Experimental Study of Radon Solubility in Linear Alkylbenzene (LAB) for Low-Background Experiments.

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Motivation & Objectives

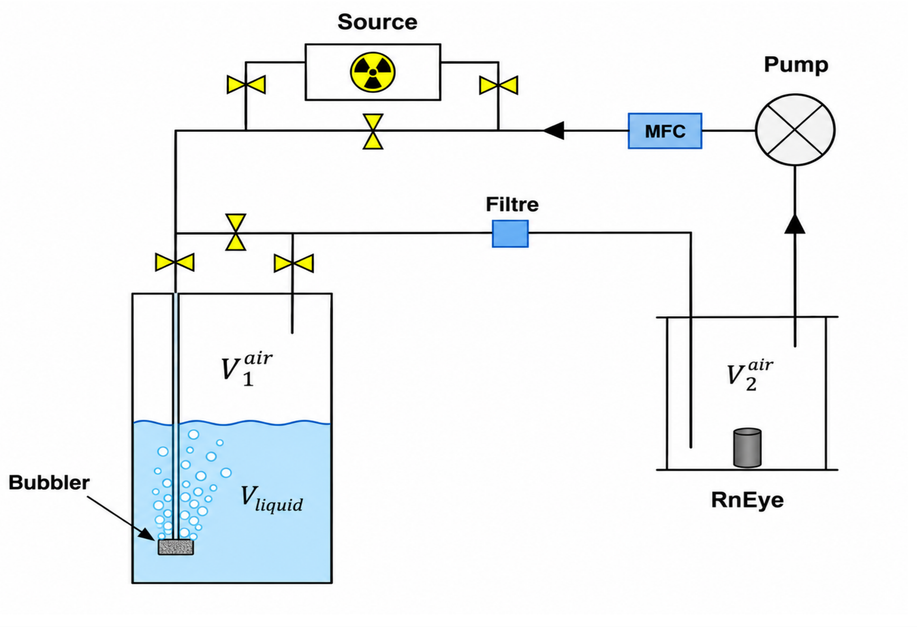
Radon-222 is an important source of radioactive background in low-background experiments based on liquid scintillators, such as **JUNO, Borexino, or KamLAND**.

In these large-volume detectors, the liquid scintillator, particularly **Linear Alkylbenzene (LAB)**, must exhibit extremely high radiopurity in order to preserve experimental performance.

Produced by $^{226}\mathrm{Ra}$ contained in detector materials, or introduced through external pathways, $^{222}\mathrm{Rn}$ can migrate into the active volume and dissolve in the liquid scintillator.

Once present in the target, its radioactive progeny contribute to the background and may limit the sensitivity of the experiment.

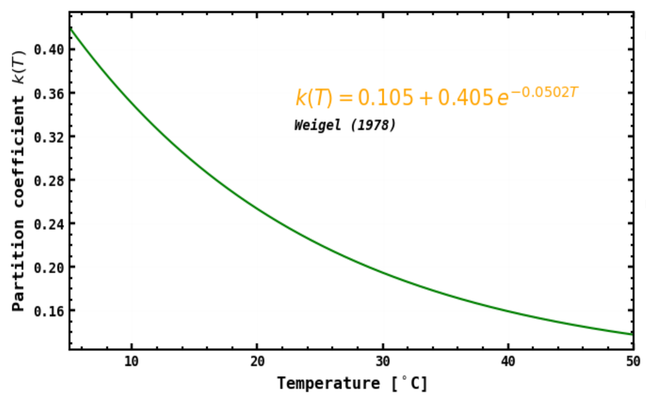
The objective of this study is to quantify radon solubility in LAB and its temperature dependence. This provides key information to assess radon transfer into the active liquid volume and to optimize radon-background mitigation strategies in low-background experiments.



Experimental Setup & Measurement Principle

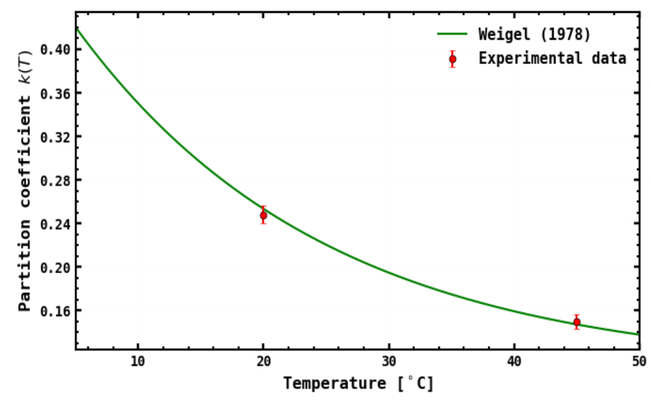
- An initial radon concentration C_0 is introduced into the gas phase and circulated through the closed-loop system.
- The radon-loaded gas is brought into contact with the liquid through the bubbler. Rn progressively partitions between the gas and liquid phases until gas–liquid equilibrium is reached.
- At equilibrium, the residual gas-phase concentration C_{air} is measured.
  - ✓ The gas–liquid partition coefficient is defined as : $\boxed{k(T) = \dfrac{C_{\mathrm{liq}}}{C_{\mathrm{air}}}}$
  - ✓ Assuming a closed system with negligible radon losses, the total radon inventory is conserved : $A_0 = A_{\mathrm{air}} + A_{\mathrm{liq}}$
  - ✓ Initially, the radon inventory in the gas phase is : $A_0 = C_0 V_2^{\mathrm{air}}$
- At equilibrium, the mass balance becomes : $C_0 V_2^{\mathrm{air}} = C_{\mathrm{air}} \left[V_1^{\mathrm{air}} + V_2^{\mathrm{air}} + k V_{\mathrm{liq}}\right]$
- The partition coefficient is therefore obtained from : $\boxed{k = \dfrac{C_0 V_2^{\mathrm{air}}}{C_{\mathrm{air}} V_{\mathrm{liq}}} - \dfrac{V_1^{\mathrm{air}} + V_2^{\mathrm{air}}}{V_{\mathrm{liq}}}}$

Measurement Method & Validation with Water



- Water was used as a reference liquid to test the experimental setup and the gas–liquid partitioning methodology, since its radon solubility is well characterized in the literature [2]
- The Rn water–air partition coefficient has been previously characterized and, at atmospheric pressure, is described between $5°\mathrm{C}$ and $50°\mathrm{C}$ by:

$$k_{\mathrm{water}}(T) = 0.105 + 0.405\, e^{-0.0502 \cdot T}$$



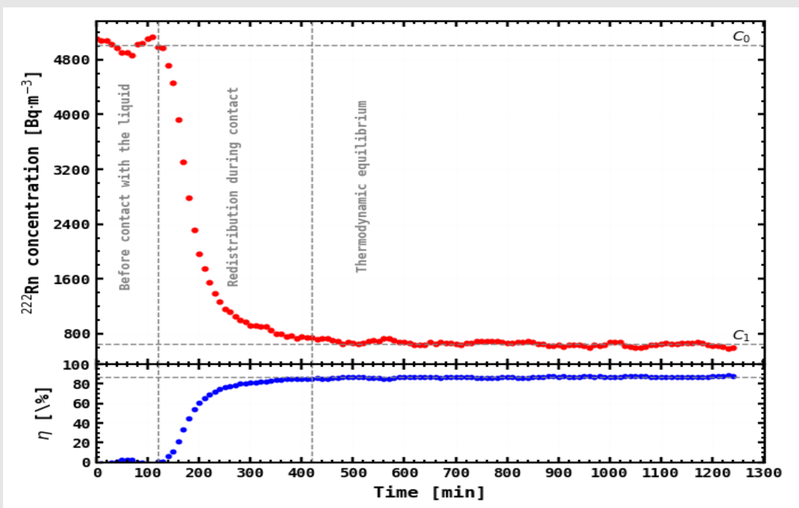
- k_{water} was measured at $20°\mathrm{C}$ and $45°\mathrm{C}$ under atmospheric pressure.
- The measured values closely follow the reference curve, confirming the reliability of the experimental setup for radon partition measurements.

The radon partitioning process is monitored in real time via the gas-phase activity (right plot). Three regimes are observed :

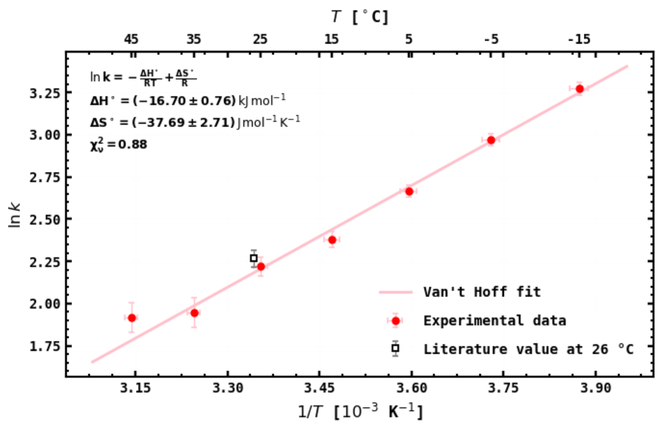
- **Before contact :** gas-phase activity is stable, defining the reference C_0.
- **Redistribution :** once bubbling starts, radon progressively transfers to the liquid, tracked by :

$$\eta(t) = \frac{C_0 - C_{\mathrm{air}}(t)}{C_0} \times 100\,\%$$

- **Equilibrium plateau :** C_{air} stabilizes at C_1, from which $k(T)$ is extracted.



Results & Discussion



- The linear behavior of $\ln k$ versus $1/T$ is well described by the Van't Hoff relation, with $\chi^2_\nu = 0.88$ supporting a thermodynamically consistent temperature dependence.
- The fit yields $\Delta H^\circ = (-16.70 \pm 0.76)\,\mathrm{kJ\,mol^{-1}}$ and $\Delta S^\circ = (-37.69 \pm 2.71)\,\mathrm{J\,mol^{-1}\,K^{-1}}$.
- The negative ΔH° indicates an exothermic transfer of radon into the liquid, explaining the increase of the k coefficient as the temperature decreases.
- Lower temperatures therefore enhance radon retention in the liquid phase.

Summary & Outlook

- The experimental setup and methodology were successfully validated using water, with measured k_{water} values consistent with the reference empirical model.
- Radon partitioning in LAB exhibits a strong temperature dependence, with k increasing from ~ 7 at $45°\mathrm{C}$ to ~ 26 at $-15°\mathrm{C}$.
  Lower temperatures therefore strongly enhance radon retention in LAB.
- **Outlook:** the high radon affinity observed in cold LAB opens the possibility of investigating cooled liquids as potential radon-capture media, complementary to conventional microporous adsorbents used in low-background experiments.

References :

[1]. Fengpeng An et al. Neutrino Physics with JUNO. J. Phys. G, 43(3):030401, 2016.
[2]. Friedrich Weigel. « Radon ». In : Chemie der Erde 38 (1978), p. 1-38.
[3]. William C. Burnett, Guebuem Kim et Derek Lane-Smith. "A continuous monitor for assessment of radon in the coastal ocean". In : Journal of Radioanalytical and Nuclear Chemistry 249.1 (2001), p. 167-172. doi : 10.1023/A:1013217821419.
[4]. Z. Xu, C. Guo, J. Liu, Y. Zhang, P. Zhang, C. Yang, Q. Tang, Y. Liu, C. Li and T. Guan, "Research of radon diffusion behavior in liquid scintillator," Journal of Instrumentation, 18 (2023) P04006. DOI: 10.1088/1748-0221/18/04/P04006.
[5]. Fast determination of indoor radon (^{222}Rn) concentration using liquid scintillation counting, Journal of Radioanalytical and Nuclear Chemistry, 312 (2017), 337–342.