Abstract

Measurement of total hadronic differential cross sections in the LArIAT experiment

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2018

Abstract goes here. Limit 750 words.

Measurement of total hadronic differential cross sections in the LArIAT experiment

A Dissertation
Presented to the Faculty of the Graduate School
of
Yale University
in Candidacy for the Degree of
Doctor of Philosophy

by
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Date you'll receive your degree

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Acknowledgements

A lot of people are awesome, especially you, since you probably agreed to read this when it was a draft.

Chapter 0

Liquid Argon Detectors at the Intensity Frontier

In the next few years, LArTPC experiments – such as the Short-Baseline Neutrino program (SBN) and DUNE – will be major players in the intensity frontier field.

0.1 Liquid Argon Time Projection Chambers at the Intensity Frontier

0.1.1 Time Projection Chamber

0.1.2 Ionization Detectors with Noble Liquids

0.1.3 LArTPC: Principles of Operation

To the bare bones, a LArTPC is a bulk of liquid argon sandwiched in a flat capacitor, equipped with a light collection system. A uniform electric field of the order of 500 V/cm is maintained constant between the faces of the capacitor. The anode is sensitive to ionization charge and it is usually made of two or more planes segmented

into multiple parallel sense wires; different geometries for the anode segmentation are under study [2]. Two processes occurs when an ionizing radiation traverses the argon active volume: the argon ionize and scintillates along the charge particle's trajectory. Details on the production and detection of ionization charge and scintillation light are provided in 0.1.5 and 0.1.5 respectively. The optical part of the detector collects the argon scintillation light in matters of nanoseconds. This flash of light determines the start time of an event in the chamber, t_0. The uniform electric field drifts the electrons from ionization towards the anode plane where the anode sense wires see either an induced current by the drifting charge (on induction planes) or the injection of the ionization charge (collection plane) [94]. The arrival time of the charge on the anode sense wires is used to measure the position of the original ionizing radiation in the drift direction. In fact, since the constant electric field implies that the drift velocity is also constant in the chamber, the position of the original ionization is simply given by the multiplication of the drift velocity by the drift time, where we define as "drift time" the difference between t_0 and the charge arrival time on the wire planes.

Combining the spatial information on the different wire planes results in the mapping of a bi-dimensional projection of the interaction pattern in the medium [1].

0.1.4   Liquid Argon Ionization Charge Detection

Electron Life Time & purity

LArTPCs use hermetically sealed and leak-checked vessels to abate the leakage and diffusion of contaminants into the system. The liquid argon filling of the volume occurs after the vessel is evacuated or purged with gaseous argon [205] to reduce

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1. The ionized argon also drifts, in the opposite directions compared to the electrons and with a much longer drift time, given that the drift time is proportional to the particle mass. Ionized argon is collected on the cathode which is not instrumented, so it is not used to infer information about the interactions in the chamber.

remaining gases in the volume. Even so, the construction of a pure tank of argon is unviable, as several sources of impurity remain. In particular, impurities can come from the raw argon supply, the argon filtration system and from the outgassing from internal surfaces. Outgassing is a continuous diffusive process producing contaminants, especially water, even after the vessel is sealed, particularly from materials in the ullage region[2]. Since research-grade argon comes from the industrial distillation of air, the impurities with the highest concentration are nitrogen, oxygen and water, generally maintained under the 1 part per million level by the vendor. Even so, a higher level of purity is necessary to achieve a free electron life time usable in meter scale detectors. Thus, argon is constantly filtered in the cryogenic system, which reduce the oxygen and water contamination to less than 100 parts per trillion. The filtration system depends on the size and drift distance of the experiment and, for experiments on several meters scale, it includes an argon recirculation system.

Space Charge Effect

Recombination Effect

0.1.5   Liquid Argon Scintillation Light

Liquid argon emits scintillation light at the passage of charged particles. LArTPCs leverage this property to determine when the ionization charge begins to drift towards the anode plane.

Scintillation Process

Scintillation light in argon peaks in the ultraviolet at a 128 nm, shown in comparison to Xenon and Kypton in Figure [183]. The light yield collected by the optical detector

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2. . While the liquid argon low temperature reduces outgassing in the liquid, this process remains significant for absorptive material (such as plastic) above the surface of the liquid phase

depends on the argon purity, the electric field, the dE/dx and particle type, averaging at the tens of thousands of photons per MeV. The de-excitation of Rydberg dimers in the argon is responsible for the scintillation light. Rydberg dimers exist in two states: singlets and a triplets. The time constant for the singlet radiative decay is 6 ns, resulting in a prompt component for the scintillation light. The decay of the triplet is delayed by intersystem crossing, producing a slow component with a time constant of ~ 1500 ns. "Self-trapped exciton luminescence" and "recombination luminescence" are the two processes responsible for the creation of the Rydberg dimers. In the first process, a charged particle excites an argon atom which becomes self-trapped in the surrounding bulk of argon, forming a dimer; the dimer is in the singlet state 65% of the times and in the triplet state 35% of the times. In case of recombination luminescence, the charged particle transfers enough energy to ionize the argon. The argon ion forms a charged argon dimer state, which quickly recombines with the thermalized free electron cloud. Excimer states are produced in the recombination, roughly half in the singlet and half in the triplet state. The light yield dependency on the electric field, on the dE/dx and particle type derives from the role of free charge in the recombination luminescence process. The spacial separation between the argon ions and the free electron cloud depends on the electric field. On one hand, a strong electric field diminishes the recombination probability, leading to a smaller light yield; on the other, it increases the free charge drifting towards the anode plane. Hence, the amount of measurable charge and light anti-correlates as a function of the electric field. Ionizing particles in the argon modify the local density of both free electrons and ions depending on their dE/dx. Since the recombination rate is proportional to the square of the local ionization density, highly ionizing particles boost recombination and the subsequent light yield compared to MIPs. The possibility to leverage this dependency for pulseshape-based particle identification has been shown in [186], [187].

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Effects Modifying the Light Yield

The production mechanism through emission from bound excimer states implies that argon is transparent to its own scintillation light. In fact, the photons emitted from these metastable states are not energetic enough to re-excite the argon bulk, greatly suppressing absorption mechanisms. In a LArTPC however, several processes modify the light yield in between the location where light is produced and the optical detector. In a hypothetical pure tank of argon, Rayleigh scattering would be the most important processes modifying the light yield. Rayleigh scattering changes the path of light propagation in argon, prolonging the time between light production and detection. The scattering length has been measured to be 66 cm [191] , shorter than the theoretical prediction of ~ 90 cm [190]; this value is short enough to be relevant for the current size of LArTPCs detectors. In fact, Rayleigh scattering worsen the resolution on t_0, the start time for charge drifting, and alters the light directionality, complicating the matching between light and charge coming from the same object in case of multiple charged particles in the detector.

Traces of impurities in argon such as oxygen, water and nitrogen also affect the light yield, mainly via absorption and quenching mechanisms. Absorption occurs as the interaction of a 128 nm photon directly with the impurity dissolved in the liquid argon. Differently, quenching occurs as the interaction of an argon excimer and an impurity, where the excimer transfers its excitation to the impurity and dissociates non-radiatively. Given this mechanism, it is evident how quenching is both a function of the impurity concentrations and the excimer lifetime. Since the triplet states live much longer than the singlet states, quenching occurs mainly on triplet states, affecting primarily the slow component of the light, reducing the scintillation yield and a shortening of the scintillation time constants.

The stringent constraints for the electron life time limit the presence of oxygen and water to such a low level that both absorption and quenching on these impurity

is not expected to be significant [210]. Contrarily, the nitrogen level is not bound by the electron life time constraints – nitrogen being an inert gas, expensive to filter. Thus, nitrogen is often present at the level provided by the vendor. The effects of nitrogen on argon scintillation light have been studied in the WArP R&D program and at several test stands. The quenching process induced by nitrogen in liquid Ar has been measured to be proportional to the nitrogen concentration, with a rate constant of ~ 0.11 μs^{-1} ppm^{-1}; appreciable decreasing in lifetime and relative amplitude of the slow component have been shown for contamination as high as a few ppm of nitrogen [1]. For a nitrogen concentration of 2 parts per million, typical of the current generation of LArTPC, the attenuation length due to nitrogen has been measured to be $\sim$30 meters [4].

Wavelength Shifting of LAr Scintillation Light

Liquid argon scintillation light is invisible for most optical detectors deployed in LArTPC, such as cryogenic PMTs and SiPMs, since a wavelength of 128 nm is generally too short to be absorbed from most in glasses, polymers and semiconductor materials. Research on prototype SiPMs absorbing directly VUV light and their deployment in noble gasses experiment is ongoing but not mature [5]. Thus, experiments need to shift the wavelength of scintillation light to be able to detect it. Albeit deployed in different ways, neutrinos and dark matter experiments commonly use 1,1,4,4-tetraphenyl-butadiene (TPB) to shift the scintillation light. TPB, whose chemical structure is shown in figure , absorbs the vacuum ultraviolet (VUV) light and emits in the visible at $\sim$ 425 nm [231], with a ratio of visible photon emitted per VUV photon absorbed of $\sim$1.2:1 [3].

Neutrino experiments typically coat their optical detector system evaporating a layer of TPB either directly on the PMTs glass surface or on acrylic plates mounted in front of the PMTs cite microboone; this technique allows the fast detection light

coming directly from the neutrino interaction. Dark matter experiments typically evaporate TPB on reflective foils mounted on the inside walls of the sensitive volume and detect the light after it has been reflected; this technique leads to a higher and more uniform light yield, though scattering effects for both the visible and VUV light augment the propagation time and hinder directionality informationsome DM detector . In order to take advantage of both these techniques, hybrid systems with PMT coating and foils are being considered for the next generation of large neutrino detectors cite SBND?.

0.1.6 Signal processing

0.2 The SBN Program: Neutrino Interaction and Detection

0.3 DUNE: Rare Decay Searches

The key elements for a rare decay experiment are: massive active volume, long exposure, high identification efficiency and low background. Figure 1 shows the current best experimental limits on nucleon decay lifetime over branching ratio (dots). Historically, the dominant technology used in these searches has been water Cherenkov detectors: all the best experimental limits on every decay mode are indeed set by Super-Kamiokande [**?**, **?**]. It is particularly important to notice that the kaon energy for the proton decay mode $p \to K^+ \bar{\nu}$ is under Cherenkov threshold. Super-Kamiokande set the limit on the lifetime for the $p \to K^+ \bar{\nu}$ mode by relying exclusively on photons from nuclear de-excitation. For this reason, an attractive alternative approach to identifying nucleon decay is the use of a Liquid Argon Time Projection Chamber (LArTPC).

LArTPCs can complement nucleon decay searches in modes where water Cherenkov detectors are less sensitive, especially $p \to K^+ \bar{\nu}$. According to [?], DUNE will have an active volume large enough, have sufficient shielding from the surface, and will run for lengths of time sufficient to compete with Hyper-K, opening up the opportunity for the discovery of nucleon decay.
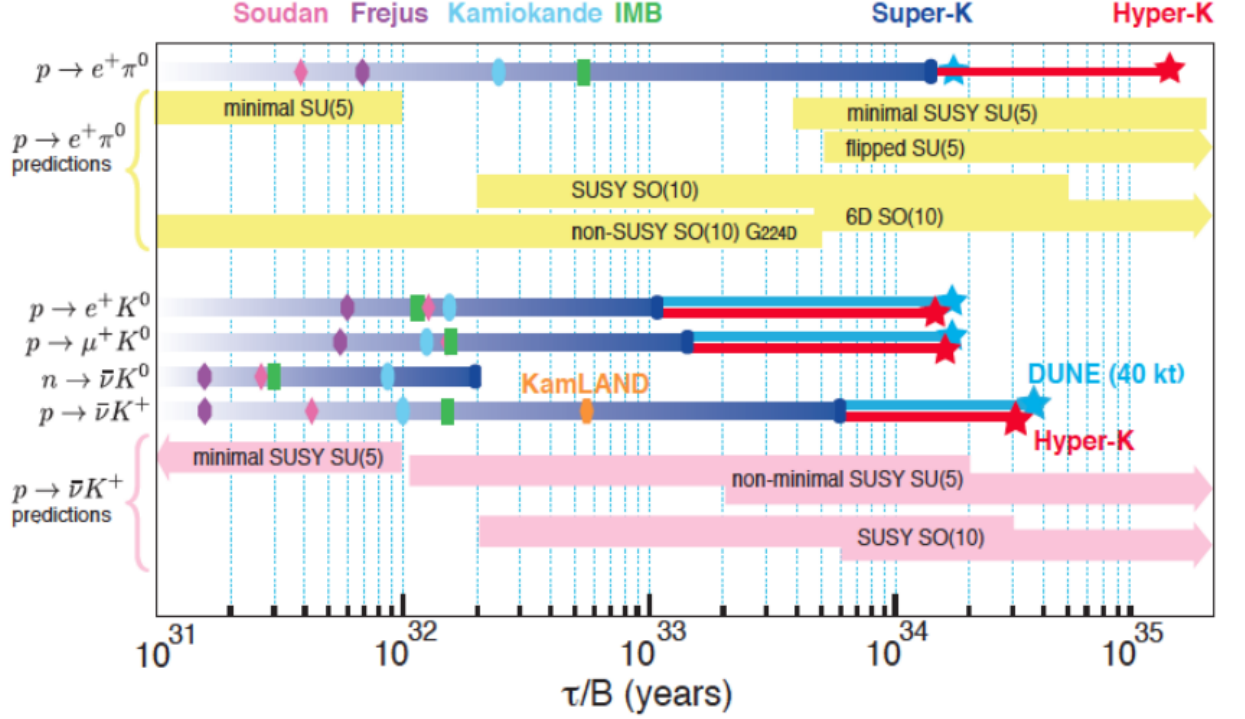

Figure 1: Proton decay lifetime limits from passed and future experiments.

0.4 Enabling the next generation of discoveries: LArIAT

LArIAT, a small Liquid Argon Time Projection Chamber (LArTPC) in a test beam, is designed to perform an extensive physics campaign centered on charged particle cross section measurements while characterizing the detector performance for future LArTPCs. LArTPC represents one of the most advanced experimental technologies
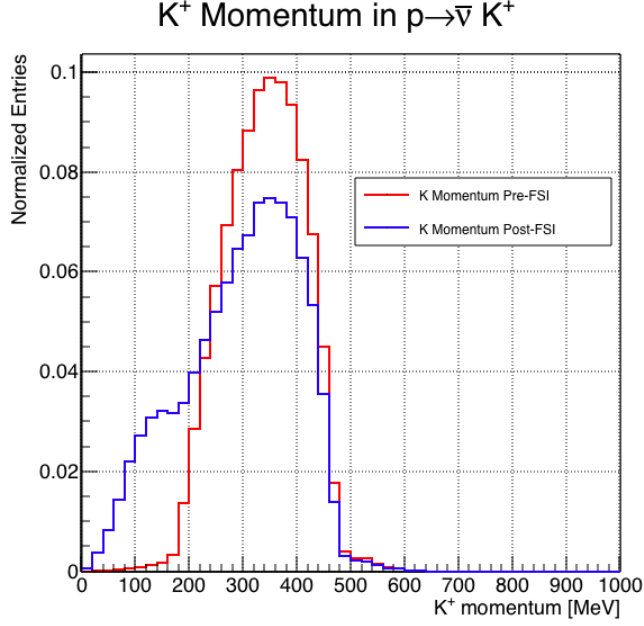
Figure 2: Momentum of the kaon outgoing a proton decay event as simulated by the Genie 2.8.10 event generator in argon. The red line represent the kaon momentum distribution before undergoing the simulated final state interaction inside the argon nucleus, while the blue line represents the momentum distribution after FSI.

for physics at the Intensity Frontier due to its full 3D-imaging, excellent particle identification and precise calorimetric energy reconstruction. This complex technology however needs a thorough calibration and dedicated measurements of some key quantities to achieve the precision required for the next generation of discoveries at the Intensity Frontier which LArIAT can provide.

The LArIAT LArTPC is deployed in a dedicated calibration test beamline at Fermilab. We use the LArIAT beamline to characterize the charge particles before they enter the TPC: the particle type and initial momentum is known from beamline information. The precise calorimetric energy reconstruction of the LArTPC technology enables the measurement of the total differential cross section for tagged hadrons. The Pion-Nucleus and Kaon-Nucleus total hadronic interaction cross section have never been measured before in argon and they are a fundamental step to shed light on light meson interaction in nuclei. Additionally, these measures provides a key in-

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put to neutrino physics and proton decay studies in future LArTPC experiments like SBN and DUNE. add paragraph on all wonderful things lariat can do... some event displays would be nice!

ADD genie proton decay kaon distribution and lariat beamline overlaied The signature of a proton decay event in the "LAr golden mode" is the presence of a single kaon of about 400 MeV in the detector.

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