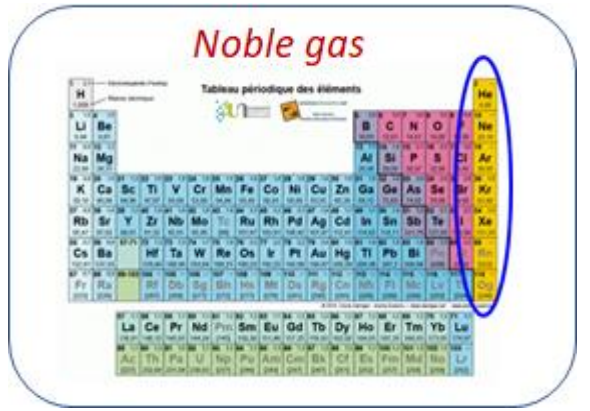
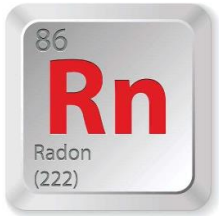
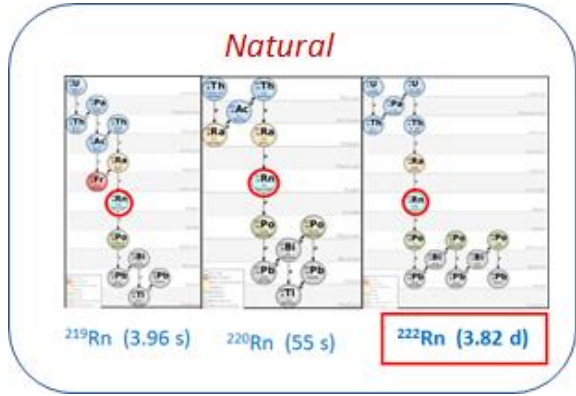


Radon adsorption in microporous materials: IRENE (Innovative mateRials for Extreme radon capture)

Réseaux des Détecteurs gazeux, LSM
Hichem Tedjdi

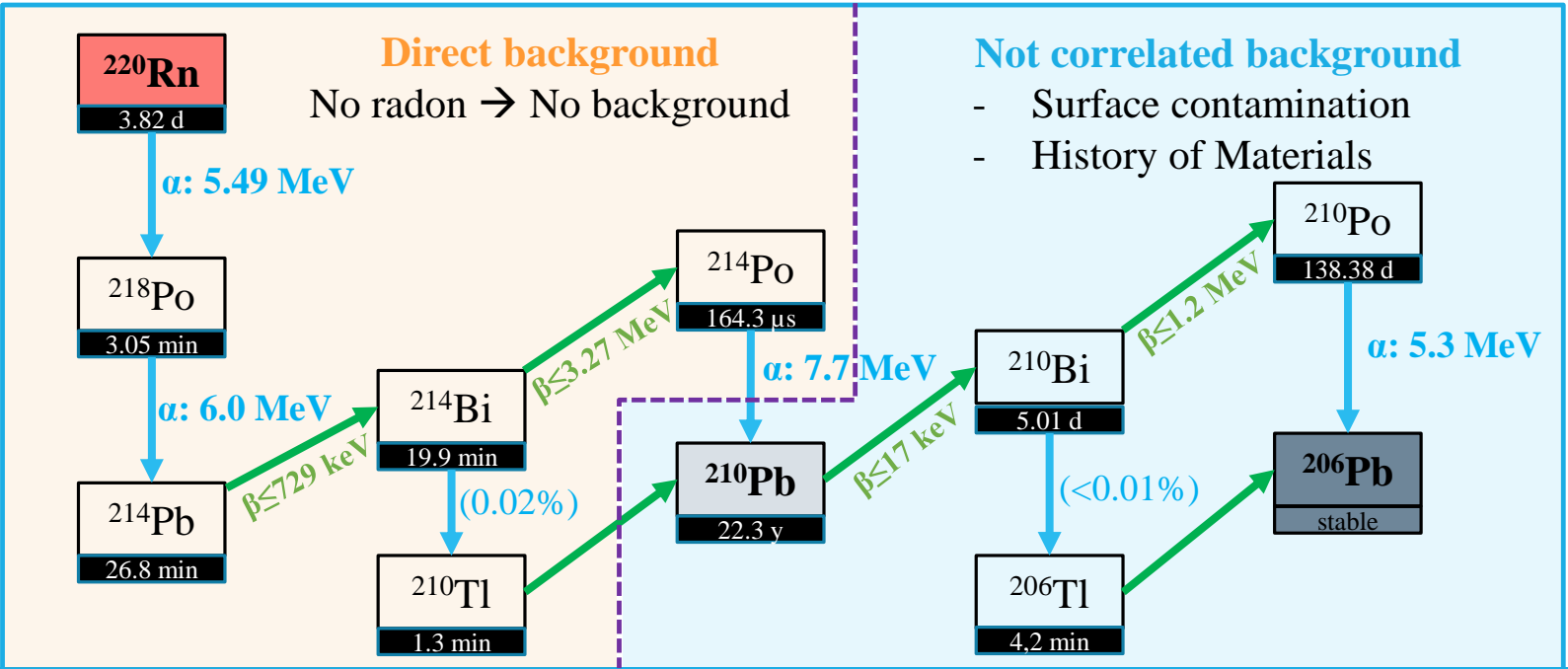
06/05/2026

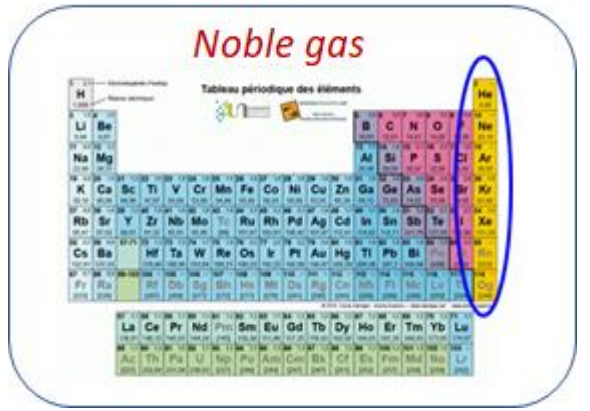
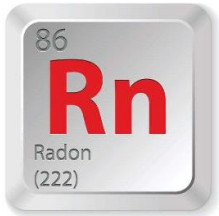
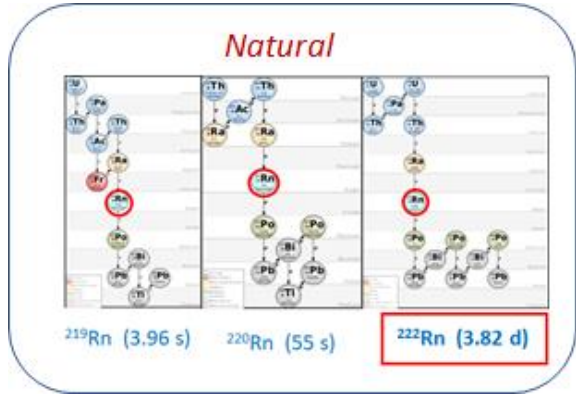


Natural, Radioactive, Noble gas from the U and Th chains

- Easy to transport, complicated to capture
- Short half-life, high intrinsic activity

→ α from 5 to 8 MeV
→ $\beta \leq 3.27$ MeV
→ $\gamma \leq 3.18$ MeV



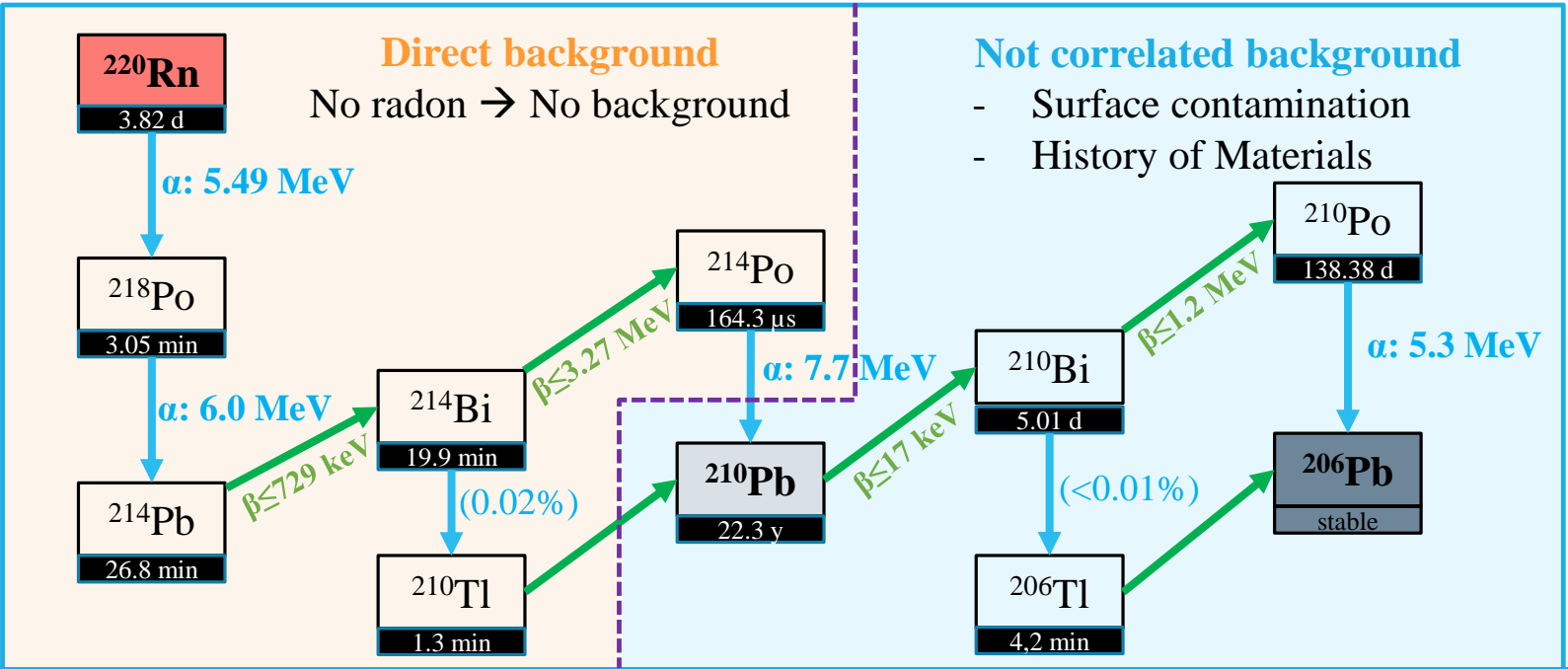


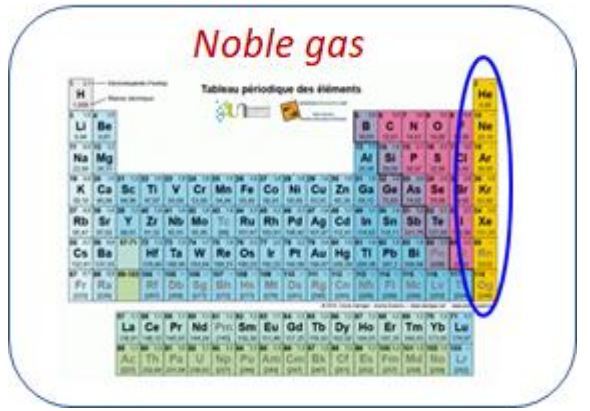
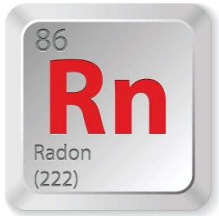
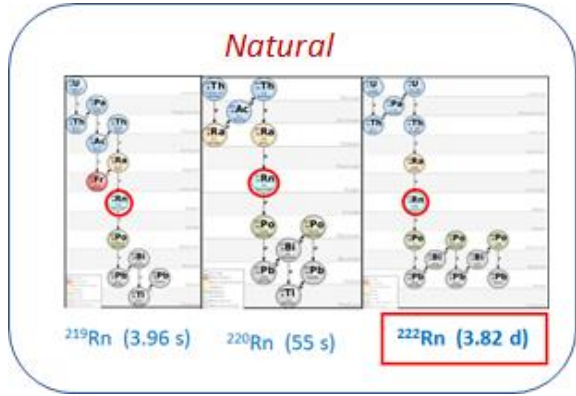
Natural, Radioactive, Noble gas
from the U and Th chains

Emanation

- Easy to transport, complicated to capture
- Short half-life, high intrinsic activity

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→ $\gamma \leq 3.18$ MeV





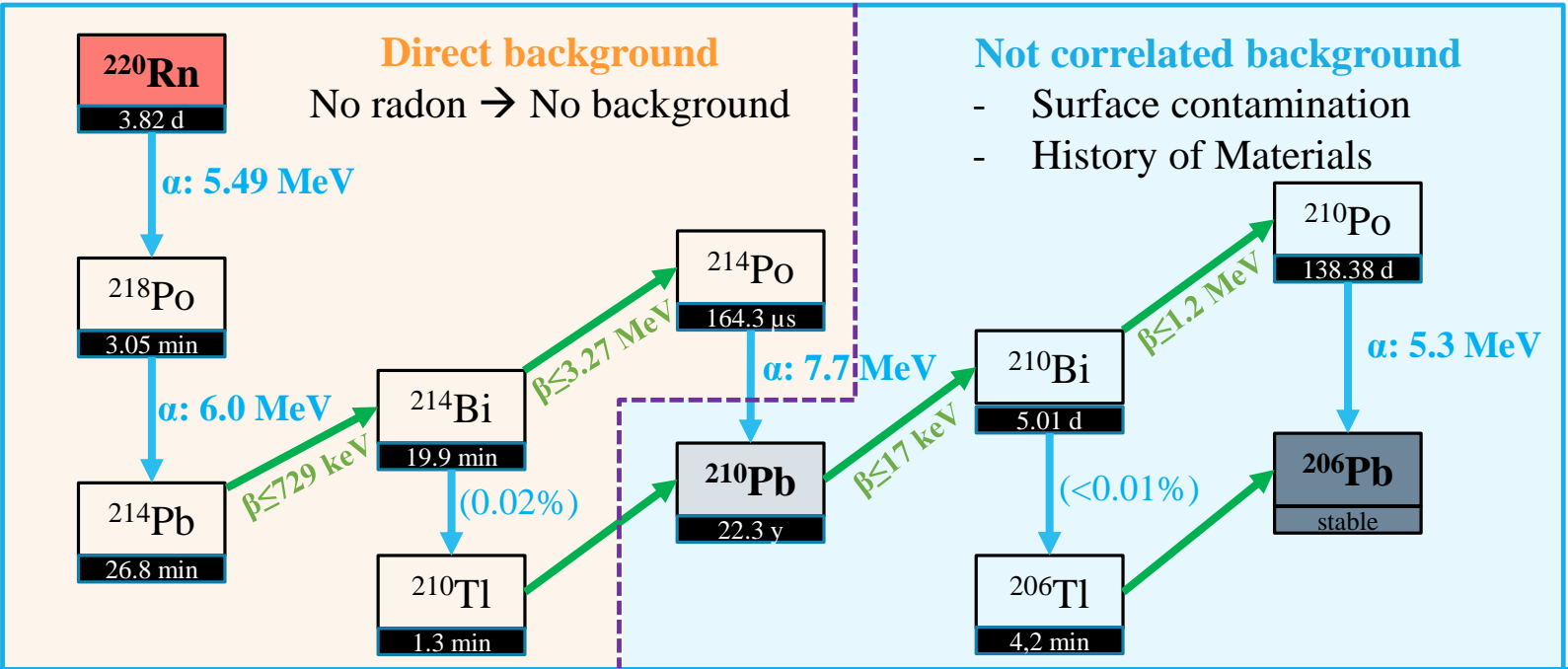
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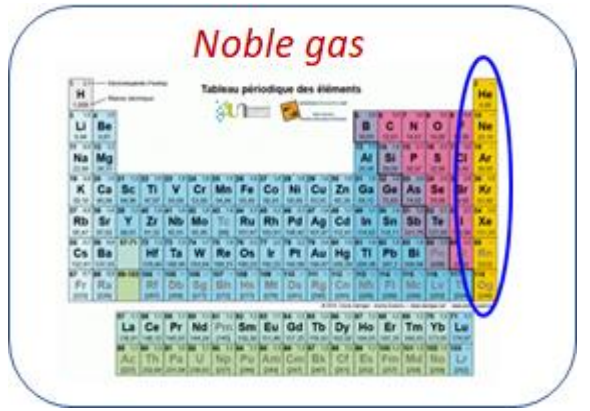
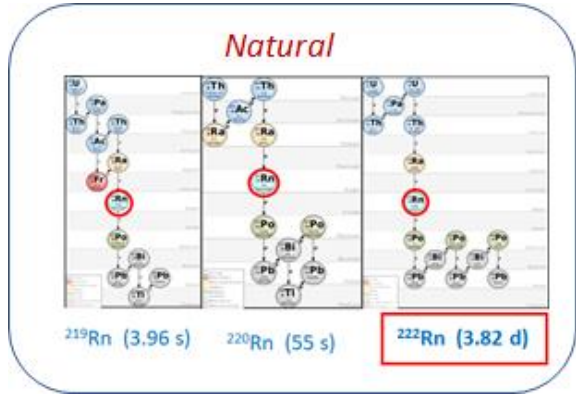
Emanation

- Easy to transport, complicated to capture
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Adsorption

- α from 5 to 8 MeV
- $\beta \leq 3.27$ MeV
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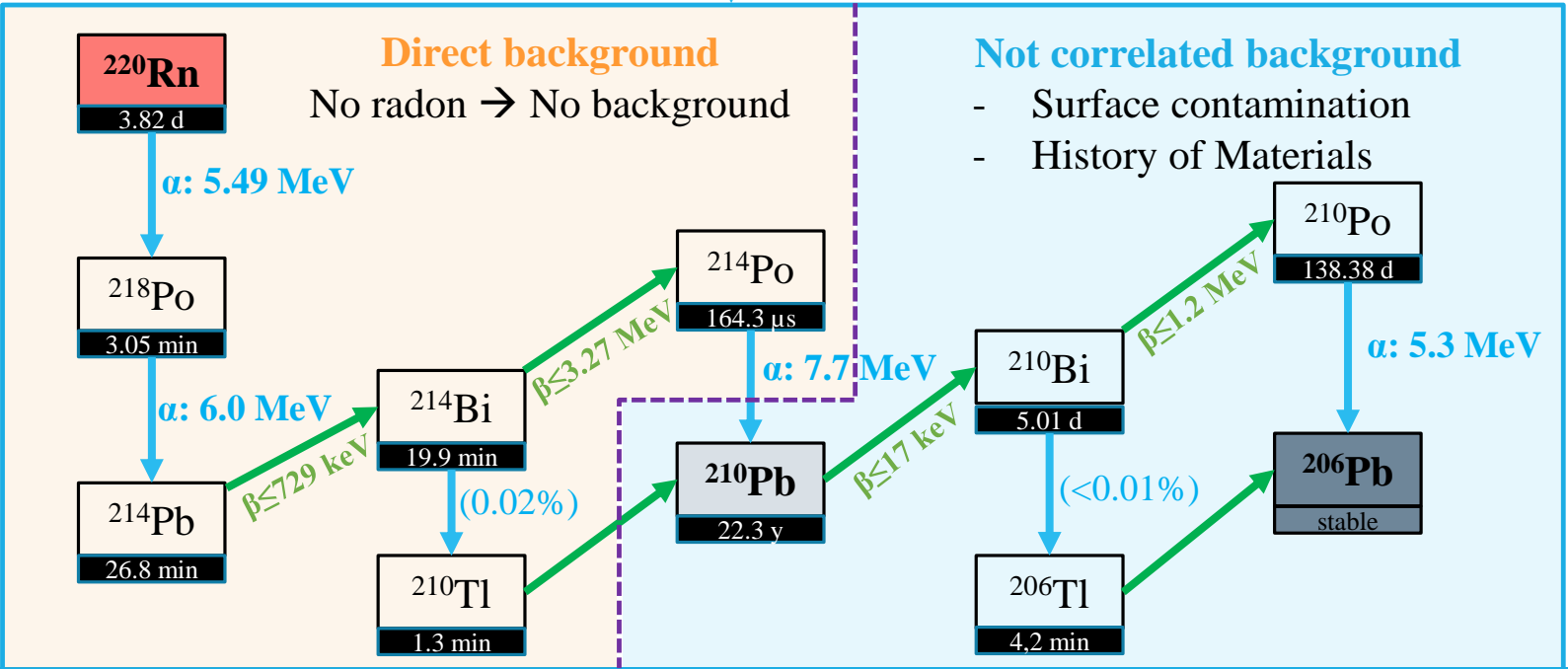
Natural, Radioactive, Noble gas
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Emanation

- Easy to transport, complicated to capture
- Short half-life, high intrinsic activity

Adsorption

→ α from 5 to 8 MeV
→ $\beta \leq 3.27$ MeV
→ $\gamma \leq 3.18$ MeV



Radon Capture

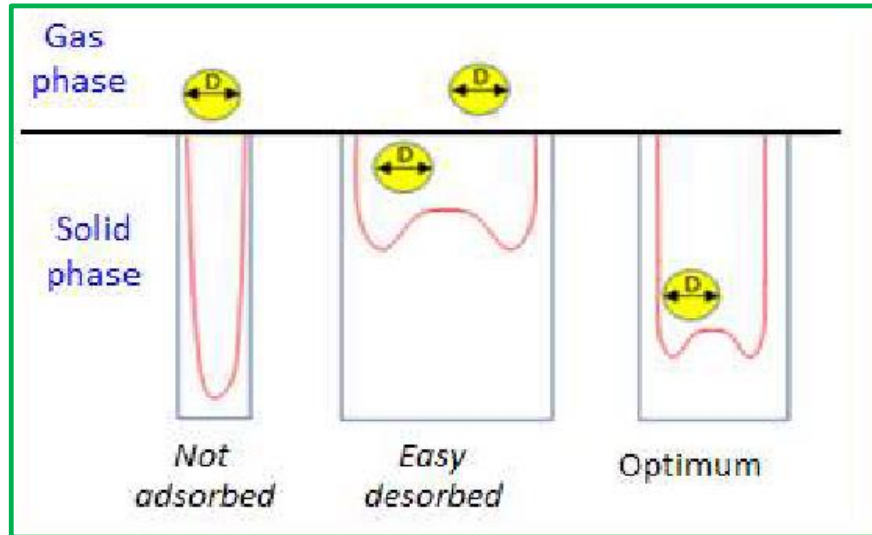
Rn is a Noble gas:

- No chemistry → Physical process

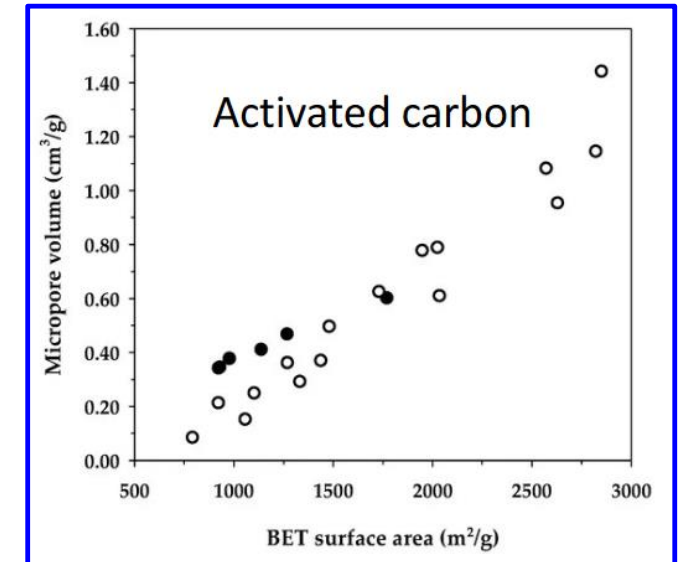
Physical adsorption:

→ **Surface** capture by Van der Waals forces

→ Use of porous materials: very high surface materials, up to 4000m²/g



Need to optimized Porosity



→ 2015 : Study of Rn capture in 50 commercial or research microporous materials (SuperNEMO)

- Activated charcoals
- Carbon molecular sieves
- Carbon aerogels (Granada Univ.)
- Molecular cages - CC3 (Liverpool Univ.)
- MOF
- Zeolites (Al, Si) (Marseille, Mulhouse Univ.)
- Dendritic polymers (Marseille)



UNIVERSITÉ D'AIX-MARSEILLE

ÉCOLE DOCTORALE PHYSIQUE ET SCIENCES DE LA MATIÈRE
(ED352)

CPPM/CiNaM

Thèse présentée pour obtenir le grade universitaire de docteur

Mention : Matière Condensée et Nanosciences

Étude et développement de substrats
microporeux pour l'adsorption du radon et
son application en physique du neutrino

NOËL Raymond

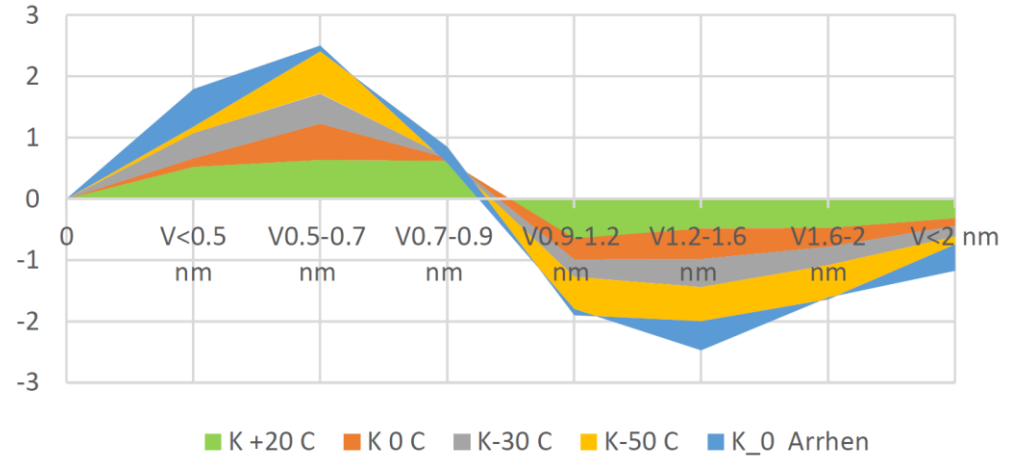
IRENE history

→ 2015 : Study of Rn capture in 50 commercial or research microporous materials (SuperNEMO)

Porosity from 0.5 to 2 nm

Échantillons	S _{BET} N ₂ (m ² /g)	V _{<0.5 nm} (cm ³ /g)	V _{0.5-0.7 nm} (cm ³ /g)	V _{0.7-0.9 nm} (cm ³ /g)	V _{0.9-1.2 nm} (cm ³ /g)	V _{1.2-1.6 nm} (cm ³ /g)	V _{1.6-2 nm} (cm ³ /g)	V _{<0.7 nm} (cm ³ /g)	V _{0.7-2 nm} (cm ³ /g)	V _{<2 nm} (cm ³ /g)
Carbosieve SIII (1)	1062	0,076	0,233	0,062	0,018	0,020	0,000	0,308	0,102	0,410
Carboxen 1000 (2)	812	0,064	0,161	0,044	0,001	0,000	0,000	0,225	0,045	0,270
Carboxen 569 (3)	299	0,074	0,011	0,000	0,000	0,000	0,000	0,085	0,000	0,085
K48S (4)	799	0,074	0,138	0,034	0,033	0,032	0,006	0,212	0,105	0,317
Nucleacarb 208C STEDA (5)	1298	0,053	0,136	0,084	0,087	0,106	0,044	0,189	0,321	0,510
SHIRASAGI G2x4 (6)	1383	0,051	0,161	0,096	0,090	0,103	0,033	0,212	0,322	0,534
Carboact (7)	1096	0,077	0,206	0,053	0,033	0,048	0,022	0,283	0,156	0,439
Environcarb 207C (8)	1073	0,075	0,181	0,058	0,046	0,050	0,011	0,256	0,165	0,421
K48 (9)	793	0,078	0,137	0,026	0,034	0,034	0,005	0,215	0,099	0,314
Nuclearcarb 208 5KI3 (10)	1315	0,057	0,145	0,081	0,084	0,110	0,046	0,202	0,321	0,522
Carboxen 1012 (11)	1140	0,074	0,145	0,054	0,076	0,078	0,016	0,219	0,223	0,443
Carboxen 1021 (12)	585	0,083	0,049	0,020	0,037	0,026	0,017	0,132	0,100	0,231
Carboxen 1016 (13)	77	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000	0,000
Carboxen 1018 (14)	804	0,061	0,155	0,045	0,010	0,024	0,014	0,216	0,092	0,308
Aquacarb 207C (15)	1040	0,063	0,165	0,066	0,044	0,052	0,019	0,228	0,181	0,409
Carbosieve G (16)	1273	0,074	0,183	0,112	0,046	0,050	0,025	0,257	0,233	0,490

Correlation Factor Adsorption v.s. porosite



Optimal porosity:

- 0.5 – 0.7 nm (Rn 0.4 nm)

Small effect on the chemical composition (Sulphur)

IRENE history

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- 0.5 – 0.7 nm (Rn 0.4 nm)

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→ 2018 : Xenon / Radon adsorption with macromolecular cages: Cryptophane



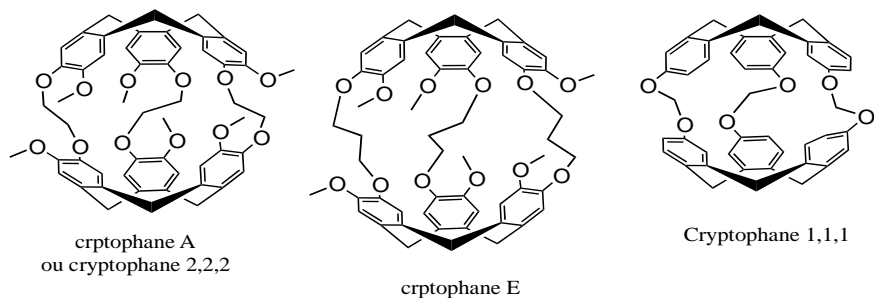
- Used for the complexing of Xe
- Adjustable size



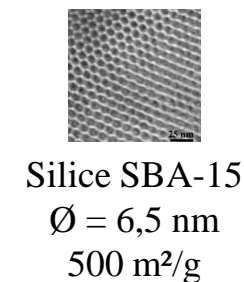
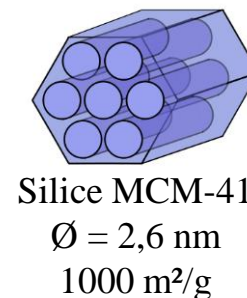
Atomic Radius		
Gas	Van der Waals (nm)	Covalent
Xe	0.216	0.130
Rn	0.220	0.145

Compétition Xe / Rn

Three types of cage



Two supports



IRENE history

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Rn Adsorption (CPPM)

Adsorbant	K (m ³ /kg) @ -30°C
YC-125: Cryptophane A/MCM-41	103,2 ± 25
YC-126: Cryptophane A/SBA-15	60 ± 15
YC-127: Cryptophane E/MCM-41	24 ± 6
YC-128: Cryptophane E/SBA-15	2 ± 6
Crystals of Cryptophane	0
AC K48 special	66,6 ± 5

Xe Adsorption (MADIREL)

Echantillon	Adsorption Xe (mmol/g)
Cryptophane A (MCM-41)	0.176 ± 0.010
Cryptophane A (SBA-15)	0.123 ± 0.006
Charbon actif Silcarbon K48	2.31 ± 0.04

13.12

IRENE history

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→ 2020 : Radon adsorption on silver zeolite



Three commercial Ag Zeolite

Zeolite	Supplier	Chemical formula	Silver content (wt%)	Pore size (Å)
Ag-ZSM-5	Riogen	$\text{Ag}_{4.8}[(\text{AlO}_2)_{4.8}(\text{SiO}_2)_{91.2}] \cdot 16\text{H}_2\text{O}$	7.9	5.2 × 5.7 and 5.3 × 5.6
Ag-13X	Sigma Aldrich	$\text{Ag}_{84}\text{Na}_2[(\text{AlO}_2)_{86}(\text{SiO}_2)_{106}] \cdot x\text{H}_2\text{O}$	35	10 × 10
Ag-ETS-10	Extraordinary Adsorbents Inc.	$\text{Ag}_{16}[\text{Si}_{40}\text{Ti}_8\text{O}_{104}]$	30	4.9 × 7.6

IRENE history

→ 2015 : Study of Rn capture in 50 commercial or research microporous materials (SuperNEMO)

Optimal porosity:

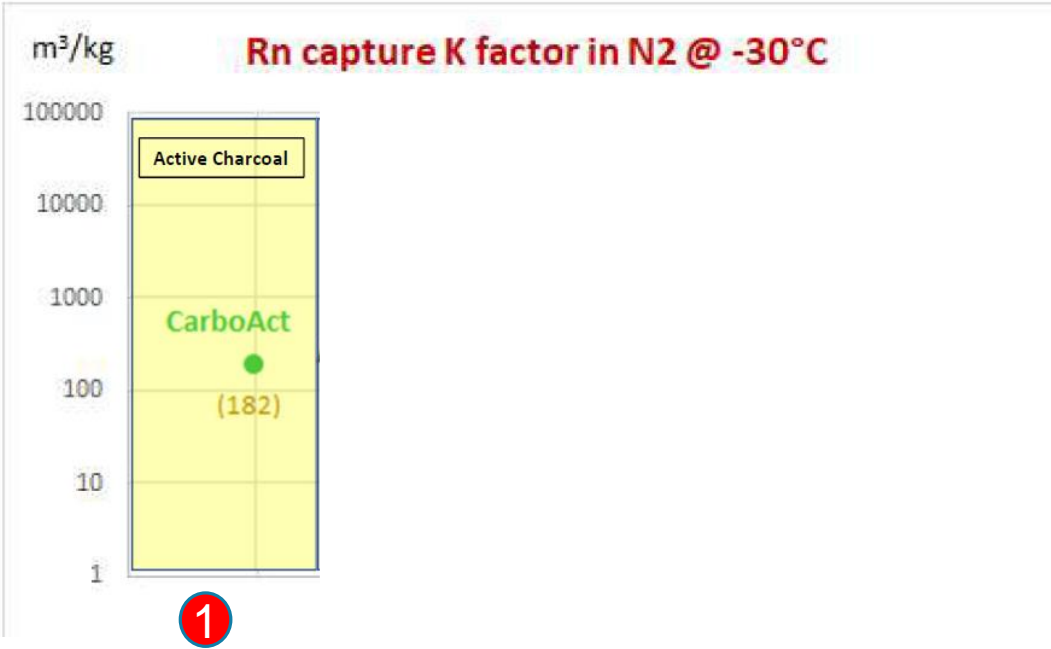
- 0.5 – 0.7 nm (Rn 0.4 nm)

Small effect on the chemical composition (Sulphur)

→ 2018 : Xenon / Radon adsorption with macromolecular cages: Cryptophane

→ 2020 : Radon adsorption on silver zeolite

$$K = \frac{\text{Rn in the Adsorbent}}{\text{Rn in the Gas}} \quad [\text{m}^3/\text{kg}]$$



① Reference charcoal (carboAct)

IRENE history

→ 2015 : Study of Rn capture in 50 commercial or research microporous materials (SuperNEMO)

Optimal porosity:

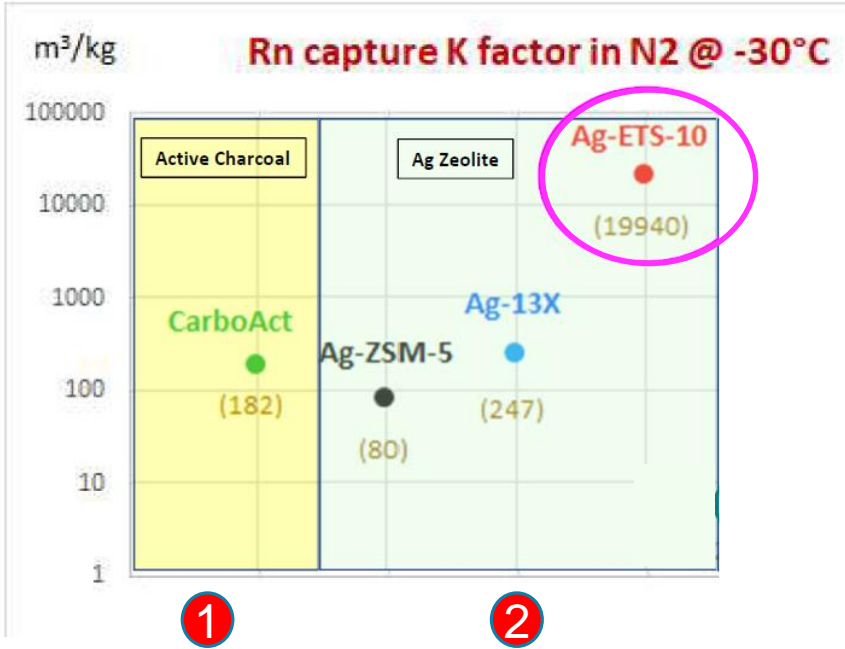
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- ① Reference charcoal (carboAct)
- ② Commercial Ag zeolites
 - Ag-ZSM-5
 - Ag-13X
 - Ag-ETS-10

IRENE history

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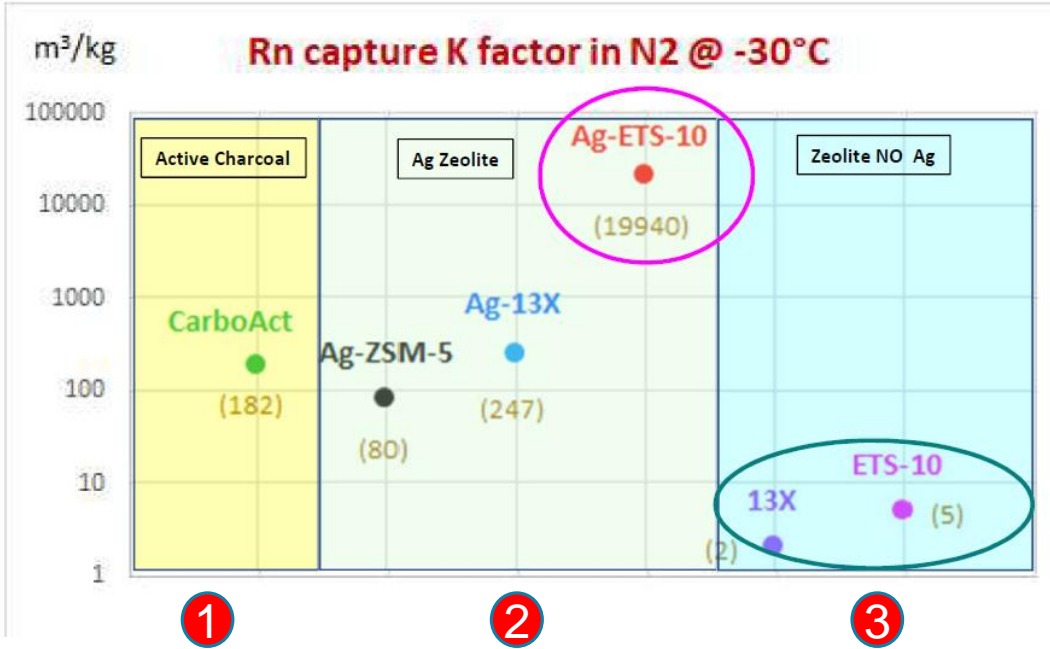
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$$K = \frac{Rn \text{ in the Adsorbent } [m^3/kg]}{Rn \text{ in the Gas}}$$



- 1 Reference charcoal (carboAct)
- 2 Commercial Ag zeolites
 - Ag-ZSM-5
 - Ag-13X
 - Ag-ETS-10
- 3 NO Ag zeolites
 - 13X
 - ETS-10

IRENE history

→ 2015 : Study of Rn capture in 50 commercial or research microporous materials (SuperNEMO)

Optimal porosity:

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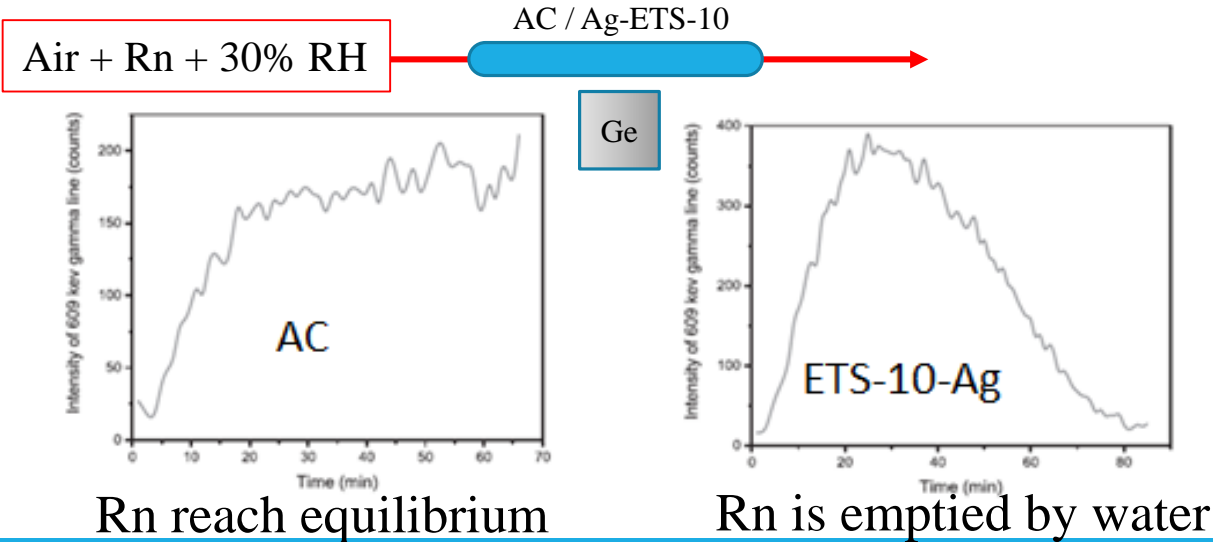
→ 2018 : Xenon / Radon adsorption with macromolecular cages: Cryptophane

→ 2020 : Radon adsorption on silver zeolite

High ²²⁶Ra concentration

Echantillon	226Ra (Bq/kg)
K48	< 0,25
NuclCarb 5TEDA	<0,3
ENvCarb 207C	0,28 +- 0,17
Shirasagi	0,164 +- 0,023
CarboAct	0,0023 +- 0,0019
ETS-10-AG	0,988 +- 0,05

High sensitivity to H₂O



IRENE history

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Small effect on the chemical composition (Sulphur)

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→ 2020 : Radon adsorption on silver zeolite

Other results

@ room temperature

Sample	Reference	K factor [m ³ /kg]
Ag-ETS-10	Heinitz et al.	3400
Ag-ZSM-5	Heinitz et al.	3500
8 Ag-FER-B	Takeuchi et al.	6500

AC @ 20°C : ~ 10 m³/kg

Very good results but not well understood

Can we do better ?

- Higher adsorption
- Improved radiopurity
- Lower sensitivity to water

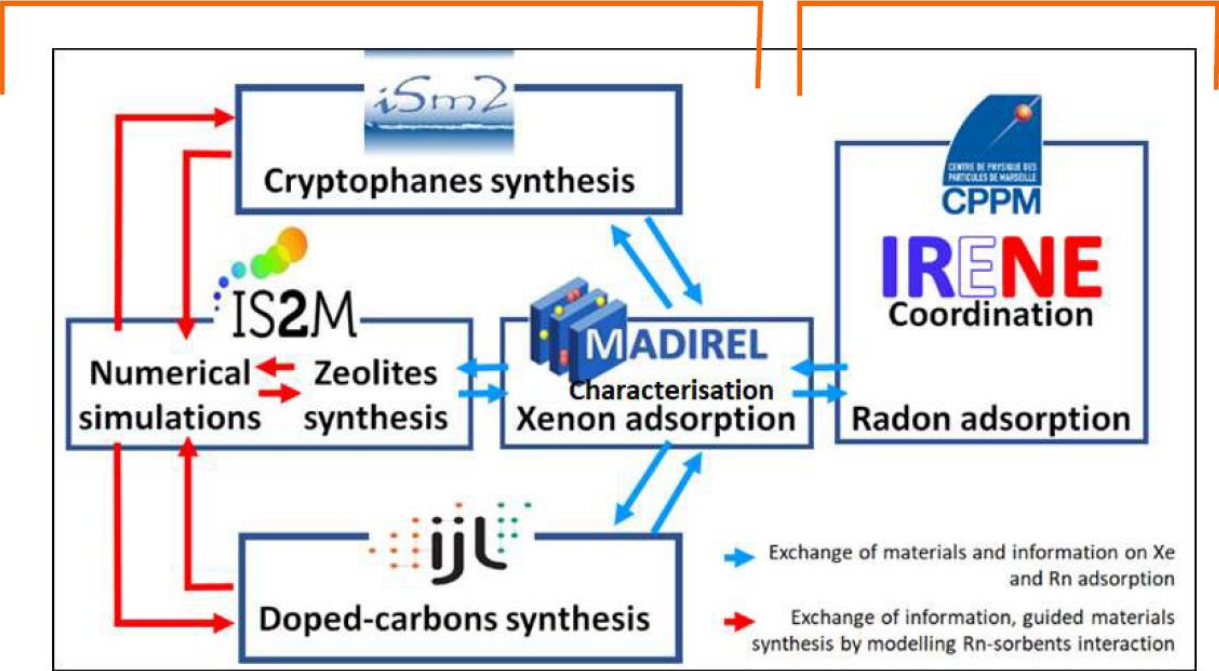
IRENE Project

Innovative mateRials for Extreme radoN capturE

Understanding and optimizing the capture of Rn in new materials

Physics Chemist

Part Physic



Project start in February 2024

Philosophy:

- Feedback between the 5 laboratories
- Modelling as a guide
- 3 families of adsorbents:
 - Zeolites
 - Mol. Cages
 - Carbon based
- Xenon as a reference gas
- Radon capture in N₂, He and Xe

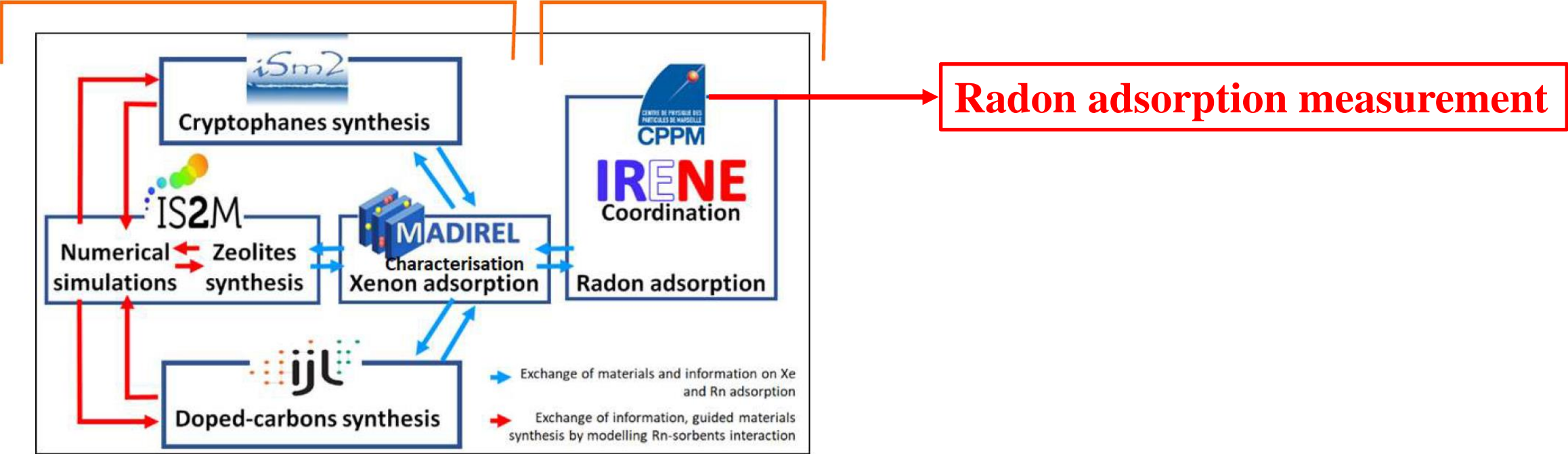
IRENE Project

Innovative materials for Extreme radon capture

Understanding and optimizing the capture of Rn in new materials

Physics Chemist

Part Physic



Radon adsorption coefficient “K”

K is the volume of radon a sample can capture:

- $$K \left[\frac{m^3}{kg} \right] = \frac{C(Rn)_{sample} [Bq/kg]}{C(Rn)_{gas} [Bq/m^3]}$$

The retention time τ is the time it take for Rn to exit the adsorbent

- $$\tau [s] = \frac{m[kg] * K [m^3/kg]}{\phi [m^3/s]}$$

And the reduction factor **R** is define as:

- $$R = \frac{Rn_{out}}{Rn_{in}} = e^{-\frac{\ln(2)}{T_{1/2}(Rn)} * \tau}$$

K can be expressed as an Arrhenius-type law:

- $$K = K_0 e^{\frac{Q}{RT}}$$

K increased exponentially with respect to 1/T

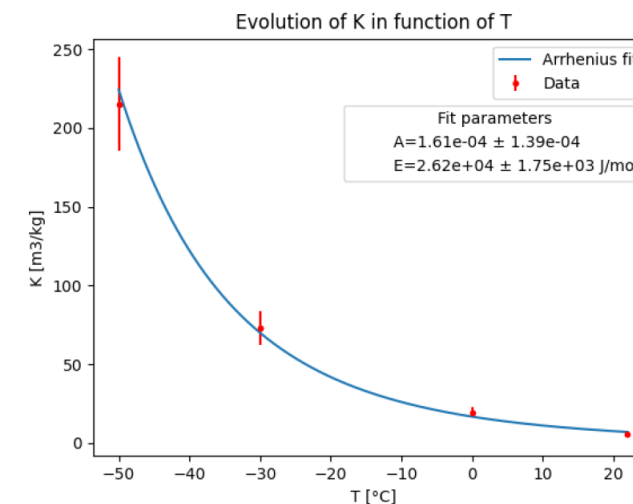


Figure 3.1: Graph of the variation of K with respect to the temperature for an adsorbent measured at CPPM. The fit is an Arrhenius-type law with factor $A = 1.61 * 10^{-4} \pm 1.39 * 10^{-4}$ and $E = 26247.17 \pm 1747.08 J/mol$.

How do we measure the K coefficient of Materials

Dynamical adsorption method

Similarly to chromatography on a column, we force Rn carried by a neutral gas (N₂, Ar, He, etc) through the adsorbent. When it is totally filled with Rn, we measure the Radon concentration inside with an HPGe. We can then calculate the K coefficient described previously.

- Measure the absolute K coefficient
- Reproducible measurement
- Take a long time (1 sample/day/bench)
- **Done in 3 step:**
 1. Activation of the sample
 2. Radonisation
 3. HPGe analysis

Activation

Objective:

- Ensure the reproducibility
- Maximum radon adsorption

Purpose:

- Removal of all traces of physically and chemically adsorbed molecules or atoms

How:

- Heating of the sample under vacuum or flow of neutral gas

Temperature and condition depends on adsorbent:

- AC/Zeolite \rightarrow 200°C+
- MOF & Molecular cage \rightarrow <100°C

CPPM activation bench:

- Temperature between 20 and 250°C
- Flow of N₂/Ar/He
- Vacuum

Heat control

Flow controller

Heater



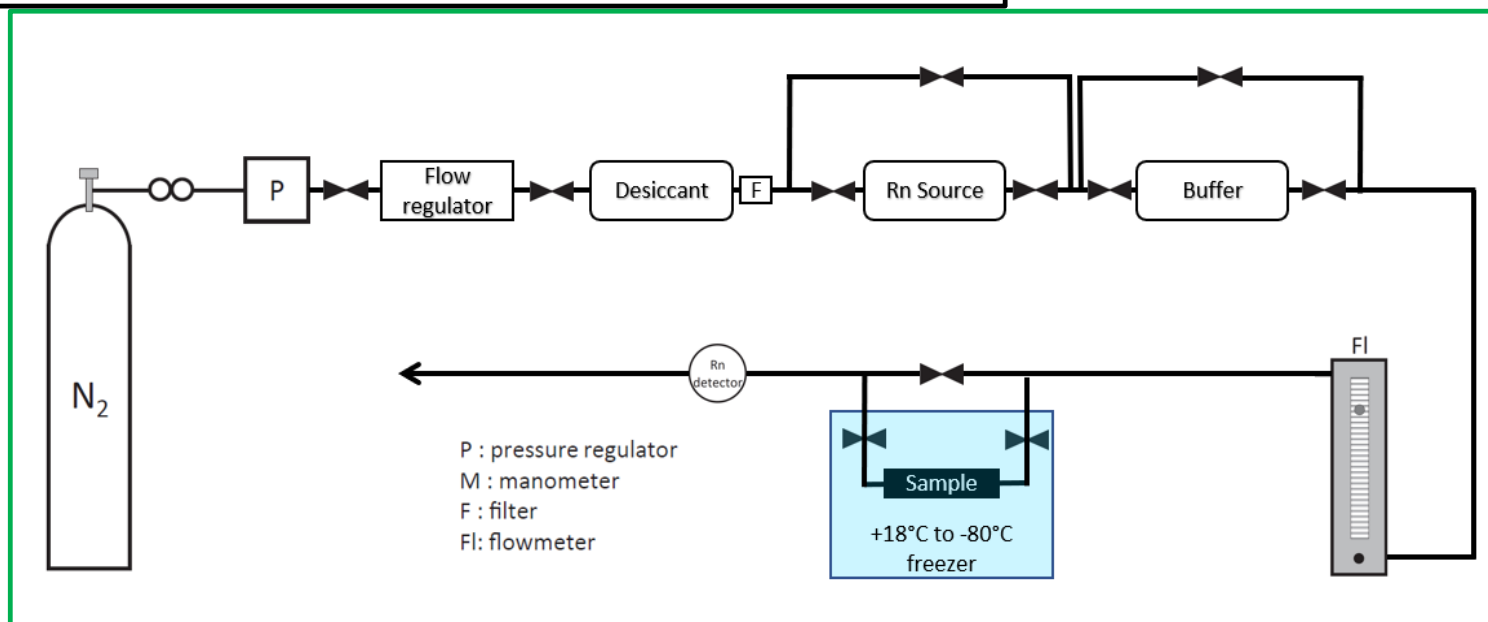
Radonisation

Set up:

- Send a constant concentration of radon through the sample
- Control of radon concentration with a Rn detector at the output
- Sample cooled at up to -80°C

CPPM platform bench:

- “Strasbourg”, open loop, $A = 932 \pm 18 \text{ Bq/m}^3$;
- “Marseille”, closed loop, $A = 1240 \pm 41 \text{ Bq/m}^3$;



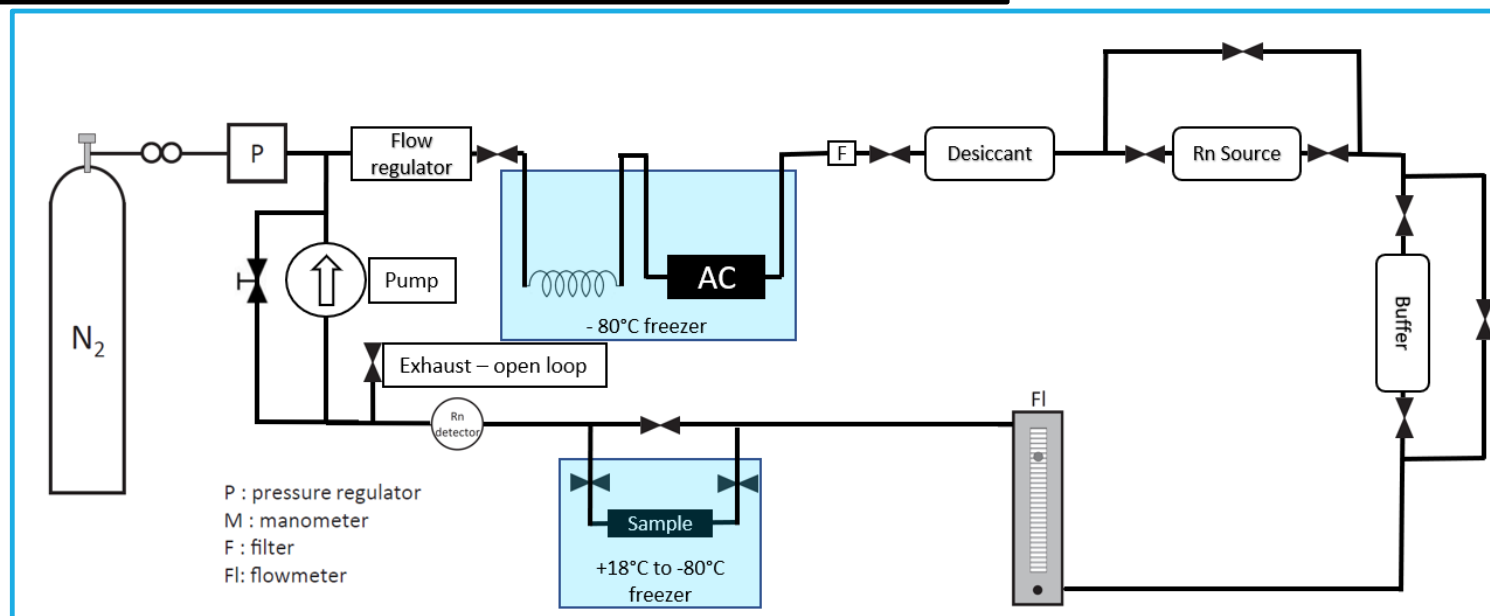
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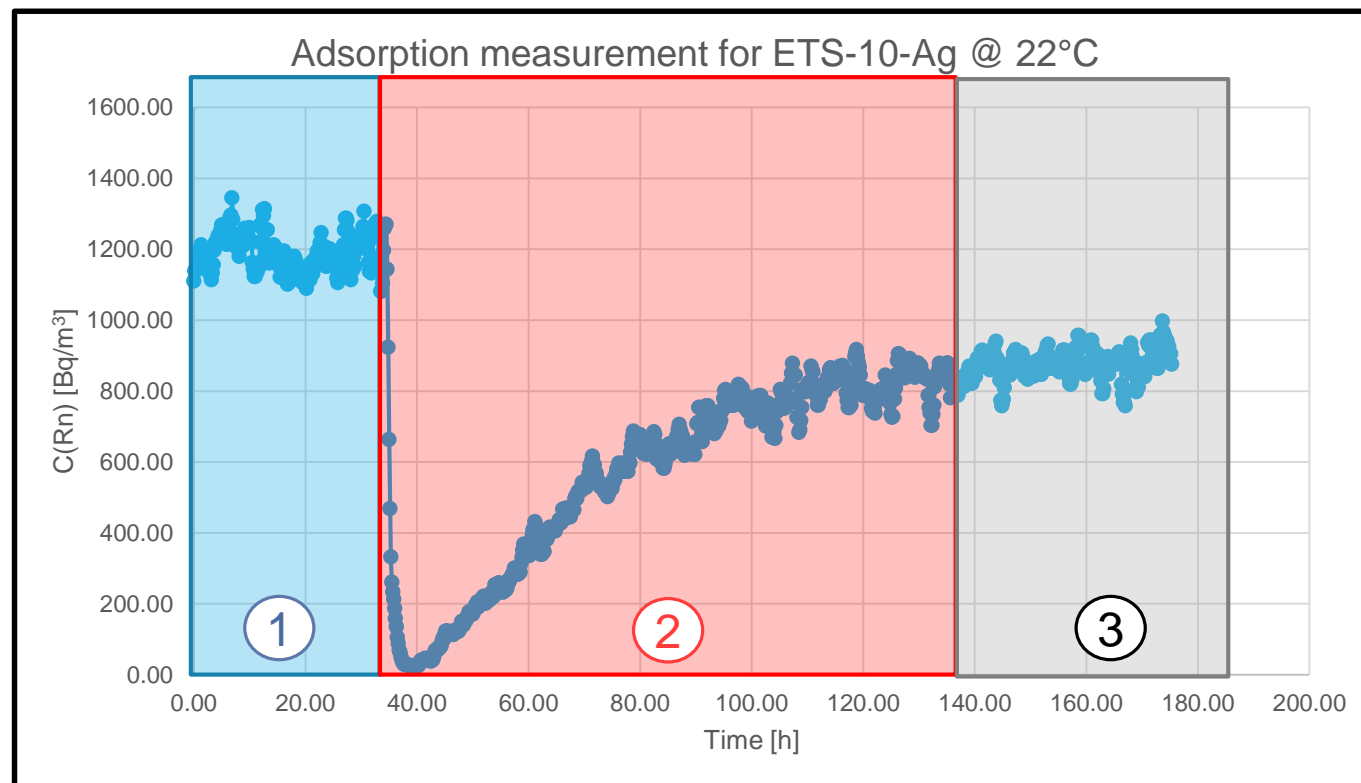
- “**Strasbourg**”, open loop, $A = 932 \pm 18 \text{ Bq/m}^3$;
- “**Marseille**”, closed loop, $A = 1240 \pm 41 \text{ Bq/m}^3$;



Radonisation

Typical Rn concentration change:

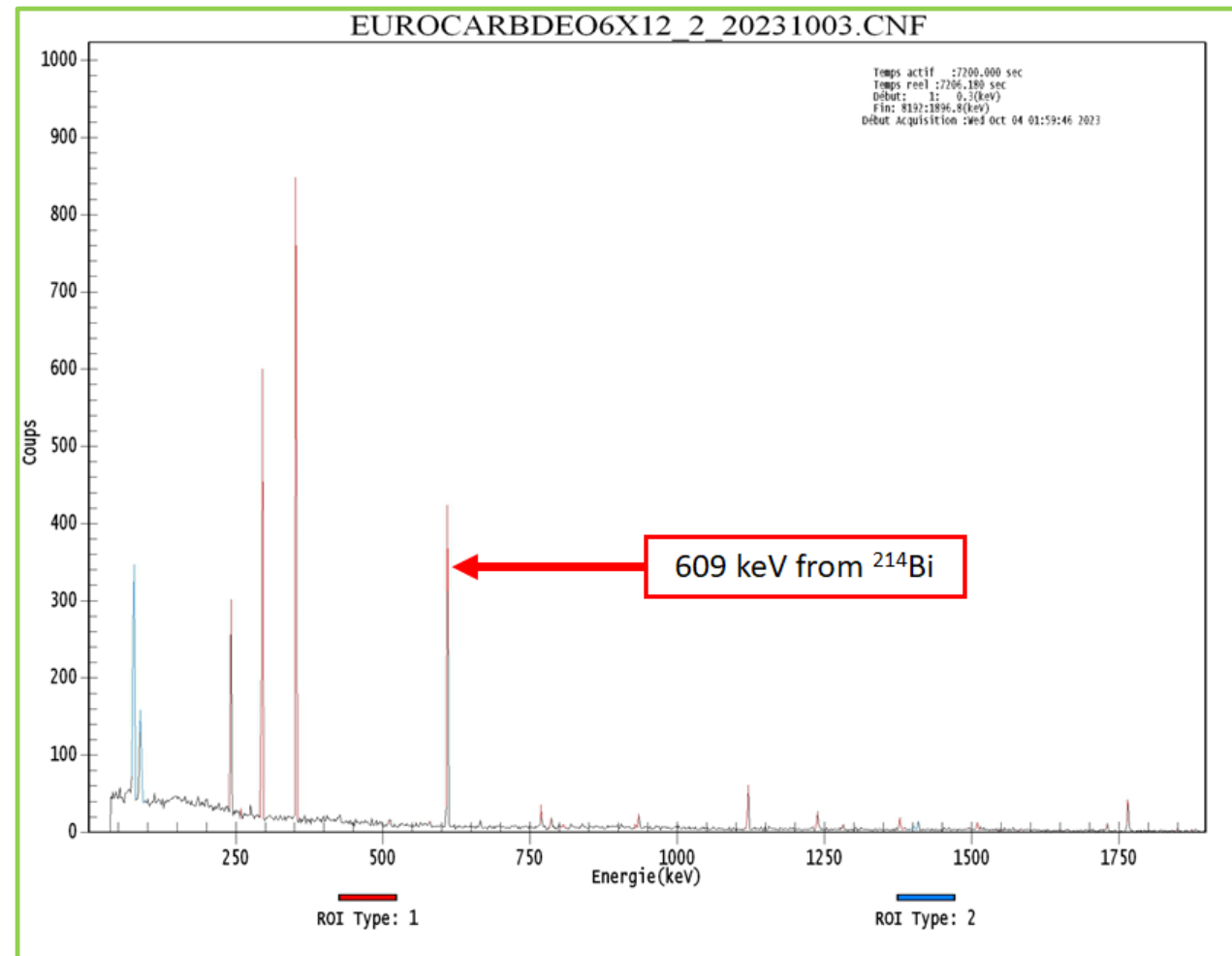
1. Carrier gas is radonised to a concentration C_1 , “initialization”
2. Flushed through the column, “adsorption”
3. $C(\text{Rn})$ stabilized at a value C_2 , “saturation”



HPGe measurement

Measurement of the Radon inside the sample by gamma spectrometry

- 100 cm³ HPGe shielded by 15cm lead shielding
- Measurement of ²¹⁴Bi 609 keV gamma line
- A_{sample} in Bq/kg



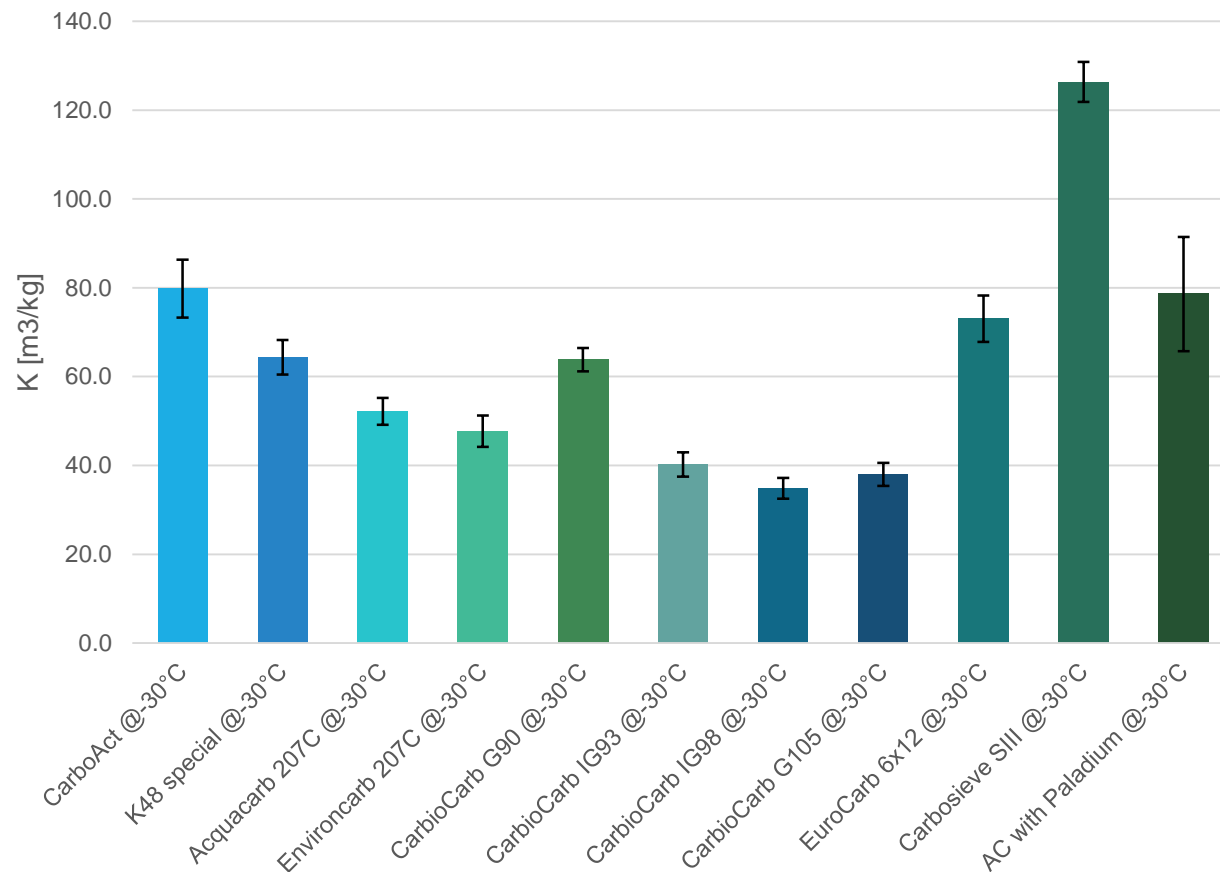
Adsorption coefficient measurement

Measurement of:

- Active Charcoal
- Molecular sieves
- Carbon aerogels
- Molecular cages
- MOF
- Zeolite
- Doped charcoal
- Etc

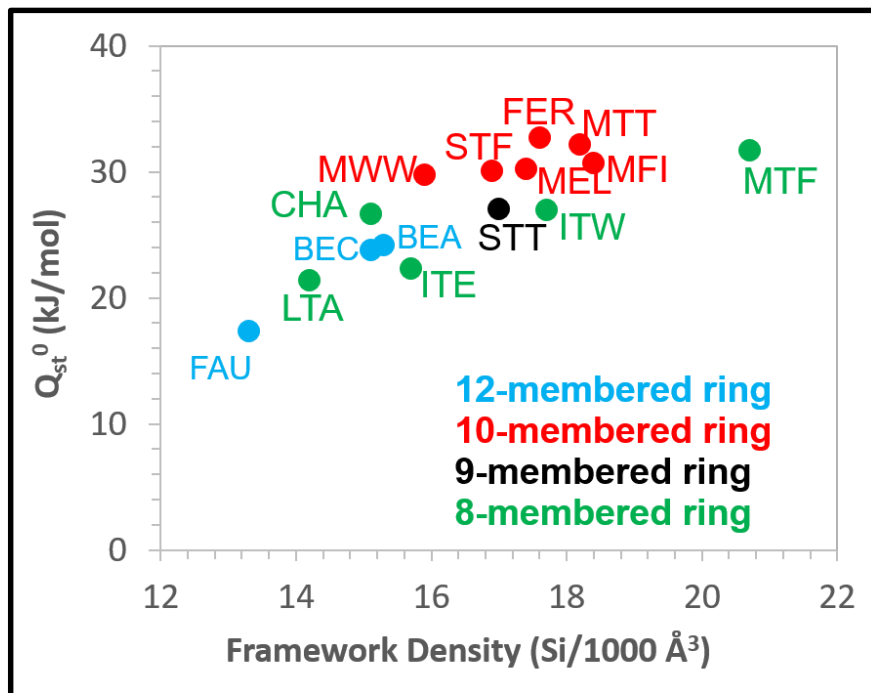
From Ambient temperature to -50°C

AC adsorption coefficient $K[\text{m}^3/\text{kg}]$ @ -30°C

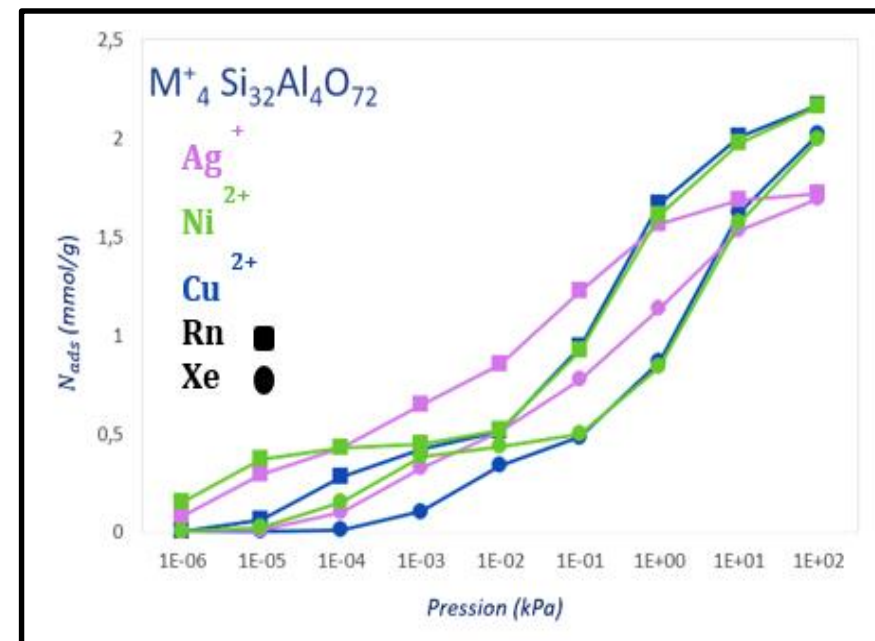


Simulations

Influence of membered ring configuration



Influence of Metal on Rn/Xe adsorption



- Zeolite with 10MR are the best candidate for Rn adsorption
- Cu⁺ Ni²⁺ should perform better than Ag⁺

Synthesis & measurement

Zeolite synthesis :

- FER – Ag (50% exchanged) → $K = 93,7 \pm 10,8 \text{ m}^3/\text{kg} @24^\circ\text{C}$ (AC standard $\sim 10 \text{ m}^3/\text{kg} @24^\circ\text{C}$)
→ $K = 543 \pm 52 \text{ m}^3/\text{kg} @-30^\circ\text{C}$
- LTA – 50% Ni^{2+} 50% Ag^+ → ongoing measurement but potentially good

Charcoal treated with HNO_3 to remove Radium:

- Base charcoal is Carbio12 G90: $A(\text{Ra}) = 0,24 \pm 0,04 \text{ Bq/kg}$
- Carbio12 G90 treated with HNO_3 : $A(\text{Ra}) < 0,16 \text{ Bq/kg}$

But the radon adsorption is reduced by a factor 2 :

- Carbio12 G90: $K = 63,83 \pm 5,3 \text{ m}^3/\text{kg}$
- Carbio12 G90 HNO_3 : $K = 34,3 \pm 3,9 \text{ m}^3/\text{kg}$

We continue to work on simulations and on the production

Ultra pure adsorbent shortage

De : "Koppes, M. (Martien)" <martien.koppes@tno.nl>
Date : 11/11/2025 00:29 (GMT+01:00)
À : "Koppes, M. (Martien)" <martien.koppes@tno.nl>
Objet : Ultra Pure Activated Carbon

End of Carboact production !

Dear Sir/Madam,

We would like to inform you that Carbo-act International is discontinuing the production of Ultra Pure Activated Carbon.

Because your organization has purchased our product in the past, we would like to bring the following to your attention:

If you are still interested in our product, a limited quantity is still available. This is offered at €7.20 per gram (previously €16.30), with a minimum order of 500 grams.

If you would like to produce Ultra Pure Activated Carbon yourself, the know-how of the production process is available for purchase upon consultation.

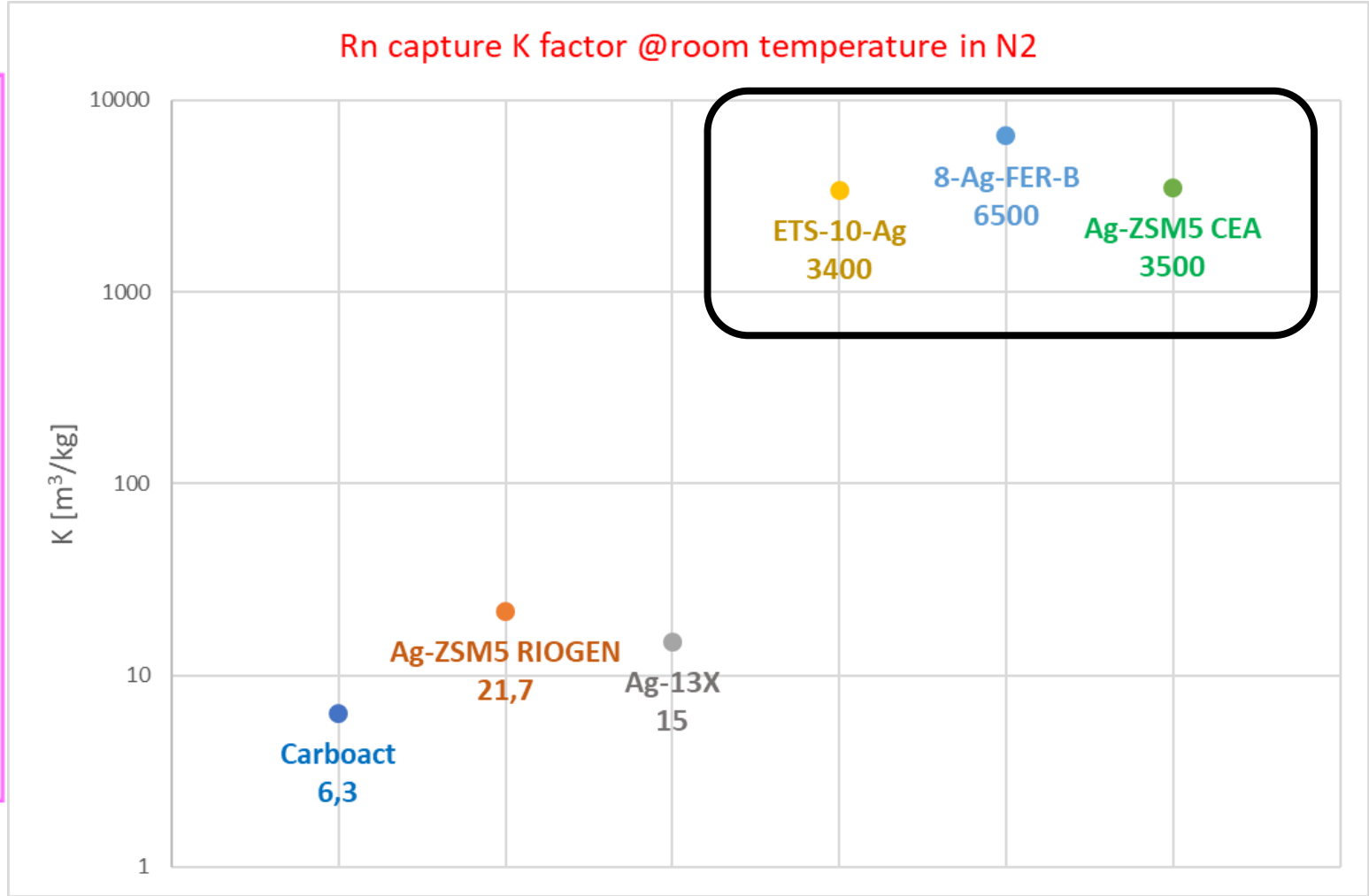
Kind regards,

Jack Peters & Martien Koppes

Carbo-act International

What options ?

$$K = \frac{\text{Rn in the Adsorbent} \text{ [m}^3\text{/kg]}}{\text{Rn in the Gas}}$$



What options ?

8-Ag-FER-B :

- Not commercial
- Did not measure it

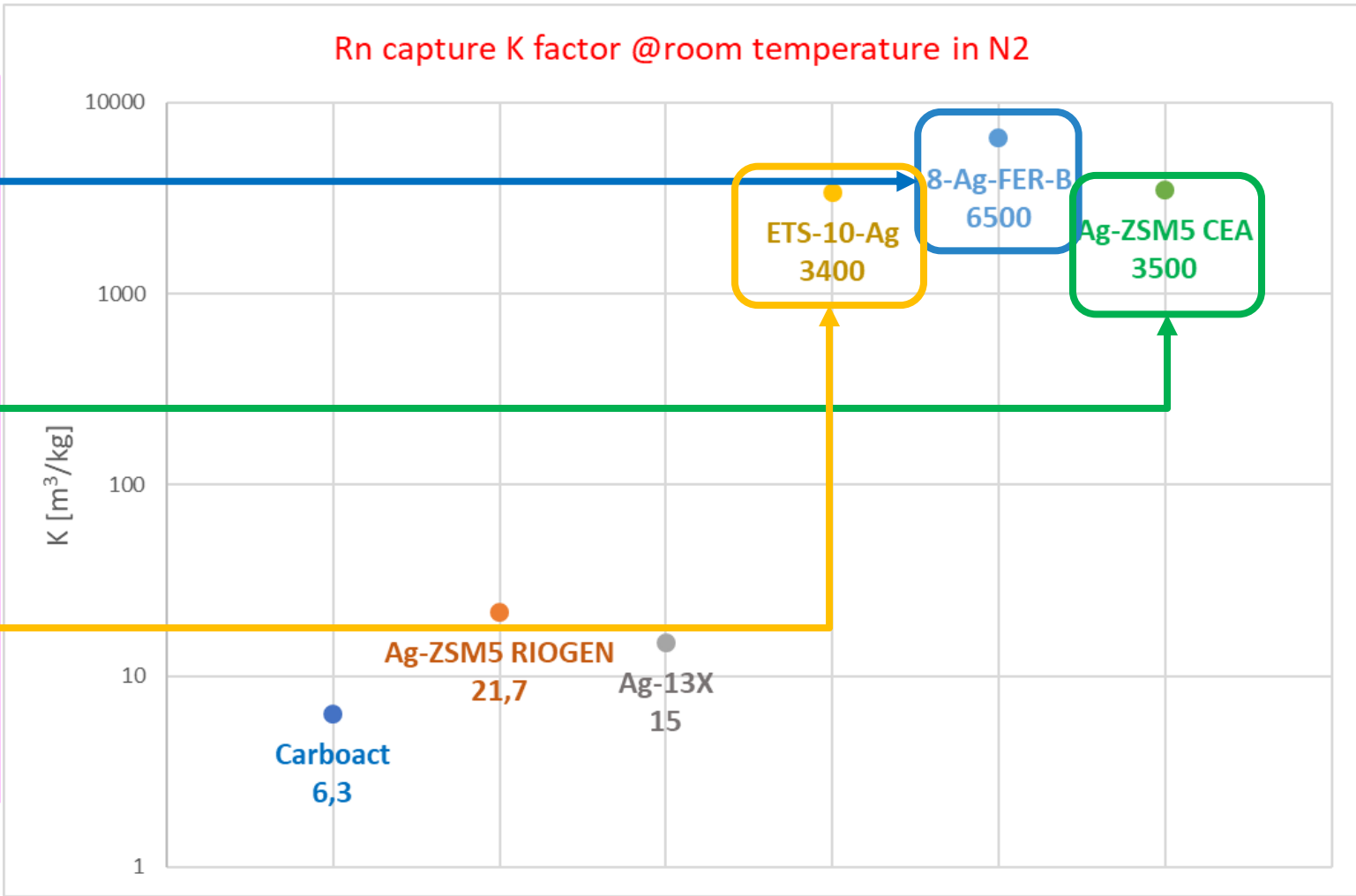
Ag-ZSM5 CEA :

- Not commercial
- Inconsistent K factor

ETS-10-Ag :

- Commercial
- High Ra concentration

$$K = \frac{Rn \text{ in the Adsorbent } [m^3/kg]}{Rn \text{ in the Gas } [m^3/kg]}$$



What options ?

ETS-10-Ag :

- Commercial
- High Ra concentration

Contact taken with Extraordinary materials

Radium mainly come from the Ag extraction:

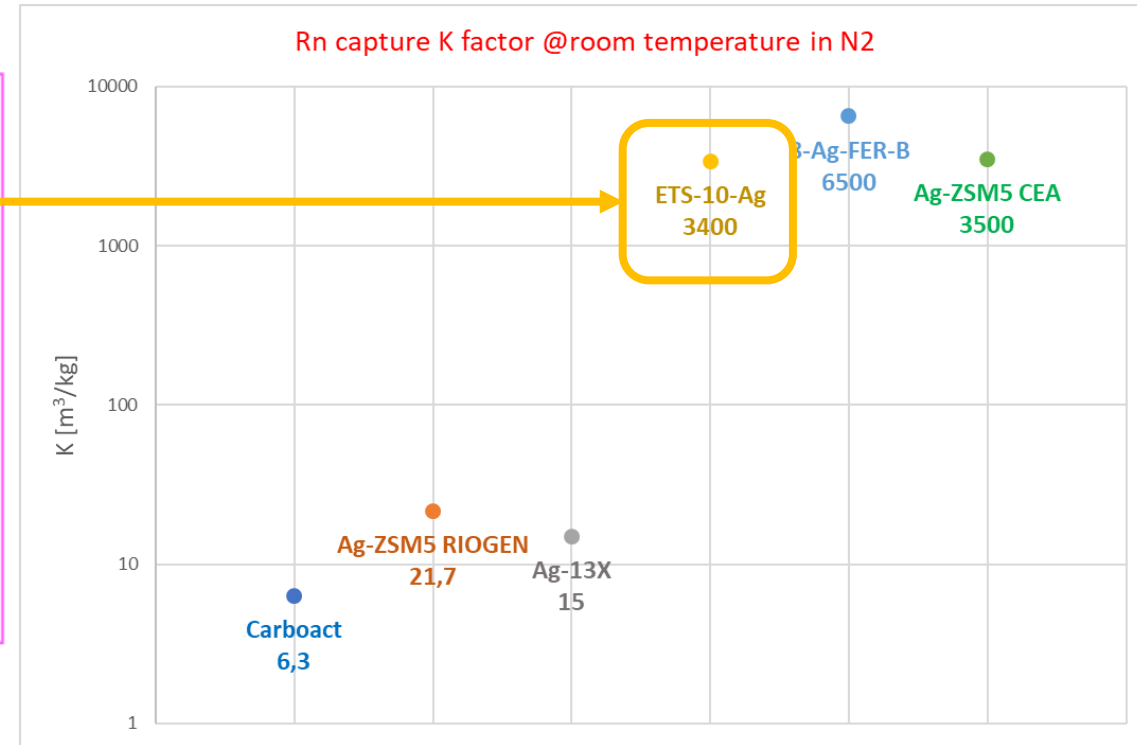
- ETS-10-Ag: $A(\text{Ra}) = 0,957 \pm 0,26 \text{ Bq/kg}$
- ETS-10: $A(\text{Ra}) = 0,3 \pm 0,12 \text{ Bq/kg}$

They will produce few grams of ETS-10 with:

- Purer Ag
- And other binder

Objective is to have an ultra pure and extraordinary adsorbent

$$K = \frac{\text{Rn in the Adsorbent}}{\text{Rn in the Gas}} \text{ m}^3/\text{kg}$$



Conclusion

- Low-energy and low-counting rate experiments require materials with extreme purity and ultra-low radon concentration.
- Materials with adsorption capacities more than 100 times higher than the best active carbons are now commercially available but they do not have the necessary purity levels and their performance are not well understood.
- Possible improvements in radon capture can be reached by choosing the right chemical composition and good porous structure.
- The objective of the **IRENE** project is to tackle the problem of radon capture in microporous materials in a scientific and coherent way, thanks to a unique consortium of physical chemists and particle physicists
- **IRENE** is now in the phase of producing new adsorbent doped with silver and other metals
- We produced a FER-Ag with an adsorption factor 10 times better than an AC → Publication ongoing

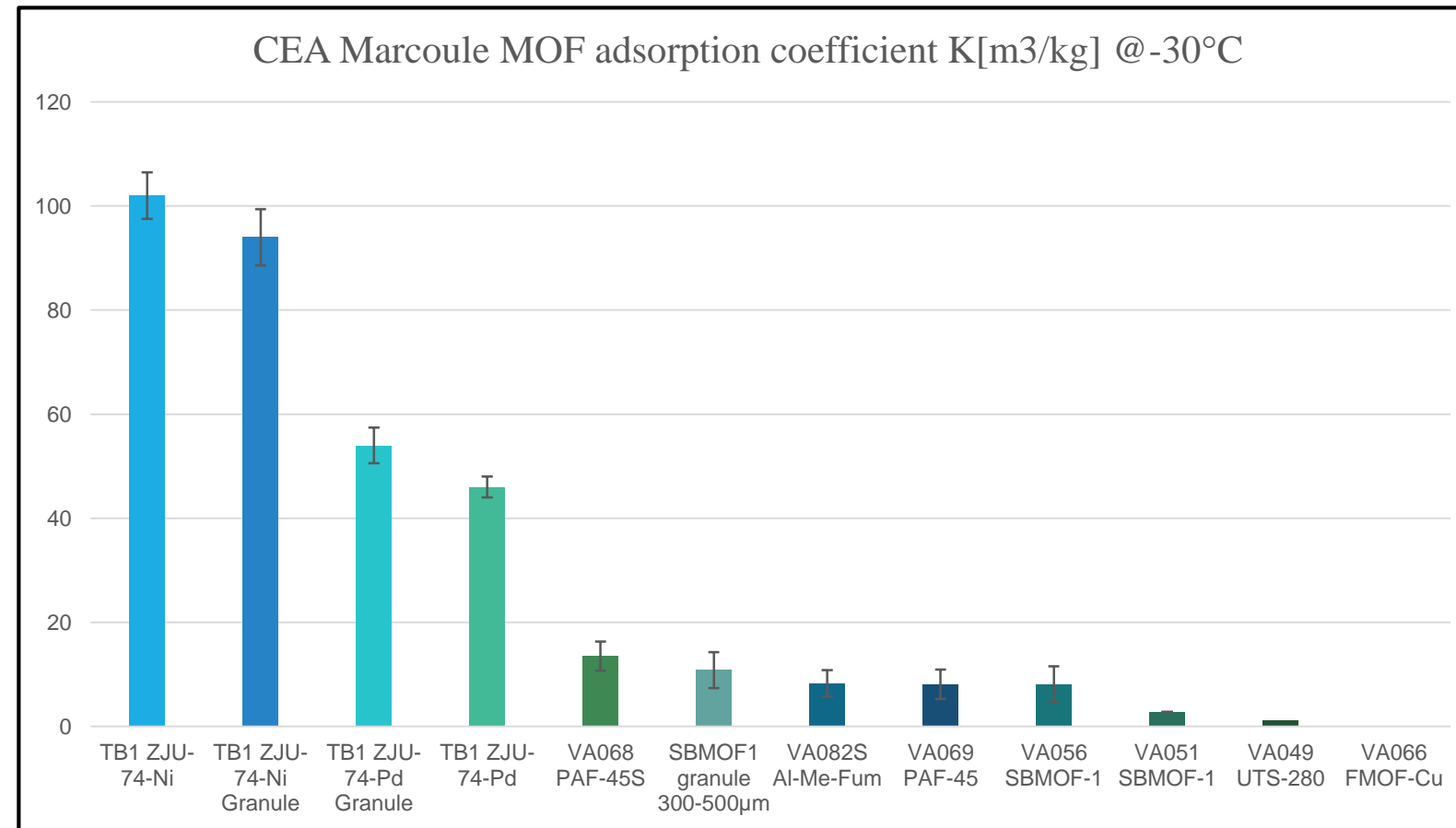
Thanks for your attention

Back up

Adsorbent measurement

12 MOF from CEA Marcoule :

- MOF with Ni is the most performant



Measurement of Extremely Adsorbent at high Temperature:

- For extremely adsorbent materials, low temperature measurement is complicated.
- Maximum K measurable for 0,2g is $39 \times 10^3 \text{ m}^3/\text{kg}$; $10^4 \text{ m}^3/\text{kg}$ for 0,8g.
- We can lower the mass, but it increase the uncertainty and enhanced the sensibility to humidity
- K can be expressed as an Arrhenius-type law:
 - $K = K_0 e^{\frac{q}{RT}}$

Goal: Estimate the K factor of extremely adsorbent materials at low temperature by measuring K at high temperature and with an higher mass.

→ Adsorption at high temperature is a advantage for the Rn purification of gas mixture.

Measurement of Extremely Adsorbent at high Temperature:

Preliminary Results with ETS-10-Ag

- ETS-10-Ag measured at -5, 22, 40, 80, 100 and 150°C, mass between 0,8 and 0,9g

Temperature [°C]	K[m ³ /kg]
-30	19940 ± 5980,8
-12	9951,9 ± 2404,6
-5	6593,8 ± 684,6
22	2332,1 ± 165,5
40	989,1 ± 63,1
80	186,5 ± 11,7
100	136,8 ± 8,0
150	29,3 ± 2,3

From DOI: 10.1093/ptep/ptad160

→ ETS-10-Ag K factor is still significant at high temperature !

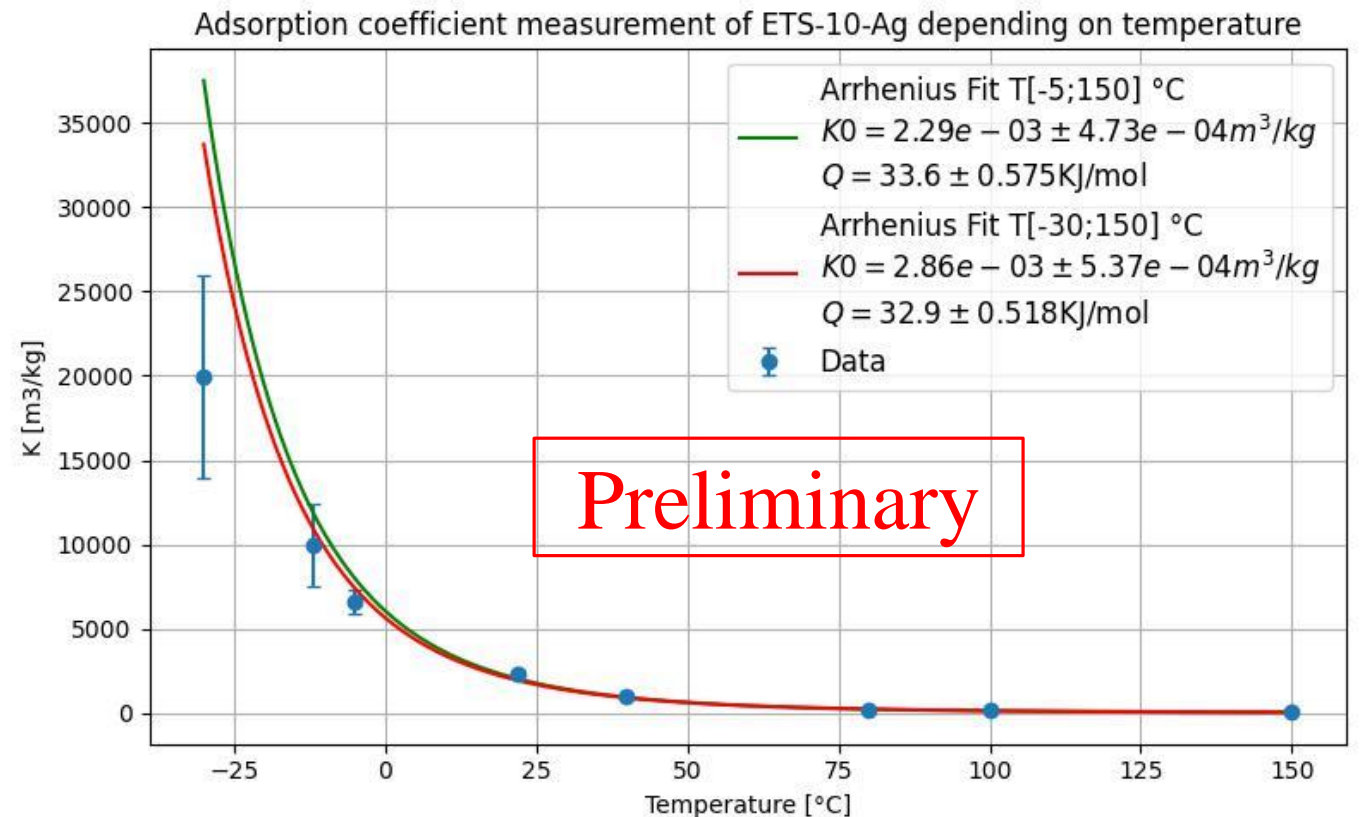
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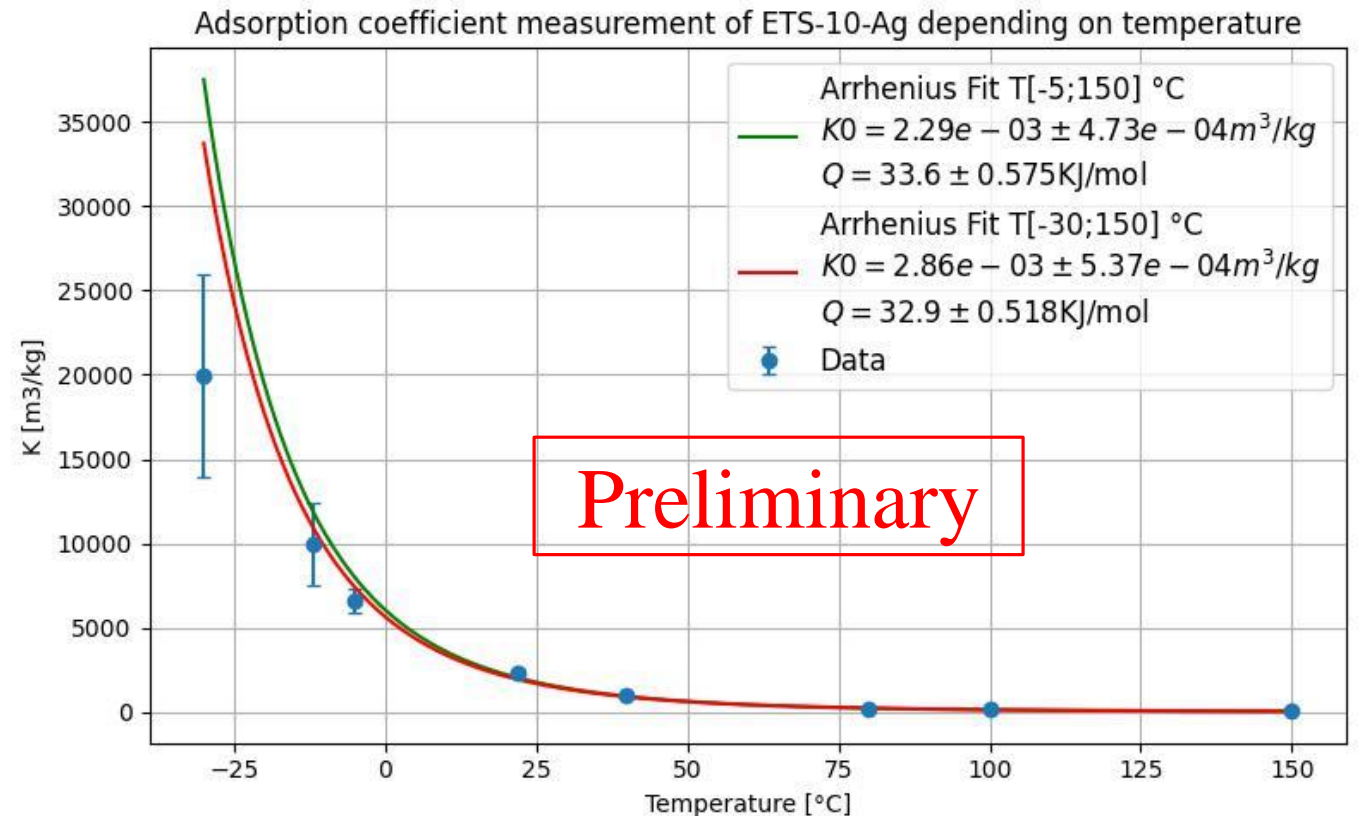


Measurement of Extremely Adsorbent at high Temperature:

Preliminary Results with ETS-10-Ag

- ETS-10-Ag measured at -5, 22, 40, 80, 100 and 150°C, mass between 0,8 and 0,9g

- Fit is in accordance with data up to -12°C.
- Need more measurement at inflexion point to improve K_0 and Q estimation.



Adsorption

Radonisation

CPPM platform bench:

- “Marseille”, closed loop, $A = 1240 \pm 41 \text{ Bq/m}^3$;

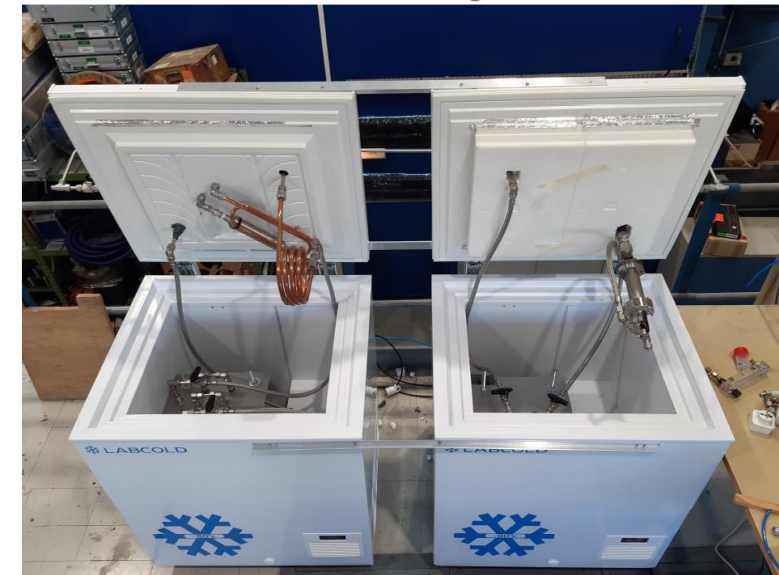
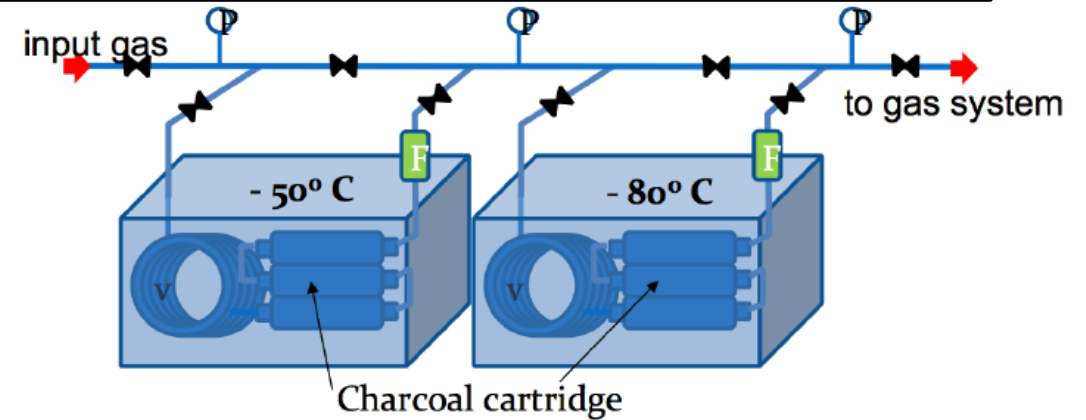


Side Project: Recycling & Purification system

- Gas price inflation since Ukraine/Russian war
 - Throw out gas is now too expensive
- Need for recycling system
- Imply purification of gas from radon and other contaminant
- Adsorption and gas system knowledge of the CPPM radon platform fit

Three system have been made:

1. **J-Trap**: Radon removal system



Side Project: Recycling & Purification system

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Three system have been made:

1. **J-Trap:** Radon removal system
2. **GPS:** Rn removal and recycling system for XIA

XIA run with Ar from LAr evaporation:

→ 1 run cost 1k€

Objective:

- Use Ar by purifying it and recycling it to reduce the run cost.



Adsorption

Side Project: Recycling & Purification system

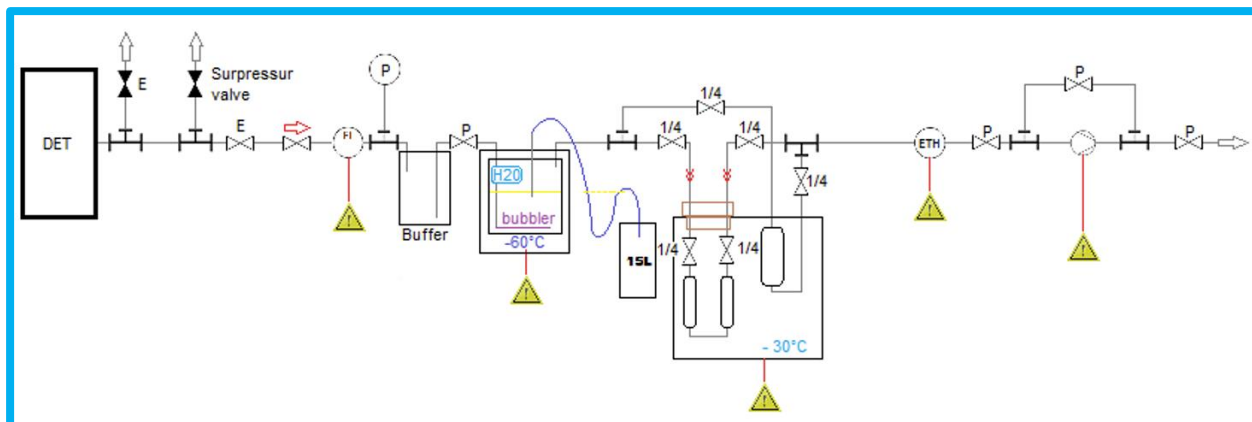
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Three system have been made:

1. **J-Trap**: Radon removal system
2. **GPS**: Rn removal and recycling system for XIA
3. **NESS**: No Ethanol System in SuperNEMO



Installed at LSM August 2024

Emanation/Exhalation

Emanation (^{226}Ra α decay)

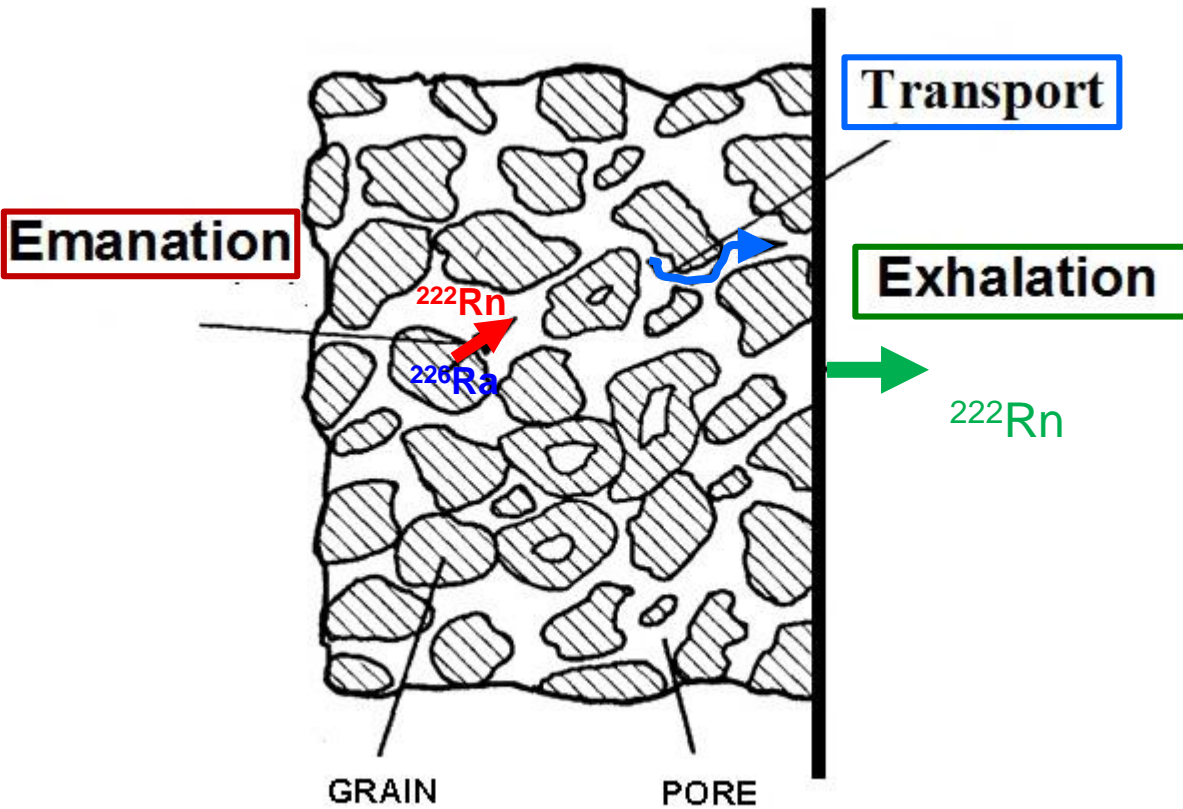
- O(5MeV) α -decay creates O(100 keV) ^{222}Rn nuclear recoil
- Recoil range 10 – 100 nm (depending on Z, density)

Transport

- Tortuosity
- Density
- Inter-grain media
- Strongly depends on temperature

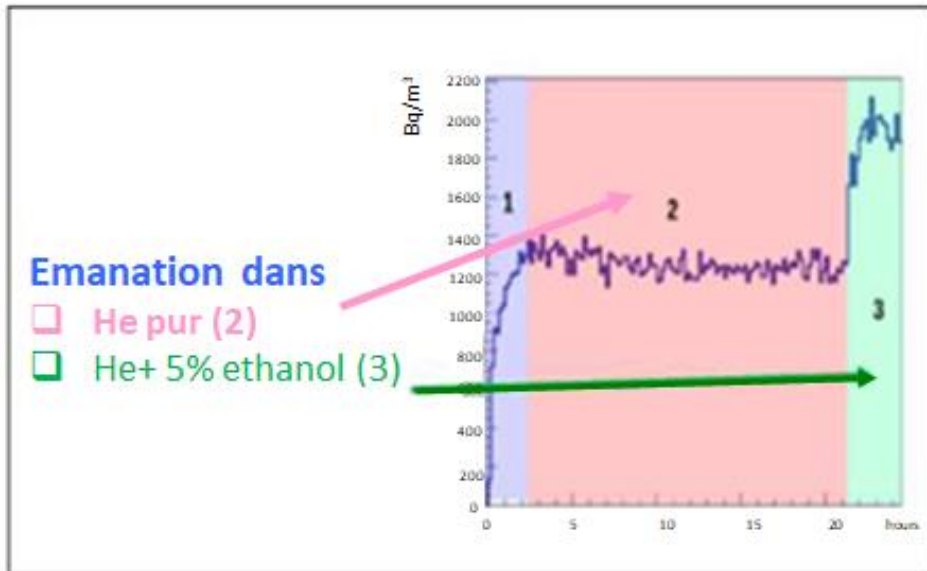
Radon exhalation

- ^{226}Ra concentration
- Porosity
- Temperature
- Pressure
- Medium (gas /liquid)
- Self-adsorption
- ...



Influence des liquides sur l'exhalation et le transport

Supernemo gas : He + 4 % ethanol + 1 % Ar



JUNO : Rn transport in 5 mm HDPE liner air/H₂O

