The propagation of scintillation light in Liquid Argon

Umut Kose
CERN

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Motivations

- Liquid Argon (LAr) is one of the most exploited target media for many rare events experiments, studying neutrinos and Dark Matter. Both the scintillation light emitted in the vacuum ultraviolet (VUV) region and the charge are used to detect and identify the event. High precision measurements require large and multi-kiloton scale detectors: long distances between interaction point and photon detection & charge collection systems.

- Optical propagation of VUV scintillation photons in LAr is not yet well understood, mainly due to a lack of measurements.

Aim:

- To study the properties of the propagation of scintillation light in liquid argon, at VUV region, (128 nm wavelength)
  - Measurement of the propagation velocity of LAr scintillation photons
  - Deriving the index of refraction and Rayleigh Scattering Length
Scintillation light production in LAr

- **Two mechanism for scintillation light production:**
  - Excitation luminescence due to the primary excitation of Ar atoms
  - Recombination luminescence originated by the formation of an excited state after recombination
  - The excimer is bound either in the singlet or in the triplet state.
  - Two decay components from de-excitation of singlet ($\tau_{\text{fast}} \approx 6 \text{ ns}$) and triplet states ($\tau_{\text{slow}} \approx 1.5 \mu\text{s}$) of dimers.

- **Emits vacuum ultraviolet (VUV) photons with 128 nm**

- **Light is emitted isotropically, 40,000 photons/MeV**

- **Very transparent to its scintillation light**
  - Rayleigh scattering $\sim (1 + \cos^2(\theta)/\lambda^4)$
  - Index of refraction $n = c/\nu$

The propagation velocity of the light in LAr not measured yet.
Dedicated setup

No electric field and purification system!

Double wall, vacuum insulated, 1500 liters cryostat

Waveforms recorded by LeCroy WR104MXI-A with sampling rate of 5 GHz.
External Trigger

A movable cosmic hodoscope, “two scintillator bars”, 50 [L] x 10 [W] x 1 [H] cm, used for triggering on cosmic muon tracks at a number of distances from the light detection system and at two different track slopes (inclinations):

**Horizontal distance:**
130 cm

**Vertical distance:**
- 30 cm (track slope $tan \alpha \sim 0.230$) *sample 1*
- 50 cm (track slope $tan \alpha \sim 0.385$) *sample 2*

**Positioning of the hodoscopes and propagation length:**

<table>
<thead>
<tr>
<th>Distance from bottom PMT [cm]</th>
<th>Distance from top PMT [cm]</th>
<th>Flying distance d [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>95</td>
<td>90</td>
</tr>
<tr>
<td>15</td>
<td>85</td>
<td>70</td>
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<tr>
<td>25</td>
<td>75</td>
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<td>35</td>
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<td>30</td>
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<tr>
<td>45</td>
<td>55</td>
<td>10</td>
</tr>
<tr>
<td>55</td>
<td>45</td>
<td>-10</td>
</tr>
</tbody>
</table>
Scintillation light detection

- Light detection system: Two 8” (20 cm) diameter R5912-MOD with 10 dynode stages photomultipliers by Hamamatsu
- Quantum efficiency ~15%
- PMT photocathode coated with TPB (230 μg/cm²)
- Gain in Liquid Argon:
  Top PMT  \(7.44 \times 10^6 @ 1520\) Volts
  Bottom PMT \(4.44 \times 10^6 @ 1600\) Volts
  JINST 13 (2018) no.10, P10030
- The PMTs are facing each other at a distance of 100 cm; the measurement volume is defined by an opaque polyethylene box 120 cm long, enclosing the tubes.
• Data taking campaign took several weeks.

• Liquid argon level kept above Top PMT base (refilling liquid argon performed for several times).

• The set-up does not include any purification system.

• The slow component of the scintillation light, $\tau_{\text{slow}}$ (the lifetime of the triplet state) is sensitive to the concentration of impurities.

• In order to monitor the consistency of overall data sets in terms of light intensity, liquid argon purity has been checked by studying slow component of the signal, no drastically change have been seen.
Scintillation light time arrival to PMT

Extracting the velocity of scintillation light in LAr:

- About 3000 waveforms analyzed for each positions and track samples.

- Scintillation light arrival time at the PMT is estimated by Constant-Fraction method (40%, 50% and 60% of the maximal amplitude) in offline analysis.

- Computing time difference between the signal arrival to at the Top PMT w.r.t. Bottom PMT ($\Delta t$).

- Get the slope of the straight line fit on a space versus time, ($\Delta s, \Delta t$), graph.
Scintillation light velocity measurement:

The scintillation light velocity (inverse) is given by:

$$\frac{1}{v_g} = 7.5 \pm 0.07 \text{(stat)} \text{ns/m}$$
**FLUKA simulation**

- FLUKA simulation is performed to probe the consistency of the analysis and the Cherenkov effect on the velocity measurement.
- Monochromatic $5 \ GeV/c$ muons generated with directions from Top to Bottom external scintillator paddles with an angular divergence of $100 \ mrad$.
- Scintillation photon yield in LAr set to $5.1 \times 10^4 \ phe/MeV$ with a Gaussian shape centred around $\lambda = 126.8 \ nm$, and FWHM = $7.8 \ nm$.
- Rayleigh scattering set at $\mathcal{L} = 90 \ cm$.
- The simulation repeated with different values of refraction index: the refraction index curve has been shifted by 5%, 15% and 20% corresponding to $\frac{1}{v_g} = 6.44, 7.45$ and $7.76 \ ns/m$.

![](image1.png)

- Arrival time of each optical photon on the PMT surface has been scored and convoluted with a triangular shape signal with a rise time of $3 \ ns$ and an arbitrary gain factor of 10.
- The resulting waveforms have been analysed with the same Constant Fraction method as applied to data.
Sensitivity of the measurement to Cherenkov light

The inclination (cosmic muon slope) has no effect on the measurement. Cherenkov light (directional) has 5% effect on the scintillation light velocity measurement.

The scintillation light velocity (inverse)

\[ \frac{1}{v_g} = 7.5 \pm 0.07 \text{(stat)} \pm 0.05 \text{(sys)} \text{ns/m} \]
Deriving the index of refraction

From the measurement of the inverse group velocity, we derive the index of refraction for LAr at $\lambda = 128 \text{ nm}$ following the same approach in “E. Grace et al. NIM A867 (2017) 204-208”.

Sellmeier Dispersion for Liquids and Solids is given by where $a_i$ experimentally determined.

$$n^2 = a_0 + \frac{a_{UV} \lambda^2}{\lambda^2 - \lambda_{UV}^2} + \frac{a_{IR} \lambda^2}{\lambda^2 - \lambda_{IR}^2}$$

A $\chi^2$ method is applied to the Sinnock&Smith data, “A. C. Sinnock, B. L. Smith, J. Phys. C: Solid State Phys. 13 (1980) 2375” recorded at 90 K for $\lambda = 350 \text{ nm and 650 nm}$ together with measured group velocity to constrain the region of interest where $n$ varies rapidly.

The index of refraction at 128 nm

$n = 1.369 \pm 0.004$
Deriving the Rayleigh Scattering:

We used derived index of refraction extrapolations to get the Rayleigh Scattering length.

\[ L = \text{scattering length, } \lambda = \text{the wavelength, } k = \text{Boltzman constant, } T = \text{temperature, } \rho = \text{density, } k_T = \text{isothermal compressibility, } n = \text{the index of refraction to the corresponding wavelength} \]

\[ L^{-1} = \frac{16\pi}{6\lambda^4} \left[ kT \rho T \left( \frac{(n^2 - 1)(n^2 + 2)}{3} \right)^2 \right] \]

The scintillation light velocity (inverse)
\[ 1/v_g = 7.50 \pm 0.07 \text{(stat)} \pm 0.05 \text{ (syst) ns/m} \]

The index of refraction at 128 nm
\[ n = 1.369 \pm 0.004 \]

The Rayleigh Scattering Length
\[ L = 91 \pm 2.8 \text{ cm (stat)} \]
## Knowledge on the parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Measured/Calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1/V g \ (ns/m)$</td>
<td>$7.50 \pm 0.07 \ (stat) \pm 0.05 \ (syst)$</td>
<td>Measured in this study</td>
</tr>
<tr>
<td>Refractive Index, $n$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$1.37$</td>
<td>Calculated [1]</td>
</tr>
<tr>
<td></td>
<td>$1.45 \pm 0.07$</td>
<td>Calculated [1]</td>
</tr>
<tr>
<td></td>
<td>$1.369 \pm 0.004$</td>
<td>Derived in this study</td>
</tr>
<tr>
<td>Rayleigh Scattering length, $L, \ (cm)$</td>
<td>$90$</td>
<td>Calculated [1]</td>
</tr>
<tr>
<td></td>
<td>$55 \pm 5$</td>
<td>Calculated [2]</td>
</tr>
<tr>
<td></td>
<td>$91 \pm 2.8 \ cm \ (stat)$</td>
<td>Derived in this study</td>
</tr>
</tbody>
</table>

Summary

- The properties of the propagation of scintillations light in the liquid argon, at $\lambda = 128\ nm$ wavelength, has been experimentally investigated in a dedicated setup at CERN. Such measurement provides a key ingredient for the interpretation of data from the current and next generation large mass liquid argon detectors as those dedicated to the search for rare events such as neutrinos or Dark Matter.

- The velocity of scintillation photons has been measured for the first time in the liquid argon.
  \[ \frac{1}{v_g} = 7.50 \pm 0.07 (\text{stat}) \pm 0.05 (\text{syst}) \text{ns/m} \]

- The obtained result is then used to derive the index of refraction and the Rayleigh scattering of the liquid argon at VUV region.
  - The index of refraction: $n = 1.369 \pm 0.004$
  - Rayleigh Scattering length: $\mathcal{L} = 91 \pm 2.8 (\text{stat}) \text{ cm}$

- FLUKA simulation performed to validate the analysis method and the effect of Cherenkov light on the scintillation light velocity measurement in Liquid Argon at VUV region.