DARK MATTER SEARCH WITH DEAP-3600 EXPERIMENT

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for the DEAP Collaboration

NUCLEUS-2020, SAINT PETERSBURG
100+ researches in Canada, Germany, Italy, Mexico, Russia, Spain, UK, and USA
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 (FB) 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 on the type of the recoil (electron or nuclear) there will be different ratio of singlet to triplet states.

$$RATIO = \frac{N\{\text{singlet states}\}}{N\{\text{triplet states}\}}$$

NUCLEAR RECOILS

$$RATIO \approx 3$$

ELECTRON RECOILS

$$RATIO \approx 0.3$$

This is the core property of liquid argon that allows Pulse Shape Discrimination.
Ar39 pulseshape and model fit incorporating several components. Ar39 beta-decays with lifetime \( \sim 269 \) years. It is a source of electron recoils in LAr.

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

Using AmBe calibration to validate PSD

Electron recoils

F\(_{\text{prompt}}\) distribution for ERs from standard physics data in the lowest 1 keVee energy bin in the WIMP-search ROI.

Energy response function, showing the number of detected photoelectrons versus energy deposited in LAr by event.

Ar39 model fit to data.
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

<table>
<thead>
<tr>
<th>Background Type</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>AV Neck FG</td>
<td>52%</td>
</tr>
<tr>
<td>AV Surface</td>
<td>8%</td>
</tr>
<tr>
<td>Cosmogenic</td>
<td>12%</td>
</tr>
<tr>
<td>Radiogenic</td>
<td>10%</td>
</tr>
<tr>
<td>Cherenkov</td>
<td>15%</td>
</tr>
<tr>
<td>ERs</td>
<td>3%</td>
</tr>
</tbody>
</table>

#### Strategy

- Use 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.

### Source Table

<table>
<thead>
<tr>
<th>Source</th>
<th>$N_{CR}$</th>
<th>$N_{ROI, LL}$</th>
<th>$N_{ROI}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERs</td>
<td>$2.44 \times 10^3$</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>$11^{+8}_{-9}$</td>
<td>$0.10^{+0.19}_{-0.09}$</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>$28^{+13}_{-10}$</td>
<td>$28^{+13}_{-10}$</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 238U.

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

Ar39 beta-decays
- Main source of Electron recoils
- 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 Cherenkov light produced near the pentagonal or neck regions
Mostly Po210 decays (daughter of Pb210 from U238 progeny)
**Most crucial background component**

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

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.
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 $3.9 \times 10^{-45}$ cm$^2$ ($1.5 \times 10^{-44}$ cm$^2$) for 100 GeV/c$^2$ (1 TeV/c$^2$) WIMP mass
**Constraints on EFT Models**

### Particle physics model

\[ \frac{dR}{dE_R} = \frac{\rho_T}{m_T} \frac{\rho_x}{m_x} \epsilon(E_R) \int_{v_{(min)}}^{\infty} v f^{\Theta} (\vec{v}) \frac{d\sigma}{dE_R} d^3\vec{v} \]

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

**Detector model**

\[ \frac{dR}{dE_R} = \rho_T \frac{\rho_x}{m_x} \epsilon(E_R) \int_{v_{(min)}}^{\infty} v f^{\Theta} (\vec{v}) \frac{d\sigma}{dE_R} d^3\vec{v} \]

**Astrophysics model**

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

### Types of Substructures:

- Gaia Sausage (Necib et al.)
- Gaia Sausage (O’Hare et al.)
- G1: Koppelman 1
- G2: Koppelman 2
- G3, G4: IC (In-falling clumps)
- G5: Helmi
- G6: Nyx

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**Constraints on dark matter-nucleon effective couplings in the presence of kinematically distinct halo substructures using the DEAP-3600 detector, 2005.14667**

Fan et al. (2010), Fitzpatrick et al. (2013)
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
• 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.