

Light-based triggering and reconstruction of Michel electrons in LArIAT

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ABSTRACT: The LArIAT Experiment aims to calibrate the liquid argon time projection chamber (LArTPC) using a beam of charged particles at the Fermilab Test Beam Facility. It is equipped with a novel scintillation light readout system using PMTs and custom SiPM preamplifier boards to detect light from reflector foils coated with wavelength-shifting TPB. A trigger on delayed secondary flashes of light captures events containing stopping cosmic muons together with the Michel electrons coming from their subsequent decay. This dedicated Michel trigger supplies an abundant sample of low-energy electrons throughout the detector's active volume, providing opportunities to study the combined calorimetric capabilities of the light system and the TPC. Preliminary results using scintillation light to study properties of the Michel electron sample are presented.

KEYWORDS: Noble liquid detectors (scintillation, ionization, double-phase); Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others); Time Projection Chambers (TPC); trigger concepts and systems.

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1. Introduction

Liquid argon time projection chambers (LArTPCs) are set to play a pivotal role in future neutrino physics research. Their scalability, sensitivity to low energies, and three-dimensional event reconstruction make them ideal for precision neutrino measurements and searches for rare processes like supernovae neutrinos and proton decay.

A dedicated calibration of this emerging technology is being carried out by the LArIAT (LArTPC In A Testbeam) Collaboration [1], which uses the refurbished ArgoNeuT detector [2] in a test beam at Fermilab to explore particle response, technical R&D, and physics topics relevant to future liquid argon detectors [3, 4, 5].

LArTPCs collect both drifted charge from ionization tracks and scintillation photons. While this scintillation light is traditionally used only for triggering and to provide absolute timing of non-beam events, it can also augment calorimetry and particle identification for sufficiently high collection efficiencies. In addition, the fast propagation of light signals compared to the TPC drift time helps in identifying topologies like delayed Michel electrons emerging from muon (μ) decays, critical for non-magnetic μ -sign determination [6]. Michel electrons also serve as a low-energy calibration source for the detector thanks to their known energy spectrum.

A light-based trigger on stopping cosmic muons that decay to Michel electrons in LArIAT is used to acquire a large sample of these events. An analysis of this sample is underway, including studies of μ^- lifetimes in LAr and the Michel photon spectrum for estimating our light yield.

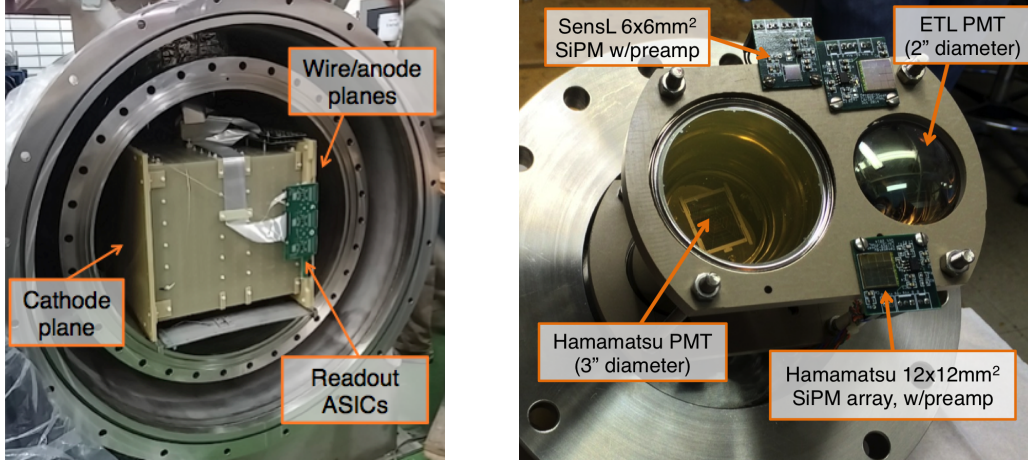


Figure 1. The LArIAT TPC inside the ArgoNeuT vacuum-insulated cryostat (left) and the light collection system mounted to the side flange (right).

2. The LArIAT Program

The goal of LArIAT is to study the response of a LArTPC to particles commonly found in the final-state of ~ 1 GeV neutrino interactions in existing and planned LAr experiments. It uses the ArgoNeuT cryostat and its refurbished TPC with an active volume of 170 liters ($47\text{ w} \times 40\text{ h} \times 90\text{ l cm}^3$) placed in a tunable tertiary beamline produced from a high-energy pion beam at the Fermilab Test Beam Facility (FTBF) [7]. The first physics run took place from May 31 to July 7 of 2015.

To accommodate a light collection system, which ArgoNeuT did not have, a side access flange on the cryostat was modified and instrumented. Two cryogenic, high-quantum efficiency PMTs and three silicon photomultipliers (SiPMs) on custom preamplifier boards are supported by a PEEK structure mounted to the flange (see Figure 1). The photosensitive windows of these devices are held 2-3 cm behind the wireplanes and peer into the active volume of the TPC.

LArIAT employs a dark-matter-like light collection method which is unique for LArTPCs used in neutrino physics. Reflective dielectric substrate foils coated in a thin layer of tetraphenyl butadiene (TPB) line the TPC's four field cage walls. Vacuum-ultraviolet (VUV) photons from LAr scintillation interact with the TPB, inducing re-emission of visible light that is reflected back into the active volume. This technique increases light collection efficiency and spatial uniformity relative to traditional light collection systems in LArTPCs where the wavelength-shifting occurs at transparent TPB-coated disks suspended in front of each PMT [3, 8].

3. Analysis of Michel electrons in LArIAT

3.1 Light-based triggering on cosmic muon Michel decays

As mentioned, scintillation's primary purpose in a LArTPC is triggering. For beam-based neutrino experiments, a flash of light observed in the TPC in coincidence with the beam gate signal is a sign that a neutrino interaction may have taken place, prompting readout of the wireplanes. Since the propagation time of photons (~ 10 s of ns) is several orders of magnitude shorter than that of ions

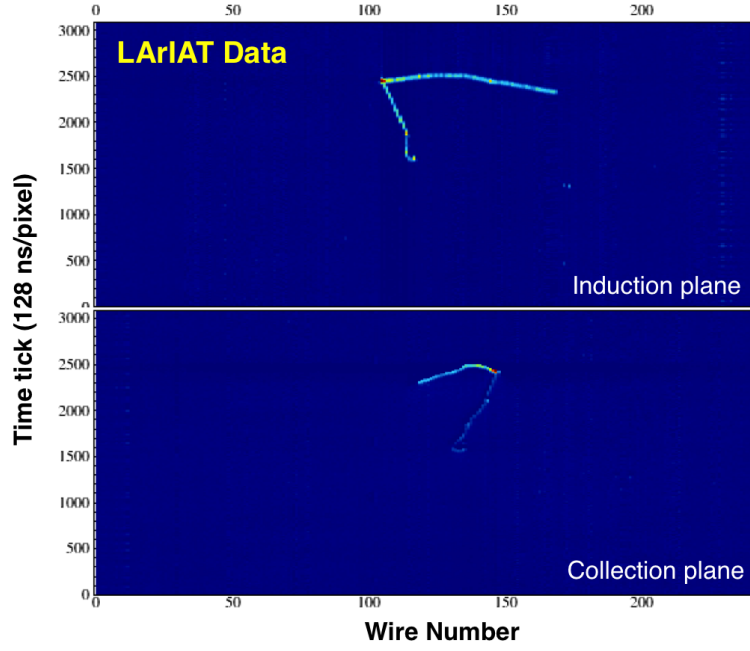


Figure 2. A stopping μ in LArIAT with its delayed decay electron, captured by the Michel trigger.

drifting along the electric field toward the wires (~ 100 s of μ s), light detection provides a reference time $t = 0$ for measuring the delayed arrival of charge onto the wires, enabling reconstruction of an event's distance from the wireplanes.

With sufficient time resolution, light signals also enable triggering on non-beam events like delayed Michel electrons from cosmic muons that stop and decay. To exploit this capability in LArIAT, a copy of each PMT's signal is amplified ($\times 10$), AC-coupled to pick off only fast rising signals, and then discriminated for use as input to subsequent trigger logic. An initial pulse opens a 7μ s gate delayed by 300 ns, and any secondary pulses registered in coincidence with this gate produces the Michel trigger. This trigger is enabled during LArIAT's cosmic readout window (when there is no beam) and collects about one event each second. Figure 2 shows an example event caught by the trigger.

The Michel trigger configuration described above was in effect for about 12 days of operation during Run I and 13,830 one-minute-long subruns¹ were processed so far, totaling 3.8 days of cumulative time the trigger was active. About 330k Michel triggers were registered, comprising $\sim 20\%$ legitimate μ decays among a background of low-luminosity accidental triggers.

For this analysis, only data from the 2-inch ETL PMT are used, which makes up 20% of the system's total projected light yield. Optical hits are reconstructed in each $28\text{-}\mu$ s waveform and used to study the time distribution of muon decays and the light produced by Michel electrons. Cuts on integrated prompt light and decay time help reject the non-Michel backgrounds mentioned above.

¹Subrun length is dictated by the accelerator supercycle duration, which includes ~ 4 seconds of beam delivered to FTBF each minute. Following each beam spill, 24 seconds of triggered cosmic data are collected.

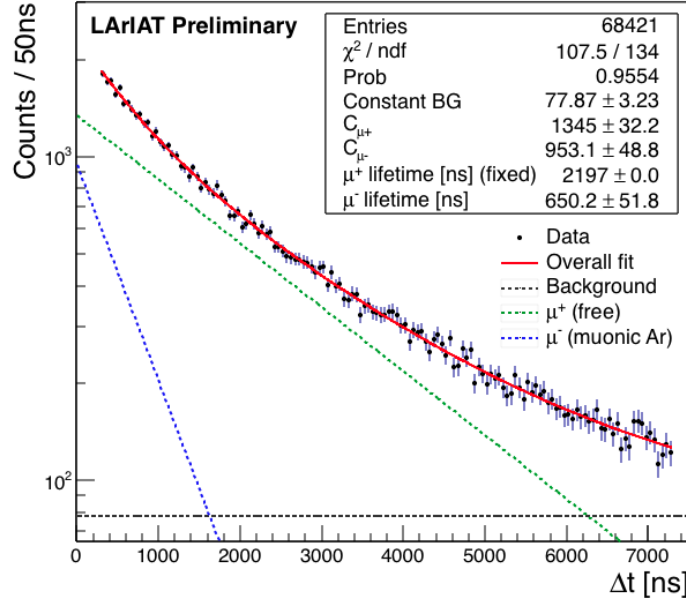


Figure 3. Preliminary time spectrum of observed electrons from μ decays. To improve sample purity, we require $PE_{100ns}^{Michel} > 25$, $PE_{100ns}^{\mu} < 150$. Error bars represent only statistical uncertainties.

3.2 Muon decay curves in liquid argon

When μ^+ come to a stop in LAr, they behave as if in vacuum and retain their inherent lifetime $\tau_{free} = 2.2 \mu s$, but stopping μ^- quickly become bound to Ar nuclei where they can undergo capture onto the nucleus with a lifetime τ_c [9]. The probability of nuclear capture thus competes with that of free decay, resulting in an effective total μ^- lifetime,

$$\tau_{\mu-} = \left(\frac{1}{\tau_c} + \frac{Q}{\tau_{free}} \right)^{-1} \quad (3.1)$$

where Q ($= 0.988$ for Ar [11]) is the Huff factor, a minor corrective term to account for the slight reduction in decay rate for bound μ^- [10].

In Figure 3, the decay times from Michel-triggered events are plotted. Cuts on the prompt photoelectrons integrated within the first 100 ns (PE_{100ns}) in the Michel-candidate and μ -candidate pulses are made to help ensure a pure sample of Michel electrons with minimal contamination from accidental triggers on scintillation light in the tail of luminous initial pulses due to cosmic-induced electromagnetic showers.

A fit is made to the data with the free μ^+ lifetime fixed to the global average of 2197 ns. The resulting μ^- lifetime is found to be $\tau_{\mu-} = 650 \pm 52$ ns, consistent with a recent measurement by Klinskih *et al.* [12] of $\tau_{\mu-} = 616.9 \pm 6.7$ ns. From Equation 4.1, our result translates to a capture lifetime $\tau_c = 918 \pm 109$ ns, in agreement with the Primakoff formula [11] prediction of 851 ns.

This result is preliminary. Studies are in progress to optimize cuts and identify potential sources of systematic bias.

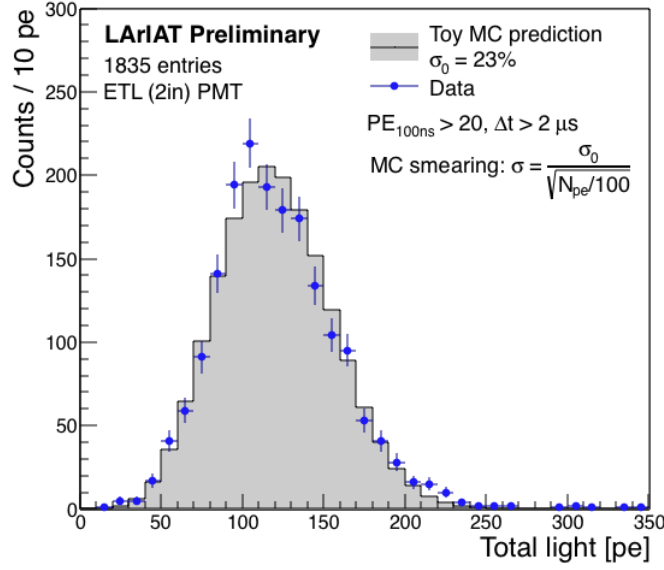


Figure 4. Photon spectrum from Michel-candidate events in LArIAT compared with the prediction from a simplified MC simulation of light propagation in LAr. Cuts on prompt light and location of μ -track endpoint (see text) are applied to both data and MC. Error bars represent only statistical uncertainties.

3.3 Light spectrum for Michel electrons

The spectrum of total light from integrated Michel-candidate pulses in a subset of our sample is presented in Figure 4. We require $PE_{100ns}^{Michel} > 20$ and $\Delta t > 2 \mu s$ to exclude low-light, non-Michel backgrounds and mitigate potential overlap of late light from the initial μ pulses.² We also require a reconstructed cosmic μ -like track with an endpoint within 15 cm of the TPC’s center to better guarantee full containment of the decay electrons.

Data are compared with a simplified toy Monte Carlo (MC) model of photon propagation in a LArIAT-like volume that includes Rayleigh scattering, wavelength-shifting, and reflections from TPB-coated foils. Global PMT efficiency for photon detection [13] averaged over the TPB emission spectrum is taken into account. Each event is approximated as a point source emanating a number of VUV photons (+/- Poisson fluctuations) determined by an energy drawn randomly from the known Michel spectrum multiplied by 24k γ/MeV , the LAr scintillation yield in LArIAT’s electric field strength of 500 V/cm. To simulate detector resolution [14], the “detected” number of photoelectrons in each event (N_{pe}) is varied randomly by a Gaussian whose width is calculated using a generic smearing function,

$$\sigma(\%) = \frac{\sigma_0}{\sqrt{N_{pe}/100}}. \quad (3.2)$$

The nominal resolution parameter σ_0 is tuned to 23% to match the shape of the data via χ^2 minimization. Drawing from the MC, the estimated light yield for the ETL PMT is about 2.8 pe/MeV

²It’s also worth noting the cut on Δt excludes $\sim 95\%$ of bound μ^- decays due to their shortened effective lifetime, so we are sensitive mainly to the “free” μ^+ Michel energy spectrum, which doesn’t suffer from smearing due to Doppler shift as is the case for Michel electrons from μ^- decaying in orbit around a nucleus [9].

in the TPC’s central region.

Further analysis is underway to identify specific contributions to the observed smearing compared to prediction, including detector resolution effects, electron recombination, and inadequacies in the simulation. For example, the toy MC generates point-source events when in reality Michel electrons are extended objects ranging $\sim 10\text{-}15$ cm – a discrepancy likely contributing to the smearing in ways not modeled by our generalized approximation.

4. Conclusion

A fast light collection system is a powerful tool in identifying Michel electrons from stopping μ decays in a LArTPC, a capability future LAr neutrino detectors will require in order to select statistically enriched samples of muon-neutrino and -antineutrino events. Michel electrons are also a “standard candle” for energy calibration. In addition, their decay times let us probe the μ^- -Ar nuclear capture rate, a quantity not yet well-measured.

Preliminary results using a sample of triggered Michel electrons in LArIAT to study μ decay curves and their scintillation spectrum have been presented. These analyses are evolving day-by-day, laying groundwork for future studies on beam- μ sign determination, ionization density of low-energy electron tracks, and calorimetry enhancement using detected light in combination with charge collected on the TPC wires.

Acknowledgments

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References

- [1] F. Cavanna, M. Kordosky, J. Raaf, B. Rebel on behalf of the LArIAT Collaboration, *LArIAT: Liquid Argon In A Testbeam*, [physics.ins-det/1406.5560].
- [2] ArgoNeuT Collaboration (C. Anderson et al.), *The ArgoNeuT Detector in the NuMI Low-Energy beam line at Fermilab*, 2012 *JINST* **7** P10019 [physics.ins-det/1205.6747].
- [3] MicroBooNE Collaboration, *The MicroBooNE Technical Design Report*, microboone.fnal.gov.
- [4] R. Acciarri et al., *A Proposal for a Three Detector Short-Baseline Neutrino Oscillation Program in the Fermilab Booster Neutrino Beam*, [physics.ins-det/1503.01520].
- [5] LBNE Collaboration (C. Adams et al.), *The Long-Baseline Neutrino Experiment: Exploring Fundamental Symmetries of the Universe*, FERMILAB-PUB-14-022 [hep-ex/1307.7335].
- [6] M. Sorel, *Expected performance of an ideal liquid argon neutrino detector with enhanced sensitivity to scintillation light*, 2014 *JINST* **9** P10002 [physics.ins-det/1405.0848].
- [7] FTBF (Fermilab Test Beam Facility), <http://ftbf.fnal.gov>.

- [8] A. Szelc, *The LArIAT light readout system*, in proceedings of *Light Detection In Noble Elements (LIDINE)*, May 29-31, 2013, Fermi National Accelerator Laboratory, 2013 *JINST* **8** C09011.
- [9] A. Czarnecki et al., *Michel decay spectrum for a muon bound to a nucleus*, [hep-ph/1406.3575].
- [10] D.F. Measday, *The nuclear physics of muon capture*, Physics Reports 354 (2001) 234-409.
- [11] T. Suzuki, D. F. Measday, *Total nuclear capture rates for negative muons*, *Phys. Rev. C* **35** (1987) 2212.
- [12] A. Klinskih, V. Egorov, M. Shirchenko, D. Zinatulina, *Muon Capture in Ar: The Muon Lifetime and Yields of Cl Isotopes*, Bulletin of the Russian Academy of Sciences: Physics, 2008, Vol 72, No. 6, pp. 735-736.
- [13] R. Acciarri et al., *Demonstration and Comparison of Operation of Photomultiplier Tubes at Liquid Argon Temperature*, [physics.ins-det/1108.5584]
- [14] K.A. Olive et al. (PDG), *Particle detectors for accelerators*, Chin. Phys. **C38**, 090001 (2014) (<http://pdg.lbl.gov>)