Srinavasan, S., "Specific effect of lithium ion on anomalous calorimetric results during long-term evolution of deuterium on palladium electrodes", submitted to Nature.

5. Wolf, K.L., Packham, N.J.C., Lawson, D.R., Shoemaker, J., Cheng, F., and Wass, J.C., "Neutron emission and the tritium content associated with deuterium loaded palladium and titanium metals", in the Proceedings of Workshop on Cold Fusion Phenomena, May 23-25, 1989,

Santa Fe, New Mexico, to be published in J. Fusion Energy.

6. Huggins, R.A. in the Proceedings of Workshop on Cold Fusion Phenomena, May 23-25, 1989, Santa Fe, New Mexico, to be published in J. Fusion Energy.

7. Van Siclen, C.D. and Jones, S.E., J. Phys. G; Nucl. Phys. **12**, 213 (1986).

8. Petrasso, R.D. et al., Nature **339**, 183 (1989); and erratum, **339**, 264 (1989).

9. Fleischmann, M., Pons, S., Hoffmann, R.J., Nature **339**, 667 (1989).

10. Petrasso, R.D., et. al. Nature **339**, 667 (1989).

11. Casten, R.F. et al., Phys. Rev. **21**, 65 (1980); Nuclear Data Sheets **41**, 151 (1984).

12. Sherr, R., in *Handbook on Nuclear Activation Cross-Sections*, Technical Reports Series No. 156, International Atomic Energy Agency, Vienna, 1974, pp. 1-13.

13. *Table of Isotopes*, 7th ed., edited by C.M. Lederer and V.S. Shirley, John Wiley and Sons, Inc., New York.

14. Heitler, W., *The Quantum Theory of Radiation*, Clarendon Press, Oxford (1954), p. 365.

15. Segre, E., *Nuclei and Particles*, W.A. Benjamin, Inc., New York (1965), p. 422.

16. Lauritsen, T., and Ajzenberg-Selove, F., Nucl. Phys. **78**, 39 (1966).

17. Holmgren, H.D., and Johnston, R.L., Phys. Rev. **113**, 1556 (1959).

18. Griffiths, G.M., Morrow, R.A., Riley, P.J., and Warren, J.B., Canadian J. Phys. **39**, 1397 (1961).