Position Reconstruction Using Photon Timing for the DEAP-3600 Liquid Argon Dark Matter Experiment

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DEAP Collaboration: 75 researchers in Canada, UK, Germany, Mexico (+ future collaborators from Italy, USA)
DEAP-3600 Detector

- **DEAP** = Dark Matter Experiment using Argon Pulse-shape Discrimination
- **3600** = 3600 kg of liquid argon (LAr) as designed target mass
- Search for scintillation signal due to elastic scattering of WIMP dark matter—argon nuclear recoils of ~ tens of keV.
LAr Scintillation

- Excited dimers formed after exposure to ionizing radiation, in singlet (6 ns) and triplet (~1.3 μs) states
  - Nuclear recoils (by WIMP, neutron, and α): higher ratio of singlet states—more prompt light
  - Electron recoils (β/γ): lower ratio of singlet states—less prompt light

- Emits UV light at wavelength of 128 nm. Passes through pure argon without being absorbed.
- TPB wavelength shifter converts UV light to visible light at wavelength of 420 nm. Passes through acrylic and collected by PMTs.
- UV-absorbing acrylic light guide (LG) helps minimize Cerenkov radiation.
Pulse-Shape Discrimination

\[ F_{\text{prompt}} = \frac{Q(-28 \text{ ns}, 150 \text{ ns})}{Q(-28 \text{ ns}, 10 \mu\text{s})} \]

- Ar39 in natural argon: \( \beta \) decay 1 Bq/kg
- Efficiently rejected by Pulse-shape Discrimination (PSD)


arXiv:1707.08042
Located in SNOLAB underground laboratory

- 2 km underground (6 km.w.e)
- Cosmic-ray muon flux $(3.77 \pm 0.41) \times 10^{-10} \text{ cm}^{-2}\text{sec}^{-1}$ (~1/70 of Gran Sasso)
• Acrylic vessel inside was resurfaced after shipped to SNOLAB, reducing $\alpha$ activity from radon daughters to $\sim 10 \alpha/m^2/day$

• 50 cm of acrylic light guides and plastic filler blocks provide thermal isolation and neutron shielding
Filled up to 3322 kg of LAr in August 2016

Collected 4.4 live days of data

Our first dark matter search result (arXiv:1707.08042)

Incident on August 17, 2016: leakage of 100 ppb N2 into LAr

Drained and re-filled to slightly lower level

DEAP-3600 has been taking data with 3256 kg of LAr since November 1, 2016
Region of Interest (ROI)

- AmBe source
- $\beta/\gamma$ band
- Nuclear recoils
- Allowing 0.2 leakage events from $^{39}$Ar

Energy threshold 80 PE (11 keVee)

Against Cerenkov events; removing 1% NR events

Removing 5% NR events

F$_{\text{prompt}}$ vs. $T_{\text{eff}}$ (keVee) for nuclear recoils from the AmBe source.
Cuts and Acceptance

- Fiducialization:
  - Cut on max scintillation PE fraction per PMT (surface)
  - Cut on charge fraction in the top 2 rows of PMTs (z-fiducial)
  - Position reconstruction algorithms have been developed and tested, but not applied as cuts
First Dark Matter Search Results from DEAP-3600

9870 kg*days

arXiv:1707.08042
First Dark Matter Search Results from DEAP-3600

As of July 2017

1.2x10^{-44} \, \text{cm}^2 \text{ for 100 GeV WIMP (90\% C.L.)}

Projected sensitivity for 3-year run: 10^{-46} \, \text{cm}^2 \text{ for 100 GeV WIMP}
Position Reconstruction

- Fit on photon charge distribution
  - Assuming a single source of light,
  - Light intensity (therefore charge in PMTs) \( \sim 1/r^2 \),
  - Probability density functions (PDFs) trained with MC,
  - Pulse charge in full event window as input
- Fit on the distribution of photon arrival timing (new fitter under development)
  - Assuming a single source of light,
  - Photon arrival time = event time + time-of-flight (TOF) + time delay (dimer decay, TPB response, PMT response)
  - Feasibility: detector large enough, time resolution good enough, UV light in LAr travels slow enough!
  - Using only first 40 ns prompt light to avoid late unphysical info (afterpulsing, …)
Fit with Photon Timing

- Fit with intensity and time of arrival for the first 40 ns of prompt light
- Group velocity of UV light = 110 mm/ns
- Group velocity of visible light = 241 mm/ns
- Construct PDFs for light emitted at vertex $x_0$ and event time $t_0$ given PMT $i$ measures charge $q_i$.

$$L\left(\{t_i, q_i\}; \vec{x}_0, t_0\right) = \prod_{i} P_{qi}^i(t_i; \vec{x}_0, t_0)$$

- Convolve singlet decay time (7 ns), TPB response time (3 ns), and PMT/Light Guild (LG) response time (1.4 ns)
Events in center area

- UV light always arrives first

Events relatively near surface

- Visible light arrives first to the PMTs at far side
- Distinct time profile at some PMTs
Consistency between Charge and Timing Fits

• Both algorithms assume a single source of light. For healthy, uniformly distributed bulk events, such as Ar39 and expected WIMP signal, the positions reconstructed by charge and by timing should agree.

• Not expect charge and timing fits to agree for
  • Events with substantial amount of afterpulsing
  • Light originating from multiple positions
  • Events in the neck

Neck events mis-reconstruction by charge
Consistency between Charge and Timing Fits

- Tested with WIMP MC events at ROI energy (80 to 240 PE)
- and Ar39 data events with higher energies to have similar amount of prompt light
- Very promising to discriminate background events from the neck, or other mis-reconstruction cases.
Conclusion

• DEAP-3600 has achieved stable operation at 7.36 PE/keVee light yield

• Better-than-expected Pulse-shape discrimination (PSD)

• No events observed in ROI in 4.44 live days of the first fill dataset

• Spin-independent WIMP-nucleon cross section $< 1.2 \times 10^{-44}$ cm$^2$ for a 100 GeV WIMP

• Second fill dataset: ongoing since November 2016; collected more than one year of data!

• Position reconstruction:
  • Photon charge algorithm, and
  • Newly developed photon timing algorithm (benefit from low group velocity of UV light in LAr)
  • Photon timing provides extra information
  • The reconstruction consistency between charge and timing is promising to reject backgrounds.
Backups
• Ar39 and Na22 are fit separately. Agree within errors.
• Ar39 spatially uniform (similar to WIMP-induced NR)
• Na22 near AV surface (similar to surface backgrounds)
• Light yield: 7.36 $^{+0.61}_{-0.52}$ (fit sys.) +/-0.22 (SPE sys.) PE/keVee
Backgrounds

- Alphas
  - $^{222}\text{Rn}$, $^{218}\text{Po}$, and $^{214}\text{Po}$ $\alpha$ decays
  - Tagged with well-defined high energy peaks and time delayed coincidence

- Neutrons
  - Dominant sources: ($\alpha$, n) and spontaneous fission
  - Constrained with in-situ measurements of gamma-rays from U/Th decay chain
  - Tagged by searching for NR followed by a neutron capture gamma-ray