MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Radon mitigation strategies for current and future liquid xenon detectors

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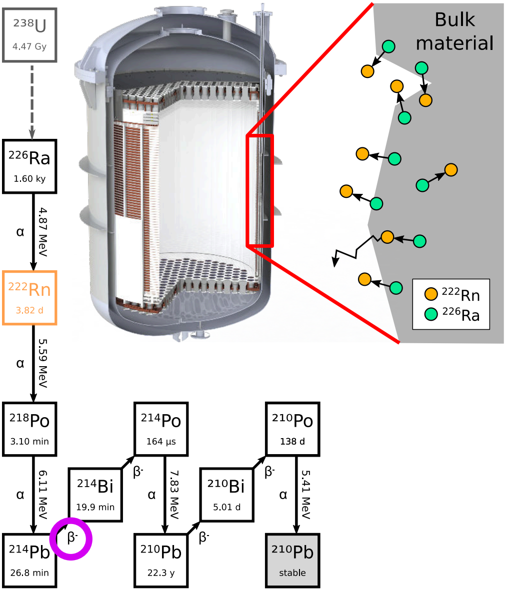
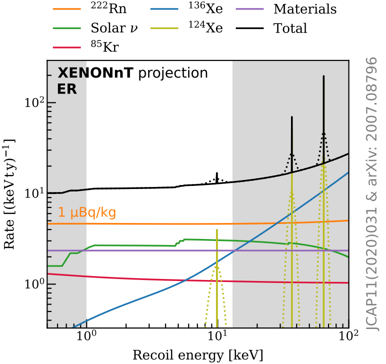
UCLA Dark Matter
Los Angeles - March, 31 2023

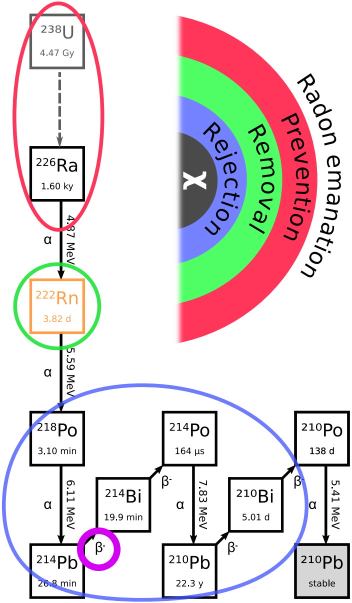
Why we care about radon...



- Low energy β decay of ^{214}Pb
- ^{222}Rn distributes homogeneously: No fiducialization possible
- Dominant background for low-ER and WIMP search



... and how to mitigate it!



- Methods that **prevent** radon from entering the active volume
- Material pre-selection, radon barriers, new detector designs

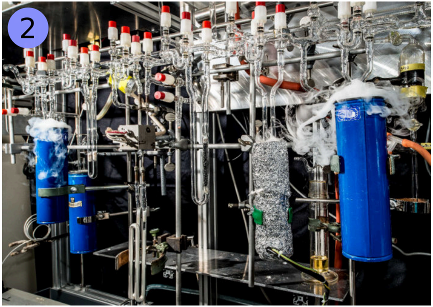
- Active **removal** of radon that has already entered the detector
- Distillation (XENONnT/PandaX-4T) and/or adsorption (LZ)

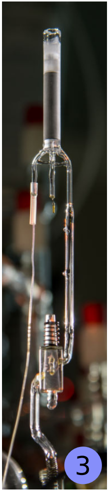
- **Rejection** of radon-induced low energy events in the analysis
- ER/NR separation and/or convection-based veto

⇒ **Optimal combination needed!**

How to measure ^{222}Rn emanation (at MPIK)

1. Extraction of ^{222}Rn e.g. from ^{226}Ra solution
2. Transfer and purification of the sample
3. Counting (proportional counters, electrostatic radon monitors) MDA ≈ 20 µBq

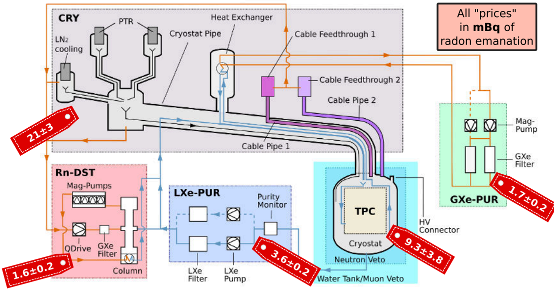




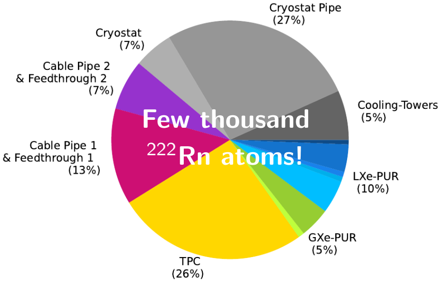
Appl. Radiat. Isot. 67, 5 889-893 (2009)

- Screening all components & selection of lowest emanating parts
- Optimized radon removal with knowledge of location of sources

Example: Mapping radon sources in XENONnT



EPJC 82 (2022) 599 & arXiv: 2112.05629



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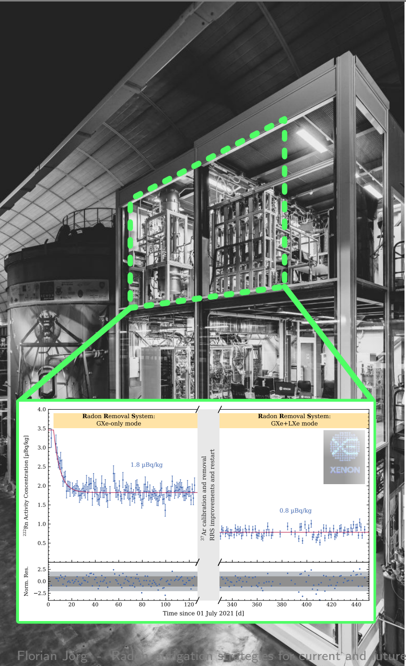

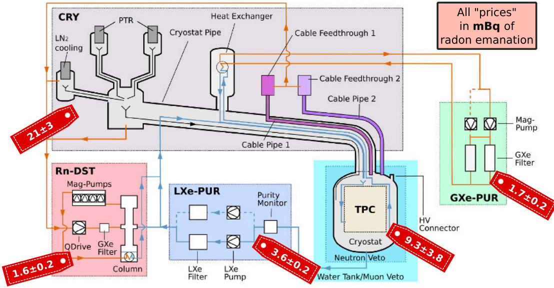

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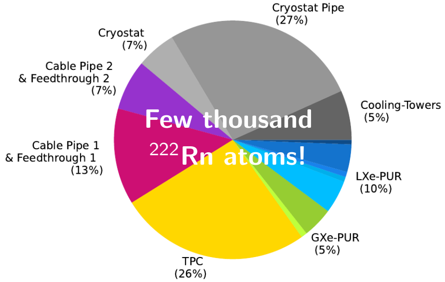
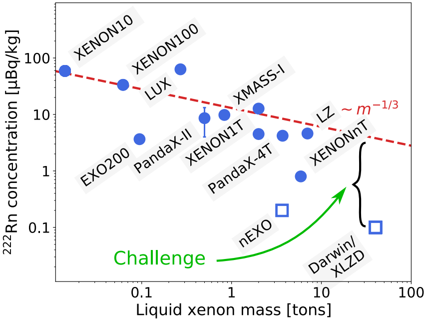


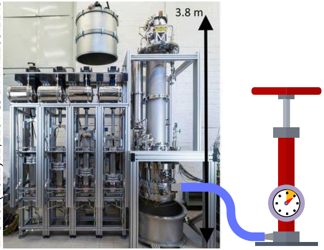
... back to the future (Darwin/XLZD)



Darwin/XLZD: Solar ν-dominated. $\Rightarrow$ Reduce ^{222}Rn concentration by 10!

- Radon "dilution" will be insufficient.
- Expected from surface-to-volume scaling: $\sim 1/\sqrt[3]{m}$
- Require additional mitigation techniques!

EPJC82(2022)12,1104 & arXiv:2205.11492



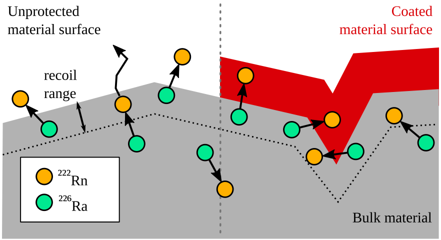
- LowRAD distillation plant (Münster)
- New radon detectors (U. Freiburg, MPIK)
- Cold radon emanation facility (RAL, UK)
- Cross-calibration and book-keeping
- Sealed TPC: Freiburg, Nagoya, San Diego
- Solid Xenon TPC (CrystaLiZe)
- **Coating-based radon barriers** (MPIK)

- Recoil emanation
  - α-decay: $^{226}\mathrm{Ra} \xrightarrow{4.9\,\mathrm{MeV}} {}^{222}\mathrm{Rn}$
  - 86 keV recoil energy
    $\Rightarrow \sim$ 14 nm (steel)
- Diffusion-driven emanation

Requirement for coating:

Thick, Tight, **Radiopure**

Radon mitigation with coatings



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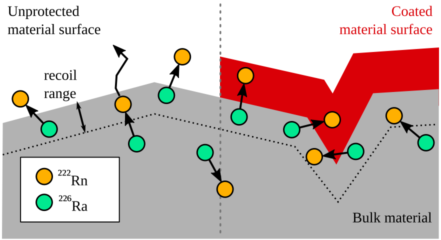
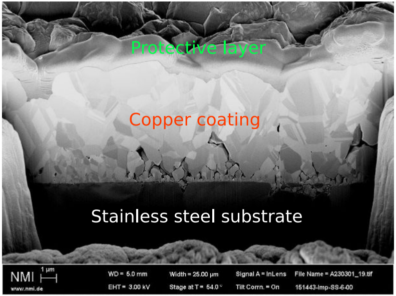
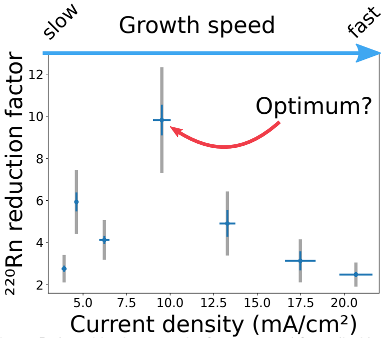


Tested coating techniques & resuslts

Method	Material	Thickness [µm]	Reduction ^{220}Rn	Reduction ^{222}Rn
Sputtering	Titanium	0.4 - 0.8	4.5	2.1 ± 0.7
Plasma spraying	Copper	3	22	-
Epoxy resin	Stycast	≈ 200	≥ 74	-
Chem. vapor dep.	Carbon	1	3	1.4 ± 0.4
Electrochem. plating	**Copper**	**5**	**130**	**1500**

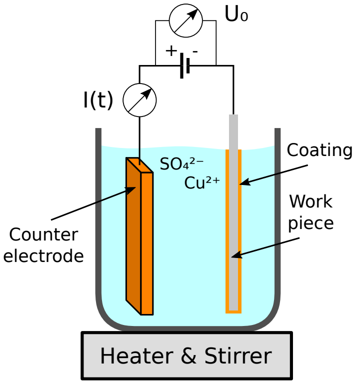
Electrochemical plating



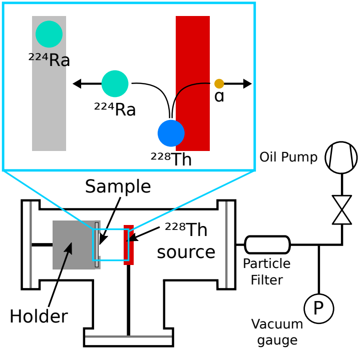


$$Cu^{2+}_{aq} + 2 \cdot e^- \rightarrow Cu_s$$

- Growth speed $\Longleftrightarrow$ coating properties
- Highest reduction: Surface current density $j \approx 10\,\mathrm{mA/cm^2}$
- Systematic study of ^{220}Rn reduction
- Using **thoriated tungsten electrodes**



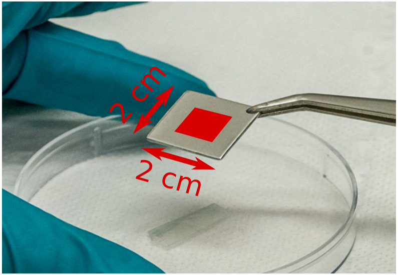
Production of implanted stainless steel samples



Recoil implantation (^{224}Ra)

- \+ Quick production "at home"
- \- Emanate $^{220}\mathrm{Rn}$ instead of $^{222}\mathrm{Rn}$
- \- Implanted activity decays with $T_{1/2} = 3.8$ days

$\Rightarrow$ **Pre-testing**



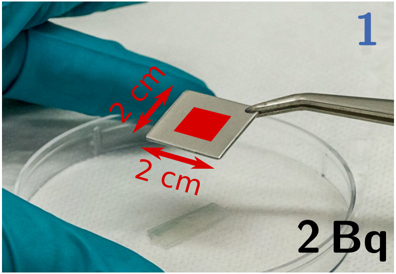
Appl.Radiat.Isot. 194 (2023) 110666 & arXiv: 2205.15926

ISOLDE @ CERN (^{226}Ra)

- \+ 2 Bq of ^{222}Rn emanation
- \+ Unchanged, clean stainless steel surface
- \- Difficult to obtain many of samples

$\Rightarrow$ **Final validation**

Best results: electrochemical plating



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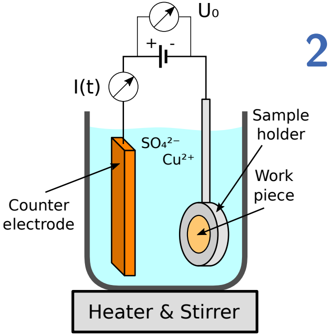
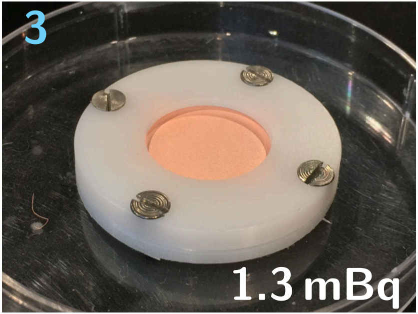
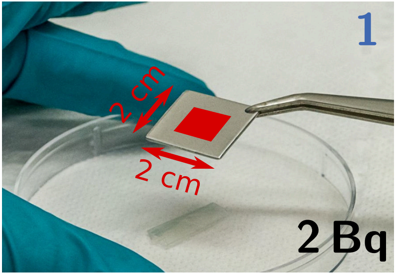


1. **Sample:** ^{226}Ra-implanted stainless steel. 2 Bq emanation of ^{222}Rn
2. **Deposition:** $Cu^{2+}_{aq} + 2 \cdot e^- \rightarrow Cu_s$ from solution 10 mA/cm^2
3. **Reduction:** By $\times$1500 with 5 µm copper.



Best results: electrochemical plating



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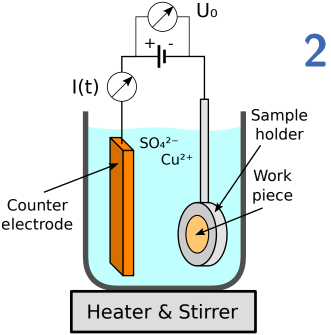

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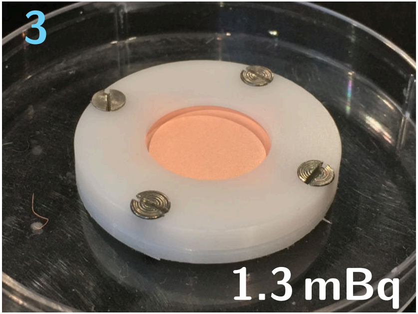
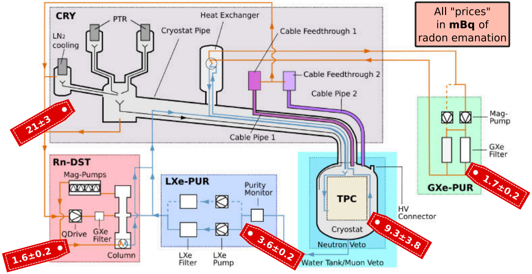
Very promising! Only first step...



Summary



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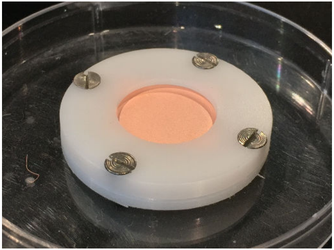
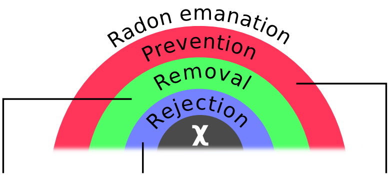


- Thorough screening & Radon distillation
- XENONnT: Achieved lowest radon background to date! *)
- Radon suppression using electrodeposited copper



- Adsorption
- **Distillation**

- ER/NR separation
- ...

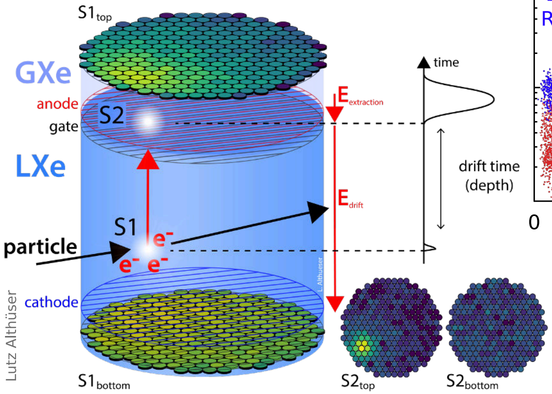
- **Screening**
- **Coating**
- ...

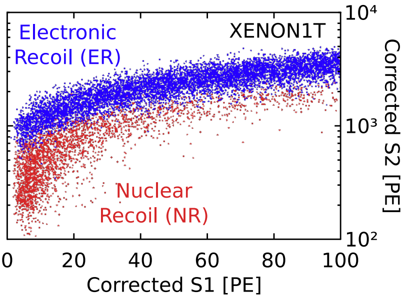
Combination of mitigation techniques required for DARWIN/XLZD & nEXO!

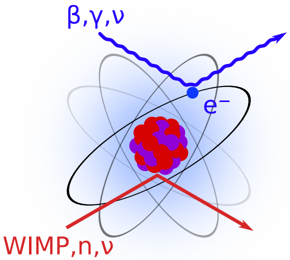
*) In a liquid xenon experiment

Backup slides

Dual-phase TPC principle

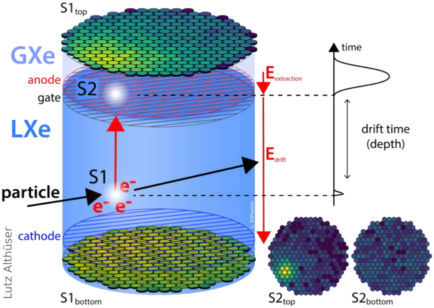






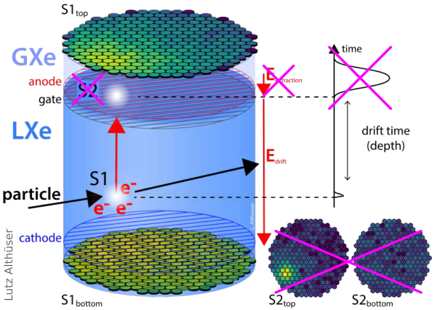
- Electron drift time ⇒ z-position
- Distribution of S2 signal ⇒ x-y-position
- S1/S2 ratio ⇒ signal discrimination

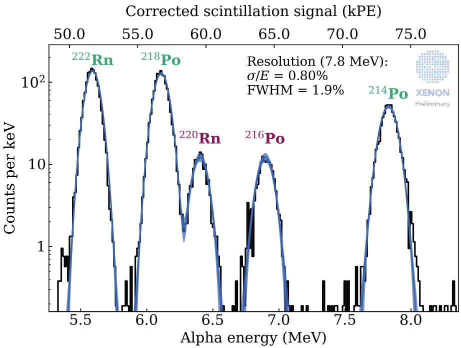
Radon measurement in XENONnT



- Searching for the (MeV) alpha decays (scintillation signal only):

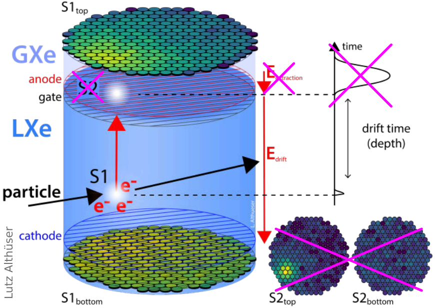
Radon measurement in XENONnT

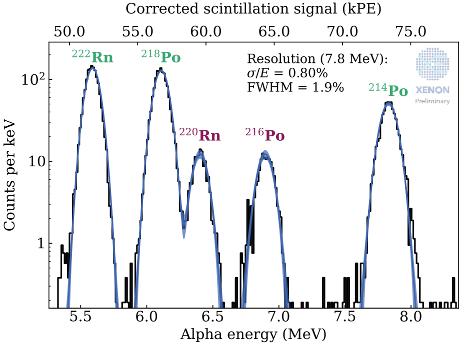




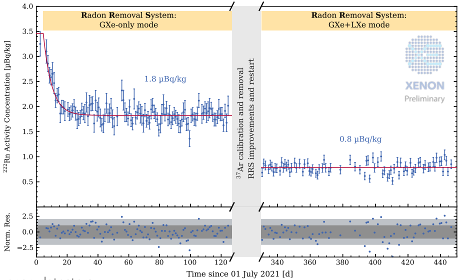
- Searching for the (MeV) alpha decays (scintillation signal only):
- Position reconstruction:
    - Area fraction top (z)
    - Center of Mass (x-y)
- 0.8% Energy resolution

Radon measurement in XENONnT



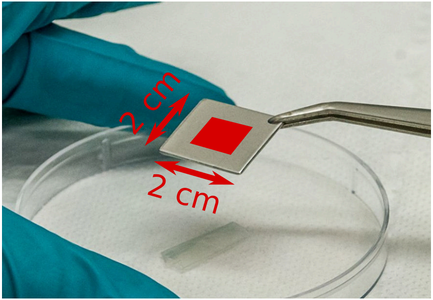


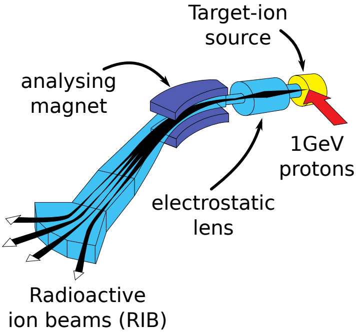
- Searching for the (MeV) alpha decays (scintillation signal only):
- Position reconstruction:
  - Area fraction top (z)
  - Center of Mass (x-y)
- 0.8% Energy resolution
- Lowest ^{222}Rn concentration ever achieved in LXe: 0.8 µBq/kg



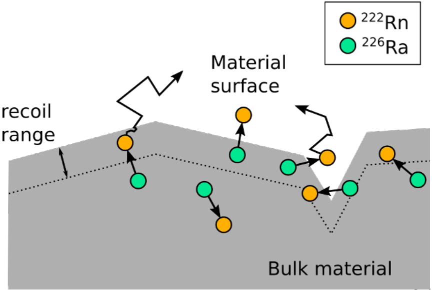
^{226}Ra implanted sample

- 5×10^{11} ^{226}Ra ions (≈ 7 Bq) implanted at 30 keV
- Ion range distribution (SRIM) $\mu = 7.9\,\mathrm{nm}, \sigma = 2.3\,\mathrm{nm}$
- + Expected emanation fraction due to recoil: 23%
- + Mechanically stable





Rep. Prog. Phys. 62, 4 527 (1999)



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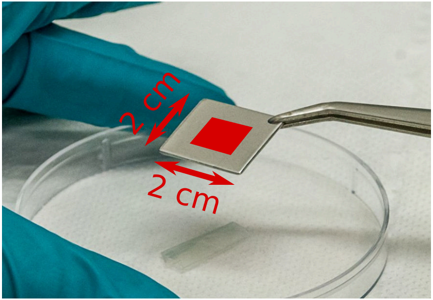

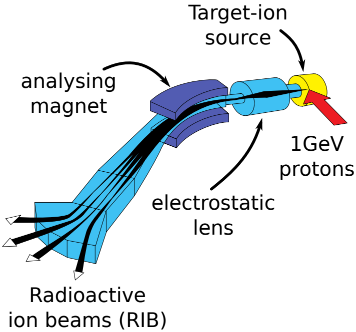

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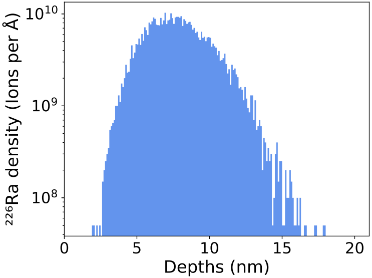

Results from full characterization

Activity (Bq)	**Sample A**	Sample B
Implantation	about 7	about 7
^{222}Rn emanation	$2.07 \pm 0.03_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}$	$2.00 \pm 0.03_{\mathrm{stat}} \pm 0.04_{\mathrm{syst}}$
γ-spectrometry	$7.4 \pm 0.1_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}$	$8.4 \pm 0.3_{\mathrm{stat}} \pm 1.0_{\mathrm{syst}}$
α-spectrometry	$8.70 \pm 0.06_{\mathrm{stat}} \, {}^{+2.0}_{-1.8}{}_{\mathrm{syst}}$	$9.13 \pm 0.10_{\mathrm{stat}} \, {}^{+0.7}_{-0.4}{}_{\mathrm{syst}}$

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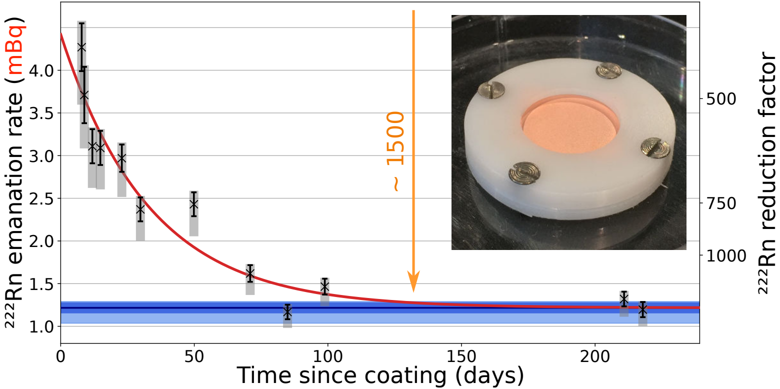
- Recoil dominated emanation of $^{222}\mathrm{Rn}$
  $\rightarrow$ Good stability with pressure, temperature, gas-type, etc.
- Emanation from a bare stainless steel surface
  $\rightarrow$ Low outgassing of impurities

Applicability and future production:

- Samples applied for radon mitigation studies; calibration of α-spectrometers; characterization of a novel radon detector
- Open beam-time proposal at ISOLDE for "mass-production"

Results using ^{226}Ra implanted stainless steel samples

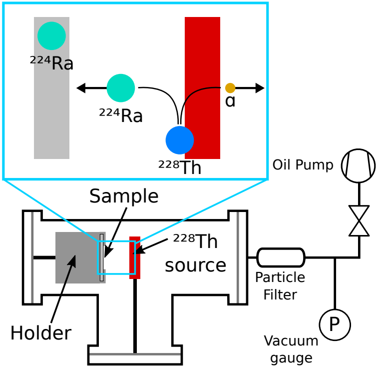


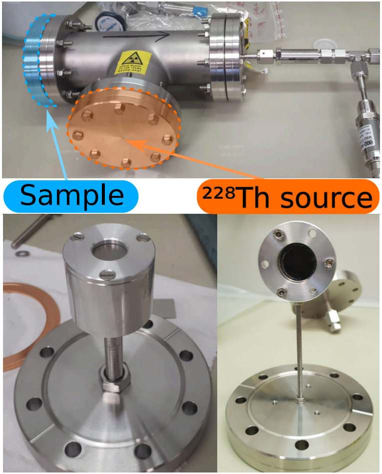
- ^{222}Rn reduction of ≈ 1500
- Translates to $D_{\mathrm{eff}} \approx 10^{-14}\,\frac{\mathrm{cm}^2}{\mathrm{s}}$
- Decreasing emanation:
  - Room temp. annealing?
  - Coating becomes "tighter"

Very promising result!

- Up-scaling of coating setup to $\mathcal{O}(10\,\mathrm{m}^2)$
- Assessing the radio purity of the coating

Production of ^{224}Ra implanted stainless steel samples





Recoil implantation

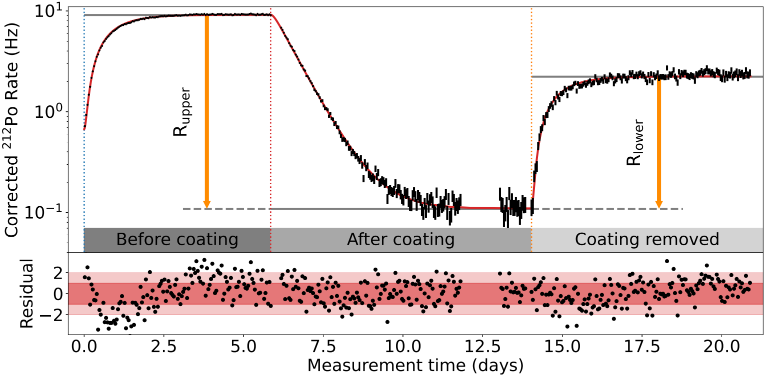
- $^{228}\mathrm{Th} \xrightarrow{5.5\,\mathrm{MeV}} {}^{224}\mathrm{Ra}$

\+ Easy and quick production "at home"

\- Emanate $^{220}\mathrm{Rn}$ instead of $^{222}\mathrm{Rn}$

\- Implanted activity decays with $T_{1/2} = 3.8$ days

Results using ^{224}Ra implanted stainless steel samples

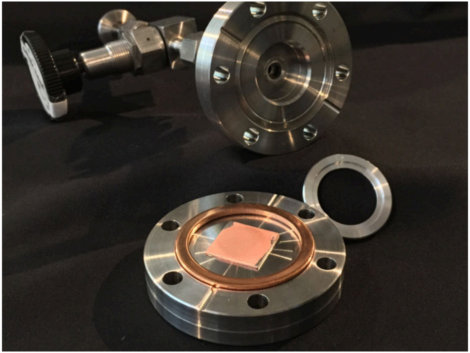


- ^{220}Rn emanation rate before and after coating
- Additional measurement of rate after removal of coating
- $R_{lower} \leq R \leq R_{upper}$

Sample	R_{lower}	R_{upper}
1	20.4±0.3	83.6±1.3
2	142±8	640±37
3	12.3±1.6	1050±140

$\Rightarrow$ Robust factor of 10 reduction

Radon-tight sealing of one sample

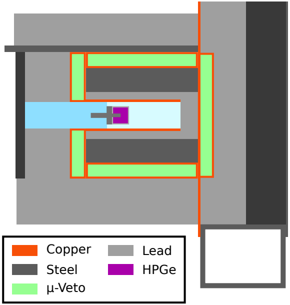


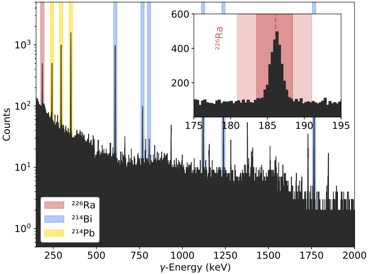
- Electrochemical plating of 5 μm copper
- ^{222}Rn reduction factor: ≈ 1500 validated using emanation measurement
- Small amount of ^{226}Ra dissolved into electrolyte

Activity (Bq)	Sample		Electrolyte
γ-Spectrometry	^{226}Ra	Rn-daughters	Rn-daughters
before coating	8.4±1.0	6.0±0.3	$\lesssim$ 0.012
after coating	7.7±1.0	7.2±0.4	0.34±0.02

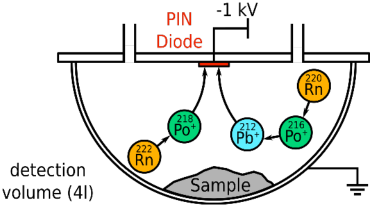
Measurement method

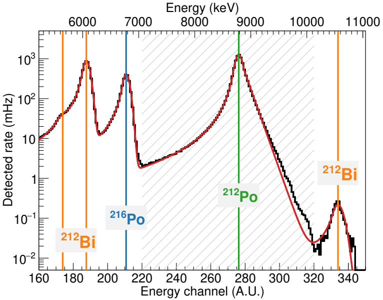
HPGe spectrometry



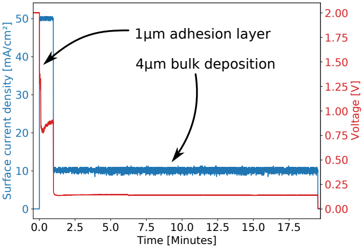


Electrostatic radon monitor

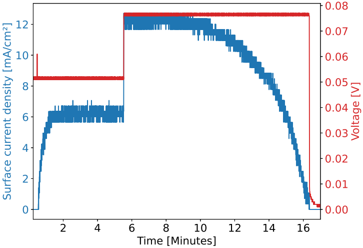




Coating



Un-coating



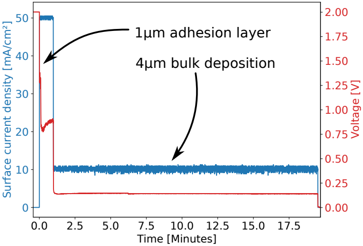
- Thickness from time-integration of current

$$m(t) = \frac{M_{\mathrm{Cu}}}{2 \cdot e \cdot N_A} \cdot \int_0^t I(t')dt'$$

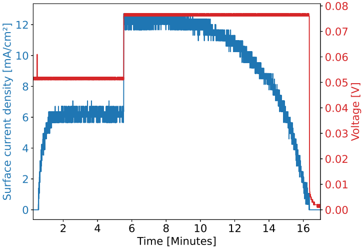
$$d(t) = \frac{m(t)}{\varrho_{\mathrm{Cu}} \cdot A}$$

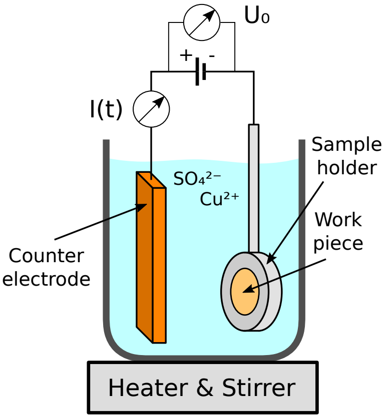
Deposition method on stainless steel

Coating



Un-coating



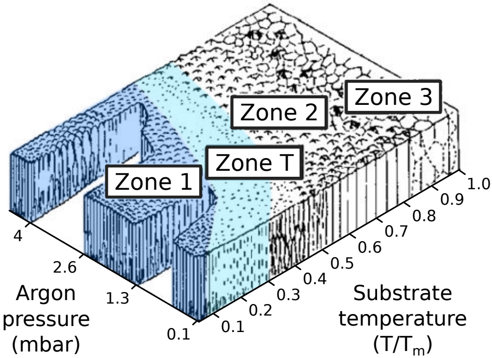


- Thickness from time-integration of current

$$m(t) = \frac{M_{\mathrm{Cu}}}{2 \cdot e \cdot N_A} \cdot \int_0^t I(t')dt'$$

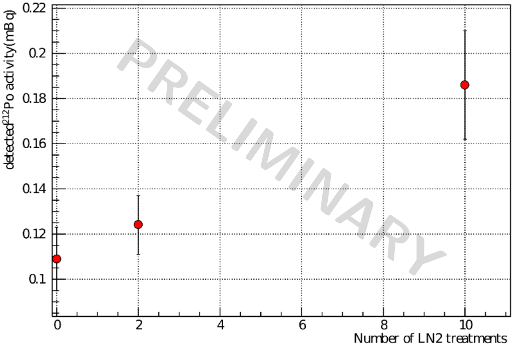
$$d(t) = \frac{m(t)}{\varrho_{\mathrm{Cu}} \cdot A}$$

Thronton model



- Morphology of sputtered coating layers mainly depends on the ratio of substrate temperature T and melting point of the deposition material T_m
- Our titanium depositions were performed at room temperature ($\Rightarrow T/T_m \approx 0.15$) $\Rightarrow$ Zone 1 and/or Zone T
- Vertically aligned grain boundaries are “highways” for Radon diffusion

Dependence of ^{220}Rn reduction factor (LN2 treatment)



- Electrodeposited copper (10 μm)
- Thoriated tungsten welding rod (∅ 4.8 mm) as base material
- Repeated temperature shock by direct submersion of the sample in liquid nitrogen (LN_2)