Theoretical Analysis and Reaction Mechanisms for Experimental Results of Hydrogen-Nickel Systems

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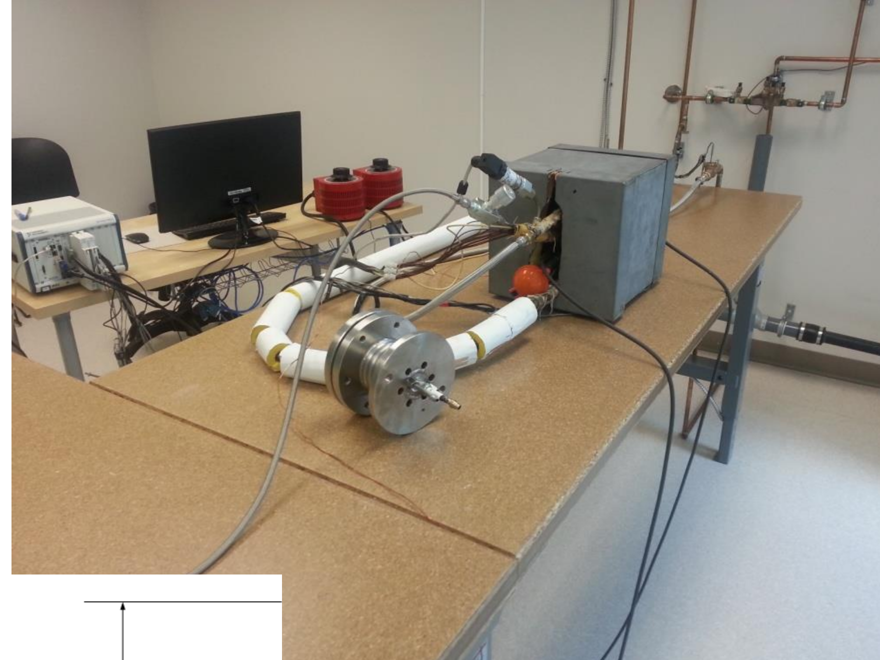
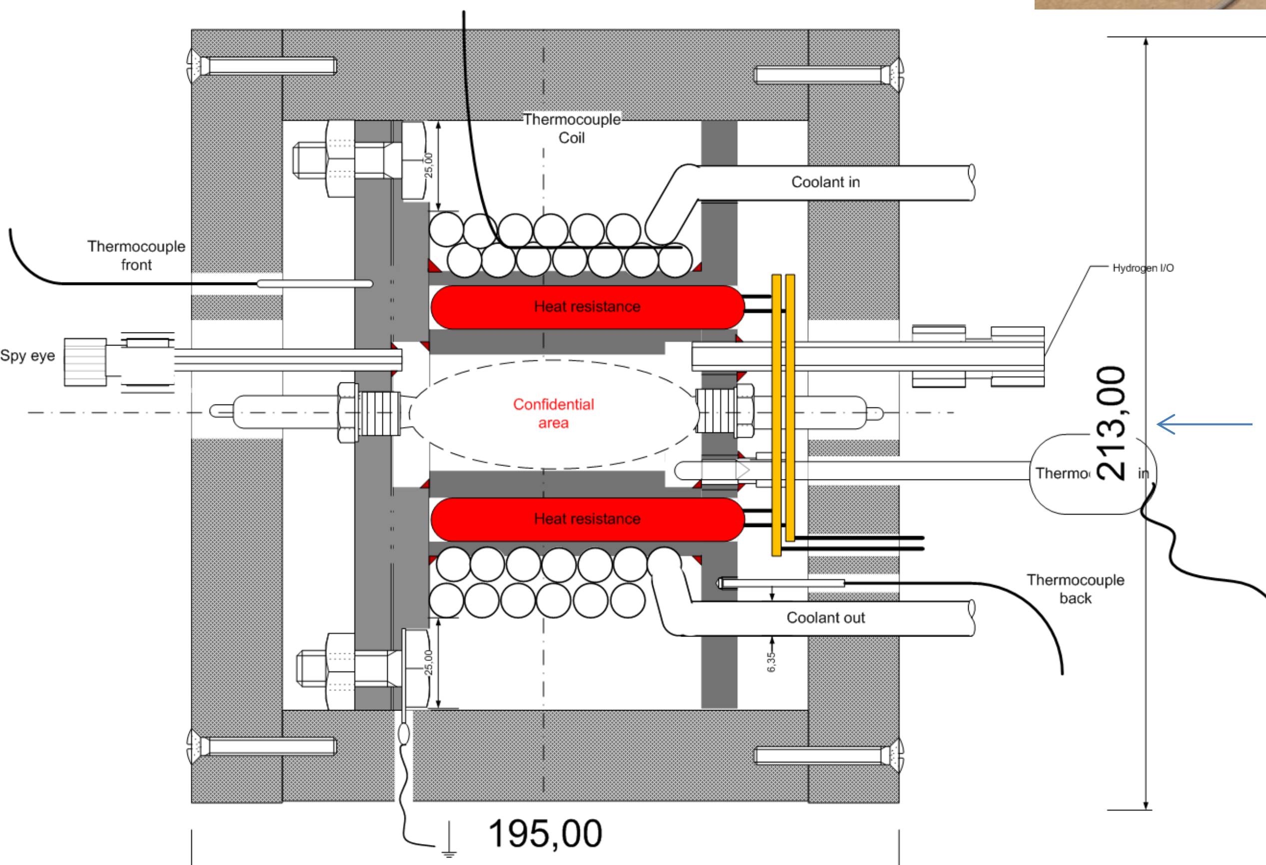
References [1] through [15] quoted in the slides are listed in the abstract

Hyperion R-5 Reactor





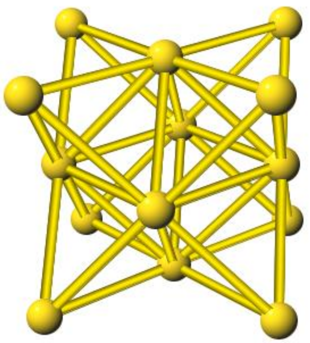
213.00 mm

Fabrications of Fuels and Reaction Cells

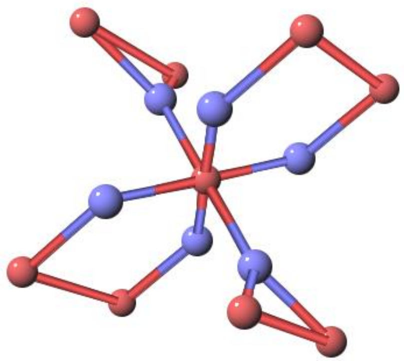
- Convert Ni Face Centered Cubic crystals to a **C4** or a **Pm3m** structure. The restructuring of the lattice is accomplished using a proprietary technique.

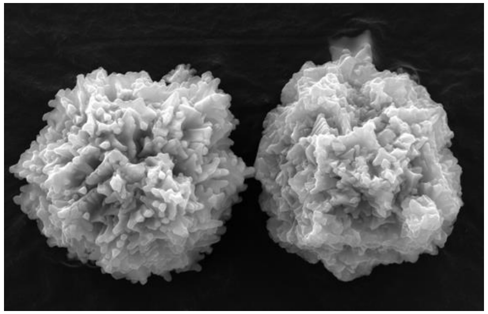
- Modified Ni crystal powders (~5 microns) are distributed in a special designed porous "cell" (~ 200 microns) to protect them from the high temperatures around the glow discharges (3500K at its surface, 14000K in the kernel)

The Face-Centered Cubic (A1) Lattice



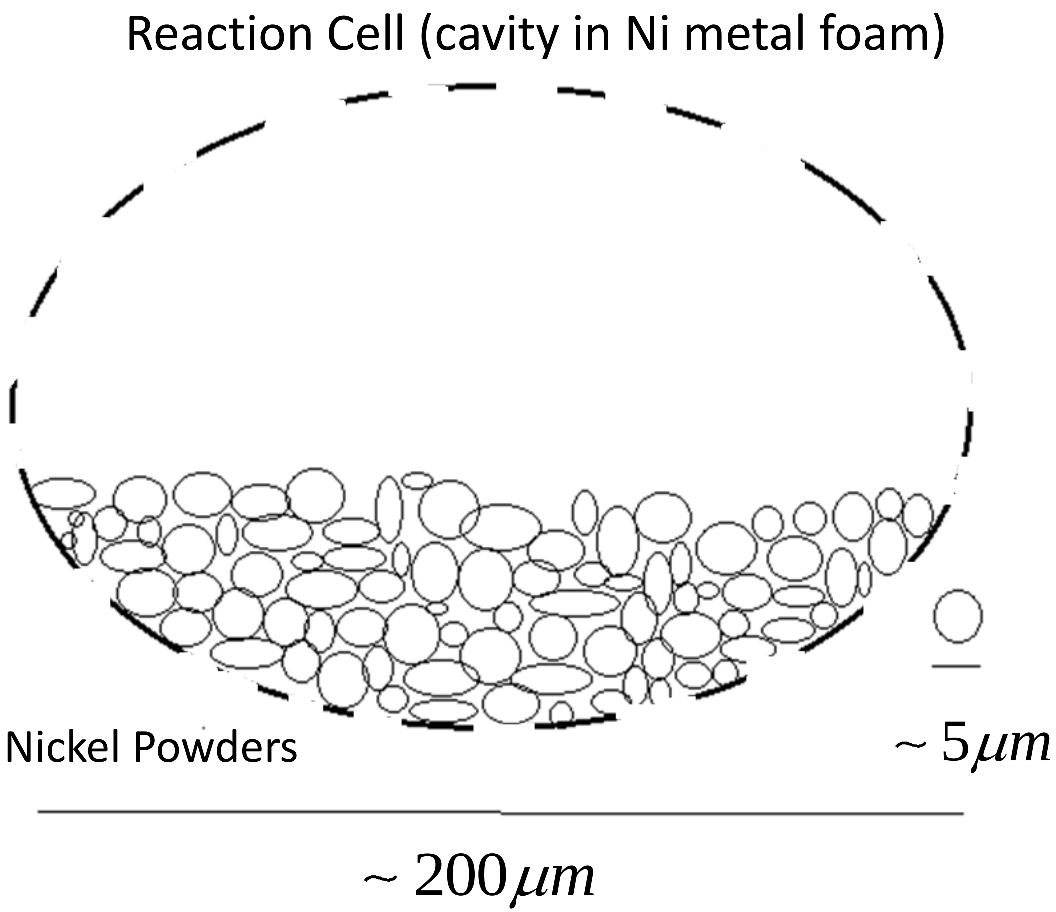
The Rutile (C4) Structure

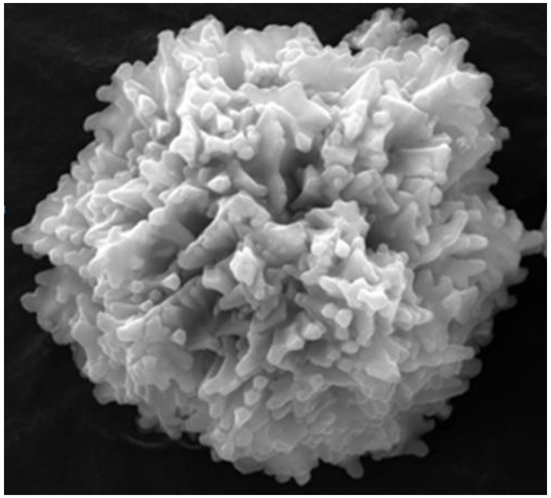




The Hyperion reactor contains a reactor core of Ni metal foam with many empty cells (chambers or cells) with average diameter of ~200 microns (μm).

Ni powders of ~ 5 microns (μm) size were inserted into the reactor chambers prior to the initiation of experiments (see Fig. below).





Ignition Stage after the Triggering

After the start of triggering sequence, the temperature inside the Hyperion reactor rise from 180 ^{0}C up to 849 ^{0}C (maximum allowed due to support material limitations) (The Curie temperature for Ni is 354 C^0)

After each triggering duty cycle , the magnetic field (at ~20 cm from the reactor) rose from ~0.6 Tesla to 1.6 Tesla during the reaction period (no triggering !)

This indicates that LENRs are producing very strong electric fields ***E*** (and currents ***I***) and very strong magnetic fields ***B=1.6 Tesla !***

$$B = \frac{\mu_0 I}{2\pi r}, \qquad \mu_0 = 4\pi \times 10^{-7}\, T \cdot m / A$$

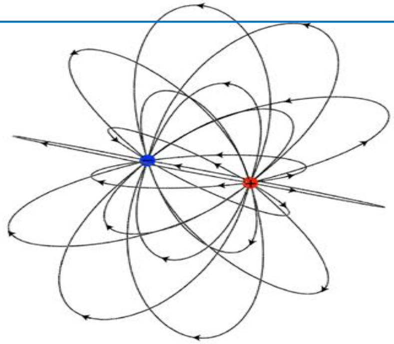
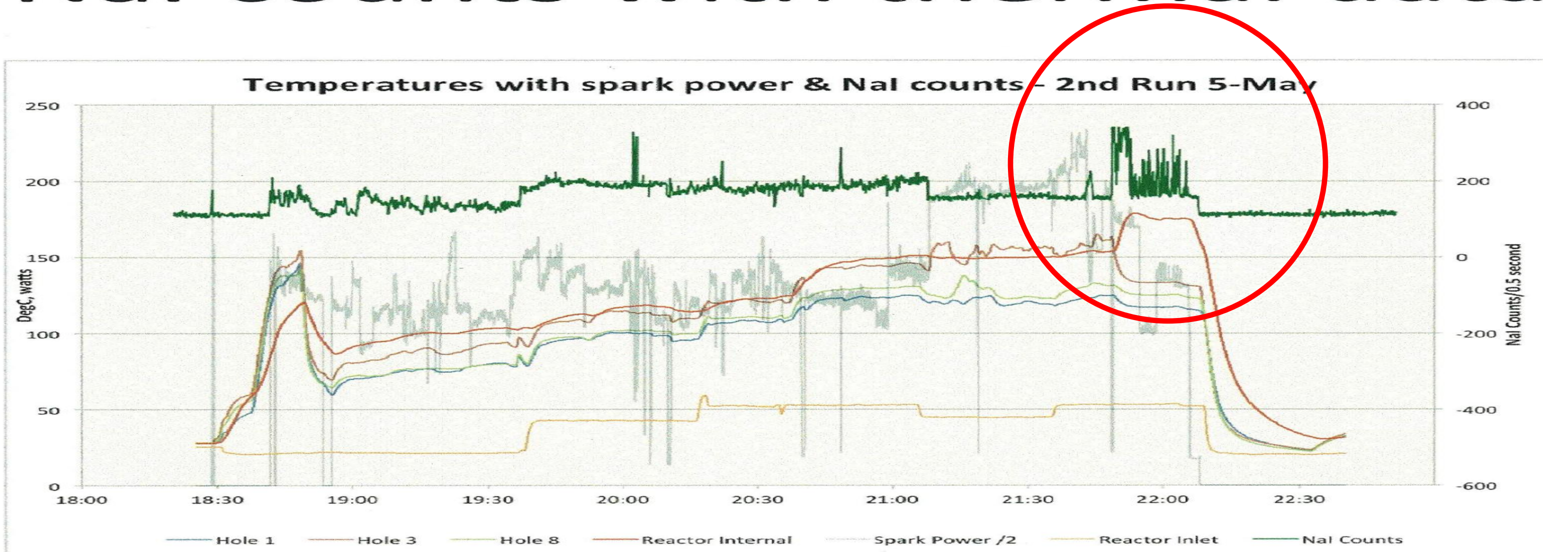


Fig. 2

No Hard Nuclear Gamma-Rays

- No gamma rays outside the energy range of 50 keV–300 keV have been observed from the experiments with the Hyperion R-5 reactor. (data from isoparabolic calorimetry experiments)

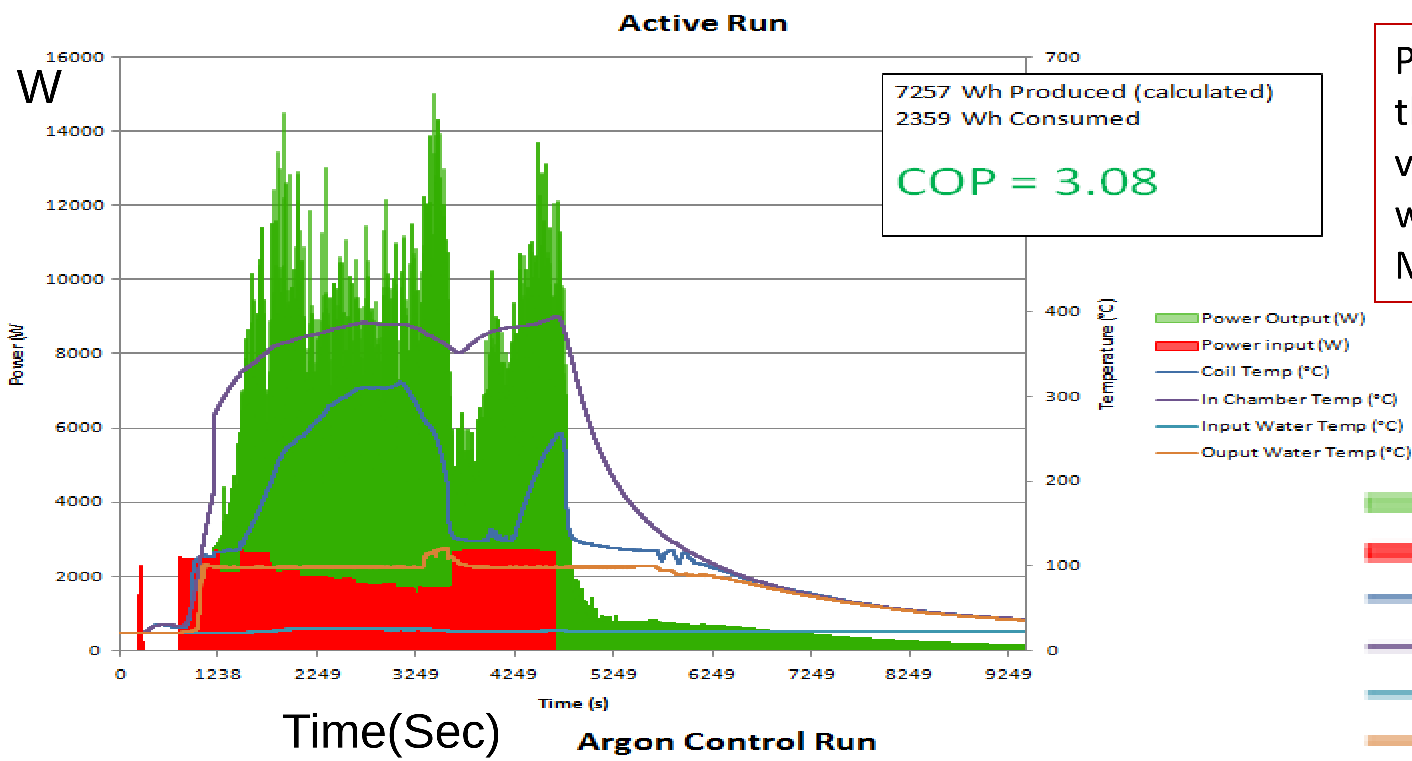
NaI counts with thermal data



The Even Ni Isotope Effect

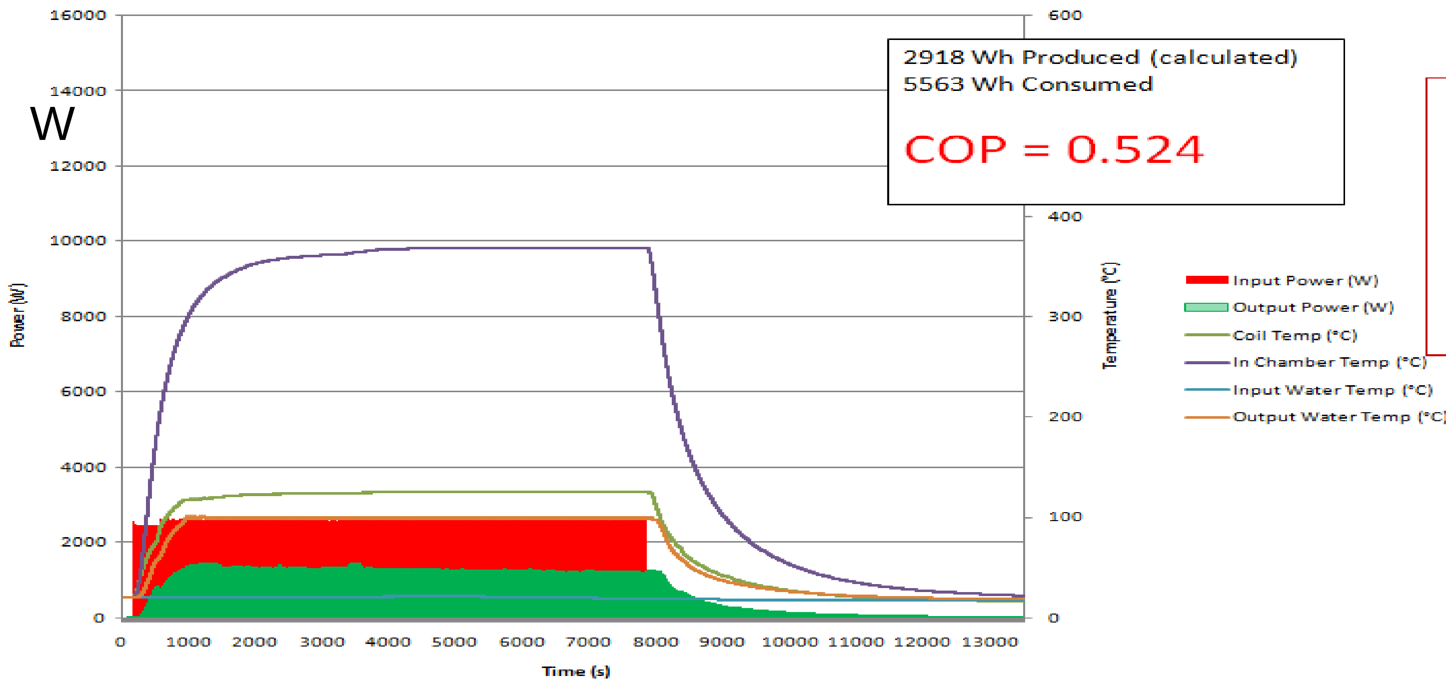
- **The excess heat was observed only with the even isotopes of Ni [1]**
- The Hyperion reactor with each of even isotopes of Ni (^{58}Ni, ^{60}Ni, ^{62}Ni, and ^{64}Ni) produced the excess heat while the odd Ni isotope ^{61}Ni does not.

The natural abundances are ^{58}Ni (68.077%), ^{60}Ni (26.223%), ^{61}Ni (1.140%), ^{62}Ni (3.634%), and ^{64}Ni (0.926%).



Plot of P_{out} and P_{in} with thermal signals vs Time with Hydrogen with flow calorimeter May 15, 2013

Power Output(W)
Power Input(W)
Coil Temp (^{0}C)
In Chamber Temp (^{0}C)
Input Water Temp (^{0}C)
Output Water Temp (^{0}C)



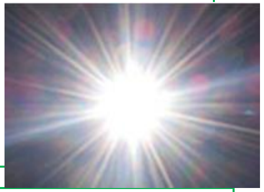
Plot of P_{out} and P_{in} with thermal signals vs Time with Argon with flow calorimeter May 16, 2006

Theoretical Explanation of Fleischmann-Pons Effect (F-P Effect) including Huizenga's three miracles [4-15] (Review/Summary)

1. One-Particle Exit Reaction Channel (Type-1, N=1): Probability P_1

$P_1 >> P_2$ Example: D + D → ^{4}He + Q(23.84MeV)

(Nano Explosion due to the total momentum conservation)



2. **Two-Particles Exit Reaction Channel (Type-2, N=2):** Probability P_2

$P_2 << P_1$ due to both centrifugal and Coulomb barriers

Example: D + D → ^{3}He + n

D + D → T + p

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V(r)\right]\Psi_E = E\Psi_E$$

$$\Psi_E = \psi_{lm}(r,\theta,\phi) = \frac{R(r)}{r}Y_{lm}(\theta,\phi) \rightarrow$$

$$\frac{\partial^2 R(r)}{\partial r^2} - \frac{2\mu}{\hbar}\left[\frac{l(l+1)}{2\mu r^2} + \frac{Z_i Z_j e^2}{r}\right]R(r) = ER(r)$$

3. **Multi-Particles Exit Reaction Channel (Type-3, N=3 or N>3):**

Probability P_3

$P_3 << P_2$, etc.

Reaction Rates for Boson Cluster-State Nuclear Fusion (BCSNF) Generalized to include Hydrogen-Metal Systems [3]

$$R_t = \frac{1}{2\pi}\left(\frac{3}{\pi}\right)^{1/2} S_{ij}\sqrt{\Omega_i\Omega_j}\,V\,\frac{n_i n_j}{Z_i Z_j}\left(\frac{\hbar}{e^2\mu}\right), \quad \mu = \frac{m_i m_j}{m_i + m_j}$$

- Only two unknown parameters are (**S_{ij}** and Ω_i):

  (i) **S_{ij}** is the astrophysical S-factor representing the nuclear force strength, and

  (ii) **Ω_i** is the probability of the Boson cluster state (BCS) occupation for the Boson specie **i**

- Important !! The Gamow factor suppression occurs with the formation of the Boson cluster state (BCS) which may include a cluster of Bosons, a BEC, etc. The BEC case is only one of special cases
- The predicted reaction rates can be compared with the experimental reaction rates, extracted from measurements by new on-line real-time mass spectrometer

Reaction Mechanisms for Hydrogen-Metal Systems

Classification of Exit Reaction Channels for Reaction: p + ${}^{A}_{Z}\mathrm{X}$

1. One-Particle Exit Reaction Channel (Type-1, N=1):

Probability $P_1 >> P_2$ Example: $p + {}^{A}_{Z}X \rightarrow {}^{A+1}_{Z+1}Y + Q$

(Nano-explosion due to the total momentum conservation)

2. **Two-Particles Exit Reaction Channel (Type-2, N=2):**

Probability $P_2 << P_1$ due to both centrifugal and Coulomb barriers

Example:

p + ${}^{A}_{Z}\mathrm{X} \rightarrow {}^{4}\mathrm{He} + {}^{A-3}_{Z-1}Z$

etc.

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2 + V(r)\right]\Psi_E = E\Psi_E$$

$$\Psi_E = \psi_{lm}(r,\theta,\phi) = \frac{R(r)}{r}Y_{lm}(\theta,\phi) \rightarrow$$

$$\frac{\partial^2 R(r)}{\partial r^2} - \frac{2\mu}{\hbar}\left[\frac{l(l+1)}{2\mu r^2} + \frac{Z_i Z_j e^2}{r}\right]R(r) = ER(r)$$

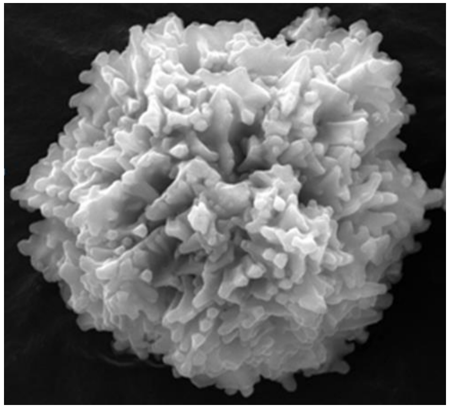
3. **Multi-Particles Exit Reaction Channel (Type-3, N=3, N>3):**

Probability P_3 $P_3 << P_2$

Important Roles of Ni in Hyperion Reactor

- Magnetic fields generated by the internal triggering could provide **magnetic alignments of Ni atoms on localized surfaces of Ni powders**
- These external magnetic fields could provide **localized magnetic trap (LMT) potentials** for Boson clusters on the surface of Ni powders (**LMTs** with short lifetimes)

- Rydberg atoms/molecules are trapped in a localized magnetic trap due to their **magnetic moments**
- Trapped Rydberg atoms are paired to form Bosons due to their **electric moments**, thus aiding the formation of Boson Cluster States (BCS) at temperatures higher than 179 ^{0}C



Proposed Reaction Mechanisms

Hydrogen molecules + Ni powders

Triggering (Glow Discharge)

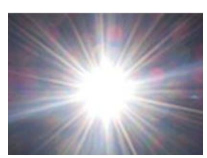
$B \approx 0.6$ Tesla

Rydberg States (atoms/molecules) created + Ni magnetized above Curie Temp. → creating nano-scale localized magnetic traps (**LMTs**) with short life-times on Ni surfaces , most probably due to Plasmon-Nanoplasma interactions [16,17]

Hydrogen Boson Cluster States (BCS) formed in **LMTs** on Ni surfaces

BCS fusions
→nano-explosions →

Decays
→nano-explosions →



- Excess Heat Generation/Distribution
+
- Produce localized Glow Discharges →

$B \approx 1.6$ Tesla !

No Hard Nuclear Gamma-Rays

- No gamma rays outside the energy range of 50 keV–300 keV have been observed from the experiments with the Hyperon reactor [1]
- Transmutation reactions involving Ni isotopes may **not be dominant reaction mechanisms but could be part of much weaker secondary reactions.**

Type-1 Reactions (Can a larger Q-value give a larger S-factor ?)

$$p + {}^{64}Ni \rightarrow {}^{65}Cu \text{ (stable) } \mathrm{Q} = 7.453 \text{ MeV}$$

$$p + {}^{62}Ni \rightarrow {}^{63}Cu\left(stable\right) \mathrm{Q} = 6.122 \text{ MeV} \qquad [\mathrm{p} + {}^{A}Ni \rightarrow {}^{A+1}Cu^{*} \rightarrow {}^{A+1}Cu + \gamma]$$

$$p + {}^{60}Ni \rightarrow {}^{61}Cu(3.33 \text{ hours}) \mathrm{Q} = 4.801 \text{ MeV}$$

$${}^{61}Cu(3.33 \text{ hours}) \text{ (e-capture)} \rightarrow {}^{61}Ni + \gamma\text{'s } (67.4129 \text{ keV} \sim 2123.93 \text{ keV})$$

$$p + {}^{58}Ni \rightarrow {}^{59}Cu(81.5 \text{ sec}) \mathrm{Q} = 3.419 \text{ MeV} \qquad [\mathrm{R}(\beta^{+} - decay) \ll R(e - capture)]$$

$${}^{59}Cu(81.5 \text{ sec}) \text{ (e-capture)} \rightarrow {}^{59}Ni + \gamma\text{'s } (310.9 \text{ keV} \sim 2682.0 \text{ keV})$$

The even Ni isotope effect (predicted in 2006 [3])

- The excess heat was observed only with the even isotopes of Ni [1]
- **This can be explained by the prediction made in 2006 [3] that the hydrogen-pair Boson clusters are Bosons and cannot co-exist with Fermions (odd Ni isotopes) in the same space or in the same trapping potential [3]**

Roles of Reactions Involving Light Nuclei

Proton-Deuteron Reaction: $p + D \rightarrow {}^3He$ (Q = 5.494 MeV)

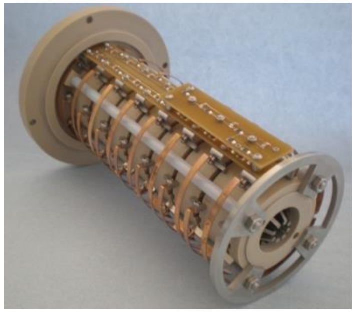
- Hydrogen gas contains deuterium as impurities (0.0125%, n_d/n_p = 1.25 x 10^{-4}), which may participate in BCSNF reactions

- For the impurity (0.0125%) of deuterium in hydrogen gas, the minimum number of hydrogen, N_{min} = ~ 0.8 x 10^4, is required to form in a two-species BCS containing at least one deuterium.

- Experimentally observed heat production rate of ~ 92 Wh would correspond to a reaction rate of R_t (n_d = 1.25 x 10^{-4} n_p) = ~ 2.8 x 10^{15} sec^{-1} with Q=5.494 MeV

- This implies that self-sustaining reactions could be improved by increasing the deuterium density **(to be tested with Hyperion R-6 reactor with the on-line real-time mass spectrometer at Defkalion Lab)**

On-Line Real-Time Mass Spectrometry	*This is a new device specially designed for laboratory testing and analyzing in situ phenomena from an operating Hyperion reactor in real time. This unique technology has been developed by Defkalion in cooperation with Fasmatech*



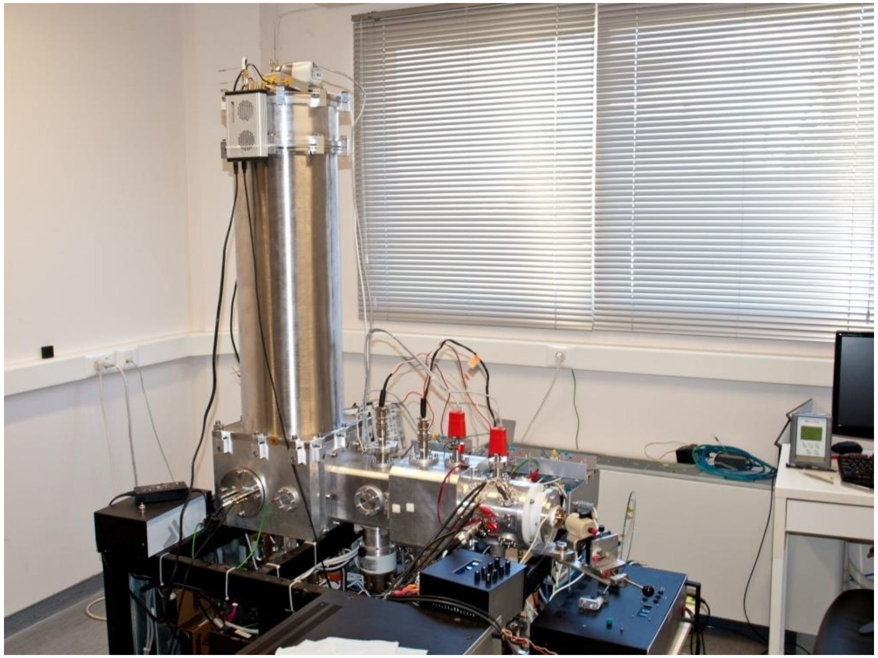


FIGURE 2. Assembly of the segmented octapole ion guide (up).
Prototype TOF MS system incorporating the ion guide. (right)

To be installed in Defkalion Labs located in Vancouver and Athens

Future Research Plan

- "LENR" in H-Ni Systems is an emerging scientific field

- **We need to carry out new basic scientific research involving both experiments and theories**

- We need more detailed and accurate experimental measurements of nuclear ashes, changes in Ni powders, etc.

- **Defkalion is planning to budget ~ 1% of its revenue for basic scientific research for these emerging fields**

- Defkalion is planning to build research-type Hyperion reactors and new measurement instrumentations (minaturized on-line real-time mass spectrometers , etc.)

- **Defkalion has called for cooperation with the scientific community**

- Defkalion is cooperating with important industrial partners on new energy applications

Future Research Plan (continued)

- So far, the theoretical reaction-rate formulae were based on analytical solutions $\Psi(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_N)$ of the approximate time-independent linear Schroedinger equations for many-body systems (Time-Independent Linear (TIL) Dynamics) [3-5]
- Such analytical formulae for the reaction rates are extremely useful for initial qualitative analysis of the experimental data.

- For more quantitative analysis of the experimental data, we need to obtain solutions $\Psi(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_N; t)$ of the time-dependent non-linear Schroedinger equations for many-body systems (Time-Dependent Non-Linear Dynamics (TDNL Dynamics))[9]

- For TDNL Dynamics, we will need numerical solutions and/or numerical simulations (in collaboration with National Instruments)

Future Research Plan (continued)

- Validity of some of theoretical methods for TIL Dynamics was confirmed by LabView numerical simulation group at National Instruments (NI)
- This NI collaboration was initiated in March 2012 with approval of Dr. Truchard (Dr. T) and is expected to continue with numerical simulations of Time-Dependent Non-Linear (TDNL) Dynamics

- For TDNL Dynamics, we will need numerical solutions and/or numerical simulations (NI collaboration)
- This theoretical field of TDNL Dynamics is expected to become an emerging field of theoretical physics for LENRs, as the more refined experimental measurements and data become available for LENRs

Summary and Conclusions

- Defkalion's Hyperion R-5 Reactor has been demonstrated to be a reliable working device producing excess heat at sufficiently high level **(1) with reliable controls and (2) with high reproducibility for practical applications → this is a breakthrough !**

- The R-6 Reactor will be generating new experimental data using the new on-line real-time mass spectrometers

- Theory of Boson cluster state nuclear fusion (BCSNF) has been used to analyze the experimental data and **has provided qualitative theoretical understanding of reaction mechanisms**

A new field is emerging
(1) as a revolutionary clean-energy technology, and
(2) as a new multi-disciplinary scientific field

"Cold fusion" is becoming hot !

Supplemental slides

References

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Triggering Reactions using Plasma Glow-Discharge Method

Pressurized hydrogen gas (1 – 8 bar) inserted in the reactor chambers.

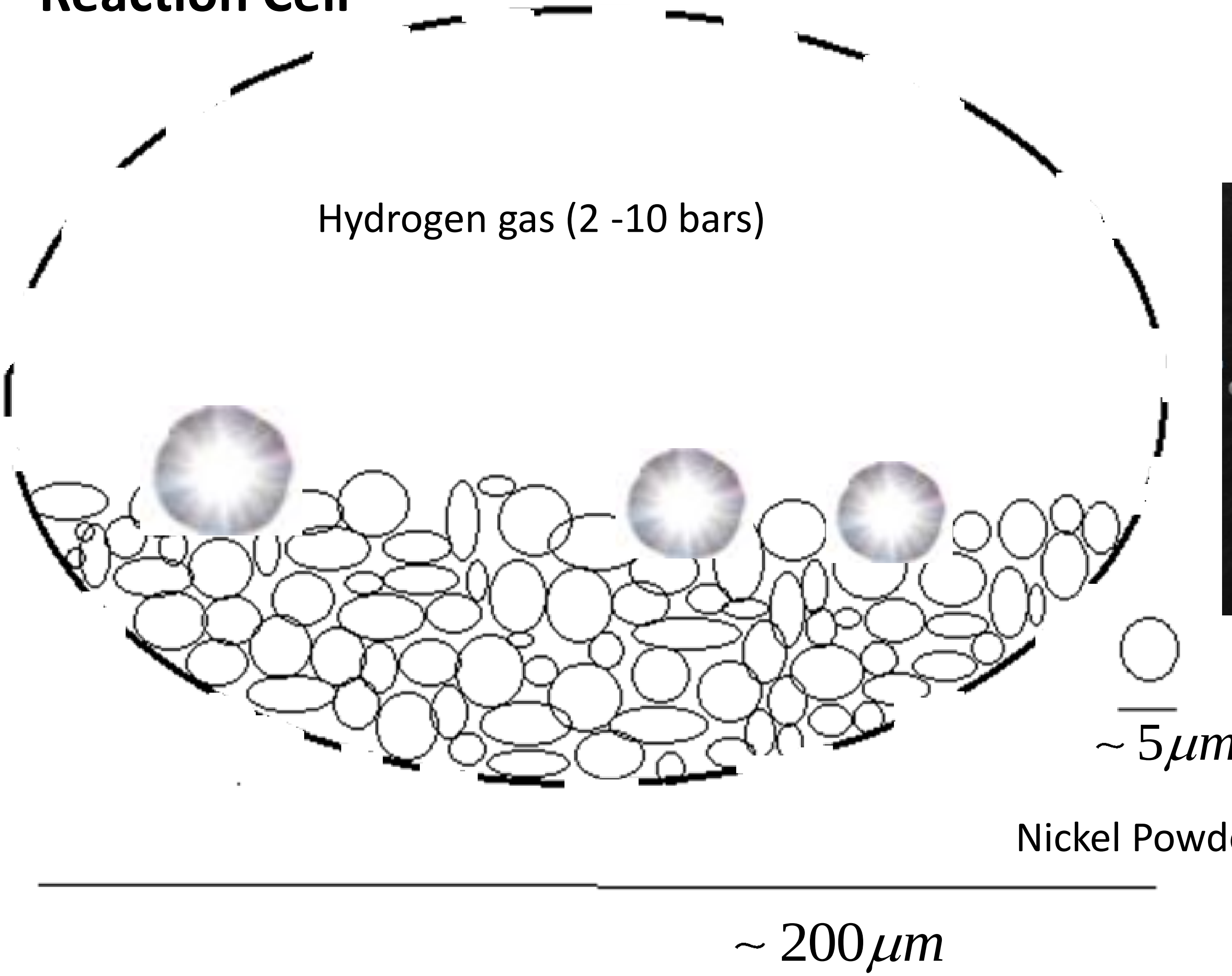
The reactor core is preheated to ~180 ^{0}C prior to the triggering

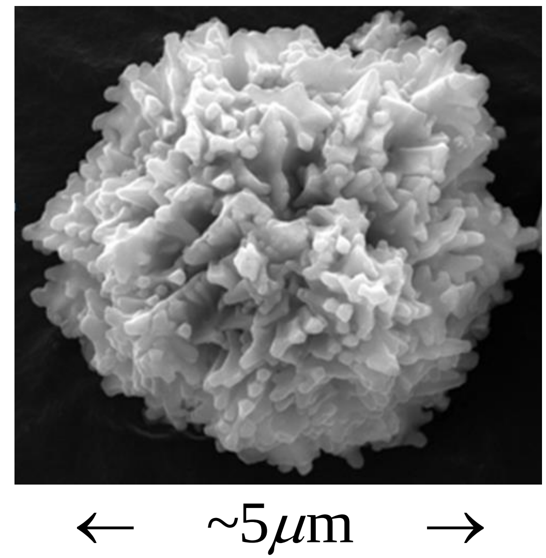
Triggering the effect is accomplished by hydrogen discharge across the two W/TZM electrodes at ***V*** = ~ 24 kV, using the current ***I*** = ~ 22 mA DC current with ~ kHz frequency

Thermal output is modulated by varying the duty cycle of trigger pulse

Nano-Explosion of a Boson Cluster State (BCS)
(due to the total momentum conservation)

Reaction Cell





Optical Theorem Formulation of Positive-Energy Scattering Between Two Charged Particles (Beam Experiments)

From the optical theorem formulation, we obtain

$$\frac{k}{4\pi}\sigma^{r}=-\frac{2\mu}{\hbar^{2}k^{2}}<\psi_{0}^{c}|\operatorname{Im}t_{0}|\psi_{0}^{c}> \qquad (1)$$

where

$$(T+V^{c})\psi_{0}^{c}(r)=E\psi_{0}^{c}(r),E>0 \qquad (2)$$

$$\sigma^{r}=\frac{S}{E}e^{-2\pi\eta}, \qquad \eta=\frac{1}{2kr_{B}}, \qquad r_{B}=\frac{\hbar^{2}}{2\mu e^{2}},\mu=m/2 \qquad (3)$$

Eq. (3) has been used to describe nuclear reactions, D(d,p)T or D(d,n)^{3}He, in free space (beam experiments) with S=55 KeV-barn.

- **Eq. (3) is for nuclear reactions at positive energies (such as for nuclear scattering experiments using beam of nuclei)**
- **It is not appropriate for describing nuclear reactions between two nuclei in a bound state (such as deuterons bound in a metal) !**

In the past, Eq. (3) is inappropriately used to argue that LENRs in metals are impossible !

For two charged particles at positive energies, we have

$$R = v\sigma^r = -< \psi^c \left| \mathrm{Im} V \right| \psi^c > (4) \qquad \mathrm{Im} V = -A\delta(\vec{r}_{ij}), A = \left(\frac{2}{\hbar}\right)\frac{Sr_B}{\pi} \quad (5)$$

Generalization to Fusion Reaction Rates for LENRs in Metals

For LENRs in metals, make the substitution $V^c \Rightarrow V^{confine} + V^c$ *and* $\psi^c \Rightarrow \psi$ to obtain

$$R_t = -\frac{2}{\hbar}\frac{\Sigma_{i<j} < \psi \left| \mathrm{Im} V_{ij}^F \right| \psi >}{< \psi | \psi >} \qquad (6)$$

where $\mathrm{Im} V_{ij}^F$ is given by the Fermi potential,

$$\mathrm{Im} V_{ij}^F = -\frac{A\hbar}{2}\delta(\vec{r}_{ij}), \qquad A = \left(\frac{2}{\hbar}\right)\frac{Sr_B}{\pi} \qquad (7)$$

ψ is the solution of the many-body Schroedinger equation

$$H\Psi = E\Psi, \qquad E < 0 \qquad (8)$$

with

$$\mathrm{H} = \mathrm{T} + \mathbf{V}^{\mathbf{confine}} + \mathbf{V}^{\mathbf{c}} \qquad (9)$$

The above general formulation can be applied to (i) deuteron-deuteron reaction in metals, (ii) proton-nucleus transmutations in metals, etc., and also possibly to biological transmutations !

Reaction Rates for Large N

$$R_{trap} = -\frac{2}{\hbar}\frac{\Sigma_{i<j} < \Psi \left| \mathrm{Im}\, t_{ij} \right| \Psi >}{< \Psi | \Psi >} \tag{10}$$

$$R_t = N_{trap} R_{trap} = \frac{N_D}{N} R_{trap} = \frac{1}{4}\left(\frac{3}{\pi}\right)^{1/2} SB\Omega V n_D^2 \tag{11}$$

S and Ω are only two unknown parameters

S is the astrophysical S-factor in units of keV-barn and

Ω is the probability of Boson ground-state (BGS) occupation

- Important !! The Gamow factor suppression occurs with the formation of the Boson ground state (BGS) which may include a cluster state, a BEC state, etc. **The BEC state case is only one of special cases**

Theoretical Significance: Nuclear fusion rate R for large N does not depend on the Gamow factor in contrast to the reaction rate for nuclear fusion in free space ! → Miracle #1 !

Deuteron fusion reactions in metal: {6} D(m) + D(m) → ^{4}He(m) + 23.847 MeV

$$\Psi_{GBS}\{(N-2)D's+(D+D)\}\rightarrow\Psi^*\{^4He+(N-2)D's\} \quad (Q=23.84\text{ MeV})$$

Total momentum conservation (Miracle #3):

$$\vec{P}_{initial}(N\bullet D's)=\vec{P}_{final}((N-2)D's,{}^4He)\approx 0$$

- Average Kinetic Energy <T> per deuteron:

$$\langle T_D\rangle\approx\langle T_{^4He}\rangle\approx\frac{Q}{N}\approx 1\text{keV}, N\approx 10^4-10^5$$

This causes the resisitivity R/R_0 to decrease !

Excess energy (Q value) is absorbed by the BEC cluster state and shared by (N-2) deuterons and reaction products (^{4}He, etc.)

→ Star-like symmetric micro/nano-scale explosion! (Observation #6)

- Other open exit channels are suppressed **(Miracle #2):**
  - {4} D(m) + D(m) → p + T + 4.033 MeV
  - {5} D(m) + D(m) → n + ^{3}He + 3.270 MeV

$$\left[-\frac{\hbar^2}{2\mu}\nabla^2+V(r)\right]\Psi_E=E\Psi_E$$

$$\Psi_E=\psi_{lm}(r,\theta,\phi)=\frac{R(r)}{r}Y_{lm}(\theta,\phi)\rightarrow$$

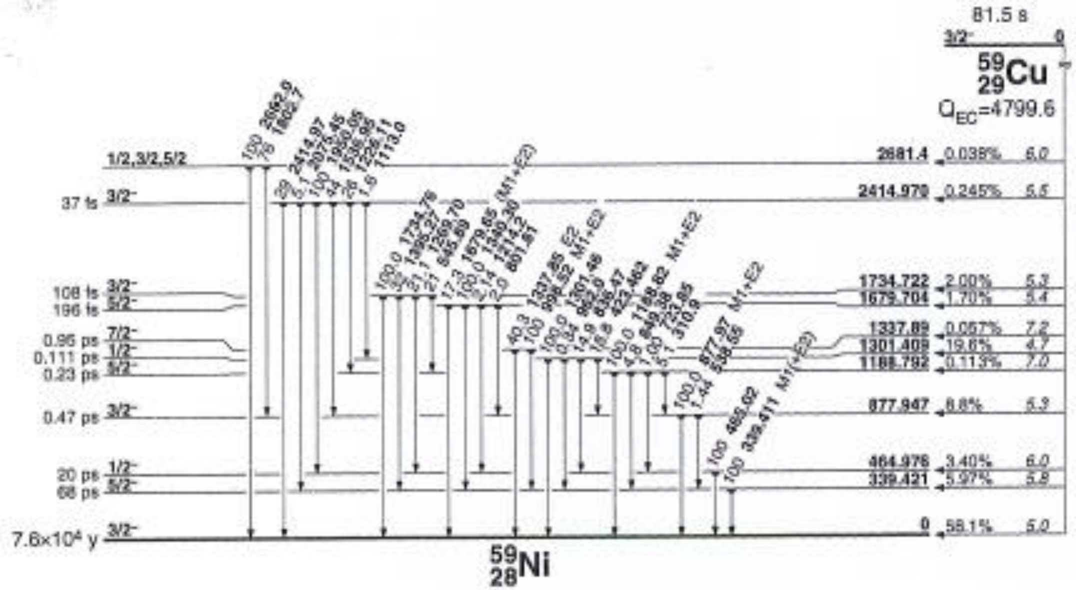
$$\frac{\partial^2 R(r)}{\partial r^2}-\frac{2\mu}{\hbar}\left[\frac{l(l+1)}{2\mu r^2}+\frac{Z_iZ_je^2}{r}\right]R(r)=ER(r)$$

Deuteron-Deuteron Reaction: D + D → ^{4}He (Q=23.38 MeV)

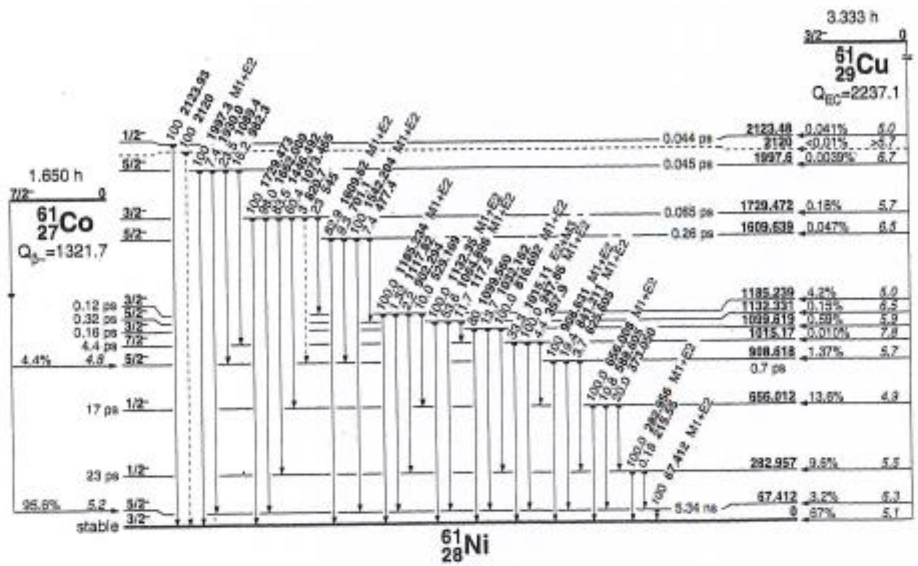
- An alternative approach would be to use ~100 % deuterium gas for the BCSNF reaction (Type-1)
- If the above reaction produces substantial excess heat, it will be the first time that the F-P effect is scaled up successfully for substantial excess heat generation
- **This would be a historical event !, even though it involves slightly different reaction mechanisms**

- Warning !

Instabilities may occur, if the deuterium density (pressure) is increased too excessively for both cases of p + D and D +D reactions

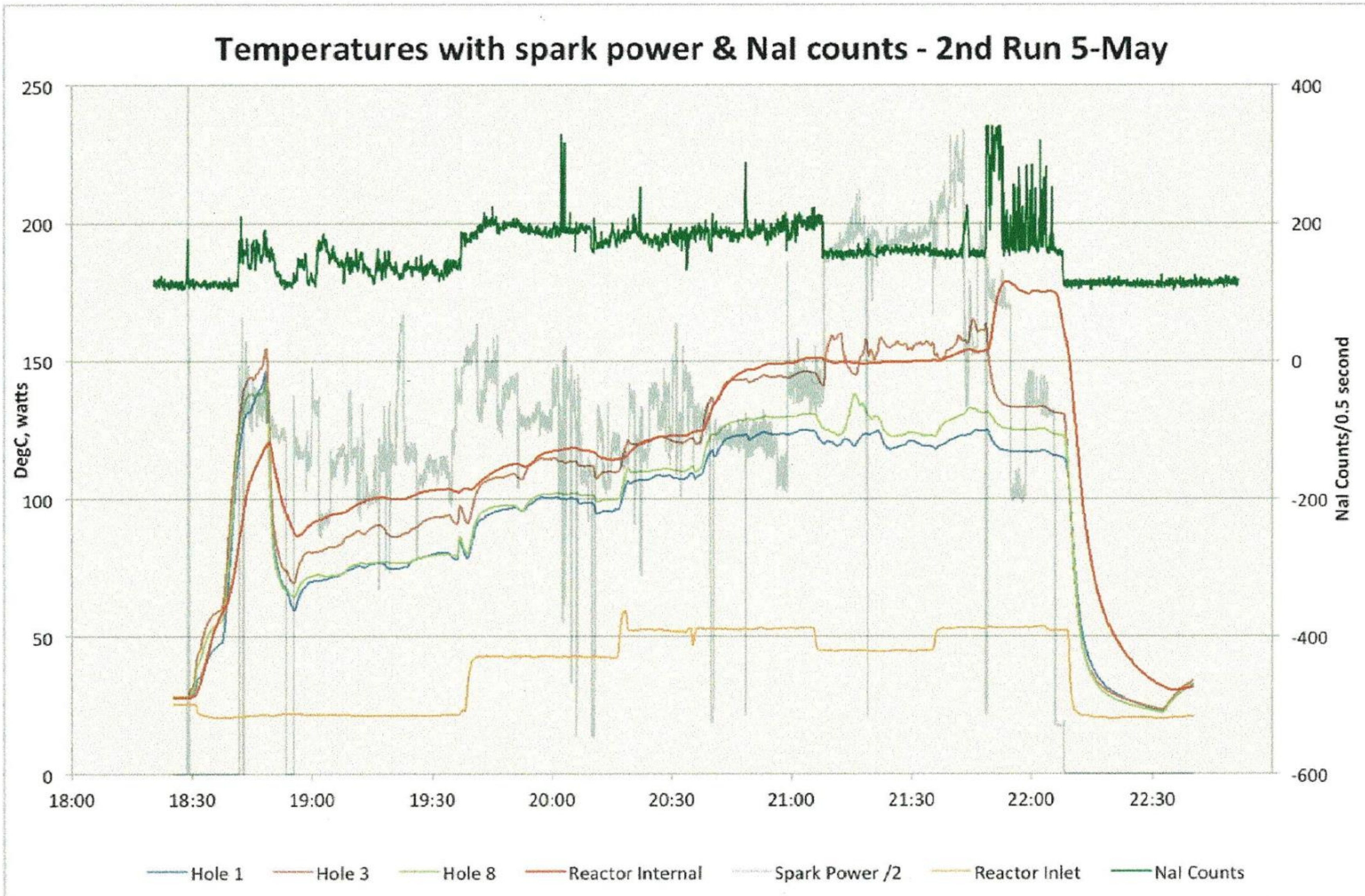


81.5 s
3/2⁻ 0
$^{59}_{29}$Cu
Q_{EC}=4799.6
2681.4 0.038% 6.0
2414.970 0.245% 5.5
1734.722 2.00% 5.3
1679.704 1.70% 5.4
1337.89 0.057% 7.2
1301.409 19.6% 4.7
1188.792 0.113% 7.0
877.947 8.8% 5.3
464.976 3.40% 6.0
339.421 5.97% 5.8
0 58.1% 5.0
1/2,3/2,5/2
37 fs 3/2⁻
108 fs 3/2⁻
196 fs 5/2⁻
0.96 ps 7/2⁻
0.111 ps 1/2⁻
0.23 ps 5/2⁻
0.47 ps 3/2⁻
20 ps 1/2⁻
68 ps 5/2⁻
7.6×10⁴ y 3/2⁻
$^{59}_{28}$Ni



3.333 h
3/2⁻ 0
$^{61}_{29}$Cu
Q_{EC}=2237.1
2123.48 0.041% 6.0
2120 <0.01% >6.7
1997.6 0.0039% 6.7
1729.472 0.16% 5.7
1609.539 0.047% 6.5
1185.239 4.2% 5.0
1132.331 0.15% 6.5
1099.819 0.58% 5.9
1015.17 0.010% 7.8
908.618 1.37% 5.7
656.012 13.6% 4.9
282.957 9.5% 5.5
67.412 3.2% 6.3
0 67% 5.1
1.650 h
7/2⁻ 0
$^{61}_{27}$Co
Q_{β^-}=1321.7
4.4% 4.8
95.6% 5.2
stable 3/2⁻
$^{61}_{28}$Ni

NaI counts with thermal data



GM and NaI Count Comparison

Radiation, if present, below noise floor of GM