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Deuteron Disintegration in Condensed Media

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We discuss the Oppenheimer–Phillips process as a possible phenomenon leading to deuteron disintegration due to polarization in the Coulomb field of a target nucleus. This reaction may be possible in the context of electrochemically compressed deuterons in a palladium cathode. The process is exothermic and may lead to neutron capture from the deuterons into the palladium isotopes, as well as between the deuterons themselves. In the last case, the equivalent of the proton branch of the D-D fusion reaction occurs in preference to the neutron branch. Such a process could provide a model for the processes involved in the observed energy release and tritium production in conjunction with neutron suppression in recent experiments. Possible interactions with Be and fertile isotopes are discussed in the context of breeding fissile isotopes in subcritical configurations.

KEY WORDS: Deuteron; Oppenheimer–Phillips reaction; disintegration; palladium; neutron capture; tritium; cold fusion; fissile isotopes.

1. INTRODUCTION

The possibility of neutron capture associated with deuteron disintegration[1] in condensed matter is discussed as a model for interpreting the processes occurring in the work on cold fusion reported by Fleischmann and Pons[2] and by Jones et al.[3] The proposed model predicts tritium production and heat generation yet neutron suppression, as appears to be the case in some recent experiments by J. Bockris at Texas A&M University reporting excess tritium and by R. A. Huggins at Stanford University measuring excess heat production.

Numerous models for the involved processes have been proposed. These include quantum-mechanical tunneling and quasi-electron formation in the deuterated lattices by Jones et al.,[3] classical oscillations of delocalized species in shallow potential wells by Fleischmann and Pons,[2] reactions between virtual-state pairs of deuterons bound by electrons of high effective mass and deuteron energy upscattering by fast ions from fusion or tritium reactions with virtual-state nuclear structure groups in palladium nuclei by Bussard,[4] the possible existence of a nuclear mass-energy resonance by J. Rand McNally,[5] a He-4 branch from the deuterium fusion reaction at ambient conditions through internal electron conversion without a large release of gamma rays by Rogers and Sandquist,[6] cosmic muons catalysis by Stacey[7] and Rafelski and Jones,[8] and formation of small deuterons clusters and many-body fusion reactions by Matsumoto.[9]

Fleischmann and Pons[2] suggest that the reactions

$$D + D \rightarrow T + H + 4.03 \text{ MeV} \quad (1)$$

$$D + D \rightarrow \text{He-3} + n + 3.27 \text{ MeV} \quad (2)$$

take place to the extent of $1\text{–}2 \times 10^{+4}$ atoms/s, whereas the data on enthalpy generation would require rates for reactions (1) and (2) in the range $10^{+11}\text{–}10^{+14}$ atoms/s, leading them to conclude that these reactions "are only a small part of the overall reaction scheme and that other nuclear processes must be involved," and they further observe that "the bulk of the energy release is due to an hitherto unknown nuclear process or processes (presumably again due to deuterons)." This paper discusses the possibility of neutron capture associated with deuteron

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disintegration due to its polarization in the Coulomb field of a target nucleus, as a model for interpreting their observations.

2. BACKGROUND AND THEORY

Early on, in the study of nuclear reactions, it was observed that (D, p) reactions occur at deuteron energies well below the Coulomb barrier of a target nucleus. Moreover, the cross sections are considerably larger than those for the corresponding (D, n) reactions.[10]

These two observations are at odds with what would be expected from the compound-nucleus model, which suggests that there should not be reactions below the Coulomb barrier and that neutron emission should predominate over proton emission from the compound nuclei formed. Oppenheimer and Phillips[11] explained this apparent anomaly based on the peculiar properties of the deuteron.

The deuteron is a loosely bound nuclear structure with a binding energy of 2.23 MeV only. This value can be calculated from

$$BE = [Z.M(\mathrm{p}) + N.M(\mathrm{n}) - M'] \times 931.5$$

or

$$BE = [Z.M(\mathrm{H}) + N.M(\mathrm{n}) - M] \times 931.5$$

where

$M(\mathrm{p})$ = mass of proton
$M(\mathrm{n})$ = mass of neutron
M' = mass of bare nucleus
M = mass of neutral nuclide
$M(\mathrm{H})$ = neutral mass of hydrogen

Thus for the deuterons,

$$BE(\mathrm{D}) = \{[M(\mathrm{n}) + M(\mathrm{H})] - M(\mathrm{D})\} \times 931.5 = 2.2246 \text{ MeV}$$

where[12,13]

$$M(\mathrm{D}) = 2.01410179 \text{ amu}$$
$$M(\mathrm{n}) = 1.00866497 \text{ amu}$$
$$M(\mathrm{H}) = 1.00782504 \text{ amu}$$

This is actually determined experimentally from the threshold for the photodisintegration reaction of the deuteron into a proton and a neutron:

$$\gamma + \mathrm{D} \rightarrow \mathrm{p} + \mathrm{n}$$

and combined with the mass-spectrograph masses of H and D to determine the neutron mass, since no accurate method for a direct measurement of the neutron mass is known.[14,15]

The deuteron binding energy is low compared with that of other nuclei: 8.48 MeV for the triton; MeV 7.72 for He-3, 28.3 MeV for the alpha-particle, 32.0 MeV for Li-6, 39.2 MeV for Li-7, and about 8.5 MeV for the average particle in a nucleus. Table I compares this value of the deuteron binding energy to that of other nuclei.[15]

The deuteron is the only known existing two-body nuclear bound system. There are no excited states of the deuteron that are stable with respect to decomposition. The absence of excited states of the deuteron, its low binding energy, and its large size (the neutron and the proton spend about one-half the time outside the range of the nuclear force) result from the weakness of the nuclear force when viewed in the context of its small range. Moreover, the charge distribution of the deuteron is very unsymmetric. Its center of mass and its center of charge do not coincide as they do in the alpha-particle. A large separation of about 4×10^{-13} cm exists between the constituents proton and neutron, which actually spend most of their time outside the range of their attractive mutual force.[15]

Volkoff[16] calculated the ratio of the Oppenheimer–Phillips penetrability to the Gamow–Condon–Gurney penetrability of the nucleus potential barrier for different nuclei of charge Z as a function of the deuteron energy in mega electron-volts. His results are shown on a logarithmic scale in Fig. 1. The most interesting feature is that the ratio increases for lower deuteron energies.

Bethe[17] also calculated the same ratio for various nuclear charges Z as a function of the ratio of the kinetic energy of the deuteron to its binding energy. It can also be observed in Fig. 2 that his calculations predict a higher ratio at lower deuteron energies, even below the deuteron binding energy.

The work of Bethe[17] and Volkoff[18] suggests that at low deuteron energy, as is expected to occur in a metal

Table I. Binding Energy (BE) of Typical Nuclei

Nuclide	BE/A (Mev/nucleon)	BE (McV)
D-2	1.12	2.23
T-3	2.83	8.48
He-3	2.57	7.72
He-4	7.08	28.30
Li-6	5.33	32.00
Li-7	5.60	39.20
Be-9	6.47	58.19
Average per nucleon	~8.50	—

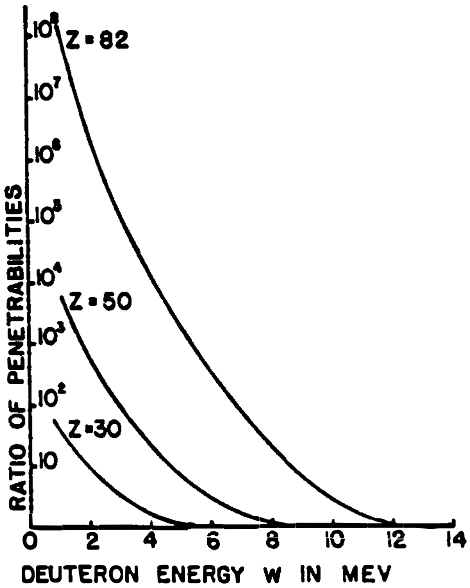

Fig. 1. The ratio of the Oppenheimer–Phillips to the Gamow penetrability of the nucleus potential barrier for different values of the atomic number Z as a function of the deuteron energy W, as reported by Volkoff.[16]

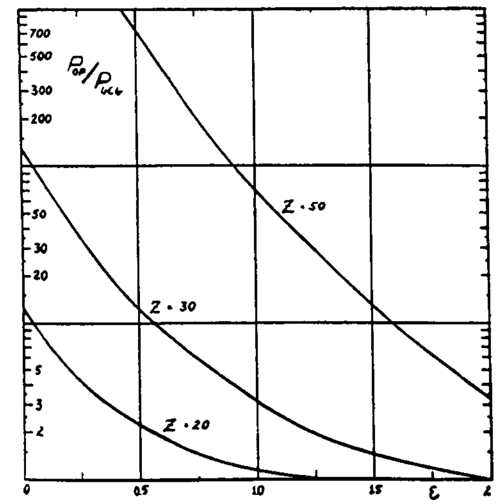

Fig. 2. The ratio of the Oppenheimer–Phillips to the Gamow penetrability of the nucleus potential barrier for different values of the atomic number Z as a function of the ratio of deuteron kinetic energy to its binding energy, as reported by Bethe.[17]

lattice, the Oppenheimer–Phillips process will predominate over classical tunneling of the Coulomb barrier.

3. DEUTERON-DEUTERON REACTIONS

If we assume that the Oppenheimer–Phillips process can occur between deuterons compressed to high pressures of the order of 10^{10} Pa,[6] where the deuterons are held as quasi-oscillators in the metal lattice, then an explanation for the reported tritium production, and heat production, yet neutron suppression, can be attempted.

Because of the finite distance between the proton and the neutron in the deuteron, when compressed in a metal lattice, one of these particles may reach the nuclear surface before the other. The nuclear interaction energies or the average binding energies per nucleon in the nucleus are much higher than the binding energy of the deuteron. As a result, the constituent of the deuteron that arrives first at the nuclear surface is quickly separated from its partner.

In an Oppenheimer–Phillips process, the Coulomb field of the nucleus polarizes the deuteron. As the deuteron approaches the nucleus, its neutron end is turned toward the nucleus, the proton end being repelled by the Coulomb force. Because of the relatively large neutron-to-proton distance in the deuteron, the neutron would reach the surface of the nucleus while the proton is still outside most of the Coulomb barrier. Because of the low binding energy of the deuteron (2.23 MeV), the action of the nuclear force on the neutron tends to break up the deuteron, leaving the proton outside the potential barrier, according to the "highly exothermic"[11] reaction:

$$X(Z,A) + \mathrm{D} \rightarrow [C(Z,A+1)] + \mathrm{p} \qquad (3)$$

where the compound nucleus $[C(Z,A+1)]$ may be stable or would decay by the emission of some other particle or by gamma emission. The nucleus X could be a palladium isotope, an isotope of lithium from the electrolytic solution, or another deuteron confined in the palladium lattice. In case the nucleus X is a deuteron, we obtain Eq. (1), with tritium as a product nucleus in addition to hydrogen. However, from the perspective of this process, what is happening can be more characterized as *a disintegration of the deuteron rather than a fusion of the two deuterons*. Interestingly it would be closer to a fission process than a fusion process. It could also be regarded as a neutron capture process. Moreover, since it is expected to occur under nonequilibrium conditions it may be closer to localized hot fusion than to cold fusion.

If the proton penetrates the Coulomb barrier and hits the target nucleus first, the ensuing reaction would be

$$X(Z,A) + \mathrm{D} \rightarrow [C'(Z+1,A+1)] + \mathrm{n} \qquad (4)$$

Again, if the nucleus X is a deuteron, then reaction (2) would ensue with a neutron and a He-3 nucleus as a result.

At relatively low energies, the neutron capture reaction of Eq. (3) is preferred to the proton capture reaction of Eq. (4). If the X nucleus is a deuteron, the charged particle reaction of Eq. (1) will be consequently favored to the neutron reaction in Eq. (2). As a consequence, one would expect more heat generation and less neutron emission than a model assuming fusion reactions where the d-d fusion reaction would have about a 50% branching ratio to the proton and the neutron branches. A model of deuteron disintegration instead of d-d fusion would effectively favor the proton branch to the neutron branch and explain part of the experimental observations.

4. DEUTERON–PALLADIUM REACTIONS

We than also consider the possibility of deuteron disintegration with the palladium lattice. In the case when the nuclide X in Eq. (3) is an isotope of palladium, one has to consider the different palladium isotopes. Table II shows the different palladium isotopes, their mass excess, their dominant radioactive decay modes, and their natural abundances. The atomic masses for all the isotopes, including the radioactive ones, are calculated from

$$M(\text{amu}) = A + \Delta/931.481$$

where

Δ = mass excess = $M - A$ (in MeV)
m = isomeric state
IT = internal conversion
EC = electron capture

Figure 3 shows that the Pd-106 isotope has the lowest value of the mass excess and is correspondingly the most stable isotope, with a natural abundance of 27.3 a/o. If we consider that the energetics of the neutron capture reaction are analogous to the (d,p) stripping reaction, then according to Evans,[15] "the energetics of the stripping reaction are indistinguishable from those in which a compound nucleus is formed and subsequently dissociates." On this basis we calculate the Q values of the neutron capture reaction in the palladium isotopes as shown in Fig. 4. It can be noticed that all the values are positive corresponding to exothermic reactions and range from 3.37 to 8.34 MeV. This is to be compared to the 4.03-MeV value for neutron capture D-D reaction of Eq. (1). If one accounts for the natural abundances of the stable palladium isotopes, one can estimate a weighted value for Q as 4.86 MeV. This demonstrates that if the proposed model applies, one can expect further heat generation from neutron capture in the palladium isotopes.

Table II. Atomic Masses of Pd Isotopes (amu) and Their Natural Abundances

Mass excess Δ (MeV)	Isotope	Atomic mass (amu)	Natural abundance a/o, decay mode	Q (MeV) (d,p)
−85.4281	Pd-101	100.90829	EC	—
−87.9259	Pd-102	101.90561	1.0	8.34
−87.4789	Pd-103	102.90609	EC	5.40
−89.4005	Pd-104	103.90402	11.0	7.77
−88.4225	Pd-105	104.90507	22.2	4.87
−89.9135	Pd-106	105.90347	27.3	7.33
−88.3716	Pd-107	106.90513	β^-	4.30
−88.1566	Pd-107^m	106.90536	IT	4.09
−89.5235	Pd-108	107.90389	26.7	7.00
−87.6065	Pd-109	108.90595	β^-	3.93
−87.4175	Pd-109^m	108.90615	IT	3.74
−88.3352	Pd-110	109.90517	11.8	6.58
−86.0350	Pd-111	110.90764	β^-	3.54
−85.8650	Pd-111^m	110.90782	IT	3.37

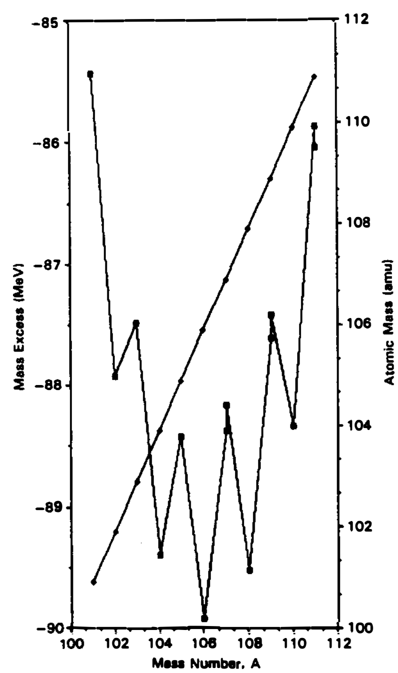

Fig. 3. Mass excess and atomic masses of the palladium isotopes.

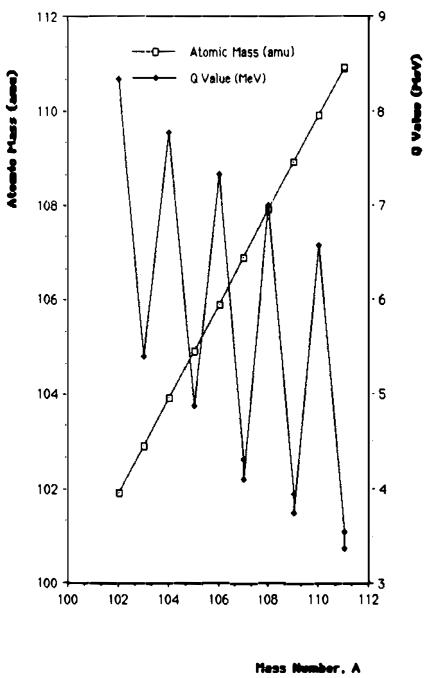

Fig. 4. Neutron capture in palladium isotopes, Q values.

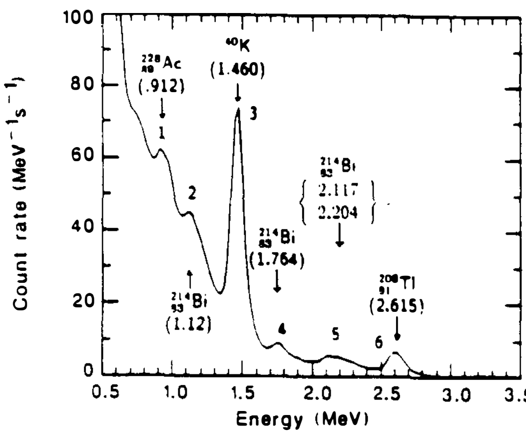

Fig. 5. Typical background gamma-ray spectrum as reported by Petrasso et al.[19]

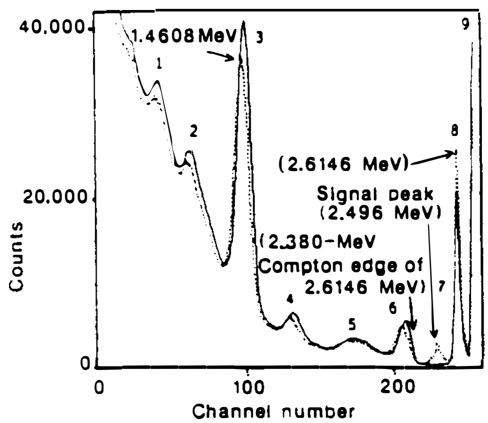

Fig. 6. Gamma-ray spectrum in the Fleischmann and Pons experiments[18] as recalibrated by Petrasso et al.,[19] showing the 7 to 9 peaks beyond the 6 Tl-208 peak.

One would also expect the generation of some radioactive species in proportion to the ratio of neutron capture reactions in palladium to those occurring among the deuteron nuclei.

In fact, in a recent report by Fleischmann, Pons, and Hoffman of the gamma-ray spectra in their experiment,[18] one can notice a peak beyond the 2.6146-MeV thallium-208 signal. This can be noticed by comparing the background gamma spectrum in Fig. 5 reported by Petrasso et al.[19] to their recalibration of the Fleischmann et al. gamma spectrum shown in Fig. 6. According to Petrasso et al., "Fleischmann et al. have identified the Tl-208 line with peak 8; we believe that it should instead be peak 6. . . ." If this argument is accepted, then one can construe peaks 7 to 9 in the Fleischmann et al. experiment as possibly arising from the postulated neutron capture reactions in palladium, instead of being just instrumental artefacts as suggested by Petrasso et al.

5. OTHER POSSIBLE NEUTRON CAPTURE REACTIONS

The same proposed mechanism can be applied to a nucleus which is capable of being polarized in the same way as the deuteron. Such a nucleus is the He-3 nucleus which contains two protons and one neutron. Upon interaction with a deuteron, the following reaction may be expected to occur:

$$X(Z,A) + \text{He-3} \rightarrow [C''(Z+1,A+2)] + \text{p} \quad (5)$$

If we consider the nucleus X to be a deuteron, then we can write the equation

$$\text{D} + \text{He-3} \rightarrow \text{He-4} + \text{p} \quad (6)$$

In fact, He-3 generated by Eq. (2) may interact with the deuterium to produce He-4, which is expected to be present in the discussed experiments to the extent of occurrence of reaction (2). This deuteron disintegration reaction, is equivalent to the D-He3 advanced-fuel fusion cycle.[20,21]

In a palladium lattice, if proven to occur, it would be a neutronless, charged-particle reaction which would lead to the generation of heat, a favorable characteristic if such deuteron disintegration processes are further developed for power production.

Another interesting application, if the discussed process is experimentally verified, is the possibility of using Be-9 as a nucleus which possesses a relatively loose last neutron. In fact, the binding energy of the last neutron in the Be-9 nucleus is just 1.6 MeV. This can be calculated as follows:

$$\mathrm{BE(Be\text{-}9)} = \{[M(\mathrm{He\text{-}4}) + M(\mathrm{He\text{-}4}) + M(\mathrm{n})] - M(\mathrm{Be\text{-}9})\} \times 931.5 = 1.5734\ \mathrm{MeV}$$

where[14,15]

$$M(\mathrm{He\text{-}4}) = 4.00260330\ \mathrm{amu}$$
$$M(\mathrm{Be\text{-}9}) = 9.01218250\ \mathrm{amu}$$

This equation corresponds to the beryllium photodisintegration reaction:

$$\mathrm{Be\text{-}9} + \gamma \rightarrow \mathrm{He\text{-}4} + \mathrm{He\text{-}4} + \mathrm{n}$$

With the exception of deuterium and beryllium, the binding energy of the last neutron for other nuclei lies between 5 and 13 MeV.[15] If Be-9 is used we can write a neutron capture reaction:

$$X(Z,A) + \mathrm{Be\text{-}9} \rightarrow [C'''(Z,A+1)] + \mathrm{He\text{-}4} + \mathrm{He\text{-}4} \quad (7)$$

If deuterium is the target nucleus, which would occur with an experiment similar to the discussed experiment with Be deuteride, the following reaction may occur:

$$\mathrm{D} + \mathrm{Be\text{-}9} \rightarrow \mathrm{T} + \mathrm{He\text{-}4} + \mathrm{He\text{-}4} \quad (8)$$

which is a charged-particle neutronless reaction.

If it is experimentally verified that the hypothesis of deuteron disintegration and neutron capture is valid, then it may also be possible to consider the electrochemical transmutation through neutron capture of the fertile isotopes to fissile ones, without the need to achieve a critical configuration. This could also provide an alternative hypothesis to explain the Oklo phenomenon in the Niger Republic as resulting from neutron capture in a flowing-water environment in addition to the presently accepted hypothesis of a system reaching a critical configuration.

The relevant nuclear reactions would be:

$${}^{2}_{1}\mathrm{D} + {}^{232}_{90}\mathrm{Th} \rightarrow {}^{1}_{1}\mathrm{H} + {}^{233}_{90}\mathrm{Th} \quad (9)$$
$${}^{2}_{1}\mathrm{D} + {}^{238}_{92}\mathrm{U} \rightarrow {}^{1}_{1}\mathrm{H} + {}^{239}_{92}\mathrm{U} \quad (10)$$

The product nuclei would decay to the fissile isotopes ^{233}U and ^{239}Pu through the reactions:

$${}^{233}_{90}\mathrm{Th} \xrightarrow[22.2\mathrm{m}]{\beta^-} {}^{233}_{91}\mathrm{Pa} \xrightarrow[27.0\mathrm{d}]{\beta^-} {}^{233}_{92}\mathrm{U} \quad (11)$$

$${}^{239}_{92}\mathrm{U} \xrightarrow[23.5\mathrm{m}]{\beta^-} {}^{239}_{93}\mathrm{Np} \xrightarrow[2.35\ \mathrm{d}]{\beta^-} {}^{239}_{94}\mathrm{Pu} \quad (12)$$

Deuteron disintegration with the fissile nuclei ^{233}U, ^{239}Pu or ^{235}U may be detectable through a large amount of energy release (200 MeV) and the ensuing fission products which are intensely beta and gamma radioactive.

6. CONCLUSIONS

A model based on the deuteron disintegration due to its polarization in the Coulomb field of a target nucleus, if verified experimentally, would favor charged-particle production to neutron production, be exothermic, and provide a possible explanation to the reported tritium production and energy release, yet neutron suppression from electrochemically compressed deuterium in condensed matter.

Experimental verification of the occurrence of reaction (1) would concentrate on the detection of the product T and H nuclei. The production of neutrons would be expected to be suppressed to the level of the ratio of the occurrence of the proton capture reaction (2) to the neutron capture reaction (1). The verification of the possible occurrence of reaction (3) would depend on the detection of isotopic shifts and the ensuing radioactive species of the Palladium isotopes. The presence of tritium in volcanic eruptions[2] would be construed as resulting from the deuteron disintegration reaction (1). On the other hand, the presence of He-3 in metals[2] would result predominantly, according to the present model, from the decay of the tritium produced from reaction (1), rather than from He-3 produced from reaction (2).

If the present hypothesis is experimentally verified, then other neutron capture reactions with Be-9, and electrochemical transmutations of the fertile isotopes into fissile ones may be possible using subcritical configurations.

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