XENON1T Background Modeling
And Statistical Techniques

Low Radioactivity Techniques 2019

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On behalf of the XENON collaboration.
The XENON Project

XENON10:
- 2005-2007
- 15 cm drift
- 25kg of Xe

XENON100:
- 2008-2016
- 30 cm drift
- 161 kg of Xe of which 62kg as target

XENON1T:
- 2012-2018
- 96 cm drift
- 3200 kg of Xe of which 2 tonnes as target

XENONnT:
- ~2019-2024
- 148 cm drift
- 8400 kg of Xe
- 5.9 tonnes as target
Xenon1T Results to Date

Spin Dependent

Wimp-pion coupling

Spin Independent

Double Electron Capture

Phys. Rev. Lett. 122, 071301

Phys. Rev. Lett. 122, 141301

Phys. Rev. Lett. 121, 111302,

What’s Behind The Analysis

Recently published full details on the Xenon1T analysis

arxiv.1902.11297
Expected events in 1.3 tonne and 278.8 days

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<table>
<thead>
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<tbody>
<tr>
<td>Electronic Recoil</td>
<td>627 ± 18</td>
</tr>
<tr>
<td>Neutron</td>
<td>1.43 ± 0.66</td>
</tr>
<tr>
<td>CEνNS</td>
<td>0.05 ± 0.01</td>
</tr>
<tr>
<td>AC</td>
<td>0.47 ± 0.27</td>
</tr>
<tr>
<td>Surface</td>
<td>106 ± 8</td>
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</table>

- The background are modeled as PDFs in S1,S2 and R and in two bins in Z.
Statistical inference: the Likelihood

A simplified version:

\[ \mathcal{L} = \text{Pois}ss(n_{\text{obs}}|N_s + \sum_j N_{bj}) \cdot \prod_{i}^{n_{\text{obs}}} \left\{ \frac{N_s f_s(x_i, \hat{\theta}_s) + \sum_j N_{bj} f_{bj}(x_i, \hat{\theta}_{bj})}{N_s + \sum_j N_{bj}} \right\} \cdot \prod_k \mathcal{G}(\hat{\theta}_k^s) \mathcal{G}(\hat{\theta}_k^{bj}) \]

Poisson Term.
\(N_s = \text{Signal events}\)
\(N_b = \text{Bkg events}\)

Extended Shape Term.
Note the dependence on nuisance parameters \(\theta\)

Nuisance parameters
Constraint term

- **Uncertainties (nuisance parameters):**
  - Signal acceptance
  - Bkg rates
  - Bkg shape uncertainties
  - “Safeguard” shape uncertainty

- **Hypothesis test related:**
  - Twosided likelihood ratio test statistics
  - Feldman-Cousins approach
Detector Response Model

- A physics model of Xenon light and charge yield (NEST), including detector response effects, is fitted simultaneously to ER and NR calibration data.

- Used to produce the S1, S2, R, Z PDFs of ER background and signal model given an energy deposit.

**ER: Electronic Recoil**

**NR: Nuclear Recoil**
Electronic Recoil Model

- Main contribution is \(^{222}\text{Rn}\) from materials 10 \(\mu\text{Bq/kg}\)
- \((82 \pm 5_{\text{sys}} \pm 3_{\text{stat}})\) events/tonne/yr/keV
- Main shape nuisance parameter:
  - Recombination fluctuation
  - Photon Yield
Shape Uncertainty On Electronic Recoil Model
The “Safeguard” Uncertainty Term

\[ f_b \rightarrow f_b + a_{mm} f_s \]

- Main motivation: It is difficult to assess uncertainties on unbinned PDF models.
- It is a Bkg Shape uncertainty constrained by simultaneous fit of the calibration sample.
- Use the most conservative shape uncertainty: the signal shape. The background is then morphed into signal

JCAP 1705 (2017) no.05, 013
The “Safeguard” Uncertainty Term
Neutron Background Model

- Mostly radiogenic neutrons from materials
- Energy release spectrum from simulation
- Rate scaled using fraction of multiple scatter in data
- $1.4 \pm 0.6$ event/tonne/yr in ROI
The Final Model

Example of total model PDF summing all backgrounds

- ER
- Surface
- Neutron
- AC
- WIMP

\[ cS2_b \] vs. \[ cS1 [PE] \]

\[ R [cm] \]

\[ R^2 [cm^2] \]
**XENONnT Is Coming...**

- **New TPC:**
  - PMTs from 248 to 494
  - 1.5 m long, 1.3 m diameter

- **Liquid Xenon Purification**
  - Up to 250 slpm
  - Can achieve above 1 ms electron lifetime

- **Online Radon distillation**

- **Neutron veto:**
  - 0.2% gadolinium doped water
  - 120 8” PMT
The XENON Collaboration

Thanks!
Extra Slides
Accidental Coincidence Model

- Random pairing of “lone” S1 and S2
- Rare (<<1 event) but likely to be in search region
- Data-driven model
Surface Event Model

- $^{222}$Rn daughters attach to the PTFE surface
- Charge loss to the wall resulting in a lower S2 → higher probability to enter the WIMP search region.
- Data-driven model
- Impact minimized by taking into account R spatial coordinate
Dual phase TPC principles

- Two signals (S1, S2) for each event which allows 3D positioning
- WIMPs interacts via a single scatter nuclear recoil
- Separation between electronic and nuclear achieved by the fraction of the charge (S2) to scintillation (S1) signal.

![Dual phase TPC diagram](image)
Dual phase TPC principles

- Two signals (S1, S2) for each event which allows 3D positioning
- Separation between electronic and nuclear recoils achieved by the fraction of the charge (S2) to scintillation (S1) signal.
## Background Models Summary

<table>
<thead>
<tr>
<th></th>
<th>1.3t</th>
<th>1.3t</th>
<th>0.9t</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass</strong></td>
<td>1.3t</td>
<td>1.3t</td>
<td>0.9t</td>
</tr>
<tr>
<td><strong>ER</strong></td>
<td>$627 \pm 18$</td>
<td>$1.62 \pm 0.3$</td>
<td>$1.12 \pm 0.21$</td>
</tr>
<tr>
<td><strong>Neutron</strong></td>
<td>$1.43 \pm 0.66$</td>
<td>$0.77 \pm 0.35$</td>
<td>$0.41 \pm 0.19$</td>
</tr>
<tr>
<td><strong>CEvNS</strong></td>
<td>$0.05 \pm 0.01$</td>
<td>$0.03 \pm 0.01$</td>
<td>$0.02$</td>
</tr>
<tr>
<td><strong>AC</strong></td>
<td>$0.47^{+0.27}_{-0.27}$</td>
<td>$0.10^{+0.06}_{-0.06}$</td>
<td>$0.06^{+0.03}_{-0.03}$</td>
</tr>
<tr>
<td><strong>Surface</strong></td>
<td>$106 \pm 8$</td>
<td>$4.84 \pm 0.4$</td>
<td>$0.02$</td>
</tr>
<tr>
<td><strong>BG TOTAL</strong></td>
<td>$735 \pm 20$</td>
<td>$7.36 \pm 0.61$</td>
<td>$1.62 \pm 0.28$</td>
</tr>
<tr>
<td><strong>WIMPs best-fit (200GeV)</strong></td>
<td>$3.56$</td>
<td>$1.70$</td>
<td>$1.16$</td>
</tr>
<tr>
<td><strong>Data</strong></td>
<td>739</td>
<td>14</td>
<td>2</td>
</tr>
</tbody>
</table>
2ν Double Electron Capture of $^{124}$Xe

- Blinded region from 56 keV to 72 keV
- Ellipsoidal 1.5 t inner fiducial volume
- Peak at $E = (64.2 \pm 0.5)$ keV and $\sigma = (2.6 \pm 0.3)$ keV
- Significance 4.4σ

Half-life $T_{1/2}^{2νECEC} = (1.8 \pm 0.5_{stat} \pm 0.1_{sys}) \times 10^{22}$ y
Radio purity

- Materials have been chosen to insure low intrinsic radioactivity.
- Minimize contamination from common $^{238}\text{U}$ $^{232}\text{Th}$ chains → neutron from fission, ($\alpha$,n) reactions from daughters and other like $^{60}\text{Co}$, $^{40}\text{K}$.
- Metal components in contact with Xe selected for low $^{226}\text{Ra}$ contamination ($\sim < 1\text{mBq/Kg}$) since it decays to Radon → mixes with Xe!

Internal nuclear recoil backgrounds

- Coming from intrinsic material radioactivity (α,n) reactions and spontaneous fission from $^{238}\text{U}$ and $^{232}\text{Th}$ chains.
- Estimated via Monte-Carlo using the material radioassay
- Overall < 1 event / ton year

ROI: region of interest, all single-scatter events within 1T fiducial target with nuclear recoil energy (4,50) KeV$_{\text{nr}}$
External NR backgrounds

- Water shield to insure a low environmental radioactivity
- 700 tonnes of deionized water
- Equipped with 84 high-QE, 8" PMTs
- Detects Cherenkov light to tag muons.
- Muon-induced neutrons are reduced to 0.01 ev/year (1T fiducial mass) with muon tagging.
- Coherent Neutrino Nucleon Scattering also negligible
Electronic recoil backgrounds

Electronic Recoil (ER) although can be separated from NR (WIMP) is a large background and can leak into the ROI.

- Online distillation campaign of $^{85}$Kr that reduces it to 0.6 ppt
- Main contributor is $^{222}$Rn emanation estimated to $\sim$10 $\mu$Bq/Kg

XENON1T: TPC

- 96 cm drift x 96 cm diameter TPC has been installed at LNGS (Italy)
- Material have been chosen after an extensive radioactivity screening campaign
- 248 low radioactivity 3" PMTs
- High QE (~35%) R11410-21 (arXiv:1503.07698)
- Covered with high reflectivity PTFE → maximize light collection efficiency
XENON1T: Xe Handling Systems

- The same system will be shared between XENON1T and nT
- Safety system for Recuperation and Storage of Xenon (ReStoX)
- Constant Xe purification with two getters working in parallel
- Online Kr distillation, no need to empty detector.
XENON1T calibration system

XENON1T offers two possible calibration methods:

- Via external sources moved on a system of belts and winches.
- Via “internal” sources, i.e. injected as gas after the purification system.
External Calibration System

- Two tungsten collimator can house exchangeable sources.
- Possibility for a third collimator to satisfy future requirements.
- A deuterium fusion neutron generator which produces 2.5 MeV neutrons can be immersed in water.
- XENON1T is expected to be able to identify neutron double scatter → measure of Leff, Qy.
- Data taken with following sources: Cs$^{137}$ and AmBe, expected Th$^{232}$
Position reconstruction using Kr83m calibration events to account for instrumental effect.