EXPERIMENTAL OBSERVATION OF NUCLEAR REACTIONS IN PALLADIUM AND URANIUM— POSSIBLE EXPLANATION BY HYDREX MODE

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Experiments with uranium are presented that show a highly exothermal reaction, which can only be of nuclear origin. One striking point of these results is that they clearly show that what is being observed is not some kind of fusion reaction of the deuterium present (only exceedingly small amounts of it are present). This is a strong indication that hydrogen can trigger nuclear reactions that seem to involve the nuclei of the lattice (which would yield a fission-like pattern of products). Confronted with a situation where some experiments in the field yield a fusion-like pattern of products (CF experiments) and others a fissionlike one (LENR experiments), one can reasonably wonder whether one is not observing two aspects of the same phenomenon. Thus, it is proposed to describe CF and LENR reactions as essentially the same phenomenon based on the possible existence of a still hypothetical proton/electron resonance, which would catalyze fissionlike reactions with a neutron sink.[1] Finally, a series of experiments is proposed to assess this hypothesis.

I. INTRODUCTION

By submitting various metals (Pd, U) containing hydrogen (from 0.2 to 70 atoms of hydrogen for 100 atoms of the host metal) to the combined action of electrical currents and magnetic fields, we have observed sizable exothermal effects. Up to 8 W were observed, for quantities of metal used in the range of 150 to 500 mg (Refs. 1 through 4). These effects are beyond experimental errors, with the energy output being typically 110 to 150% of the energy input and not of chemical origin. Exothermal effects are in the range of 7000 MJ/ mole of metal in the case of palladium and 2000 MJ/ mole of metal in the case of uranium, indicating a nuclear origin. To be in line with the terminology used in the field, we shall call "excess energy (excess power when appropriate)" the energy of the reaction(s) that are the cause of these exothermal effects. New chemical species also appear in the processed metals, comparable to those observed in other experiments.[5-7] We have made no attempt, in the experiments we have run since 1996, to measure possible productions of helium and tritium (such as are observed by other experimenters[8-12]), but we don't exclude that they might be produced. We shall report in detail on our last results

with uranium and summarize those we had previously obtained with palladium. We shall finally present a detailed and critical review of two classes of experiments that are obtained by various experimenters: those tending to show a fusionlike pattern of products (CF reactions) and those showing a fissionlike one (LENR reactions). The various explanations will also be reviewed.

II. EXPERIMENTAL DESCRIPTION

II.A. Experimental Setup (General Strategy)

The calorimetric measurements have been made using calorimeters exchanging heat with a heat sink maintained at a regulated temperature: either (a) by measuring the temperature difference between the outlet and the inlet of a regulated and measured flow of silicon oil cooling the processed sample (heat flow calorimeter) or (b) by measuring the heat flux flowing from the calorimeter to the heat sink (heat flux calorimeter).

To activate the metal samples, two different methods were used:

1. The palladium, in the form of two parallel wires (40 cm long and 250 μm in diameter), acted as one of the electrodes of an ozonizer filled with hydrogen and was thus submitted to the action of partial discharges breaking through the hydrogen gap (high voltage, frequency ~3000 Hz) (Ref. 2). The dielectric barrier was a Pyrex glass tube, so the partial discharges (that form the ozonizer discharge) were in contact only with the palladium and the Pyrex tube, which contains no Zn and Cu and only trace amounts of Mg.

2. The uranium was in the form of small lathe turnings ($10 \times 3 \times 0.2$ mm), which were submitted to the combined action of a pulsed current and a magnetic field as will be described later.

After the experiments, the metal samples were analyzed for trace element variations.

II.B. Activation of the Sample and Calorimetric Setup

In the case of palladium, the activation and calorimetric methods have already been described (see Ref. 2).

In the case of uranium, preliminary experiments have been described.[3] Since then, improvements have been achieved, both on the activation of the sample and on the calorimetric measurements. We thus describe these methods in detail.

The uranium metallic sample is activated by passing a high-intensity pulsed direct current (dc) through it, as shown in Fig. 1. The electrodes (soft steel) are polished and an O-ring placed between them prevents a too fast oxidation of the uranium (runs up to 10 days were thus possible). The direction of the current is parallel to that of a high-intensity magnetic field (up to 1 T, generated by two Co/Sm permanent magnets able to withstand 300°C). The metal (natural uranium, containing 0.7% of ^{235}U) is in the form of a thin foil (lathe turnings $10 \times 3 \times 0.2$ mm), weighing 150 to 300 mg (see Fig. 1). The whole assembly is placed between two insulated metallic plates, pressed by four steel bolts that close the magnetic circuit. With this setup, the current density flowing through the sample is high and with a direction parallel to that of the magnetic field.

II.B.1. Two Types of Calorimeters Have Been Used

There are two types of calorimeters that have been used (see Fig. 2):

1. a high-precision, low-temperature Seebeck calorimeter, measuring the total heat flux flowing from the calorimeter to the heat sink, through six square (46- × 46-mm) Seebeck modules.[a] The temperature of the reactor is limited to 80°C and the precision is 5 mW.
2. a low-precision, high-temperature calorimeter, measuring the lateral heat flux, through a layer of thermocouples (J type), mounted in opposition on both sides of a Teflon sheet (1 mm thick), wrapped around the reactor and the magnets. The temperature of the reactor can reach 200°C, and the precision of the calorimeter is 100 mW.

The uranium sample is part of an electrical circuit that is represented in Fig. 3 (which gives an overall description of the experimental setup).
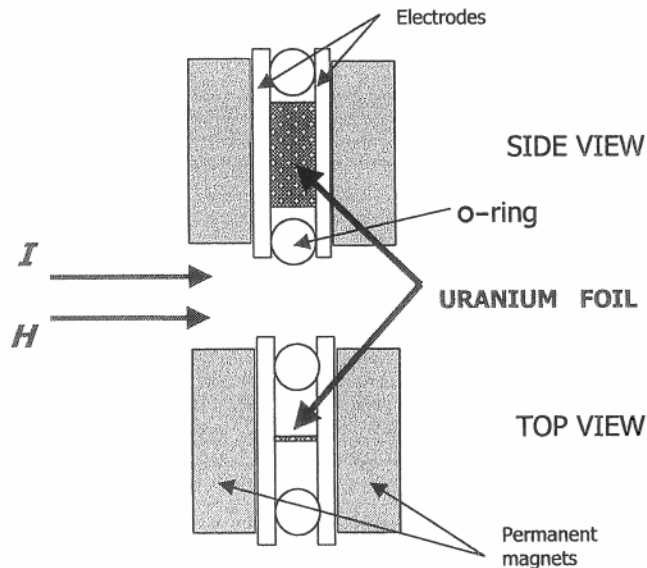

Fig. 1. Sample activation in the case of uranium.

II.B.2. Principle and Description of the Electrical Measurements

We need to measure the electrical power P that is dissipated in our experimental device:

$$P = \frac{1}{T}\int_0^T u(t)i(t)dt \leq \langle U \rangle \cdot \langle I \rangle \ ,$$

where $\langle U \rangle$ and $\langle I \rangle$ are the root-mean-square (rms) values of the tension and the intensity. Then, P is equal to $\langle U \rangle \cdot \langle I \rangle$ when our experimental device (the uranium metal under test) is a pure resistance (no inductance or capacitor). We checked that this was indeed the

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[a] From MELCOR AMS Electronics.

case and also that the electromagnetic emission of the antenna formed by the uranium foil was well within experimental errors. To do that we measured the resistance and the impedance of the uranium under treatment and found, for a large range of values, that these two parameters are equal. This verification was done according to the following procedure.

HIGH PRECISION SEEBECK CALORIMETER

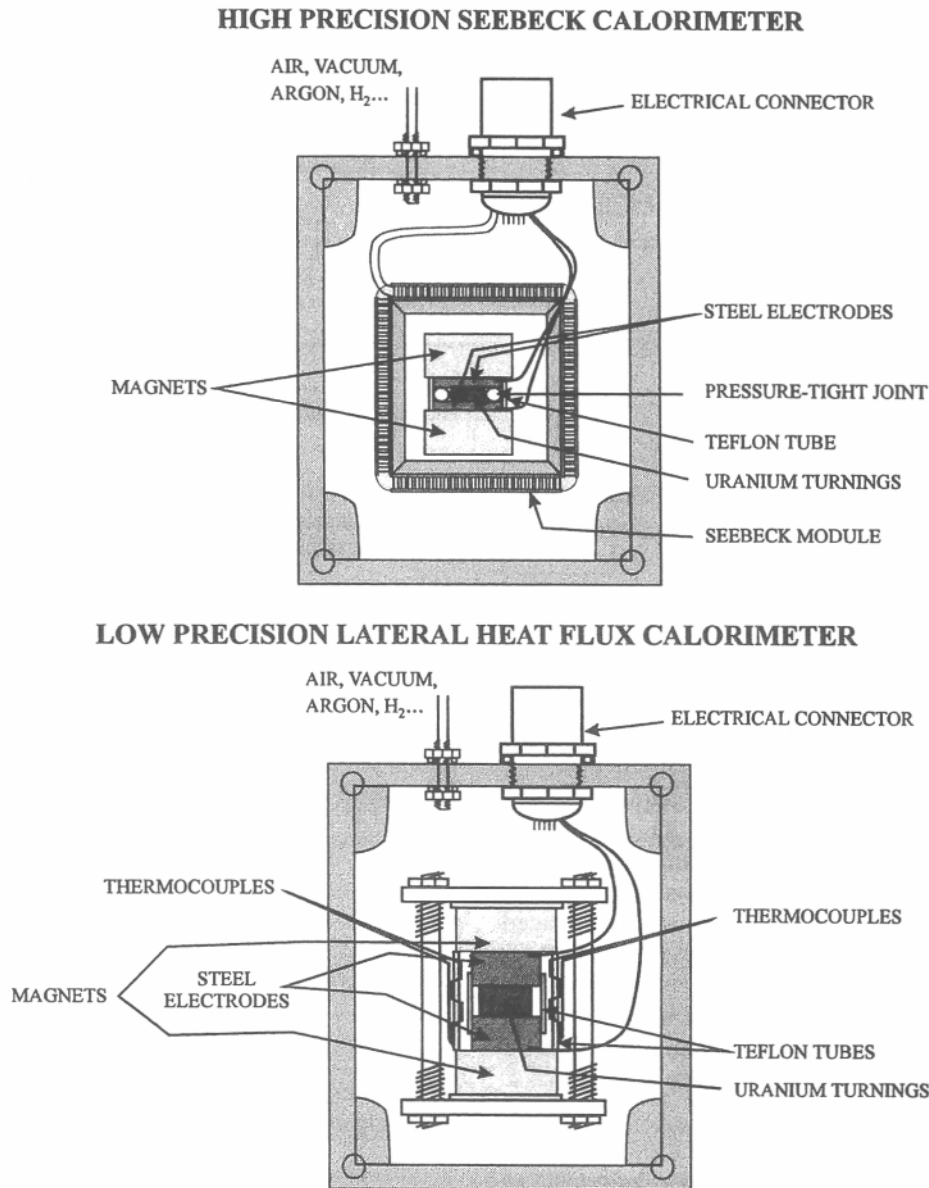## LOW PRECISION LATERAL HEAT FLUX CALORIMETER

Fig. 2. Low- and high-precision calorimeters.

The AOIP SA multichannel data acquisition system that we use is designed to measure the tension (or the intensity) of a direct current. With a pulsed current, the given value is the mean one:

$$\overline{U} = \frac{1}{T}\int_0^T u(t)dt \,,$$

where T is the integration time ($T = 140$ ms, i.e., ~700 signal periods).

The pulsed tension generated by opening and closing the transistor 5000 times/s is a periodic signal, which has been shown (oscilloscope) to contain three harmonics: the main one at 5 kHz and two smaller ones, respectively, ~1 and 10 MHz [Eq. (1)]. This signal can be represented by a Fourier series, and we have the following:

$$\langle U \rangle = \sqrt{\overline{U}^2 + \sum \langle U \rangle_i^2} \,, \tag{1}$$

with $\langle U \rangle_i$ being the rms values of the tensions due to the various harmonics.

In a similar way,

$$\langle I \rangle = \sqrt{\overline{I}^2 + \sum \langle I \rangle_i^2} \,, \tag{2}$$

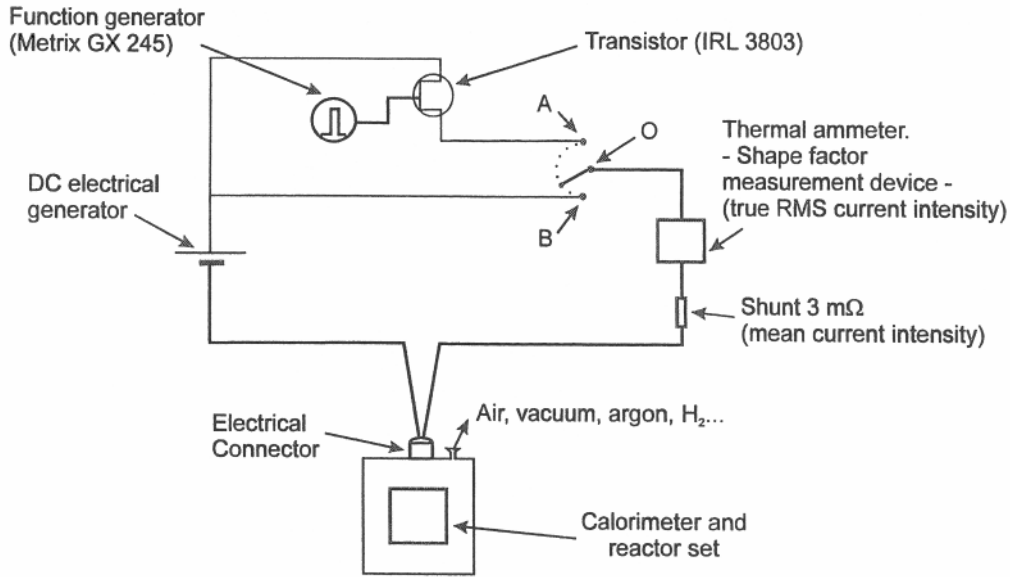with $\langle I \rangle_i$ being the rms values of the intensities due to the various harmonics.

Fig. 3. Overall experimental setup.

To measure $\sum \langle U \rangle_i$, we have used a high frequency probe,[b] with bandwidth 500 Hz to 30 MHz. Combining with the measure of $\overline{U}$ (AOIP SA data acquisition system), we can calculate $\langle U \rangle$ by relation (1).

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[b] ELDITEST GE 7130.

To measure $\langle I \rangle$, we use a thermal ammeter placed on the circuit (see Fig. 3). This ammeter consists of a total heat flux calorimeter (Seebeck type), in which is placed a thin film resistor *(R = 0.050 Ω, Caddock MP 930)* having no inductive or capacitive component and constant when the frequency of the tension increases up to 50 MHz. The heat flux calorimeter is calibrated using a direct current, yielding a relation between $V_{Seebeck}$ and $\bar{I}$:

$$V_{seebeck} = R \cdot \left(\bar{I}\right)^2_{dc} + B \quad . \tag{3}$$

When a pulsed tension is used, we use relation (3) to infer the rms intensity $\langle I \rangle$ of the current in the whole circuit, from the response (3) of this calorimeter.

We thus have for the ammeter the following:

resistance $R_A = \dfrac{\bar{U}_A}{\bar{I}}$

and

impedance $Z_A = \dfrac{\langle U \rangle_A}{\langle I \rangle}$.

We have checked that R_A is equal to Z_A, confirming that the resistance of the ammeter has no inductance and that its electromagnetic emission is within experimental errors.

We then use the value of $\langle I \rangle$ measured by the ammeter to measure the electrical power that is injected in the uranium foil. If $\langle U \rangle_U$ and $\bar{U}_U$ are the rms and mean values of the tension across the uranium foil (measured in the same way as for the ammeter), we have

resistance $R_U = \dfrac{\bar{U}_U}{\bar{I}}$

and

impedance $Z_U = \dfrac{\langle U \rangle_U}{\langle I \rangle}$.

Here again, we have checked that R_U is equal to Z_U, with the same conclusion as for the ammeter, and we have

electrical power injected in the uranium:

$$W_U = R_U \cdot \langle I \rangle^2 \quad .$$

(Note that this method for measuring the injected power gives results identical to the one used in Ref. 3, but demonstrates that the uranium is purely resistive and the electromagnetic emission is negligible).

II.B.3. Description of the Overall Experimental Setup

A dc electrical generator delivers electrical power into a reactor containing the uranium metal. The electrical power is delivered either in the form of a constant direct current, through connection OB or in the form of a pulsed current through connection OA. The pulsed current is shaped by the action of a transistor,[c] which is triggered by a function generator[d] (Fig. 3).
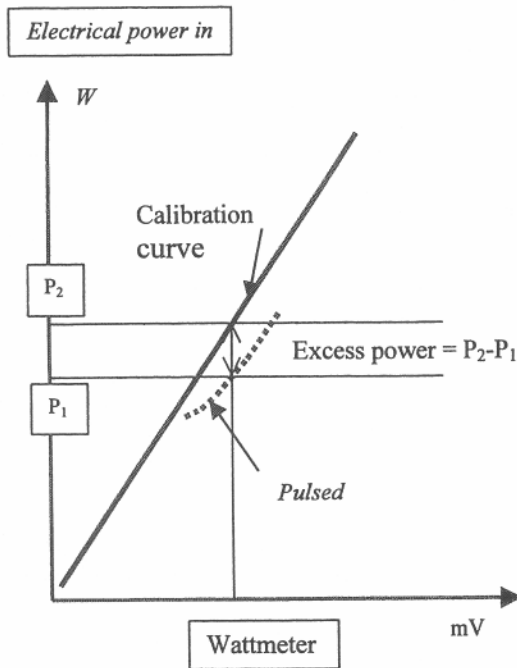

Fig. 4. Excess power measurement principle.

Natural uranium, thin foils ($10 \times 3 \times 0.2$ mm thick) are placed between two cylindrical soft steel electrodes and magnets according to Fig. 1. Two wires are fixed by solder on the electrodes, allowing electrical current to be passed through the uranium foil. Four wires allow the measurement of $\langle U \rangle_U$ and $\overline{U}$.

The whole assembly is finally placed in one of the two calorimeters, itself placed in a watertight aluminum box, equipped with the required passages for the wires conducting the current to the reactor and those connecting the various sensors to the AOIP SA multichannel data acquisition system that monitors the experiment. The box is placed in the regulated cryothermostat, where it can exchange heat with water maintained at 15°C.

Under these conditions, the oxidation of the uranium sample is controlled at a very low rate for periods of up to 10 days (and temperatures up to 200°C when the second type of calorimeter is used).

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[c] From International Rectifier Power MOFSET, type IRL3803.
[d] Metrix GX 245.

To calibrate the calorimeters, we assume that no excess energy is generated when a constant direct current is passed through the sample. If we plot the dc power injected in the uranium as a function of the Seebeck voltage of the calorimeter, we obtain a quasi-linear relationship (a quadratic fit has been used for the calculations). This relation is shown in Fig. 4 and constitutes the baseline for the calorimeters (only Joule heating is supposed to occur in that case). The excess energy generated when a pulsed direct current is used is then assessed against that baseline. This excess energy is thus a minimum.

When we switch to pulsed currents (without any other change in the experimental setup), the points obtained are systematically on the right side of the calibration curve shown in Fig. 4, meaning that an exothermal reaction is occurring in the experiment. The excess power generated can be computed from the calibration curve of the calorimeter and the electrical power injected in the uranium.

II.B.4. Variations of Trace Elements in the Treated Samples

The trace elements in the treated samples varied in the different cases. In the case of palladium, the chemical composition modifications were assessed in the following way: After the experiment, the palladium wires were removed from the reactor and a 20-cm piece of one of them (in the center of the 40 cm facing the outer copper electrode and weighing 120 mg) was dissolved and analyzed by inductively coupled plasma-mass spectroscopy (ICP-MS) (Commissariat à l'Energie Atomique at Bruyères-le-Chatel) for all elements, except Fe, Ru, Rh, and Ag that were assessed by inductively coupled plasma-Auger electron spectroscopy (ICP-AES). A virgin sample of palladium wire of the same batch and same length was also analyzed according to the same procedure.

In the case of uranium, the chemical composition modifications were assessed by mass spectrometry:

1. low- or medium-resolution ICP-MS for all species (from Be to U) and for lead isotopic ratios
2. thermal ionization mass spectrometer for uranium isotopic ratios.

The ICP-MS measurements were performed by two different laboratories (Cogema at Pierrelate and the Centre National de la Recherche Scientifique central lab at Solaize) and the thermal ionization MS only by the first laboratory. The results by ICP-MS from both laboratories on the same set of samples are very similar.

The dissolution procedure (by HCL or HNO_3) of the samples has already been described.[3]

III. EXPERIMENTAL RESULTS

III.A. Palladium Case

Regarding excess energy, Table I summarizes the thermal results obtained in experiment 3H06 (light hydrogen/palladium). It can be seen that very significant excess energy productions have been observed, over long periods. Note that the combustion of all the hydrogen used in the experiment (26.36 mmole H) would have yielded 6400 J to be compared with 16,018,300 J actually obtained.

TABLE I
Excess Energy in the Palladium Case

Period	Duration (s)	H Consumed (mmole H)	Excess Energy On Period (J)	Mean Excess Power (W)	Excess Energy (eV/atom H)	Power Input (W)
Calibrating	230,000	0	0			Calibrating
Increasing	695,000	9.88	1,737,500	2.5	1,800	Increasing
I	1,390,000	9.63	5,838,000	4.2	6,300	115
II	342,000	1.41	1,846,000	5.4	13,600	150
III	767,000	5.44	6,596,000	8.6	12,600	150
Total	342,4000	26.36	16,018,300	4.7	9,000	

For the new species in the treated sample, Table II summarizes the variations in chemical species between the virgin and the treated sample. Note that the figures are for the 20 cm out of 40 cm of the wire that was analyzed. When required (calculation of energy per atom), these figures are multiplied by four (two for the length analyzed and two because of the double wire).

The average excess energy per new atom formed is thus some 65 MeV. The order of magnitude of proton-induced fission reactions for palladium is 30 MeV (Ref. 13). Similar proton-induced fission reactions for platinum would yield some 103 MeV. The amount of 65 MeV could be interpreted in two ways:

1. Not only palladium reacts but also higher mass nuclei in the lattice.

2. A reaction different than a proton-induced fission reaction occurs, yielding more energy.

TABLE II
New Species in Treated Samples in the Palladium Case

Elements	3H06 (atom)	Blank (atom)	3H06—Blank (atom)
Li	5.2×10^{14}	1.0×10^{14}	0.04×10^{16}
Mg	2.5×10^{17}	2.2×10^{16}	23.0×10^{16}
Al	7.2×10^{16}	2.7×10^{15}	7.0×10^{16}
Cr	1.1×10^{16}	1.3×10^{15}	0.97×10^{16}
Mn	3.9×10^{14}	2.6×10^{14}	0.01×10^{16}
Fe	2.8×10^{16}	1.3×10^{16}	1.6×10^{16}
Ni	3.3×10^{15}	2.5×10^{15}	0.09×10^{16}
Cu	4.7×10^{15}	1.8×10^{15}	0.3×10^{16}
Zn	4.8×10^{16}	4.8×10^{15}	4.3×10^{16}
Ir	2.3×10^{14}	1.9×10^{14}	3.8×10^{13}
Pt	3.0×10^{14}	5.2×10^{14}	-2.2×10^{14}
Au	2.9×10^{14}	4.0×10^{14}	-1.1×10^{14}

It will be seen later that the reaction we propose (hydrex catalyzed fission reactions) indeed yield more energy than proton-induced fission.

When these results were obtained, we attributed the apparition of a new species to pollution due to the action of the discharge. We have revisited our experimental setup and now draw the following conclusions:

1. Zinc, copper, nickel, iron, manganese, and chromium are indeed present in the reactor (steel spring and brass hook holding it), but they are at some 10 to 15 cm from the discharge, and a transport mechanism to the palladium wire is not at all obvious.

2. Aluminum is certainly present as a constituent (2 to 3%) in the Pyrex glass struck by the discharge, and we see a 30 times increase of its content in the treated sample. But B, which is also a constituent of the Pyrex (up to some 15%), shows no variation in the treated sample. On the contrary, Mg, which is a trace component of the Pyrex glass used, shows a 10 times increase. Moreover, if we attribute the apparition of Al and Mg to the effect of the discharge, this transport would involve three times more Mg atoms than Al.

The only new species appearing in the treated sample, which might be accounted for by pollution from the discharge, is thus Al. The three major new species (Mg, Zn, and Fe), amounting to some 58×10^{16} atoms, have thus likely been generated in the palladium (40 cm), yielding a mean energy per atom of some 170 MeV, which is an upper limit of the energy released per atom by the treatment to which the palladium has been submitted. Note that Zn have been observed by other experimenters.[5-7]

III.B. Uranium Case

Regarding excess energy, Table III summarizes the results of two experiments. Experiment 1 has been run with the high-precision/low-temperature reactor. This experiment was terminated when the temperature of the reactor reached 80°C. Experiment 2 was run with the low-precision/high-temperature reactor. This experiment was terminated when the excess power was back to zero.

TABLE III

Excess Energy in the Uranium Case

Experiment	Duration (s)	Excess Energy (J)	Mean Excess Power (W)	Peak Excess Power (W)	Mean Power Input (W)
1	510,000	80,300	0.16	0.22	3.2
2	1,000,000	1,150,000	1.15	1.3	2.8

It can be seen that with both calorimeters, significant excesses of energy were observed. Figures 5 and 6 (injected power as a function of the Seebeck voltage) show that in both experiments, the differences between the dc calibrations and the runs with pulsed direct current are well beyond experimental errors, with the measures with the high-temperature/low-precision calorimeter being more scattered. Moreover, in the run with the high-temperature/low-precision calorimeter, two reactors, one with an uranium foil and one with a copper/ nickel alloy foil of the same dimensions, were installed in series in the electrical circuit of Fig. 3 (two high-temperature/low-precision calorimeters were used). It can be seen that the response of the copper/nickel alloy is centered on the calibration curve. Figures 7 and 8 show the evolution of the excess power with time for both experiments. It is clear that experiment 2 has been run to its term (excess power back to zero, with a final temperature of 180°C), whereas experiment 1 was stopped for technological reasons (reactor temperature). From the comparison of the results, temperature appears to be an important parameter. In Fig. 8, 3σ error bars are indicated.
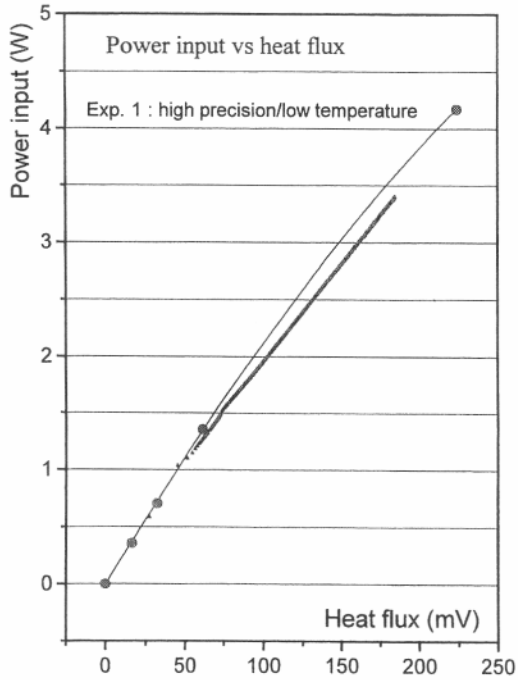
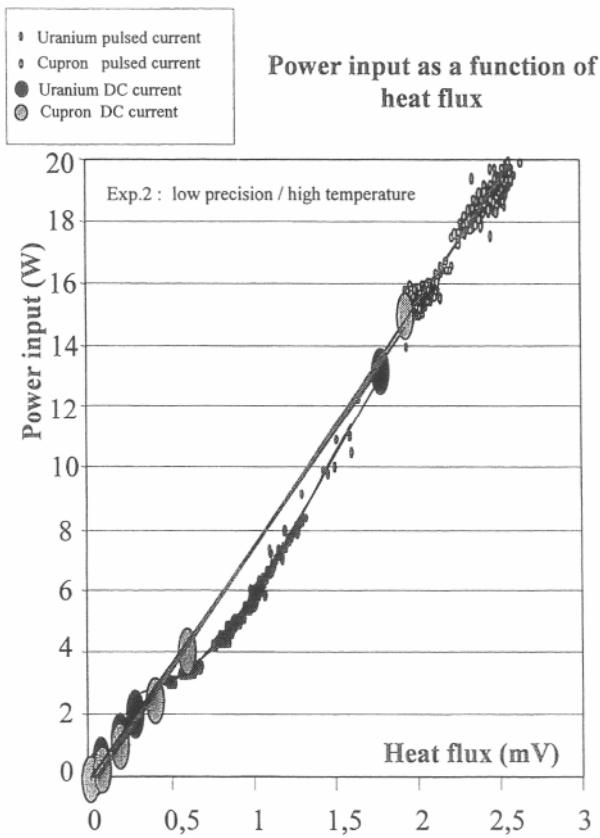**Fig. 5. Excess power measurement with the uranium/high-precision calorimeter.**

Fig. 6. Excess power measurement with the uranium/low-precision calorimeter.

Experiment 2 has been run to its term. There are only a few species present in the experiment:

Number of uranium atoms 3.5×10^{20}
Number of hydrogen atoms 5.4×10^{17}
                                (based on the
                                manufacturer's
                                analysis)
Number of deuterium atoms 8.9×10^{13}
Number of trace element atoms 1.4×10^{17}.

It is interesting to calculate the order of magnitude of the energy of reaction required, when we suppose that it originates from one of the species present. We find the following:

Per uranium atom   0.020 MeV
Per hydrogen atom   13.2 MeV
Per deuterium atom   79.5 GeV
Per "trace element" atom   50 MeV.

From these figures, the excess energy comes neither from some chemical reaction of the uranium (oxidation, for instance), nor from some kind of fusion of the deuterium present. Thus, a reasonable hypothesis is that the energy production comes from a nuclear reaction between hydrogen and uranium (and/or some trace elements). Thus, to understand what happens, we have to look at the trace elements and their variations after activation.
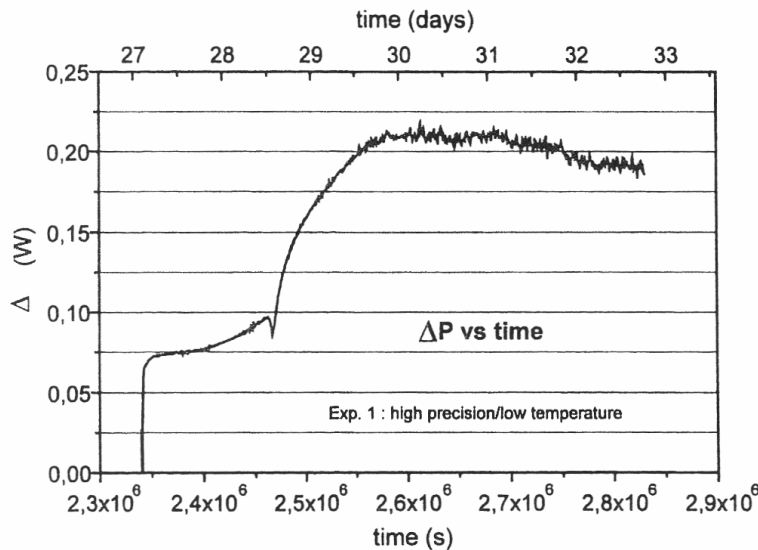

Fig. 7. Excess power as a function of time, measured with the uranium/high-precision calorimeter.

For the new species in the treated samples, Table IV summarizes the variations of the amounts of trace elements, between virgin samples (mean value for 14 samples) and treated samples (mean value for 27 samples). For the treated samples, only elements differing by more than 2σ from the virgin samples were taken into account. Note that these results should be considered as only indicative, because we are averaging experiments with variable excess powers.

Iron was not measured by ICP-MS, due to interference, but is lower than 200 ppm in all samples, with no significant variations between the virgin and treated ones. The ICP-MS trace analysis of the soft steel from which the electrodes are made shows the presence of Cr (400 ppm), Co (100 ppm), Cu (500 ppm), and Zn (86 ppm). To explain the amounts of these elements found in the treated uranium samples (mean uranium samples weight is 300 mg) by pollution from the electrodes, we should find some 100000 ppm of Fe in the treated samples. The actual figure being <200 ppm, we conclude that these elements were generated in the uranium by the treatment.
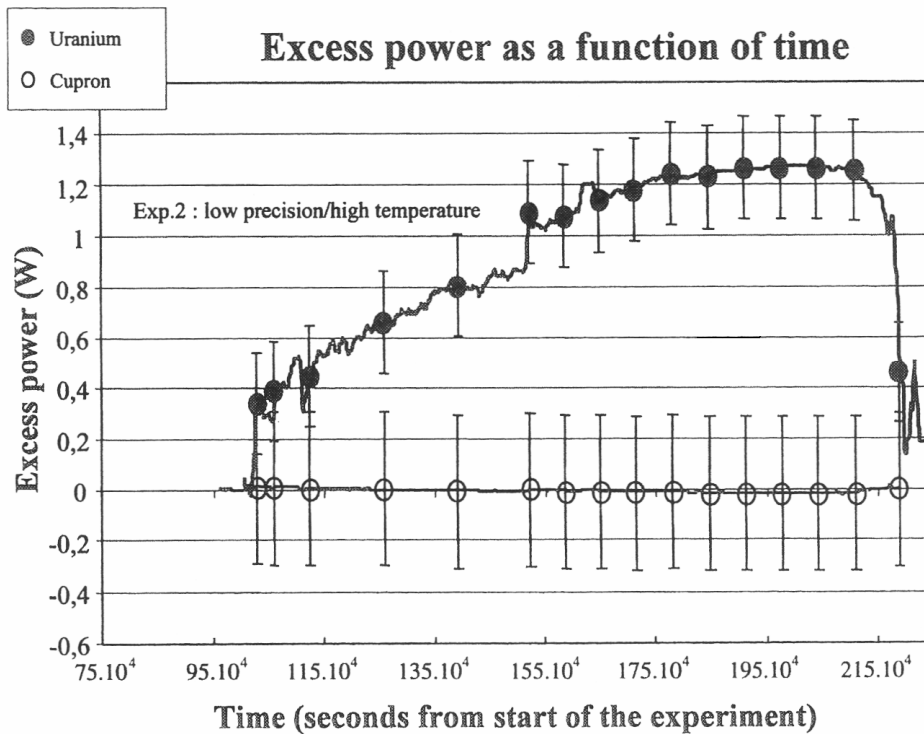

Fig. 8. Excess power as a function of time, measured with the uranium/low-precision calorimeter.

TABLE IV

New Species in Treated Samples in the Uranium Case

Elements	Mean Yields in Virgin Samples, 14 Samples (ppm weight)	Standard Deviation in Virgin Samples	Mean Yields in Treated Samples, 27 samples (ppm weight)
Cr	1	0.9	8
Co	1.5	1	11
Ni	12	2	22
Cu	7	2	18
Zn	9	14	49
Mo	1	0.1	4
La	2	3	7
Pr	1	1	5
Sm	1	1	6
Eu	1	1	36

IV. COMPARISON WITH OTHER EXPERIMENTERS

Our results clearly point to a fissionlike pattern of by-products, which might result from a fissionlike nuclear reaction, triggered by the presence of hydrogen in the uranium lattice. It seems thus interesting to compare our results with those of other experimenters. This was done, with the greatest care and taking into account all information available on these experiments (we, of course, do not have all the information). One can easily distinguish two classes of results in the field:

1. those showing a fusionlike by-product pattern. The conditions and results of these experiments are summarized in Table V (fusionlike experiments).
2. Those showing a fissionlike by-product pattern. They are summarized in Table VI (fissionlike experiments).

IV.A. Comments on Fusionlike Experiments

Three points seem of importance:

1. There is a striking relation (in three experiments[8-10] out of four) between the excess heat and the ^{4}He production. The ratio between these two quantities yields an amount of energy of 32- to 38-MeV per atom ^{4}He produced, indicating a too low ^{4}He production to fit the known energy of the *d-d* fusion reaction (24 MeV). In one experiment,[8] additional ^{4}He was found (after compositional and thermal cycling), yielding a figure of 23 MeV, in very good agreement with the expected value. However, no indication is given on the temperature obtained during the thermal cycling, which is of importance because it is known that at least 800°C are required to expel all ^{4}He trapped in a palladium lattice.

2. Only "small amounts" of ^{4}He were found in a cathode that gave more than 60 MJ of excess energy.[8,11] In the same experiment, high levels of ^{3}He (compared to air) were found and mainly attributed to the decay of ^{3}H initially formed.

3. In an experiment of the same aforementioned type,[5,11] Zn has been detected in significant amounts by neutron activation analysis. The excess energy per atom Zn is high and in the range of fission reactions.

IV.B. Comments on Fissionlike Experiments

Three points seem of importance:

1. The trace elements that appear in the treated sample can be separated into two classes, one comprising elements from Cr to Zn, which is common to all experiments, and the other depending on the metal processed.

2. The excess energy is low for tungsten (0.07 MeV) (Ref. 7) and for nickel (2.7 MeV) (Ref. 6) and high for palladium (67 MeV) (Ref. 1) and uranium (49 MeV) (Ref. 1). In this latter case, it is in the range of fission reactions.

3. The hydrogen consumed in the case of palladium is several orders of magnitude higher than in the case of uranium.[1]

IV.C. Conclusions on the Various Experiments

Although all types of experiments point to nuclear-like energies of reaction, there is a certain apparent incoherence when all the results are put together. Confronted with this situation, we have two options:

1. The first one is to consider that the experimental results in the field are 100% sure and that we have to derive several theories adapted to each experimental case.

2. The second one is to consider that although globally valid, the experimental results in the field need to be improved before we are in a position to derive a correct theory.

We have chosen the second approach. But before suggesting some experimental improvements and analyzing their potential consequences on our understanding of the phenomena, we would like to strongly stress that this approach is usual in science. A positive criticism should by no means be used to argue that all experimental results in the CF/LENR field are wrong! They just have to be improved.

<p align="center">TABLE V</p>
<p align="center">Other Experimenters and the Fusionlike Pattern</p>

	Fusionlike Pattern			
References	Refs. 8 and 9	Refs. 8 and 10	Ref. 8	Refs. 8 and 11
Metal	Palladium	Palladium	Palladium	Palladium
Activation means	Open cell electrolysis D_2O+Pd	Loading of D_2 on Pd/carbon catalyst	Open cell electrolysis D_2O+Pd	Closed cell electrolysis of hollow Pd cathode sealed to contain Pd powder
Calorimetric method	Seebeck calorimetry	Heat flow calorimeter (delta T/Ref + T gradient)	Mass-flow calorimeter	Mass-flow calorimeter
Excess power (maximum) (mW)	50		400	10000
Excess power (mean) (mW)			13	
Ratio in/out (%)				103
Duration of experiment (s)			6.63×10^6	6.4×10^6
Excess energy (J)			85×10^3	6.4×10^7
Elements produced				
^{4}He	1 to 3 ppb	>5200 ppb	300 to 2000 ppb	Small amounts
^{3}He				Significant quantities ^{3}He/^{4}He $= 10^4 \times$ (^{3}He/^{4}He)$_{air}$
^{3}H				10^{15} seams at origin of ^{3}He
Zn				10^{19} (Ref. 5)
Total elements produced			1.4×10^{16}	10^{19}
Energy per elements produced (MeV/atom ^{4}He)	32	32	38	39.3 per atom Zn
Main conclusions	Correlation ^{4}He/excess heat; only 75% of expected ^{4}He	Good correlation ^{4}He/excess heat; only 75% of expected ^{4}He	Good correlation ^{4}He/excess heat; only 62% of expected ^{4}He	Production of ^{3}H and ^{3}He (mainly from ^{3}H)
Theoretical explanation	Refs. 15 through 19			

TABLE VI
Other Experimenters and the Fissionlike Pattern

	Fissionlike Pattern			
References	Ref. 7	Ref. 1	Ref. 1	Ref. 6
Metal	Tungsten	Palladium	Uranium	Nickel
Activation means	High-intensity electrolysis (plasma electrolysis) Open cell W cathode	Ozonizer discharge	Pulsed current + magnetic field through the sample	Electrolysis with thin films of metals on μ-spheres. 1000 μ-spheres
Calorimetric method	Open cell. Isoperibolic calorimeter and flow calorimetry	Mass-flow calorimeter	Seebeck calorimeter	Mass-flow calorimeter
Excess power (maximum) (mW)		10,000	1500	500
Excess power (mean) (mW)		4700	1150	
Ratio in/out (%)	200	106	141	
Duration of experiment (s)		3.4×10^6	10^6	1.1×10^6
Excess energy (J)	10^5	1.6×10^7	1.1×10^6	5.6×10^5
^{4}He				
^{3}He				
^{3}H				
Mg		9.2×10^{17}		
Al	2.7×10^{19}	2.8×10^{17}		
Si	1.3×10^{19}			2.5×10^{17}
P				
S				1.8×10^{16}
Elements produced				
Cl				
Ca	5.8×10^{18}	Not measured	Not measured	
Ti	10^{19}			5.3×10^{15}
Cr	1.6×10^{19}	3.9×10^{16}	1.1×10^{16}	1.2×10^{17}
Fe	2.7×10^{19}	6×10^{16}	Not measured	2.6×10^{17}
Mn				8×10^{16}
Co			1.4×10^{16}	1.9×10^{15}
Ni	1.9×10^{17}	3.2×10^{15}	1.4×10^{16}	Bulk
Cu		1.2×10^{16}	1.5×10^{16}	1.6×10^{17}
Zn	6.9×10^{18}	1.7×10^{17}	5.1×10^{16}	3.8×10^{16}
Ge	9.8×10^{18}			9.3×10^{15}
Se				10^{17}
As				3.9×10^{16}
Mo			2.6×10^{15}	
Pd	2.8×10^{18}			6.7×10^{15}
Cd				8.8×10^{16}
Ag	6×10^{17}			1.2×10^{17}
In	5.7×10^{18}			
Sn				3.1×10^{15}
Te				7.5×10^{15}
La			3.0×10^{15}	
Pr			2.4×10^{15}	
Sm			2.8×10^{15}	
Eu			1.9×10^{16}	
Pb				2.9×10^{15}
Elements consumed H		1.6×10^{22}	5.4×10^{17}	
Total elements produced	8.8×10^{18} (For 1 mg)	1.5×10^{18}	1.4×10^{17}	1.3×10^{18}
Energy per atom trace (MeV/atom)	0.07	67	49	2.7
Main conclusions	Fissionlike products pattern	Fissionlike products pattern	Fissionlike products pattern	Fissionlike products pattern
Theoretical explanation	Ref. 20	Refs. 1 and 19	Refs. 1 and 19	Ref. 17

IV.D. Positive Criticism of the Experimental Results and Suggestions for Future Experiments

From the previous analysis, the following remarks can be made:

1. In a fusionlike pattern experiment, Zn is present as by-product. The energy of reaction is in the range of fission reactions (39 MeV per atom Zn).

2. In the same experiment, ^{4}He production is called "small" with no figure, tending to prove that the ^{4}He production was much lower than expected. This, with other results, tends to prove that the recovery of ^{4}He strongly depends on the "postexperiment" treatment of the metal.

3. Still in the same experiment, ^{3}He and ^{3}H are found, the latter being stated as being the source (by β^- decay) of most of the former. Normally, when a *d-d* fusionlike pattern occurs, even with a strong alteration of the branching ratios (considerable increase of the ^{4}He channel), one should expect the ^{3}He and the ^{3}H channel to be of the same order of magnitude. This is because the splitting of ^{4}He* into ^{3}He + *n* or ^{3}H + *p* is a very fast process (10^{-22} s), involving only the strong nuclear force. For the duration of the experiment (6.4×10^6 s) and the total production of ^{3}H (some 10^{15} atoms), the neutron production should have thus been of some 0.7×10^8 neutrons/s, which should have been easily detected.

4. In fissionlike experiments, the energy of reaction per trace atom formed is in the range of fission reactions for palladium and uranium (67 and 49 MeV, respectively) and much lower for tungsten and nickel (0.07 and 2.7 MeV, respectively).

5. In the experiment with palladium, the hydrogen consumption is several orders of magnitude higher than in the one with uranium (1.6×10^{22}, compared to 5.4×10^{17} atoms).

From these remarks, we would like to suggest the following experimental improvements in the CF-LENR field:

1. to analyze both trace elements and helium in the same experiment as suggested by the aforementioned remark 1
2. to adopt a standard procedure to recover the helium from an experiment (remark 2)
3. to carefully monitor any neutron production during an experiment (remark 3)
4. to adopt activation methods such as used for uranium, that are less prone to pollution than electrolysis, for instance (remark 4)
5. to measure the hydrogen consumption by hydrogen analysis (uranium) rather than from a pressure balance that can be subject to leakage (palladium) (remark 5).

V. POSSIBLE COHERENT EXPLANATION OF ALL EXPERIMENTAL RESULTS

V.A. Preliminary Remarks

There are at least two steps before being able to derive a correct theory in the field of CF and LENR reactions:

1. The first step is a kind of accountant or chemist balance: Put on one side all species entering the overall reaction and, on the other, all species resulting from the overall reaction. This can only be the result of mass balances. We, of course, appreciate the difficulty of such mass balances in the field, especially on main components (metal, hydrogen).

2. The second step is to figure out and demonstrate with the tools used in solid physics (quantum mechanics, mainly), that in a lattice, reactions are possible to explain step 1, that would otherwise be impossible or negligible in a vacuum.
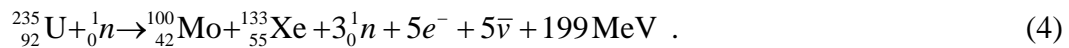
The point where we are now is that most theoretical approaches [13-16] are based on a first step, which is indeed to consider that what happens is a modified fusion reaction of the deuterium present in the experiment. This is of course a perfectly respectable hypothesis for the first step (and of course the simplest one!) provided that it can be firmly experimentally established. (Note that most theoretical methods developed could be easily used to substantiate other first steps.)

A few other theoretical approaches are based on a first step, which is to consider that what happens is a special kind of fission reaction.[17-20]

Finally, we have proposed[1] a first step that involves hydrogen and the nuclei of the lattice, yielding all products observed in CF and LENR reactions, and which we are aiming at definitively proving experimentally.

V.B. Proposal for Another First Step

To start with, we write one of the numerous overall reactions that describe the induced fission of ^{235}U:

$$^{235}_{92}\text{U} + ^{1}_{0}n \rightarrow ^{100}_{42}\text{Mo} + ^{133}_{55}\text{Xe} + 3^{1}_{0}n + 5e^{-} + 5\bar{\nu} + 199\,\text{MeV} \quad . \tag{4}$$

Induced fission was discovered in 1934 by Fermi. The concept of the neutrino was first introduced by Pauli in 1930 and experimentally proven by Reines and Cowan in 1953. So, in fact, a balance as (4) could only have been written many years after the discovery of induced fission.

In the problem we are faced with, we propose to take the reverse approach, that is,
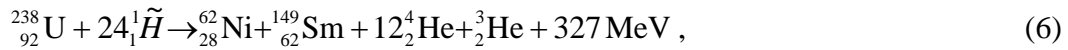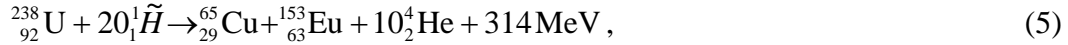
1. write an experimentally proven overall balance
2. give a not yet proven but plausible path for a theoretical explanation
3. accept to be obliged to wait a long time (years, decades ?) for this path (or a similar) to be proven
4. develop, meanwhile, applications that are likely to be socially of great interest.

V.C. Three (Among Others) Possible Reactions, Describing the First Step (Uranium Case)
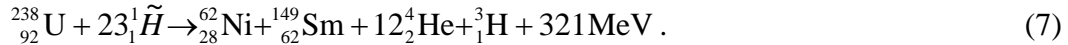
We have observed the following facts in our (and others) experiments:

1. no (or very small) variations of the radioactivity of the treated sample. This indicates the formation of stable products in the great majority of cases.
2. apparition in the treated sample of products in the group Cr, Fe, Ni, Co, Cu, Zn, and Ge. A substantial amount of these products does not come from pollution of the sample (see earlier). Moreover, experiments in Refs. 6 and 7 show significant departures in the isotopic composition of these products.
3. Strong indication of hydrogen consumption (see earlier).
4. presence of Zn in a sample that has also yielded helium and tritium.[5]

We thus write the three following overall balances, which take into account all these observations and are just a result of the requirement for the proton, neutron, and electron balances to be equilibrated:

$$\ _{92}^{238}U + 20\ _{1}^{1}\tilde{H} \rightarrow\ _{29}^{65}Cu +\ _{63}^{153}Eu + 10\ _{2}^{4}He + 314\,\mathrm{MeV}, \tag{5}$$

$$\ _{92}^{238}U + 24\ _{1}^{1}\tilde{H} \rightarrow\ _{28}^{62}Ni +\ _{62}^{149}Sm + 12\ _{2}^{4}He +\ _{2}^{3}He + 327\,\mathrm{MeV}, \tag{6}$$

and

$$\ _{92}^{238}U + 23\ _{1}^{1}\tilde{H} \rightarrow\ _{28}^{62}Ni +\ _{62}^{149}Sm + 12\ _{2}^{4}He +\ _{1}^{3}H + 321\,\mathrm{MeV}. \tag{7}$$

These three reactions are only a few among many possible overall reactions. Note that (6) and (7) should be less frequent than (5) (they depend on the parity of the final products). It is interesting to calculate the number of reactions with energy ~320 MeV, which are required to generate the amount of energy measured in the uranium experiment run with the low-precision calorimeter (1,150,000 J). We find 2.3×10^{16} reactions that correspond (5) to an overall consumption of hydrogen of 4.6×10^{17} hydrogen atoms. The comparison with the amount of hydrogen initially present (5.4×10^{17}) can explain why the reaction came to an end and is a good confirmation of the proposed overall reaction.[5]

A simulation indicates that the products pattern (in atomic percent), of all possible overall reactions, would be something like the following:

^{4}He   85%
Mixture (Fe... Zn, Ba...Eu)   14%
^{3}He + tritium   1%.

V.D. One (Among Others) Possible Reaction, Describing the First Step (Palladium Case)

The following Eq. (8), resulting from proton and neutron mass balances, explains our observations:

$$\ _{46}^{106}Pd + 10\tilde{H} \rightarrow\ _{30}^{64}Zn +\ _{12}^{24}Mg + 7\ _{2}^{4}He + 47\,\mathrm{MeV}. \tag{8}$$

Equation (8) shows the energy of reaction (47 MeV) is higher than the corresponding energy for proton-induced fission reactions (30 MeV).

Reactions such as (5), (6), (7), and (8) are very likely to be impossible with normal hydrogen. This is why we wrote $\tilde{H}$ as the symbol for a hypothetical form of hydrogen that could take part in such reactions. Before proposing a possible candidate for $\tilde{H}$, we shall list a number of its properties that could be of interest:

1. It should be formed under the sole action of the electromagnetic force (coulomb + magnetic) that is a chemical species by nature. In that way, it could naturally be formed in a purely chemical environment (the metal lattice).

2. It should be of nuclear dimension, in order to be able to interact easily with the nuclei of the lattice.

3. It should be electrically neutral at nuclear distances, which is a consequence of the requirement for a nuclear dimension.

4. It should be a resonance (or transient, or metastable species) that is of finite lifetime, requiring energy to be formed and releasing energy when going back to the unbound proton/electron system.

5. The energy of formation should be in the order of magnitude of energies found in the lattice (few electron volts, Fermi energies).

V.E. The Hydrex Hypothesis

It has been shown by a quantum electrodynamics calculation[21] that resonances of long lifetime (seconds), nuclear dimensions (femtometres), and low energy of formation (electron volts) could exist. This concept seems to look like the "shrunken hydrogen atoms" proposed by various authors.[22,23] It is indeed very different in two ways: Being a metastable state, it needs energy to be formed (a few electron volts) and reverts to normal hydrogen after a few seconds, liberating back its energy of formation (it is thus not the source of the energy observed). Its formation can be described as the electron spin-proton nuclear spin interaction becoming first order in the lattice environment (whereas, it is third order in a normal hydrogen atom). A concept similar to Ref. 21, but yielding a stable state has been developed.[24] The corresponding copious emission of X rays that should have been observed to explain the measured energies of reaction were not detected. Note that in Ref. 19 a concept is given of a shrunken atom, solidly based on a plasma dielectric explanation. The high electron concentration, in the swimming electron layer at metal interfaces,[19] invoked to increase the screening factor, could also favor the synthesis of hydrex. Moreover, we consider that the hydrex cannot yield a neutron because this reaction is strongly endothermic. To explain our results we put forward the following working hypothesis: in a metal lattice and under proper conditions, the formation of such resonances (metastable state) could be favored. We propose to call them hydrex, and we assume that they are actually formed in CF and LENR experiments.

V.F. The Action of Hydrex on a Nucleus of the Lattice

Once formed, a number of hydrex could gather round a nucleus of the lattice to form a cluster of nuclear size and of very long lifetime compared to nuclear time (10^{-22} s). They

are likely be polarized by the electrostatic potential of the nucleus. The cluster can thus be described as a nucleus, surrounded at nuclear distance, first by a negative layer (the electrons of all the hydrex of the cluster) and then by a positive layer (the protons of these hydrex). The formation of the cluster would result in all hydrex involved transferring their kinetic energy to the nucleus, which would thus be in an excited state. In this excited cluster, nuclear rearrangements could take place, yielding mainly ^{4}He, nuclei of atomic masses smaller than that of the host metal, and small amounts of ^{3}He and tritium. Because this nuclear rearrangement is a many body reaction, the products formed should be stable products in their ground states, with most of the reaction energy being carried away as kinetic energy by the alpha particles formed. The inevitable excess of neutrons would react with the surrounding hydrex protons to yield mainly ^{4}He and small amounts of ^{3}He and ^{3}H. This last point is a general feature of hydrex catalyzed reactions. It explains why their energies of reaction are always higher than those of the corresponding fission reaction: The energy generated by the combination of the protons of the hydrex with the excess neutrons (resulting from the fission of the nucleus) to yield ^{4}He adds to the energy of fission. In the case of uranium, the energy of the fission reaction is some 200 MeV and the catalyzed fission is some 320 MeV. The corresponding figures for palladium are 30 and 47.
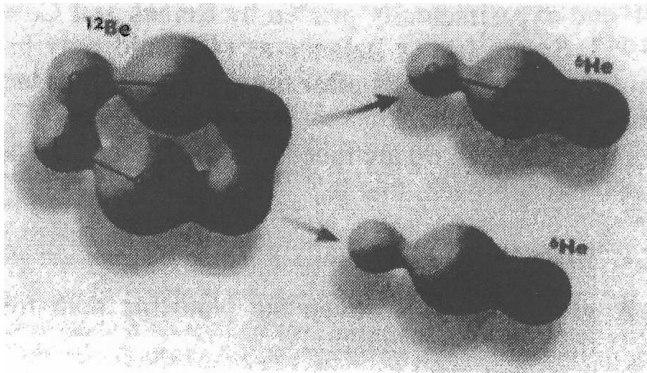

Fig. 9. Common sense picture of excited ^{12}Be.

An indication of the type of nuclear rearrangement that might occur can be speculated from the most recent and proven concepts on the structure of nuclei. Beryllium-12 has been recently experimentally proven to be formed by the association of two alpha particles, bound together by four neutrons.[25] This confirms previous theoretical calculations, pointing to the same structure.[26] Figure 9 (Ref. 27) is a "common sense" illustration of this bound state, which looks very much like a nuclear-molecular state,[28] with the neutrons acting like the covalent bounding of electrons observed in chemical molecules.[25]

We can thus speculate that in its highly excited state in the cluster, a uranium nucleus could evolve into two or three very stable nuclei (one of the group around Fe and one of the group around Eu, or three of the group around Fe), bound by a cloud formed by the excess neutrons of the uranium [see Fig. 10 (Ref. 27)]. The binding neutrons would then react with the surrounding protons of the hydrex, to yield mainly ^{4}He and unbounded stable nuclei.

VI. CONCLUSION

As a conclusion, we would like to propose a strategy to have a clear idea of the first step of CF-LENR reactions. We appreciate the difficulty of achieving a correct mass balance on the main components of the system: the atoms of the lattice and the hydrogen (deuterium). Thus, we propose

1. to process various metal-forming metallic hydrides (palladium, tantalum, uranium, etc.)
2. to measure the variations of the trace elements in the lattice and the production of ^{4}He (^{3}He and ^{3}H)
3. to see whether by recombining the products, the initial nuclei (palladium, tantalum, uranium, etc.) can be reconstructed.

In case of success, this would be a strong experimental proof of the proposed scheme, which could then be called the following: nuclear catalysis with neutron sink.
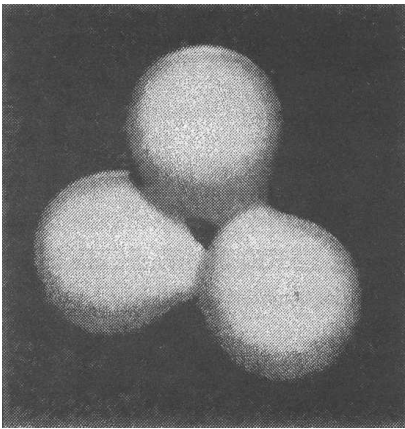

Fig. 10. Possible common sense picture of excited ^{238}U.

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