Gaseous photomultipliers and liquid hole-multipliers for future noble-liquid detectors

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CRYOGENIC GASEOUS PHOTOMULTIPLIERS
Dual-phase LXe TPC with Gaseous Photo-Multipliers (GPMs)

- Potentially low-cost (in-house module assembly)
- $4\pi$ coverage (improved sensitivity to low-mass WIMPs)
- 90-95% filling factor (compared to 50-60% with PMTs)
- ~10-fold better position resolution through smaller pixels → better calibration and background discrimination?
**Thick Gas Electron Multiplier (THGEM)**

~ 10-fold expanded GEM

**Chechik VIENNA 2004**

- Drilled
- Etched

**SIMPLE, ROBUST, LARGE-AREA**

**Printed Circuit-Board Technology**

- Robust, if discharge no damage
- Can be cascaded for high gain
- Effective single-photon detection when coupled to a photocathode
- Few-ns RMS time resolution
- Sub-mm position resolution
- Can be made of radio-pure materials
- Cryogenic operation: OK
- Broad pressure range: 1 mbar - few bar

Thickness 0.4-1mm

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Top array GPM – triple THGEM with reflective CsI

Pixel readout

Reflective Cesium Iodide (CsI) photocathode

Ne/CH₄

Xe

UV window

~10 mm
Wall GPM – semitransparent + reflective CsI

Ne/CH$_4$ ~10 mm

Semitransparent CsI

Reflective CsI

Pixel readout

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WIS Liquid Xenon (WILiX) facility: playground for detector R&D

WILiX schematic view

4” triple-THGEM
GPM

Smaller cryo-GPM see: Duval 2011 JINST 6 P04007

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First-ever demonstration of S1 & S2 recording by GPM coupled to dual-phase LXe TPC!

Detect single photons AND massive S2 signals!

October 24 2014
Gain and stability

- \(\sim 1 \cdot 10^5\) enough for >90% single-PE detection above noise
- Gain reproducible to 10-15% over many days
- **NO SPARKS** at \(1.1 \cdot 10^5\) for alpha S1+S2 with ~100-fold larger cosmics S2!
  (discharge probability < 3 \cdot 10^{-6})
Energy resolution

$\alpha S1 \sim 30$ PEs

$\sigma/E = 11\%$

Ne/CH$_4$(5%)  
514 torr, 180K  
Gain $1.1 \cdot 10^5$

S2 energy resolution similar to XENON100

$\alpha S2 \sim 5000$ PEs

60 keV $\gamma$

$\sigma/E = 8.7\%$

$\alpha$ & $\gamma$ coincidence
Time resolution

GPM signal lags by ~200 ns after PMT

But with only ~1.2 ns jitter!
Overall QE and expected PDE (top array)

$$QE_{eff} = QE_{CsI} \times A_{eff} \times \varepsilon_{ext} \times \varepsilon_{col}$$

- $QE_{eff}$: probability to get a photoelectron into a THGEM hole per photon passing the window
- $QE_{CsI}$: intrinsic CsI QE (at LXe temp)
- $A_{eff}$: fraction of detector area covered with CsI
- $\varepsilon_{ext}$: extraction efficiency – the probability that a photoelectron will not be backscattered to the CsI
- $\varepsilon_{col}$: collection efficiency – the probability that an extracted photoelectron will be pulled to a THGEM hole
Now 0.77
Can be optimized to >0.85

\[
\text{QE}_{\text{CsI}}
\]

\[
\varepsilon_{\text{ext}}
\]

\[
\varepsilon_{\text{col}}
\]
QE/PDE of top GPM array - bottom (optimistic) line

\[ Q_{\text{eff}} = Q_{\text{Csl}} \times A_{\text{eff}} \times \varepsilon_{\text{ext}} \times \varepsilon_{\text{col}} \approx 0.25 \times 0.85 \times 0.85 \times 1 = 0.18 \]

- Including window transmission (0.9) and probability for signal above noise (~ 0.95) we expect \( PDE \approx 0.15 \)
- With a filling factor of 0.9-0.95 the overall PDE is expected to be ~ 0.14
- PMTs: for QE=0.36, collection efficiency 0.9 and filling factor 0.5 \( \rightarrow \) PDE = 0.16
- For wall GPM we expect PDE > 0.2
**Light Yield with \(4\pi\) coverage (wall GPM)**

- DARWIN-like 2m LXe TPC with wall GPMs & 90% transparent field cage
- Top & bottom arrays: PMTs (QE=36%, CE=90%, filling factor=55%), or GPMs with equivalent overall PDE; XENON1t-like meshes
LIQUID HOLE MULTIPLIERS
BIGGER IS BETTER?

- S2/S1 discrimination in XENON100 and LUX – fantastic!
- Will it work on a few-meter diameter TPC?
- Grids and liquid surface must be parallel everywhere at all times

\[ S_2 \sim N_e E_{gas} d_{gas} \]

- Concerns: tilt, ripples, grid deformation, level variations with conditions
  → loss of \( S_2 \) resolution → loss of discrimination power!

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Can one have $S_1 + S_2$ in single phase liquid-only TPC?

4π geometry with immersed GPMs

LXe level

Recent alpha-induced scintillation $S_1$ and $S_2$ electroluminescence signals recorded from a 10 micron diameter wire in LXe.

E. Aprile et al.; 2014 JINST 9 P11012

K. Giboni 2011
2014 JINST 9 C02021, 2014 JINST 9 P12007

L. Arazi, 7th Symp. on Large TPCs, Paris, Dec 17 2014
Can we generate S2 in the holes of an immersed THGEM?

Arazi et al 2013 JINST 8 C12004

**YES WE CAN!**
Too good to be true?

- Photon yield: \(~600\) photons/e in THGEM hole at \(~30\) kV/cm
- S2 onset: few kV/cm

Arazi et al 2013 JINST 8 C12004
Our present understanding: a “Bubble Chamber”

- **S2 signals already at few kV/cm** *(as in Xe gas)*
- **S2 responds to pressure:**
  - **Disappears** after step increase in pressure *(bubbles collapse)*
  - **Reappears** when decreasing pressure *(bubbles form again)*

**Hypothesis:**
S2 produced in gas bubbles trapped under the THGEM
Near future: controlled bubbling by carefully-adjusted heating → high resolution

Bubbles formation

Graph showing:
- T(cold finger) = 163K, 1.3 bar steady state bubbling
- S2 rate [Hz]
- Set T(cold finger) = 173K, P → 2.1 bar, bubbling stops
- T(chamber bottom) = 179.35K, 2.1 bar, bubbling restarts
- No bubbling, chamber temperature rising slowly
- 1.5 h of super-steady bubbling

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S2 generation in bubbles is surprisingly steady

Stability + controlled effect + resolution + low-field operation ➔ should be exploited towards single-phase noble-liquid DM detectors!

Repeatable S2 yields over many weeks

Energy resolution with non-spectroscopic alpha source

Several tens of photons/e- @ 3kV

Resolution ~ 12%
Getting close to XENON100 with PMTs

Oct. 2014

low energy tail resulting from energy depositions inside the non-spectroscopic α source
Proposed Implementation in single-phase TPC

- THGEM top coated with CsI
- **Resistive wires underneath, to form bubbles in controlled way**
- $S_1$ photoelectrons & $S_2$ electrons focused into holes, inducing electroluminescence in bubbles
- If THGEM field too low – replace by GEM, or GEM+CsI followed by THGEM
Maybe something like this?
Summary

- Future large scale dark matter experiments call for new solutions
- Gaseous detectors *raison d’être*: affordable large-area coverage
- \(4\pi\) coverage by GPMs \(\rightarrow\) large improvement in sensitivity for low-mass WIMPs
- Top-array GPMs will have 10-fold better position resolution \(\rightarrow\) better calibration, background estimation and rejection?
- In-house assembly \(\rightarrow\) significant reduction in cost compared to PMTs
- First results with 4” GPM (top array): large dynamic range, good stability, energy and temporal resolution; overall PDE close to PMTs
- **R&D on wall GPM underway**
- LHMs: for now a curiosity, but may open new options for multi-ton experiments