Rethinking Reactants

A new look at helium and heat production in LENR experiments

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Abstract*: A variety of experimental results observed in heat and/or helium producing LENR experiments will be analyzed resulting in a coherent interpretation of observed results. This will lead to the conclusion that the type of reaction producing ^{4}He and heat is one where ^{4}He is a reactant as well as a product and where deuterium is the essential fuel. Based on this conclusion a working hypothesis is formed about how such a reaction could take place in heavily deuterated metals. An important prediction is made that the introduction of (fast) alphas can have a great impact on the production rate and success of experiments that only sporadically produce ^{4}He and heat.*

1 Introduction

Since the claim by Fleischmann and Pons in 1989 of nuclear reactions taking place producing anomalous excess heat in highly deuterated palladium many experiments have been performed and papers have been published about the phenomena commonly referred to as "cold fusion". In 2004 the DoE performed a review of this new field. The paper "New Physical Effects in Metal Deuterides" by Hagelstein et al. was written as a summary of a subset of the research performed thus far and was used by the DoE as basis for its review.

This "New Physical Effects"-paper contains an analysis of several experiments that showed clear results under reasonably well known conditions. The results of these experiments were examined in order to clarify certain characteristics of the phenomena and interpreted theoretically in order to form a somewhat coherent picture of the nature of the reaction(s) that were taking place. Especially the latter was received with great skepticism and concern since the notion of D-D fusion at room temperature producing ^{4}He and no gamma radiation was regarded as being in conflict with several fundamental theoretical notions and experimental findings. Also the observation of excess heat without ^{4}He in one of the experiments that was thoroughly discussed in the paper seemed to be in conflict with the interpretation of the FP-effect producing heat by fusion of two D atoms.

The purpose of this paper is to re-examine several of these and other experiments and analyze their results in relation to each other with the intent to form a coherent interpretation of the (heat producing) phenomena as a whole. The focus of the examination will therefore be on experiments that show (fairly) clear results concerning certain aspects of the phenomena: some aspects can be more clearly seen in one type of experiment while other aspects are much more apparent in other types of experiments.

The conclusion of ^{4}He being a product as well as reactant that will arise from this analysis will be largely theory-neutral and is based primarily on experimental observation and subsequent analysis. This conclusion is then used as base for the hypothesis of how this type of reaction may take place in heavily deuterated metals. Both this analysis and hypothesis are meant to be used for discussion during the seminar for which this draft paper was prepared.

2 Heat and helium in "New Physical Effects"

The paper "New Physical Effects in Metal Deuterides" by Hagelstein et al. was written as a summary of a subset of the research performed on anomalous effects in metal deuterides in the years since the initial claims in 1989 made by Fleishmann and Pons. It focused for a large part on excess heat production in what are now also known as LENR experiments.

In "New Physical Effects" [1] several important experiments were discussed and their results analyzed. Some of them concerned common characteristics of LENR experiments discovered over the years such as loading ratio of D/Pd and current density in FP experiments. Other experiments (in section 3 and 4 of the paper) were used to demonstrate the temporal as well as quantitative correlation between helium and heat produced. In particular three experiments were given much attention. These same three experiments will also be analyzed in this paper.

2.1 Three "model" experiments

The reason why these experiments were and are important is that they show clear results and distinguish themselves in areas relevant for obtaining insight in the process responsible for producing heat and/or helium. Below is a short description of these experiments and why they are of interest.

- **Complete ^{4}He measurement – FP-type Cell M4**

  An attempt was made to measure all ^{4}He from a sealed FP-type experiment that produced excess heat. Much effort was taken to precisely measure the ^{4}He by making sure no contamination from external sources influenced the measurements. This experiment (Cell M4) is considered one of the best measurements of total amount of helium produced by an experiment for which the excess heat was also measured.

- **Time resolved ^{4}He measurement – Case experiment**

  The Case experiment is a gas loading experiment using carbon supported palladium in a helium tight container. Deuterium gas is used and the system is heated to about 250 degrees Celsius. This type of experiment has shown a strong time correlation between excess heat and helium possible because ^{4}He was measured many times during the active period of the experiment. To this date this is one of the best time resolved measurements of ^{4}He and heat.

- **Highly pure D_2 and high loading – Arata DS-cathode experiment**

  The Arata DS cathode experiments have the unique property of being a gas loading experiment even though electrolysis is also used. This is due to the double structured cathode which does not allow anything but D-atoms inside the inside of the cathode void in which a fine Pd powder resides. This experiment therefore effectively uses highly pure D_2 gas without any (gaseous) contamination. This also means that any ^{4}He found in the Pd powder after the experiment could not have come from external sources.

These experiments and their results were discussed and analyzed in "New Physical Effects" and showed evidence of excess heat and/or helium.

2.2 Theoretical interpretation

Using the results of these experiments it was shown that ^{4}He and heat were not only time correlated but that there also was a likely quantitative correlation between the two. It was argued that the measured amount of MeV per ^{4}He was consistent with the *fusion reaction of 2D into ^{4}He*. The use of this specific (strong) nuclear reaction seemed to be indicative of the underlying theoretical framework with which these helium and heat producing experiments were explained.

2.2.1 Review and issues

The paper "New Physical Effects" was used by the DoE to review this new field. While some of the reviewers were to some degree convinced that there were indeed anomalous effects occurring in deuterated metals due to the presented experiments and their results they also expressed (deep) concerns about the theoretical interpretation of these results [2]. Two of these are:

- **Issues with the idea of D-fusion at room temperature:** the penetration of the coulomb barrier, the claim that ^{4}He would be the main product of this reaction and the lack of gamma radiation detected. Attempts to explain these issues "raised serious concerns regarding the assumptions postulated in the proposed theoretical model of the explanation of ^{4}He production".

- **Inconsistency between proposed theory and discussed experiment:** the DS-cathode experiments did not produce any noticeable ^4He in relation to the excess heat generated. Heat generated in this experiment clearly was not generated by a fusion reaction of 2D resulting in ^4He.

Although the reviewers mentioned many more issues, these two are especially important for the current discussion about helium and/or heat.

2.2.2 Implication of 24 MeV per ^4He

The use of the 2D into ^4He fusion reaction as explanation of what is taking place in the experiments discussed seemed to have been based primarily on the fact that around 24 MeV per ^4He was measured in certain experiments. However even if an exact measurement of 23.85 MeV per ^4He was found in each experiment producing ^4He and heat this still would not imply a fusion reaction between two D atoms occurred.

Shown below are reactions based on fusion (left) as well as weak interactions (right) that produce ^4He with the exact same Q-value (23.85 MeV):

Fusion			Q (MeV)
D + D	→	$^4He + \gamma$	23.847
	or		
4D	→	$^8Be^*$	
$^8Be^*$	→	$^4He + {}^4He$	47.694

Q = ***23.85*** MeV per ^4He

Weak interaction			Q (MeV)
$W_{elec} + e^-$	→	$\tilde{e}^-$,	
$\tilde{e}^- + d^+$	→	$2n + \nu_e$	-3.007
$W_{elec} + e^-$	→	$\tilde{e}^-$,	
$\tilde{e}^- + d^+$	→	$2n + \nu_e$	-3.007
$^4He + 2n$	→	^6He,	
^6He	→	$^6Li^+ + e^- + \bar{\nu}_e$	4.481
$^6Li + 2n$	→	^8Li,	
^8Li	→	$^8Be^+ + e^- + \bar{\nu}_e$,	
$^8Be^{(3.01)}$	→	$^4He + {}^4He$	25.380

Q = ***23.85*** MeV per ^4He

The reactions to the right form the "nuclear cycle" proposed by Widom and Larsen in [3]. This cycle includes the transmutation of ^4He into ^6Li, which in turn is transmuted into ^8Be followed by decay into two ^4He atoms. The energy released by these reactions is 29.86 MeV[1], which starts with one ^4He atom and 4 neutrons and ends up with two ^4He atoms. However since these neutrons are considered to come from the endothermic reactions of electron capture by deuterons the total amount of energy per produced ^4He is exactly 23.85 MeV. Widom and Larsen indicate this by calculating that the electron mass enhancement must be 6.88 for deuterons (as opposed to 2.531 for hydrogen atoms) for electron capture to occur which corresponds to a required energy of 3.007 MeV.

The implication of 23.85 MeV per ^4He is therefore not that D-D fusion occurred but that ^4He is formed by D atoms as essential fuel. Whether this is achieved by a reaction which is catalytic in nature (like the one proposed by WL-theory where ^4He acts as a catalyst) or by direct D-fusion cannot be determined by the Q-value per ^4He. It is important to note that for the above fusion and weak interaction reactions their predicted input fuel and output products are also the same (D and ^4He respectively). Given this combined with the issue the reviewers had with D-fusion theory itself and its inability to explain some seemingly contradictive results it would be prudent to re-

[1] In [3] Widom and Larsen use the (approximate) numbers 26.91 and 2.95 which also adds up to 29.86 MeV. The difference here is merely due to assignment of the mass of (3) electrons to either of these two sets of reactions. The more accurate assignment is used here.

examine these experiments in a largely theory-neutral way. Based on the findings of this examination a determination can then be made whether and how these main issues can be resolved.

3 Analysis of LENR experiments

First the three "model" experiments mentioned in section 2.1 will be analyzed in section 3.1, 3.2 and 3.3. Based on their clear results and given the particular nature of each of these experiments an attempt will be made to determine what kind of reactions are taking place in these heat and/or helium producing experiments.

Based on this initial assessment several other experiments will be analyzed in section 3.4, 3.5 and 3.6. These are mixed ^{4}He/D2 gas experiments performed by Arata using sono implantation and laser welding techniques, the experiment by Mizuno which showed evidence of a long sustained "heat-after-death" effect and finally results from SPAWAR co-deposition experiments showing evidence of particle emissions.

Each of these experiments reveals certain aspects of the type of reaction taking place in heat and helium producing experiments. Along the way these findings are combined to form a coherent interpretation of the results of these experiments. The reasoning used in order to come to the conclusion that ^{4}He is both a reactant and a product and D being the essential fuel is illustrated in a diagram in Appendix A as a set of implications. It can be seen that the strength of the conclusion depends not solely on the strength of each implication but also shows that (weak or strong) implications from experimental results strengthen each other forming a fairly solid case for this conclusion to be correct or being close to it.

3.1 Complete ^{4}He measurement – Sealed FP-experiment: Cell M4

The experiment performed at SRI and discussed in "New Physical Effects" is one of the few experiments where an attempt was made to extract all ^{4}He after excess heat was produced and make careful measurements of both excess heat and ^{4}He. The following figure (Fig. 1) shows a history of this experiment (Cell M4):

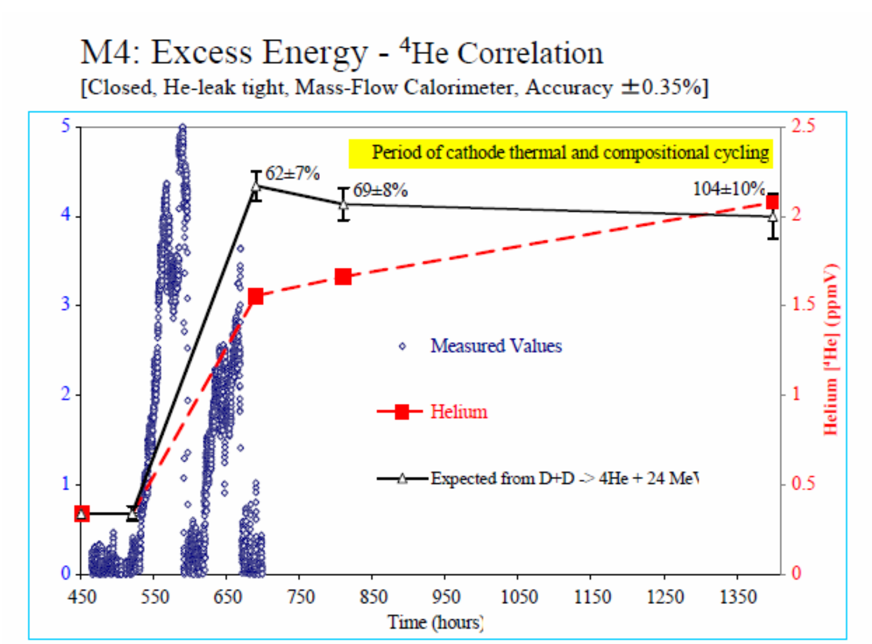


Figure 1. (from [4]) Measurement of ^{4}He from experiment Cell M4 (SRI)

After the experiment produced excess heat, several ^{4}He measurements were made. The initial measurement showed ~62% of what was expected from a ^{4}He producing reaction at 23.85 MeV per ^{4}He atom. However, after another measurement a few days later it was found that the palladium was slowly releasing more ^{4}He. An attempt was made to remove all the ^{4}He out of the palladium by waiting and by thermal and compositional cycling. The last measurement showed an amount of ^{4}He that was close (104±10%) to the expected value. This showed that the reaction responsible for the ^{4}He produced is ~23 MeV per ^{4}He atom for this experiment.

When D atoms are considered to be the main fuel for ^{4}He production the amount of energy per ^{4}He is expected to be around 24 MeV per ^{4}He atom. However if other light elements - like Li of B, assuming they are present at the start of an experiment - are the main fuel in reactions producing ^{4}He this value is expected to be much lower: this is due to the higher binding energy for per nucleus in comparison to D atoms. It should be noted that this particular experiment did contain Li in its solution.

Other experiments have shown significant amount of excess energy and ^{4}He as well. Several of these show a much higher release of energy per ^{4}He while only very few show (significantly) less. In table 1 is a short (and incomplete) list of experiments and their measured/estimated MeV per ^{4}He[5-8].

Performed by	MeV per ^{4}He	Type
M. McKubre (SRI International)	22.85 (first measurement: 38)	(LiOD)
M. Miles (U.S. Navy - China Lake)	25, 39, 44, 52, 62, 83, 88	(LiOD)
V. Violante (ENEA)	~22, ~35, ~50	(LiOD)[2]
B. Bush (Univ. of Texas)	~24, ~37, ~46	(LiOD)[2]
M. McKubre (SRI International)	31	(Case)

Table 1. Measured energy per ^{4}He from different experiments

The range of these results starts with ~22 and ends with 88 MeV per ^{4}He. The top one is the one already discussed showing a decrease of 38 to 22.85 MeV per ^{4}He due to cathode thermal and compositional cycling (and long waiting) for the ^{4}He to be released.

If the slow release of ^{4}He from the palladium is responsible for the main error in these measurements then you would expect most of these measured numbers to be higher than the actual amount of energy released per ^{4}He. This is because a lot or even most ^{4}He would not have been released yet while virtually all heat is released and measured. What would not be expected is a large amount of measurements to be much lower than the actual amount of energy released per ^{4}He. Since most measurements lie above 23.85 MeV per ^{4}He it is unlikely the reaction producing most ^{4}He releases much less than 23.85 MeV energy per ^{4}He.

However what is also apparent from the measurements above is the wide range of energy per ^{4}He. It is not easy to attribute the higher ones to ^{4}He trapping alone. It is therefore possible more than one reaction is occurring in at least some of these experiments. Isotopic changes have been found in some FP-type experiments however it has not been possible to determine to what extend these reactions have attributed to the heat seen in these experiments.

The above measurements thus suggest that even though the amount of energy per produced ^{4}He is close to 24 MeV (and unlikely to be 11.2 MeV per ^{4}He as it would have to be if Li and D were the main fuel) there could be other reactions taking place producing heat but not helium. If such reactions would occur simultaneously with ^{4}He producing reactions it will be very hard to make any determination what these reactions are. What would be needed is an experiment where one of these reactions is isolated from the others or where one of these reactions is somehow "turned off". This would allow a much better analysis of reactions taking place and their possible reactants.

3.2 Highly pure D_2 and high loading – Arata DS-cathode experiment

The DS-cathode experiment was developed Arata and Zhang and has some unique characteristics. The double structured cathode (see depiction of this cathode in upper right corner in figure 2 below) is filled with a fine powder of palladium. During electrolysis D-atoms enter the inner cavity of the cathode where this powder resides. This then ensures very high loading of D into Pd. It also makes sure that any contaminants in the electrolyte (like lithium) cannot enter this hollow. In essence the environment inside the cathode is that of highly pure D gas and very fine Pd

[2] Numbers estimated from figures in papers

powder. Any ^{4}He or ^{3}He measured inside the cathode after the experiment must therefore have originated from inside the cathode.

Several of these kinds of experiments had been executed and showed large amount of excess heat over long periods of time. These experiments are therefore regarded as one of the most successful experiments in the field of LENR. It would seem that because of the pure Pd/D environment and the high loading they were very suitable to create excess heat.

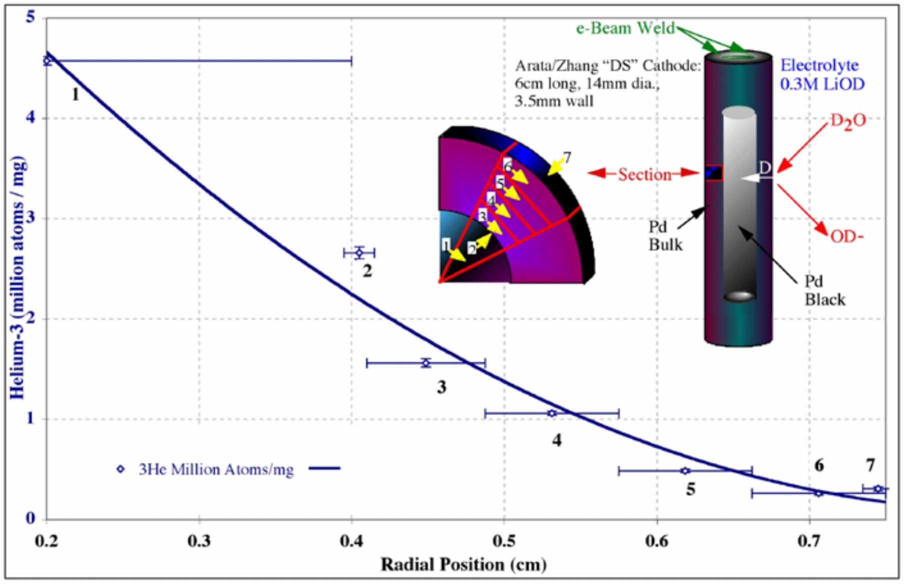


Figure 2. (from [1]) Illustration of DS-cathode and measurements of ^{3}He

An attempt was made by SRI to replicate these results and also to measure any ^{4}He or ^{3}He produced by this experiment. If the ^{4}He found in other FP-type experiments was produced by a fusion reaction of D then it was expected it would also be produced in this experiment. If so Arata and Zhang would have all but eliminated other possible reactions which might have been responsible for ^{4}He production (such as a reaction between Li and D mentioned above) since it would then be shown Li would was not needed to produce ^{4}He.

However even though this experiment showed a large amount of excess heat at SRI it showed no sign of ^{4}He. The same was true for the measurements performed by Arata and Zhang (only 0.05% of the expected ^{4}He was found when compared to the excess heat). This is a very significant result because it shows that no DD-fusion occurred in these experiments. It showed that heat without helium could be produced in LENR experiments. It also strongly suggests that in order to produce ^{4}He, LENR experiments need another (light element) reactant besides D. This reactant was apparently missing in these DS cathode experiments.

It was shown that some ^{3}He and T was produced. Even though the amounts measured are not enough to account for the excess heat it did show other reactions were taking place. Above is a figure (Fig. 2) showing that the ^{3}He (and T) were produced inside the cathode since more is found on the inside than on the outer layers of the cathode. This therefore confirms that the heat producing reaction took place inside the cathode as well and any produced ^{4}He was unlikely to be lost.

The value of the result of these DS-cathode experiments (and follow-up measurements) should not be underestimated: light elements like Li, B and He are essentially absent but the amount of excess heat generated from these experiments is very large and cannot be of chemical origin. However the results are quite striking: essentially no ^{4}He was produced at all.

Interestingly the analysis of the palladium powder of the DS-cathodes showed signs significant isotopic changes of Pd 110/108 [9]. These apparent transmutations could be responsible for the excess heat measured. But if deuterium had reacted with Pd it would suggest that one of the reactants (in this case D) is able to react with different reactants. So depending on the available reactants this would lead to ^{4}He in some experiments while it would lead into transmutations of Pd (or other heavy elements) in other experiments.

When considering the analysis in section 3.1 that D is likely to be the essential fuel due to closeness of 24 MeV per ^{4}He in heat producing LENR experiments, and considering what is learned from Arata DS-cathode experiments that heat producing LENR experiments are likely to need a reactant other than D is to produce ^{4}He, it is tentatively concluded that the reaction producing heat and helium must be catalytic in nature. That is: two D atoms directly or indirectly react with a catalyst which produces the same catalyst and ^{4}He. The question then raised here is which catalyst is needed to produce ^{4}He.

3.3 Time resolved ^{4}He measurement – Case experiment

The question from the previous section is what could be missing that would be used to form ^{4}He. The Case experiment is a gas loading experiment which did produce ^{4}He. It shows a strong time correlation between excess heat and helium which suggests that the ^{4}He producing reaction is the main reaction taking place. It also shows a 31 MeV per ^{4}He so its main product is likely to be helium.

Exponential growth in Case experiment

The production of helium and heat over time is shown below in the experiment SC2 performed by SRI (Fig 3):

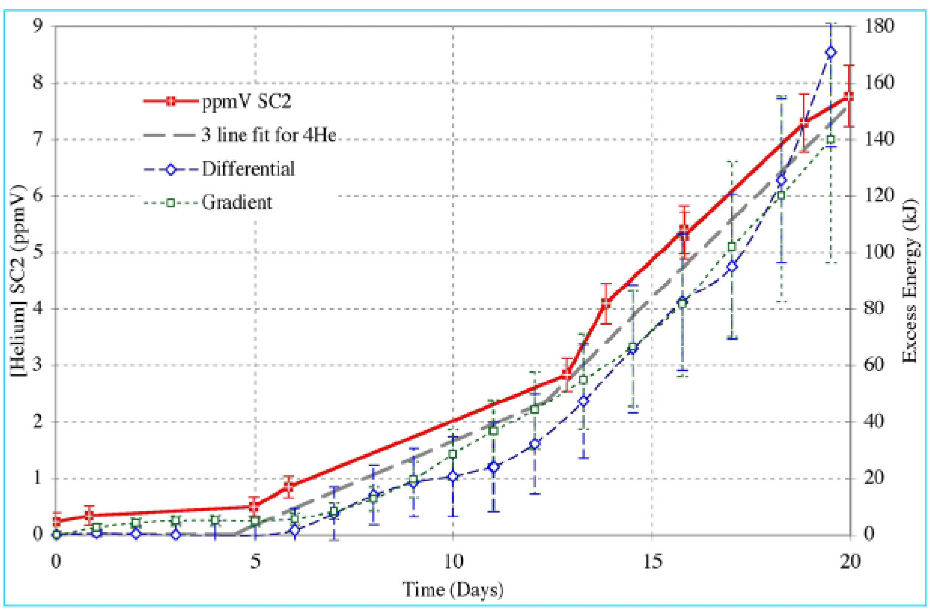


Figure 3. (from [1]) Heat and helium measurements for Case SC2 experiment

Besides the strong time correlation between ^{4}He and heat it also quite clearly shows an exponential growth in both helium and heat. This would suggest that some kind of cumulative effect is occurring in this experiment. Other Case experiments also show approximately exponential growth patterns. The rate of ^{4}He production therefore appears dependent on the amount of ^{4}He present. In other words: it looks like ^{4}He can improve the rate of production of ^{4}He in Case experiments.

Delays dependent on initial ^{4}He in Case experiments

Several more Case experiments have been performed (by SRI) and their ^{4}He measurements over time are shown the following graph (Fig 4):

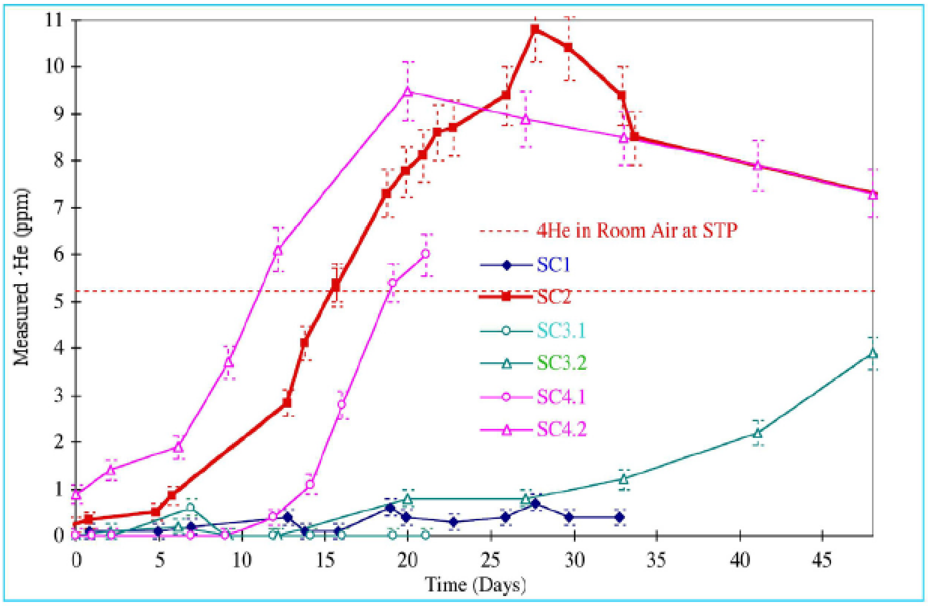


Figure 4. (from [1]) Heat and helium measurements for several Case experiments

What can be seen is several experiments with different "starting" times but about the same peak ^{4}He production rate (SC4.2, SC2 and SC4.1). Interestingly the delays approximately correlate with the lack of ^{4}He at the start of the experiments. Experiments that contained more initial ^{4}He start sooner than experiments that had only very little initial ^{4}He. Another experiment (SC3.2) shows a much slower increase but because there are more measuring points its exponential growth can quite clearly be seen.

These Case experiments therefore indicate an important role of ^{4}He for the production of ^{4}He. If ^{4}He itself were a catalyst needed to produce ^{4}He using D as essential fuel then it would be expected that ^{4}He would grow exponentially: with each reaction the amount of catalyst grows (doubles the ^{4}He) which allows for more subsequent reactions to take place.

What is thus suggested by Case experiments is that ^{4}He is in fact one of the reactants required to produce ^{4}He in LENR experiments. If so this would also explain that without ^{4}He (which was deliberately absent in the Arata DS-cathode experiments discussed in section 3.2) no ^{4}He will be produced. And if only very little ^{4}He is initially present very little ^{4}He is produced. But since the growth of ^{4}He is expected to be exponential at some point the same amount ^{4}He is produced as in experiments which started with more initial ^{4}He. This is what is seen in the above Case experiments.

The tentative conclusion reached here is therefore that ^{4}He is both reactant as well as product in a catalytic reaction where D is the essential fuel. It would require at least two D atoms to produce additional ^{4}He. The type of reaction is illustrated here (where $^4X \approx 2D$):

$$^4He + {}^4X \rightarrow {}^4He + {}^4He \quad (1)$$

This is quite different from the proposed direct fusion of D in the paper "New Physical Effects" even though the same experimental results were analyzed. While it has already been argued that D-D fusion does not explain these three experiments (in section 3.1, 3.2 and 3.3) in a coherent way more experiments will be discussed to examine if there is additional evidence for the type of reaction proposed above and how it could even be confirmed.

3.4 Mixed ^4He/ D_2 experiments - Sono implantation and Laser welding (Arata)

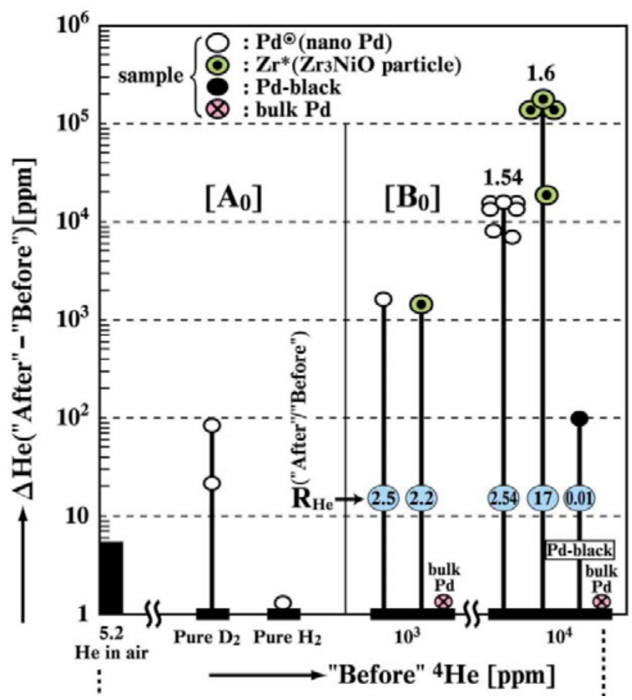
In order to confirm that reactions of the above type are responsible for ^4He production in LENR experiments an experiment is needed which uses mixed $^4He/D_2$ gases. Such an experiment would have to produce ^4He fairly consistently given the same amount of $^4He/D_2$ ratio and input energy. If ^4He is a reactant then the ratio of $^4He/D_2$ should have a significant influence on the amount ^4He production in such an experiment. If not then ^4He is unlikely to be a reactant. In order for this to be measured more accurately it would be beneficial to keep all other parameters of the experiment the same most notably the amount of input energy.

Thus by varying this $^4He/D_2$ ratio while applying the same amount of input energy one could determine whether the ^4He has any influence on the amount of ^4He produced. If more ^4He is produced with higher $^4He/D_2$ ratios then this would strongly suggest that ^4He is in fact a reactant and would to a large extend confirm the proposed conclusion.

Helium 4 by Helium 4

Unfortunately many of the experiments that have measured the amount of ^4He have had their ^4He carefully removed before the experiment began. However, Arata and Zhang have performed exactly the type of experiments proposed: laser welding and sono-implantation experiments that used different mixtures of ^4He and D_2 gases and where the same amount of energy is inputted for each experiment [10].

The results from these mixed gas experiments are quite revealing. When a sample loaded with nearly pure D_2 was subjected to laser welding a fair amount of ^4He was generated. However when the samples were loaded with a mixture of D_2 and ^4He the generated amount of ^4He was profoundly higher. In fact the experiment showed that the more ^4He was added the more ^4He was produced. In the following figure the results of the laser welding experiments are shown (Fig. 5):



^4He start (ppm)	Δ^4He (ppm)
~ 0	**~100**
1 000	**2 500**
10 000	**15 400**

Table 2. Laser welding using Nano-Pd

^4He start (ppm)	Δ^4He (ppm)
1 000	**2 200**
10 000	**160 000**

Table 3. Laser welding using Zr*

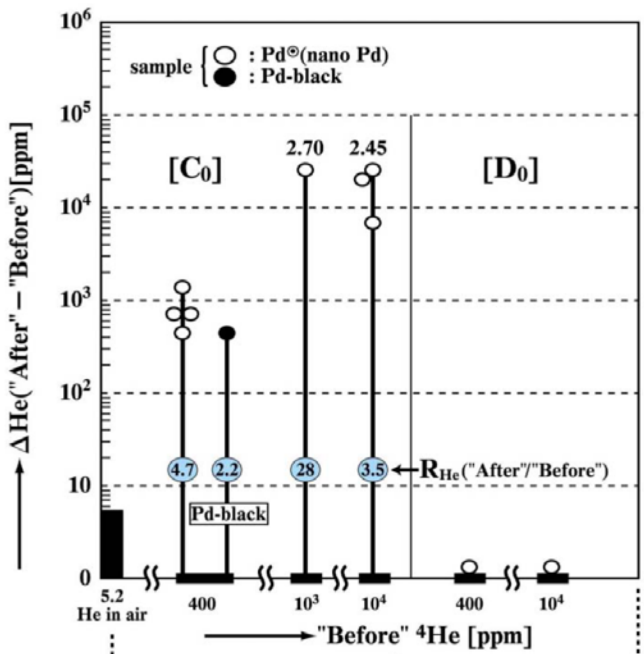
Figure 5. (from [10]) Laser welding results with pure D_2 and H_2 (left) vs. mixed $D_2/^4He$ gases (right)

On the left side the results from the experiment performed with either pure H_2 or pure D_2 are shown. As a control it shows that when H_2 is used no ^4He is produced. When (nearly) pure D_2 is used around 100 ppm of ^4He is produced. But when a mixture of D_2 and ^4He was used several orders of magnitude more ^4He was generated. When put in table form (table 2 and 3) the results clearly show that there is a very strong influence by the presence of ^4He on the production of ^4He.

It was calculated that in the case of Zr* with 10^4 ppm of ^4He (which lead to 170 000 ppm of ^4He after the experiment) between 10^{19} and 10^{20} atoms of ^4He were produced by just 10 seconds of (on average) 300 Watts laser exposure. To put this into perspective: if output/input energy ratio is a way of measuring the effectiveness of an experiment then this would be several orders of magnitude better than the best so far (which is ~25x). So these results show very clear and direct influence of initial ^4He on the amount of ^4He production. This then demonstrates the important role of ^4He as a reactant for producing ^4He in these experiments.

Sono-implantation

Similar experiments using sono-implantation were performed. The results of these experiments show the same kind of dependence on ^4He for the amount of ^4He produced (Fig. 6):



^4He start (ppm)	Δ^4He (ppm)
400	**1 480**
1 000	**27 000**
10 000	**24 500**

Table 4. Sono-implantation using Nano-Pd

^4He start (ppm)	Δ^4He (ppm)
400	**480**

Table 5. Sono-implantation using Pd-black

Figure 6. (from [10]) Sono-implantation results with mixed $D_2/^4He$ gases (left) vs. mixed H_2 (7%)/$D_2/^4He$ (right)

On the right side the result of a control is shown that used a mixture of H_2 (7%)/$D_2/^4He$. No ^4He was produced and it showed that no enrichment of ^4He was taking place when ^4He was added (which might occur due to absorption of D_2 or H_2 after the experiment). On the left side the results from the experiment performed with mixed $D_2/^4He$ gases are shown which are also shown in table form (table 4 and 5).

Interestingly, although the increase of 400 ppm to 1 000 ppm of initial ^4He did increase ^4He production significantly, the increase of initial ^4He from 1 000 ppm to 10 000 ppm did not increase the amount of produced ^4He any further. It appears that a maximum amount of ^4He production (rate) was achieved in these experiments. This indicates that, although ^4He is one of the reactants other factors have become the limiting factor in ^4He production.

Overall, these mixed gas studies show very clearly the influence of initial ^4He on the production of ^4He. In fact these experiments quite unambiguously show that ^4He is not just the product but also the reactant. This then comes very close to confirming that the reaction that causes ^4He production also requires ^4He as a reactant where D is the essential fuel.

3.5 Sustained chain reaction – Mizuno's "heat after death" experiment

Of interest in the above experiments is that in most cases around 2-5 times the amount of helium which was present before the experiment began was produced (indicated by R_{He} in Fig 7 and 8). There are however two exceptions where far more helium was produced. This is the case for Nano-Pd with a concentration of 10^3 ppm of helium and for Zr* with a concentration of 10^4 ppm of helium. This hints at the possibility of a "runaway" event happening or sometimes referred to as a "heat-after-death" effect where the experiment produces heat and/or helium after the input power has already been shut down.

There have been several reports of this so called "heat after death" effect but for one of Mizuno's experiments it occurred on a massive scale and for a long time [11]. What happened is reported by Mizuno and although it could be called anecdotal evidence it tells something about the nature of the reactions that occur in FP-type experiments. In essence the Pd/D_2O experiment was still producing heat after the input power was shut down. It kept producing heat and was placed in water for cooling. For 10 days many liters of water were evaporated. The total estimated amount of excess heat by this experiment after power shutdown was about 85 MJ which is quite astounding.

Usually FP-type experiments require input energy to produce excess heat. However it appears that in this case a threshold was reached where the experiment could sustain itself. This kind of effect suggests a sustained chain reaction taking place which produces enough energy for it to be continuing. If the interpretation of this "heat after death"-effect being a form of a sustained chain reaction taking place is correct then this gives several new insights about the nature of the reactions taking place.

A well known sustainable nuclear chain reaction is that of ^{235}U and neutrons. From this reaction several aspects will be highlighted that make it a sustainable chain reaction. The main requirements for a chain reaction to be sustainable are considered to be the following:

- **Product is a reactant**: for the reaction(cycle) to be a chain reaction one of the products must be a reactant of the reaction(cycle). In the case of ^{235}U these are the neutrons.

- **Multiple identical products**: for a chain reaction to be sustainable more than one of these products (which also act as reactants for subsequent reactions) must result from the reaction. In the case of ^{235}U about 2.4 neutrons are produced with each successful split reaction.

- **Delivery of reactants to fuel**: in order for a chain reaction to keep occurring the reactants (that are produced) must be delivered to new fuel. In the case of ^{235}U neutrons travel through the uranium and if there is enough (critical) mass they will react with ^{235}U.

Given these (rather unique) requirements the proposed reaction for ^4He will be looked at in order to see if it is a reaction of this type. If so this would further strengthen the conclusion that ^4He is produced this way in LENR experiments.

Below is a table showing that the proposed reaction does indeed conform to these requirements:

	Enriched Uranium	Deuterated Palladium
Fuel	^{235}U	D
Product also a reactant	n	^4He
Multiple of these products	~2.4x n	2x ^4He
Delivery to fuel	Kinetic energy neutron	Kinetic energy helium

Table 6. Comparison between enriched uranium and deuterated palladium regarding chain reaction components

Here deuterium is considered to be the main fuel and ^4He is a reactant but also a product. In the case of deuterated metals the ^4He is considered to initiate the reaction with D where its kinetic energy it got from being a product is thought to be instrumental to make this happen. What the above shows is that there is at least the potential of a chain reaction occurring with the proposed reaction for ^4He production.

3.6 Particle emissions – SPAWAR co-deposition experiment

The SPAWAR experiments use a co-deposition technique in order to ensure high loading of Pd with deuterium when Pd is deposited in a cathode. When using CR-39 detectors it has been made possible to determine if particle emissions were occurring and of which type and energy these particles are.

After performing the experiments a large amount of pits were found in the CR-39 which after analysis are shown to be particle tracks. Interestingly there is a ~90% decrease of these tracks when the CR-39 is coated with a 6 μm Mylar. This material is capable of stopping <1.05 MeV alpha particles and <0.45 MeV protons.

Calibration curves have shown that a large part of observed pits are consistent with pits caused alpha particles. This means that a substantial amount of the charged particles emitted from these experiments are alpha particles with a kinetic energy close to or lower than 1.05 MeV when they reach the CR-39. Since these kinds of alpha particles only travel very short distances in (heavy) water the observed alpha particle pits are considered to be only a small fraction of the total amount of alpha particle emissions in the experiment.

Further evidence of the energy of these alpha particles is obtained from computer modeling. Below is a picture and an illustration of the observed pits found in the CR-39 after etching:

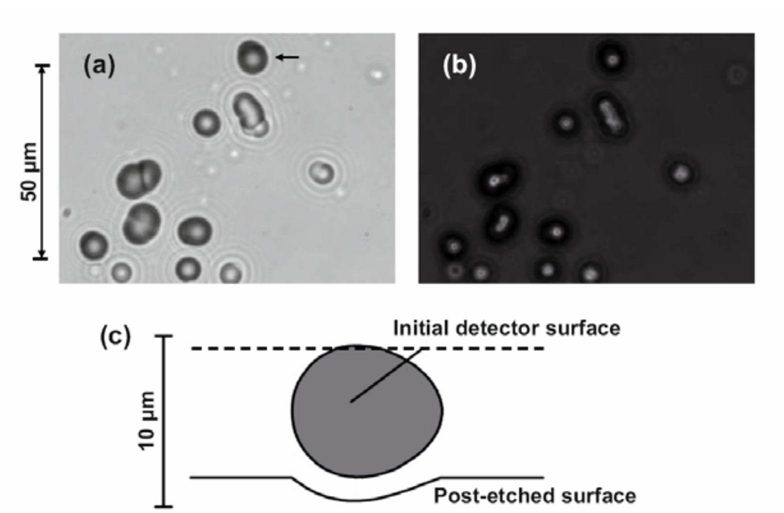


Figure 7. (from [12]) Track marked in (a) and seen in (b) computer modelled in (c)

What has been determined is that in the above example the alpha particle is modeled to have an kinetic energy of 1.3 MeV when it hits the CR-39 with an angle of around 35 degrees.

If these observed pits are indeed from alpha particles caused from the proposed reaction then this reaction should be producing ^{4}He with close to or slightly more than 1.3 MeV of kinetic energy. If two ^{4}He alpha particles are produced at the same time by decay of ^{8}Be it would mean the ^{8}Be must be in an excited state of 2.6 MeV (or a little more). For ^{8}Be this is most likely to be the 3.01 MeV excited state (which is a known result from ^{8}Li beta decay).

The main conclusion then of the analysis of the sections 3.1 – 3.6 is that the following type of reaction takes place in ^{4}He and heat producing LENR experiments:

$$^4\mathrm{He} + {}^4\mathrm{X} \rightarrow {}^8\mathrm{Be}^{(3.01)} \rightarrow {}^4\mathrm{He} + {}^4\mathrm{He} \qquad (2)$$

This conclusion is based primarily on experimental results and analysis thereof. It is therefore largely theory-neutral and can form the basis for a hypothesis that tries to explain how this kind of reaction could take place. One such possible hypothesis will be discussed in the following section.

4 Working Hypothesis

Below will be presented a working hypothesis in order to explain how the proposed chain reaction could take place in deuterated palladium. It should be noted the analysis in section 3 is not founded on the following hypothesis but the other way around: the working hypothesis assumes the proposed chain reaction from section 3.6 is largely correct.

First since D is the fuel it is assumed that the reaction (2) is split into two phases:

$$^{4}He + {}^{2}X \rightarrow {}^{6}Li \quad (3)$$
$$^{6}Li + {}^{2}X \rightarrow {}^{8}Be \rightarrow {}^{4}He + {}^{4}He \quad (4)$$

where $^{2}X \approx D$.

For this to happen, the coulomb barrier must somehow be overcome between $^{4}He/^{6}Li$ and D. This essentially leaves two options: either $^{4}He/^{6}Li$ becomes more "neutral" or D-ions do. One possibility is that muons are involved and act as electromagnetic shields for $^{4}He/^{6}Li$ (to which several must be "stuck") to continuously reacting with D atoms. This appears quite unlikely and will not be discussed here further.

Another possibility is that some D-ions completely lose their electrical charge or alternatively their coulomb barrier is somehow significantly reduced. $^{4}He/^{6}Li$ would then be able to react with those "neutral" D-ions. It is assumed here (for now) that this is in fact happening.

The following figure (primitively) illustrates what could happen if deuterons would become "neutral" in a Pd/D lattice where ^{4}He and ^{6}Li ions are already produced by the proposed chain reaction and are therefore assumed to have some kinetic energy: (Fig. 8)

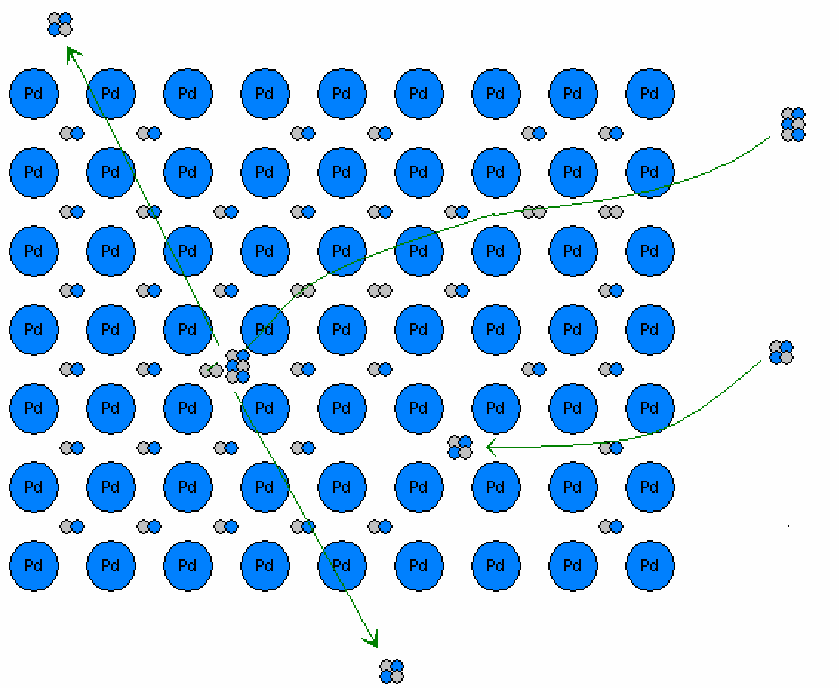


Figure 8. Illustration of ^{4}He and ^{6}Li moving through Pd filled mostly with D and reacting (or not) with "neutral" D-ions

When ^{4}He and ^{6}Li ions are moving this relatively high kinetic energy through a Pd lattice loaded with D it is assumed that they would tend to travel through the parts with least electrical charge and also end up in a position of the lattice with less electrical charge than elsewhere. If the lack of electrical charge is caused by the absence of D then nothing special is expected. However if the lack of electrical charge is caused by D-ions who have lost their charge then the chance of ^4He and ^6Li reacting with those D-ions is greatly enhanced. This is especially true if ^4He and ^6Li land virtually on top of a location where a D-ion was positioned before it lost its charge.

When ^4He or ^6Li react with D it is expected that due to the recoil energy from the reaction the resulting products (^6Li and ^4He respectively) will have significant kinetic energy which would start over the whole process. If loading (D/Pd) is very close or 1.0 then there would be less chance the ^4He and ^6Li ions end up in empty locations (with no D) but instead at locations where D-ions have (just) lost their charge. This would then explains why high loading (>~ 0.85) is required in order to obtain excess heat in LENR experiments since otherwise most chain reactions would quickly end in these empty cavities. An apparent additional requirement for this to work is that the “neutral” D-ions should not move from their location very much.

This leads to the question how D-ions lose their electrical charge. The answer can be found in the observation by many experiments of Tritium. It is clear that in LENR experiments when Tritium is produced much less neutrons were detected than expected (5) from D-D fusion [13].

$$T >> n_{detected} \tag{5}$$

This means the Tritium is unlikely to have been produced by any fusion reaction. The only fusion reaction with reactants that could possibly be present in Pd/D environments is a fusion reaction between two D atoms (other possible fusion reactions would all require highly unlikely neutron rich isotopes in order to produce T). It is well known however that D-D fusion produces as much Tritium as fast (and detectable) neutrons.

Since this is not seen, the only explanation for Tritium must be that it is produced by reactions with neutrons that cannot be detected: (ultra) low momentum and/or trapped neutrons. If these are the same neutrons allowing the above reaction to occur then the requirement of them not moving is also largely fulfilled.

If deuterons are therefore transformed into (di-)neutrons (by electron capture) then reaction (3) and (4) will actually consist of the following reactions:

$$^4He + 2n \rightarrow {}^6He, \tag{6}$$
$$^6He \rightarrow {}^6Li^+ + e^- + \bar{\nu}_e \tag{7}$$

$$^6Li + 2n \rightarrow {}^8Li, \tag{8}$$
$$^8Li \rightarrow {}^8Be^+ + e^- + \bar{\nu}_e, \tag{9}$$
$$^8Be^{(3.01)} \rightarrow {}^4He + {}^4He \tag{10}$$

Other possible reactions that produce Tritium are then:

$$^6Li + n \rightarrow {}^4He + T \tag{11}$$
$$D + n \rightarrow T \tag{12}$$
$$D + 2n \rightarrow T + n \tag{13}$$

And when Tritium decays into ^3He this would allow a reaction with 2 neutrons and ^3He:

$$T \rightarrow {}^3He \tag{14}$$
$$^3He + 2n \rightarrow {}^4He + n \tag{15}$$

Reactions (6)-(10) are part of a chain reaction and are therefore expected to be producing the predominant products when these chain reactions can be sustained. When ^6Li initially fails to react with two neutrons the reaction (11) is possible. Since ^6Li is essentially an end-point of a chain reaction, many are expected to be retained in the Pd. If single neutrons later react with these ^6Li atoms this can cause a fair amount of T to be produced. Because his reaction also produces a fast alpha particle it can start new chain reactions as well. When deuterium and neutrons react (12)-(13) Tritium and (detectable) neutrons can be produced. And the reaction (15) would produce a very fast neutron which could split a carbon atom into three alpha particles.

Discussion

Analysis of experiments performed in section 3 has lead to the conclusion that ^{4}He is a reactant producing ^{4}He with D as fuel. The above proposed working hypothesis poses quite significant theoretical challenges. It requires electron capture to occur and two neutrons to stay essentially where they are created. Also gamma radiation and hard X-ray should not be emitted or be shielded. Some of these challenges have been faced (e.g. by WL-theory) while others remain to be addressed.

However, an important prediction can already be made based the analysis in section 3 alone. Given that the proposed (chain) reaction requires ^{4}He to start one reasonable prediction is that introducing ^{4}He in the form of either gas or (fast) alpha particles could (re-)start a chain reaction of this kind and could therefore significantly increase the chance of production of ^{4}He and heat in experiments that otherwise produce ^{4}He and heat only sporadically. One possibility is that impurities containing traces of uranium might already have been responsible for triggering these reactions (due to alpha decay) and started (bursts) of excess heat production is at least some experiments. Also mixed gas experiments discussed in section 3.4 have already shown that (sono-) implantation of ^{4}He or excitation by laser of ^{4}He can significantly increase production of ^{4}He. It is therefore proposed to add (fast) alpha particles to current experiments to validate this prediction.

The analysis in section 3 and subsequent hypothesis in section 4 were not possible without (an examination) of many years of experimental work and resulting data. Even though experiments may not always have been performed as systematically as desired (due to many reasons) this source of information is extremely valuable. When considering a new and systematical approach to this new field in science this consideration should be taken into account.

5 Conclusion

Since the beginning of "Cold fusion" helium-4 and excess heat have often been produced at the same time. It was clear very early on that this kind of "fusion" was different from any kind known thus far. It would seem that somehow nature had found a way to bring together two D-atoms at room temperature in a palladium lattice. It was therefore assumed by many in the field that direct D-D fusion occurred. However many other strange aspects of the phenomena became clear such as the amount of Tritium and neutrons detected.

If results from LENR are seen as pieces of a large and complex puzzle then it can be argued that heat and helium are two major pieces. These two pieces of the puzzle have been put together by many from almost the beginning by assuming that heat and helium are the product of direct D-D fusion. But other pieces that were found since then did not seem to fit together at all. Something was clearly missing or simply wrong.

As it turns out these two large pieces do not actually fit well together but require a third piece in between: a catalyst. Nature however had played a trick on those who have been trying to understand this phenomenon for a long time: this catalyst turns out to be the product itself. And this is why it had never been recognized as such. Only when extreme care was taken to remove all helium-4 from a system did it become clear that heat but no helium was produced. This then was followed by experiments using mixed gases which unambiguously showed the role of the product as a reactant.

Because product and reactant are the same this reaction is of a special kind: it has the ingredients to be a sustainable chain reaction. This then is the reason why helium-4 and heat are the main products from LENR experiments. It is the hope of the author that other pieces will soon fall into place and that the conclusions made here will be verified in upcoming experiments.

Nature might just have lost a secret.

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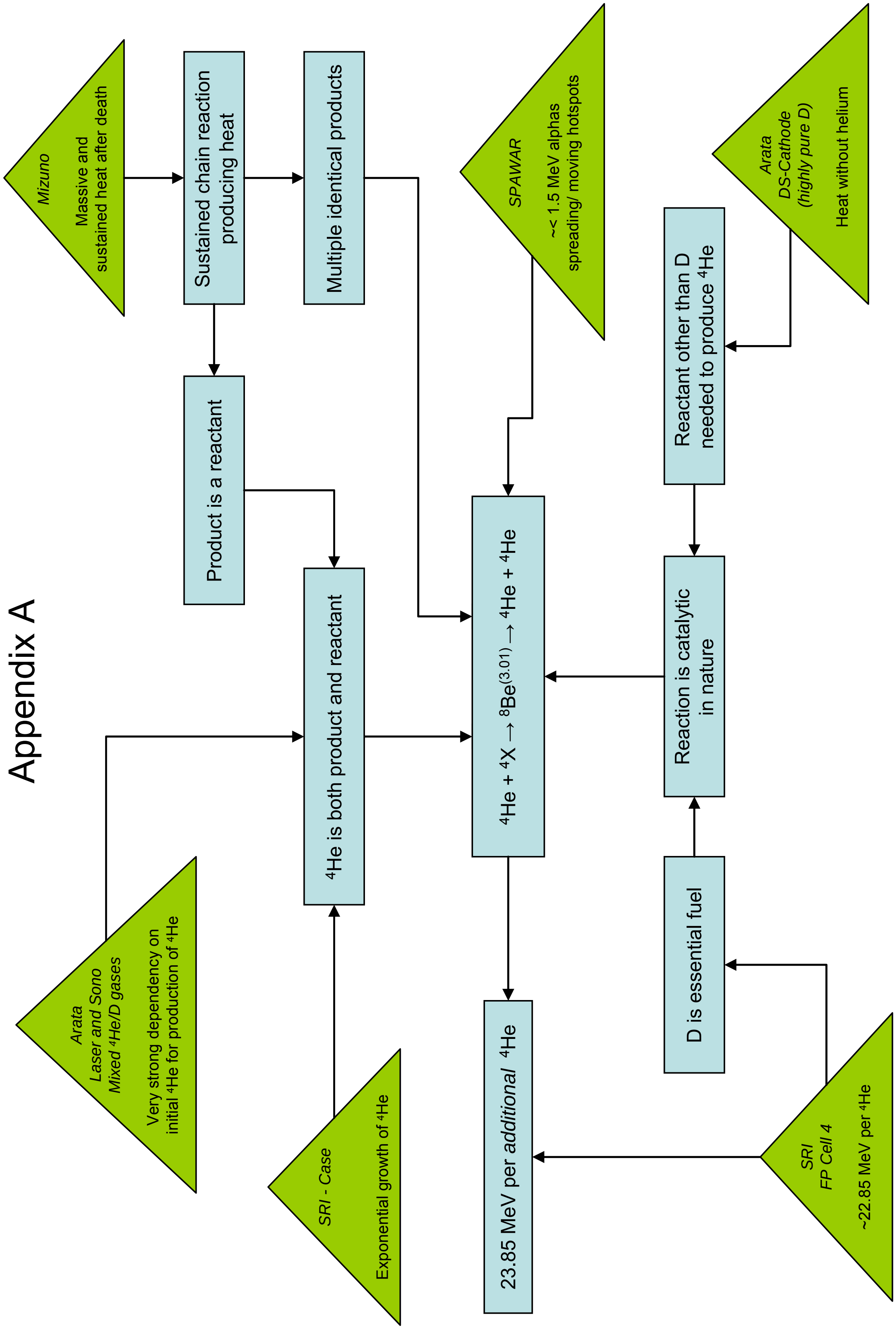
Appendix A


Mizuno
Massive and sustained heat after death
Sustained chain reaction producing heat
Multiple identical products
Product is a reactant
SPAWAR
~< 1.5 MeV alphas spreading/ moving hotspots
Arata DS-Cathode (highly pure D)
Heat without helium
Reactant other than D needed to produce 4He
Arata Laser and Sono Mixed 4He/D gases
Very strong dependency on initial 4He for production of 4He
4He is both product and reactant
4He + 4X → 8Be(3.01) → 4He + 4He
Reaction is catalytic in nature
SRI - Case
Exponential growth of 4He
23.85 MeV per additional 4He
D is essential fuel
SRI FP Cell 4
~22.85 MeV per 4He