DarkSide-20k and the Direct Dark Matter Search with Liquid Argon

Tom Thorpe for the DarkSide collaboration
Overview

- Dual phase Argon TPCs
- DarkSide-50
- DarkSide-20k technologies
- Prototypes
- Summary
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Primary event discrimination exploits the S1 time signature.
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• X and Y are reconstructed by localizing the S2 signal
• Z is reconstructed via the drift time (time difference between S2 and S1)
• Further event discrimination can be done with S2
Why Liquid Argon?

- Excited states relax by emitting 128 nm photons
- Very different decay times of singlet (~7 ns) vs. triplet (~1500 ns) state
- Electron recoils cause a higher fraction of triplet states than nuclear recoils
- Results in superior electron rejection
- DS-50 rejected $1.5 \times 10^7$, all, ER events in AAr run from 8.6 - 65.6 keV
  - Statistics limited
- DEAP-3600 has just shown an ER leakage factor of $4.1 \times 10^{-9}$ from 15.6 - 32.9 keV w/ 90% NR acceptance

\[ f_{90} \sim 0.7 \]

\[ f_{90} \sim 0.3 \]

\( \text{arxiv:1410.0653} \)

\( \text{arxiv:1902.04048} \)
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$f_{90}$ – fraction of light arriving within first 90 ns

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Nuclear Recoil (NR) $S1 \leq S2$

Electron Recoil (ER) $S1 << S2$

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Past, current experiments joining forces

DEAP-3600
DarkSide-50
MiniCLEAN
ArDM

59 institutions, > 400 researchers, 14 countries: Brazil, Canada, China, France, Greece, Russia, Italy, Mexico, Poland, Romania, Spain, Switzerland, UK, USA.

DarkSide-20k: 2022 - (LNGS)

Argo: ~ 2029 - (SNOLAB)

~ 300 tonnes
• Water Cherenkov detector
  • Stainless steel cylinder d=11 m; h=10 m
  • 1,000 tonnes of ultra pure water
  • Active veto for muons and passive shield for external radiation
  • 80 8” PMTs

• Liquid scintillator detector
  • 4 m stainless steel sphere
  • 30 tonnes of Boron loaded scintillator
  • Active gamma and neutron veto thanks to $^{10}$B loading
  • 110 8” PMTs

• Inner LAr TPC...
• PTFE cylinder containing 46 kg (37 kg fiducial) LAr
• Inner surfaces coated with wavelength shifter - Tetraphenyl Butadiene (TPB)
• Cathode and anode have Indium Tin Oxide (ITO) transparent layers on the fused silica windows and TPB coating
• 38 3” Hamamatsu PMTs R11065; 19 each on top and bottom
• Fused silica diving bell to contain the 1 cm gas pocket
DarkSide-50 Inner TPC

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- 38 3” Hamamatsu PMTs R11065; 19 each on top and bottom
- Fused silica diving bell to contain the 1 cm gas pocket
- Underground Argon (UAr)
  - Argon extracted from CO₂ wells in Colorado
  - Further purification via a cryogenic distillation column at Fermilab
  - Result is \(1.4 \pm 0.2 \times 10^3\) fewer \(^{39}\)Ar events than atmospheric Argon
DarkSide-50 Results (High Mass)

- Exposure = 532 live days x 31.3 kg = 16660 kg*days
- $1.14 \times 10^{-44}$ cm$^2$ @ 100 GeV
- Underground Ar (UAr) activity $\sim$ 0.7 mBq/kg
- $\text{LY} \sim 8$ photoelectrons/keV

Physical Review D 98 (10), 102006 (2018)
DarkSide-50 Results (Low Mass)

• Low-Mass: S2-only analysis
  • Physical Review Letters 121 (8), 081307 (2018)
  • arxiv:1802.06994

• Sub-GeV: S2-only analysis; DM-Electron
  • Physical Review Letters 121 (11), 111303 (2018)
  • arxiv:1802.06998
If the number of background events is < 0.1, assuming the correct model, then as few as five events would claim discovery.
We want:
• To increase exposure by $\sim 10^3$ or $10^4$
• Same total number of background events: $< 0.1$

We need:
• Less radioactivity
• Photo detectors optimized for 87K
- ProtoDUNE like cryostat
- Optical and EM barrier
- Neutron veto will use Gd doped acrylic panels and Atmospheric Argon (AAr)
- Inner TPC will be a sealed acrylic vessel containing UAr
- Separate cryogenic systems for UAr and AAr volumes
- Acrylic knowledge from DEAP-3600 is being implemented
- Silicon Photo Multipliers (SiPMs) will replace PMTs in TPC and veto (not shown)
Individual SPADs 25-30 μm²
Single SiPM ~ 1 cm²

Single tile (24 SiPMs; (2|3_)x4; ~ 5 cm x 5 cm)

Front End Board

V_{bias}

TIA

x4 then summed

PDM
Photo Detection Module (Tile + FEB in acrylic cage; base detection unit; one summed readout channel)

25 PDMs with mechanical support structure; base mechanical unit for DS-20k; routing structure for power and signal readout contained

87K also allows for electronic advantages!

~ 5 cm x 5 cm x 5 cm

~ 25 cm x 25 cm x 5 cm

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• Photo Detection Efficiency (PDE) ~50%
• FBK, Trento IT, NUV-HD-LF tech
  • Optimized for LAr temperatures
  • > 90% fill factor
• Power consumption required to be < 100 μW/mm²
• 0.1 Hz/mm² dark count rate
• < 10 ns timing resolution
• Single Photo Electron (SPE) resolution
• High SNR

Details:

arxiv:1706.04213 arxiv:1706.04220 arxiv:1610.01915

SNR ~ 24

Preliminary
• FBK technology transfer to LFoudnry (Avezzano, IT) for production of raw SiPM wafers
• Production facility for SiPM based photo electronics located at LNGS
• Equipment procurement has begun
• DS-20k production will be the first task
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• Equipment procurement has begun
• DS-20k production will be the first task
• Final testing facility for 25cm² photo detectors is being constructed in Naples

~40m
Underground Argon (UAr)

Production - Urania - CO, US
Underground Argon (UAr)

**Production - Urania - CO, US**

**Purification - Aria - Sardinia, IT**

- Ground/sea transport
- Final product will allow for multi-tonne scale experiments
Aria - First Results w/ Nitrogen

Isotopic separation between $^{14}$N-$^{14}$N and $^{14}$N-$^{15}$N

Preliminary

S $\approx 1.29$

18/10/19 19/10/19 20/10/19 21/10/19 22/10/19
17:30:00 02:07:20 10:44:40 19:22:00 03:59:20 05:36:40 21:14:00 05:51:20 14:28:40 23:06:00 07:43:20

0.4906 $\pm$ 0.0001

0.8002 $\pm$ 0.0001

1.571e+09 $\pm$ 6.161e+01

3.23e+04 $\pm$ 3.36e+01

~24m
• Measure the depletion factors of the UAr produced by Urania and Aria
• Depletion factor of $10^4$ should give ~85 events per week
• 99.99% OFHC Cu; Acrylic coated w/ TPB
• ~1L active volume
• 2 x 1cm$^2$ SiPMs as photo sensors (DArTeye)
• To be housed in center of ~1 tonne AAr in the ArDM detector, CanFranc, acting as veto

Design and construction of a new detector to measure ultra-low radioactive-isotope contamination of argon. DarkSide collaboration; In preparation for JNIST.

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Active Neutron Veto

- Primary work in Genoa and Torino
- No more organic liquid scintillators at LNGS...
- Will utilize LAr and Gd doped acrylic panels
- 10 cm thick vessel surrounding TPC
- 300 tonnes AAr; ~3000 "PDMs"
- Requires higher dynamic range than the inner TPC
- Integrated front end electronics
- R&D for reflector and WLS is ongoing
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Inner TPC

- Sealed octagonal acrylic vessel
- ~50 tonnes Depleted underground Argon (DAr)
  - 20 tonnes fiducial
- 8280 PDMs
  - Split evenly on top/bottom
- Clevios conductive polymer coating
- TPB coating for WLS
Inner TPC

• Sealed octagonal acrylic vessel
• ~50 tonnes Depleted underground Argon (DAr)
  • 20 tonnes fiducial
• 8280 PDMs
  • Split evenly on top/bottom
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• TPB coating for WLS

Xiang Xiao
Development of photosensor and inner detector in DarkSide-20k experiment
Thursday, 5 Dec 2019, 16:50
SNH 4002 (Messel)

350 cm drift

360 cm
• Scaled down version of DS-20k inner TPC
• ~ 350 kg active volume
• 250 PDM channels, possibly 370
• Assembly starting Summer 2020
• Photo electronics are being produced and tested in Italy
• Cryogenics work is being done at CERN
• Acrylic vessel work is being done in Canada (DEAP)
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• ~ 350 kg active volume
• 250 PDM channels, possibly 370
• Assembly starting Summer 2020
• Photo electronics are being produced and tested in Italy
• Cryogenics work is being done at CERN
• Acrylic vessel work is being done in Canada (DEAP)
• Deployed at CERN
• Integrated with DS-20k technologies
• First LAr run with TPC and source just finished
• First experience of DAQ and analysis with 25 channel photo detectors in a LAr TPC
• New TPC design proven successful; fully functional
• Observed first S2 signals
• Run after the new year will study details of S2; X-Y
• Integrated with 20k technologies
• Deployed at CERN
• Utilizing base mechanical units for photo detectors
• First LAr run with TPC and source just finished
• Observed first scintillation light from full photo detector
• Another run planned for January
Summary

- Dual phase Argon TPCs are a proven technology for background-free dark matter searches
  - Zero background > 10 GeV
- The GADMC is now pooling resources with DarkSide-20k as the next step
- DarkSide-20k could reach the neutrino floor using key technologies:
  - Large scale production of novel SiPM based cryogenic photo detectors
  - Extraction and purification of large quantities of low radioactivity underground Argon
  - TPC technologies – Clevios, reflectors, SS wire grid, gas pocket formation...
  - Active neutron veto utilizing atmospheric Argon, Gd doped acrylic, SiPMs
  - Acrylic structural R&D
  - Acrylic knowledge and experience from DEAP-3600
- DarkSide-20k technology could also decrease the low mass WIMP cross section by orders of magnitude
- The future of this technology (Argo) aims to reach well into the neutrino floor
Thank You
DarkSide-50 Background Spectra (Low-Mass)

The graph illustrates the background spectra for DarkSide-50, focusing on low-mass dark matter (DM) candidates. The x-axis represents the number of electrons ($N_{e^-}$) and the y-axis represents the events per day in units of $N_{e^-} \times [kg \times day]$. The data points are compared to theoretical predictions for different DM masses ($M_\chi$): 2.5 GeV/c$^2$, 5.0 GeV/c$^2$, and 10.0 GeV/c$^2$. The background contributions include data, G4DS MC All, cryostat $\gamma$-rays, PMTs $\gamma$-rays, and $^{39}$Ar + $^{85}$Kr.

The graph shows a comparison between the observed data and the theoretical models, highlighting the regions where the data align with or deviate from the expected spectra.

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DarkSide-50 Limit (Low-Mass)
DarkSide-50 Results (Sub-GeV; DM-Electron)

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**Events / [N\text{e}^- \times kg \times day]**

<table>
<thead>
<tr>
<th>Energy [keV\text{ee}]</th>
<th>Data</th>
<th>G4DS MC All</th>
<th>10 MeV/c^2</th>
<th>Cryostat $\gamma$-rays</th>
<th>PMTs $\gamma$-rays</th>
<th>$^{35}$Ar + $^{85}$Kr</th>
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<td>0.2</td>
<td>10^2</td>
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<tr>
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**Dark Matter-Electron $\sigma^e$ [cm^2]**

<table>
<thead>
<tr>
<th>$F_{em}$</th>
<th>DarkSide-50</th>
<th>XENON100</th>
<th>XENON10</th>
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<tbody>
<tr>
<td>1</td>
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