Liquid Hole Multiplier (LHM) - “local dual-phase TPCs”: potential tools for future noble-liquid detectors

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‘Classical’ dual-phase Time Projection Chamber

- Hit pattern on top PMT array $\rightarrow x,y$
- Time difference $t_2 - t_1 \rightarrow z$
- $S_2/S_1 \rightarrow$ background discrimination

Current leading DM LXe experiments: XENON1t, PANDA X-II
Future: XENONnt, LZ: few t LXe
Next decade: & DARWIN 50 t LXe...
LAr: Dark Side 20K

See refs in: Aalbers (DARWIN), JCAP11(2016)017
http://arxiv.org/abs/1606.07001

- LXe: Dark Side 20K
- GXe: cathode
- WIMP: $z = v \cdot (t_2 - t_1)$
- Gate
- Top PMTs
- Bottom PMTs
- anode $\sim 10$ kV/cm
- ~1 kV/cm
- $S_2/S_1$ nuclear recoil $\prec$ electron recoil
concerns regarding S2-signal uniformity in large-diameter (few-meters) dual-phase TPCs

“waves”, parallelism of mesh vs liquid...

A possible configuration of a 50 t LXe DARWIN detector. The TPC is surrounded by highly reflective PTFE walls, closed by the cathode and anode electrodes on bottom and top, respectively. Shown is a TPC with 2 photo-sensor arrays made of circular PMTs with 3” diameter. The final sensor type, however, is not yet defined – being subject to R&D. Aalbers (DARWIN), JCAP11(2016)017 http://arxiv.org/abs/1606.07001

Our goal: Search for a new concept for S1 & S2 detection in a single-phase, liquid-only, detector
Noble (liquid) Dreams


Detection solutions for LARGE-VOLUME noble-liquid detectors
Originally proposed: Liquid Hole-Multipliers **LHM** in single-phase **LXe**

- Simultaneous detection of $S_1$ scintillation UV-photons & $S_2$ ionization electrons by a cascade of CsI-coated THGEM electrodes.
- Electron multiplication via electroluminescence, EL (+ maybe little charge gain) in the holes.
- Optical readout (or maybe charge readout)

**DREAM:**

- Electroluminescence (EL) threshold: $\sim 400 \text{ kV/cm}$ - on wires
- $e$-avalanche threshold: $\sim 1 \text{ MV/cm}$ on wires

**But: LXe prior art:**

- Observed large signals! Arazi 2013 *JINST* 8 C12004
- $\Rightarrow$ EL: in gas bubbles Arazi 2015 *JINST* 10 P08015
A new concept: Bubble-assisted Liquid Hole Multiplier (LHM)

Precise control of the liquid-gas interface:
- better S2 resolution
- potentially better S2/S1-based background discrimination

Reality:
- Perforated electrode (GEM or THGEM) coated on top with a CsI photocathode;
- Heating-wires grid forms a stable bubble underneath, by buoyancy;
- No need for heating after formation;
- A position-sensitive photon detector (e.g. SiPM array) is located below;
- Ionization electrons focused into the holes create EL light (S2) when crossing the liquid-gas interface into the bubble;
- Primary scintillation (S1) photons impinging on the photocathode release photoelectrons which are focused into the holes and create similar EL signals (S1’);
- The lateral coordinates of the EL signals are reconstructed by the photon detector.

Arazi, 2015 JINST 10 P08015
Erdal, 2015 JINST 10, P11002
Erdal, 2019 JINST 14, P01028

A. Breskin
MPGD2019 La Rochelle, May 5-10 2019
Competitors in bubble formation: La Rochelle UNIVERSITY!

Science Infuse
Typical waveform of an alpha-particle event, recorded by a PMT below the bubble

**S1**: primary light passing through holes

**S1’**: EL light from bubble, by photoelectrons emitted from the CsI photocathode

**S2**: EL light from bubble, by ionization electrons from track

Erdal, NIMA 845 (2017) 218

Light yield, resolution & PDE ➔ hole-electrode geometry
LHM Electrodes investigated

THGEM | Standard GEM | Single-conical GEM | Single-conical GEM
---|---|---|---
Insulator | FR4 | polyimide | polyimide | polyimide
Thickness | 0.4 mm | 50 μm | 50 μm | 125 μm
Hole diameter(s) | 0.3 mm | top/mid/bottom 70/50/70 μm | top/bottom 300/340 μm | top/bottom 300/400 μm
Hole pitch | 1 mm | 140 μm | 600 μm | 600 μm
Cu thickness | 20 μm | 5 μm | 5 μm | 5 μm
Hole rim | 50 μm | -- | -- | --

30mm diameter

Erdal, 2018 *JINST* 13 P12008
Primary source of difference of EL-yield between electrodes: efficiency of electron transfer across liquid-gas interface

Intense field across the bubble: Up to 5-fold EL yield enhancement

Erdal, 2018 JINST 13 P12008

MPGD2019 La Rochelle, May 5-10 2019
**Energy resolution**

**Ionization electrons → EL**

- **S2**
  - SC-GEM (t=125 μm)
  - $\Delta V_{\text{GEM}} = 1,400$ V
  - $E_d = 0.5$ kV/cm
  - $E_t = -1$ kV/cm
  - $V_{\text{PMT}} = -600$ V
  - $\sigma / \mu = 5.5\%$

- **Scintillation-induced photons → CsI → EL**
  - **S1'**
    - SC-GEM (t=125 μm)
    - $\Delta V_{\text{GEM}} = 1,400$ V
    - $E_d = 0.5$ kV/cm
    - $E_t = -1$ kV/cm
    - $V_{\text{PMT}} = -600$ V
    - $\sigma / \mu = 6.5\%$

- **Counts**
  - **S2**
    - Around 7,000 ionization electrons/event
  - **S1'**
    - Around 1,700 photoelectrons/event

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For reference: XENON100 had $\sigma / E \approx 11\%$ for the same number of S2 electrons

**BUT**: Better resolution expected for these numbers of e’s & hν’s → possible losses!

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Erdal, 2018 *JINST* **13** P12008

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Imaging LHM with SiPMs – first results

Hamamatsu VUV4 quad-SiPM array (4 6x6mm² elements); quartz window

Image reconstruction by center of gravity: \[ \vec{R} = \frac{A \sum L_i \cdot \vec{R}_i}{\sum L_i} \]

Erdal 2019 JINST 14 P01028

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Image of $\alpha$-particles of ring-shaped $^{241}$Am source

5.5MeV alphas $\rightarrow$ $\sim$7000 electrons/event

THGEM: 
Φ0.3 holes, 0.7 spaced
$\alpha$ range in LXe: $\sim$40$\mu$m

LHM reconstruction

LHM Reconstruction resolution of THGEM holes: $\sim$200$\mu$m

Erdal 2019 JINST 14 P01028

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Image and S2 spectrum of a 4mm diameter $^{55}$Fe source

5.9 keV x-rays $\rightarrow$ ~200 electrons per event

Photoelectron range in LXe: $\sim$1.5 $\mu$m

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Effective CsI Quantum Efficiency in LXe & photon detection efficiency PDE estimates

QE ~ 30% also obtained by Aprile, NIM A338 (1994) 328

→ GEM-LHM at 1300 V: theoretical PDE > 20% (assuming full PE collection)
  But so far in LHM: measured PDE ~ 5%
What limits the PDE?

- Electrons must penetrate a potential barrier (0.69 eV)* to cross from liquid-to-bubble.
- **Hypothesis:** bubble curvature + tangential field component → electrons glide towards bottom electrode before tunneling.
- The situation (e.g. curvature) varies with hole-electron geometry.
- There might be an issue related to surface “wetting”.
- Ongoing R&D.

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Simulation of electric field lines in the hole with a protruding spherical bubble.
(1) proposed e- trajectory from the liquid, gliding on the liquid-gas interface and reaching the GEM bottom face.
(2) proposed e- trajectory from the liquid, gliding on the interface and tunneling into the vapor phase.
LHM-based LXe TPC for DM searches?

“Local Dual-Phase” TPC

Higher S1 light-yield → lower WIMP detection threshold

R&D within DARWIN
LAr LHM-TPC for Nucl. Phys. Experiments

eexample: fast-n detectors for future experiments with Rare Isotope beams (NSCL and FRIB, with M. Cortesi et al.)

conceptual scheme of an LHM-TPC fast-n detector MODULE.

Large solid-angle “wall” of LHM-TPC neutron-detector MODULES, in single cryostat.

n-efficiency ~1; ns timing; sub-mm resolution; n-γ discrimination
Summary & Outlook

- LHM: Combined charge and light detection with CsI-coated hole-electrode;
- BEST: Single-Conical GEM (125mm thick)
  - highest photon yields: $\sim 400 - 2000$ photons/e-/4$\pi$
  - Energy resolution: $\sigma/E \sim 6\%$ for $\sim 7,000$ ionization electrons & $\sim 1700$ PEs;
  - Good localization: LHM/Quad-SiPM - reconstruction resolution $\sim 0.2$mm;
  - Current PDE $\sim 5\%$ (expected 20%) – probably inefficient e-transfer to bubble.

NEXT:
- Improve PDE: new electrode structures & configurations;
- Model/understand e-transfer through liquid-vapor interface;
- Validate 100 – 200 mm diameter LHM/SiPM modules;
- Operate in “deep sea” $\rightarrow$ 2.7m deep DARWIN LXe Demonstrator (Uni. Zr)
- LHM in LAr $\rightarrow$ neutrino physics, Heavy-ion experiments, neutron detectors...
Closing remarks to the younger generation

• Do not take things for granted.
• Detector Physics is flourishing: ever growing demands in many fields.
• The community seeks new ideas.
• Room for crazy ones!
• Be courageous: push your own ideas!
• Never get discouraged by criticisms!
GRAND MERCI
to Paul, Committee members, Secretaries, Assistants, Caterers... & presenters!

A la prochaine!