Radon induced surface contaminations in low background experiments

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OUTLINE

* Rare event physics

* DBD bolometric experiments

* Background sources in bolometric experiments

* \(^{222}\text{Rn}\) induced surface contaminations
  * Mechanisms
  * \(^{222}\text{Rn} \) “Sticking Factor” \((\Sigma_{\text{Rn}})\)

* Conclusions
Low background experiments

rare events

DBD2ν & DBD0ν
DM interactions with RM
rare α/β decays

elusive rates

\(< 10^{-2} - 10^{-4} \, \text{c/keV/kg/y}\)
\(< 10^{-3} - 10^{-4} \, \text{c/kg/d}\)
\(< 10^{-2} - 10^{-xx} \, \text{c/kg/d}\)

Low radioactive techniques are used:

* material selection
* underground installation
* (re)contamination control
* highly sensitive detectors
Sensitivity for DBD0ν

\[ S_{0ν} \propto a.i. \sqrt{\frac{M \cdot t}{B \cdot ΔE}} \]

\( S_{0ν} \): half-life corresponding to the minimum number of detectable signals above background at a given C.L.

- \( i.a. \): isotopic abundance
- \( M \): detector mass
- \( t \): measuring time
- \( B \): background
- \( ΔE \): energy resolution

**Q_value:** 2995 keV  
**Material:** ZnSe  
**Enriched a.i.:** 95%  
**Source Mass:** 15 kg of Se-82  
**Projected Bkg:** \(~10^{-3}\) c/keV/kg/y  
**Resolution:** \(~10\) keV @ROI  
**Sensitivity \( T_{1/2} \):** \(~10^{26}\) y in 5 y

**Q_value:** 2528 keV  
**Material:** TeO₂  
**Natural a.i.:** 34%  
**Source Mass:** 206 kg of Te-130  
**Projected Bkg:** \(~0.01\) c/keV/kg/y  
**Resolution:** \(~5\) keV @ROI  
**Sensitivity \( T_{1/2} \):** \(~10^{26}\) y in 5 y

*F. Alessandria et al., arXiv:1109.0494*
Surface background issue

Cuoricino: • first large array (62 bolometers = ~41 kg) for DBD
• high statistics (exposure: 19.75 kg(Te$_{130}$) x y)
• energy resolution @ DBD0ν: 6.3±2.5 keV

Cuoricino: 

- background @ DBD0ν (2.5 MeV): 0.17 c/keV/kg/y

External high energy γ (232Th) 35%

Degraded α struggling from TeO$_2$ and Cu surface contaminations (232Th & 238U) 65%

CUORICINO final energy spectrum
α decays ($^{210}$Po $Q=5.4$ MeV) may occur on surfaces of Cu structure or on the detectors.

N.B. bolometers are fully-active detectors

$E_{\text{tot}} = E_\alpha + E_{\text{recoil}}$

1-2-4 may induce a bkg in the "high energy region"

3-4-5 in the "low energy" region

M. Clemenza, C. Maiano, L. Pattavina, E. Previtali, Eur. Phys. J. C 71, 1805 (2011)
Radon induced contaminations

$^{210}$Po is the most intense source of surface contaminations in DBD bolometric experiments (and not only).

$^{238}$U $\tau = 4.5 \times 10^9$ y

Radon decay chain

- $^{222}$Rn $\tau = 3.8$ d
  - $\alpha$ 5.5 MeV - 100%
- $^{218}$Po $\tau = 3$ m
  - $\alpha$ 6 MeV - 100%
- $^{214}$Pb $\tau = 27$ m
  - $\beta$ 1 MeV - 100%
- $^{214}$Bi $\tau = 20$ m
  - $\beta$ 3.3 MeV - 99%
- $^{214}$Po $\tau = 0.16$ ms
  - $\alpha$ 7.7 MeV - 100%

- $^{210}$Pb $\tau = 22.3$ y
  - $\beta$ 16 keV; 63 keV
- $^{210}$Bi $\tau = 5.01$ d
  - $\beta$ 1.17 MeV - 99%
- $^{210}$Po $\tau = 138.4$ d
  - $\alpha$ 5.3 MeV - 100%
  - $\gamma$ 803 keV - 0.001%
- $^{206}$Pb $\tau$ = stable
Why $^{222}$Rn?

Radon is the most intense air-borne contaminant

$^{210}$Pb and $^{210}$Po are $^{222}$Rn daughters and background sources

Is $^{222}$Rn the primary source of surface background?

* Storage of material in non-ultra-pure containers
* Handling in non-controlled environment
* Not appropriate surface cleaning

* ....

$^{222}$Rn can induce a re/contamination of $^{210}$Pb and $^{210}$Po?

- Exposing an radio-pure material to $^{222}$Rn will contaminate the sample?
We expressly expose different radio-pure materials to an atmosphere rich in $^{222}\text{Rn}$. We analyze the surface contaminations of the samples due to the exposure.

* We evaluate the probability that a nucleus of $^{222}\text{Rn}$ (or daughters) can stick on the surface of the sample ($^{222}\text{Rn}$ Sticking Factor).

* We analyze the mechanisms/dynamics that lead to sample recontaminations.

**Box with hermetic enclosures**

**Samples and $^{238}\text{U}$ sources**

**Surface barrier detector**

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*M. Clemenza, C. Maiano, L. Pattavina, E. Previtali, Eur. Phys. J. C 71, 1805 (2011)*
Samples exposure

| MATERIAL | Exposure [days] |
|----------|----------------|
| Copper   | 1076           |
| PTFE     | 1140           |
| Si       | 1080           |
| TeO₂     | 1183           |
| ZnSe     | xxxx           |

\[ \text{\^{222}Rn} \text{ concentration inside the Rn-box} \]

\[ @ \text{saturation} \quad \sim 320 \text{ kBq/m}^3 \]

* Po isotopes stick to the surfaces
* \(^{214}\text{Po}\) and \(^{210}\text{Po}\) peak+tail
* Tails extend to low energy

After the exposure we measure the sample
210Po contaminant & ΣRn

170h measurement acquired after \( \tau(222\text{Rn}) > t >> \tau(218\text{Po}, 214\text{Po}) \)

* No evidence of 222Rn contamination
* 210Po contamination produces a continuum
* 210Po activity is proportional to exposure time (for the same materials)
* 210Po increases with time

Sticking Factor (Σ) for a nucleus that interacts with a surface (S) is defined as:
The ratio between the number of nuclei that stick on a surface \( A_{210\text{Pb}}^0 \cdot \tau_{210\text{Pb}} \) and the total number of nuclei that are close enough to the surface to stick \( \Gamma \sim \text{Rn concentration} \).

\[
\Sigma_{\text{Rn}} = \frac{A_{210\text{Pb}}^0 \cdot \tau_{210\text{Pb}}}{\Gamma \cdot S \cdot t_{\text{exp}}}
\]

| MATERIAL  | Σ_{Rn}               |
|-----------|----------------------|
| Copper    | \((1.86\pm0.10) \cdot 10^{-9} \) |
| PTFE      | \((3.06\pm0.22) \cdot 10^{-10} \) |
| Si        | \((3.97\pm0.54) \cdot 10^{-10} \) |
| TeO2      | \((3.75\pm0.21) \cdot 10^{-10} \) |
| ZnSe      | measurement on going |

N.B. We refer to 210Pb activity because we assume that after a long period of time \( (t \gg \tau_{1/2\text{Rn}}) \), all the 222Rn daughters have decayed and have populated the 210Pb level.
**Sticking Factor** (\(\Sigma\)) for a nucleus that interacts with a surface (\(S\)) is defined as:

\[
\Sigma_{\text{Rn}} = \frac{A_{\text{Pb}}^0 \cdot \tau_{\text{Pb}}}{\Gamma \cdot S \cdot t_{\text{exp}}}
\]

the ratio between the number of nuclei that stick on a surface \(A_{\text{Pb}}^0 \cdot \tau_{\text{Pb}}\) and the total number of nuclei that are close enough to the surface to stick (\(\Gamma \sim \text{Rn concentration}\)).

\[
A_{\text{Po}} = A_{\text{Pb}}^0 \frac{\lambda_{\text{Po}}}{\lambda_{\text{Po}} - \lambda_{\text{Pb}}} (e^{-\lambda_{\text{Po}}t} - e^{-\lambda_{\text{Pb}}t})
\]

* No evidence of \(^{222}\text{Rn}\) contamination
* \(^{210}\text{Po}\) contamination produces a continuum
* \(^{210}\text{Po}\) activity is proportional to exposure time (for the same material)
* \(^{210}\text{Po}\) increases with time

| MATERIAL | \(\Sigma_{\text{Rn}}\) |
|----------|------------------|
| Copper   | \((1.86\pm0.10) \cdot 10^{-9}\) |
| PTFE     | \((3.06\pm0.22) \cdot 10^{-10}\) |
| Si       | \((3.97\pm0.54) \cdot 10^{-10}\) |
| TeO2     | \((3.75\pm0.21) \cdot 10^{-10}\) |
| ZnSe     | Measurement on going |

**N.B.** We refer to \(^{210}\text{Pb}\) activity because we assume that after a long period of time (\(t \gg T_{1/2\text{Rn}}\)), all the \(^{222}\text{Rn}\) daughters have decayed and have populated the \(^{210}\text{Pb}\) level.
$^{210}$Pb production

$^{210}$Po contamination is driven by $^{210}$Pb contamination
$\Rightarrow$ $^{210}$Po activity does not decrease with time

$^{210}$Pb on the surface can be produced by:

* direct $^{210}$Pb surface sticking (prompt)

* $^{218}$Po & $^{214}$Po isotopes sticking (delayed)

$^{210}$Pb evaluated from $^{210}$Po contamination.
“prompt” (t ~ h) and “delayed” (t ~ 1.5 y).

In Clean Room design Po isotopes contamination must be kept under control.

$^{210}$Po production mechanism

$A^0 (^{210}\text{Pb})_{\text{delay}} / A^0 (^{210}\text{Pb})_{\text{prompt}} = \sim 6$

~85% of $^{210}$Pb contamination is generated by Rn fast daughter decays ($^{218}$Po and $^{214}$Po)
Conclusions

- Surface contaminations are a serious limitation for low background experiments

- Rn exposure of ultra-pure samples induce re-contaminations

- $^{210}\text{Pb}$ (and especially Po isotopes) contaminations must be took under strict controls

- We have evaluated the sticking probability of $^{222}\text{Rn}$, long-term exposure are dangerous
However the events that are in the tail are a small fraction of the overall activity (about 15%), assuming the continuum contribution negligible. We compare the plots in Fig. 4.19, which show the differential activity measurements (that are just the difference of two acquired spectra of the same sample), for each polonium nuclide for a copper and a tellurium dioxide sample: we see that the trends for the activities (dots) of $^{218}$Po (plots e and f) and $^{214}$Po (plots c and d) have the same shape, and are in agreement with the simulations (continuum lines). The simulations concern the time evolution of the contaminant activities once they are taken away from the main sources ($^{222}$Rn). In fact the $^{218}$Po activity decreases with a proper decay constant ($T_{218}$Po = 3.1 min) while the $^{214}$Po activity after an initial increase falls with a decay constant given by equation 3.23, which is in complete agreement with the result presented in Fig. 3.10. If we look at plots a and b, which describe $^{210}$Po activity, we see that the experimental data are not in agreement with the simulations, the reason for this behavior is due to the fact that the time needed for the lower part of the Rn chain to reach the secular equilibrium is quite long because of the long $^{210}$Po half-life. The Polonium-210 is trying to reach the equilibrium but it needs about $4 \cdot T_{210}$Po to get to it, in the meanwhile the activity is increasing linearly. These plots corresponds exactly to a zoom in on the origin of the Cartesian axes of Fig. 3.9 b, it is an exponential function.

All the analyzed slabs have the same trend for the activity, but different values. The reason is probably linked to the chemical features of materials like copper and...
Analysis of the Contaminants (3)

In differential spectra ($\Delta T >> \tau_{Rn}$) there is no Rn evidences

$^{210}\text{Po}$ is mainly implanted, it is not just $^{210}\text{Pb}$ deposition

$A_{\text{exp}} = 118.8 \text{ C/h}$
$A_{\text{meas}} = 100.5 \text{ C/h}$
$\sim 15\%$ peak

Copper slab “cleaned” with $\text{H}_2\text{O}$-ethanol-$\text{H}_2\text{O}$
Po210 tails

Table 4.3:

| Sample          | Material     | Exposure time | Diffusion depth    |
|-----------------|--------------|---------------|--------------------|
| Rame_BaseMen    | Copper       | 63 days       | 430±20 nm          |
| Rame_OFHC       | Copper       | 56 days       | 410±20 nm          |
| Rame_OFHC_brv   | Copper       | 16 days       | ***                |
| TeO2.2Mis       | Tellurium Oxide | 73 days     | 940±20 nm          |
| TeO2.1Mis       | Tellurium Oxide | 49 days     | 500±20 nm          |
| TeO2_brv        | Tellurium Oxide | 14 days     | ***                |
| Teflon          | PTFE         | 117 days      | 100±20 nm          |
Sticking factor

We suppose to have a surface (S) exposed to a high radon concentration atmosphere (n, particles per unit volume). If we wish to compute the number of radon nuclei which hit our surface per unit time and unit surface (it is just a flux), \( \Gamma \), we have to consider the number of nuclei in the volume \( v \cdot t \), where \( v \) is the particles velocity and \( t \) the unit time. If we integrate the solid angle with which all the particles in the \( v \cdot t \) see the surface \( S \):

\[
\Gamma \left[ \frac{\text{hits}}{\text{cm}^2 \cdot \text{sec}} \right] = \int_0^{2\pi} \int_0^{\frac{\pi}{2}} d\theta \sin \theta \int_0^v dr r^2 \left( \frac{S \cos \theta}{4\pi r^2} \right) \frac{n}{S} = \frac{n \cdot v}{4}
\]

\[
\Gamma = 2.86 \cdot 10^6 \frac{\text{hits}}{\text{cm}^2 \cdot \text{sec}}
\]

\[
v = \sqrt{\frac{k_b T}{m}}
\]
The bolometric technique

Energy deposited in the absorber produces a measurable temperature rise.

The heat capacity of the crystal must be very small (→ low temperature ~10 mK)

Absorber
- M ~ 0.75 kg
- C ~ 10^{-9} J/K
- ΔT/ΔE ~ 100μK/MeV

Thermometer
- R = R_0 \exp[(T_0/T)^{1/2}]
- R ~ 100 MΩ
- ΔR/ΔE ~ 3 MΩ/MeV

Heat-sink: Copper
Thermal conductance (G): PTFE & gold wires
Absorber: ZnSe
Thermometer: Ge-NTD

\[ \Delta T = \frac{E}{C} \]