Hydrogen triggered exothermal reaction in uranium metal

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Abstract

An exothermal reaction has been observed when submitting metallic uranium to the combined action of a magnetic field and an electrical current. The set-up used to study the phenomenon is described and results are given. A tentative explanation is given, based on the possible existence of a still hypothetical proton/electron resonance.

Keywords: Uranium; Magnetic field; Electrical current; Exothermal nuclear reaction; Proton/electron resonance

1. Introduction

We report here results obtained by submitting uranium metal to the combined action of a pulsed electrical current and a magnetic field. We have observed what seems to be an exothermal reaction occurring in the uranium. The magnitude of the exothermicity observed is too high to be explained by any known chemical reaction. We thus present a tentative explanation based on a hypothetical - and purely electromagnetic - resonance proton/electron that could "catalyze" certain nuclear reactions of the uranium nuclides. The protons involved are initially present in the uranium metal we use. The manufacturer indicate an hydrogen content from 3 to 10 ppm weight (metal obtained by magnesium reduction of the oxide). This hydrogen content is a common value for uranium prepared using this method [1]. This tentative explanation is substantiated by the first indications given by the mass spectrometry analysis of the uranium samples obtained in the preliminary experiments.

2. Experimental strategy

Preliminary simplified calorimetric experiments (experiment placed in a box exchanging heat with the air of the laboratory kept at 25°C, heat flux measured by the temperature of the uranium metal), had given indications of an exothermal reaction occurring in the metal. When certain types of currents (pulsed currents) were passed through it and a magnetic field was simultaneously applied, more thermal energy was recovered than electrical energy was put in. The analysis of the treated uranium samples compared to the virgin ones showed the apparition of a significant amount of lead. Moreover, by monitoring the gamma activity of the samples during and after treatment, we observed no important variation of this activity [2].

Given these preliminary results, we thought it was worth looking more in details into this reaction. The strategy we decided to follow has two steps:

- first: improve the calorimetry and master the conditions under which the phenomenon occurs
- second: analyze the treated uranium samples by mass spectrometry (including isotopic ratios) to confirm the apparition of lead we observed in the preliminary experiments, monitor the gamma activity of these samples and test various other metals to compare their behavior to that of uranium.

In parallel, we have tried to find a plausible, but still hypothetical, explanation for the phenomenon.

We have now achieved the first step. We are going to describe the experimental set-up and report the results it yields. We shall also present the hypothetical explanation we propose.

Before that, a brief summary of the preliminary experiments will be given.

3. Summary of the main results of the preliminary experiments

3.1. Thermal effect

Uranium samples (turnings of natural uranium metal) were pressed in a small reactor between two steel electrodes (12 to 16 mm diameter, 10 mm long), themselves placed between two permanent magnets of comparable diameter (remanence around 1 T). The reactor was placed in a tight aluminum box, kept under argon atmosphere and could be heated to the required temperature by a resistor. The heat flux was monitored by the measurement of the reactor temperature. Three preliminary experiments yielded the results summarized in Table 1 when a pulsed current was passed through the uranium.

Table 1
Results of preliminary experiments

Experiment	A	B	C
Mean power due to the reaction (W)	3.8	0.8	1.2
Total energy of reaction during the experiment (kJ)	56.2	129.6	184.4
Reactor temperature (°C)	160-210°C	200°C	170°C
Uranium weight (mg)	545	540	553
Energy of reaction from U processed (MJ/mole U)	24.5	57.1	19.5
Pulsed current intensity (A)	16 to 0 (U oxidation)	15	13

Table 2
Results

Experiment	Ref.	Ref.	A	B	C
Pb content (ppm)	2.1	2.7	156	209	440
Energy of reaction per atom Pb produced (MeV/ Pb atom)	-	-	1.8	3	2

3.2. Mass spectrometry analysis

Uranium samples were dissolved in two steps: uranium react with hydrochloric acid rapidly to form uranium (IV) chloride and a black precipitate of hydrated uranium (III-IV) oxide. Hydrogen peroxide is then added to the solution for a complete dissolution of the precipitate to obtain a clear uranyl chloride solution [3].

The samples were analyzed by ICP-MS. Reference samples exhibit very low lead quantity, whereas samples that had been treated with pulsed current under a magnetic field (sample A, B and C) exhibit a much higher lead quantity. Combining these results with those obtained in the calorimetric measurements yields the Table 2.

It is clear from Tables 1 and 2 that no chemical reaction involving the uranium can explain the observed difference between the energy input and the energy output and that this difference per atom of lead produced point towards a nuclear reaction involving the uranium nuclei.

3.3. Gamma photons registration

Gamma photons emitted by the uranium samples during and after treatment were registered (Ortec germanium detector). We only observed small variations of the samples total activity (up to plus or minus 10% of the initial total activity). Most of the variations are observed on the peaks of the first daughter of the ^{238}U: ^{234}Th. These variations are well above background fluctuations. They are nevertheless hardly compatible with an acceleration of the well known deactivation route leading from ^{238}U to ^{206}Pb, acceleration which could explain the calorimetric results and the lead level we observe (the gamma activity would tremendously increase). This point will be dealt with later.

4. Principle of the improved calorimetric measurements now in use

The observation of the phenomenon was done in the following conditions:

- uranium metal at relatively high temperature – 200°C – without oxidation
- experiment of several days
- a sufficient amount of uranium – more than 500 mg – in order to allow subsequent analysis of the sample by mass spectrometry
- the passage of a high electrical current: 15 A
- the presence of a high magnetic field: 1 tesla

This precludes the use of classical calorimetric methods as for instance currently available Calvet or Seebeck calorimeters (whether the total heat flux is measured by thermocouples or by the Seebeck effect of a semiconductor). The experiment indeed requires a minimum volume of 500 cm^3 and we do not have such equipment in the lab.

We have thus been compelled to develop an alternative approach, adapted to the required conditions for the phenomenon to be observed and presenting a sufficient degree of reliability. The principle of the calorimetric measurement is to compare the thermal effect of a pulsed current versus the thermal effect of a direct current. Fig. 1 is a description of the overall experimental set-up.
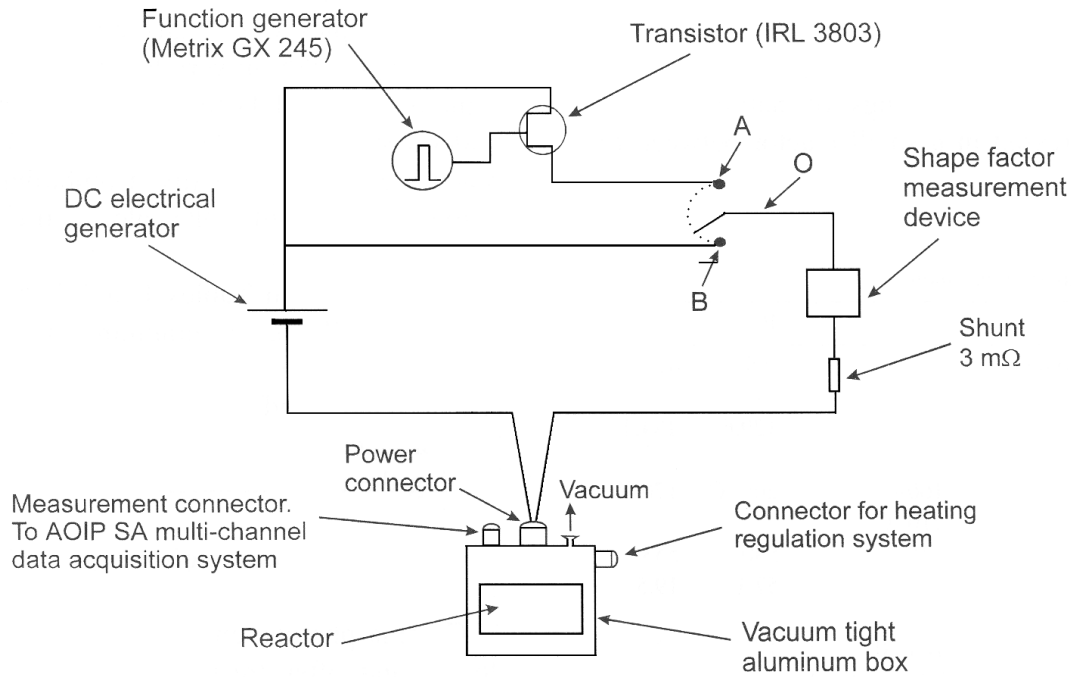

Fig. 1. Description of the experimental set up.

4.1. Principle and description of the electrical measurements

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

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

where $\langle U \rangle$ and $\langle I \rangle$ are the root-mean-square (rms) values of the tension and the intensity.

$P = \langle U \rangle \cdot \langle I \rangle$ if there is only pure resistance in our experimental device. $\langle U \rangle \cdot \langle I \rangle$ appears to be an upper limit of the dissipated power. We decided to neglect any possible non-resistive component of our experimental device. Thus, the dissipated power we consider is a maximum value of the real dissipated power.
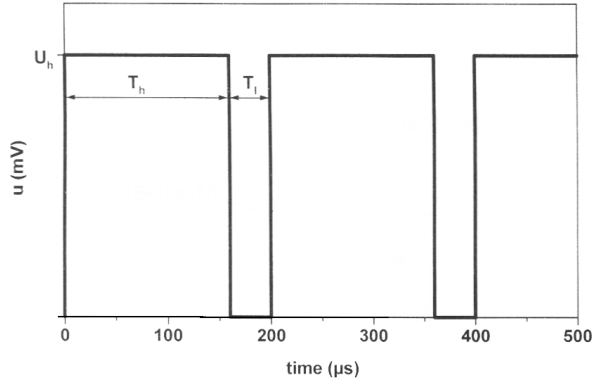
Fig. 2. Shape of the pulsed current.

The AOIP SA multi-channel data acquisition system we use is designed to measure the tension (or the intensity) of a direct current. With a pulsed current (Fig. 2) the given value is the mean one:

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

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

$$\overline{U} = \frac{T_h}{T_h + T_1}\cdot U_h \; , \tag{1}$$

$$\langle U \rangle = \sqrt{\frac{1}{T_h + T_1}\int_0^{T_h + T} u^2(t)\,\mathrm{d}t}$$

$$= \sqrt{\frac{T_h}{T_h + T_1}}\cdot U_h \; , \tag{2}$$

From Eqs. (1) and (2) we have

$$\langle U \rangle = \sqrt{\frac{T_h + T}{T_h}\cdot \overline{U}} \tag{3}$$

and

$$\langle I \rangle = \sqrt{\frac{T_h + T}{T_h}\cdot \overline{I}} \tag{4}$$

Thus

$$P = \frac{T_h + T}{T_h}\cdot \overline{U}\cdot \overline{I} \tag{5}$$

$f=(T_h+T_l)/T_h$ is a factor, which depends on the shape of the pulsed current. In order to access this shape factor, we measure the thermal flux out of a thin film non-inductive resistor in line with the experimental device. The resistor was put in a cubic aluminum box. On each side of the box there is a thermoelectric generator that utilizes Seebeck effect. The six thermoelectric generators are in line and we measure the voltage $V_{Seebeck}$. This simple calorimeter is calibrated with direct current, we obtain a correlation $V_{Seebeck} = A \cdot \left(\overline{U}_r \cdot \overline{I} \right)_{DC} + B$. Then we infer the shape factor f from the response of this calorimeter, from the measured $\overline{U}_r$ the resistor voltage and from $\overline{I}$ when we use a pulsed current.

4.2. Description of the experimental device

A DC electrical generator delivers electrical power into a reactor containing the uranium metal. The electrical power is delivered either in the form of constant direct current, through connection OB or in the form of pulsed current through connection OA. The pulsed current is shaped by the action of a transistor (International Rectifier Power MOFSET type IRL 3803), which is triggered by a function generator (Metrix GX 245) (Fig. 1).

Natural uranium metal turnings (3 mm width, 0.1 to 0.3 mm thick and cut into pieces of about 10 mm length) are placed between two cylindrical iron electrodes (16 mm diameter), according to Fig. 3. The first electrode is 9 mm long and the second 22 mm (central electrode, with a 10 mm hole in its center). A third electrode, identical to the first one is placed in contact with the central electrode. Two wires are fixed by solder on electrodes 1 and 3, allowing electrical current to be passed through electrode 1, the uranium turnings, the central electrode and electrode 3. Three wires allow the measure of U_U and U_{RE}. Two identical magnets (10 mm length, 15 mm diameter are placed in contact with electrodes 1 and 3 in such a way that they generate, through the uranium and the electrodes, a magnetic field parallel to the axis of the electrodes. They are made from cobalt/samarium, have a magnetic remanence of 1 T and can withstand 300°C without loosing their magnetism. Three temperature sensors (Pt 100) are placed in the central electrode: two at each ends, in two 3 mm diameter holes bored at 4 mm from the two edges of this electrode, and one in the central, 10 mm diameter hole and measure respectively T_U (temperature of the uranium side), T_{RE} (temperature of the reference resistor side) and T_{reg} (regulation of the temperature level of the experiment).
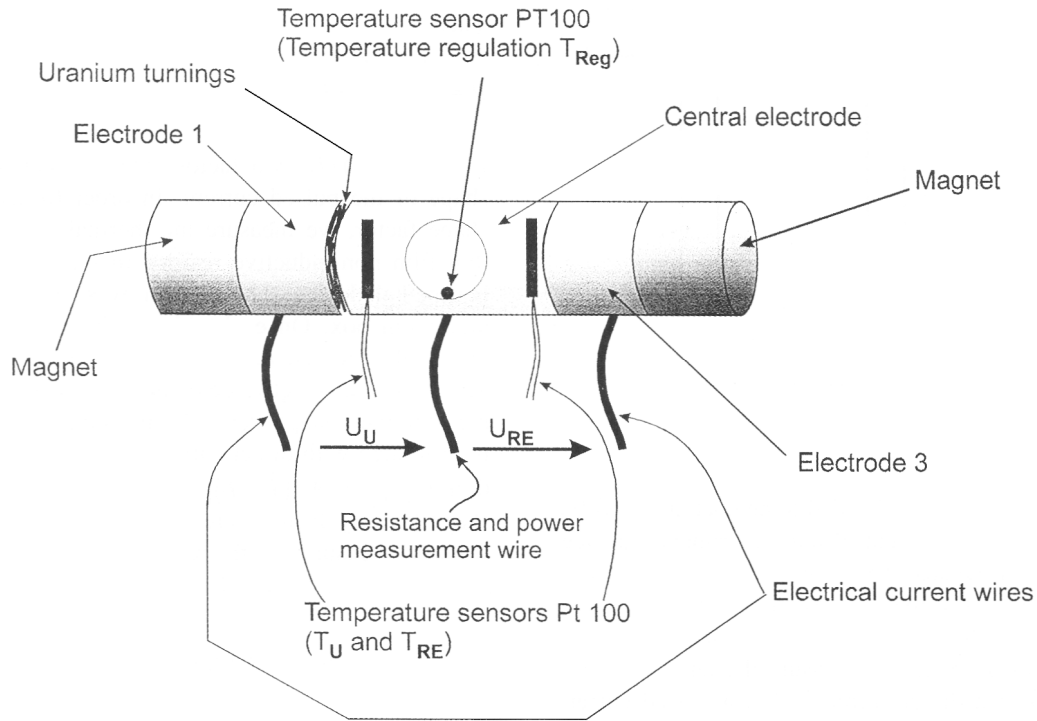
Fig. 3. Reactor.

The three electrodes and the two magnets are enclosed in two identical aluminum cylinders acting as a regulated heater (see Fig. 4). Each cylinder is 50 mm diameter and 40 mm long. A hole in the cylinders allows the exit of the wires connected to the electrodes. Four heating cartridges 76 mm long and 6.3 mm diameter (RS component) are introduced in four holes bored through the aluminum cylinders and heat them in a regulated way (Auto-tune temperature controller CAL 9400, delivering electrical power to the heating cartridges from a DC generator on a zero/full power basis). The two aluminum cylinders are pressed against the ends of both magnets by the action of four bolts, parallel to the four heating cartridges (and not represented in Fig. 4).

The whole assembly is finally placed in a vacuum tight 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 multi-channel data acquisition system that monitors the experiment. The box is kept under vacuum (5 to 10 Pa) by the action of a vacuum pump. Under these conditions, the oxidation of the uranium sample is controlled at a very low rate for periods of several days and temperatures of the heater up to 200°C.

The differential power measurement device functions as follows:

- the temperature of the heater is set at a given value T_{reg} (generally around 200°C). Preliminary measurements have shown that $\Delta T = T_U - T_{RE}$ varies slowly when increasing T_{reg} from ambient to 170°C and remains constant above 170°C up to 220°C. Let $(\Delta T)_0$ be the value of ΔT when the heater has reached its preset value T_{reg}. The mean power dissipated by the heater to maintain T_{reg} at 200°C is typically around 60 W.

- a direct current is then passed through the three electrodes. The resistance R_U of the contacts steel / uranium turnings / steel is typically between 5 and 15 mΩ and the corresponding resistance R_{RE} of the reference contact resistance steel / steel between 2 and 5 mΩ. The Joule power $W_U = \langle U \rangle \cdot \langle I \rangle = f \cdot \overline{U}_U \cdot \overline{I}$ on the uranium side is thus higher than the Joule power $W_{RE} = \langle U_{RE} 0 \rangle \cdot \langle I \rangle = f \cdot \overline{U}_{RE} \cdot \overline{I}$ on the reference side and ΔT increases. The intensity of the direct (or pulsed) current we use is limited to 15 A. The power injected in the electrode system is thus limited to less than 6 W, which is a small fraction of the power required to maintain the heater at 200°C. The joule effect is thus a perturbation of the total heating and the relative temperature difference $\Delta T - (\Delta T)_0$ is a linear function of the difference $\Delta P = W_U - W_{RE}$:

$$\Delta T - (\Delta T)_0 = K \cdot \Delta P \tag{6}$$

K is essentially determined by the geometry of the electrodes and by their thermal conduction properties (the experiment being under vacuum, the main heat transfer mechanism is conduction). This relation has been checked experimentally to be very accurate.

If an exothermal reaction, yielding a power P_E, takes place in the uranium, relation (6) is no longer valid and is replaced by:

$$\Delta T - (\Delta T)_0 = K \cdot (\Delta P + P_E) \ . \tag{7}$$

We measure K when passing direct currents of various intensities in the electrodes. In all our experiments, we have observed that when plotting ΔP versus $\Delta T - (\Delta T)_0$ we obtain a very good linear relation:

$$\Delta P = K^{-1} \cdot (\Delta T - (\Delta T)_0) \ . \tag{8}$$

If we switch to pulsed currents (without changing the experimental set-up) the points obtained are systematically on the right side of this straight line as explain on the scheme Fig. 5. We can calculate P_E from the measurements of W_U, W_{RE} and $\Delta T - (\Delta T)_0$ when passing the pulsed current and the correlation obtained when passing the direct current:

$$P_E = K^{-1} \cdot (\Delta T - (\Delta T)_0) - \Delta P_{pulse} \ . \tag{9}$$

Remark. Two second order corrections have to be taken into account to get precise measurements:

- Due to small modifications in the heating power of the cartridges, we observe a small and continuous drift of $(\Delta T)_0$ during the course of an experiment (0.03 to 0.07 K/day). We measure this drift and accordingly correct the temperature differences.
- Both resistance R_U and R_{RE} vary slowly with time. When this variation is too fast, $\Delta T - (\Delta T)_0$ is somewhat lagging behind ΔP, resulting when ΔP increases during the calibration with direct current, in an under estimation of the power injected

given by (8). In order to be on the safe side, we eliminate these points from correlation (8), which represent 5 to 10% of the points.
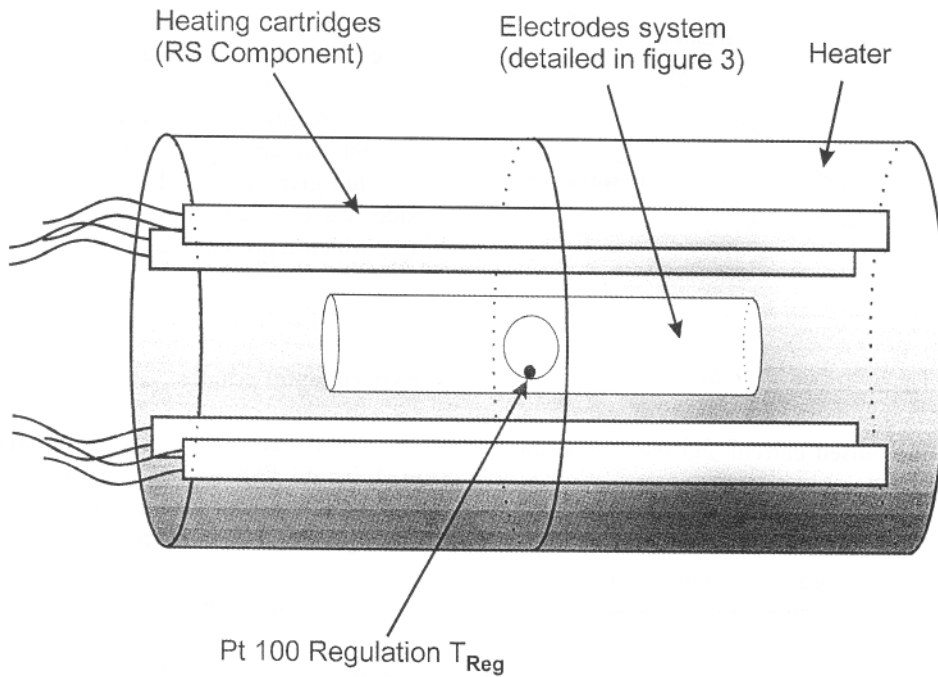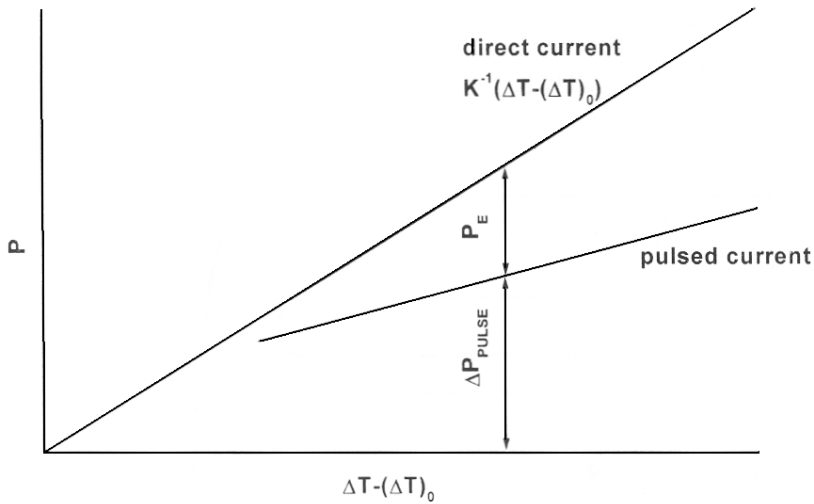

Fig. 4. Reactor heating system.

Fig. 5. P versus ΔT-$(\Delta T)_0$.

5. Experimental results

We report here the results of an experiment run with uranium. 788 mg of uranium turnings were placed in the reactor and the experiment was run according to the following protocol.

5.1. Experimental protocol

The following operations are run in sequence.

- Measurement of $(\Delta T)_0$. The heater is heated at four temperatures (T_{Reg} = 170, 190, 200 and 210°C), to check the absence of variation of $(\Delta T)_0$ with T_{Reg}. $(\Delta T)_0$ is taken at the temperature of the experiment (around 200°C). Duration 24 h. The temperature of the reactor is then set at T_{Reg} = 200°C.
- Calibration of the shape factor measurement device. A direct current (three intensities: 5, 10 and 15 A) is passed through the experimental set-up (Fig. 2, contact OB closed). Duration 36 h. This yields a relation (10) between $\left(\overline{\overline{U}}_r \cdot \overline{I}\right)_{DC}$ and V_{Seebeck}. A linear relation gives a correlation coefficient higher than 99%.

$$V_{Seebeck} = A \cdot \left(\overline{\overline{U}}_r \cdot \overline{I}\right)_{DC} + B \qquad (10)$$

- Establishment of the relation between ΔP and $\Delta T - (\Delta T)_0$ when a direct current is passed through the metal under test (baseline of the experiment). This is done at the same time as the calibration of the shape factor measurement device and yields relation (3). A linear relation gives a correlation coefficient higher than 99%.
- Determination of the drift of $(\Delta T)_0$ with time. The DC current is cut and $(\Delta T)_0$ is measured at T_{Reg} = 200°C
- Effect of the pulsed current on the metal under test. The contact OB is switch to OA and kept in this position for several days.
- Determination of the drift of $(\Delta T)_0$ with time. The pulsed current is cut and $(\Delta T)_0$ is measured at T_{Reg} = 200°C.
- Back-checking of relation (3) and (10). The direct current is switched on again (contact OB closed) and various intensities are passed through the experimental device to yield an f factor calibration curve and a baseline of the experiment extending on both sides of the results obtained with the pulsed current (see below).
- Determination of the drift of $(\Delta T)_0$ with time. The DC current is cut-off and $(\Delta T)_0$ is measured at T_{Reg} = 200°C.

5.2. Presentation of the results

Fig. 6 shows how the measured ΔP varies as a function of the $\Delta T - (\Delta T)_0$ measured.

For direct current, the experimental points fall (with a correlation coefficient better than 0.99) on a straight line. The corresponding coefficient K^{-1} of relation (3) is 989 mWK^{-1}.

The situation is different when pulsed current is passed through the uranium. All points fall on the right side of correlation (3), indicating that the power P_E of an exothermal reaction occurring in the uranium is added to the power generated by the Joule effect in it.

We can then use relation (9) to calculate P_E and consider its evolution with time. Fig. 7 shows this evolution. It can be seen from this graph that:

- P_E is about zero (mean value – 10 mW, standard deviation 15 mW), when a direct current is passed through the uranium (before and after the pulsed current is passed through it).
- P_E is continuously increasing from some 50 mW to nearly 900 mW, when a pulsed current is passed through the uranium sample.
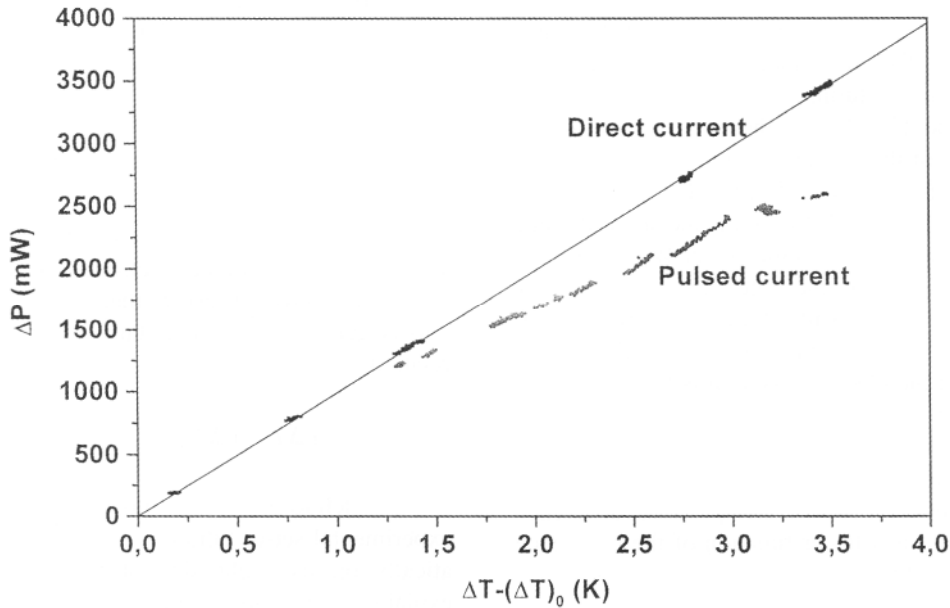

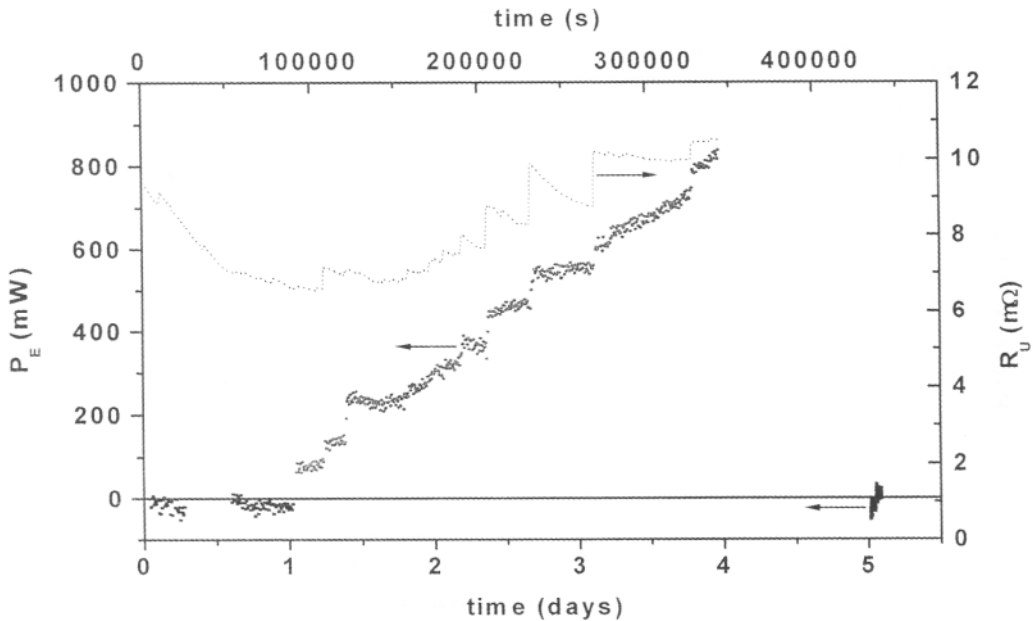**Fig. 6. Experimental results (P versus ΔT - $(\Delta T)_0$).**

Fig. 7. Experimental results (P_E and R_U versus time).

5.3. Discussion of the results

We now discuss some possible trivial explanations of these results:

- Effect of the shape factor f. We find for relation (10) the following coefficients: $A = 110.5$ mV/W and $B = 21.9$ mV. From these values, we can calculate the shape factor as

$$f = \frac{\left(V_{Seebeck}\right)_{measured}}{\left(V_{Seebeck}\right)_{from(10)}} \quad .$$

  Over the whole duration of the experiment, the following mean values were obtained $f = 1.00$ (standard deviation 0.004) for the periods when direct current was passed and $f = 1.30$ (standard deviation 0.009) when pulsed current was passed. From these figures, we can conclude that the properties of the transistor that shapes the pulsed current have not varied significantly during the experiment. Moreover, the shape factor f is very close to the theoretical one (1.29) calculated from the T_1 and T_h used in this experiment. The variations of f are thus second order, whereas the ratio $P_E(W_U+W_{RE})$ is continuously increasing from 0 to 28% during the experiment (as can be seen in Fig. 8). This second order variation cannot thus account for this result.

- effect of the variations of the resistance of the uranium. As can be seen in Fig. 7, the resistance of the uranium has varied during the experiment. Periods of stability of this parameter are found for instance between day 3 and day 4, when P_E continuously increased. This increase cannot thus be attributed to the lagging of $\Delta T - \left(\Delta T\right)_0$ behind ΔP. In the period day 2 to day 3, the resistance of the uranium has increased twice abruptly. It can be seen in Fig. 7 that P_E has also increased sharply but has come back to the general trend of P_E after the subsequent decrease of the resistance.

From these considerations, we conclude that no trivial explanation can account for the observed value of P_E. This value is of an order of magnitude comparable to what we observed in our preliminary experiments and justifies the strategy we have chosen.
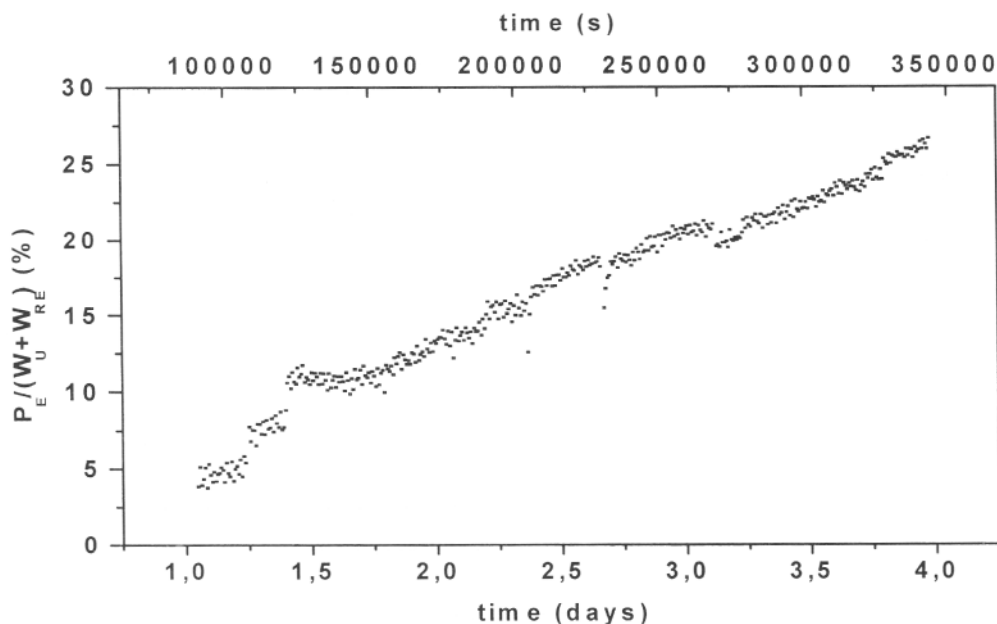
Fig. 8. Experimental results ($P_E/(W_U + W_{RE})$ versus time).

6. A possible and hypothetical explanation of these results

We give here a possible *but still hypothetical* explanation of the phenomenon we observe and this for two reasons:

- we use this explanation as a guideline for our experiments.
- it might thus help the reader to understand our approach.

We assume the possibility of the existence of a resonance between a proton and an electron, yielding a particle of almost nuclear dimensions (a few fm) and we examine the possible consequences of the existence of such a particle.

The hydrogen atom is one of the best known objects of physics and its properties can be completely calculated up to the third order interactions (hydrogen hyperfine structure). This last interaction results from the effect of potentials, which are very strong at very short distances of the electron from the proton, but are only third order when averaged on the whole volume of the atom (magnetic interactions between the proton and the electron, described by the hyperfine structure Hamiltonian).

The question has been raised [4,5] whether this interaction could yield a much smaller object than the known hydrogen atom. In such an object, it would of course be first order on the whole interaction volume.

A quantum electrodynamics calculation was performed on the proton/electron system [6,7], pointing to the possibility of the existence of a resonance (life time of a few seconds, dimensions of a few fm and an endothermic energy of formation of a few eV). This resonance has been proposed to explain some hypothetical nuclear reactions [8,9].

We assume the existence of this resonance (which for simplicity of language we propose to call hydrex: ${}_{1}^{1}\widetilde{H}$. We guess some of its properties and use them to improve its

synthesis and explain how it could act on nuclei to "catalyze" certain classes of nuclear reactions.

6.1. Main properties of hydrex that can reasonably be imagined

- The magnetic moment of the electron should have the same direction as the nuclear moment of the proton (probably parallel in the ground state and antiparallel in excited states).
- Hydrex can be polarized in the high electrical field of a big nucleus (it could even be a small permanent electrical dipole).

6.2. How do we try to improve the synthesis of hydrex

We start from protons enclosed in a dense medium (metallic hydrides where they have a high mobility) and favor their collisions with the conduction electrons by passing an electrical current through the hydride. As we think that these collisions are more efficient to form hydrex if the magnetic moments of the two particles have the same direction (whether they are parallel or antiparallel) we apply to the metallic hydride a magnetic field (of intensity as high as possible) having the same direction as the current. Note that contrary to the situation in vacuum, the protons and the electrons are submitted to potentials due to the lattice that could also favor the formation of hydrex.

6.3. How hydrex, when formed, could "catalyze" certain nuclear reactions

Hydrex as we imagine it, is an electric dipole with almost nuclear dimensions. It can thus be attracted by a uranium nucleus. Perhaps, one uranium nucleus and several hydrex could form a cluster, with a lifetime on the order of seconds, which is considerably higher than typical nuclear time (10^{-22} s). Thus, in this nuclear cluster, unusual nuclear reactions could take place. Let us now examine two of them:

- Hydrex assisted α emission: the presence of several polarized hydrex in contact with an uranium nucleus can modify its Coulomb barrier. Simple calculations, using a layer model, have shown that the initial barrier (height 32 MeV, thickness some 50 fm) could be split into two barriers: a first one close to the uranium nucleus with same height, but much thinner (some 5 fm), followed, after a potential well, by a second one of smaller height (15 to 17 MeV) and thickness 35 fm (the level of the potential well depends on the number of hydrex in the cluster). Since the works of Gamow, Gurney and Condon in 1928, it has been well known that the probability of alpha emission of a nucleus can vary considerably with small variations of the height and thickness of the Coulomb barrier [10]. We thus think that the rate of alpha emission of the ^{238}U can be considerably increased in our experiment due to the formation of the hydrex/uranium clusters [2].
- ω emission of the uranium: this is a reaction with no classical equivalent, that could explain the absence of tremendous increase of the β^- emission that should be observed after an increase of the rate of the α emission. The first daughter of ^{238}U is ^{234}Th, which decays into ^{234}Pa through β^- emission (1/2 life time 24 days). In the hydrex/uranium cluster, 2 neutrons of the uranium could react with 2 hydrex, to yield ^{232}Th and ^{4}He according to the reaction:

$$^{234}_{90}\text{Th} + 2^{1}_{1}\tilde{\text{H}} \xrightarrow{\quad\omega\quad} {}^{232}_{90}\text{Th} + {}^{4}_{2}\text{He} + 17.3 \text{ MeV}$$
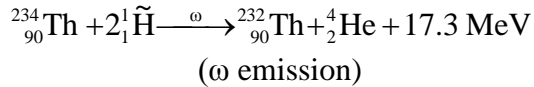
(ω emission)

The combination of these 2 types of reactions could give a route from uranium to lead without β^- emission.

7. Perspectives and conclusion

The improved calorimetric device that we have developed confirms our preliminary experiments. The level of the power liberated in the uranium by the exothermal reaction that we measure with the new device compares well with what we found previously: 0.9 W versus 3.8, 0.8 and 1.2 W. Moreover, the oxidation of the uranium can be controlled, provided the vacuum of the experiment is of good quality.

We thus have planned a series of experiments to:

- measure the lead content of the uranium after treatment (including isotopic ratio) and compare this level with the energy liberated by the exothermic reaction.
- test other metals to see if similar phenomenon are observed with them.

References

1. P. Pascal, in: Nouveau traité de chimie minérale, Tome XV, Masson, Paris, France, p. 159.
2. J.J. Dufour, J.H. Foos, X.J.C. Dufour, ICCF7 Proa, ENECO, Salt Lake City, USA, pp. 113-118.
3. R.P. Larsen, Anal. Chem. 31 (1959) 545.
4. A.O. Barut, J. Kraus, J. Math. Phys. 17 (1976) 506.
5. A.O. Barut, G. Craig, Physica A 197 (1993) 275.
6. J.R. Spence, J.P. Vary, Phys. Lett. B 254 (1991) 1.
7. J.R. Spence, J.P. Vary, Phys. Lett. B 271 (1991) 27.
8. F.J. Mayer, J.R. Reitz, Fusion Technology 20 (1991) 367.
9. R. Antanasijevic, I. Lakicevic, Z. Marie, D. Zevic, A. Zaric, J.P. Vigier, Phys. Lett. A 180 (1993) 25.
10. J. Foos, in: Manuel de radioactivité à l'usage des utilisateurs, Formascience, Orsay, France, pp. 25-33.