Scintillation and optical properties of xenon-doped liquid argon

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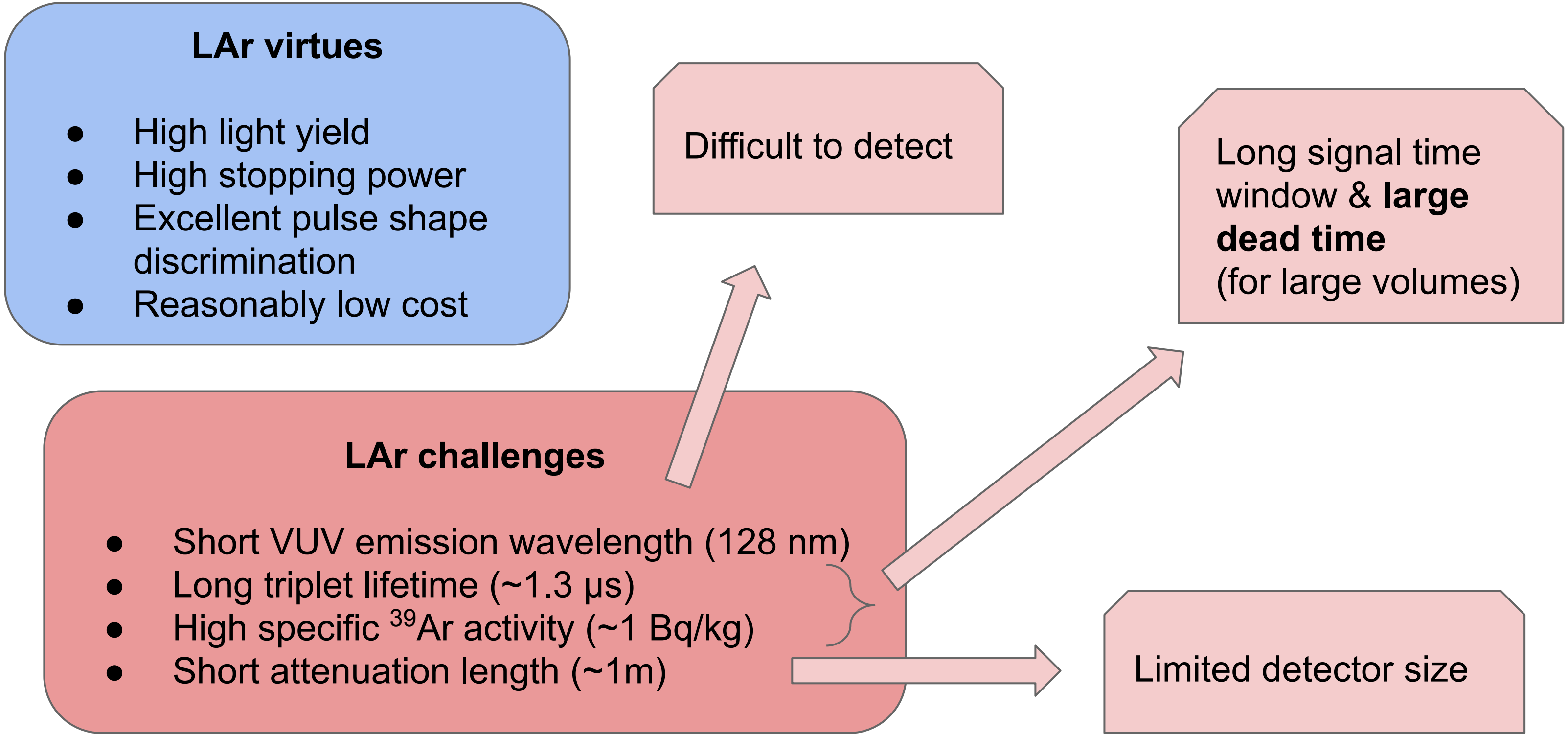
Introduction

Liquid argon (LAr) is a widely employed scintillation and shielding medium… but not perfect



LAr virtues

- High light yield
- High stopping power
- Excellent pulse shape discrimination
- Reasonably low cost

LAr challenges

- Short VUV emission wavelength (128 nm)
- Long triplet lifetime (~1.3 μs)
- High specific ^{39}Ar activity (~1 Bq/kg)
- Short attenuation length (~1m)

Difficult to detect

Long signal time window & **large dead time** (for large volumes)

Limited detector size

Xenon doping improves the scintillation and optical properties of LAr

LAr challenges

- Short VUV emission wavelength (128 nm)
- Long triplet lifetime (~1.3 μs)
- High specific ^{39}Ar activity (~1 Bq/kg)
- Short attenuation length (~1m)

LXe properties

- Longer emission wavelength (**175 nm**)
- Shorter triplet lifetime (**~20 ns**)
- Much more expensive

Xenon-doped liquid argon (XeDLAr) properties

- Longer emission wavelength (175 nm)
- Short triplet lifetime
- Long attenuation length (less scattering)
- Cost efficient

XeDLAr needs to be investigated more thoroughly

Previous works

- Measurements of **only subsets** of parameters w.r.t. Xe concentration
    - Relative pe yield: Y_{rel}
    - Effective triplet lifetime: τ_3
    - Effective attenuation length: λ_{att}
- Moderate volumes: 30 mL to 100 L
- No measurement of actual xenon concentration in liquid phase

This work

- **Simultaneous** measurements of Y_{rel}, τ_3 and λ_{att} at Xe concentrations from 3 to 300 ppm(m)
- Large mass of ~1 t
- **Measurements** of the actual **Xe concentration** in the **liquid** and gas **phase**

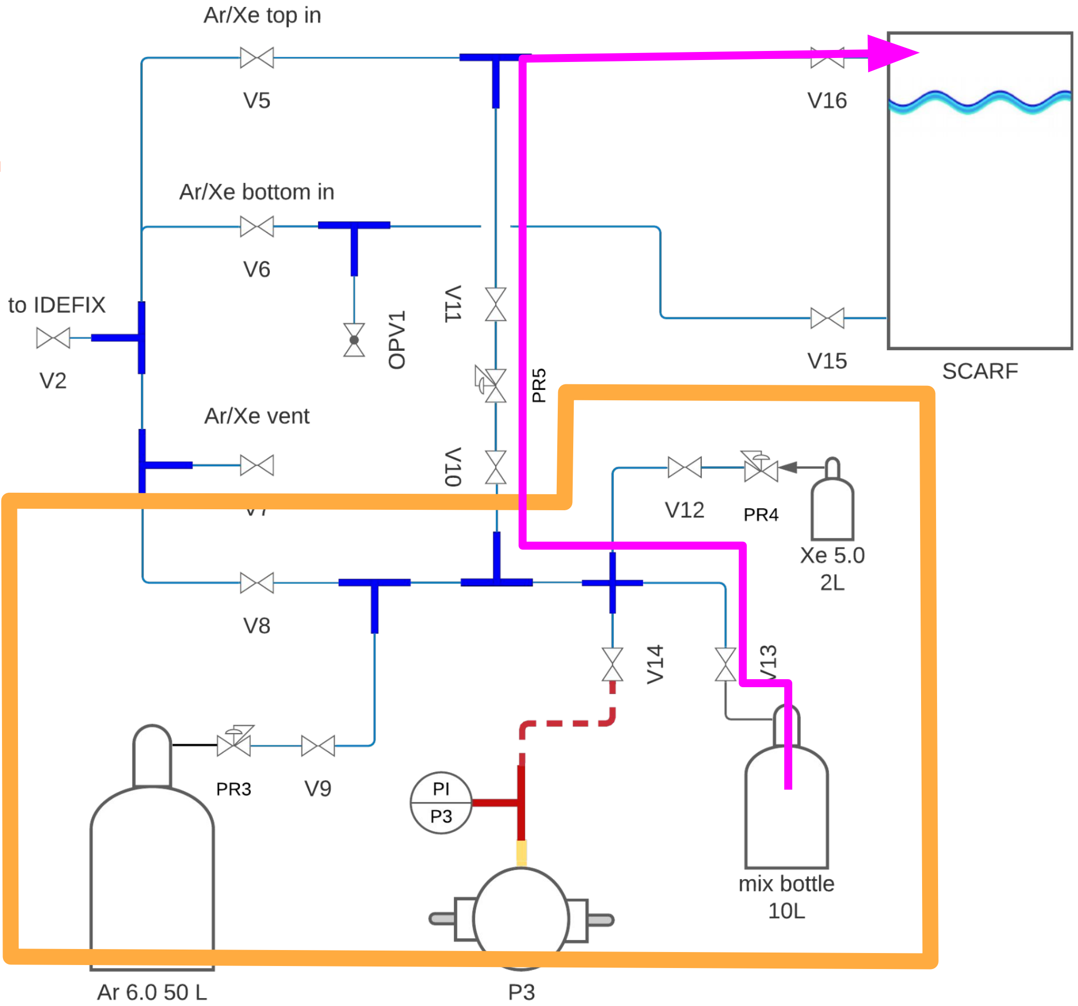
The literature includes: Kubota et al., *Nucl. Inst. Meth. Phys. Res.* 196.1 (May 1982); C. G. Wahl et al., *JINST* 9 P06013 (June 2014); N. McFadden et al., *Nucl. Inst. Meth. A* 1011 (Sep. 2021).
And contributions from our chair: A. Neumeier et al., *Eur. Phys. J. C* 72.10 (Oct. 2012); A. Neumeier et al., *EPL 109.1* (Jan. 2015); A. Neumeier et al., *EPL* 111.1 (July 2015); A. Neumeier et al., *Nucl. Inst. Meth. A* 800 (Nov. 2015)

Experimental Setup

Xenon is diluted with argon before injection

To prevent xenon freezing and cluster formation, a strongly diluted xenon-argon mixture is prepared.

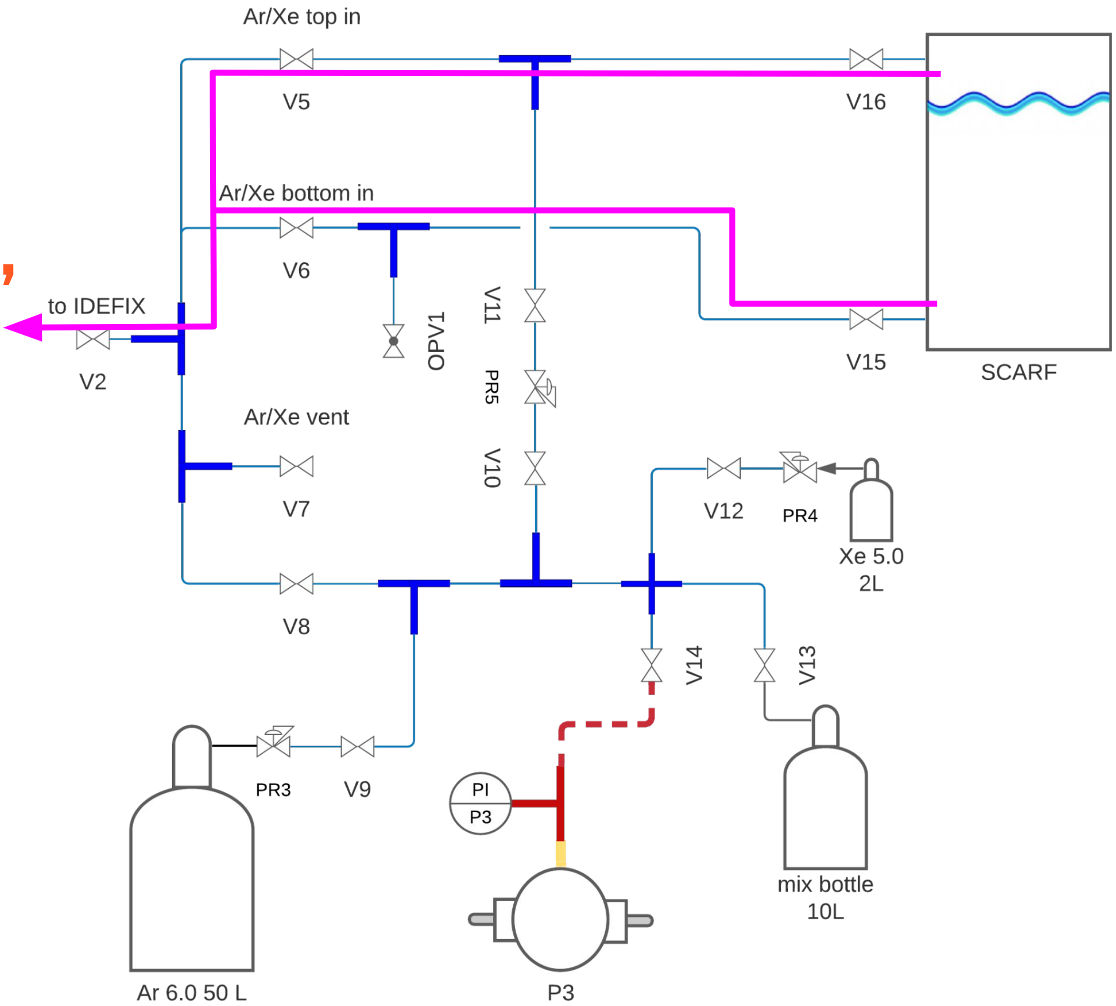
The xenon-argon mixture is injected into the gas phase of SCARF.



SCARF: Subterranean Cryogenic ARgon Facility.
A 1 t LAr test stand at TU-Munich.

The xenon content is measured by a mass spectrometer system, IDEFIX

When the liquid phase is measured, a vacuum pump enforces fast evaporation, retaining the original xenon concentration throughout the phase transition.



IDEFIX: Impurity DEtector For Investigation of Xenon. A quadrupole mass spectrometer system.

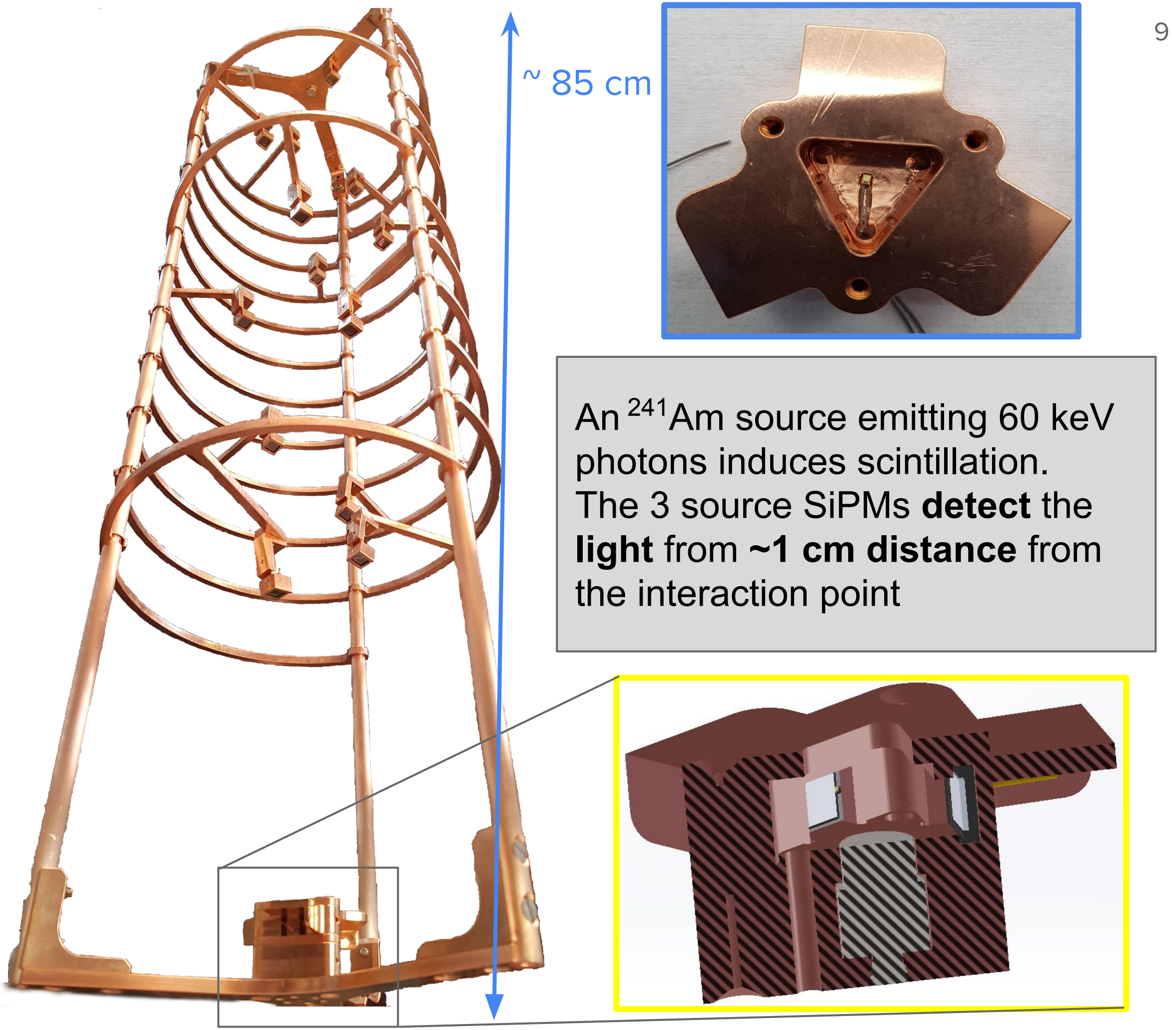
The scintillation is observed by a triggered SiPM array, LLAMA

LLAMA measures **simultaneously**

- The relative photo-electron yield
- Effective triplet lifetime
- Effective attenuation length

with 16 VUV sensitive SiPMs (Hamamatsu VUV4) located at different distances from the light source.

LLAMA: Legend Liquid Argon Monitoring Apparatus
[M. Schwarz et al., *ANIMMA 2021* (July 2021)]



An ^{241}Am source emitting 60 keV photons induces scintillation. The 3 source SiPMs **detect** the **light** from **~1 cm distance** from the interaction point

Results

The measured Xe concentrations in the liquid phase match the target values

Investigated xenon concentrations: 0, 3, 10, 50, 100 and 300 ppm(m).

For 50 ppm(m) and above, mass spectrometer data is available for the liquid phase.

Below 50 ppm(m) the experimental method was not yet mature.

Target c_{Xe} [ppm(m)]	**Measured c_{Xe} [ppm(m)]**
50	37.9 +/- 7.9
100	87.8 +/- 8.9
300	360 +/- 59

The measured, low Xe concentrations at 50 ppm(m) and 100 ppm(m) are due to loss of xenon from the gaseous phase during condensation.

Uncertainties dominated by 5% repeatability systematic of a vacuum gauge.

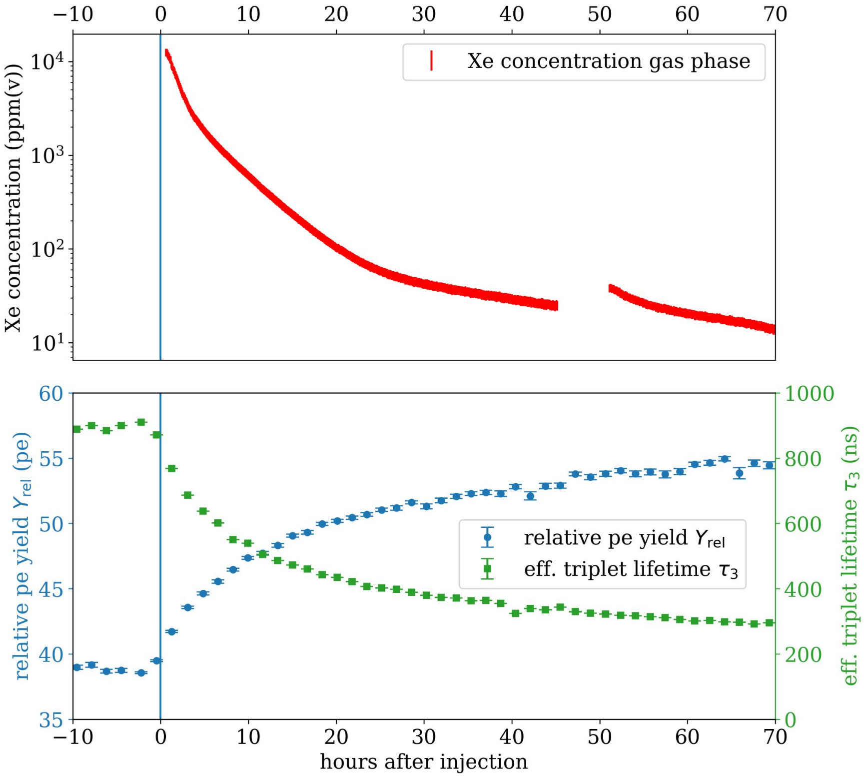
The properties of XeDLAr change immediately after Xe-Ar mixture injection

Decrease of Xe concentration in the gas phase ➔ transition into liquid phase.

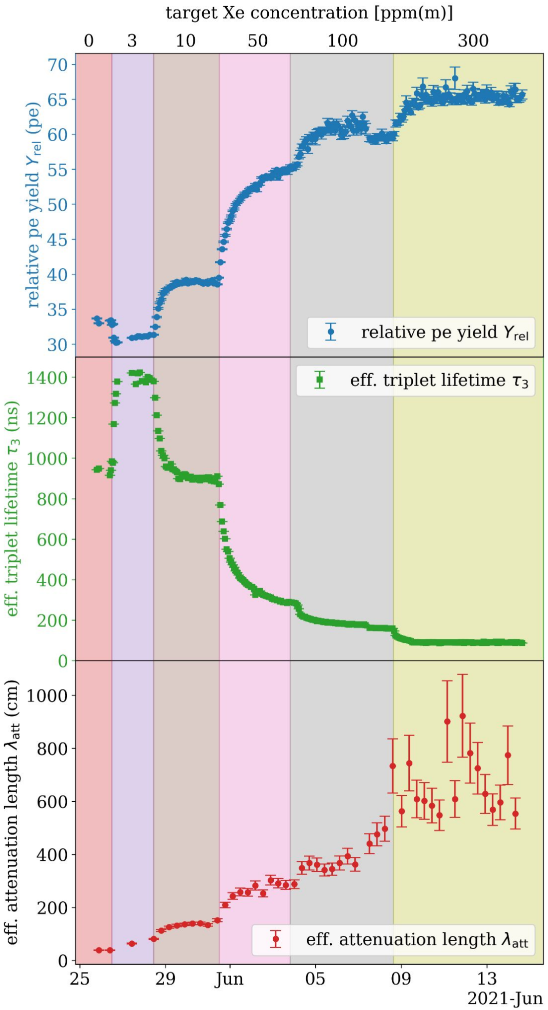
Interruption and jump due to intermittent measurement.

Xe entering liquid phase ➔ change in parameters

Increase of relative pe yield Y_{rel} and decrease of effective triplet lifetime τ_3



Initial Xe concentration in this plot: 10 ppm(m), concentration after injection: 50 ppm(m)

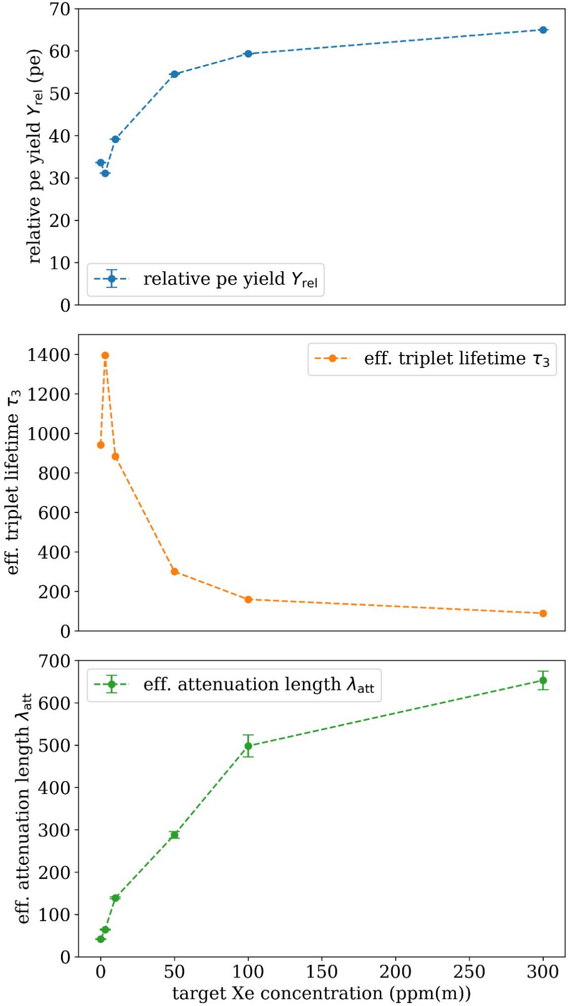


Key optical parameters as function of time for all Xe concentrations

To our knowledge, first time observation of decrease of photo-electron yield and increase of effective triplet lifetime at few ppm(m). Currently under study.

Stable scintillation performance of mixture over 6 days (300 ppm(m) time frame).

Key optical parameters as function of Xe concentrations



Relative **photo-electron yield** Y_{rel} approximately **doubles** (N.B. large part due to increased PDE of VUV4 SiPMs).

Effective triplet lifetime τ_3 **reduces** from ~1 µs **to ~100 ns**.

Effective attenuation length λ_{att} **increases** more than a factor of 10, **to over 6 meters** at 300 ppm(m).

The effects saturate at a few hundred ppm(m), as expected from [A. Neumeier et al., *EPL* 109 (Jan. 2015)].

Conclusion

Summary, Conclusion & Outlook

- Xenon doping can improve LAr for specific applications
- A characterization campaign on XeDLAr from 3 to 300 ppm(m) Xe concentration was presented
    - Y_{rel}, τ_3 and λ_{att} were measured simultaneously in a single setup
    - The actual Xe concentration was determined and confirmed successful doping
- Observation of strong effects!
- Stable optical properties at 300 ppm(m) were demonstrated for 6 days
- The measurements are part of an R&D program for LEGEND (minimize dead time, maximize instrumented LAr volume)