Diffusion of radon daughters in polymer

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Motivation

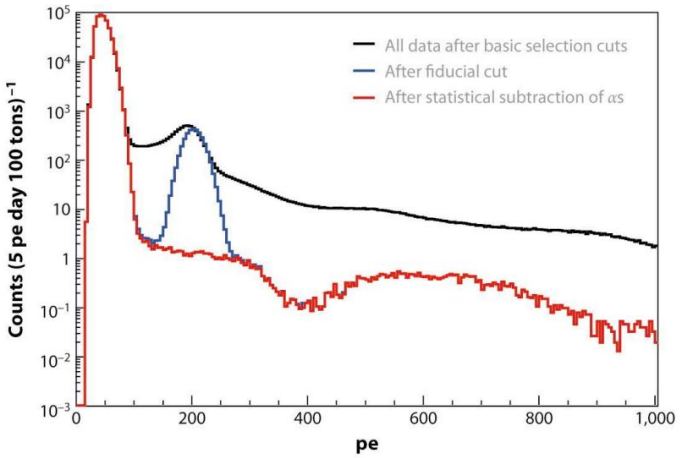
Daughters of Rn-222 which is known to deposit on and diffuse into surfaces, leading to sustained backgrounds supported by the decay of long-lived 210Pb.

$$^{210}\mathrm{Pb} \xrightarrow[32.2\mathrm{y}]{\beta} {}^{210}\mathrm{Bi} \xrightarrow[7.23\mathrm{d}]{\beta} {}^{210}\mathrm{Po} \xrightarrow[199.63\mathrm{d}]{\alpha} {}^{206}\mathrm{Pb}.$$

Surface background rates from Po-210 α-decays in Borexino, DEAP3600 and MiniCLEAN shows the significant disagreement between expected background rates and those observed.

A model including the diffusion of polonium in detector materials can explain the experimental results.

Borexino data



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Borexino : Expected surface alpha background <0.25 uBq/m2

DIffusion process

The radioisotopes deposited on the surface diffuse into the film according to the diffusion equation

$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2}.$$

Analytical solution for a surface-deposited source with semi-infinite slab boundary conditions

$$C(x,t) = \frac{Q}{\sqrt{4\pi Dt}}\exp\left(-\frac{x^2}{4Dt}\right),$$

where

(i) Q is the deposited amount of the source;
(ii) D is the diffusion coefficient;
(iii) $x \geq 0$ is the spatial coordinate;
(iv) $t > 0$ is time.

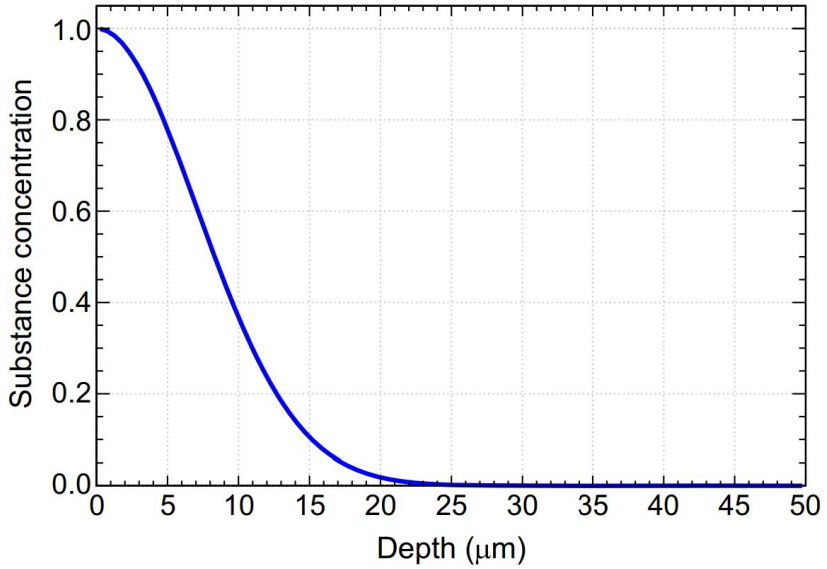


FIG. 1. Concentration of substance within a thin membrane due to diffusion.

Pb-210 deposition system

Pb-210 was deposited onto a 50 μm-thick nylon film using a Model 2000A radon source (Pylon Electronics, 25 kBq).

The source was connected to an acrylic tube of diameter 1cm operated with N_2 gas at ~200 mbar.

A 3.5 kV electric field was applied across the tube to focus radon progeny ions onto the film surface.

Positively charged Po-214 ions drifted under the electric field and deposited onto the foil at the tube end.

The deposited Po-214 subsequently decayed, producing a surface-localized Pb-210 source.

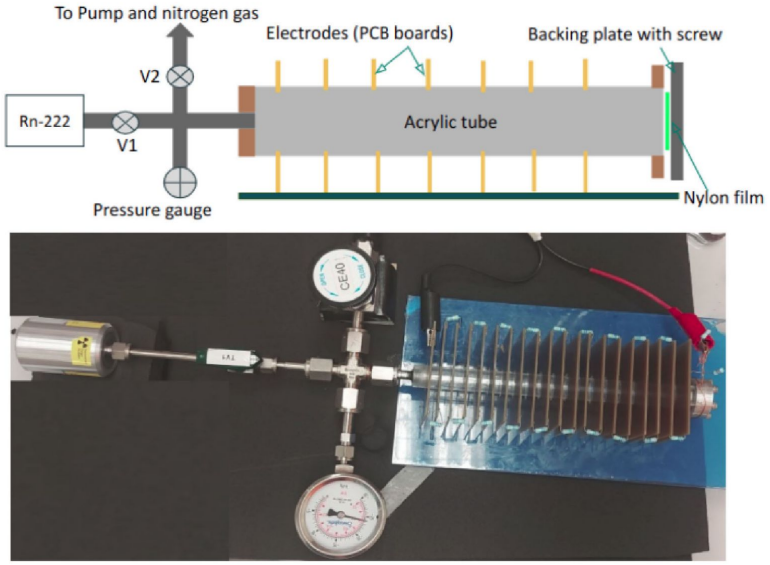


FIG. 2. Top: diagram of the radon daughter deposition chamber showing the components. Bottom: photo of the assembled system.

A localized Pb-210 source was created by electrostatically collecting positively charged Po-214 ions onto a 1-cm-diameter region of a 50 μm nylon film.

Deposition efficiency

Factors Affecting Radon Daughter Deposition Efficiency

Geometrical losses: ratio of source volume to transport tube volume. Deposition of progeny on tube walls before reaching the sample.

Charge-state effects: a fraction of Po daughters may become neutralized or negatively charged, reducing electrostatic collection.

Recoil losses: daughter nuclei may recoil away from the foil following Po decay.

Collection Efficiency Determination

Deposition efficiency was evaluated by counting **^{214}Po α decays** immediately after removing the sample from the deposition chamber.

Measured collection efficiency: ~50%.

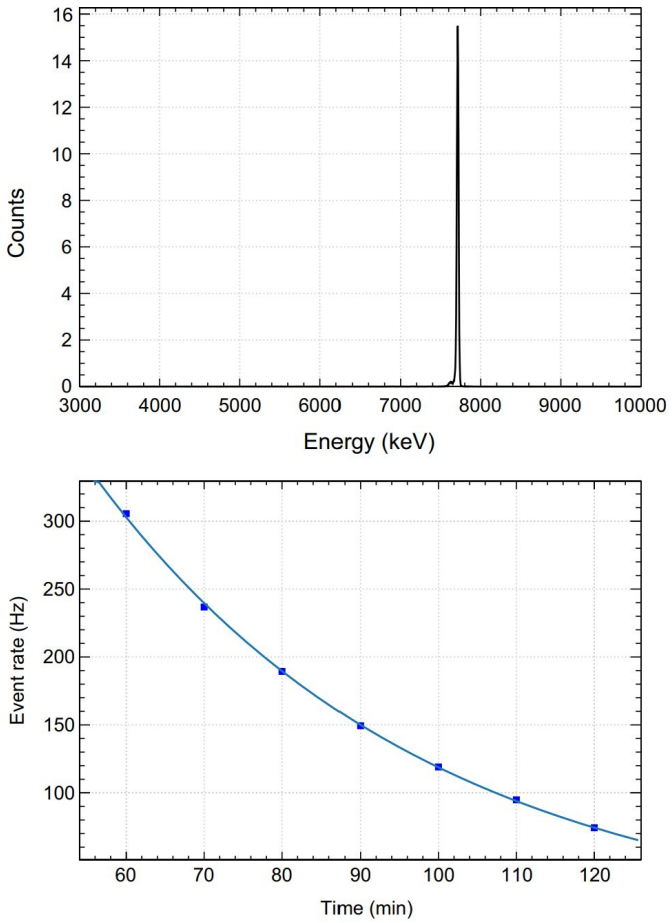


FIG. 4. Top: ^{214}Po induced α energy from the sample within a few hours after removal from the deposition chamber. Bottom: the ^{214}Po rate versus time. The ^{214}Po events are the integration of 7.69-MeV peak.

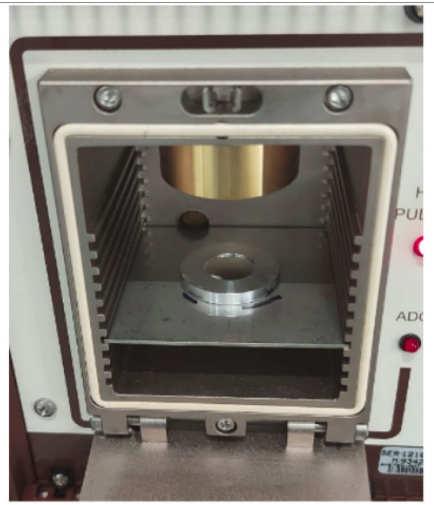
Measurement system and humidity exposure

Pb-210 diffusion monitored using an α-particle counter, it is calibrated with an Am-241 α source.

Measurements performed over ~1 year.

Sample initially stored at 40% relative humidity (RH) and after 200 days, it was exposed to 95% RH for 6 days.

Effect of humidity on Pb-210 diffusion investigated through long-term α-activity measurements.



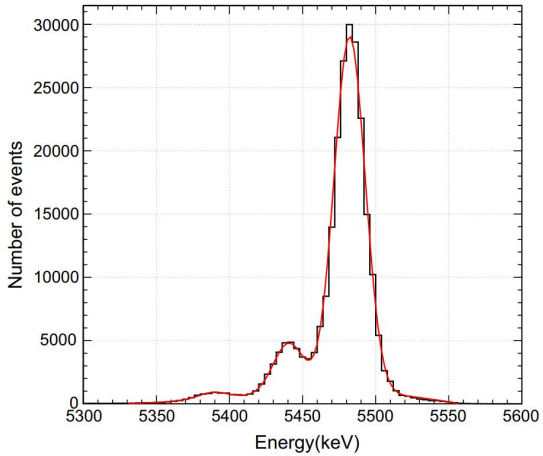


FIG. 3. Top: a photo of α spectrometer in which an ^{241}Am source is placed for calibration and efficiency estimation. Bottom: an α energy spectrum from the ^{241}Am source.

Sample measurement

Exposure to high humidity causes a sharp increase in diffusion, evidenced by a larger number of events originating from within the film.

Both Pb-210 and Po-210 diffuse into the nylon matrix.

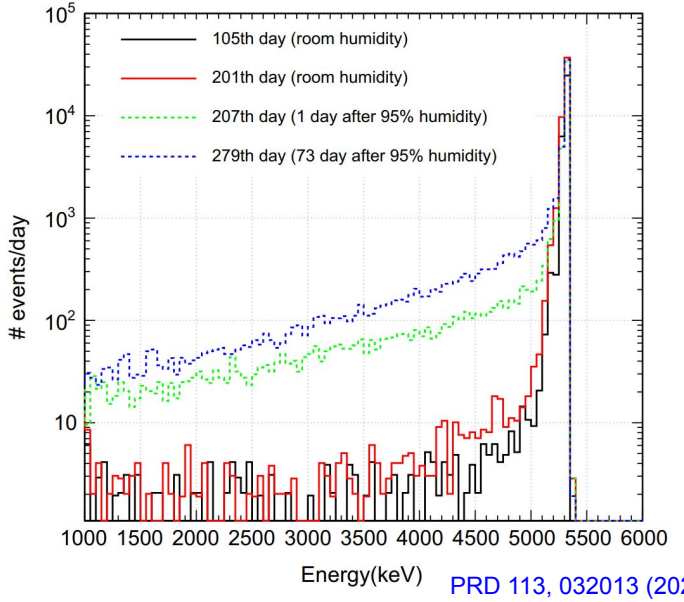
Po-210 diffusion is observed immediately after humidity exposure, as the full-energy α peak shifts toward lower energies due to increased energy loss within the film.

Pb-210 diffusion becomes apparent only in long-term measurements, reflecting the ingrowth of Po-210 from Pb-210 decay.

The evolution of Pb-210-induced activity follows the ~200-day characteristic timescale associated with the Pb-210 → Po-210 decay chain.

$$R_\alpha = A_0(1 - e^{-(t-t_0)/\tau_{Po}})$$

where Rα is the rate of Po-210 after time t, and t0 is the time when the initial Pb-210 contamination occurred.



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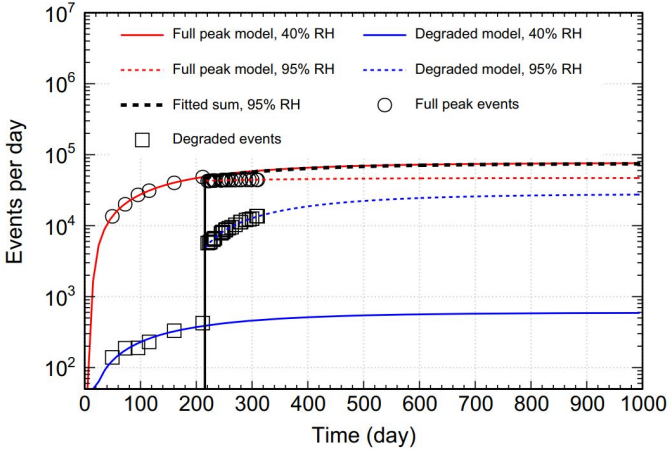
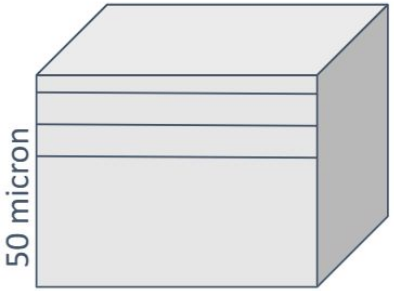
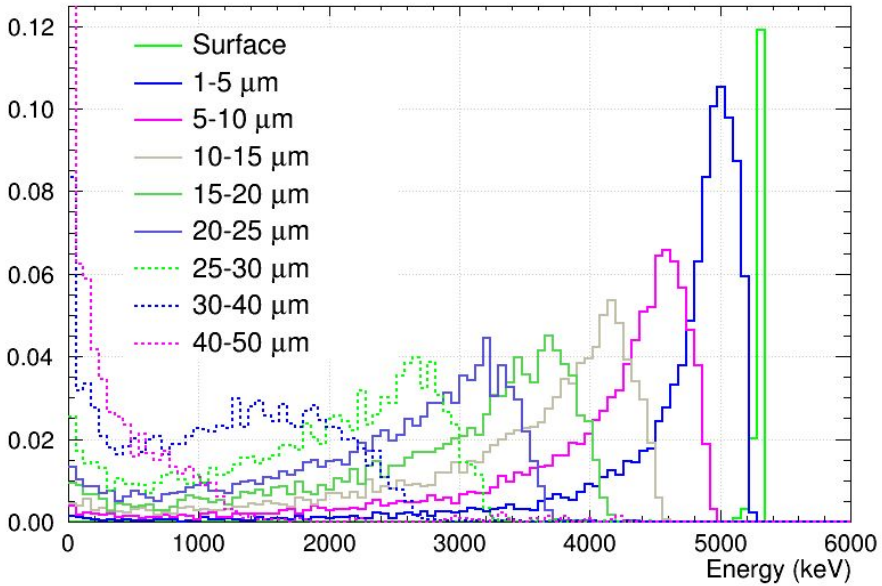


Simulation

Simulated the 5.3 MeV bulk alpha in a 50 micron thick nylon sample.

Position (thickness) cut provides the energy spectrum for different thickness of nylon layer.





Fit with data

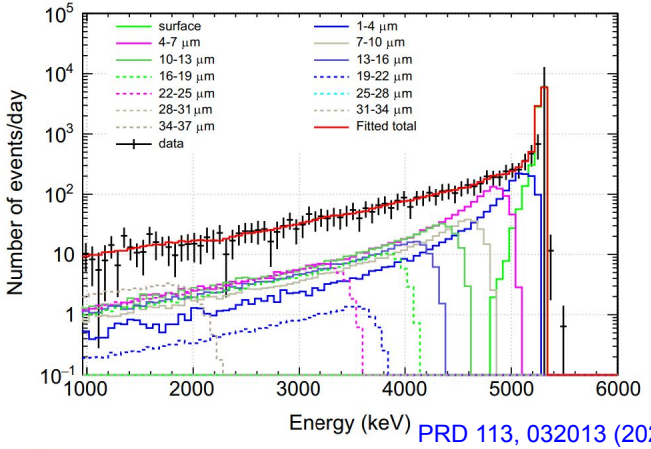
Data are separated into two components:

- Po-210 diffusion events (early-time, immediately after humidity exposure)
- Pb-210 related events (long-term ingrowth contribution following radioactive decay to Po-210)

Surface depth distribution is extracted by fitting data with Monte Carlo (MC)–generated α spectra for different effective layer thicknesses.

Depth-dependent event distributions are modeled to reconstruct the activity profile within the film.

Diffusion coefficients are obtained by fitting the extracted depth profiles with a diffusion equation.



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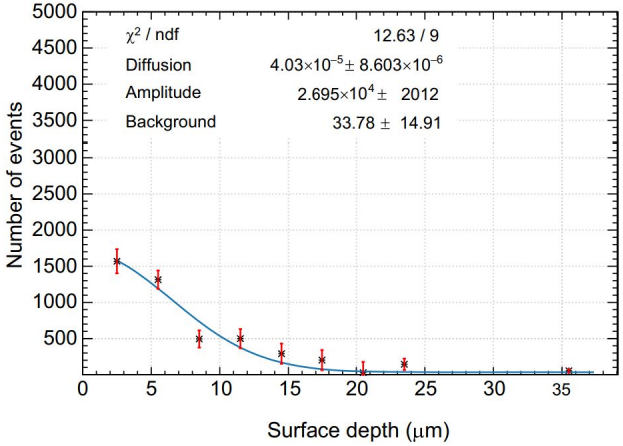

DIffusivity and uncertainty

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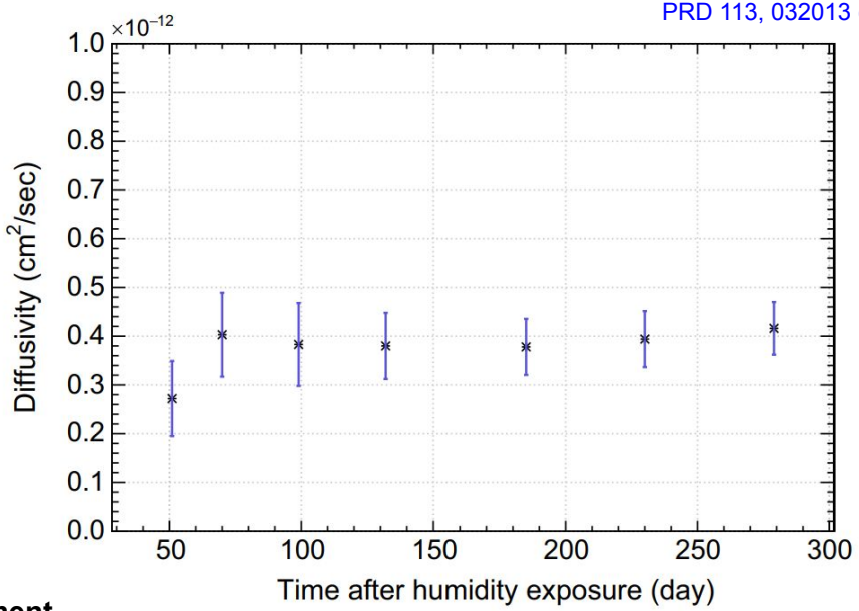
Sample positioning in the α-counter, affecting detection efficiency and solid-angle acceptance.

Radioactive decay during storage in the humidity chamber, reducing the effective activity at the time of measurement.

Energy scale calibration uncertainty, impacting event selection and spectral separation.

Statistical and fitting uncertainties arising from the model used to extract diffusion parameters.



Diffusion coefficients obtained from this measurement

Relative Humidity	Diffusion Coefficient (cm²/s)
95% (Po-210)	$(3.94 \pm 0.98) \times 10^{-13}$
95% (Pb-210)	$(4.03 \pm 1.01) \times 10^{-13}$
40% (both isotopes)	$< 1.14 \times 10^{-15}$

Summary and outlook

Radon daughter diffusion is a significant background source, particularly relevant for low-background physics experiments.

This work investigates the diffusion behavior of ^{210}Po and ^{210}Pb in nylon films.

The study demonstrates that environmental conditions, especially humidity, strongly influence diffusion processes.

Future work will extend measurements to additional humidity levels and different polymers, with a focus on acrylic materials.

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Diffusion of ^{210}Pb and ^{210}Po in nylon

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Radon and its progeny constitute a major source of background in rare-event physics experiments, such as those searching for dark matter, neutrinos, and neutrinoless double β decay, due to their origin as unavoidable decay products of natural uranium. In particular, ^{222}Rn and its long-lived daughter ^{210}Pb can diffuse from detector material surfaces, resulting in sustained background contributions. To investigate this process, a system was developed using a controlled radon source, a vacuum chamber with a high electric field, and a thin nylon-6 film to enable deposition of radon progeny onto the film surface. Nylon-6 was selected for the initial measurement given its history in low-background experiments. We intend to systematically study diffusion in various polymers in the future. Our setup allowed for controlled study of the diffusion behavior of ^{210}Pb and its daughter ^{210}Po under varying humidity conditions. Our results show that both ^{210}Pb and ^{210}Po diffuse significantly in nylon under high relative humidity, which can potentially lead to internal contamination and increased background in low-background detectors. The diffusivity of ^{210}Pb was found to be lower than 1.14×10^{-15} cm^2/s at 40% relative humidity (RH) and to be $(4.03 \pm 1.01) \times 10^{-13}$ cm^2/s at 95% RH. The diffusivity of ^{210}Po at 95% RH was measured to be $(3.94 \pm 0.98) \times 10^{-13}$ cm^2/s. These findings underscore the importance of controlling environmental humidity and material exposure to radon in the design of ultralow-background experiments.

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