A qualitative analysis of isotopic changes reported in LENR experiments

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A few patterns are identified in the isotopic changes seen in LENR experiments. These patterns are shown to be consistent with the parallel operation of several related processes: α decay, α capture, fragmentation of heavier nuclides following upon α capture, and β decay/electron capture. The results of several researchers working in the field are examined in the light of these processes. The analysis developed here is then applied to the 2014 report by Levi *et al.* on the test of Andrea Rossi's E-Cat in Lugano, Switzerland, whose fuel and ash assays are found to be broadly consistent with the isotope studies. The different processes are seen, then, to operate in systems making use of palladium, nickel, electrolysis, gas diffusion and glow discharge. A suggestion is made as to what might be inducing these decays and capture and fragmentation reactions.

1 Introduction

One of the lines of research in the field of condensed matter nuclear science, which seeks to understand the phenomenon of low energy nuclear reactions (LENR), has been the observation and characterization of the appearance of new elements and the shift in relative amounts of various isotopes. A striking example of this research is that of Yasuhiro Iwamura and co-workers. In one kind of experiment, they placed cesium on a substrate that consisted of layers of palladium and calcium oxide, and then permeated the substrate with deuterium gas [1]. After one week, the amount of cesium was found to have decreased while praseodymium appeared in its place. When strontium was used, molybdenum eventually appeared. Iwamura *et al.* suggested that reactions along the following lines were taking place:

$$^{133}_{55}\mathrm{Cs} \rightarrow {}^{141}_{59}\mathrm{Pr}$$

$$^{88}_{38}\mathrm{Sr} \rightarrow {}^{96}_{42}\mathrm{Mo}$$

It is not obvious what might be causing these transitions. Iwamura and co-workers noted that the transmutations occurred when D_2 gas was used and did not happen when H_2 gas was used, and the suggestion has been made that the shifts involve the capture of several deuterons [2, 3].

The appearance of new elements of medium and low atomic weight has also been seen in the LENR transmutation literature. After an experiment has been running for a while, nuclides like ^{57}Fe and ^{48}Ca might appear, in relative amounts that are different from the natural abundances. In palladium cathode glow discharge experiments, Alexander Karabut reported seeing an increase in elements that were roughly half the atomic weight of palladium, suggesting some kind of fragmentation was happening [4]:

$$\begin{aligned} {}^{105}\mathrm{Pd} &\rightarrow [\mathrm{Pd}]* \\ &\rightarrow {}^{48}\mathrm{Ca} + {}^{57}\mathrm{Fe} + 16.0\,\mathrm{MeV} \end{aligned}$$

$$\begin{aligned} {}^{104}\mathrm{Pd} + 2\,\mathrm{d} &\rightarrow [\mathrm{Pd};2\mathrm{d}]* \\ &\rightarrow {}^{44}\mathrm{Ca} + {}^{64}\mathrm{Ni} + 45.4\,\mathrm{MeV} \end{aligned}$$

Savvatimova and Gavritenkov also thought that fragmentation of heavier elements might be occurring [5]:

$$\alpha + {}^{102}_{46}\mathrm{Pd} \rightarrow {}^{22}_{10}\mathrm{Ne} + {}^{84}_{38}\mathrm{Sr} + 3.2\,\mathrm{MeV}$$

As far back as 1996 the possibility of fission was raised by Mizuno, Ohmori and Enyo [6].

These and similar suggestions are worthy of further exploration. Are such patterns specific to individual experiments and research groups, or are they ones that are of a more general nature? As we will see, these patterns are seen in many different experiments, suggesting they are indeed general. In what follows we will try to make sense of them by developing an analysis that assumes that the processes below are present and active in LENR through the agency of some common mechanism that is not yet understood:

1. α decay is induced;
2. α capture takes place, leading to
   (a) accumulation of isotopes with $Z + 2$ atomic number and $A + 4$ atomic mass, and to
   (b) fragmentation to lighter elements; and
3. β decay and electron capture are induced.

By and large these processes are not novel suggestions and have been proposed by the researchers looking at transmutations in one or another form for many years. For the present analysis we will stick to these particular processes and assume that ones that could conceivably have the same effect, such as multiple-deuteron capture, are misinterpretations of the evidence.

First we look at the results of Iwamura *et al.* in order to get a sense of what successive α captures might look like in the context of LENR (Section 2). We then examine the experiments of Mizuno (Section 3) and Karabut, Savvatimova and co-workers (Section 4) to add to this picture the evidence for fragmentation of heavier nuclides. We then review one of two isotope analyses carried out on behalf of Levi *et al.* for their test

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of Andrea Rossi's E-Cat (Section 5). Finally, we consider some of the implications of the present approach and explore the features of an underlying mechanism (Section 6).

Our assumption that the processes above are occurring in LENR to a sufficient extent to explain the transmutation results requires that we also accept the following consequences if we are to remain within the bounds of the experimental record:

4. processes (1–3) tend to result in stable daughter nuclides;
5. prompt α's that are born within a deuterium-loaded cathode lead to much less penetrating radiation than has been proposed [7];
6. a process similar to internal conversion overwhelms γ emission as a channel for the transition of excited daughter nuclei to the ground state;
7. the prompt γ photon that accompanies an α capture when it is needed in order to conserve momentum is replaced by a competing channel, such as the excitation of one or more electrons;
8. electron capture overwhelms positron emission as a competing channel for β^+ decay; and
9. the presence of deuterium is often a condition for bringing about processes (1–3), although hydrogen can serve this role as well in some cases.

In the research we will examine, pains have been taken to ensure that what was being reported was not experimental artifact. Nonetheless others have had difficulty replicating some of the results [8, 9]. For the purpose of exploring the present hypothesis we will assume that despite such difficulties the LENR isotope studies are not generally in error and see where this takes us.

2 Iwamura *et al.*

Several studies by Iwamura and co-workers show evidence of α capture. In one study, they deposited cesium on a Pd/CaO/Pd multi-layer substrate, permeated it with D_2 gas and found praseodymium afterwards [1]. In the discussion they reasoned that since cesium and praseodymium have only one stable isotope, these particular isotopes were the ones they had detected; on this basis they believed there had been a transition from ^{133}Cs to ^{141}Pr. It is difficult to imagine how four deuterons might have been captured simultaneously. Instead we might suspect that what was seen was a chain of two α capture reactions proceeding one after another:

$$\alpha + {}^{133}\mathrm{Cs} \rightarrow {}^{137}\mathrm{La} + \gamma + 1.5\,\mathrm{MeV}$$
$$\alpha + {}^{137}\mathrm{La} \rightarrow {}^{141}\mathrm{Pr} + \gamma + 1.3\,\mathrm{MeV}$$

Perhaps the intermediate nuclide ^{137}La, which is unstable, decayed before it was detected; or perhaps it was consumed too quickly by the second reaction to build up in any quantity.

In another set of cases Iwamaura *et al.* saw strontium decrease and molybdenum replace it. The largest increase was in ^{96}Mo. Reasoning from the fact that ^{88}Sr is the most abundant isotope of strontium, they suggested that ^{88}Sr transmuted to ^{96}Mo. Again we see evidence for a chain of α capture reactions:

$$\alpha + {}^{88}\mathrm{Sr} \rightarrow {}^{92}\mathrm{Zr} + \gamma + 2.9\,\mathrm{MeV}$$
$$\alpha + {}^{92}\mathrm{Zr} \rightarrow {}^{96}\mathrm{Mo} + \gamma + 2.8\,\mathrm{MeV}$$

In yet another study Iwamura *et al.* placed barium on a Pd/CaO/Pd multi-layer substrate, permeated it with D_2 gas and observed that the barium had been replaced by samarium [10]. When they used enriched barium, they think they may have also seen ^{137}Ba go to samarium but were less confident of this result. The case of barium provides a hint that the α capture reactions are not always exothermic:

$$\alpha + {}^{137}\mathrm{Ba} \rightarrow {}^{141}\mathrm{Ce} + \gamma + 0.1\,\mathrm{MeV}$$
$$\alpha + {}^{141}\mathrm{Ce} \rightarrow {}^{145}\mathrm{Nd} + \gamma - 1.6\,\mathrm{MeV}$$
$$\alpha + {}^{145}\mathrm{Nd} \rightarrow {}^{149}\mathrm{Sm} + \gamma - 1.9\,\mathrm{MeV}$$

In order for this particular chain to have been possible, one presumes that the α would have needed $\sim 2\,\mathrm{MeV}$ or more of energy. Since the typical energies of α's emitted from an α emitter are in the range of 4–9 MeV, the necessary energy would no doubt have been available if an α emitter was present. Consistent with the difficulty Iwamura et al. had in confirming the transmutation of ^{137}Ba, however, it would be not be unexpected if chains with one or more endothermic steps were relatively attenuated.

Up to now we have oversimplified things. The actual transitions that would have taken place would have been more complex than the ones shown above, because ^{141}Ce does not occur in nature and is unstable against β decay. Let us denote the capture of an α particle by nuclide A, which causes it to go to B, with the notation "A $\alpha\rightarrow$ B," the β^- decay of C to D with "C $\beta^-\!\!\rightarrow$ D" and the transition of E to F by way of electron capture with "E $\varepsilon\rightarrow$ F." The following might be a more realistic set of transitions, then, under a presumptive flux of α particles:

- ^{137}Ba $\alpha\rightarrow$ ^{141}Ce (syn.) $\alpha\rightarrow$ ^{145}Nd $\alpha\rightarrow$ ^{149}Sm
- ^{137}Ba $\alpha\rightarrow$ ^{141}Ce (syn.) $\beta^-\!\!\rightarrow$ ^{141}Pr $\alpha\rightarrow$ ^{145}Pm (syn.) $\varepsilon\rightarrow$ ^{145}Nd $\alpha\rightarrow$ ^{149}Sm
- ^{137}Ba $\alpha\rightarrow$ ^{141}Ce (syn.) $\beta^-\!\!\rightarrow$ ^{141}Pr $\alpha\rightarrow$ ^{145}Pm (syn.) $\alpha\rightarrow$ ^{149}Eu (syn.) $\varepsilon\rightarrow$ ^{149}Sm

Nuclides labeled "syn." are synthetic radioisotopes that do not appear in nature and can be expected to decay quickly. Here we see that there are at least three paths to ^{149}Sm. For each isotope of barium found in nature—^{130}Ba through ^{138}Ba—there will be a similar set of chains, some of which will also lead to an isotope of samarium. To account for the appearance of ^{149}Sm, we had to relax our assumption that α captures lead to stable daughters, so from now on we will consider it a heuristic rather than a hard-and-fast rule.

In a study in 2000, Iwamura, Takehiko Itoh and Mitsuru Sakanodone looked at changes in isotopes over time [11]. Once more the experiment involved the diffusion of D_2 through Pd/CaO/Pd multi-layer substrates. Iwamura *et al.* saw shifts in the ratios of the different isotopes of sulfur in relation to those found in nature. The ratio $^{33}S/^{32}S$ was larger than the natural one by an order of magnitude, implying that there was more ^{33}S, or less ^{32}S, or both, than usual. The ratio $^{34}S/^{32}S$ was also significantly larger than normal. The ratio of $^{34}S/^{32}S$ was not much different from the natural one. When plain palladium was used in place of Pd/CaO/Pd, the ratios of sulfur were very close to the natural ones, and the amounts of all isotopes of sulfur were orders of magnitude less, indicating that nothing happened. Continuing with our assumption of the presence of a flux of α particles, in this case only when deuterium and Pd/CaO/Pd were used, we can potentially infer the following α capture/β decay chains, which will give us the observed ratios as a result of the relative accumulation or depletion of the relevant isotopes:

1. ^{28}Si (92.2%) $\alpha\rightarrow$ (slow) ^{32}S (fast) $\alpha\rightarrow$ ^{36}Ar $\beta^+\beta^+\hookrightarrow$ ^{36}S $\alpha\rightarrow$ ^{40}Ar

2. ^{29}Si (4.7%) $\alpha\rightarrow$ (fast) ^{33}S (slow) $\alpha\rightarrow$ ^{37}Ar (syn.) $\varepsilon\rightarrow$ ^{37}Cl

3. ^{30}Si (3.1%) $\alpha\rightarrow$ (fast) ^{34}S (slow) $\alpha\rightarrow$ ^{38}Ar

In the same study, Iwamura *et al.* showed the evolution over time of two groups of elements: carbon, magnesium, silicon and sulfur; and fluorine, magnesium, aluminum and sulfur. In one set of trials, where at the start only palladium and carbon were to be found on the Pd/CaO/Pd substrate, during the diffusion of D_2 gas over a period of hours, carbon decreased, silicon and sulfur increased and magnesium increased and then decreased. On the basis of this information and our starting assumptions we can piece together the following chains:

- ^{12}C (98.9%) $\alpha\rightarrow$ ^{16}O $\alpha\rightarrow$ ^{20}Ne $\alpha\rightarrow$ ^{24}Mg $\alpha\rightarrow$ ^{28}Si $\alpha\rightarrow$ ^{32}S $\alpha\rightarrow$ ^{36}Ar
- ^{13}C (1.1%) $\alpha\rightarrow$ ^{17}O $\alpha\rightarrow$ ^{21}Ne $\alpha\rightarrow$ ^{25}Mg $\alpha\rightarrow$ ^{29}Si $\alpha\rightarrow$ ^{33}S $\alpha\rightarrow$ ^{37}Ar
- ^{14}C (trace) $\alpha\rightarrow$ ^{18}O $\alpha\rightarrow$ ^{22}Ne $\alpha\rightarrow$ ^{26}Mg $\alpha\rightarrow$ ^{30}Si $\alpha\rightarrow$ ^{34}S $\alpha\rightarrow$ ^{38}Ar

Within these series we can recognize the shorter chains (1–3), above, starting at silicon, which helped us to understand the ratio of sulfur.

When lithium was deposited on a Pd/CaO/Pd substrate using LiOD electrolysis, Iwamura and co-workers saw a different evolution over time. Magnesium increased and then decreased, fluorine increased and then decreased, silicon gradually increased and aluminum increased significantly. We might imagine that something like this was happening:

- ^{6}Li $\alpha\rightarrow$ ^{10}B $\alpha\rightarrow$ ^{14}N $\alpha\rightarrow$ ^{18}F (up, down) $\alpha\rightarrow$ ^{22}Na $\alpha\rightarrow$ (fast) ^{26}Al (slow) $\alpha\rightarrow$ ^{30}P (syn.) $\beta^+\hookrightarrow$ ^{30}Si
- ^{6}Li $\alpha\rightarrow$ ^{10}B $\alpha\rightarrow$ ^{14}N $\alpha\rightarrow$ ^{18}F (up, down) $\alpha\rightarrow$ ^{22}Na $\alpha\rightarrow$ (fast) ^{26}Al (slow) $\beta^+\hookrightarrow$ ^{26}Mg (up, down) $\alpha\rightarrow$ ^{30}Si
- ^{7}Li $\alpha\rightarrow$ ^{11}B $\alpha\rightarrow$ ^{15}N $\alpha\rightarrow$ ^{19}F (up, down) $\alpha\rightarrow$ ^{23}Na $\alpha\rightarrow$ (fast) ^{27}Al (slow) $\alpha\rightarrow$ ^{31}P $\alpha\rightarrow$ ^{35}Cl

It is now possible to assemble a larger mosaic of the transitions in the range of the nuclides we have just considered. A more complete analysis reveals four series of transitions under α capture and β decay running from lithium up to the heavier elements; these series are described in Appendix A.

There are a number of isotopes that were not reported in the experiments by Iwamura and co-workers whose presence is implied by this analysis, including ^{10}B, ^{23}Na and ^{14}N. Some of these elements are gasses, the less reactive of which can be expected to have partly escaped from the surface of the Pd/CaO/Pd substrate before they could be registered in the *in situ* analysis. Others may have been assumed to have been contamination and not reported. In yet other cases it may be that the element was consumed too quickly to accumulate. If it could be conclusively established that a required intermediate step is never present for a given daughter, even in small amounts, this would be evidence that the daughter nuclide goes back to fragmentation of a heavier nuclide or perhaps that the general approach being taken here is mistaken.

3 Mizuno *et al.*

In the research of Iwamura and co-workers we were able to discern how isotopes might accumulate and in some cases decrease through the processes of α capture and β decay. Next we look at the work of Tadahiko Mizuno, Tadayoshi Ohmori, and others, to explore the possibility of fragmentation of heavier elements into lighter ones.

In 1996, Mizuno, Ohmori and Michio Enyo looked at elements present on palladium cathodes after electrolysis [6]. When electrolysis was carried out with a current density above 0.2 A/cm^2, new elements appeared as far as one micron below the surface of the cathode, in amounts 10–100 times the background counts, in some cases well beyond what would be expected if they were due to impurities in the electrolytic cell. Elements found by different methods included Ca, Ti, Cr, Mn, Fe, Co, Cu, Zn, As, Ga, Sb, Cd, Sn, Pt, Pb, Te, I, Hf, Re, Ir, Br and Xe.

Mizuno *et al.* suggested that impurities in the cell such as Li, D_2O, Pd, Pt, K, Na, Ca, B, C, Ag and Fe might have provided the starting material for the transmutations. While this is possible and perhaps even likely, let us take a look at what fragmentation of heavier elements such as palladium, another process they proposed, might look like, keeping in mind that the progenitors must be available in sufficient quantities to explain the appearance of daughters at levels 10–100 times the background counts.

What are needed are reactions that produce the nuclides that were seen and not large numbers of nuclides that were at levels too low to report. Here are some candidates that would arise from the fragmentation of a short-lived compound nucleus that forms upon α capture, where an α is ejected with the fragments:

$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{44}\mathrm{Ca} + {}^{58}\mathrm{Fe} + \alpha + 15.7\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{46}\mathrm{Ca} + {}^{56}\mathrm{Fe} + \alpha + 15.8\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{48}\mathrm{Ca} + {}^{54}\mathrm{Fe} + \alpha + 12.5\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{48}\mathrm{Ti} + {}^{54}\mathrm{Cr} + \alpha + 17.5\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{49}\mathrm{Ti} + {}^{53}\mathrm{Cr} + \alpha + 15.9\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{50}\mathrm{Ti} + {}^{52}\mathrm{Cr} + \alpha + 18.9\,\mathrm{MeV}$$
$$\alpha + {}^{104}\mathrm{Pd} \rightarrow {}^{46}\mathrm{Ca} + {}^{58}\mathrm{Fe} + \alpha + 15.9\,\mathrm{MeV}$$
$$\alpha + {}^{104}\mathrm{Pd} \rightarrow {}^{48}\mathrm{Ca} + {}^{56}\mathrm{Fe} + \alpha + 15.4\,\mathrm{MeV}$$
$$\alpha + {}^{104}\mathrm{Pd} \rightarrow {}^{50}\mathrm{Ti} + {}^{54}\mathrm{Cr} + \alpha + 19.0\,\mathrm{MeV}$$
$$\alpha + {}^{105}\mathrm{Pd} \rightarrow {}^{48}\mathrm{Ca} + {}^{57}\mathrm{Fe} + \alpha + 16.0\,\mathrm{MeV}$$
$$\alpha + {}^{106}\mathrm{Pd} \rightarrow {}^{48}\mathrm{Ca} + {}^{58}\mathrm{Fe} + \alpha + 16.5\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{27}\mathrm{Al} + {}^{75}\mathrm{As} + \alpha + 2.3\,\mathrm{MeV}$$

The following reactions are similar to the ones we just looked at, but in this case the α particle is consumed in the reaction:

$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{48}\mathrm{Ca} + {}^{49}\mathrm{Co} + \mathrm{p} + 12.6\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{52}\mathrm{Cr} + {}^{54}\mathrm{Cr} + 26.8\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{50}\mathrm{Ti} + {}^{56}\mathrm{Fe} + 26.5\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{48}\mathrm{Ti} + {}^{58}\mathrm{Fe} + 25.1\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{49}\mathrm{Ti} + {}^{57}\mathrm{Fe} + 23.2\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{53}\mathrm{Cr} + {}^{53}\mathrm{Cr} + 25.1\,\mathrm{MeV}$$
$$\alpha + {}^{104}\mathrm{Pd} \rightarrow {}^{54}\mathrm{Cr} + {}^{54}\mathrm{Cr} + 26.9\,\mathrm{MeV}$$
$$\alpha + {}^{104}\mathrm{Pd} \rightarrow {}^{50}\mathrm{Ti} + {}^{58}\mathrm{Fe} + 26.6\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{31}\mathrm{P} + {}^{75}\mathrm{As} + 12.0\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{36}\mathrm{Ar} + {}^{70}\mathrm{Zn} + 14.3\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{38}\mathrm{Ar} + {}^{68}\mathrm{Zn} + 19.2\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{40}\mathrm{Ar} + {}^{66}\mathrm{Zn} + 18.4\,\mathrm{MeV}$$
$$\alpha + {}^{104}\mathrm{Pd} \rightarrow {}^{40}\mathrm{Ar} + {}^{68}\mathrm{Zn} + 18.1\,\mathrm{MeV}$$
$$\alpha + {}^{104}\mathrm{Pd} \rightarrow {}^{38}\mathrm{Ar} + {}^{70}\mathrm{Zn} + 17.3\,\mathrm{MeV}$$
$$\alpha + {}^{106}\mathrm{Pd} \rightarrow {}^{40}\mathrm{Ar} + {}^{70}\mathrm{Zn} + 17.1\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{35}\mathrm{Cl} + {}^{71}\mathrm{Ga} + 13.6\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{37}\mathrm{Cl} + {}^{69}\mathrm{Ga} + 15.6\,\mathrm{MeV}$$
$$\alpha + {}^{104}\mathrm{Pd} \rightarrow {}^{37}\mathrm{Cl} + {}^{71}\mathrm{Ga} + 14.9\,\mathrm{MeV}$$

As can be seen, most of the daughters in the two sets of reactions are present in the long list of elements that were reported. However, not all of the daughters are in the list. Although zinc was found among the elements on the palladium cathodes, for example, argon was not mentioned. This might be explained by the fact that argon is a noble gas and could have escaped the system before being measured; or perhaps it was ignored because Ar^+ was one of the two ions used for sputtering in the secondary ion mass spectrometry (SIMS) measurements, the other of which was O^+.

The group found that isotopes at odd mass numbers were generally present at levels higher than the natural abundances while ones at even mass number were lower. We do not attempt to evaluate this claim at this point or to seek an explanation for it. One wonders whether the result is a general one or one that was specific to something in their experimental setup.

4 Karabut, Savvatimova, *et al.*

Now let us take a look at a glow discharge experiment carried out by by Alexander Karabut. Palladium and titanium cathodes were loaded with deuterium and then subject to glow discharge under D_2, Xe and Kr [12]. The ions in the discharge were accelerated to up to 1–2 keV of energy. Excess heat and x-rays were seen. Afterwards, SIMS was used to analyze the isotopic content to a depth of 800 nm into the cathodes. Table 1 shows the results of a SIMS analysis of one of the palladium cathodes, adapted from a larger table, from which rows for nuclides for which the change was unclear have been omitted. As can be seen, for each isotope there is a significant difference in the relative abundance near the surface and deeper into the cathode. In some cases there was an increase and in others a decrease. Presumably there are explanations such as contamination that might account for these changes, but we will continue in our assumption that they are related to LENR.

Here we will go along with an understanding common in LENR research that whatever is happening in a system like this occurs at or near the surface. The “log

	Percent of total for scan				
Nuclide	10 nm	50 nm	700 nm	800 nm	Log change (LC)[a]
^{6}Li	0.075	0.22	0.21	0.16	−0.3
^{7}Li	0.84	0.53	0.45	0.47	0.3
^{12}C	0.93	0.63	0.47	0.54	0.2
^{13}C	0.19	0.15	0.05	0.06	0.5
^{48}Ti	1.1	1.23	1.1	0.66	0.2
^{52}Cr	0.62	0.41	0.31	0.1	0.8
^{57}Fe	5.5	3.25	3.53	3.16	0.2
^{59}Co	1.0	1.0	1.4	1.5	−0.2
^{66}Zn	0.21	0.43	0.54	1.0	−0.7
^{80}Se	4.0	3.4	2.5	2.3	0.2
^{85}Rb	2.2	3.4	3.3	3.6	−0.2
^{88}Sr	3.1	4.4	4.2	6.0	−0.3
^{90}Zr	2.4	1.5	2.3	5.8	−0.4
^{111}Cd	2.8	3.0	3.0	3.4	−0.1
^{112}Cd	3.4	3.2	4.2	4.5	−0.1

[a] $log\{A(10\,\mathrm{nm})/A(800\,\mathrm{nm})\}$.

Table 1: Isotopes found on the surface of a palladium cathode, adapted from Karabut [12].

change" column in Table 1 shows the log ratio of the amounts found in the scan at 10 nm to those at 800 nm.

Following are some possible reactions that might account for increases in some of the nuclides:

$$\alpha + {}^{104}\mathrm{Pd} \rightarrow {}^{12}\mathrm{C} + {}^{48}\mathrm{Ca} + {}^{48}\mathrm{Ti} + 5.7\,\mathrm{MeV}$$
$$\alpha + {}^{104}\mathrm{Pd} \rightarrow {}^{12}\mathrm{C} + {}^{48}\mathrm{Ca} + {}^{48}\mathrm{Ti} + 5.7\,\mathrm{MeV}$$
$$\alpha + {}^{105}\mathrm{Pd} \rightarrow {}^{13}\mathrm{C} + {}^{48}\mathrm{Ca} + {}^{48}\mathrm{Ti} + 3.6\,\mathrm{MeV}$$
$$\alpha + {}^{105}\mathrm{Pd} \rightarrow {}^{48}\mathrm{Ca} + {}^{57}\mathrm{Fe} + \alpha + 16.0\,\mathrm{MeV}$$
$$\alpha + {}^{107}\mathrm{Ag} \rightarrow {}^{11}\mathrm{B} + {}^{48}\mathrm{Ca} + {}^{52}\mathrm{Cr} + 5.0\,\mathrm{MeV}$$
$$\alpha + {}^{107}\mathrm{Ag} \rightarrow {}^{7}\mathrm{Li} + {}^{48}\mathrm{Ca} + {}^{56}\mathrm{Fe} + 3.9\,\mathrm{MeV}$$
$$\alpha + {}^{112}\mathrm{Cd} \rightarrow {}^{20}\mathrm{Ne} + {}^{48}\mathrm{Ca} + {}^{48}\mathrm{Ca} + 7.3\,\mathrm{MeV}$$

The nuclide ^{48}Ca was not identified in the SIMS analysis, but it is found at the same mass peak as ^{48}Ti, another nuclide that was identified. The nuclides ^{11}B, ^{20}Ne and ^{56}Fe were present in the analysis, but their change was unclear, so they have been left out of Table 1. Nuclide ^{107}Ag is a decay product of ^{107}Pd, which is unstable against β^- decay. As in previous sections, we have considered only a small number of the possible reactions, and this list is intended to serve as an illustration of how one might go about coming up with a starting point. If we ease the restriction we have adopted that daughter nuclides should be relatively stable, a number of other possibilities open up as well.

The reactions above could potentially explain the cases in which a lighter nuclide increased. In addition, we should try to understand the depletion seen in some of the lighter nuclides. Such changes are harder to account for in this particular instance using the present assumptions. Transitions along the following lines might have been responsible for the depletions:

- ^{6}Li $\alpha\rightarrow$ ^{10}B $\alpha\rightarrow$ ^{14}N
- ^{46}Ca $\beta^-\beta^-\rightarrow$ ^{46}Ti
- ^{48}Ca $\beta^-\beta^-\rightarrow$ ^{48}Ti
- ^{59}Co $\alpha\rightarrow$ ^{63}Cu
- ^{66}Zn $\alpha\rightarrow$ ^{70}Ge
- ^{76}Ge $\alpha\rightarrow$ ^{80}Se
- ^{85}Rb $\alpha\rightarrow$ ^{89}Y
- ^{88}Sr $\alpha\rightarrow$ ^{92}Zr
- ^{90}Zr $\alpha\rightarrow$ ^{94}Mo
- ^{111}Cd $\alpha\rightarrow$ ^{115}Sn
- ^{112}Cd $\alpha\rightarrow$ ^{116}Sn

The challenge here is that few if any of the nuclides on the right-hand side saw an unambiguous change. This might be because a process outside of the present analysis depleted the nuclides on the left-hand side, or it might be because another process depleted the resultant daughter nuclides in turn. Note, however, how ^{46}Ca and ^{48}Ca go to titanium under $\beta^-\beta^-$ decay. This fact helps to make sense of the fragmentation reactions above that were used to understand cases where isotopes saw an increase. Those reactions invariably included calcium as a daughter, while an increase in an isotope of titanium

	Abundance (ppm)						
		4 hours		40 hours			
Nuclide	Initial[a]	Irradiated	Underlying	Irradiated	Underlying	LC_4[b]	LC_{40}[c]
^{6}Li	0.06	–	–	2.5	–	–	1.6
^{7}Li	0.08	11	5	6.5	4.5	2.1	1.9
^{10}B	0.07	–	–	–	2	–	–
^{11}B	0.07	3	2–10	4	3	1.6	1.8
^{23}Na	0.44	7	13	10	2.5	1.2	1.4
^{27}Al	6	25–50	4	15	1.5	0.6	0.4
^{28}Si	9	–	0.3	2	1	–	−0.7
^{29}Si	7	–	1.5	3	1.5	–	−0.4
^{30}Si	6	3–4	11	3	1.5	−0.3	−0.3
^{32}S	7	0.5	0.3	0.5–2	0.3	−1.1	−1.1
^{39}K	3	4	1.5	3	–	0.1	0.0
^{41}K	3	5	3	4	0.3	0.2	0.1
^{47}Ti	1.2	43–60	–	–	1.5	1.6	–
^{48}Ti	1.4	–	2.5	370	1.5	–	2.4
^{49}Ti	1.3	100	2	357	2.5	1.9	2.4
^{50}Ti	1.7	65	–	–	2	1.6	–
^{78}Se	0.23	<0.9	16	<1	<1	0.6	0.6
^{80}Se	0.3	<0.5	11	0.7	0.7	0.2	0.4
^{85}Rb	<0.03	3000	1700	<0.13	1.7	5.0	0.6
^{90}Zr	<0.05	1200	4.4	500	<0.1	4.4	4.0
^{91}Zr	<0.05	1220	–	1000	<0.5	4.4	4.3
^{93}Nb	<2	360	2	20	1	2.3	1.0
^{98}Mo	0.4	–	7.5	–	–	–	–
^{100}Mo	1.8	1600	–	2500	1	2.9	3.1
^{103}Rh	7	5–2.3	1	<2–4	<2–4	−0.5	−0.5
^{107}Ag	1	1	3.2	63	3	0.0	1.8
^{109}Ag	1	–	2.5	50	1.5	–	1.7
^{115}In	<0.04	20	4	12	1	2.7	2.5

[a] One standard deviation is 0.15–0.30 ppm.
[b] $log\{A(Irradiated \sim 4\,\mathrm{h})/A(Initial)\}$.
[c] $log\{A(Irradiated \sim 40\,\mathrm{h})/A(Initial)\}$.

Table 2: Impurities found on palladium cathodes
after glow discharge, adapted from Savvatimova *et al.* [13].

at the same mass is what was reported. Needless to say, something interesting is happening in experiments if the rate of double-β decay has somehow been increased.

The changes in the study by Karabut that we just looked at were close to the threshold of detection. More significant were changes seen in a 1996 study by Irena Savvatimova, Yan Kucherov and Karabut [13], in which some of the nuclides we wondered might be present in Ref. [12] were in fact seen. Cathodes made of 99.99 and 99.9 grade 100 µm palladium foil were exposed to deuterium glow discharge and then analyzed by a different laboratory using SIMS and x-ray fluorescence. The results provided evidence for a complex fission-fusion process. Table 2 summarizes some of them.

Before we attempt to identify a set of candidate reactions, we can note several trends in Table 2. As the authors point out, in some cases there was not much of a change during the time from 4 hours to 40 hours, and, in a handful of cases, the amount had actually decreased at 40 hours. In the cases where the amount of a nuclide went up and then down, we are reminded of what was seen in the *in situ* analyses carried out by Iwamura *et al.* in which amounts of elements were seen to evolve over time [11]. An increase followed by a decrease suggests that a fast reaction generated the isotope early on and then a second, slower reaction gradually consumed it. Another point is that the amounts appear to be well within statistical significance, as evidenced by the standard deviation of 0.15–0.30 for the initial abundances. One remarkable detail is how much larger some of the values for the log change are in comparison to the experiment by Karabut [12] discussed above. It is noteworthy as well that many of the isotopes are the same, although the lists are not identical.

Once more we seek an initial set of reactions that will be suggestive of a more rigorous analysis that could be carried out. Consider, then, the following reactions:

Ratio	Sample[a]	Natural value (N_n)	Experimental value (N_e)	N_n/N_e
$^{48}Ti/^{46}Ti$	1	9.82	2.4	3.80
	2	9.82	6.15	1.50
$^{48}Ti/^{47}Ti$	1	10.12	4	2.50
	2	10.12	7.3	1.40
$^{48}Ti/^{49}Ti$	1	13.42	12	1.10
	2	13.42	8.9	1.50
$^{52}Cr/^{53}Cr$	1	8.8	14.3	0.62
	2	8.8	11.3	0.78
$^{56}Fe/^{57}Fe$	1	41.7	10	4.17
	2	41.7	46.4	0.90

[a] (1) Sample subjected to deuterium glow discharge; (2) sample located beneath the irradiated one.

Table 3: Isotope ratios for two palladium samples, adapted from Savvatimova and Gavritenkov [5].

$$\alpha + {}^{103}\mathrm{Rh} \rightarrow {}^{22}\mathrm{Ne} + {}^{85}\mathrm{Rb} + 4.6\,\mathrm{MeV}$$
$$\alpha + {}^{103}\mathrm{Rh} \rightarrow {}^{107}\mathrm{Ag} + \gamma + 2.8\,\mathrm{MeV}$$
$$\alpha + {}^{105}\mathrm{Pd} \rightarrow {}^{12}\mathrm{C} + {}^{48}\mathrm{Ca} + {}^{49}\mathrm{Ti} + 6.8\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{9}\mathrm{Be} + {}^{48}\mathrm{Ti} + {}^{49}\mathrm{Ti} + 0.2\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{6}\mathrm{Li} + {}^{49}\mathrm{Ti} + {}^{51}\mathrm{V} + 1.2\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{6}\mathrm{Li} + {}^{50}\mathrm{Ti} + {}^{50}\mathrm{V} + 1.1\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{7}\mathrm{Li} + {}^{48}\mathrm{Ti} + {}^{51}\mathrm{V} + 0.3\,\mathrm{MeV}$$
$$\alpha + {}^{104}\mathrm{Pd} \rightarrow {}^{7}\mathrm{Li} + {}^{50}\mathrm{Ti} + {}^{51}\mathrm{V} + 1.8\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{27}\mathrm{Al} + {}^{78}\mathrm{Se} + \mathrm{p} + 1.4\,\mathrm{MeV}$$
$$\alpha + {}^{104}\mathrm{Pd} \rightarrow {}^{27}\mathrm{Al} + {}^{80}\mathrm{Se} + \mathrm{p} + 0.7\,\mathrm{MeV}$$
$$\alpha + {}^{102}\mathrm{Pd} \rightarrow {}^{90}\mathrm{Zr} + {}^{12}\mathrm{C} + \alpha + 0.8\,\mathrm{MeV}$$
$$\alpha + {}^{105}\mathrm{Pd} \rightarrow {}^{18}\mathrm{O} + {}^{91}\mathrm{Zr} + 2.7\,\mathrm{MeV}$$
$$\alpha + {}^{104}\mathrm{Pd} \rightarrow {}^{15}\mathrm{N} + {}^{93}\mathrm{Nb} + 0.1\,\mathrm{MeV}$$
$$\alpha + {}^{130}\mathrm{Ba} \rightarrow {}^{15}\mathrm{N} + {}^{115}\mathrm{In} + \alpha + 2.2\,\mathrm{MeV}$$

In addition to the above reactions, there are these α capture and β decay transitions:

- $^{28}\mathrm{Si}\ \alpha\rightarrow\ ^{32}\mathrm{S}\ \alpha\rightarrow\ ^{36}\mathrm{Ar}$
- $^{29}\mathrm{Si}\ \alpha\rightarrow\ ^{33}\mathrm{S}\ \alpha\rightarrow\ ^{37}\mathrm{Ar}$ (syn.) $\varepsilon\rightarrow\ ^{37}\mathrm{Cl}\ \alpha\rightarrow\ ^{41}\mathrm{K}$
- $^{30}\mathrm{Si}\ \alpha\rightarrow\ ^{34}\mathrm{S}\ \alpha\rightarrow\ ^{38}\mathrm{Ar}$
- $^{48}\mathrm{Ca}\ \beta^-\beta^-\rightarrow\ ^{48}\mathrm{Ti}$
- $^{50}\mathrm{V}\ \varepsilon\rightarrow\ ^{50}\mathrm{Ti}$
- $^{50}\mathrm{Ti}\ \alpha\rightarrow\ ^{54}\mathrm{Cr}$
- $^{107}\mathrm{Pd}\ \beta^-\rightarrow\ ^{107}\mathrm{Ag}$
- $^{96}\mathrm{Zr}\ \alpha\rightarrow\ ^{100}\mathrm{Mo}$
- $^{105}\mathrm{Pd}\ \alpha\rightarrow\ ^{109}\mathrm{Cd}\ \varepsilon\rightarrow\ ^{109}\mathrm{Ag}$

In the two sets of reactions, most of the salient changes in isotope found in Table 2 are potentially accounted for. Also, the ^{50}V daughter of one of the fragmentation reactions will go to ^{50}Ti following upon electron capture.

We conclude this section by looking at the ratios of different isotopes of iron, chromium and titanium found in a 2005 study by Savvatimova and D. V. Gavritenkov [5]. Isotopes from two samples of palladium that had been exposed to deuterium glow discharge were examined using thermal ionization mass spectrometry (TIMS). Table 3 shows the ratios of these isotopes in the two samples and compares them to the natural ratios.

The two samples were from the same run, in which sample 1 was exposed to deuterium glow discharge while sample 2 was shielded beneath sample 1. Let us focus on sample 1. If we continue with our assumption that there is a flux of α particles that is resulting in α capture reactions, we can learn something about the rates of the reactions operating on the different isotopes for a given element. We can infer from Table 3, for example, that since the ratio $^{48}\mathrm{Ti}/^{47}\mathrm{Ti}$ is 2.5 times the natural ratio, one or more of the following must have been true:

- The rate of increase of ^{47}Ti was relatively fast.
- The rate of increase of ^{48}Ti was relatively slow.
- The rate of decrease of ^{47}Ti was relatively slow.
- The rate of decrease of ^{48}Ti was relatively fast.

This information can be used to label the relevant α capture transitions:

- $^{43}\mathrm{Ca}\ \alpha\rightarrow$ (fast) $^{47}\mathrm{Ti}$ (slow) $\alpha\rightarrow\ ^{51}\mathrm{Cr}$ (syn.) $\varepsilon\rightarrow\ ^{51}\mathrm{V}$
- $^{44}\mathrm{Ca}\ \alpha\rightarrow$ (slow) $^{48}\mathrm{Ti}$ (fast) $\alpha\rightarrow\ ^{52}\mathrm{Cr}$

Putting together what we know from Table 3, we obtain this picture of sample 1:

- $^{42}\mathrm{Ca}\ \alpha\rightarrow$ (fast) $^{46}\mathrm{Ti}$ (slow) $\alpha\rightarrow\ ^{50}\mathrm{Cr}$

- ^{43}Ca $\alpha\rightarrow$ (fast) ^{47}Ti (slow) $\alpha\rightarrow$ ^{51}Cr (syn.) $\varepsilon\rightarrow$ ^{51}V
- ^{44}Ca $\alpha\rightarrow$ (slow) ^{48}Ti (fast) $\alpha\rightarrow$ (fast) ^{52}Cr (slow) $\alpha\rightarrow$ (slow) ^{56}Fe (fast) $\alpha\rightarrow$ ^{60}Ni
- ^{45}Sc $\alpha\rightarrow$ ^{49}V (syn.) $\varepsilon\rightarrow$ (fast) ^{49}Ti (slow) $\alpha\rightarrow$ (slow) ^{53}Cr (fast) $\alpha\rightarrow$ (fast) ^{57}Fe (slow) $\alpha\rightarrow$ ^{61}Ni

What is noteworthy about the labels is that even though this information was inferred from five separate ratios in Table 3, the story they tell about the rate at which the transitions proceeded in the run is consistent, as seen in the fact that the labels on either side of some transitions are the same. This, then, offers further circumstantial evidence for the notion that α capture and β decay/electron capture were taking place in four parallel series, each involving a different set of isotopes. We do not know at this point whether these rates are general ones or whether they were specific to the experiment by Savvatimova *et al.* [5]. In addition, the relative amounts will be modified by any fragmentation reactions that yield the same nuclides, complicating the analysis considerably.

5 Levi *et al.*

Next we consider Appendix 3 to the report by Levi *et al.* [14]. The report describes a test of Andrea Rossi's E-Cat, billed as a reactor capable of producing many watts of excess heat using nickel and hydrogen. The test was carried out in Lugano, Switzerland, in March 2014. The appendix, by Ulf Bexell and Josefin Hall, presents the results of SEM/EDS and ToF-SIMS assays of the "fuel" and "ash" placed into and taken from the device. They found at least three different types of particles in the fuel and two in the ash, each containing a distinct combination of elements. What was measured by Bexell and Hall was highly variable and depended upon the type of particle that was selected. For this reason our analysis is necessarily schematic. We seek only to get a sense of whether the assay is broadly consistent with what has been seen in the the isotope studies reviewed above.

Looking over the graphs in Appendix 3 to the report, there are a number of details that catch the eye. In some cases there were new peaks for ions at masses that cannot be seen in the fuel; in others it is unclear whether the ions represented new isotopes or whether they might have been found in the fuel in a more exhaustive search. In addition, some peaks will have resulted from cluster ions. Table 5 presents several of the clearer changes:

Isotope shifts	
Large decrease	^{7}Li, ^{58}Fe, ^{58}Ni, ^{60}Ni
Moderate increase	^{53}Cr, ^{62}Ni, ^{67}Zn, ^{77}Se, ^{91}Zr
Large increase	^{6}Li

Table 5: Isotope shifts found in Appendix 3 of Levi *et al.* [14].

The largest increase by far was in ^{6}Li, and the largest decrease was in ^{7}Li, to a similar extent. The two shifts might have been linked, such that ^{7}Li somehow went to ^{6}Li. Within the present framework no explanation immediately comes to mind. One possibility is that energetic α's led to spallation, in which a neutron was knocked off of the ^{7}Li. If that is what happened, it would imply neutrons commensurate with the change in ^{6}Li/^{7}Li, which may or may not be ruled out by the lack of detection of neutrons in the laboratory, keeping in mind that the shift was spread out over a month and lithium may not have contributed to whatever heat was produced. Another possibility is that a neutron tunneled from ^{7}Li to a nickel lattice site, leaving a ^{6}Li behind [15, 16], but this lies outside of the scope of the present discussion, as there is no obvious reason why it would happen as a result of the current approach. One thing that becomes clear is that attempting to generalize about the ratio of ^{6}Li/^{7}Li across both this test and the LENR transmutation studies is difficult. In some cases the ratio goes up and and in others it goes down.

In addition there were decreases in ^{58}Fe, ^{58}Ni and ^{60}Ni and increases in ^{62}Ni, ^{53}Cr, ^{67}Zn, ^{77}Se and ^{91}Zr. The nuclide ^{69}Ga was also present in significant quantities, although the change in amount was unclear. For understanding the changes in ^{53}Cr, ^{62}Ni and ^{77}Se we can start with the different α capture series in Appendix A to this paper:

- ^{49}Ti $\alpha\rightarrow$ ^{53}Cr
- ^{58}Fe $\alpha\rightarrow$ ^{62}Ni
- ^{58}Ni $\alpha\rightarrow$ ^{62}Zn (syn.) $\beta^{+}\!\!\rightarrow$ ^{62}Cu (syn.) $\beta^{+}\!\!\rightarrow$ ^{62}Ni
- ^{60}Ni $\alpha\rightarrow$ ^{64}Zn
- ^{61}Ni $\alpha\rightarrow$ ^{65}Zn (syn.) $\varepsilon\rightarrow$ ^{65}Cu $\alpha\rightarrow$ ^{69}Ga $\alpha\rightarrow$ ^{73}As (syn.) $\varepsilon\rightarrow$ ^{73}Ge $\alpha\rightarrow$ ^{77}Se $\alpha\rightarrow$ ^{81}Kr
- ^{64}Ni $\alpha\rightarrow$ ^{68}Zn

The series starting at ^{60}Ni and ^{64}Ni do not go to mass peaks that can be found in the appendix by Bexell and Hall to the Lugano report [14]. It is possible that the series starting at ^{60}Ni, which had a significant count, got all the way to ^{80}Kr and then left the ash as an inert gas, but in order for that to have happened, at least seven transitions would need to have taken place. Another possibility is that the authors of the appendix

	Fuel		Ash		
Ion	Count	Abundance (%)	Count	Abundance (%)	Natural abundance (%)
$^{6}Li^{+}$	15804	8.6	569302	92.1	7.5
$^{7}Li^{+}$	168919	91.4	48687	7.9	92.5
$^{58}Ni^{+}$	93392	67	1128	0.8	68.1
$^{60}Ni^{+}$	36690	26.3	635	0.5	26.2
$^{61}Ni^{+}$	2606	1.9	0	0	1.8
$^{62}Ni^{+}$	5379	3.9	133272	98.7	3.6
$^{64}Ni^{+}$	1331	1	0	0	0.9

Table 4: Measured and natural occurring abundances for Li and Ni ions in fuel and ash, respectively, Appendix 3 of Levi *et al.* [14].

assumed zirconium was an impurity and omitted it from the spectra, but this seems unlikely. At this point we do not have a compelling account of the change in ^{60}Ni.

By contrast it is clear how ^{58}Ni (68.1%) and ^{58}Fe (0.3%) could end up at ^{62}Ni. In addition we can see that ^{69}Ga goes to ^{77}Se, and we get a sense of what might be leading to an increase in ^{53}Cr. The source of the ^{49}Ti, which does not correspond to a mass seen in Appendix 3 to the Lugano report, might come from the first of the following two reactions, which also offers a source for the ^{67}Zn:

$$\alpha + {}^{112}\mathrm{Sn} \rightarrow {}^{49}\mathrm{Ti} + {}^{67}\mathrm{Zn} \qquad + 30.2\,\mathrm{MeV}$$
$$\alpha + {}^{112}\mathrm{Sn} \rightarrow {}^{21}\mathrm{Ne} + {}^{91}\mathrm{Zr} + \alpha + 5.0\,\mathrm{MeV}$$

The second reaction potentially explains the ^{91}Zr; presumably ^{21}Ne, an inert gas, would have escaped from the ash before it could be measured.

In order for the reactions proposed above to have merit, we should try to identify a possible α emitter. There are three SIMS spectra that hint that there might have been a smaller quantity of elements at masses $m > 100$ in the fuel in addition to the light elements. While it is true that many of the ions at these mass peaks could have been cluster ions, there might also have been single isotopes as well. A closer look at the data suggests that samarium, rhenium and hafnium might have been present [17], all of which are α emitters and could possibly have provided the necessary flux of α particles.

In this section we attempted to apply our analysis to the fuel and ash assays included in Appendix 3 to the Lugano E-Cat test report. There have been some difficulties in doing so as well as some questions that have come up, for which more information would be needed in order to investigate them. But by and large the possibilities that have been raised are suggestive and are broadly consistent with what has been seen in the LENR isotope studies, hinting that some form of LENR might in fact have been occurring during the March 2014 E-Cat test.

6 Discussion

We have looked at experiments from several researchers who have focused on isotope changes in LENR, seeking to understand whether the results can be explained by several related processes—α decay, α capture, fragmentation following upon α capture, and β decay/electron capture—that are somehow being induced by something that is happening in the experiments. These processes are not novel suggestions and have been put forward in one form or another by the researchers themselves as well as by others. The possibility that the rate of α decay can be increased, for example, has been proposed [18, 19], explored [20, 21] and, apparently, reduced to practice in patents [18, 22]. α capture and subsequent fragmentation have been suggested as well [5], and laser-induced fission has been seen [23]. Such proposals and claims, if more widely known, would be controversial. Rod Nave describes the half-life of an α emitter such as polonium as a value that is fixed by fundamental, immutable constants of nature [24]. At least one doctoral dissertation has looked at the question of whether β decay can be induced and concluded that it cannot [25]. A theoretical objection to the notion that a flux of α particles might occur in significant quantities in LENR is that such a flux would produce radiation that is not seen [7]. While this is an interesting proposition, it must retain the status of an informed guess until such a time as it can be experimentally confirmed or falsified.

A related point to mention is that typical energies for α's following upon α decay are 4–9 MeV. Dividing by the number of nucleons gives 1–2.4 MeV/nucleon, a ratio that is relatively low by nuclear standards, and that would be even lower if we were to allow the possibility that α decay might be induced in isotopes that have up to now been considered stable [26]. A similar calculation can be carried out for the energy per nucleon in the daughters of a fragmentation reaction. At the higher end of the energies for the reactions considered above is the fragmentation of ^{104}Pd following upon α capture, producing ^{52}C4 and ^{54}Cr along with a Q-value of ~ 26 MeV. In this case there will be ~ 0.3 MeV/nucleon, which will be evenly distributed between the nearly equal-mass daughters.

Assuming that α and β decay can be induced, are these processes and the related process of fragmentation what underlie LENR as an experimental phenomenon, or are they secondary ones that sometimes occur alongside a more basic process that is responsible for most of the excess heat and helium that are observed? To make this question more precise, are these processes what are behind the excess heat and helium, and the correlation between heat and helium, that are seen in the Pons and Fleischmann effect, which arises in palladium electrolytic systems under the right conditions? Arguments can be made for and against this proposition. One argument that has been made against transmutation as being the primary source of LENR is that it cannot occur at a rate sufficient to produce measurable energy [27]; another objection has been that transmutations cannot account for the ratio of energy per ^{4}He that has been found [28]. But it is hard to know how to quantify these objections, in light of various difficulties in accounting for all of the transmutation products that occur in an experiment, including distinguishing possible daughter nuclides from contamination arising from various sources in the electrolytic cell. If the daughters of fragmentation reactions are counted among transmutations, the task is even more difficult, and it is clear that a substantial amount of energy could ultimately be accounted for if many of the elements that up to now have been assumed to be contaminants are the instead result of fragmentation reactions.

A ratio that is sometimes seen is that of 22.4–23.8 MeV/^{4}He, which was observed in a partially successful experimental run that was part of a larger experiment conducted at SRI in 1998 [29, 30]. This ratio has been adduced as evidence that excess heat goes back to the fusion of deuterium nuclei in some way, however indirectly. The ratio is one that is in need of confirmation; but even if it ends up being confirmed and is found to be relatively stable across experiments, there is more than one way to obtain a result that is consistent with it. One proposal that has been suggested is that there could be a lower-energy helium-producing process occurring in parallel with whatever is producing most of the heat [28], which is compatible with the notion that α decay is the source of the helium, while fragmentation of heavier elements is what is generating much of the heat, together with whatever heat is produced by α captures and β decays.

What is the α emitter in each experiment responsible for the flux of α particles causing many of the transmutations? This is difficult to say, but we can speculate. In Section 5, above, on the 2014 Lugano test, samarium, rhenium and hafnium were identified as possibilities. In the palladium experiments it might be the platinum anode that is sometimes used or perhaps heavy impurities in either the cathode or the anode. What is it that would induce increased activity in α and β emitters? If it proves to be the case that α decay and fragmentation following upon α capture are indeed responsible for many of the transmutations, then we will strongly suspect the Coulomb barrier has been suppressed by some amount through electron screening. The process of α decay is fundamentally a quantum mechanical tunneling process, and the width of the Coulomb barrier is what limits the rate at which it proceeds. A narrowing of the width would be expected to happen as a result of increased time spent in and near the nuclear volume on the part of electrons [18, 31].

In the case of β decay, we might suspect that the same surplus of electron charge density is also responsible. Although the weak interaction is a comparatively slow one, it can be thought of as having a cross section, and increasing the electron density in the nucleus is analogous to increasing the intensity of a beam of incident particles, thereby increasing the number of interactions. Where positron emission is a dominant decay mode, the presence of additional electron charge could cause electron capture to overwhelm this channel. One also suspects that daughter nuclei left in an excited state following upon an α capture or β decay will impart the energy of the transition to the ground state to electrons in the vicinity, and that something similar is also happening with the prompt γ photon that is required in order to conserve momentum [32] in some cases of α capture.

We can also ask whether the cross section for α capture, which is the reverse process of α decay, might also be increased somewhat by the suppression of the Coulomb barrier, as well as the rate of spontaneous fission.

It should be mentioned that not infrequently the experimental techniques employed to study isotope shifts in LENR might themselves be partly responsible for whatever processes are causing the changes, perhaps most notably the high-energy synchrotron beam used by Iwamura *et al.* [10], but also anytime a researcher employs energy-dispersive x-ray spectroscopy or similar methods that could modify the electronic environment. Although the results of such studies are valuable, the situation appears to be similar to that found in quantum mechanics, where the act of measuring the system potentially has the effect of changing the results that are obtained.

Finally, we have yet to account for the role of deuterium and hydrogen, the former of which was needed in some of the transmutation experiments in order to see any effect. Whatever role they play, there is reason to think it might be more subtle than has been assumed in the past, namely, as progenitors to fusion reactions. For example, they might somehow catalyze the various decay and capture processes through a modification of the electronic environment in the substrate. For reasons unknown at this point, deuterium often does a better job of this, which is not to say that hydrogen might not be as effective or even preferable in some less-explored configurations. The differences seen in

deuterium arc lamps in comparison to hydrogen arc lamps highlight the fact that they have different properties and may have different affects on the electronic environment when present near the surface or within the bulk of a cathode.

7 Conclusion

We have explored several processes that have been suggested in one form or another by researchers looking at transmutations in LENR over the years—α decay, α capture, fragmentation of heavy compound nuclei following upon α capture, and β decay/electron capture—and found these processes to be broadly consistent with the changes in isotopes that have been reported across the work of different researchers. Something in the experiments appears to be inducing these processes. If these processes are indeed occurring at an accelerated rate, it is unclear whether they fully account for LENR or whether they are secondary to some more central process. It would not be too surprising, however, if upon further investigation they were found to be responsible for the most part for the helium, excess heat and correlation between helium and excess heat that are seen in the Pons and Fleischmann effect. The analysis developed in this paper has been applied to the fuel and ash assays included in the report of the 2014 Lugano E-Cat test by Levi *et al.*, which were found to be largely consistent with what has been seen in the LENR isotope studies. Suppression of the Coulomb barrier by electron screening has been mentioned as a possible candidate for whatever is responsible for inducing α decay, and the requisite surplus of electron charge density as what might be inducing weak interaction processes such as β decay.

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A α capture series in light elements

Following are four series of α capture and β decay chains that describe the transitions between light isotopes as energetic α's are captured. The four series have been referred to here as the *helium series*, the *beryllium series*, the *deuterium series* and the *lithium series*, in analogy to the four actinide α decay chains, called the *thorium*, *neptunium*, *uranium* and *actinium series*. The α capture series below have been anticipated at various points in LENR isotope studies, e.g., in Ref. [5] for α capture and Ref. [33] for β decay. The list goes back even further if one includes hypothetical reactions of the form ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X} + 2n \cdot \mathrm{d} \rightarrow {}^{\mathrm{A+4n}}_{\mathrm{Z+2n}}\mathrm{Y}$, which are understood here to arise instead from successive α captures.

The daughters of a parent nuclide within a given series will remain in that series as as long as α decay and simple β decay are the only processes involved. If one knows that ^{81}Kr is the product of a series of α captures and β decays going back several steps, one can infer that ^{73}Ge was among the progenitors. Only a process other than α capture or β decay, such as neutron capture, spallation, or β delayed neutron emission will change the series to another one.

Isotopes that do not have a parent nuclide earlier in the series are underlined. The label "CD" denotes the generally short-lived nuclides expected from the cluster decay of a heavier nuclide, and "syn." denotes synthetic radionuclides that do not occur in significant quantities in nature. Spontaneous fission becomes energetically possible at atomic masses greater than 92 [34].

A.1 Helium series ($4n$)

The name for this series comes from ^{4}He, the first element with $4n$ nucleons, although it seems unlikely that helium itself participates as a parent nuclide. The part of this series that extends from ^{12}C to ^{44}Ti is familiar in astrophyics under the heading of the α process.

- $\underline{^{12}\mathrm{C}}$ $\alpha\rightarrow$ ^{16}O $\alpha\rightarrow$ ^{20}Ne $\alpha\rightarrow$ ^{24}Mg
- $\underline{^{24}\mathrm{Ne}}$ (CD) $\beta^-\rightarrow$ ^{24}Na $\beta^-\rightarrow$ ^{24}Mg
- ^{24}Mg $\alpha\rightarrow$ ^{28}Si
- $\underline{^{28}\mathrm{Mg}}$ (CD) $\beta^-\rightarrow$ ^{28}Al (syn.) $\beta^-\rightarrow$ ^{28}Si
- ^{28}Si $\alpha\rightarrow$ ^{32}S
- $\underline{^{32}\mathrm{Si}}$ (CD) $\beta^-\rightarrow$ ^{32}P $\beta^-\rightarrow$ ^{32}S
- ^{32}S $\alpha\rightarrow$ ^{36}Ar
- ^{36}Ar $\beta^+\beta^+\rightarrow$ ^{36}S $\alpha\rightarrow$ ^{40}Ar $\alpha\rightarrow$ ^{44}Ca $\alpha\rightarrow$ ^{48}Ti
- ^{36}Ar $\alpha\rightarrow$ ^{40}Ca $\alpha\rightarrow$ ^{44}Ti (syn.) $\varepsilon\rightarrow$ ^{44}Sc (syn.) $\beta^+\rightarrow$ ^{44}Ca $\alpha\rightarrow$ ^{48}Ti
- $\underline{^{48}\mathrm{Ca}}$ $\beta^-\beta^-\rightarrow$ ^{48}Ti
- $\underline{^{48}\mathrm{Ca}}$ $\alpha\rightarrow$ ^{52}Ti (syn.) $\beta^-\rightarrow$ ^{52}V (syn.) $\beta^-\rightarrow$ ^{52}Cr
- ^{48}Ti $\alpha\rightarrow$ ^{52}Cr
- ^{52}Cr $\alpha\rightarrow$ ^{56}Fe $\alpha\rightarrow$ ^{60}Ni $\alpha\rightarrow$ ^{64}Zn
- ^{64}Zn $\beta^+\beta^+\rightarrow$ ^{64}Ni $\alpha\rightarrow$ ^{68}Zn
- ^{64}Zn $\alpha\rightarrow$ ^{68}Ge (syn.) $\varepsilon\rightarrow$ ^{68}Ga (syn.) $\beta^+\rightarrow$ ^{68}Zn
- ^{68}Zn $\alpha\rightarrow$ ^{72}Ge $\alpha\rightarrow$ ^{76}Se $\alpha\rightarrow$ ^{80}Kr $\alpha\rightarrow$ ^{84}Sr
- $\underline{^{76}\mathrm{Ge}}$ $\alpha\rightarrow$ ^{80}Se $\alpha\rightarrow$ ^{84}Kr $\alpha\rightarrow$ ^{88}Sr $\alpha\rightarrow$ ^{92}Zr $\alpha\rightarrow$ ^{96}Mo
- ^{84}Sr $\beta^+\beta^+\rightarrow$ ^{84}Kr $\alpha\rightarrow$ ^{88}Sr
- ^{84}Sr $\alpha\rightarrow$ ^{88}Zr (syn.) $\varepsilon\rightarrow$ ^{88}Y (syn.) $\varepsilon\rightarrow$ ^{88}Sr

- $^{88}\mathrm{Sr}\ \alpha\rightarrow\ ^{92}\mathrm{Zr}\ \alpha\rightarrow\ ^{96}\mathrm{Mo}$
- $\underline{^{96}\mathrm{Zr}}\ \beta^{-}\beta^{-}\rightarrow\ ^{96}\mathrm{Mo}$
- $\underline{^{96}\mathrm{Zr}}\ \alpha\rightarrow\ ^{100}\mathrm{Mo}\ \beta^{-}\beta^{-}\rightarrow\ ^{100}\mathrm{Ru}$

A.2 Beryllium series $(4n+1)$

- $\underline{^{9}\mathrm{Be}}\ \alpha\rightarrow\ ^{13}\mathrm{C}\ \alpha\rightarrow\ ^{17}\mathrm{O}\ \alpha\rightarrow\ ^{21}\mathrm{Ne}\ \alpha\rightarrow\ ^{25}\mathrm{Mg}\ \alpha\rightarrow\ ^{29}\mathrm{Si}\ \alpha\rightarrow\ ^{33}\mathrm{S}\ \alpha\rightarrow\ ^{37}\mathrm{Ar}$ (syn.) $\varepsilon\rightarrow\ ^{37}\mathrm{Cl}\ \alpha\rightarrow\ ^{41}\mathrm{K}\ \alpha\rightarrow\ ^{45}\mathrm{Sc}\ \alpha\rightarrow\ ^{49}\mathrm{V}$ (syn.) $\varepsilon\rightarrow\ ^{49}\mathrm{Ti}$
- $\underline{^{49}\mathrm{Sc}}$ (syn.) $\beta^{-}\rightarrow\ ^{49}\mathrm{Ti}$
- $^{49}\mathrm{Ti}\ \alpha\rightarrow\ ^{53}\mathrm{Cr}\ \alpha\rightarrow\ ^{57}\mathrm{Fe}\ \alpha\rightarrow\ ^{61}\mathrm{Ni}\ \alpha\rightarrow\ ^{65}\mathrm{Zn}$ (syn.) $\varepsilon\rightarrow\ ^{65}\mathrm{Cu}\ \alpha\rightarrow\ ^{69}\mathrm{Ga}\ \alpha\rightarrow\ ^{73}\mathrm{As}$ (syn.) $\varepsilon\rightarrow\ ^{73}\mathrm{Ge}\ \alpha\rightarrow\ ^{77}\mathrm{Se}\ \alpha\rightarrow\ ^{81}\mathrm{Kr}$
- $^{81}\mathrm{Kr}\ \varepsilon\rightarrow\ ^{81}\mathrm{Br}\ \alpha\rightarrow\ ^{85}\mathrm{Rb}$
- $^{81}\mathrm{Kr}\ \alpha\rightarrow\ ^{85}\mathrm{Sr}$ (syn.) $\varepsilon\rightarrow\ ^{85}\mathrm{Rb}$
- $^{85}\mathrm{Rb}\ \alpha\rightarrow\ ^{89}\mathrm{Y}\ \alpha\rightarrow\ ^{93}\mathrm{Nb}\ \alpha\rightarrow\ ^{97}\mathrm{Tc}\ \varepsilon\rightarrow\ ^{97}\mathrm{Mo}$
- $\underline{^{109}\mathrm{Ag}}\ \alpha\rightarrow\ ^{113}\mathrm{In}$
- $\underline{^{113}\mathrm{Cd}}\ \alpha\rightarrow\ ^{117}\mathrm{Sn}$
- $^{113}\mathrm{In}\ \alpha\rightarrow\ ^{117}\mathrm{Sb}$ (syn.) $\beta^{+}\rightarrow\ ^{117}\mathrm{Sn}$
- $\underline{^{137}\mathrm{Ba}}\ \alpha\rightarrow\ ^{141}\mathrm{Ce}$ (syn.) $\beta^{-}\rightarrow\ ^{141}\mathrm{Pr}$

A.3 Deuterium series $(4n+2)$

This series has been called the *deuterium series* because deuterium is the first nuclide at $4n+2$ nucleons, although it is not expected to participate.

- $\underline{^{6}\mathrm{Li}}\ \alpha\rightarrow\ ^{10}\mathrm{B}\ \alpha\rightarrow\ ^{14}\mathrm{N}$
- $\underline{^{14}\mathrm{C}}$ (CD) $\beta^{-}\rightarrow\ ^{14}\mathrm{N}$
- $\underline{^{14}\mathrm{C}}$ (CD) $\alpha\rightarrow\ ^{18}\mathrm{O}$
- $^{14}\mathrm{N}\ \alpha\rightarrow\ ^{18}\mathrm{F}$
- $^{18}\mathrm{F}\ \beta^{+}\rightarrow\ ^{18}\mathrm{O}$
- $^{18}\mathrm{F}\ \alpha\rightarrow\ ^{22}\mathrm{Na}$
- $^{18}\mathrm{O}\ \alpha\rightarrow\ ^{22}\mathrm{Ne}$
- $^{22}\mathrm{Na}\ \beta^{+}\rightarrow\ ^{22}\mathrm{Ne}$
- $^{22}\mathrm{Na}\ \alpha\rightarrow\ ^{26}\mathrm{Al}$
- $^{22}\mathrm{Ne}\ \alpha\rightarrow\ ^{26}\mathrm{Mg}$
- $^{26}\mathrm{Al}\ \beta^{+}\rightarrow\ ^{26}\mathrm{Mg}$
- $^{26}\mathrm{Al}\ \alpha\rightarrow\ ^{30}\mathrm{P}$ (syn.) $\beta^{+}\rightarrow\ ^{30}\mathrm{Si}$
- $^{26}\mathrm{Mg}\ \alpha\rightarrow\ ^{30}\mathrm{Si}$

- $\underline{^{30}\text{Mg}}$ (CD) $\beta^-\!\!\rightarrow {}^{30}\text{Al}$ (syn.) $\beta^-\!\!\rightarrow {}^{30}\text{Si}$
- ^{30}Si $\alpha\!\rightarrow {}^{34}\text{S}$
- ^{34}S $\alpha\!\rightarrow {}^{38}\text{Ar}$ $\alpha\!\rightarrow {}^{42}\text{Ca}$ $\alpha\!\rightarrow {}^{46}\text{Ti}$
- $\underline{^{34}\text{Si}}$ (CD) $\beta^-\!\!\rightarrow {}^{34}\text{P}$ (syn.) $\beta^-\!\!\rightarrow {}^{34}\text{S}$
- $\underline{^{46}\text{Ar}}$ (CD) $\beta^-\!\!\rightarrow {}^{46}\text{K}$ (syn.) $\beta^-\!\!\rightarrow {}^{46}\text{Ca}$
- ^{46}Ca $\beta^-\beta^-\!\!\rightarrow {}^{46}\text{Ti}$
- ^{46}Ca $\alpha\!\rightarrow {}^{50}\text{Ti}$
- ^{46}Ti $\alpha\!\rightarrow {}^{50}\text{Cr}$
- $\underline{^{50}\text{Ca}}$ (CD) $\beta^-\!\!\rightarrow {}^{50}\text{Sc}$ (syn.) $\beta^-\!\!\rightarrow {}^{50}\text{Ti}$
- ^{50}Cr $\beta^+\beta^+\!\!\rightarrow {}^{50}\text{Ti}$
- ^{50}Cr $\alpha\!\rightarrow {}^{54}\text{Fe}$
- ^{50}Ti $\alpha\!\rightarrow {}^{54}\text{Cr}$ $\alpha\!\rightarrow {}^{58}\text{Fe}$
- ^{54}Fe $\beta^+\beta^+\!\!\rightarrow {}^{54}\text{Cr}$
- ^{54}Fe $\alpha\!\rightarrow {}^{58}\text{Ni}$
- ^{58}Fe $\alpha\!\rightarrow {}^{62}\text{Ni}$
- ^{58}Ni $\beta^+\beta^+\!\!\rightarrow {}^{58}\text{Fe}$
- ^{58}Ni $\alpha\!\rightarrow {}^{62}\text{Zn}$ (syn.) $\beta^+\!\!\rightarrow {}^{62}\text{Cu}$ (syn.) $\beta^+\!\!\rightarrow {}^{62}\text{Ni}$
- ^{62}Ni $\alpha\!\rightarrow {}^{66}\text{Zn}$ $\alpha\!\rightarrow {}^{70}\text{Ge}$ $\alpha\!\rightarrow {}^{74}\text{Se}$
- ^{74}Se $\beta^+\beta^+\!\!\rightarrow {}^{74}\text{Ge}$ $\alpha\!\rightarrow {}^{78}\text{Se}$
- ^{74}Se $\alpha\!\rightarrow {}^{78}\text{Kr}$
- ^{78}Kr $\beta^+\beta^+\!\!\rightarrow {}^{78}\text{Se}$
- ^{78}Kr $\alpha\!\rightarrow {}^{82}\text{Sr}$ (syn.) $\varepsilon\!\rightarrow {}^{82}\text{Rb}$ $\beta^+\!\!\rightarrow {}^{82}\text{Kr}$
- ^{78}Se $\alpha\!\rightarrow {}^{82}\text{Kr}$
- ^{82}Kr $\alpha\!\rightarrow {}^{86}\text{Sr}$ $\alpha\!\rightarrow {}^{90}\text{Zr}$ $\alpha\!\rightarrow {}^{94}\text{Mo}$
- $\underline{^{82}\text{Se}}$ $\alpha\!\rightarrow {}^{86}\text{Kr}$ $\alpha\!\rightarrow {}^{90}\text{Sr}$
- ^{90}Sr $\beta^-\!\!\rightarrow {}^{90}\text{Y}$
- ^{90}Sr $\alpha\!\rightarrow {}^{94}\text{Zr}$ $\alpha\!\rightarrow {}^{98}\text{Mo}$
- ^{98}Mo $\beta^-\beta^-\!\!\rightarrow {}^{98}\text{Ru}$
- ^{98}Mo $\alpha\!\rightarrow {}^{102}\text{Ru}$

A.4 Lithium series $(4n + 3)$

- $\overline{^{7}\text{Li}}$ $\alpha\!\rightarrow {}^{11}\text{B}$ $\alpha\!\rightarrow {}^{15}\text{N}$ $\alpha\!\rightarrow {}^{19}\text{F}$ $\alpha\!\rightarrow {}^{23}\text{Na}$ $\alpha\!\rightarrow {}^{27}\text{Al}$ $\alpha\!\rightarrow {}^{31}\text{P}$ $\alpha\!\rightarrow {}^{35}\text{Cl}$ $\alpha\!\rightarrow {}^{39}\text{K}$ $\alpha\!\rightarrow {}^{43}\text{Sc}$ (syn.) $\beta^+\!\!\rightarrow {}^{43}\text{Ca}$ $\alpha\!\rightarrow {}^{47}\text{Ti}$ $\alpha\!\rightarrow {}^{51}\text{Cr}$ (syn.) $\varepsilon\!\rightarrow {}^{51}\text{V}$ $\alpha\!\rightarrow {}^{55}\text{Mn}$ $\alpha\!\rightarrow {}^{59}\text{Co}$ $\alpha\!\rightarrow {}^{63}\text{Cu}$ $\alpha\!\rightarrow {}^{67}\text{Ga}$ (syn.) $\varepsilon\!\rightarrow {}^{67}\text{Zn}$ $\alpha\!\rightarrow {}^{71}\text{Ge}$ (syn.)

$\varepsilon\rightarrow {}^{71}\mathrm{Ga}\ \alpha\rightarrow {}^{75}\mathrm{As}\ \alpha\rightarrow {}^{79}\mathrm{Br}\ \alpha\rightarrow {}^{83}\mathrm{Rb}$ (syn.) $\varepsilon\rightarrow {}^{83}\mathrm{Kr}\ \alpha\rightarrow {}^{87}\mathrm{Sr}$

- $\underline{{}^{87}\mathrm{Rb}}\ \beta^{-}\rightarrow {}^{87}\mathrm{Sr}$
- $\underline{{}^{87}\mathrm{Rb}}\ \alpha\rightarrow {}^{91}\mathrm{Y}$ (syn.) $\beta^{-}\rightarrow {}^{91}\mathrm{Zr}$
- ${}^{87}\mathrm{Sr}\ \alpha\rightarrow {}^{91}\mathrm{Zr}$
- ${}^{91}\mathrm{Zr}\ \alpha\rightarrow {}^{95}\mathrm{Mo}\ \alpha\rightarrow {}^{99}\mathrm{Ru}\ \alpha\rightarrow {}^{103}\mathrm{Pd}$ (syn.) $\varepsilon\rightarrow {}^{103}\mathrm{Rh}\ \alpha\rightarrow {}^{107}\mathrm{Ag}$
- ${}^{107}\mathrm{Pd}\ \beta^{-}\rightarrow {}^{107}\mathrm{Ag}$
- ${}^{107}\mathrm{Ag}\ \alpha\rightarrow {}^{111}\mathrm{In}$ (syn.) $\varepsilon\rightarrow {}^{111}\mathrm{Cd}\ \alpha\rightarrow {}^{115}\mathrm{Sn}$
- $\underline{{}^{115}\mathrm{In}}\ \beta^{-}\rightarrow {}^{115}\mathrm{Sn}$