DEAP-3600 Dark Matter Search at SNOLAB

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Carleton University

for the DEAP Collaboration

DBD 18
Waikoloa
Liquid noble gas detectors

Why noble elements?
• (At least) two available detection channels: scintillation and ionization
• Avenue to reject electron recoil backgrounds (from $\gamma$ / $\beta$ activity)
• High light yield, transparent to their own scintillation
• Easy to purify and scalable to very high masses

Ar and Xe are used for WIMP detection
Single vs. dual phase

- Electronic recoil discrimination:
  - S2/S1 in Xe
  - PSD with S1 (scintillation only) in Ar; S2 signal used for position reconstruction

- A single phase detector of several hundred tonnes could be realized
  - PSD with currently-demonstrated low-radioactivity underground Ar mitigates electron recoil backgrounds;
  - position reconstruction mitigates external-source events
DEAP-3600 \textit{@} SNOLAB

Muon flux [cm$^{-2}$ s$^{-1}$]

Equivalent depth under flat surface [km w.e.]

2070 m underground

[A. Ianni TAUP17]
DEAP-3600 Collaboration

75 researchers in Canada, UK, Mexico and Germany

+ new DarkSide groups from Italy, US and Spain
DEAP-3600 Dark Matter Search

- **Single phase liquid argon** approach: simple, scalable, inexpensive

- 3.3 tonne target (1000 kg fiducial) in sealed ultraclean Acrylic Vessel

- Vessel is “resurfaced” in-situ to remove deposited Rn daughters after construction
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- In-situ vacuum evaporated TPB wavelength shifter (~10 m² surface)

- Bonded 50 cm long light guides + polyethylene shielding against neutrons

- 255 Hamamatsu R5912 HQE PMTs 8-inch (32% QE, 75% coverage)
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- 255 Hamamatsu R5912 HQE PMTs 8-inch (32% QE, 75% coverage)
- Detector immersed in 8 m water shield, instrumented with PMTs to veto muons
- Located 2 km underground at SNOLAB
Background mitigation strategy

- **β/γ events**: dominated by $^{39}\text{Ar}$ beta decay rate, 1 Bq/kg
  - pulse shape discrimination is very powerful in liquid argon $\sim 10^{-10}$

- **surface events**: Rn daughters and other surface contamination
  - procured ultrapure materials (screening, quality assurance, co-operation with suppliers)
  - surfaces sanded in-situ
  - limited exposure to radon rejection factor: $\sim 10^{-3}$
  - position reconstruction & fiducialization
  - other analysis techniques $\sim 10$

- **neutron recoils**: $(\alpha,n)$+fission, cosmogenic $\mu$-induced
  - SNOLAB depth + water Cerenkov muon veto
  - clean detector materials (material assay, quality assurance)
  - shielding
Fabrication and Assay of DEAP Acrylic

- Fabrication from pure MMA monomer at RPTAsia (Thailand), strict control of radon exposure for all steps, to $< 10^{-20}$ g/g $^{210}$Pb (RPT was fabricator of the SNO Acrylic Vessel)

- Assay of production acrylic $< 2.2 \times 10^{-19}$ g/g $^{210}$Pb
  (Corina Nantais M.Sc. Thesis 2014, <0.2 bkg events/3 years)

Monomer cast at RPT Asia, 2010

Thermoformed Panel at RPT Colorado

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DEAP Acrylic Vessel Fabrication

Reynolds Polymer (Colorado)

Panels thermoformed and bonded into sphere
At RPT Colorado (2011)

Machined at U of A (2011, 2012)

Shipped to SNOLAB, neck and light guides bonded (2012-2014)

University of Alberta

Underground at SNOLAB
Bonding light guides to the DEAP AV, underground at SNOLAB

Light guides bonded then annealed in radon-reduced air oven

>5 meter attenuation length in light guide acrylic!

DEAP AV in “The Rotator” at SNOLAB

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Light guides on AV

Reflectors on light guides

PMT and inner detector installation Oct 2014
Dark Matter in Hollywood

WIMP detector in "Scorpion TV series on CBS"

2018
An 18 foot tall sanding robot was deployed in the AV to remove inner surface layer of acrylic “The Resurfacer”

2016 J. Phys.: Conf. Ser. 718 042025
DEAP-3600 wavelength shifter (TPB) evaporation system

Evaporator source installation in a Rn-free atmosphere, through a glovebox.

Evaporation source and deployment system

UV illuminated coating on a small test acrylic vessel (20" diameter).

B. Broerman, M. Kuzniak et al., Application of the TPB Wavelength Shifter to the DEAP-3600 Spherical Acrylic Vessel Inner Surface, JINST 12 P04017 (2017)
Construction of DEAP-3600 was completed in early 2016

Detector paper: 1712.01982, accepted Astroparticle Physics J.
First Results from the DEAP-3600 Dark Matter Search with Argon at SNOLAB

P.-A. Amaudruz,1 M. Baldwin,2 M. Batygov,3 B. Beltran,4 C. E. Bina,4 D. Bishop,1 J. Bonatt,5 G. Boorman,6 M. G. Boulay,7,5 B. Broerman,5 T. Bromwich,8 J. F. Bueno,4 P. M. Burghardt,9 A. Butcher,6 B. Cai,5 S. Chan,1 M. Chen,5 R. Chouinard,4 B. T. Cleveland,10,3 D. Cranshaw,5 K. Dering,5 J. DiGiossefo,5 S. Dittmeier,1 F. A. Duncan,10,3,4 M. Dunford,7 A. Erlindson,7,11 N. Fatemighomi,5 S. Florian,5 A. Flower,7,5 R. J. Ford,10,3 R. Gagnon,5 P. Giampa,5 V. V. Golovko,11,5 P. Gorel,4,10,3 R. Gornea,7 E. Grace,6 K. Graham,7 E. Gulyev,1 R. Hakobyan,4 A. Hall,6 A. L. Hallin,4 M. Hamstra,7,5 P. J. Harvey,5 C. Hearns,5 C. J. Jillings,10,3 O. Kamaev,11 A. Kemp,6 M. Kuźniak,7,5 S. Langrock,3 F. La Zia,6 B. Lehnert,7 J. J. Lidgard,5 C. Lim,1 T. Lindner,1 Y. Linn,1 S. Liu,4 P. Majewski,2 R. Mathew,5 A. B. McDonald,5 T. McElroy,4 T. McGinn,7,5 J. B. McLaughlin,5 S. Mead,1 R. Mehdyaev,7 C. Mielniczuk,4 J. Monroe,6 A. Muir,1 P. Nadeau,10,5 C. Nantais,5 C. Ng,4 A. J. Noble,5 E. O’Dwyer,5 C. Ohlmann,1 K. Olchanski,1 K. S. Olsen,4 C. Ouellet,7 P. Pasuthip,5 S. J. M. Peeters,8 T. R. Pollmann,9,5 E. T. Rand,11 W. Rau,5 C. Rethmeier,7 F. Retière,1 N. Seeburn,6 B. Shaw,1 K. Singhaaro,1,4 P. Skensved,5 B. Smith,1 N. J. T. Smith,10,3 T. Sonley,10,5 J. Soukup,4 R. Stainforth,7 C. Stone,5 V. Strickland,1,7 B. Sur,11 J. Tang,4 J. Taylor,6 L. Veloce,5 E. Vázquez-Jáuregui,12,10,3 J. Walding,6 M. Ward,5 S. Westerdale,7 E. Woolsey,2 and J. Ziebinski1

(DEAP-3600 Collaboration)
4.4 live days

Selected ROI for < 0.2 leakage from β’s

Cuts for instrumental and external events

2223 kg fiducial mass

9,870 kg-day exposure

No events observed in ROI

Light yield consistent with expectation

\[ \text{LY} = 7.80 \pm 0.21 \text{ (fit syst.)} \pm 0.22 \text{ (SPE syst.) PE/keVee} \]
DEAP-3600 Timeline and Datasets

1st LAr fill: Jun - Aug 2016
- 10 day stable period selected as dataset
- 3322 kg of LAr in detector
- 4.4 live day dataset (9.9 tonne-days fiducial exposure)
- Leak in neck region on August 17, 2016:
  - Contamination of LAr with \( \approx 100 \) ppb \( \text{N}_2 \)
  - Drain and re-fill LAr to slightly lower liquid level

2nd LAr fill: Sep - Oct 2016
- 1 yr dataset recorded (Nov 2016 - Nov 2017)
  - 3256 kg of LAr in detector
- 247 live day dataset (not blind)
- Stable detector without LAr circulation
- Blinding scheme since Jan 2018 (20% of data visible)
- Plan to run until 2020
Detector stability

Preliminary

Long lifetime [us]

Date [month year]

Expected from observed LAr triplet lifetime

Fit

Light Yield at 2.6 MeV [PE/keV]

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Pulse shape discrimination (PSD)

Ar singlet and triplet excited states have well separated lifetimes (6ns vs. ~1.5us)

**Single phase LAr:**
scintillation channel is sufficient for $\beta/\gamma$ rejection
no need for the ionization channel

\[
F_{\text{Prompt}} = \frac{N_{\text{prompt}}}{N_{\text{prompt}} + N_{\text{Late}}}
\]

PMT signal:

- **Neutron (AmBe)**: Prompt: 0-150ns
- **$\gamma^{(22}\text{Na)}$**: Late: 150ns-10μs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ar</th>
<th>Xe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield ($x10^4$ photons/MeV)</td>
<td>4</td>
<td>4.2</td>
</tr>
<tr>
<td>Prompt time constant $\tau_1$</td>
<td>6 ns</td>
<td>2 ns</td>
</tr>
<tr>
<td>Late time constant $\tau_3$</td>
<td>1.5 μs</td>
<td>21 ns</td>
</tr>
<tr>
<td>$I_1/I_3$ for electrons</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$I_1/I_3$ for nuclear recoils</td>
<td>3</td>
<td>1.6</td>
</tr>
<tr>
<td>$\lambda$ (peak) nm</td>
<td>128</td>
<td>174</td>
</tr>
<tr>
<td>Rayleigh scattering (cm)</td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td>$T_{\text{eff}}$ (keV$_{ee}$)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PSD in DEAP-3600

100-fold increase in statistics since the 1st paper

9.87 tonne × days
(Aug 2016)

1.87×10^7 events
Approx. 15.4 - 30.9 keVee

Better than conservative prediction: lower noise, excellent LY uniformity

546.7 tonne × days
(Nov 2016 - Oct 2017)

1.36×10^9 events
Approx. 12.9 - 30.9 keVee

- Good PSD of \( \beta \) events down to 11 keVee!
- Best ever demonstrated at low energy, expect to meet design goal for the full sensitivity run
- Combined with low-radioactivity argon (depleted in \(^{39}\)Ar by a factor of >1500):
  
  Can use PSD for WIMP search with several hundred tonnes of argon
**Experimental Signatures**

Ar scintillation:
- excimers are created
  - singlet: 6 ns
  - triplet: 1500 ns
  - wavelength: 128 nm

Pulse shape discrimination (PSD) parameter:
\[ fprompt = \frac{\text{prompt light (150 ns)}}{\text{total light (10000 ns)}} \]

- alphas on surface (lose energy)
- full energy alphas (in argon)

**WIMP ROI**
- neutrons
- degraded α's

**39Ar**

**γ’s**

“nuclear recoil band”

“beta/gamma band”

DEAP 3600 commissioning data
Dominant internal background above $^{39}\text{Ar}$ is $^{42}\text{Ar}$, which is produced through:

$^{40}\text{Ar} (\alpha, 2p)^{42}\text{Ar}$ in upper atmosphere, maybe successive $n$ captures on argon, so may be lower in underground argon
**42Ar / 42K Specific Activity**

- 42Ar is mainly produced via (α,n) reactions on 40Ar in the outer atmosphere.
- The decay chain with 42Ar - 42K is the dominant background in GERDA and LEGEND 0νββ experiments. The specific activity is debated in the literature (table below)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Technique</th>
<th>Activity [μBq/kg]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBA</td>
<td>LAr ion. det.</td>
<td>&lt; 61.4 (90% CL)</td>
<td>Ashitkov et al. 1998</td>
</tr>
<tr>
<td>DBA</td>
<td>LAr ion. det.</td>
<td>&lt; 44.0 (90% CL)</td>
<td>Ashitkov et al. 2003</td>
</tr>
<tr>
<td>GERDA Phase I</td>
<td>HPGe γ-spec.</td>
<td>= 91$^{+8}<em>{-20}$ - 168$^{+22}</em>{-18}$</td>
<td>GERDA 2016</td>
</tr>
<tr>
<td>DBA</td>
<td>LAr ion. det.</td>
<td>= 92$^{+22}_{-46}$</td>
<td>Barabash et al. 2016</td>
</tr>
<tr>
<td>DEAP-3600</td>
<td>Scintillation</td>
<td>= 39.6 ± 5.8</td>
<td>unpublished preliminary</td>
</tr>
</tbody>
</table>

42K has a prominent signature in DEAP-3600 above 2.6 MeV (BG model left). Different systematics apply compared to GERDA and DBA. A significantly lower specific activity is measured.
Neutron Backgrounds

- Neutrons recoil $^{40}$Ar similar to WIMPs
- Neutrons produced by $(\alpha, n)$ reactions, fission or muons
- Extensive neutron MC campaign using radio-purity assays and $(\alpha, n)$ yields from SOURCES-4C
  - Dominant source is $(\alpha, n)$ in PMT glass ($\approx$70%)
  - Well constrained from $\gamma$-background and consistent with target values

Data driven limit on neutron interactions:

- **Tag with capture gammas:**
  - 2.2 MeV $\gamma$ form $^1$H in acrylic
  - 6.1 MeV $\gamma$-cascade from $^{40}$Ar in LAr
  - Search for n - $\gamma$ coincidences

- **Preliminary result:**
  - No coincidence found above expected random background
  - In 4.4 day dataset (consistent with target value)

- Measurement in 1-year dataset in upcoming publication (2018)
Alpha backgrounds

30 – 300 times lower Rn levels than in Xenon-based experiments (LUX, XENON, PandaX)!

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Activity/Rate</th>
<th>Target</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEAP-3600</td>
<td>0.2 μBq/kg</td>
<td>LAr</td>
<td>C. J. Stanford, Ph.D. thesis, Princeton University (2017)</td>
</tr>
<tr>
<td>DarkSide-50</td>
<td>1.74 μBq/kg</td>
<td>LAr</td>
<td></td>
</tr>
<tr>
<td>PandaX-II</td>
<td>6.6 μBq/kg</td>
<td>LXe</td>
<td>Phys. Rev. D 93, 122009 (2016)</td>
</tr>
<tr>
<td>LUX</td>
<td>66 μHz/kg</td>
<td>LXe</td>
<td>Physics Procedia 61 (2015) 658–665</td>
</tr>
<tr>
<td>XENON-1T</td>
<td>10 μBq/kg</td>
<td>LXe</td>
<td>XeSat2017 talk [link]</td>
</tr>
</tbody>
</table>

- Stable throughout 1 yr data taking

\[
\begin{align*}
\text{Component} & \quad \text{Activity} \\
\text{222Rn LAr} & \quad (1.8 \pm 0.2) \times 10^{-1} \mu\text{Bq/kg} \\
\text{214Po LAr} & \quad (2.0 \pm 0.2) \times 10^{-1} \mu\text{Bq/kg} \\
\text{220Rn LAr} & \quad (2.6 \pm 1.5) \times 10^{-3} \mu\text{Bq/kg} \\
\text{210Po AV surface} & \quad 0.22 \pm 0.04 \text{ mBq/m}^2 \\
\text{210Po AV bulk} & \quad <3.3 \text{ mBq}
\end{align*}
\]
“Geometric” backgrounds

Degraded light collection from high energy events shifts them to lower energies, where we look for WIMPs.

Additional cuts and position reconstruction to mitigate this background (details in upcoming paper)
Position Reconstruction

Position reconstruction using spatial information (only) mitigates surface events

(position was for $10^{-3}$ leakage into fiducial volume, details in upcoming paper)

Also developed time-of-flight fitter, further reduces mis-reconstruction. Note that UV light speed is **11 cm/ns in LAr**!
DEAP-3600 Current Status and Highlights

First results published (4.4) days data, low radon and neutron backgrounds. PRL 121 171801 (2018)

Excellent pulse-shape discrimination of $\beta/\gamma$'s from nuclear recoils, works as expected up to the scale of DEAP-3600 but require lower $^{39}$Ar for larger detector. With underground argon (x1400 reduction), PSD is sufficient for ktonne-year exposure (ie to the neutrino floor with a 300-tonne detector).

Aside:
DEAP= “Dark matter Experiment using Argon Pulse-shape discrimination”

Currently completing analysis of one-year dataset, plan to submit by end of 2018. Improved optical calibration, position reconstruction, backgrounds model.

Global Argon Dark Matter Collaboration (Sep 2017)

Over 350 researchers from
- DarkSide
- DEAP
- ArDM
- MiniCLEAN

DS-20K → multi-100-T

collaborating on future program:

- Completion of current science and R&D programs by each collaboration

- Joint collaboration on DS-20k at LNGS
  (DEAP groups formally joined around September 2017)

- Extraction of 50 tonnes of low $^{39}$Ar underground argon for DS-20k, then
  ~400 tonnes for future detector (~5 years extraction)

- Joint collaboration on future multi-hundred-tonne LAr detector, site
  and detector technology TBD (mid-2020’s)
Dark Matter Sensitivity

$\beta/\gamma$ discrimination: solar pp neutrino ES and other ER backgrounds not a concern in argon due to PSD, ~100 events per tonne-year in xenon requires improved ER vs NR discrimination to reach “neutrino floor”

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END
Expect limit of 41 μBq/kg in atmospheric argon (Inst. Exp. Tech. vol 46 issue 2, pp 153-160 March 2003), perhaps reduced in underground argon

Require O(10 pBq/kg) for 10% background to solar neutrino measurement; can we assay to that level?
DEAP-3600 Timeline

2006-2012  Design and component fabrication
2012-2015  Construction and assembly at SNOLAB
2015-2016  Commissioning and Cooldown
2016 Nov 1 Start of production data taking
2017 July   First result released PRL 121 071801 (2018)
2018 Jan 1  Start of blinded running
2018 Fall   2\textsuperscript{nd} result to be released (first year open dataset)
2020 March  Nominal 3 tonne-year dataset collected