Note on the possibility of low-energy nuclear transmutations

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With the passage of time, the experiments of Pr Focardi [1] appear crucial for the excess energy observed when certain metals, and in particular nickel, are confined in gaseous hydrogen at high temperature.

Let us recall the results:

Experiment A: The rated excess power is: 38.9 +/- 1.5 W, for a temperature approximately 700 K (430°c), with a stainless steel bar (ÿ = 5 mm, l = 90 mm) covered with a thin layer of nickel approximately 0.1 mm thick, for electrolytic deposit. With a mass of nickel of about 1.3 grams, the specific power is estimated at 30 W/g.

Experiment B: A nickel rod of the same dimensions is used under conditions similar. The excess power is less: 23.0 +/- 1.3 W, despite a much larger mass of nickel.

From these two experiments, it can be deduced that the excess energy comes from a thin layer, on the surface of the samples, and must be linked to the charge ratio, in number of atoms, rc = H/Ni, produced in this layer. This charge ratio is probably optimal in experiment A, whereas in experiment B, the diffusion of hydrogen in the mass of nickel decreases the charge ratio at the surface of the bar.

A specific power of 30 W/g, i.e. for approximately 1022 atoms of Ni, cannot come from atomic phenomena, which leads to seek a nuclear origin by involving LENR (Low Energy Nuclear Reaction) . The radiation measurements around the experiments have never been significant, so there remains the hypothesis of transmutation of nickel into copper, after capture of a proton, it was put forward by Pr Focardi and Rossi [2]. This transition is exo-energetic but comes up against strong objections, the main one being the Coulomb repulsion. Indeed, the Coulomb barrier, of the order of 6.7 MeV, appears impassable for protons whose energy, due to thermal agitation in solid nickel, is at most of the order of 0.2 eV .

Several hypotheses have been considered for the circumvention of the Coulomb barrier. One of the most interesting is that of Yeong Kim [3], it involves bosons which, according to the Bose-Einstein statistics can associate, the Pauli exclusion principle does not applying more. The even isotopes of nickel (Z even and A even) are composite bosons: 0+, spin number = 0 and even parity.

But, instead of uniting like Yeong Kim, protons between them and then associating them with the even isotopes of nickel, we will consider that neutral hydrogen, ie the proton with an electron in the Böhr orbit, is a composite boson. The ½ spins of the proton and the electron have two possibilities of association, either antiparallel with s = 0, or parallel with s = 1. There is therefore a possibility of association of the even isotopes of Ni, 0+, with l neutral hydrogen with spin number s=0. When s = 1, the energy of the electron is very slightly higher than the energy of the electron when s = 0. The transition s = 1 ÿ s = 0 is responsible for the line at 21 cm from hydrogen (Harold Ewen, Franck Purcell).

A crystal lattice is seen as a stack of spheres representing atoms, the interstices between the spheres can be occupied by hydrogen in the form of ions. They have geometrically defined positions, the octahedral and tetrahedral sites, which depend on the arrangement of the crystal lattice: face-centered cubic like nickel, cubic
centered, compact hexagonal, etc. Octahedral sites are less narrow than tetrahedral sites, and their occupation leads to less mechanical stress in the crystal lattice. It is assumed that they are occupied in priority and preferentially, compared to the tetrahedral sites. In the event that the octahedral sites are all occupied, the H/Ni charge ratio, in number of atoms, is equal to 1, i.e. there is equivalence between the number of ions and the number of nickel atoms. During the diffusion of hydrogen, the movement of the ions takes place in leaps, going from one site to another vacant site. The movements are accelerated by the thermal agitation resulting from a rise in temperature.

Assuming preferential directionless emission from the occupied octahedral sites, the ions can head towards a lattice atom. The reconstitution of a neutral hydrogen atom thanks to an electron taken from the conduction band allows the formation of a boson which, if it has spin = 0, has no orientation in space. It is comparable to 10-11 m. The boson of a sphere of radius equal to the radius of the Böhr orbit, that is rB
= 5.29. spin = 0, corresponding to an even isotope of the nickel nucleus, has very restricted dimensions

of the nucleus, that is a radius of 4 to 5.10-15 m, negligible compared to the radius rB of the Böhr orbit. Two bosons with spin 0 are independent with respect to rotations in space and, with respect to the crystal lattice, a change of position between a nickel nucleus and a neutral hydrogen atom should therefore be of no consequence. The association cross section of these two bosons is then equivalent to: ÿ .(rB)^{2} .

At the time of boson association, the proton is at distance rB from the nickel nucleus and its immediate capture cannot be envisaged. We arrive at a configuration where the nickel nucleus is on the periphery of the entity represented by the neutral hydrogen atom. The procession electronics of the nickel nucleus is not concerned by the association of bosons but the constituent electron of the neutral hydrogen boson has a role to play. Indeed, it does not appear impossible that it is interposed for a very short time between the proton and the nickel nucleus. Taking into account the speed ve of the electron on the Böhr orbit, this time is of the order of 2 . RN / ve , RN is the radius of the nickel core. With ve = ÿ. c, c being the speed of the light, and ÿ = 1/137.036, the inverse of the fine structure constant, we obtain the velocity ve = 2.188.106 m. s^{-1}, which leads to an interposition time of less than 10-20 seconds incompatible with the estimated power-to-weight ratio.

The neutral hydrogen boson is animated by a speed function of the thermal agitation. This speed, or vp, corresponds approximately to that of the proton which holds most of the mass. A time interval, namely: ÿt = rB / vp , is therefore necessary for the proton to reach the nickel nucleus. We are led to consider that following the association of the bosons, the Coulomb repulsion is neutralized during the time ÿt. This repulsion should however be all the stronger as the distance to the nucleus decreases, unless the electron remains
intercalated between the proton and the nickel nucleus. The positive electric charge of the nickel nucleus can brake the motion of the orbital electron. The phase agreement between the Louis de Broglie wave and the frequencies of the constituents of neutral hydrogen is no longer respected. The constraint to stay on the base orbit with the quantum number n = 1 no longer exists, the electron and the proton become free particles and form a couple [p+e-]. The electron tends to stay near the positive charge of the nickel nucleus. The proton, animated by the speed vp can approach the electron by traversing the radius rB during the time ÿt.

In this eventuality, the pair [p+e-] behaves like a neutron although it cannot be a neutron since there is a mass defect corresponding to 0.782 MeV. To give an image, the couple [p+e-] is comparable to a Trojan horse. It allows the proton to cross the potential barrier and thus come within range of the nuclear forces of the nickel nucleus. The electron is not a nuclear particle, so it is rejected or at least, according to the principle of indistinguishability, an electron is expelled by the compound nucleus resulting from the absorption of the couple [p+e-] for a short instant. A transmutation, after capture of the proton, makes it possible to have a surplus of potential energy transferred to the expelled electron in the form of kinetic energy. In this process, there is an incoming electron and an outgoing electron, so the lepton number is preserved.

Conversely, if there is no interposition of the electron, the association of bosons breaks up and the neutral hydrogen is diffused. This event probably accounts for the vast majority of interactions.

The process envisaged for the capture of a proton goes through a chain of events, some of which seem difficult to carry out. Each step of the process is conditioned by the occurrence of the previous event to which a probability can be attributed. The realization of the process will therefore be represented by a product of probabilities.

In a crystal lattice, the basic element is the unit cell for which we can define the number and position of the nuclei and of the sites capable of hosting the hydrogen ions. For nickel, with a face-centered cubic crystal lattice, the unit cell has 4 nuclei (8 at the corners of the cube, counting as 1/8, and 6 at the center of the faces counting as ½), 4 octahedral sites, plus 8 tetrahedral sites. Only the 4 octahedral sites are considered since they are supposed to be occupied in preference to the tetrahedral sites. There is 1 octahedral site in the center of the cube and 12 sites on the edges counting for ¼, making a total of 4 sites. The optimal charge ratio, in number of atoms, is then: H/Ni = rc = 1.

The calculation of the probabilities is carried out for a cell of which all the octahedral sites are occupied, that is to say for rc = 1. This is an optimal configuration which seems difficult to ensure during an experiment. With rc < 1, it is possible to weight the resulting reaction probability by rc, but this process is not always justified because the distribution of occupied sites within a large network is random with the possibility of occupation of tetrahedral sites.

For each step of the process, the elementary probability is detailed below:

1) – ps : probability that a neutral hydrogen atom has a spin number = 0.

We retain the hypothesis of equiprobability for the realization of s = 0 or s=1, which leads to ps = ½, although the lowest energy configuration with s = 0 is arguably slightly more likely

2) – pG : geometric probability.

This is the probability that, starting from an octahedral site, the proton, after reconstitution of the neutral hydrogen, can reach a nickel nucleus. The cross-section of the target is extended to the dimension of the Böhr orbit for the association of bosons 0. The geometric probability is the sum of the fractional solid angles in the unit cell: pG = ÿ ÿ ÿ $(rB)^2$. fi / $((di)^2$ · 4 ÿ), with di , distance between the octahedral sites identified by the index i, and the different nickel nuclei. The factor fi characterizes the fraction of presence in the lattice of the nuclei and of the sites.

For a face-centered cubic lattice, pG = (26/3). (rB / a)2 , the distances di are evaluated from the edge a of the mesh which is calculated by the relation: a3 = nn, the number of atoms present in · M/(N ÿ. 106), with the elementary mesh, M the mass number in g/mol, ÿ the density in g.cm-3 and N the Avogadro's number.

3) – pi : probability that the electron is intercalated between the proton and the nucleus, thus canceling the Coulomb repulsion.

The motion of the electron in the Böhr orbit is on any circumference of the sphere of radius rB. The effective area on the surface of this sphere is approximately ÿ. (NR)
^{2} with RN , radius of the nickel core.

The probability pi is therefore: pi = ÿ . (NR) ^{2} / 4 . ÿ . (rB) ^{2} = (1/4) . (RN / rB) ^{2} .

When the process has reached this stage, the association of bosons is effective. For nickel, we have: pG . pi = (26/3) . (rB / a)2 . (1/4) . (RN / rB) ^{2} = (13/6) . (RN / a)2 . The product pG . ft is independent of rB, , which seems to show that the association of bosons is characteristic of the crystal lattice for the nuclei considered.

4) – pt : temporal probability.

It is the probability so that the duration of interposition of the electron is sufficient in spite of its high speed ve on the orbit of Böhr. The probability pi takes into account all the positions of the orbits on the surface of the sphere of radius rB but, on a particular orbit, the position of the electron is not defined. The duration of the passage of the electron in front of the nucleus is approximately: 2 est: 2 .ÿ ÿ rB / ve .
. RN / ve , the total time for the electron to travel in one orbit
The temporal probability is therefore: pt = RN / ÿ . rB .

5) – pc : probability of proton capture.

With the assumption that the "Trojan horse", i.e. the pair [p+e-], behaves like a neutron, the capture probability is: pc = ÿc / ÿt neutron capture and ÿt total interaction cross section of the , with ÿc cross section of neutron with the nickel nucleus. The range of energies involved in the process is less than 0.1 eV, for neutrons it is the range of thermal energies represented by the Maxwell-Boltzmann distribution characteristic of the temperature of the medium. This distribution is

asymmetrical, the average energy is: 3/2 . k. T, (k, Boltzmann constant and T absolute ,
temperature). The most probable energy corresponding to the maximum of the neutron velocity distribution is: k . T. At ordinary temperature, i.e. 20° C, the neutron velocity is 2200 m. s $^{-1}$ and the corresponding energy, called thermal energy, is 0.025 eV. The capture cross section is a property of the particles and nuclei present, so it is assumed that the capture cross section ÿc remains almost identical to the value given for the thermal energy. On the other hand, the value of the total cross section ÿt depends on the energy and therefore on the temperature, because of the diffusion of the particles by the nuclei. For low energies, the order of magnitude of the Louis de Broglie wavelength is around 10-10 m, a value much greater than the size of the nickel nucleus,
of the order of some 10-15 m. In the decomposition of the wave into partial waves, the impact parameter is therefore much greater than 10-15 m, the only quantum number to be taken into consideration is: l = 0. A neutron of low energy, or the couple [p+e-], behaves then as a projectile of radius equal to: ÿ / 2. ÿ undulatory. , ÿt is therefore dependent on phenomena In particular, the diffraction behind the obstacle of the nucleus doubles the apparent surface and the value of ÿt is: ÿt = 2 . ÿ(ÿ/2.ÿ) ^{2} = ÿ ÿ /2.ÿ

According to Louis de Broglie's theory, ÿ is equal to Planck's constant divided by . c / (2 . mE . therefore have for the couple [p+e-]: ÿ = h E)1/2 with h, momentum, we

Planck's constant, c , speed of light, mE , energy equivalent of the mass of the couple [p+e-] slightly different from the mass of the proton, E is the kinetic energy of the couple. For the most probable energy, we have: E = k . T. Finally, the probability of proton capture is :

$$pc = 4k. ÿ . me . \quad . T.ÿc / h2 \; . vs^{2}$$

The reaction probability is the product of the elementary probabilities which have just been explained:

$$pr = ps . (pG.pi) .pt . pc = 0.5 . ((13/6) . (RN / a)2) . (RN /ÿ.rB) . \quad 4k. ÿ . me . \quad . T \; . ÿc / h2 \; . c2$$

RN , the radius of the target nucleus, can be calculated by the approximate relation: $RN = R0 . HAS^{1/3}$ with for R0, the empirical value: R0 = 1.23.10-15 m, A being the mass number of the target nucleus. Finally, we obtain for the probability of nickel transmutation:

$$(1) \quad pr = ((13/3) . (R0)^{3} . (mE / rB) . HAS . k . T. ÿc) / (a . h \; . c)2$$

The relation (1) above is established for an elementary cell taken in a crystal lattice with centered cubic faces. It relates to nickel for which we have experimental results allowing a possible verification. But apart from the geometry factor, it can be applied to any crystal lattice provided that the geometric probability pG is recalculated.

For nickel, the potential transmutation energy is: ÿ = 2XMNi + Mp - 2X+1MCu
With respectively, MNi, Mp and MCu, the masses / c2 expressed in MeV of nickel, proton and copper. Even atomic masses are represented by 2X. It is still necessary to ensure that the transmutations are feasible, The isotopes of Cu formed after capture of a proton are 3/2 fermions, of odd parity, we have: J' = 0 + ½ + l, with l =1, orbital quantum number in the shell model, bringing the parity change by: (-1)l .

What is possible with nickel is not necessarily possible with other elements, for example palladium, which is capable of absorbing 900 times its volume of hydrogen. Palladium has even 0+ isotopes and a face-centered cubic lattice. Transmutation to silver is not observed since in heavy water electrolysis experiments light water electrolysis is often used as a control and no excess energy is recorded. In silver transmutation, the isotope 103Ag has spin 7/2, even parity, the other isotopes have spin ½ and odd parity: J' = 0 + ½ + l, l = 3 or 0

and with (-1)l conservation or change of parity is not obtained.

When the Cu isotope formed is not stable, it is necessary to take into account the energy level: Q, of this isotope. If ÿ is less than Q, transmutation cannot be performed. Following the capture of a proton, the decay of radioactive 61Cu is leptonic, by electronic capture, with the possibility of the emission of a few positrons, the energy Q is not recoverable, carried away almost entirely by a neutrino.

Table I below gathers the transitions of the even isotopes of nickel, after capture of a proton, with their energy balance.

Table I

Transition	ÿ (MeV)	Q (MeV)	Er (MeV)
58Ni ----> 59Cu	2.90802	4.7984	ÿ too low, transition impossible
60Ni ----> 61Cu	4.28903	2.2376	2.0514
62Ni ----> 63Cu	5.61176	0	5.61176
64Ni ----> 65Cu	6.94286	0	6.94286

The residual energy Er is transferred to the outgoing electron in the form of kinetic energy. It remains to define, for the electrons, the emission proportions which depend on the isotopic percentage of the nickel isotope involved in the transmutation, and on the capture cross section for this isotope.

Table II below shows the isotopic percentages of nickel as well as the corresponding cross sections. Values are obtained from reference [4]. The last column gives the weighting of the capture cross section by the isotopic percentages of nickel. Isotopes that do not result in transmutation are eliminated, resulting in a weighted cross section of only 1.302 barns.

Table II

Isotope	% isotope	ÿc (barn)	%i. ÿc /100
58Ni	68.077	4.5	impossible transition
60Ni	26,223	2.9	0.760
61Ni	1,140	2.5	odd, not concerned
62Ni	3,635	14.5	0.527
64Ni	0.926	1.63	0.015

Sum = 1.302 barn

Table III below gives the energy of the electrons emitted, the proportion of emission ie: pe = (% i . ÿc / 100)/ 1.302, as well as the weighted average energy.

Table III

Transition	Ee- (MeV)	pe	Ee- . pe (MeV)
60Ni ----> 61Cu	2.0514	0.5838	1;1976
62Ni ----> 63Cu	5.61176	0.4046	2.2704
64Ni ----> 65Cu	6.94286	0.0116	0.0804
			Sum = 3.5484 MeV

The average energy released by all the even isotopes is: 3.548 MeV. The emission proportion pe also represents the proportion of the copper isotope formed by transmutation. We therefore have: 63Cu at 40.46% and 65Cu at 1.16%, with for 61Ni, an increase of 58.38% which is added to the 1.14% of the natural isotope, after the decrease of 61Cu, (half-life: 3.333 h), by electronic capture at 100% and almost total loss of energy.

With an average energy of 3.548 MeV per transmutation, i.e. 5.68.10-13 joule, it takes 5.28.1013 transmutations per second and per gram of nickel for the estimated specific power of 30 W/g at 700 K.

Given the proportions of the isotopes produced, one can wonder if it is possible to observe the appearance of copper and the modification of the isotopic composition of nickel. Considering for example stable operation for 30 days at 700 K, the energy produced is approximately 7.78.107 joules. The number of nuclei produced per gram is, for 61Ni: 7.98.1019 nuclei, after decrease of 61Cu, for 63Cu: 5.53.1019 nuclei and for 65Cu : 1.59.1018 nuclei. The 61Ni produced represents less than 0.8% of the Ni atoms already present and the copper less than 0.6%. At the end of the experiment, it therefore seems difficult to observe differences in the isotopic composition except perhaps by proceeding chemically.
Indeed, in copper transmuted from nickel, the 63Cu / 65Cu ratio should be 34.88 instead of 2.44 in natural copper.

In relation (1) for the calculation of pr, the characteristic data of the metal and its crystal lattice are, on the one hand the mass number A and the capture cross section ÿc for the isotope considered and on the other hand, the geometry factor 13/3 as well as the length, a of the edge of the cell. The variable element is the absolute temperature T, the other elements are constants. It is therefore possible to calculate an approximate value of pr, a function of ÿc and of T by replacing A, a dimensionless number, by the numerical value of M, namely 58.6934.
Using the following constants: mE = 9.38783.108 eV; rB = 5.29.10-11 m;
k = 8.61734.10-5 eV.K-1 ; h = 4.13567.10-15 eV.s; c=299792458 ms-1 ; a = 3.52.10- 10 m, we

obtains the probability of reaction in a cell of the crystal lattice and under optimal conditions, that is to say with a charge ratio equal to 1 or at least very close to unity. pr = 3.8.103 . ÿc .
T , with ÿc in m2 and T in kelvin.

There are 4 Ni atoms in a unit cell, for one atom we therefore have pr / 4, and for 1 gram of nickel, or approximately 1,026.1022 atoms, the reaction possibilities are given by the factor fp = 9.7473.1024 . ÿc . T

Because of the path rB that the proton must accomplish, to be within range of the nuclear forces after association of the bosons, the number of possible reactions is limited by the time interval, ÿt = rB / vp , vp is the speed of the proton, assimilated to the speed of the couple [p+e-], vp = c . (2.kT/ mE) $^{1/2}$ = c. (2.k/ mE) $^{1/2}$. T $^{1/2}$. Let fv , a factor related to the speed of the proton on the rB path, fv = vp / rB = 2.4289.1012. T1/2 , depends only on the temperature T and on the assumption that neutral hydrogen is a composite boson.

The number of transmutations, per unit of time and per gram of nickel, is then: Nt = fp . fv = 9.7473.1024. 2.4289.1012 . ÿc . T3/2 = 2.3675.1037 . ÿc . T3/2 (transmutations per second and per gram)

The average value of ÿc , after weighting was estimated at 1,302.10-28 m2 . For the absolute temperature T, we therefore have:

Nt = 3.08.109 . T3/2 transmutations. s-1 . g-1 .

Each reaction releases an average of 3.548 MeV, i.e. Et =5.68.10-13J, the specific power is then:

P (W/g) = Nt . Et = 1.75.10-3 . T3/2

For the temperature of Pr Focardi's experiment A, i.e. approximately 700 K, the calculation of the specific power gives 32 W/g compared to the estimated 30 W/g. The agreement is satisfactory taking into account the uncertainty on the power measured but especially because of the imprecise evaluation of the mass of nickel involved, deduced from an approximate thickness of the electrolytic deposit.

It can be noted that with the hypotheses set out above, there is no energy threshold for the transmutations, yet Pr Focardi evokes an “excited state with a critical temperature”. For a given load ratio, the evaluation of the power depends on the method used, the sensitivity of the measurement system with its background noise, which can give the appearance of an energy threshold and therefore of a critical temperature. However, the existence of a threshold linked, for a given temperature, to the charge ratio produced in the nickel is quite possible.

With nickel, the agreement between the calculated value and the experimental value is satisfactory, but one can wonder, on the one hand if there is possibly a happy coincidence, and on the other hand if the agreement persists with d other metals of even atomic number.
Only experiments can remove doubts, the most immediate method consisting in

check the emission of electrons and if possible confirm it by the energy spectrometry of these electrons.

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