Radon Assay and Reduction in XENON1T

Stefan Brünner

July 8, 2016
Dark Matter – The unsolved Mystery

One of the most challenging questions in modern Cosmology is the identity and nature of Dark Matter.

- galaxy rotation curves
- gravitational lensing
- structure formation

evidences on different scales
Dark Matter - Detection Strategies

XENON
Dark Matter Project

liquid xenon for direct WIMP detection

(Weakly Interacting Massive Particles)

**XENON10** (2006)
25kg liquid xenon

**XENON100** (2008)
160kg liquid xenon

**XENONnT** (2006)
~7t liquid xenon

**XENON1T** (2015)
3t liquid xenon
Two-phase TPC detection principle

Two-phase TPC (Time Projection Chamber)
3D-position reconstruction (define fiducial volume for background discrimination)
S2/S1 ratio allows nuclear- and electronic-recoil discrimination
XENON100 – No Hint for Dark Matter

**Sensitivity on WIMP-nucleon cross-section:**
- spin-independent: \( \sigma_{\text{WIMP-nucleon}} = 2.0 \times 10^{-45} \text{ cm}^2 \) (\( m_\chi = 55 \text{ GeV/c}^2 \))
- spin-dependent: \( \sigma_{\text{WIMP-neutron}} = 3.5 \times 10^{-40} \text{ cm}^2 \) (\( m_\chi = 45 \text{ GeV/c}^2 \))

**Background:** \( 5.3 \times 10^{-3} \) evts/kg/keV/day

excellent MC/data agreement

---

**XENON1T**

Sensitivity goal:
\( \sigma_{\text{WIMP-nucleon}} = 1.6 \times 10^{-47} \text{ cm}^2 \)

Background goal:
\( 1.8 \times 10^{-4} \) evts/kg/keV/day

XENON100 TPC
**XENON1T – Background expectation**

### Nuclear Recoils (NR)
- Neutrons (radiogenic, muon-induced)
- Water tank as muon veto
- Coherent neutrino-nucleus scattering

### Electronic Recoils (ER)
- Radioactivity ($\beta,\gamma$) from detector components
- Shielding, self-shielding of xenon
- Intrinsic background from $^{85}$Kr and $^{222}$Rn

---

**Expectation values of events in XENON1T, in 2 t·y exposure**

<table>
<thead>
<tr>
<th>Signal ($\mu_8$)</th>
<th>No discrimination</th>
<th>99.75% ER discrimination</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 GeV/c$^2$ WIMP ($\sigma = 2 \cdot 10^{-45}$ cm$^2$)</td>
<td>0.68</td>
<td>0.27</td>
</tr>
<tr>
<td>10 GeV/c$^2$ WIMP ($\sigma = 2 \cdot 10^{-46}$ cm$^2$)</td>
<td>4.65</td>
<td>1.86</td>
</tr>
<tr>
<td>100 GeV/c$^2$ WIMP ($\sigma = 2 \cdot 10^{-47}$ cm$^2$)</td>
<td>7.13</td>
<td>2.85</td>
</tr>
<tr>
<td>1 TeV/c$^2$ WIMP ($\sigma = 2 \cdot 10^{-46}$ cm$^2$)</td>
<td>8.85</td>
<td>3.54</td>
</tr>
</tbody>
</table>

**Background**
- Total ER ($\mu_{bER}$): 1300
- NR from neutrons: 1.10
- NR from CNNS: 1.18
- Total NR ($\mu_{bNR}$): 2.28

---

**XENON1T collaboration, arXiv:1512.07501**

---

**XENON1T collaboration, arXiv:1512.07501**

---

**XENON1T collaboration, arXiv:1512.07501**

---

**XENON1T collaboration, arXiv:1512.07501**

---

**XENON1T collaboration, arXiv:1512.07501**
**Intrinsic Background Source** \( ^{222}\text{Rn} \)

**Emanation as radon source**

Traces of \(^{238}\text{U}\) in every material

Radioactive noble gas \(^{222}\text{Rn}\) emanates from detector materials

Emanation is a permanent source of Rn

---

**Intrinsic Background**

Rn distributes homogeneously in the LXe target

Radon progenies (\(^{214}\text{Pb}\)) can induce background

No shielding possible!
Mitigating Background - Radon Screening

**Careful material selection to avoid emanation**
Measurement of bulk impurities (spectrometry) often not sufficient

**Radon screening at MPIK**
Measurement of the radon emanation rate of every detector material

---

**Miniaturized Proportional Counter**
- Background: ~1 count/day
- Sensitivity: ~20 μBq

**Electrostatic Rn-Monitor**
- Ionized Rn progenies are drifted towards a PIN diode
- Sensitivity: ~1 mBq
XENON1T – Emanation results

Integral measurement of the cryostat including TPC
preliminary result:
(19 +/- 4) mBq
Radon Distillation – Online Radon removal

Online radon removal system
Part of the existing gas purification loop
Needs to handle gas flow of ~100 slpm

Separate radon from xenon
Radon retains in the removal system for several half-lives
Drops out naturally from system by radioactive decay

Krypton distillation
Successfully used in XENON100
Distillation column for XENON1T
Purification to ppq-level (x $10^{-15}$)

Special case: Radon distillation
Continuous distillation during detector operation
No ‘off gas’ allowed (no loss of xenon)
Radon is dropped out only by radioactive decay

Saturation vapor-pressures of noble gases
The HeXe Setup – probe Rn distillation

Single-stage distillation
Measurement of radon depletion in the boil-off gas phase
Cold-head for xenon liquefaction
Bell-structure separates gas volume

The Heidelberg Xenon system (HeXe)
The HeXe Setup – probe Rn distillation

Measurement procedure
Fill HeXe with radon enriched xenon which is liquefied at the cold-head
Recuperate the boil-off xenon inside the bell-structure with a regulated mass-flow through a radon monitor
Electrostatic radon monitor measures continuously the radon activity concentration in the xenon gas
The HeXe Setup – probe Rn distillation

Proof of radon reduction in boil-off gas!
Radon reduction by a factor $\sim$5 measured

Complementary measurements with proportional counters confirm results

Measurements at higher recuperation flows of up to 6 slpm show same reduction factor

Systematic 'bell-effect' still under investigation
Online Rn-distillation at XENON100

Rn-detector XENON100
Alpha-peaks of $^{222}\text{Rn}$ and progenies easy to identify
BiPo analysis for complementary radon monitoring

Extension of gas purification loop
Integration of XENON1T krypton column in purification loop
Integration of a radon emanation source
Online Rn-distillation at XENON100

**Radon emanation source**
426 viton O-rings as radon source
~70 mBq activity brought into XENON100 TPC

**Rn-distillation setup at XENON100**

**Operation of Kr-column**
XENON1T phase I krypton column

'Inverse' operation with respect to Kr distillation
Rn is enriched in the liquid reservoir (reboiler)

Purified xenon from the columns top is pumped back into XENON100

Situation at XENON100 during the distillation campaign
Online Rn-distillation at XENON100

The graph shows the activity concentration of $^{222}$Rn [μBq/kg] over time. The data is divided into five periods (I-V). Period IV highlights an open radon source with a value of $518 \pm 8$. Period V shows a 2nd distillation run. The lower graph displays the ratio of BiPo/$^{222}$Rn over time, peaking at $0.50 \pm 0.01$. The x-axis represents dates in the format [day/month].
Online Rn-distillation at XENON100

**Type I and Type II emanation sources**
Type I: sources inside the detector
Type II: sources placed directly before removal system

**Online Rn-distillation demonstrated**
Distillation column reduces radon by a **factor of 75 (95% CL)**
Reduction of type I sources strongly dependent on flow

---

**Model of Rn concentration in XENON100**

\[
\frac{dN(t)}{dt} = k_1 - f \cdot N(t) - \lambda_{Rn} \cdot N(t) + \frac{k_2 + f \cdot N(t)}{R}
\]

- $N$ represents the number of radon atoms in the cryostat.
- $k_1$ is the initial concentration rate.
- $f$ is the flow rate.
- $\lambda_{Rn}$ is the decay rate of radon.
- $k_2$ is the decay rate of radon.
- $R$ is the radon removal efficiency.

---

**Diagram Details**
- Type II Rn-sources: getter pump
- Flow purification loop: 100 - 300 slpm
- $^{222}$Rn enriched
- $^{222}$Rn depleted
- XENON1T cryostat
- Recirculation Flow in
- Recirculation Flow out
- $^{222}$Rn decay
- Emanation
Summary

Radon is the dominating source of background (ER) in XENON1T
Emanation measurements to find only detector materials having low radon emanation
Unique radon screening facility at MPIK

Radon removal by cryogenic distillation
Xenon boil-off gas is depleted in radon with respect to the liquid phase.

Online radon removal system demonstrated with XENON100
Integration of a cryogenic distillation column into the XENON100 gas purification loop
Radon activity concentration could be reduced by a factor of 20 inside XENON100

THANK YOU FOR YOUR ATTENTION
Measure Rn-Emanation at the μBq Level

Emanation vessel is filled with carrier gas.

Emanated radon is extracted via a cooled activated carbon trap.

The radon is adsorbed while the carrier gas is pumped out.

Transfer collected radon into detector.
Recent XENON100 Results

Exclusion of Leptophilic Dark Matter
Selection of 70 live days of electronic recoil
XENON100 data, where DAMA signal is highest

mixed Mirror DM: 3.6σ Exclusion
Luminous DM: 4.6σ Exclusion
Axial-vector coupling: 4.4σ Exclusion
Recent XENON100 Results

Search for Event Rate Modulation
The DM interpretation of DAMA/ LIBRA annual modulation as being due to WIMPs electron scattering through axial vector coupling is disfavored at 4.8-σ from a PL analysis.