A small dual-phase xenon TPC with APD and PMT readout for the study of liquid xenon scintillation

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Outline

- motivation for MainzTPC
- design and status of MainzTPC
- gain and quantum efficiency avalanche photo diodes
- summary and outlook
Tension in the low WIMP mass regime: Do we understand our detector threshold well?
Principle of a dual-phase xenon TPC

z-position
reconstructed by electron drift time:
\[ z = \Delta t \cdot v_{\text{drift}} \]

x/y-position
position of S2 detected by a photosensor array
nuclear recoil (NR) neutron, WIMP

electronic recoil (ER) electron, gamma

S2/S1 (NR) < S2/S1 (ER)

Background discrimination in DM experiments

Similar in:
2013: E. Aprile et al. (XENON100 Collab.): “Dark Matter Results from 225 Live Days from XENON100 Data”
Charge and scintillation yield

<table>
<thead>
<tr>
<th>charge yield</th>
<th>scintillation yield</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Graph of charge yield vs. Drift Field" /></td>
<td><img src="image2.png" alt="Graph of scintillation yield vs. Energy" /></td>
</tr>
</tbody>
</table>

Phys. Rev. 97, 081302: E. Aprile et al. “Simultaneous measurement of ionization and scintillation from nuclear recoils in liquid xenon as target for a dark matter experiment”

Phys. Rev. D 87, 115015: L. Baudis et al.: “Response of liquid xenon to Compton electrons down to 1.5keV”


Phys. Rev. D 88, 012006: E. Aprile et al. (XENON100 Collab.): “Response of the XENON100 Dark Matter Detector to Nuclear Recoils”
Dark Matter results

background from neutrinos
Hints from the 80's:

**Different scattering particles**

- Electron: $t_e = 45$ ns
- Alpha: $t_\alpha = 4.2$ ns, $t_\beta = 22$ ns, $I_\alpha/I_\beta = 0.43$
- Fission fragments: $t_\beta = 4.1$ ns, $t_\gamma = 21$ ns, $I_\beta/I_\gamma = 1.52$

Different time constants need to be disentangled

**Systematic tests**

**Scintillation pulse shape**

A complementary background discrimination method?

Physical Review B - A. Hitachi, T. Takahashi: “Effect of ionization density on the time dependence of luminescence from liquid argon and xenon”

Scintillation pulse shape
A complementary background discrimination method?

2010:
pulse shape of LXe scintillation
78keVr @ 0.06kV/cm

2011:
PSD in LXe without E-field
Cf252 data


Goal:
Measurement and understanding of low energy response of liquid xenon
- primary scintillation
- ionization
- S1 pulse shape

Means:
- Simultaneous measurement of light and charge
- 3D position reconstruction

MainzTPC:
Optimized for Compton scattering with little passive material and fast electronics.
Cryogenic system with Compton setup

TPC inside cryostat

Ge-detector

Pulse tube refrigerator + LN2 emergency cooling

Collimator for γ-source
Cryogenic system with Compton setup

TPC inside cryostat

Ge-detector

pulse tube refrigerator + LN2 emergency cooling

collimator for $\gamma$-source
MainzTPC: design

- **top PMT**
- **bottom PMT**
- **8 APDs**
  - x/y position resolution
- **meshes**
  - high transparency
  - fine pitch
- **field cage**
  - PCB => low passive mass
- **d = 52 mm**
Avalanche Photo Diodes: RMD S1315

**RMD S1315:**
- active area: 14x14 mm²
- no housing - little passive material
- QE ~ 30% @ 178 nm
  
  (P. Shagin et al 2009 JINST 4 P01005)

**position reconstruction:**
- G4: resolution < 1.3 mm
- using **relative** amount of light seen by each APD

**What are APDs?**
- photo diodes with internal gain (typically ~10²-10³)
- gain depending on temperature and bias voltage

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[Diagram of position reconstruction and APDs]
gain measurement:
- pulsed blue LED
- measure spectra at different bias voltages
- using different strength of LED pulses to cover full gain range
Incomplete charge collection

$\Rightarrow U_{\text{bias}} < 400\text{V}: \text{gain} < 1$

Gain vs. bias voltage - reference APD

Gain = 1 @ 400V
incomplete charge collection
$U_{\text{bias}} < 400V$: gain < 1

**gain vs. bias voltage - reference APD**

Gain vs. bias voltage

- LED strong
- LED medium

**gain = 1 @ 400V**
gain vs. bias voltage - reference APD

Gain vs. bias voltage

- LED strong
- LED medium
- LED weak

gain = 1 @ 400V

incomplete charge collection => $U_{bias} < 400V$: gain < 1
Incomplete charge collection

\[ U_{\text{bias}} < 400 \text{V}: \text{gain} < 1 \]
gain vs. bias voltage - all APDs

**colors**: APDs from wafer A  
**black**: APD from wafer B

\[ T = 176.3 \text{ K} \pm 0.3 \text{ K} \]
\[ \Delta T < 0.1 \text{ K} \text{ for each APD} \]
\[ g(T) = g_0 \cdot \exp(-k_0 \cdot (T - T_0)) \]

fixed Parameter: \( T_0 = 170.3 \, K \)

free parameters: \( g_0, k_0 \)

\[ k_0 = \frac{\partial \log(g)}{\partial T} \]

\( k_0 \) (1050V) = 0.0085
\( k_0 \) (1300V) = 0.0232
\( k_0 \) (1500V) = 0.0510
\( k_0 \) (1550V) = 0.0879
QE calculation depends on:
• number of photons generated
• solid angle
• APD gain

\[
QE = \frac{N^\text{measured}}{N^\text{hit}} = \frac{Q^\text{measured}}{N^\text{hit}} \cdot \text{gain} \cdot e
\]
APD quantum efficiencies

![Graph showing APD quantum efficiencies for different APD numbers. The x-axis represents the APD number, and the y-axis represents the relative quantum efficiency. The graph includes a bar for the reference APD and notes about APD used before... bad treatment and APD from wafer B.](image-url)
Summary

- TPC optimized for Compton scatter experiment built
- Compton setup built up
- Light detectors characterized (APDs)
- Commissioning next weeks
- Measurement of light/charge yield for electron recoils this summer
- Measurement of scintillation pulse shape for electron recoils this summer

Thanks to all collaborators:

Pierre Sissol
Melanie Scheibelhut
Rainer Othegraven
Christopher Hils
Dr. Cyril Grignon
Prof. Uwe Oberlack

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http://xenon.physik.uni-mainz.de/
Questions?

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Readout system

**Struck SIS3305**
- 10 bit FADC
- 2/4/8 channels
- 5/2.5/1.25 GS/s
- 1.5 GHz bandwidth

**Struck SIS3316**
- 16 bit FADC
- 16 channels
- 125 MS/s
- 62.5 MHz bandwidth

*digitize PMT signal with good time-resolution*

*digitize Ge-detector and APDs with good energy-resolution*
principle dual-phase TPC

S1: primary scintillation

- interaction
  - excitation \( \text{Xe}^* \)
  - ionization \( \text{Xe}^+ \)
  - dimers \( \text{Xe}_2^* \)
  - free \( e^- \)

- scintillation light S1
- ground state \( 2 \text{Xe} \)
- secondary scintillation S2
### Table of Measured QEs

<table>
<thead>
<tr>
<th>APD</th>
<th>Relative QE</th>
<th>Absolute QE</th>
</tr>
</thead>
<tbody>
<tr>
<td>426-2-7 (reference)</td>
<td>100 %</td>
<td>25.9 %</td>
</tr>
<tr>
<td>426-2-1</td>
<td>29.2 %</td>
<td>7.6 %</td>
</tr>
<tr>
<td>426-2-3</td>
<td>125.4 %</td>
<td>32.5 %</td>
</tr>
<tr>
<td>426-2-4</td>
<td>92.6 %</td>
<td>24.0 %</td>
</tr>
<tr>
<td>426-2-5</td>
<td>109 %</td>
<td>28.2 %</td>
</tr>
<tr>
<td>426-2-9</td>
<td>102.2 %</td>
<td>26.5 %</td>
</tr>
<tr>
<td>393-3-10</td>
<td>45.8 %</td>
<td>11.9 %</td>
</tr>
</tbody>
</table>

- 426-2-7 (reference) and 393-3-10 are different wafers.
- 426-2-1 and 426-2-9 used before; maybe bad treatment.