Recent Progress from the DEAP-3600 Dark Matter Direct Detection Experiment

Jocelyn Monroe,
RHUL & KEK

International Symposium on Revealing the History of the Universe with Underground Particle and Nuclear Research

University of Tokyo
May 12, 2016
Outline

Experiment Strategy

The DEAP-3600 Detector

Recent Progress, Commissioning and Calibration
DEAP Collaboration: 65 researchers in Canada, UK, and Mexico
so far: <1 event at $\sim 1\times10^{-45}$ cm$^2$, therefore need at least $1\times10^{-47}$ cm$^2$ sensitivity for 100 events to measure $M_X, \sigma$
Single Phase Liquid Nobles, a la Neutrinos

high light yield from $4\pi$ PMT coverage, self-shielding of liquid target, only detect scintillation

no electric fields = scale to large mass (O(100 T))
1) no pile-up from ms-scale electron drift in TPC
2) no recombination in E field
but background discrimination from scintillation only!

XMASS: 832 kg LXe detector at Kamioka, running from 2013, upgrading PMTs to reduce backgrounds, future 5T detector.

DEAP/CLEAN: LAr at SNOLAB. DEAP 3.6T, MiniCLEAN 0.5T commissioning now, DEAP physics start Summer 2015, project <0.6 background/3000 kg-days, 1E-46 cm$^2$ sensitivity
Why Argon

price, ease of purification, and LAr scintillates ~40 photons/keV with fast and slow components

identify, reject electronic backgrounds via pulse shape vs. time difference

• Very large detectors possible, without solar neutrino-electron scattering backgrounds

• Critically important for LAr: Ar-39 background beta decay at 1 Bq/kg, with 550 keV endpoint.


DEAP-3600: measures PSD to 3E-8 in DEAP-1, predict >1E-10 in DEAP-3600 (arXiv:0904.2930)

DarkSide-50: measure depletion x1600, in 50kg detector, zero background limit (arXiv:1510.00702)

ARGO: Coordination of LAr detectors, ArDM will test depleted UAr samples with 100x sensitivity.

‘ppb-ppt’ pulse shape discrimination (PSD): leakage probability of electrons into nuclear recoil $F_{\text{prompt}}$ region** leverages x250 difference in scintillation time constants in Ar.

**Fancier statistics gain ~10x in PSD leakage, Astropart. Phys. 65 (2014) 40

Jocelyn Monroe
Outline

Experiment Strategy

The DEAP-3600 Detector

Recent Progress, Commissioning and Calibration
DEAP-3600 Detector

85 cm radius acrylic sphere contains 3600 kg of liquid argon (LAr)

★ TPB coats inside surface of sphere, to wavelength shift from 128 nm to 420 nm

★ viewed by 255 8” Hamamatsu R5912 HQE PMTs (32% QE, 75% coverage)

★ 50 cm of acrylic light guide between LAr and PMTs to mitigate PMT neutrons

★ PTFE filler blocks between light guides to moderate neutrons

Outer steel shell prevents LAr / water mixing (important for safety!)

Inside 8.5m diameter water tank, with 48 8” R1408 PMTs for muon veto, and to moderate cavern neutrons and gammas.

6200’ underground in SNOLAB Cube Hall
Background Strategy

Electrons and Gammas:
• Ar-39 decay rate \( \sim 1 \text{ Bq/kg}, Q=550 \text{ keV}. \) Dominates data rate.
• mitigated with pulse shape discrimination (PSD)
• threshold for PSD determines energy threshold for dark matter search

Alphas and Radon Progeny:
• stringent radiopurity control, ex-situ assays
• resurfacing of vessel before TPB + argon fill
• fiducialization, determines fiducial volume for dark matter search

Neutrons and Gammas:
• passive moderation
• cross-check with active tagging: measure neutron inelastic scattering gammas
• stringent radiopurity control for (alpha,n)

<table>
<thead>
<tr>
<th>Background (in Fid Vol)</th>
<th>DEAP-3600 Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radon in Ar</td>
<td>&lt; 1.4 nBq/kg</td>
</tr>
<tr>
<td>Surface α’s</td>
<td>&lt; 100 μBq/m²</td>
</tr>
<tr>
<td>Neutrons (all sources)</td>
<td>&lt; 2 pBq/kg</td>
</tr>
<tr>
<td>Ar-39</td>
<td>&lt; 2 pBq/kg</td>
</tr>
<tr>
<td>Total (3 tonne-yr)</td>
<td>&lt; 0.6 events</td>
</tr>
</tbody>
</table>
Background target corresponds to <0.2 events in 3 Tonne-years.

This requires 1E-10 leakage of electrons into WIMP region.

Projected leakage in DEAP-3600 is <1E-10, based on fitting DEAP-1 data over 60-260 PE + noise model from measurements of DEAP-3600 electronics.

Main increase in PSD from light yield: (conservative) projection is 8 PE/keVee.

Effect of systematics in PE counting is important!

Developed Bayesian PE counter to reduce variance for DEAP-3600, and full PMT after pulsing model and correction.

*Caldwell, et al., Astropart. Phys. 65 (2014) 40*
Dangerous Radon (Rn) backgrounds come from decay of Rn progeny on surfaces, and between Acrylic Vessel (AV) and wavelength shifter (TPB).

Dominant source of Rn comes from plate-out on AV and acrylic during manufacture and construction.

So, sand off a thin layer of acrylic from inside of the detector before TPB deposition, x25 reduction.

With a gigantic robot!
Radon Mitigation in DEAP-3600

Dangerous Radon (Rn) backgrounds come from decay of Rn progeny on surfaces, and between Acrylic Vessel (AV) and wavelength shifter (TPB).

Dominant source of Rn comes from plate-out on AV and acrylic during manufacture and construction.

So, sand off a thin layer of of acrylic from inside of the detector before TPB deposition, x25 reduction.

With a **gigantic** robot!
Radon Mitigation: Resurfacer

Deposited 3 μm of TPB in two runs (total 200 hours).

TPB thickness chosen to optimize light level vs. background from Po-210 decays.

Based on material assay and exposure history of the acrylic vessel, the projected residue activity after resurfacing is ~10 α/m²/day.

Measured residue activity in 1 month vacuum run (1/16) prior to cool down for LAr fill.
Dominant source of neutron backgrounds comes from (alpha,n) in PMT glass.

**Passive**: shield LAr target from PMTs by 50 cm of acrylic to moderate this neutron flux.

**Active**: tag inelastic neutron scatters by characteristic gammas.

(A. Butcher, PhD thesis 2015)

Validate both active and passive mitigation efficiency using external tagged AmBe source.

<table>
<thead>
<tr>
<th>(In 3 years)</th>
<th># of neutrons (produced)</th>
<th>Events in ROI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic vessel</td>
<td>&lt;44 (Ge γ-assay)</td>
<td>&lt;0.096</td>
</tr>
<tr>
<td>Light guides</td>
<td>&lt;127 (Ge γ-assay)</td>
<td>&lt;0.015</td>
</tr>
<tr>
<td>Filler blocks</td>
<td>&lt;173 (Ge γ-assay)</td>
<td>&lt;0.034</td>
</tr>
<tr>
<td>PMTs</td>
<td>2.6x10</td>
<td>0.140</td>
</tr>
<tr>
<td>PMT mounts</td>
<td>7565</td>
<td>0.010</td>
</tr>
<tr>
<td>Rn emanation</td>
<td>&lt;44</td>
<td>&lt;0.081</td>
</tr>
<tr>
<td>Rn deposition (3 months)</td>
<td>38</td>
<td>0.010</td>
</tr>
<tr>
<td>Other sources</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>Total</td>
<td>&lt;2.7x10</td>
<td>&lt;0.35</td>
</tr>
</tbody>
</table>
Outline

Experiment Strategy

The DEAP-3600 Detector

Recent Progress, Commissioning and Calibration
DEAP-3600 Construction

Acrylic vessel

light guide bonding

Bonding complete

Annealing in place
N. Seeburn,
RHUL PhD student

View down neck

completed inner detector

Steel Shell in the veto tank

May 12, 2016 / p. 17

DEAP-3600 Construction

PMT Installation

Detector Installation in Veto Tank
DEAP-3600 Construction

LAr cool down started Feb. ‘16!

SNOLab Cube hall

Deck Installation

Argon purification system

Process Systems and Electronics

Jocelyn Monroe
DEAP-3600 Calibration Systems

0. Optical Calibration Systems:
• in-situ array of reflectors, fed by LEDs via fibers, fixed in position in 20 light guides + 2 at neck
• movable, multi-wavelength laser-diffuser flask

1. Radioactive Source Calibrations:
• tagged Na-22 source Cal A,B,E pipes, Cal F racetrack
• tagged AmBe source in vertical pipes
• hot Th-232 source at neck, in vertical pipes
• Ar-39 in-situ

All have been deployed!
In-Situ PMT Commissioning

Acrylic Array of Reflectors fed by LEDs + Fibers:
• initial voltage scans to verify gain matching
• low- and high-occupancy calibrations
• detector stability monitoring
• trigger performance validation
• detector simulation optical model tuning
• trigger performance validation
• PMT afterpulsing measurement
PMT Charge Calibration

PMT charge calibration model fits calibration data and dark rate data well for low+high occupancy.

Gain uniformity better than 10% before PMT voltage adjustment for fine gain matching.
Physics trigger on analog sum of charges on groups of PMTs (ASUM) to make decision.

Data compression (ZLE) happens on-board the waveform digitizers.

AARF data used to verify SPE calibration with full vs. ZLE waveforms, and estimate trigger threshold in PE.

demonstrated stable operation at 2 kHz trigger rate ~ few PE threshold for detector.
In-Situ Optics Commissioning

Multi-wavelength laser-fed diffuser flask deployed through glovebox into detector
- \( z = +55,0,-55 \) cm
- \( \phi = 0,90,180,270 \)
- wavelength = 375, 405, 455 nm
- measure PMT + light guide relative efficiencies, consistent with AARFs
- extract TPB uniformity for optical model

7% spread in relative PMT efficiencies

100% of PMTs working, but 3 with bad termination

in-situ laser calibration campaigns in gas-filled detector in July, Aug. 2015
PMT Time Calibration

PMT signal digitization at 250 MHz. Raw signal has up to 32 ns offset from trigger, cable lengths, board-to-board timing, etc.

Electronics pulse pattern generator (PPG) signal injection for channel-to-channel timing correction:

Laserball timing calibration used to measure timing offsets for each channel and correct.

Resulting PMT peak time spread: ~1 ns RMS
Calibration R&D Ex-Situ

What if we see 5 events? How would we know if its a signal?

• ex-situ measurement input to calibration analysis,
  (i) reduce systematics on energy, radius reconstruction,
  (ii) break correlations between parameters for MC tuning

- measure angular distribution of TPB emission
- measure TPB scattering length
- measure the Rayleigh scattering length in LAr
- measure the scintillation time constant temperature dependence
Water Veto

Before water fill, event rate in detector PMTs dominated by Cherenkov from gammas
- after water fill, rate drops as expected

Expected muon rate ~1.6/day
- measure high energy event rate of ~1/day

example high energy event:
Summary & Outlook

DEAP3600 will be the 1st demonstration of single-phase liquid Argon technology.

- discovery reach of $10^{-46}$ cm$^2$ in 3 T-yrs exposure,
- LAr filling now....  Stay tuned!

• prototype for kT-scale, O(10s) keV threshold detector for 'low-energy frontier' physics

Neutrino lesson: key to large, low-rate sensitive detectors is simple, open-volume design.
Other Slides
Alpha Scintillation in TPB

TPB wavelength-shifts from 128 nm to visible (fluorescence) ex-situ test benches for spectrum, efficiency, angular dist.  
V. M. Gehman et al., NIM A 654 1 (2011) 116-121

Alpha scintillation in TPB has rejection power, ex-situ test stand finds $11 \pm 5$ and $275 \pm 10$ ns fast and slow time constants, and fast:total intensity ratio of $0.67 \pm 0.03$ (cf. 7 ns and 1600 ns, and 0.75)  
T. Pollmann et al., NIM A 635 1 (2011) 127-130
The Low-Background Frontier: Status and Prospects

Billard et al. (2014)

Complementary with High-Energy Frontier

1 event/kg/day
1 event/100 kg/day
1 event/100 kg/100 days

Scalability of Detector Technology

Complementary with High-Energy Frontier

New Techniques for Backgrounds

Jocelyn Monroe