PROCEEDINGS OF SCIENCE

The LArIAT experiment and the charged pion total interaction cross section results on liquid argon

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We present here a study of the charged pion-nucleus total interaction cross section in liquid argon performed at the Liquid Argon In A Testbeam (LArIAT) experiment. The LArIAT beam line instrumentation is used to identify the pion candidates and measure their momentum prior to them entering the Liquid Argon TimeProjection Chamber (LArTPC). The calorimetric energy reconstruction of the LArTPC technology enables the measurement of the total differential cross section for pion interactions. The pion-nucleus total interaction cross section has never been measured before on argon and it is a crucial step in shedding light on meson interaction in heavy nuclei. Additionally, since charged pions are produced in noticeable numbers in neutrino-nucleus interactions for neutrino energies of a few GeV, this measurement is a fundamental input to both the Short-Baseline and Long- Baseline neutrino programs.

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1. Introduction:

The Liquid Argon Time Projection Chamber (LArTPC) with its excellent particle identification capability, 3D imaging and precise calorimetric energy reconstruction represents the most advanced experimental technology for particle physics, mainly neutrino physics. At present the neutrino programme in US is mainly based on the use of liquid argon TPC technology. There are ongoing effort to build TPC's of various scales for Fermilab short baseline and long baseline programme to understand the properties of neutrinos. It is very crucial to have a detailed understanding about the neutrino-neucleon interactions in argon to design for the precision neutrino oscillation experiment. Pion interactions play a critical role in understanding systematic uncertainties in neutrino experiments conducted at the GeV energy scale. Charged pions are produced in noticeable numbers in neutrino interactions with nuclei for neutrino energies of a few GeV. When a neutrino interacts with argon nucleus, the reconstruction of neutrino energy largely depends on the measurement of the pion energy. The interaction cross section of the pion strongly affects the possibility of detecting and measuring the pions. Since the predicted pion cross section for interactions with nuclei is large, especially near the Δ resonance energy region, pion cross-sections can strongly impact the neutrino oscillation measurement. Thus, the precise measurement of the pi-Ar interaction cross-section is important to future liquid argon neutrino experiments, in particular, current (MicroBooNE) and future (SBN and DUNE) neutrino oscillation experiments.

The Liquid Argon In A Testbeam (LArIAT) experiment is part of the international US neutrino program[1, 2] in the Fermilab Test Beam Facility (FTBF) at Fermilab. The aim of the experiment is to characterize LArTPC performance in the energy range relevant to both the Short-Baseline (MicroBooNE, SBND, ICARUS) and Long-Baseline (DUNE) neutrino experiments. The LArIAT TPC is exposed to a tertiary charged particle beam comprised of pions ($\pi^{\pm}$), muons ($\mu^{\pm}$), protons (p), kaons ($k^{\pm}$) and electrons (e) in the range 200 MeV to 2 GeV. One of the top physics goals of the LArIAT experiment is to measure charged hadron-Ar total interaction cross-section and with exclusive channel, experimental determination of the e to γ-initiated shower separation, kaon identification and interaction topology, charge sign determination of $\mu^{\pm}$ in the absence of magnetic field, study of nuclear effects in argon and Geant4 validation for hadrons interaction models. Regarding the detector R&D goal, LArIAT is going to study ionization and scintillation light system and optimization of LArTPC fully-automated event reconstruction and particle ID techniques.

The plan of the article is as follows. We give a brief overview of the LArIAT experiment in sec 2. We present the first measurement of π-Ar total interaction cross section in sec 3. We end with conclusion in sec 4.

2. Overview of LArIAT Experiment:

The LArIAT experiment uses a vacuum-jacketed and super-insulated cryostat with a capacity of 550 liters, which was originally designed for the ArgoNeuT [3] experiment, and also uses a refurbished LArTPC, which contains 170 liters of active volume placed in a test beam at the Fermilab Test Beam Facility (FTBF). Figure 1 shows a schematic overview of the LArIAT experiment. The layout of the LArIAT experiment can be divided into two parts: beam related components and liquid argon related components.

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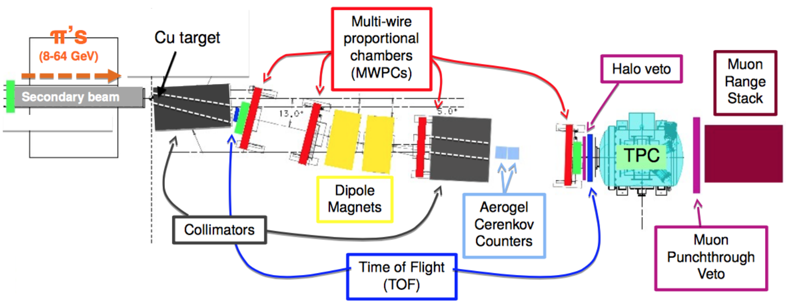

Figure 1: LArIAT beamline detector and TPC

2.1 Tertiary Beam Line

A primary beam of 120 GeV protons impinges onto an aluminum target to create a secondary beam composed primarily of pions; the energy of the secondary beam can be magnetically tuned between 8 and 80 GeV. This beam then impinges on a copper target to create the tertiary beam seen by LArIAT, which is correspondingly tunable in the range 0.2-1.5 GeV.

2.2 Beamline Detectors

The Beam related components consist of : a TOF detector, multi-wire proportional chambers (MWPC), Cherenkov detectors, bending magnets and veto paddles, which are aligned along the LArIAT beamline for the selection of momentum window and for offline particle mass identification.

2.3 LArTPC

The liquid argon part consists of the LArTPC, the liquid argon scintillation light detectors, the LArTPC read-out cold electronics,the liquid argon cryostat, and the cryogenic system connected to the cryostat for liquid argon cooling and purification.

The LArIAT TPC has an active volume of 90 cm x 47 cm x 40 cm (length x width x height) with the drift length of 47 cm. The electric field is uniform over the entire TPC drift volume with a nominal value of 500 V/cm from the cathode to the anode. There are three planes of wires (Ground, Induction and Collection). Induction and Collection plane wires are instrumented with dedicated cold electronics to collect the ionization electrons created during a charged particle passage through the argon. Each of the two planes consists of 240 wires oriented at $\pm 60^\circ$ relative to the beam axis, with 4 mm anode wire spacing. Signals on the wires are processed and analyzed through LArSoft, a dedicated framework for LArTPC event reconstruction.

The LArIAT light collection system consists of an array of two high quantum efficiency cryogenic photomultiplier tubes (PMT) and three Silicon PhotoMultiplier Detectors (SiPM), which are deployed in liquid argon and mounted behind the wire planes of the TPC.

3. Measurement of π^--Ar total interaction cross-section :

Pion interactions with matter have been a central topic in particle physics for decades. Over the past forty years, an extensive set of pion scattering experiments have been conducted at various meson factories. One of the main goals of the LArIAT experiment is the first experimental measurement of charged pion cross section on Ar in the (0.2 - 2.0) GeV energy range.

Using the granularity of the LArTPC, we have considered wire to wire spacing as the series of "thin-slab" targets in our analysis. Considering a particle impinging on a slab of target material, the probability of the particle's passing through the slab without interaction can be expressed as

$$P_{surviving} = e^{-\sigma nz} = 1 - P_{interacting} \tag{3.1}$$

Probability of interaction $P_{interacting}$ can be estimated as the ratio of the number of particles interacting in the slab ($N_{interacting}$) to the number of particles impinging on the slab ($N_{incident}$)

$$P_{interacting} = \frac{N_{interacting}}{N_{incident}} = 1 - e^{-\sigma nz} \tag{3.2}$$

In case of the "thin-slab" approximation, where z is small and the energy E of the particle entering the slab is approximately equal to its energy exiting the slab, this relation can be expanded to give the following expression for the cross-section

$$\sigma(E) = \frac{1}{nz}\frac{N_{interacting(E)}}{N_{incident}(E)} \tag{3.3}$$

A schematic picture of "thin-slab" approach used by LArIAT is shown in Fig2

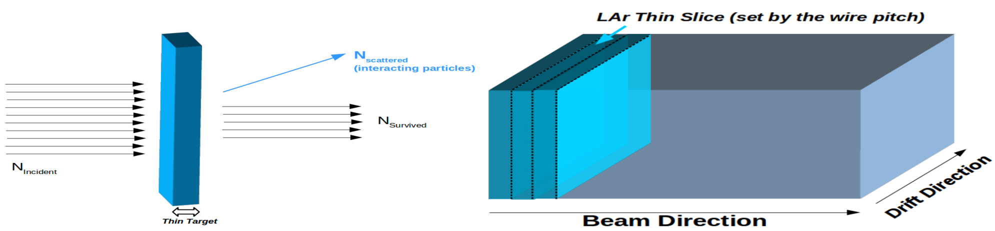

Figure 2: Schematic representation of the "thin slab" approach used by for the analysis

3.1 Pion track selection

In this analysis, the measurement of "total" pion cross-section includes multiple processes: elastic and inelastic scattering, charge exchange, pion absorption and pion production. The backgrounds to these processes can be classed in two groups: nonpion backgrounds (e.g. interactions from the other particles of the beam), and pions backgrounds from other processes (pion decay and

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Particle species	π^-	e^-	γ	μ^-	K^-
Beam composition before cuts	48.4%	40.9%	8.5%	2.2%	0.035%
Percentage passing selection	74.5%	3.6%	0.9%	90.0%	70.6%

Table 1: A table of the beam composition in terms of particle species

capture). The latter group is topologically very difficult to distinguish from some signal processes. For this reason, the analysis uses background subtraction to account for pion backgrounds; the selection cuts aim only to remove non-pion backgrounds.
Selection has been done using the following method
1. Separate $\mu/\pi/e$ from protons (p) and kaons (K) using the time of flight detector information.
2. Unique matching between extrapolated track from the wire chamber track and the TPC track.
3. The identified TPC track is then examined and vetoed if it displays the profile of an electromagnetic shower (to remove electrons from the selected sample).

After the selection cut, we define histograms of incident pion in which an incident pion is observed (i.e. the pion track is present) and the interacting histogram in which an incident pion interacts (i.e. the pion track terminates, in a vertex or otherwise). These histograms are binned in kinetic energy, with the energy in the nth slab traversed by the pion being calculated as follows:

$$E_n = (\sqrt{p_{reco}^2 - m_\pi^2} - m_\pi) - E_{loss} - \sum_{i=0}^{n-1} (\frac{dE}{dX}_i) \times z_i \tag{3.4}$$

where p_{reco} is the reconstructed momentum obtained from the wire chambers, E_{loss} is a constant adjustment for energy loss in the dead material directly upstream of the TPC (e.g. the front face of the cryostat), and z_i is the slab depth.
By dividing the interacting histogram by the incident histogram, we recover $\sigma(E)$ as defined Equation 3.3.

3.2 Result

This analysis uses data collected during LArIAT's initial run, which lasted from May 2015 to July 2015. Applying the selection to the LArIAT Run 1 negative charge data resulted in 2,290 events being selected from an initial sample of 32,064. Beam composition before and after cuts is shown in table1.

Analysing these events with the method described above we get the cross-section as shown in figure3. This is the world's first measurement of a π^- cross-section on argon. The agreement between data and simulation appears good except in the first energy bin, in which deficiencies in the Monte Carlo simulation are suspected. Full simulation of the LArIAT beamline is under development, and may resolve this discrepancy. The systematic uncertainties shown at this point are also preliminary as mentioned in table 2. At this time the uncertainty from pion decay and capture backgrounds remains unaddressed.The assessment of all systematics is still ongoing; as well as improving our analysis techniques, we also expect to make significant gains from bringing

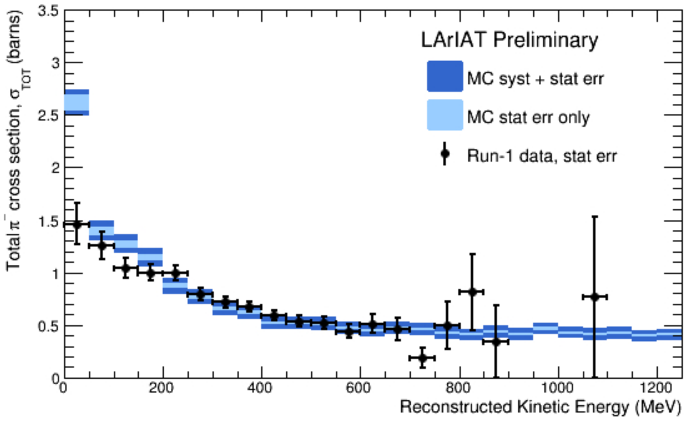

Figure 3: First measured total π^- -argon cross-section (LArIAT Preliminary[4]).

Uncertainty on the $\frac{dE}{dX}$ calibration	5%
Uncertainty on the energy loss from dead material upstream of the TPC	3%
Uncertainty on the contamination from through-going muons	3%
Uncertainty on the reconstructed momentum from the wire chambers	3%

Table 2: Systematic uncertainties applied for the analysis

in the currently unused auxiliary systems (i.e. the aerogel Cherenkov detectors and the muon range stack) to better parameterise the muon backgrounds.

4. Conclusion

LArIAT has done the first measurement of the π^--Ar cross-section using the RunI data sample and is compared with the expectation from Monte Carlo. This is an important measurement for liquid argon neutrino detectors, and the first of many such measurements LArIAT is positioned to make. Further studies to remove intrinsic background such as π^- capture, π^- decay are currently in progress. We are also in a process of using more beamline detectors to improve the sample purity. More analyses are forthcoming from the LArIAT collaboration using RunII data which took place between February and August 2016.

References

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[4] Asaadi J on behalf of the LArIAT Collab., LArIAT First Total π-Ar Cross Section Measurement, FNAL Joint Experimental-Theoretical Physics Seminar, 2016.