Review on LAr Detectors

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@Tohoku Univ., Sendai

International symposium on revealing the history of the universe
with underground particle and nuclear research 2019
Outline

- Introduction (LArTPC)
- Recent Results on WIMP Search
  - DarkSide-50 (incl. S2-only Analysis)
  - DEAP3600
- R&D efforts by ANKOK in Japan
  - Maximizing Light Yield
  - R&D on VUV(128nm)-sensitive SiPM
  - S1/S2 electric-field dependency (up to 3kV/cm)
- Scaling up toward the v floor (DarkSide-20K & Beyond)
- Summary & Outlook
A Brief History on “LAr-TPC”

First proposed by Prof. Carlo Rubbia in 1977 (CERN EP INT-77-8)

Concept: “Electronic Bubble Chamber”

THE LIQUID-ARGON TIME PROJECTION CHAMBER:
A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

ABSTRACT

It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm³ and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.

Many technical developments done by ICARUS(LNGS) (now to DUNE(US) for the next generation ν experiment)

https://www.phy.bnl.gov/wire-cell/
WARp in 2000’s

- **Exp. Parameters:**
  - 2.3L-TPC (1kV/cm E-drift) with one-side PMTs (on top in gas)
  - Exposure: 96.5kgd
    - 1.83kg (fid.) x 52.8 days
  - $LY = 1.26$ PE/keVnr
  - E-thre. > 55 keVnr (0 event obs.)

★ **First result for Ar-WIMP interaction**

- Not only the WIMP Search,
  - Effects of Oxygen contamination in LAr
  - Effects of Nitrogen contamination in LAr
  - Specific activity of $^{39}$Ar in natural Ar
  - Discovery of “Underground Argon”

☞ “Pioneer of double phase Ar detector”

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Astro.Phys.28(2008) 495-507
Now.... LAr Detectors in the World

- DEAP/CLEAN@SNOLAB
- ReD (WARP) DarkSide@LNGS
- ARIS
- SCENE
- DUNE/MicroBooNE (Neutrino experiment)
- ArDM@Canfranc
- ANKOK

Underground WIMP Search Experiments

Property Measurement or/and in R&D Phase
Argon Property

- A-dependent search strategy is essentially important for galactic WIMP, where Argon plays crucial role together with Xenon.

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<tr>
<th></th>
<th>LHe</th>
<th>LNe</th>
<th>LAr</th>
<th>LXe</th>
</tr>
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<tbody>
<tr>
<td>A (Mass Number)</td>
<td>4</td>
<td>20</td>
<td>40</td>
<td>131</td>
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<td>Boiling point (K)</td>
<td>4.2</td>
<td>27</td>
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<td>Density (g/cm³)</td>
<td>0.13</td>
<td>1.2</td>
<td>1.4</td>
<td>3.0</td>
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<td>Radiation length (cm)</td>
<td>755</td>
<td>24</td>
<td>13</td>
<td>2.8</td>
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<tr>
<td>Scintillation (γ/keV)</td>
<td>20</td>
<td>15</td>
<td>40</td>
<td>42</td>
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<tr>
<td>Scintillation λ (nm)</td>
<td>80</td>
<td>77</td>
<td>128</td>
<td>175</td>
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<tr>
<td>Fast time constant</td>
<td>10ns</td>
<td>18ns</td>
<td>6ns</td>
<td>4ns</td>
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<tr>
<td>Slow time constant</td>
<td>13s</td>
<td>15μs</td>
<td>1.5μs</td>
<td>22ns</td>
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<tr>
<td>% in atmosphere</td>
<td>5x10⁻⁴</td>
<td>2x10⁻³</td>
<td>0.93</td>
<td>9x10⁻⁶</td>
</tr>
</tbody>
</table>

Ref) A.Hitachi, PRB27, 9 (1983) etc

$M_{WIMP}=100\text{GeV}$

39Ar Isotope:
- β-emitter @1Bq/kg in AAr
- half-life of 269 years
- Q value of 565 keV

→ Strong PSD Rejection
→ Depletion/Distillation
DarkSide-50@LNGS

Radon-free (Rn levels < 5 mBq/m³)

Assembly Clean Room

1,000-ton Water Cherenkov
Cosmic Ray Veto

30-ton Liquid Scintillator
Neutron and γ’s Veto
Veto efficiency > 99.1%

Inner detector TPC
filled with 150 kg of liquid
Underground Ar
AAr Result $\Rightarrow$ UAr for $^{39}$Ar suppression

◆ **DS50 with AAr (in 2013-2014)**
- Exposure: 1422 kgd (37kg x 47 days)
- $LY = 7.0$ PE/keVee@200V (7.9PE@null)
- $1.5 \times 10^7$ ER events from $^{39}$Ar activity
- Energy-thre. $> \sim 40$ keVnr (0 event obs.)
  → Set 90% C.L. limit

$\Rightarrow$ **Underground Ar (UAr)**

$^{39}$Ar is produced by cosmogenic activation via $^{40}$Ar(n,2n)$^{39}$Ar

→ 150 kg successfully extracted from a CO$_2$ wells in Colorado (USA)

★ $^{39}$Ar depletion factor $> 1400$

$^{39}$Ar in UAr $< 1$ mBq/kg
Latest Result from DS-50 w/ UAr-532d

- **DS50 with UAr** ($^{39}$Ar $\sim$ 0.73mBq/kg)
  - Total Exposure: 16,660 kgd (~0.05 ton-year)
  - Expected bkg: $0.09 \pm 0.04$ events
  - 50(1)% acc.@ 60(40) keVnr
  - **Zero event** observed after unblind

<table>
<thead>
<tr>
<th>Background Type</th>
<th># of Event</th>
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<tbody>
<tr>
<td>Surface alphas</td>
<td>0.001</td>
</tr>
<tr>
<td>Cosmogenic N</td>
<td>&lt;0.0003</td>
</tr>
<tr>
<td>Radiogenic N</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Electron recoil</td>
<td>0.08</td>
</tr>
</tbody>
</table>

![WIMP Signal Region](image)

10^{-44} @ 100GeV

PRD98 102006 (2018)
To lower the effective energy threshold, drop S1 requirement (lose PID and z-info.) → Background-limited analysis (à la XEONO100’s low mass search: PRD94 092001(2016))

“Single-Electron Detector”
- Sensitive to a single extracted electron, amplified in the gas region by 23PE/e-.
  (Trigger efficiency is 100% at >30PE)
- PMTs have almost zero dark rate@87K

→ E-threshold can be below 1keVnr

# of e increases in low energy
→ ~ 6e-/keVnr

4e- threshold: sensitive to all mass range (especially for lower mass) but contaminated by events not included by bkg model → Weaker limits

7e- threshold: for M>3.5GeV (well modeled by simulation)
Result for low mass WIMP search

PRL 121 081307 (2018) ← Editor’s Suggestion!

Signal uncertainties:
- NR ionization yield
- Single electron yields

Bkg uncertainties:
- Rates, ER ionization yield are included in binned profile LH.

★ For $M_\chi > 1.8$ GeV, insensitive to choice of energy quenching fluctuations. But below 1.8 GeV, it is impossible to claim exclusion without realistic fluctuation model or additional constraints.

→ Left for Future work

The world's best limit for low mass below ~5 GeV
◆ Single Phase $4\pi$ LAr Detector with 3.3 ton target (AAr) inside the ultraclean acrylic vessel at SNOLAB (2km underground).

◆ ~1000kg LAr after fiducial cuts, PSD only.

◆ Vacuum evaporated TPB on 10m$^2$ surface

◆ 255 Hamamatsu 8-inch PMTs (R5912)
  - QE: 32%, 75% coverage

◆ LAr Detector immersed in 8m water shield, instrumented with PMTs for muon veto.
**Latest Result from DEAP-3600**

- First results with 4.4 live days (fid. exposure 9.87 ton-day)
  → Updated with 231 days (total exposure 758 ton-day)

- Data collected in Nov. 2016-Oct. 2017, 824 kg after applying all fiducial cuts
  → Fid. exposure: 190 ton-day

- LY = 6.1 PE/keVee

- ROI: ~50 to ~100 keVnr

- Exp. Bkg: 0.46 ev
  - 0 event observed.

- World’s best limit ever achieved by non-Xe (DS50 x 2 !)

- **3.9x10^{-45} @ 100 GeV**

- **arxiv1902.04048**

- **PRL121, 071801 (2018)**

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R&D Activity in Japan (ANKOK)

◆ At Waseda Univ., we built LArTPC test-stand and achieved high purity (<ppb) and high E-field by CW circuit inside LAr.

- Maximizing Light Yield including R&D on VUV-MPPC
- Understanding scintillation(S1) and Ionization(S2) process for low recoil energy and also high E-field up to 3kV
Efforts for Maximizing Light Yield

- Scintillation light: 40γ / keVee (physics)
  - Reduced by WLS, detector-geo. and PMT QE etc.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>L.Y./ keVee</th>
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<tbody>
<tr>
<td>WARP</td>
<td>~ a few PE (1.3PE/keVnr)</td>
</tr>
<tr>
<td>Darkside50</td>
<td>7.9 PE @null</td>
</tr>
<tr>
<td>DEAP3600</td>
<td>6.1-7.8 PE</td>
</tr>
<tr>
<td>ArDM</td>
<td>1.1 PE</td>
</tr>
<tr>
<td>SCENE</td>
<td>6.3 PE</td>
</tr>
<tr>
<td>ARIS</td>
<td>6.4 PE</td>
</tr>
</tbody>
</table>

- Tested by our small single-phase detector to see/confirm “maximum LY”.

- ANKOK made well-controlled TPB evaporation system

- 11.5 PE/KeVee established!
  - limited by PMT QE(30%) only!

Paper preparation underway
R&D on “VUV-direct-sensitive” MPPC

- The most optimal photo-sensor should have High PDE and direct sensitivity to 128nm VUV LAr scintillation light.
- Since 2014, collaborating with HAMAMATSU photonics, we have performed R&D on VUV-MPPC.

◆ We successfully detect 128nm without TPB and measured the PDE for LAr scintillation light.
  → Current max PDE is ~12%, still too low for the purpose of WIMP search.
  → R&D to be continued.

◆ As a test, 4 VUV-MPPCs are mounted near the liquid surface of the 2-phase detector at our test-stand.
  - Coincidence signal with top-bottom PMTs was observed for S1 & S2.
Argon Property Measurements

- Compared to Xe (NEST), Argon property is not so systematically understood.
  → Recently many efforts have been done by various groups in the world.

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<thead>
<tr>
<th></th>
<th>Signal</th>
<th>Recoil Energy</th>
<th>Drift-Field</th>
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<tr>
<td></td>
<td></td>
<td>ER [keV_{ee}]</td>
<td>NR [keV_{nr}]</td>
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<tr>
<td>ANKOK</td>
<td>S1, S2</td>
<td>2–60</td>
<td>10–150</td>
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<td>SCENE [101, 105]</td>
<td>S1, S2</td>
<td>41.5</td>
<td>10.3–57.3</td>
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<tr>
<td>ARIS [102]</td>
<td>S1</td>
<td>42–511</td>
<td>7.1–117.8</td>
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<tr>
<td>Joshi et al. [126]</td>
<td>S2</td>
<td>2.82</td>
<td>6.7</td>
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<tr>
<td>Sangiorgi et al. [127]</td>
<td>S2</td>
<td>0.27, 2.82, 5.89</td>
<td>–</td>
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<tr>
<td>Bondar et al. [128, 129, 130]</td>
<td>S2</td>
<td>25, 59.5</td>
<td>80, 233</td>
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</table>

★ Table from T. Wasimi’s Ph.D thesis (ref # in there)

- ANKOK has performed S1&S2 simultaneous fit for low energy ER/NR region, up to 3kV/cm by NEST inspired functions (Doke-Birks & TIB models).
E-dependence of S2/S1 ratio

ANKOK Data

TIB + Dork-Birks

Quenching factors up to 3kV/cm

- Using $^{252}$Cf neutron with TOF method, we tag and specify incident neutron momentum and generate MC sample with GEANT4 accordingly.
- At each E-field (0 to 3kV/cm) and TOF bin (14 bins in total), **S1 and S2 spectra are simultaneously fitted** with Mei Model/TIB model functions.

M. Kimura, KY et.al. arxiv 1902.01501
Future of Ar Detector
“Scaling up toward the $\nu$ floor”

★ Special Thanks to C. Galbiati (Princeton) for the latest materials & information!
Global Argon DM Collaboration (GADMC)

→ DarkSide-20K@LNGS
More than 350 collaborators from ~80 institutes
DARKSIDE-20K

- A 20 tons fiducial argon detector fully filled with Underground Argon (Total 50 tons).
- Cryogenic low-bkg SiPMs ($14m^2$) instead of PMTs.
- 100 ton-year background-free search for DM.
- Approved by INFN & NSF with €80M capital cost.
  - Construction started, completion by 2022.
  - Veto based on CERN tech for ProtoDUNE cryostat,
    → TPC acrylic vessel surrounded by AAr as n-veto.

ProtoDUNE: Two identical cryostats built at CERN

- LNG technique from industry
- 8m x 8m x 8m for each one (750 ton)
- Construction: 55 weeks(NP04), 37 weeks(NP02)
  → Installable in underground
**Underground Argon \(^{39}\text{Ar} \text{free})**

**URANIA** funded by INFN, start operation in 2020

- Procurement of 50 tons of UAr from Colorado source, the same as for DS50.
- Extraction of 250kg/day with 99.9% purity
- UAr transported to Sardinia for final chemical purification at ARIA

**ARIA** ready by the end of 2020

- Big cryogenic distillation column in Seruci.
- Final chemical purification of the UAr.
- Can process O(1 ton/day) with \(10^3\) reduction of all chemical impurities.
- Ultimate goal is to isotopically separate \(^{39}\text{Ar}\) from \(^{40}\text{Ar}\) at the rate of 10kg/day in Seruci-I.

Sardinia
DARKSIDE Low Mass (DS-LM)

- **1 ton fiducial Ar detector specific to WIMP mass < 10 GeV.**
- Depleted UAr ($^{39}$Ar<1μBq/kg) by multi-path cryogenic distillation.
- S2-only analysis:
  - Lower threshold than DS-50 by reducing the single electron bkg.
  - Need low energy calibrations for NR below 1keVnr
- ★ This is actually “1-ton prototype” of DS-20K and will allow
  - validation of the design of TPC mechanics and cryogenics
  - integration tests of the custom SiPMs and full readout electronics & DAQ.

★ **SiPM (Silicon photomultiplier):**
- 50% PDE@420nm(after TPB-WLS) → High LY
- Much lower radioactivity than PMTs
- Cost effective and great stability (low-voltage)
- Suitable device at LAr temperature (low dark rate)

Status: R&D completed. Facility for large scale production of PhotoDetector Module (PDM) will be ready in Fall 2019 with produce rate of the order of 15 m$^2$ per year.
DARKSIDE-LM & -20K Sensitivity

- Low Mass (DS-LM)
- High Mass (DS-20k)
Going Further: “ARGO”

- The Ultimate (Last!?) Double Phase Ar Detector for WIMP:
  A 300-ton fiducial Ar detector filled with underground Argon

3000 ton-year exposure to reach the neutrino floor
### Timeline for “Bright Future” by Argon

<table>
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<th>17</th>
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<td>GADMC</td>
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</table>

- **DarkSide-20k**
  - a 20-tonnes fiducial argon detector
  - 100 tonne\(\times\)year background-free search for dark matter

- **GADMC**
  - a 300-tonnes depleted argon detector
  - 1,000 tonne\(\times\)year background-free search for dark matter

→ Expect to start in 2022

*Slide from G. Fiorillo*
Summary & Outlook

◆ In the last years, significant progress of LAr detectors has been made:
  - Physics outcomes (DarkSide50/DEAP3600 etc)
  - Deep understanding of Ar response (SCENE/ARIS/ANKOK)
  - Basic Technologies (UAr, Cryostat, Cryo-SiPM etc)
    → now Ar is pretty mature media/detector, we know how to deal with!

◆ Next-10-year program is well planned based on world-wide collaboration (GADMC) to cover both low & high mass dark matter.
  ★ Also for further possibility, aiming for directionality, ReD (Recoil Directionality in LAr) experiment that also utilizes SiPMs is actively ongoing (partially proto-DSLM).

◆ Putting all together, i.e. High LY & Low Bkg by SiPM, UAr, Radiopurity, PID makes Ar Detector a good candidate as a leading experiment toward ν floor.
  → Together with Xe, ready to reveal the mystery of the Dark Matter!
  ★ The race has to be always competitive 😊