Extreme gas purification for dark matter and neutrino physics experiments

- The IRENE project -

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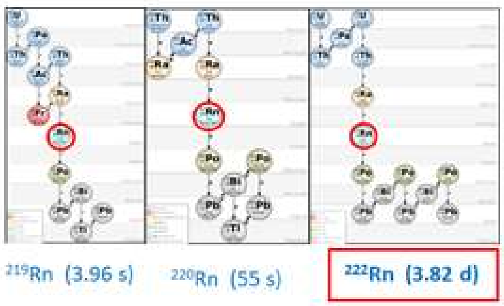
LPSC - 18 June 2026

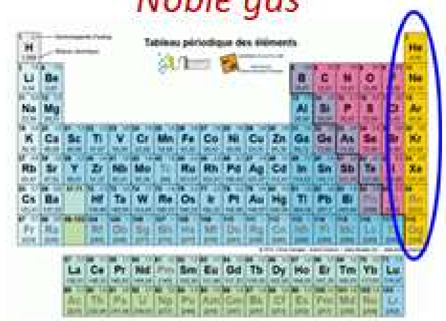
Natural, Radioactive, Noble gas from the U and Th chains

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

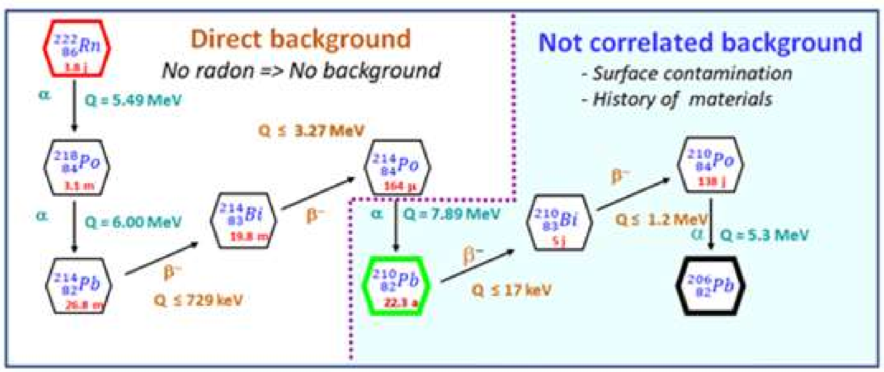
Natural



Noble gas



Radioactive



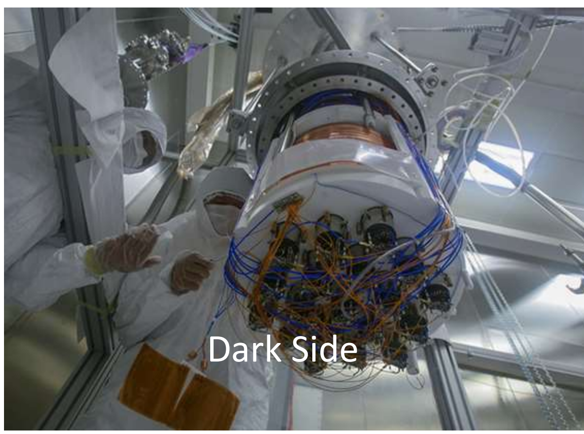
α	5 to 8 MeV
β	≤ 3,27 MeV
γ	≤ 3,18 MeV
Neutron	(α,n) on light nucleus

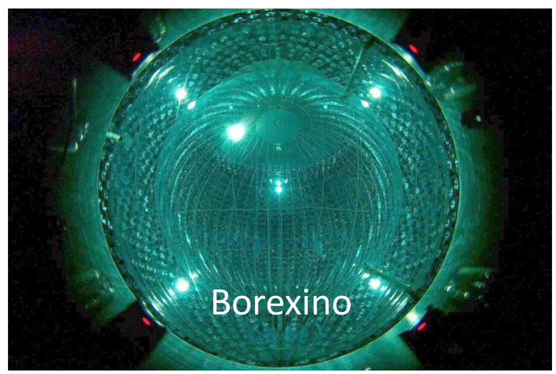
Low energy + Low counting => Very Low Radioactive Background

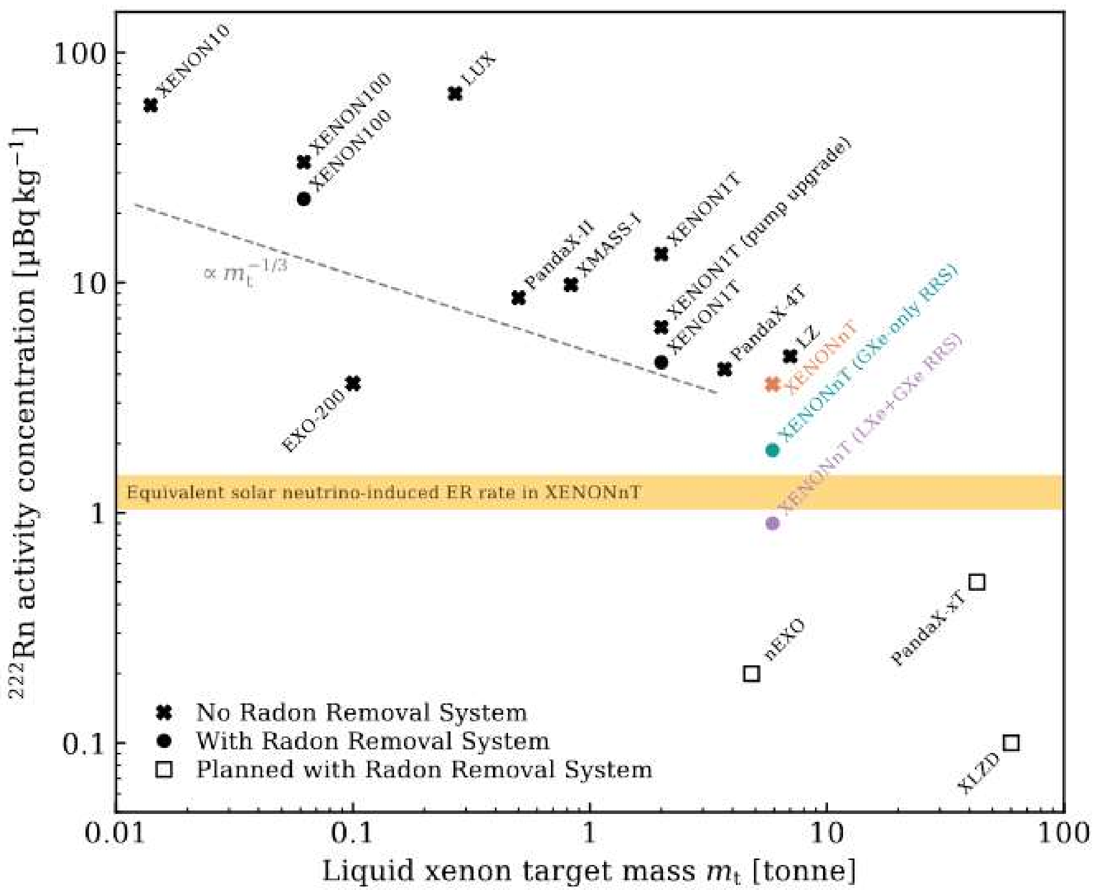
Requirements

~ µBq/m^3,kg in ^{222}Rn

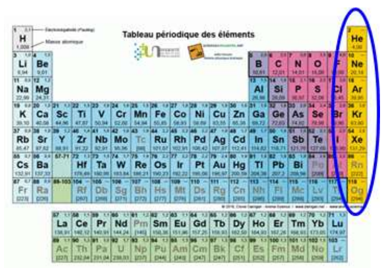
$\sim 1 \; atom \; Rn \; in \; 10^{25} \; gas \; atoms$







XENON10
XENON100
XENON100
LUX
PandaX-II
XMASS-I
XENON1T
XENON1T (pump upgrade)
XENON1T
PandaX-4T
LZ
XENONnT
XENONnT (GXe-only RRS)
XENONnT (LXe+GXe RRS)
EXO-200
$\propto m_t^{-1/3}$
Equivalent solar neutrino-induced ER rate in XENONnT
nEXO
PandaX-xT
XLZD
No Radon Removal System
With Radon Removal System
Planned with Radon Removal System
^{222}Rn activity concentration [µBq kg^{-1}]
Liquid xenon target mass m_t [tonne]
100
10
1
0.1
0.01

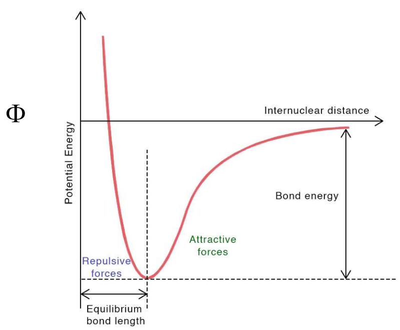


Radon Capture

Hydrure d'argon	Hydrure de krypton	Hydrure de xénon
		HXeH
		HXeI
		HXeBr
	HKrCl	HXeCl
HArF	HKrF	
HKrCN		HXeCN
		HXeNC
		HXeOH
		HXeO
		HXeOXeH
		HXeSH
		HXeNCO
	HKrCCH	HXeCCH
	HKrCCCN	HXeCCCN
		HXeCCXeH
		HXeCC
	HKrCCCCH	HXeCCCCH

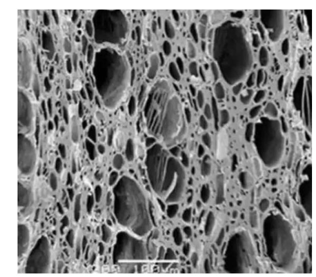
Rn is a noble gas => no chemistry

Capture ——> Physical Adsorption

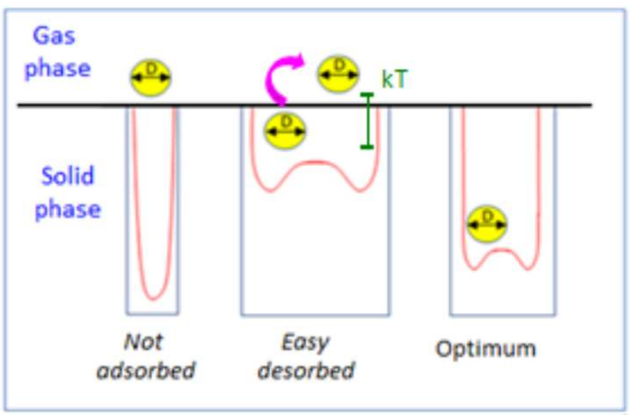


=> Surface capture by weak Van der Waals forces

——> porous materials : very high surface area up to 3000 m^2/g



Active Charcoal



But not all pores are equally effective

Need to optimise porosity

Radon adsorption at CPPM

The way to IRENE

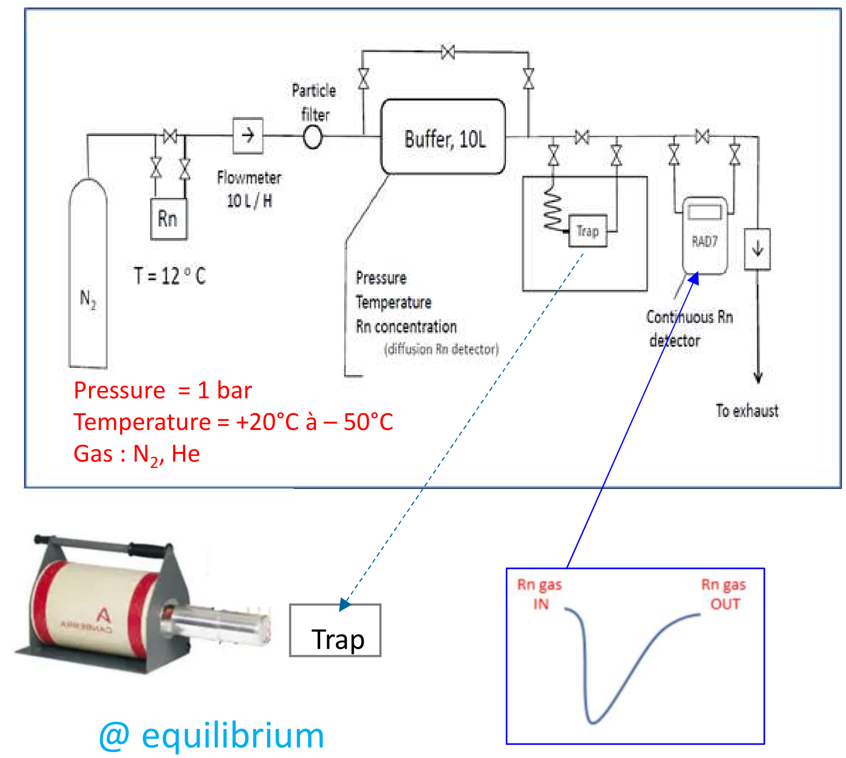
❖ *2015 : Study of Rn capture in 50 commercial or research microporous materials (SuperNEMO)*

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

Thèse Raymond Noel

$$\text{Adsorption : } k = \frac{C_{Rn}^{sample}}{C_{Rn}^{gas}}$$

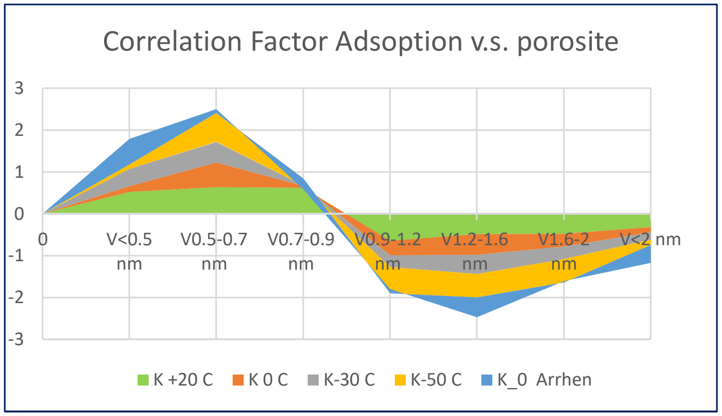
Adsorption factor



Results

Microporosity 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

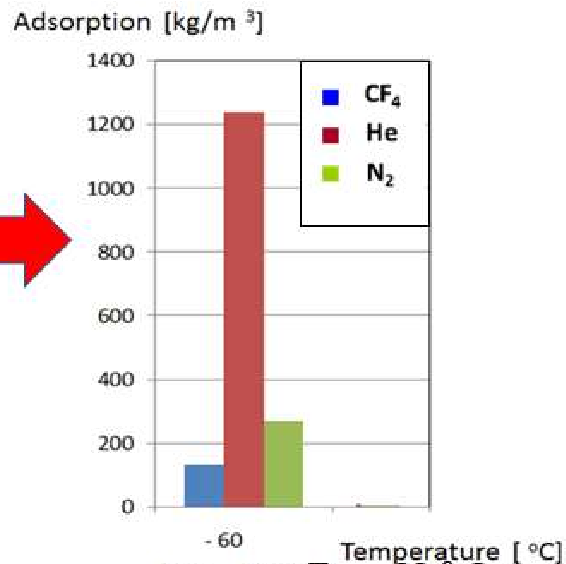


- Optimal porosity : 0.5 - 0.7 nm
- Small effect on the chemical composition (sulphur)

Adsorption competition

Compétition avec gaz porteur

Atome	Atom. Radius (nm) Van der Waals
He	0.140
N	0.150
CF4	0.155
Xe	0.216
Rn	0.220

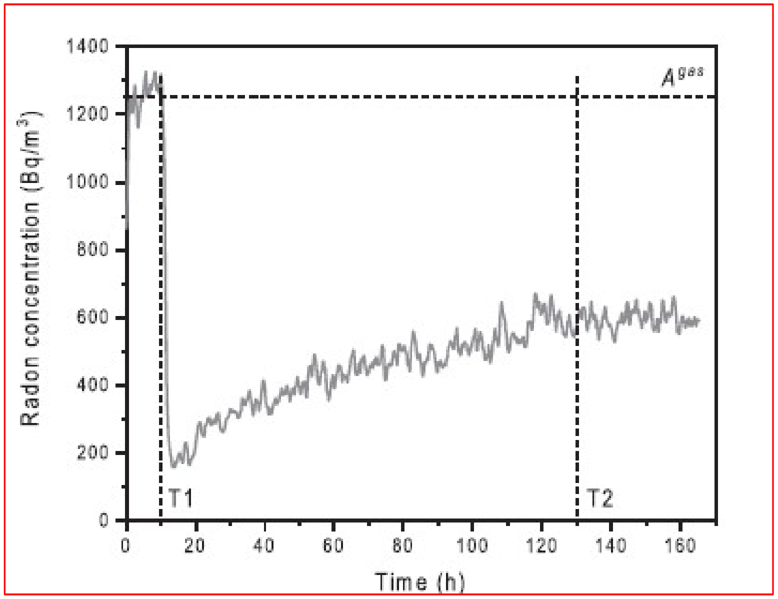


T = - 60 ˚C

The purification of xenon by chromatography is a great challenge

❖ *2020 : Capture of Rn in commercial silver zeolite by dynamic adsorption*

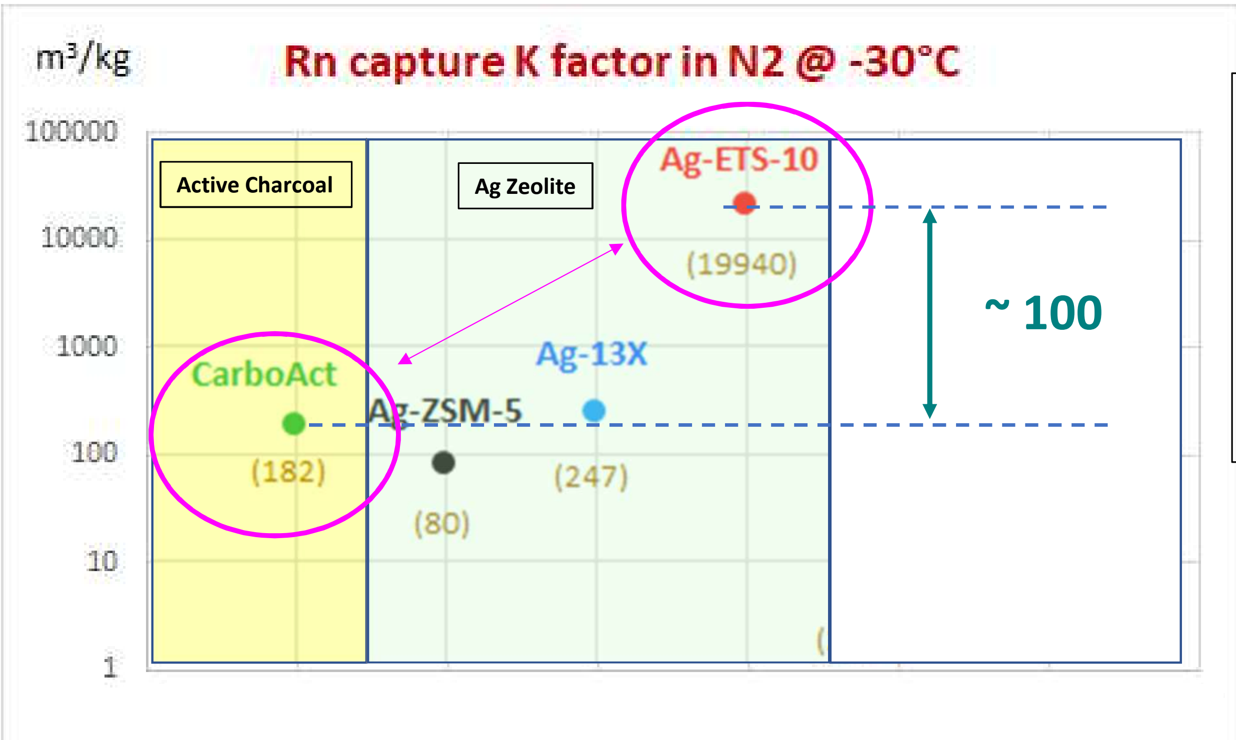
Zeolite	Supplier	Chemical formula	Silver content (wt%)	Pore size (Å)
Ag-ZSM-5	Riogen	$Ag_{4.8}[(AlO_2)_{4.8}(SiO_2)_{91.2}] \cdot 16H_2O$	7.9	5.2 × 5.7 and 5.3 × 5.6
Ag-13X	Sigma Aldrich	$Ag_{84}Na_2[(AlO_2)_{86}(SiO_2)_{106}] \cdot xH_2O$	35	10 × 10
Ag-ETS-10	Extraordinary Adsorbents Inc.	$Ag_{16}[Si_{40}Ti_8O_{104}]$	30	4.9 × 7.6



Breakthrough curbe @-30°C in
0.2 g ETS-10-Ag, **60 l/h** N_2

Some results

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



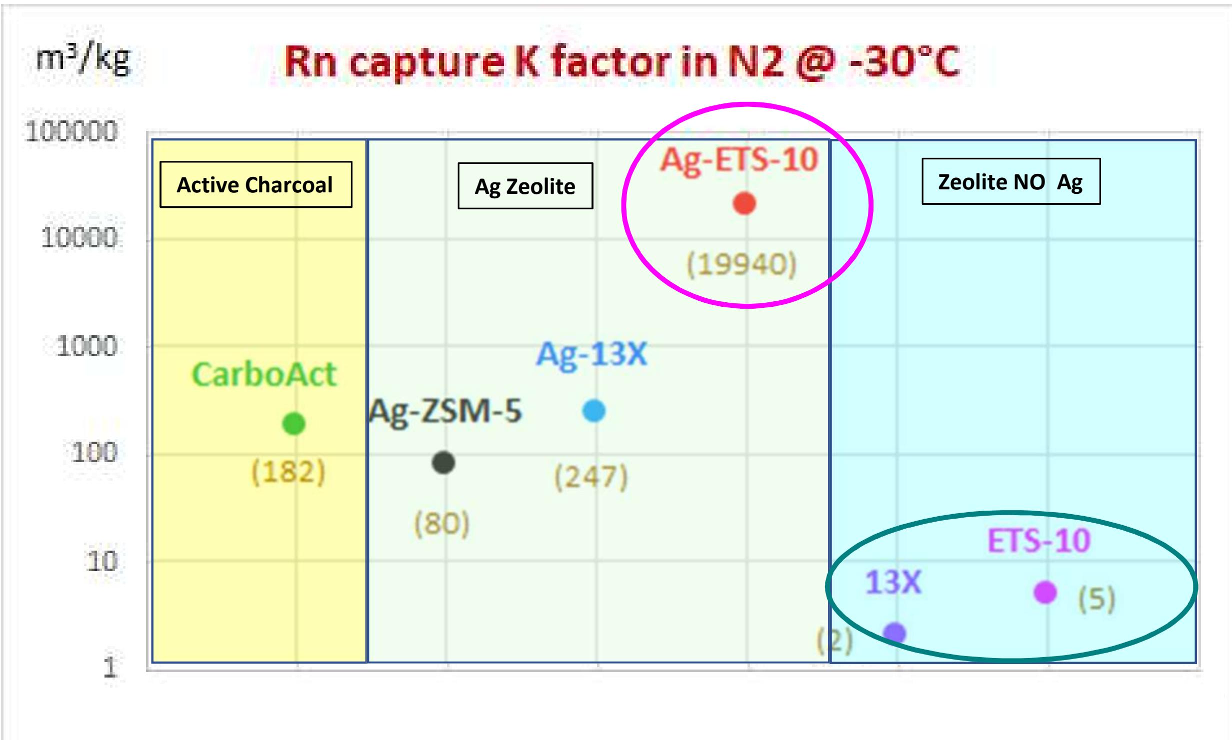
1 Reference charcoal (CarboAct®)

3 Commercial Ag zeolites

- Ag-ZSM-5
- Ag-13X
- Ag-ETS-10

Some results

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



1 Reference charcoal (CarboAct®)

3 Commertial Ag zeolites
- Ag-ZSM-5
- Ag-13X
- Ag-ETS-10

2 NO Ag zeolite
- 13X
- ETS-10

Huge impact of silver on adsorption

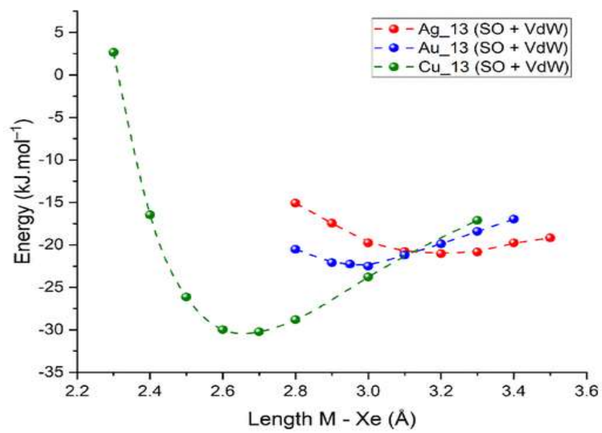
Echantillon	226Ra (Bq/kg)
K48	< 0,25
Shirasagi	0,164 +- 0,023
CarboAct	0,0023 +- 0,0019
ETS-10-AG	0,988 +- 0,05

Negative point for Ag - ETS-10 commercial adsorbents

=> High Rn emanation (^{226}Ra)

Positive point

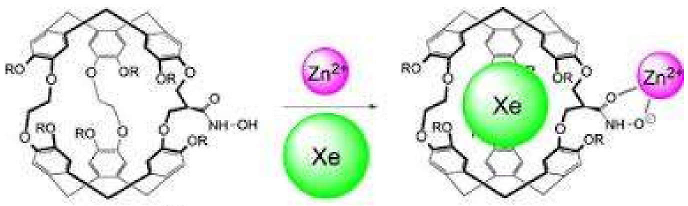
=> Potential improvements (Ni, Cu, ..)



Energy of the bond as a function of the length of M–Xe for the 13-atom clusters of silver, copper, and gold

A. Monpezat et al., *ACS Omega* **2021** *6* (47), 31513-31519

❖ 2018 Xenon / Radon adsorption with macromolecular cages: Cryptophane



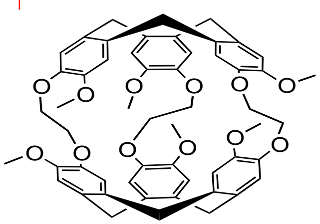
2; R = $CH_2COO^{\ominus}$

- Used for the complexing of Xe
- Ajustable size

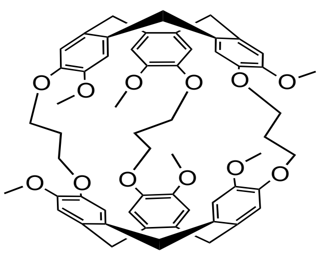
Institut des Sciences Moléculaires de Marseille
iSm2
UMR 7313

Three types of cages were studied on two types of supports

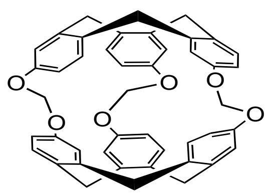
cages



crptophane A
ou cryptophane 2,2,2

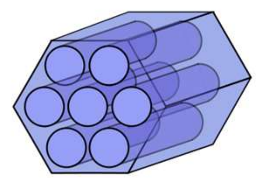


crptophane E



Cryptophane 1,1,1

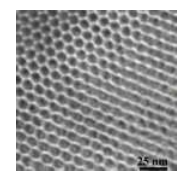
supports



Silice MCM-41

diamètre de 2,6 nm

1000 m^2/g



Silice SBA-14

6,5 nm.

500 m^2/g

Adsorption du Rn (CPPM)

Température Adsorbeur	K ($m^3.kg^{-1}$) @ -30 °C
YC-125 : Cryptophane A/ MCM-41	*107 ± 18*
YC-126 : Cryptophane A/ SBA-15	*60 ± 15*
YC-127 : Cryptophane E/ MCM-41	*24 ± 6*
YC-128 : Cryptophane E/ SBA-15	*2 ± 6*
YC-129 : Cucurbit[6]uril/MCM-41	*0*
Cristaux de Cryptophane A	*0*
Charbon actif Silcarbon K48	130 ± 25

1.21

Adsorption du Xe (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

Preliminary but very promising result

Xe / Rn selectivity

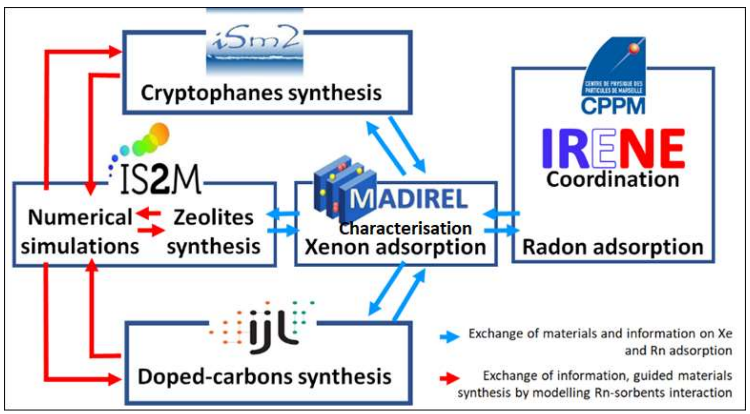
The IRENE project

(Innovative mateRials for Extreme radoN capture)

Understanding and optimising the capture of Rn in new materials

Consortium of 5 laboratories (particle physics, physical chemistry and organic chemistry to study radon capture, <u>motivated by subatomic physics</u>.

4 years project (2024 – 2028)



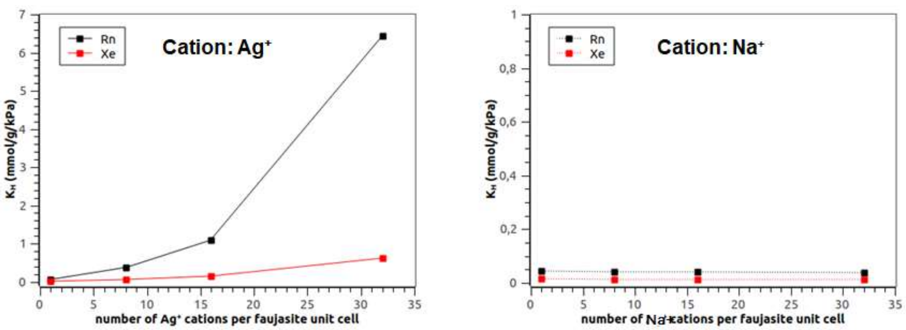
Project philosophy

- Feedback between the 5 laboratories
- Modelling as a guide
- Three families of adsorbents (Zeolites, Cages, Carbon-based)
- Xenon as a reference gas
- Radon capture in N_2, He, and Xe

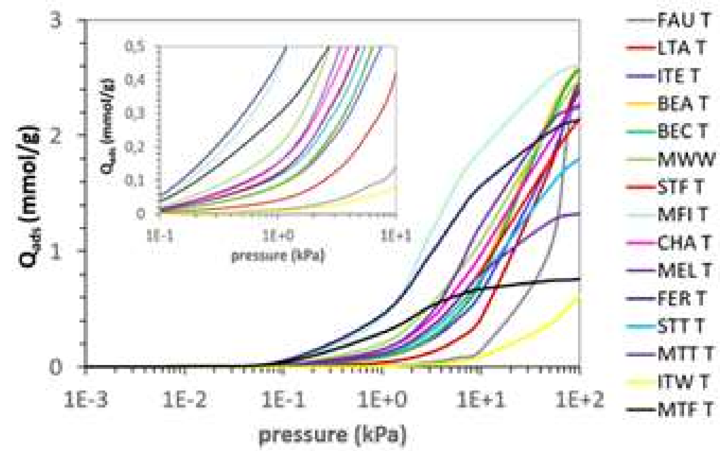
Some preliminary results from simulation

How chemical composition of zeolite influences Rn & Xe adsorption

FAU

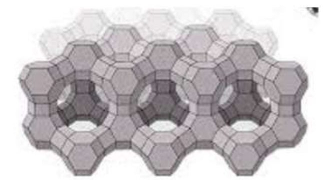


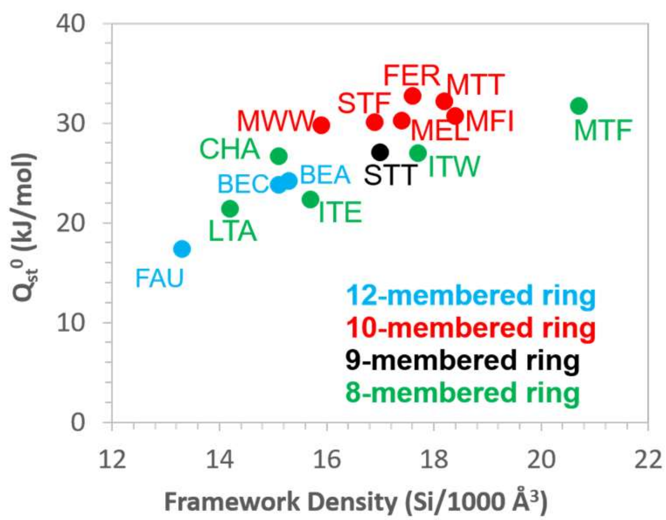
Simulated Rn adsorption isotherms @ 298K for several zeolite structures

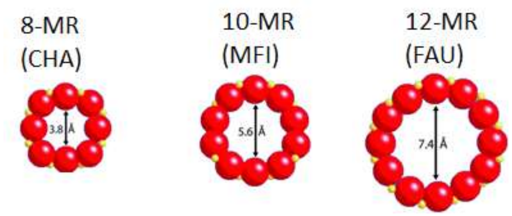


Some preliminary results from simulation

Goal: Find the zeolite with the best performance for Rn adsorption.





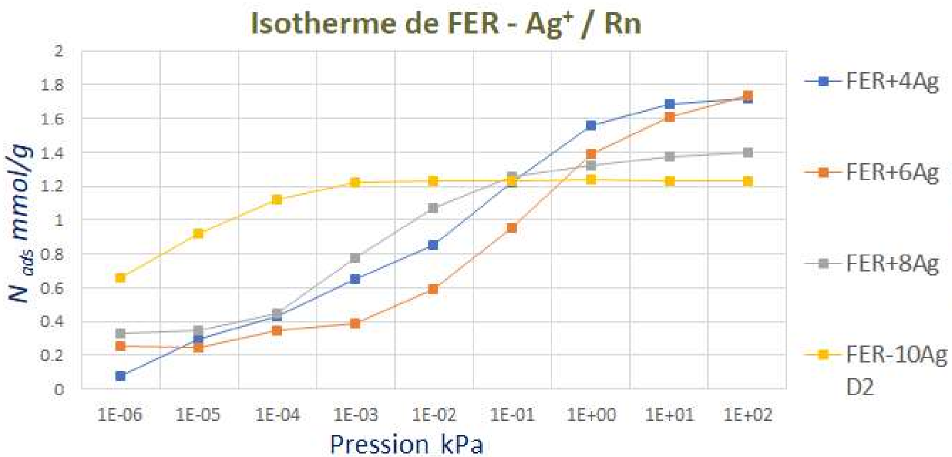


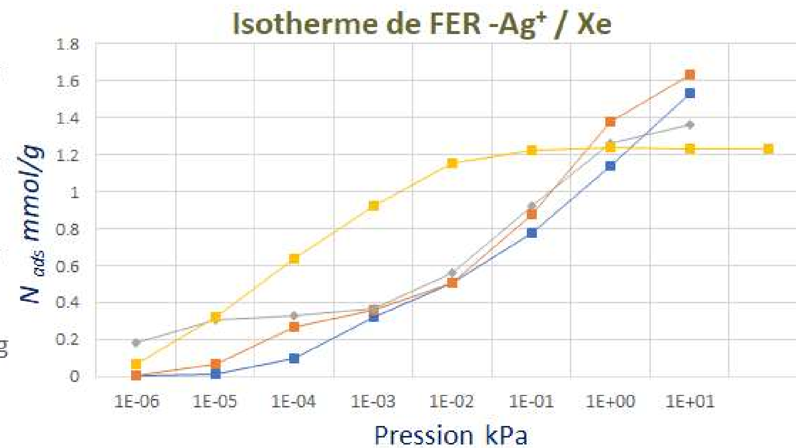
Zeolites	Rapport Si:Al min
FER	>6
MWW	>18
MTT	>10
MEL	>20
MFI	>13
STF	>20

→ **Les zéolithes à 10MR** (Membered Ring) **sont les meilleurs candidats pour l'adsorption du Rn**

Some preliminary results from simulation

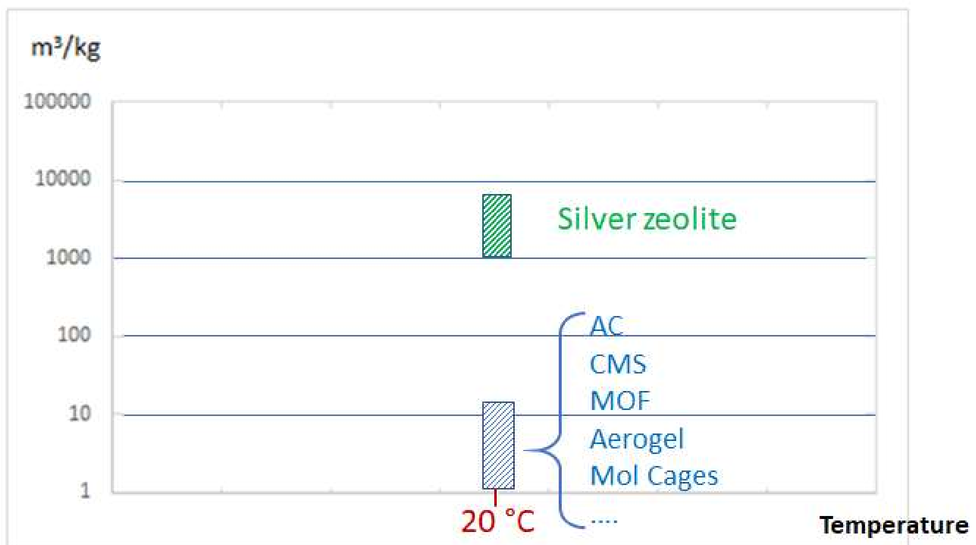
Effet de rapport Si/Al sur les propriétés d'adsorption de Rn et Xe : FER avec 4,6,8, 10 cations d'Ag^+





«Exploring the Science of Adsortion : Materials , Methodologies, and Emerging Direction »

Oleksandra Veselska, Shefali Vaidya, Olivier Llido, Miroslav Macko, Irena Deroche, Sandrine Bourrelly, J. Busto



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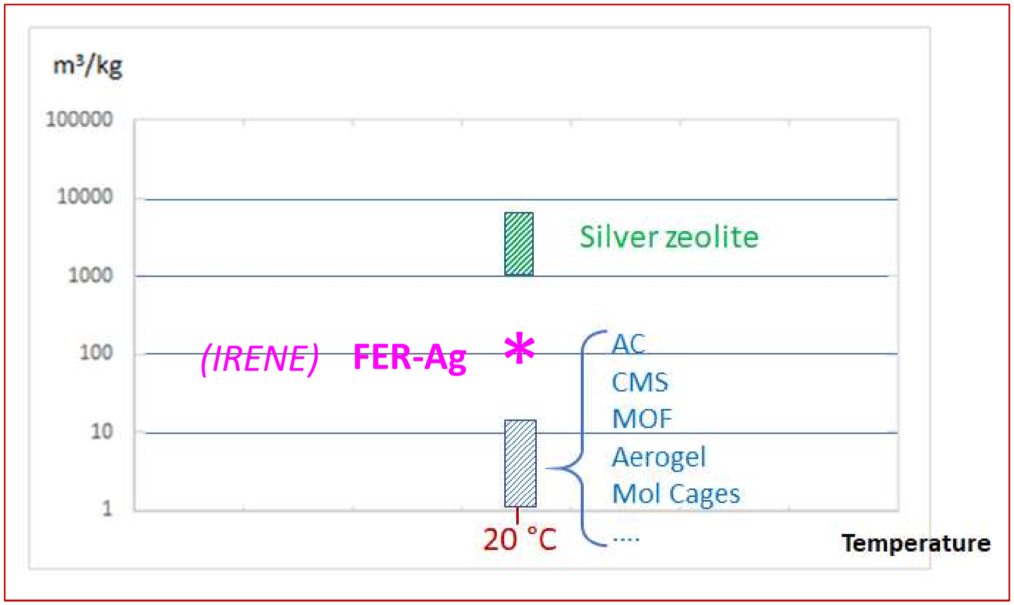


Conclusion

- Low-energy and low-counting rate experiments require extremely low concentration of radon.

- Traditionally, activated carbons has been used to capture radon with a good efficiency. However the purification levels reached are not always sufficient.

- 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

Thank you for your attention

Porosity

Activated Charcoal : universal adsorbent (very big surface area ,
big stability, not toxic, low cost , ...)

Very popular for radon capture


Radiation Measurements

Prediction of radon removal efficiency for a flow-through activated charcoal system and

Journal of Physics G: Nuclear and Particle Physics

PAPER

Characterization and long-term performance of the Radon Trapping Facility operating at the Modane Underground Laboratory

Radiation Measurements

Studies on radon adsorption characteristics of different charcoals used as amplifiers for the track detectors

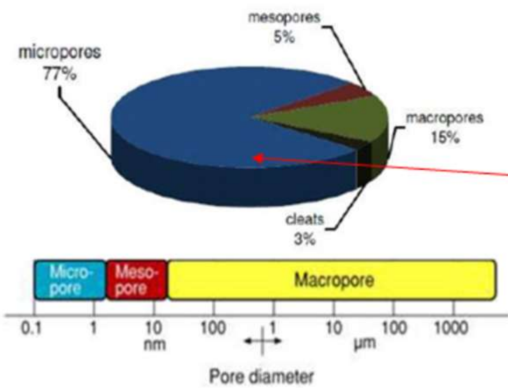
International Journal of Environmental Research and Public Health

MDPI

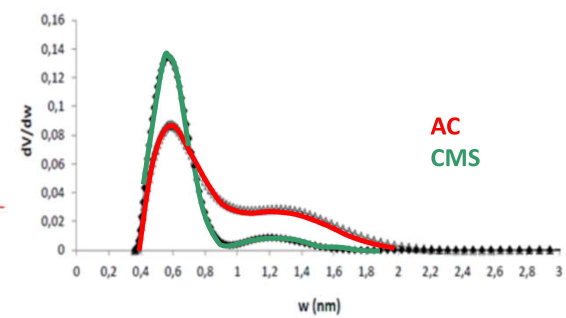
Article

Radon Adsorption in Charcoal

Andreas Maier, Jesse Jones, Sonja Sternkopf, Erik Friedrich, Claudia Fournier and Gerhard Kraft



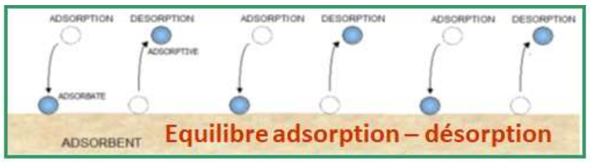
Pore distribution in standard activated carbon



Micropores distribution in an activated carbon and in Carbosieve® SIII carbon molecular sieve

Adsorption v.s. retention time

Charcoal column



Retention time τ_r

- $\Rightarrow$ No permanent capture
- $\Rightarrow$ Rn slowing down -> τ_r (retention time)

$$\tau_r = \frac{m \cdot k}{\Phi}$$

Retention time

$$\mathcal{R} = \frac{Rn_{out}}{Rn_{in}} = exp\left[-\frac{\ln(2) \times \tau_r}{T_{1/2}}\right]$$

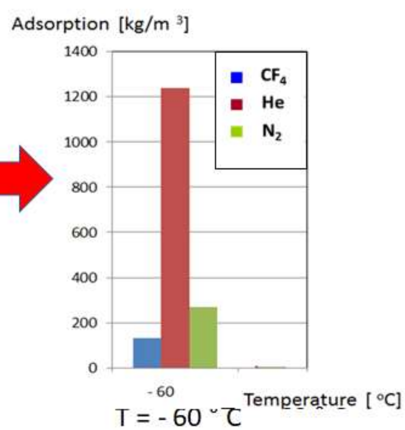
Rn reduction factor

If $\tau_r \gg T_{1/2}$
=> Rn disappearence

Adsorption competition

Compétition avec gaz porteur

Atome	Atom. Radius (nm) Van der Waals
He	0.140
N	0.150
CF4	0.155
Xe	0.216
Rn	0.220



The purification of xenon by chromatography is a great challenge