DARK MATTER SEARCH WITH DEAP-3600 EXPERIMENT

Alexey Grobov (Kurchatov Institute) for the DEAP Collaboration
100+ researches in Canada, Germany, Italy, Mexico, Russia, Spain, UK, and USA.
Dark matter detection principle

Hunt for the unseen
A whir, bubble, flash of light
Dark matter escapes

Aric Guite, Robert Provencher, Douglas Takayesu
DEAP-3600 detector

DEAP-3600 is a single-phase liquid argon (LAr) direct-detection dark matter experiment.

Location: 2km underground at SNOLAB (Sudbury, Canada).

Target: 3279 kg of LAr (30 cm of GAr on top) in a spherical acrylic vessel (AV)

Light detection: 255 PMTs connected to AV by 45 cm light guides (LGs).

Construction: Filling of the detector done through the neck with LN2 cooling coil. AV and PMTs enclosed in stainless steel shell.

Shielding: Filler blocks between LGs used for thermal insulation and neutron shielding. Steel shell is immersed in 300 tons of H2O, viewed by 48 veto PMTs. Neck of the detector has 4 Neck veto PMTs.
Excited argon dimers can be either singlet or triplet states, which have different decay time (7ns and 1.3µs). Depending in type of the recoil (electron or nuclear) there will be different ration of singlet to triplet states.

This allows to distinguish between nuclear and electron recoils by shape of the scintillation pulse.

\[
F_{\text{prompt}} = \frac{\sum_{t=10 \, \mu s}^{60 \, ns} PE(t)}{\sum_{t=-28 \, ns}^{10 \, \mu s} PE(t)}
\]

Ar39 pulsedshape and model fit incorporating several components. Ar39 beta-decays with lifetime ~269 years. It is a source of electron recoils in LAr.
Fprompt distributions

Electron recoils

Fprompt distribution for ERs from standard physics data in the lowest 1 keVee energy bin in the WIMP-search ROI.

Nuclear recoils

Using AmBe calibration to validate PSD

Response calibration & energy reconstruction

Response calibration & energy reconstruction

Alpha decays in LAr bulk

Ar39 model fit to data.

Energy response function, showing the number of detected photoelectrons versus energy deposited in LAr by event.
DEAP-3600 utilizes two complementary position reconstruction algorithms

- Spatial distribution of PMT hits (PE-based algorithm)
- Time residual based algorithm

Estimates from the PE-based (red) and time residual-based (blue) algorithms of the contained mass of LAr within a radius of the reconstructed position.
Backgrounds model: components and approach

- Cosmogenic neutrons
- Radiogenic neutrons
- Cherenkov light
- Alpha-decays
- Ar39 component
- Other possible backgrounds?

- Using MC simulations, sidebands and calibration to develop the model
- Validate it on control regions in data
- Develop event selection based on background model
- Predict number of events in ROI

<table>
<thead>
<tr>
<th>Source</th>
<th>(N_{CR}^{\alpha, \beta, \gamma})</th>
<th>(N_{ROI, LL}^{\alpha, \beta, \gamma})</th>
<th>(N_{ROI}^{\alpha, \beta, \gamma})</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERs</td>
<td>(2.44 \times 10^9)</td>
<td>(0.34 \pm 0.11)</td>
<td>(0.03 \pm 0.01)</td>
</tr>
<tr>
<td>Cherenkov</td>
<td>&lt; (3.3 \times 10^5)</td>
<td>&lt; 3890</td>
<td>&lt; 0.14</td>
</tr>
<tr>
<td>Radiogenic</td>
<td>(6 \pm 4)</td>
<td>(11^{+5}_{-9})</td>
<td>(0.10^{+0.10}_{-0.09})</td>
</tr>
<tr>
<td>Cosmogenic</td>
<td>&lt;0.2</td>
<td>&lt;0.2</td>
<td>&lt;0.11</td>
</tr>
<tr>
<td>AV surface</td>
<td>&lt;3600</td>
<td>&lt; 3000</td>
<td>&lt; 0.08</td>
</tr>
<tr>
<td>AV Neck FG</td>
<td>(28_{-10}^{+13})</td>
<td>(28_{-10}^{+13})</td>
<td>(0.49^{+0.27}_{-0.26})</td>
</tr>
<tr>
<td>Total</td>
<td>N/A</td>
<td>&lt; 4910</td>
<td>0.62^{+0.31}_{-0.28}</td>
</tr>
</tbody>
</table>
Neutrons

Cosmogenic

Cosmogenic neutrons are produced by high energy atmospheric muon interactions with the detector and its environment

- Muons are tagged when passing through muon veto

Radiogenic

Radiogenic neutrons can be produced in the \((\alpha,n)\) reaction triggered by \(\alpha\)-decays from Uranium/Thorium chains or by the spontaneous fission of \(^{238}\)U.

Main source of neutrons – PMT Glass. Neutron rate is reduced by the passive shielding.

Mitigation is done by:

- Estimation of flux with material assays
- Neutron capture analysis: tagging NR event closely followed (1ms) by high energy ER event

### Beta particles and gamma rays

**Ar39 beta-decays**
- Main source of ERs
- Have low Fprompt values

**Cherenkov light**
- Produced in the acrylic or PMT glass
- Have high Fprompt values
- Calibrated with U232 source
- Mitigated by removing events with more than 40% of the total event charge in one PMT
- Fiducial radius cut removes diffuse light

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**Graph:**
- Leakage probability vs. Fprompt
- Data and Model curves
- 90% NR acceptance
- 50% NR acceptance
- 1 leakage event in 3 tonne years
- Fiducial radius cut removes diffuse light
Alpha decays: Surface AV

Mostly Po210 decays (daughter of Pb210 from U238 progeny)
Alpha decays: Neck

Rates:
Inner flowguide, inner surface: 14.1 μHz
Inner flowguide, outer surface: 16.8 μHz
Outer flowguide, inner surface: 22.7 μHz

Most crucial background component

This background is mitigated with:

- Accounting for early pulses in GAr PMTs
- Upper Fprompt cut
- Charge fraction in top 2 rows of PMTs
- Neck veto PMTs
- Position reconstruction consistency
ROI definition and Acceptance

WIMP ROI (black) along with the ER (blue), NR (green) and neck-decay (pink) bands that define the boundaries.
WIMP search results

No events remained in the ROI after all cuts

90% confidence upper limit on the spin-independent WIMP-nucleon cross sections

Exclude cross sections above $3.9 \times 10^{-45} \text{ cm}^2$ ($1.5 \times 10^{-44} \text{ cm}^2$) for 100 GeV/c$^2$ (1 TeV/c$^2$) WIMP mass
Constraints on EFT models

\[ \frac{dR}{dE_R} = \frac{\rho_T}{m_T} \left( \frac{m_X}{m_N} \right)^{\epsilon(E_R)} \int_{v_{(m.in)}}^{\infty} v f^{\oplus} (\vec{v}) \left( \frac{d\sigma}{dE_R} \right) d^3\vec{v} \]

Detector model

Astrophysics model

\[ f^{\{gal\}} (\vec{v}) = (1 - \eta_{sub}) f^{\{SHM\}} (\vec{v}) + \eta_{sub} f^{\{sub\}} (\vec{v}) \]

Particle physics model

\[ L_{int} = \sum_{n,p} \sum_i c_i^{(N)} O_i \chi^+ \chi^- N^+ N^- \]

Types of Substructures:

- Gaia Sausage (Necib et al.)
- G2: Koppelman 2
- G3, G4: IC (In-falling clumps)
- G6: Nyx L. Necib et al., arXiv:1907.07190
Constraints on EFT models

Gaia Sausage (Necib et al.)

Gaia Sausage (O’Hare et al.)

G1 streams

G2 streams

G3 streams

G4 streams

G5 streams

G6 streams
COMING SOON

- Blind Analysis of 3 years of data.
- Multivariate analysis for mitigation of alpha decays in the neck: Boosted Decision Trees, Random Forest and Convolutional Neural Networks.