Status and Future Prospects of the DEAP-3600 Dark Matter Search

Shawn Westerdale (Carleton University) for the DEAP-3600 Collaboration

NDM2018 - 30 June, 2018
The DEAP Collaboration: 75 researches in Canada, UK, Germany, and Mexico (+ future collaborators from Italy and USA)
The DEAP-3600 dark matter detector

- Direct detection of Weakly Interacting Massive Particles
- Located at SNOLAB
- Filled with 3.3 tonnes of LAr in an acrylic vessel
- Single phase
  - Detects scintillation light
- Target background: 1 < event in 3 tonne-years
- Target sensitivity: spin-independent WIMP-nucleon cross section of $10^{-46}$ cm$^2$ at 100 GeV
DEAP underground at SNOLAB

DEAP-3600 (Cube Hall)

World’s largest nickel

2 km underground (6 km.w.e overburden)
The DEAP-3600 dark matter detector

- 3.3 tonnes of LAr with a ~30 cm GAr layer
- GAr purified in process systems, and radon abatement systems
- GAr fed into acrylic neck, where $N_2$ cooling coils condense the Ar
- Acrylic flow guides ensure smooth fluid flow during filling, potential recirculation
- 3.3 tonnes of LAr with a ~30 cm GAr layer
- 5 cm thick acrylic shell contains the LAr

More details in arXiv:1712.01982
The DEAP-3600 dark matter detector

- Stainless steel sphere with Rn-scrubbed N₂ environment encases acrylic vessel
- 255 low radioactivity Hamamatsu R5912 HQE PMTs (See arXiv:1705.10183)
- 45 cm long acrylic light guides transport visible light to the PMTs, provide thermal insulation and shielding
- Alternating layers of high density polyethylene & polystyrene between light guides for additional insulation & shielding
- 3 µm thick coating of TPB converts UV LAr scintillation to visible spectrum

More details in arXiv:1712.01982
The DEAP-3600 dark matter detector

Neck veto:
10 cm tall bundle of Kuraray Y11 (200M) wavelength shifting optical fibres coupled to 4 Hamamatsu R7600-300 PMTs

Water Cherenkov muon veto (~300 tonnes)

48 Hamamatsu R1408 PMTs

More details in arXiv:1712.01982
The signal we’re looking for

- WIMP scatters on argon nucleus

(Not to scale)
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By looking for events with a lot of fast scintillation light, we can identify nuclear recoils, which may be caused by WIMP interactions
Energy response calibrated on $^{39}$Ar $\beta$ decay spectrum

- Atmospheric LAr has ~1 Bq/kg of $^{39}$Ar
- In 3.3 tonnes, that’s ~3.3 kBq
- $^{39}$Ar $\beta$ decays with a 565 keV endpoint
- $^{39}$Ar $\beta$ spectrum fit to ER band
- Consistent with a light yield ~7.5 PE/keVee in region of interest
- Compare to multi-MeV $\gamma$-ray lines to test linearity at high energies
WIMP events are rare, and the sensitivity for a 5σ discovery drops off quickly as the backgrounds increase.

Calculations of the number events one would have to observe to reject the no-WIMP hypothesis at 5σ, with Poisson statistics and profiling over background uncertainties.
Our main backgrounds

- **Cosmogenic backgrounds**
  - Esp. muon-induced neutrons
- **Electron recoil backgrounds**
  - $^{39}$Ar $\beta$ decays
  - $\gamma$-rays
- **$\alpha$ decays**
- **Radiogenic neutrons**
Cosmogenic background mitigation

From A. Ianni, TAUP 2017

6 km.w.e. overburden drastically reduces muon flux; water Cherenkov muon veto tags remaining cosmogenic backgrounds
Our main backgrounds

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  - $^{39}\text{Ar}$ β decays
  - γ-rays
- α decays
- Radiogenic neutrons
γ and β backgrounds: mitigate with pulse shape discrimination

γ backgrounds from radioactive contamination

β backgrounds primarily from $^{39}$Ar ~ 1 Bq/kg
→ 3.3 kBq in DEAP!

$F_{\text{prompt}} = \frac{\text{Prompt PE}}{\text{Total PE}}$


γ and β backgrounds: mitigate with pulse shape discrimination

- Surface α decays
- α decays in bulk LAr
- Various γ-rays
- WIMP ROI
- Nuclear Recoil (NR) band
- Electronic Recoil (ER) band
- $^{39}$Ar β decays (565 keV endpoint)

γ and β backgrounds: mitigate with pulse shape discrimination
Good agreement between PSD model and AmBe NR calibration data
Powerful ER rejection with good NR acceptance

Leakage prob <10^{-7} (90% NR acceptance)

- 90% N.R.A. projection: 10^{-8}
- 50% N.R.A. projection: 10^{-10}

Lower electronics noise than DEAP-1 → Better PSD!

Data, 120-240 PE
DEAP-1 prediction
Effective model
Our main backgrounds

- Cosmogenic backgrounds
  - Esp. muon-induced neutrons
- Electron recoil backgrounds
  - $^{39}\text{Ar} \beta$ decays
  - $\gamma$-rays
- $\alpha$ decays
- Radiogenic neutrons
Bulk $\alpha$ decays

- $^{222}$Rn: $(1.8\pm0.2)\times10^{-1}$ $\mu$Bq/kg
- $^{214}$Po: $(2.0\pm0.2)\times10^{-1}$ $\mu$Bq/kg
- $^{220}$Rn: $(2.6\pm1.5)\times10^{-3}$ $\mu$Bq/kg

Lowest Rn contamination of any noble liquid dark matter experiment!
Surface backgrounds

$^{210}$Po on the inner surfaces of the detector may decay and send recoiling $\alpha$ or $^{206}$Pb nuclei into the LAr.

$^{210}$Po $\tau_{1/2} = 138$ d
$E(\alpha) = 5.3$ MeV
$E^{(206}\text{Pb)} = 103$ keV
$^{210}$Po on the inner surfaces of the detector may decay and send recoiling $\alpha$ or $^{206}$Pb nuclei into the LAr. On the surface the $\alpha$ may lose energy before entering LAr and end up in region of interest.

$^{210}$Po $\tau_{1/2} = 138$ d
$E(\alpha) = 5.3$ MeV
$E(^{206}$Pb) = 103$ keV
Reduce surface backgrounds by removing the surfaces

Based on ex-situ assays and predictions

![Graph showing decay rate vs. depth in acrylic]

- Shave off \(~0.4\) mm from the surface

Further reduce surface backgrounds by vetoing events that reconstruct near the surface
In-situ surface background estimate

(See arxiv:1707.08042)
α decays in the neck

α decays in the flow guides of the neck may produce light in a LAr film

The geometry in the neck may shield light from reaching the PMTs and push the high energy decays down into the region of interest

These backgrounds can be mitigated based on their PMT hit pattern and timing
Our main backgrounds

- Cosmogenic backgrounds
  - Esp. muon-induced neutrons
- Electron recoil backgrounds
  - $^{39}$Ar $\beta$ decays
  - $\gamma$-rays
- $\alpha$ decays
- Radiogenic neutrons
Neutron backgrounds

Neutrons can be produced by nuclear reactions in detector components:
- \((\alpha,n)\) reaction
- Spontaneous fission

They may then scatter on argon nuclei and produce a WIMP-like signal.
Mitigated with careful material selection...

SNOLAB Ge well detector

PMT Borosilicate Glass (dominant neutron source)

$^{238}\text{U}$ Decay Chain
- $^{238}\text{U}$ to $^{230}\text{Th}: \sim 920$ mBq/kg
- $^{226}\text{Ra}$ to $^{206}\text{Pb}: \sim 225$ mBq/kg

$^{235}\text{U}$ Decay Chain
- Full chain: $\sim 25$ mBq/kg

$^{232}\text{Th}$ Decay Chain
- Full chain: $\sim 140$ mBq/kg

Close work with RPT to develop highly radiopure acrylic
... passive shielding, and fiducial cuts

Preliminary simulations:
- 1 out of $\sim 10^4$ neutrons will make it into LAr with enough energy to produce a visible signal
- < 0.25 n/year will produce a signal in 1 tonne fiducial volume and ROI

Neutron mean free path in acrylic $\sim$ 2 cm

50 cm
Predictions validated in-situ

Not a fit! U and Th γ rates are with a factor of 2 of assay results

Search for neutron capture γs in coincident with NR in a control region are consistent with MC
Construction begins at SNOLAB

Begin 1st fill

Detector stable

Seal failure

Begin 2nd fill

2nd fill complete

2012

June 2016

Aug. 7, 2016

Aug. 17, 2016

Sept. 3, 2016

Oct. 24, 2016

Seal failure at acrylic-steel interface in the neck caused Rn-scrubbed $N_2$ to enter the LAr

Forced us to drain and refill detector to 3.3 tonnes
First paper dataset

- 4.4 live days during first fill, before seal failure
- 2.2 tonne fiducial mass
- 0 events in ROI

Strict data quality/stability run selection criteria during commissioning dataset

1% NR acceptance loss

Upper bound to reduce backgrounds

Expectation of 0.2 PSD leakage events

5% NR acceptance loss

NDM 2018 (30 Jun.)
S. Westerdale (Carleton University)
First paper exclusion curve

See arXiv:1707.08042

- 4.4 live days during first fill, before seal failure
- 2.2 tonne fiducial mass
- 0 events in ROI
Stable running since October 2016

- Preparing an unblind analysis of ~250 live days of data in the second fill (... coming soon!)
- Blinding scheme in place for data after Jan 2, 2018
- Plans for improving energy calibration with $^{83}$mKr source
- Target exposure: 3 tonne-years
LAr Tech: The Next Generation

Joining the Global Argon Dark Matter Collaboration

DarkSide-20k target: 100 tonne·year

Future multi-hundred tonne LAr detector exposure: 1 ktonne·year
WIMP signal acceptance from 4.4 day commissioning limit

<table>
<thead>
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<th>Cut</th>
<th>Livetime</th>
<th>Acceptance %</th>
<th>#(\text{ROI}_{\text{evt.}})</th>
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<td>Physics runs</td>
<td>8.55 d</td>
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<td>Stable cryocooler</td>
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<td>Stable PMT</td>
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<td>Max charge fraction per PMT</td>
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<td>Max scintillation PE fraction per PMT</td>
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<td>Charge fraction in the top 2 PMT rings</td>
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<tr>
<td>Total</td>
<td>4.44 d</td>
<td>96.94±0.03</td>
<td>66.91±0.20</td>
</tr>
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</table>
The August 17 Seal Failure

Leak developed between butyl o-rings and steel shell region

~100 ppb N\textsubscript{2} into LAr

Drained and refilled to slightly lower level by October 2016

Continued taking data at new level since November 1, 2016 – 3322 kg

Rn-scrubbed N\textsubscript{2} gas in steel shell
Calibration methods

Sources deployed in tubes wrapping around steel shell (~1 d/month): $^{241}$AmBe, $^{22}$Na, $^{228}$Th

Laser ball: Lowered into neck once before filling.

Pulsed, uniform light source for optics calibration

Light injection fibers for daily PMT gain calibration