MONTE CARLO SIMULATIONS OF THE XENON1T EXPERIMENT

ASTROPARTICLE SCHOOL 2018 - BÄRFELS-OBERTRUBACH - #41

LUTZ ALTHÜSER – l.althueser@uni-muenster.de
ON BEHALF OF THE XENON COLLABORATION
XENON COLLABORATION

MONTE CARLO SIMULATIONS OF THE XENON1T EXPERIMENT

LUTZ ALTHÜSER - XENON COLLABORATION - ASTROPARTICLE SCHOOL 2018 - BÄRFELS-OBERTRUBACH - #41
XENON1T – DIRECT DARK MATTER DETECTION

TOTAL LXe mass: 3.2 tonnes

XENON1T

LOW ENERGY BACKGROUND [t*keV]^2

ACTIVE LIQUID XENON TARGET MASS

LXe

LUX

PANDA X-II

XENONnT

TOTAL LXe mass: 8.3 tonnes

~465 PMTs

XENON10

XENON100

XENON10

XENON100

2005

2008

2013

2016

22 kg

105 kg

250 kg

580 kg

2000 kg

2019

6000 kg

2005

2008

2013

2016

2016

2019

2000 kg

6000 kg

5.3

2.6

1.9

0.2

LUTZ ALTHÜSER - XENON COLLABORATION - ASTROPARTICLE SCHOOL 2018 - BÄRFELS-OBERTRUBACH - #41
XENON1T – DIRECT DARK MATTER DETECTION

SR0 (32 days)  
SR1 (246 days)
XENON1T – DIRECT DARK MATTER DETECTION

- Water shield (700 t high purity water)
- Active muon shield (84 8-inch PMTs)
- TPC with 2 t LXe (3.2 t total) and 248 3-inch PMTs (127 top / 121 bottom)
- TPC drift length and diameter ~1 m
WORKING PRINCIPLE OF THE TIME PROJECTION CHAMBER (TPC)

- Particle source
- Particle propagation
- Energy deposition
- Charge and light (S1) emission

MONTE CARLO SIMULATIONS OF THE XENON1T EXPERIMENT

LUTZ ALTHÜSER - XENON COLLABORATION - ASTROPARTICLE SCHOOL 2018 - BÄRNFELS-OBERTRUBACH - #41
WORKING PRINCIPLE OF THE TIME PROJECTION CHAMBER (TPC)

Particle source → Particle propagation → Energy deposition → Charge and light (S1) emission → Electron drift

Energy deposition:
- GXe (7 cm)
- LXe (1 m)

Charge and light (S1) emission:
- Energy deposition
- Optical photon propagation (S1 + S2)
- PMT + electronics response
- Trigger + reconstruction
- Selection

Electron drift:
- S2 signal (extraction + scintillation)

Other components:
- Water shield (700 t high purity water)
- Active muon shield (84 8-inch PMTs)
- TPC with 2 t LXe and 248 3-inch PMTs

Field strengths:
- 0.082 kV/cm
- 12 kV/cm
- 8 kV
- 4 kV

Drift time (depth) → TPC drift length and diameter ~1 m

Time

Electrical field

Optical photon propagation
WORKING PRINCIPLE OF THE TIME PROJECTION CHAMBER (TPC)

- Particle source
- Particle propagation
- Energy deposition
- Charge and light (S1) emission
- e⁻
  - Electron drift
    - S2 signal (extraction + scintillation)
      - Optical photon propagation (S1 + S2)
        - PMT + electronics response
          - Trigger + reconstruction
            - Selection

Water shield (700 t high purity water)
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Energy deposition
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Optical photon propagation (S1 + S2)
- PMT + electronics response
  - Trigger + reconstruction
    - Selection

Electron drift
- S2 signal (extraction + scintillation)
  - Optical photon propagation (S1 + S2)
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        - Selection
INTEGRATION OF THE MONTE CARLO TOOLS

- Simulate propagation of any particle source in the detection volume with GEANT4 and several additional tools (“Patch scripts”)
- Convert energy depositions to number of photons and electrons
- Distribute generated photons depending on the interaction position on the photomultiplier tubes (PMTs) and generate actual detector signals (FAX)
- Process and analyze MC data in the same way as actual measurements

- Particle source
  - Kr-83m, Rn, Cs, ...
- Particle propagation
  - GEANT4 (NEST)
- Energy deposition
- Charge and light (S1) emission
- e⁻
- Electron drift
  - S2 signal (extraction + scintillation)
- Optical photon propagation (S1 + S2)
- PMT + electronics response
- Trigger + reconstruction
- Selection

- XENON1T TPC
- DAQ
- FAX (FAke XENON experiment)
- PAX (Processor for Analyzing XENON)
- HAX (Handy Analysis for XENON)
Optical photon simulations in XENON1T

- Distribution of photons on the PMTs is following per-PMT optical photon simulations with GEANT4
- GEANT4 optical simulations parameters (reflectivities, absorption lengths, ...) are tuned by fitting MC simulations to Kr-83m measurements
GEANT4 SIMULATION GEOMETRY

- Water tank and muon veto
- Connection to support building
- Inner and outer cryostat (TPC)
GEANT4 SIMULATION GEOMETRY

- Diving bell filled with GXe
- PTFE pillars
- Field shaping electrodes
- Cathode
- PMTs
- PTFE reflector
- PTFE bottom plate
- Copper plate
- PMT bases
GEANT4 SIMULATION GEOMETRY

Anode: 3.5 mm / 0.178 mm
Gate mesh: 3.5 mm / 0.127 mm
Cathode: 7.75 mm / 0.216 mm
GEANT4 OPTICAL PHOTON PROPAGATION

S1 signals
- Whole TPC from cathode to LXe/GXe transition (~100 cm)
- Confined to LXe
- 7eV photons

S2 signals
- Thin disc between LXe/GXe transition and Anode (~1 mm)
- Confined to GXe

Optical photon simulation corrections
- Exclude PMTs that are not included in the measurements
- Correct by the Quantum Efficiency (# of photons @photocathode) and Collection Efficiency (# electrons @1st dynode) for each PMT
GEANT4 OPTICAL PHOTON PROPAGATION

Fitting optical simulations to Kr-83m data

- **Kr83m data**
- **MC v1.0.0**
- **Trip PMTs**
- **Bottom PMTs**

<table>
<thead>
<tr>
<th>parameter</th>
<th>fitted values</th>
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</thead>
<tbody>
<tr>
<td>LXe refraction index</td>
<td>1.69</td>
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<tr>
<td>LXe Rayleigh scatter length</td>
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<tr>
<td>LXe absorption length</td>
<td>5000cm</td>
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<tr>
<td>GXe absorption length</td>
<td>50cm</td>
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<tr>
<td>LXe PTFE reflectivity</td>
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<tr>
<td>GXe PTFE reflectivity</td>
<td>99%</td>
</tr>
<tr>
<td>top screening mesh transp.</td>
<td>96.5%</td>
</tr>
<tr>
<td>anode transparency</td>
<td>89.8%</td>
</tr>
<tr>
<td>gate mesh transparency</td>
<td>92.7%</td>
</tr>
<tr>
<td>cathode transparency</td>
<td>97.2%</td>
</tr>
<tr>
<td>bottom screening mesh transp.</td>
<td>97.2%</td>
</tr>
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</table>
FAKE XENON EXPERIMENT

- Using Geant4 particle tracks
  - Baseline fluctuations
  - Photoionization
  - SPE/DPE shape
  - PMT gains/QE/CE/after-pulses/dark counts/noise/…

- Waveform generation:
  - Baseline fluctuations
  - Photoionization
  - SPE/DPE shape
  - PMT gains/QE/CE/after-pulses/dark counts/noise/…

**MONTE CARLO SIMULATIONS OF THE XENON1T EXPERIMENT**

**LUTZ ALTHÜSER**
**XENON COLLABORATION**
**ASTROPARTICLE SCHOOL 2018**
**BÄRFELS-OBERTRUBACH**

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COMPARISON OF FAX SIMULATIONS TO KR-83m DATA

Waveforms observed within PAX

Event 0 from Unknown, Recorded at 2017/08/29, 13:24:55 UTC, 2703d5984 ns

Event 11030 from 170829_0654, Recorded at 2017/08/29, 07:28:33 UTC, 6990201056 ns
COMPARISON OF FAX SIMULATIONS TO KR-83m DATA

S1 light collection efficiency/light yield
Background simulations

- Material backgrounds from $^{40}$K, $^{60}$Co, $^{232}$Th and $^{238}$U chains
- Extensive material screening during construction

- Position reconstruction allows for fiducialization and self-shielding
- Flat material contribution in ROI
Measured spectrum and simulation

![Graph showing measured spectrum and simulation](image)

- **Rate [keV·cm²·kg⁻¹·d⁻¹]**
- **Energy [keV]**
- **Materials**
  - Xe-125
  - Xe-129m
  - Pb-214
  - Kr-83m
  - ER solar
  - Xe-136

- **Summed spectrum**
- **Blinded for 0νββ and DEC**

**Legend**
- **Xe-125**
- **Xe-129m**
- **Pb-214**
- **Kr-83m**
- **ER solar**
- **Xe-136**

**Axis Labels**

- **Y-axis**: Rate [keV·cm²·kg⁻¹·d⁻¹]
- **X-axis**: Energy [keV]

**Title**
- Measured spectrum and simulation

**Note**
- PRELIMINARY
SUMMARY

Light collection efficiency and backgrounds well understood
- Direct measurements with Kr-83m calibrations
- Agreement with optical Monte Carlo simulations (Geant4)
- Agreement with measured energy spectrum (official unblinding soon)

Simulations with FAke Xenon experiment
- Same data processing tools (PAX/HAX/LAX)
- Agreement with RAW data from the detector
- Performance testing of data cuts/selections

XENONnT coming soon!
- Twitter: @XENON1T
- Blog: www.xenon1t.org
MONTE CARLO SIMULATIONS OF THE XENON1T EXPERIMENT
COMPARISON OF FAX SIMULATIONS TO KR-83m DATA

Improved S2 simulation

- Implement detailed mesh structure
- Generate photons in a volume defined by electric field simulations
- Generation volume with an actual density distribution
Electric field simulations of S2 electrons

- S2 photons are generated along the path of electrons drifting towards the anode
- Most of the S2 photons are produced close to the anode, resulting in a significantly lower amount of photons in the center of each mesh cell
### GEANT4 OPTICAL PHOTON PROPAGATION

**Fitting optical simulations to Kr-83m data**

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<th>fitting range</th>
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<td>1.69</td>
<td>1.56 to 1.69</td>
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<td>30cm</td>
<td>30cm</td>
<td>5cm to 100cm</td>
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<tr>
<td>LXe absorption length</td>
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<td>5000cm</td>
<td>10cm to 80000cm</td>
</tr>
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- Optical photon propagation (S1 + S2)
- PMT + electronics response
- Trigger + reconstruction
- Selection

Including detector dependent corrections

S2 light yield map (top)

MC v0.3.0

S2 area fraction top [%]

Relative S2 light yield

XENON1T TPC

GEANT4 (v4.9.2 + NEST)

FAX (FAke XENON experiment)

PAX (Processor for Analyzing XENON)

HAX (Handy Analysis for XENON)
COMPARISON OF FAX SIMULATIONS TO KR-83m DATA

S1 light collection efficiency/ light yield
XENONnT