XURICH II – First dual-phase xenon TPC with SiPM readout and its ultra-low energy calibration with 37-Ar

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INTRODUCTION AND MOTIVATION
DUAL-PHASE XENON TIME PROJECTION CHAMBER

Dual-phase TPC working principle

- Detect prompt scintillation light (S1) and delayed ionisation signal (S2)
- Reconstruct z-position from drift time and (x,y) from S2 localization

Particle interactions

- S1/S2 ratio depends on particle type

Particle type discrimination

- Electron recoil (ER)
- Nuclear recoil (NR)
- Gammas & electrons
- WIMPs or neutrons

ER (β, γ)
NR (WIMP, n)
Background signal
DUAL-PHASE XENON TIME PROJECTION CHAMBER II

WIMP landscape

spin-independent WIMP nucleon cross-section

• Above 5 GeV/c² best limits set by liquid noble gas TPCs

Present limits

Near future sensitivities

DARWIN’s sensitivity

See talks on XENON and DARWIN on Thursday afternoon!

Cross Section [cm²]

WIMP Mass [GeV/c²]

Photosensors in TPCs

• Traditionally: Photomultiplier tubes

• Under consideration: Silicon Photomultipliers

Radioactivity
Longterm stability
Position resolution

Bulkiness

High operation voltage

Cost

Dark Count Rate

Created with the Dark Matter Limit Plotter by T. Saab and E. Figueroa

Created May 16, 2015

Cross Section [cm²]

WIMP Mass [GeV/c²]
SETUP AND SIPMS
XURICH II TPC

- Small-scale \((31 \text{ mm (d)} \times 31 \text{ mm (h)})\) dual-phase TPC designed to study interactions in \(\text{LXe} < 50 \text{ keV}\)
- \(2 \times 2\) S13371 VUV-4 MPPCs from Hamamatsu in the top array – 16 channels!
- Mounted on \(\times 10\) pre-amplifier board
- 2-inch R9869 PMT from Hamamatsu at the bottom
- Up to 1 kV/cm drift field
- 10 kV/cm extraction field
- SiPM upgrade in Summer 2018, since then 10 months of stable operation

Credits: A. James, F. Girard

PERFORMANCE AND LONGTERM STABILITY OF THE SiPMS

- Weekly monitoring of the gain with model independent single photoelectron calibration (measured with blue LED)
- Gain very stable over time
- Dark count rate as expected for the temperature in the gas phase (c.f. JINST 13 (2018) P10022)

![Graph showing gain stability over time](image1)

![Graph showing gain uniformity among channels](image2)
- Top array enables for event position reconstruction in (x,y) ~1.5 mm
- Use ‘center of gravity’ algorithm:
  \[
  (\hat{x}, \hat{y}) = \frac{1}{\sum_{i=0}^{15} S_i^2} \sum_{i=0}^{15} S_i^2 \cdot (x_i, y_i)
  \]
- Center, scale and map onto a circle
- Electrons are focused to the knots of the gate mesh
- Arrangement of the sensors in a square gives bias to the center of the TPC -> Correct for it by comparing with the gate CAD (arccos with linear region up to 10 mm)
Top array enables for event position reconstruction in (x,y) ~1.5 mm

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EVENT POSITION RECONSTRUCTION

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CALIBRATION WITH $^{83}\text{m} \text{Kr}$ AND $^{37}\text{Ar}$
S. Hochrein, B.Sc. Thesis: *Calibration of the first dual-phase xenon time projection chamber with silicon photomultiplier readout*

$^{83}\text{Rb}$

$T_{1/2} = 86.2\text{ d}$

62 %

571.1 keV

30 %

562.0 keV

74 %

41.6 keV

26 %

9.4 keV

$T_{1/2} = 156.8\text{ ns}$

6 %

0 keV

$^{83}\text{Kr}$

$T_{1/2} = 1.83\text{ h}$

32.2 keV

9.4 keV

$^{83}\text{mKr}$

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$^{83}\text{Kr}$

stable

Average of SiPM channels (top)

S1 Delay

S2 Delay

Graphical representation of decay times and energies for $^{83}\text{Rb}$ and $^{83}\text{mKr}$.
83mKr – DATA SELECTION AND CUTS

83mKr

- **T_1/2 = 86.2 d**
- 62% of 571.1 keV
- 30% of 562.0 keV
- 74% of 41.6 keV
- 26% of 9.4 keV
- 6% of 0 keV

32.2 keV

- **T_1/2 = 1.83 h**
- 74% of 41.6 keV
- 26% of 9.4 keV
- 6% of 0 keV

9.4 keV

83Kr
- **stable**
- 62% of 571.1 keV
- 30% of 562.0 keV
- 74% of 41.6 keV
- 26% of 9.4 keV
- 6% of 0 keV

**Counts**

- b \cdot e^{a \cdot t}; a = -4.36 \mu s^{-1}, b = 1.2e+03, t_{1/2} = (158 \pm 6) ns
- time window 525 ns - 1625 ns

**Average of SiPM channels (top)**

**S1 Delay [10 ns]**

**S2 Delay**
83mKr – DATA SELECTION AND CUTS

- **83Rb**
  - $T_{1/2} = 86.2$ d

- **83mKr**
  - $T_{1/2} = 1.83$ h
  - $T_{1/2} = 156.8$ ns
  - 6 %
  - 30 %
  - 62 %
  - 74 %
  - 26 %

- S1 Delay:
  - 0 keV
  - 9.4 keV
  - 41.6 keV
  - 562.0 keV
  - 571.1 keV

- S2 Delay:
  - 32.2 keV
  - 9.4 keV

Cuts:

- #S1 ≥ 2 && #S2 ≥ 2
- Difference S1/S2 delays: ±1 σ
- S2 width ∈ [97.7, 2.3] % Quantile
- S2 area fraction top ∈ [0.21, 0.31]
- S1/S2 delay ∈ [~0.5, ~2.0] µs
- -25 mm ≤ z ≤ -5 mm; r ≤ 9.7 mm

Average of SiPM channels (top)
83mKr – RESULTS

- Combined energy scale:
  \[ E = (N_\gamma + N_{e^-}) \cdot W = \left( \frac{S_1}{g_1} + \frac{S_2}{g_2} \right) \cdot W \]

- Detector response parameters:
  \[ g_1 := \frac{S_1}{N_\gamma} \quad g_2 := \frac{S_2}{N_{e^-}} \]
  \[ g_1 = (0.150 \pm 0.009) \text{ PE}/\gamma \]
  \[ g_2 = (32.7 \pm 1.1) \text{ PE}/e^- \]
$^{37}\text{Ar} – \text{MOTIVATION}$

- Low-keV, internal source, mixed with the xenon
- Moderate half-life: $(35.01 \pm 0.02)$ d
- Decays 100 % to stable chlorine by electron capture:
  \[ e^- + ^{37}\text{Ar} \rightarrow ^{37}\text{Cl} + \nu_e \]
- Q-value: $(813.87 \pm 0.20)$ keV
- Energy release in form of X-rays accompanied by Auger electrons

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Energy release [keV]</th>
<th>Branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>K capture</td>
<td>2.8224</td>
<td>90.02 %</td>
</tr>
<tr>
<td>L capture</td>
<td>0.2702</td>
<td>8.90 %</td>
</tr>
<tr>
<td>M capture</td>
<td>0.0175</td>
<td>0.93 %</td>
</tr>
</tbody>
</table>

$^{37}\text{Ar}$ – SOURCE PRODUCTION AND INTRODUCTION

- Via thermal neutron capture on $^{36}\text{Ar}(n,\gamma)$: $\sim 5$ barn
- Use natural argon: 0.334 % abundance of $^{36}\text{Ar}$
- 1.5 cm$^3$ at 0.9 bar per quartz glass ampule (8 µg $^{36}\text{Ar}$)
- Swiss Spallation Neutron Source at Paul Scherrer Institute Villigen, Switzerland: $10^{13}$ neutrons cm$^{-2}$s$^{-1}$, 13500 s
- Estimated initial activity per ampule (4 in total): 20-22 kBq

Inspired by C. Hils, Diploma Thesis: Studie von internen Kalibrationsmethoden für Flüssig-Xenon TPCs zur direkten Suche nach Dunkler Materie
$^{37}\text{Ar} - \text{POPULATION AND CUTS}$

- Estimated activity introduced into the detector: 2.7 kBq -> 200 Bq inside the TPC

<table>
<thead>
<tr>
<th>Cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation cut</td>
</tr>
<tr>
<td>Single Scatter Cut</td>
</tr>
<tr>
<td>-29 mm $\leq z \leq$ -2 mm; $r \leq$ 10 mm</td>
</tr>
<tr>
<td>S2 area fraction top $\in [0.14,0.32]$</td>
</tr>
<tr>
<td>S2 width $\in [95,5]$ % Quantile</td>
</tr>
</tbody>
</table>

- 2.82 keV
- Gas events
- 968 V/cm
- 0.27 keV
- Single e-, BG, 0.0175 keV?
\( ^{37}\text{Ar} - \text{RESULTS} \)

- Light yield: \((4.4 \pm 1.4)\) PE/keV
- Charge yield: \((1290 \pm 129)\) PE/keV
- \( T_{1/2} = (35.21 \pm 0.27) \) d
  - Literature: \((35.01 \pm 0.02) \) d

Half-life 2.82 keV line

To be investigated

Single e\(^{-}\)-emission + 0.0175 keV?
SUMMARY AND OUTLOOK

• First working dual-phase xenon TPC with SiPM array
• Operating under stable conditions over almost one year
• $^{83}\text{m}Kr$- and $^{37}\text{Ar}$-calibrations successfully performed
• Finalise $^{37}\text{Ar}$-analysis (all drift fields, g1 & g2, low-S2-only-population, diffusion during source injection,...) and compare to $^{83}\text{m}Kr$
• Coming soon: NEST-comparison
• Plan for the next months: Upgrade with SiPM bottom array to check cryogenic behaviour of pre-amplifier board and work on channel clustering as well as triggering
SUMMARY AND OUTLOOK

• First working dual-phase xenon TPC with SiPM array
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THANK YOU FOR YOUR ATTENTION!
TOP ARRAY OF SILICON PHOTOSNEDS

- 2 × 2 S13371 VUV-4 MPPCs (12 × 12) mm² from Hamamatsu, each has 4 (6 × 6) mm² independent segments, (50 × 50) μm² cells
- 10× low-noise non-inverting feedback operational amplifier
- Operational voltage: 51.5 V
- Photon detection efficiency ~24 % at 178 nm
- Gain ~3.1×10⁶
- Dark Count Rate: 0.8 Hz/mm² at LXe temperature
- Optical Crosstalk Probability ~3 %
S. Hochrein, B.Sc. Thesis: *Calibration of the first dual-phase xenon time projection chamber with silicon photomultiplier readout*

**EVENT POSITION RECONSTRUCTION II**

\[
x_{\text{uncorrected}} = \frac{1}{\sum_{i=0}^{15} s_2} \sum_{i=0}^{15} s_2^i x_i
\]

\[
y_{\text{uncorrected}} = \frac{1}{\sum_{i=0}^{15} s_2} \sum_{i=0}^{15} s_2^i y_i
\]

\[
y_{\text{scaled}} = \frac{y_{\text{uncorrected}} - \Delta y}{c}
\]

\[
x_{\text{scaled}} = \frac{x_{\text{uncorrected}} - \Delta x}{c}
\]

\[
y_{\text{mapped}} = c \cdot y_{\text{scaled}} \cdot \sqrt{1 - \frac{1}{2} x_{\text{scaled}}^2}
\]

\[
x_{\text{mapped}} = c \cdot x_{\text{scaled}} \cdot \sqrt{1 - \frac{1}{2} y_{\text{scaled}}^2}
\]

\[
x_{\text{corrected}} = \frac{-d_{\text{TPC}}}{n} \arccos\left(\frac{r_{\text{mapped}}}{r_{\text{mapped, max}}}\right) + \frac{d_{\text{TPC}}}{2}
\]

\[
y_{\text{corrected}} = \frac{-d_{\text{TPC}}}{n} \arccos\left(\frac{r_{\text{mapped}}}{r_{\text{mapped, max}}}\right) + \frac{d_{\text{TPC}}}{2}
\]
# 37Ar – SOURCE PRODUCTION AND INTRODUCTION II

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Abundance</th>
<th>Half-life</th>
<th>Decay mode</th>
<th>Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>36Ar</td>
<td>0.334%</td>
<td>stable</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>37Ar</td>
<td>syn</td>
<td>35.01 d</td>
<td>ε</td>
<td>37Cl</td>
</tr>
<tr>
<td>38Ar</td>
<td>0.063%</td>
<td>stable</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>39Ar</td>
<td>trace</td>
<td>269 y</td>
<td>β⁻</td>
<td>39K</td>
</tr>
<tr>
<td>40Ar</td>
<td>99.604%</td>
<td>stable</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>41Ar</td>
<td>syn</td>
<td>109.34 min</td>
<td>β⁻</td>
<td>41K</td>
</tr>
</tbody>
</table>

**RGA Spectrum Ampule (Vacuum subtracted)**

- **Contaminants from walls/welds**
- **H₂**, **Ar⁺⁺**, **CO⁺⁺**, **Ar⁺**, **CO₂⁺**

**Sample preparation for activation**

**Packaged activated samples**

**Filter in ampule chamber**

**Argon filling setup**
$^{37}$Ar – Cuts

Fiducial volume cut

Area fraction top cut

S2 width cut

$$F = P_0 + P_1 \times \text{drifttime} + \sqrt{P_2} \times \text{drifttime}$$
$^{37}$Ar – CORRECTIONS

**S2 area correction**

**Exponential fit**

**Free electron lifetime:**

$(129.6 \pm 0.8) \mu s$

**S1 bottom area correction**

*4\textsuperscript{th} order polynomial fit*

**S1 top area correction**
$^{37}$Ar – RESULTS II
LIGHT AND CHARGE YIELD AT LOW ENERGIES