Energy response and position reconstruction in the DEAP-3600 dark matter experiment
TAUP 2017, Sudbury

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24/07/2017
Located at SNOLAB, 2 km underground at 6000 mwe:
The experiment:

- Pixelated detector
- capable to hold 3600 kg LAr target material, currently filled to 3260 kg
- 255 PMTs to measure energy and position of events in the LAr
- AV coated with wavelength shifter TPB
- Detection of WIMPs via nuclear recoils with a target sensitivity to WIMP-nucleon cross section $10^{-46} \text{ cm}^2$ at WIMP masses of 100 GeV

Running stable since November 2016
Radioactive Calibration Sources

- \(^{39}\text{Ar}\)
  - Internal source
  - \(\beta^–\) emitter with \(Q = 565\) keV
  - From cosmic ray interaction on \(^{40}\text{Ar}\)
  - Isotropically distributed in LAr

- \(^{22}\text{Na}\)
  - External source
Discriminating the $^{39}$Ar signal using PSD:

$$f_{\text{prompt}} = \frac{q_{\text{prompt}}}{q_{\text{event}}}$$

- Ar Dimer states with different life times:
  - Singlet $\tau$ 6 ns - predominantly nuclear recoils
  - Triplet $\tau$ 1500 ns - predominantly electromagnetic events

→ Percentage of light signal in prompt light as indication of singlet state population

DEAP-1 calibration data
Astroparticle Physics 85 (2016) 1-23
Understanding the energy response using $^{39}$Ar, Gas phase calibration:

- Light yield uniformly scaled to match the simulation to data

Cool down phase, before fill
Understanding the energy response using $^{39}\text{Ar}$, LAr phase calibration:

- Light yield uniformly scaled to match the simulation to data

First fill data
External $^{22}\text{Na}$ source allows tagged monoenergetic gamma rays:
The low energy feature

Cartoon of γ-ray down scattering in acrylic

Plot and data from NIST.gov
X-ray mass attenuation coefficients
The low energy feature

Cartoon of γ-ray down scattering in acrylic

Plot and data from NIST.gov
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Both the Rising and Falling Edge in Distribution Energy Deposit Arise from Electromagnetic Physics

Example: 511 keV γ
Simulated energy deposit in liquid argon.

Plot and data from NIST.gov
X-ray mass attenuation coefficients
Fits on the $^{22}$Na spectrum:

Fit on low energy feature
Fits on the $^{22}\text{Na}$ spectrum:

Fit on full spectrum: consistency check only

Excluded from fit – 0.511 MeV + 1.27 MeV coincidence not in fit model
Combining $^{39}$Ar and $^{22}$Na:

Saturation effects at high energies not yet accounted for

WIMP ROI: $80 - 240$ PE

$$c_0 + c_1 \text{PE} + c_2 \text{PE}^2$$

Preliminary light yield:

$$LY = 7.36^{+0.61}_{-0.52} \text{(fit syst.)} \pm 0.22 \text{(SPE syst.) PE/keV}_{ee} \text{ @80 PE}$$
Measurement of event position:

Two main approaches possible:
- Time-based
- Charge-based
Measurement of event position:

Two main approaches possible:
- Time-based

- Finite speed of light
- PMT hit time proportional to source distance from PMT
- Absolute vertex resolution uniform across volume
- Dependent on scintillator response times, PMT transit time, DAQ quality

\[ t_1 < t_2 \]
Measurement of event position:

Two main approaches possible:

- **Charge-based**
  - Charge patterns of the PMTs
  - Point-like source: closer PMTs expected to have more photon hits and charges
  - Pattern detector dependent
  - Vertex resolution improved towards the edge of the detector
Measurement of event position:

Two main approaches possible:
- Time-based
- Charge-based

DEAP-3600 small enough for charge-based vertex reconstruction to deliver the better position resolution
How it is done:

MC

- MC model of the detector with optics
- Simulation with high statistics of isotropically distributed source
- Look-up table
- MC truth position in detector
- PMT charge pattern

Data

- PMT charge pattern
- Minimisation algorithm
- Fitted event position

Work in progress!
Fiducialisation and de-biasing using $^{39}$Ar:

- Isotropic $^{39}$Ar distribution
- Map true radius to reconstructed radius
- Account for energy dependence

**MC**
- MC model of the detector with optics
- Simulation with high statistics of isotropically distributed source
- Map at different energies of corrected position vs truth position
- MC truth position in detector
- Reconstructed position

**Data**
- Fitted event position
- Applying correction map
- Corrected event position
Fiducialisation and de-biasing using $^{39}$Ar:

- Fiducial mass from activity of de-biased $^{39}$Ar decay spectrum after applying fiducial cuts consistent with 2222 kg of LAr

Work in progress!
$^{22}$Na studies to understand surface backgrounds:

- $^{22}$Na low energy feature at low energies near ROI helps determine fiducial cut parameter

Work in progress
The Deap-3600 collaboration:

The speakers operational support was provided by NSERC
Back Up
DEAP-3600 calibration program:

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<th>Calibration Source</th>
<th>Calibration goal</th>
<th>Notes</th>
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<tr>
<td>Laserball</td>
<td>Optical (PMT) calibration</td>
<td>vacuum runs only</td>
</tr>
<tr>
<td>LED Light Injection</td>
<td>Optical (PMT) calibration, monitoring</td>
<td>used in all run phases</td>
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<tr>
<td>$^{22}\text{Na}$</td>
<td>Energy and position reconstruction, gamma response</td>
<td>Argon phase</td>
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<tr>
<td>AmBe</td>
<td>Energy calibration, gamma and neutron response</td>
<td>Argon phase</td>
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<tr>
<td>$^{39}\text{Ar}$</td>
<td>Intrinsic, energy and position reconstruction</td>
<td>Argon phase</td>
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</table>

- **Argon phase**: gas phase (GAr), partial fill phase, liquid argon phase (LAr)
- **LED Light Injection system** with fibres installed on PMTs
- **External calibration sources**: $^{22}\text{Na}$ (1 MBq) and AmBe (74 MBq)
- **Intrinsic calibration source**: $^{39}\text{Ar}$ (expected 1.01 Bq/kg)
Single Photon counting:

Ideal measurement: single photon counting correcting for PMT effects
De-excitation photons (128 nm) →
TPB (420 nm) → Photoelectron
cascade in PMTs

arXiv:1705.10183

- Translation of PMT pulses to
  number of photoelectrons
  observed using charge division
  (qPE)
Correction of different effects necessary:

Effects to correct on PE estimator:

- **PMT effects:**
  - After-pulse (AP): caused by back-scatter of electrons on PMT dynodes
  - Saturation of PMTs
  - Dark noise

- **Other effects:**
  - Pile-up of two or more events in same event window

arXiv:1705.10183