Nuclear Inst. and Methods in Physics Research, A ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Advances in liquid argon detectors

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ARTICLE INFO

Keywords:
Particle detectors
TPC
Calorimeters
Neutrinos
Imaging

ABSTRACT

Liquid noble gas detectors have driven particle physics research and technology in many sub-fields for many years. Recently their impact as a target and detector medium has been applied to neutrino physics research. As new results and new questions appear in neutrino physics, new detector technologies in general have been explored to keep pace with the requirement of higher statistics, higher precision experiments. Liquid argon time projection chamber devices have emerged as the detector of choice for accelerator based, massive, precision, neutrino detection. In particular, in the last decade, results from test stands and experiments have driven the development of this technology towards large scales. From the MicroBooNE experiment, SBND, and ICARUS on the Short Baseline program at Fermilab to the scale required for the huge DUNE experiment, these detectors are enabling precision neutrino physics for neutrino oscillations. And if history is our guide, as a new detection technology, liquid argon time projection chambers will likely teach us unexpected things.

In this paper we present the general features of liquid argon time projection chambers for neutrino physics, a brief history of the technology and details of recent research and development that is driving the design of the detectors under construction. Finally, some comments on future R&D envisioned and the impact of this work on other fields is described.

Contents

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https://doi.org/10.1016/j.nima.2018.07.010
Received 20 March 2018; Received in revised form 3 July 2018; Accepted 3 July 2018
Available online xxxx

1. The liquid argon time projection chamber

Liquid argon time projection chambers (LAr TPCs) combine precision topological information with total absorption calorimetry to produce photographic-like 3D images particle interactions. The LAr TPCs presently or soon to be taking data are of the so-called single phase class of detectors where ionization charge is read-out directly in the liquid, without charge multiplication. It is the advances in single phase design that are described in detail here. Double phase LAr TPCs, with charge extraction and amplification in the gas above the liquid, are also in the design and prototyping phase although have yet to be used in a physics experiment. These and the status of R&D for these is described in later sections.

The millimeter scale precision imaging and total absorption calorimetry, combined with the ability to scale these detectors to very large scales make them ideal detectors for neutrino physics in a wide range of energies (~ 0.01 to 10 GeV). As a result, LAr TPCs have become the detectors of choice for large scale precision oscillation and cross section neutrino experiments, specifically those in the short and long baseline oscillation program based at Fermilab. R&D on these detectors in the last decade have enabled a progression of test stands and of experiments at the ~100–1000 ton scale culminating in the 70 kton LBL DUNE experiment. This body of work builds on decades of pioneering development bringing LAr TPCs from concept to realization. A detailed review of this work can be found here [1] and in references therein. In this paper, we focus on more recent developments towards the realization of DUNE. What we have learned through recent prototyping and test stands and through the progression of LAr TPC experiments leading to this, is described here (see Fig. 1 for single phase schematic).

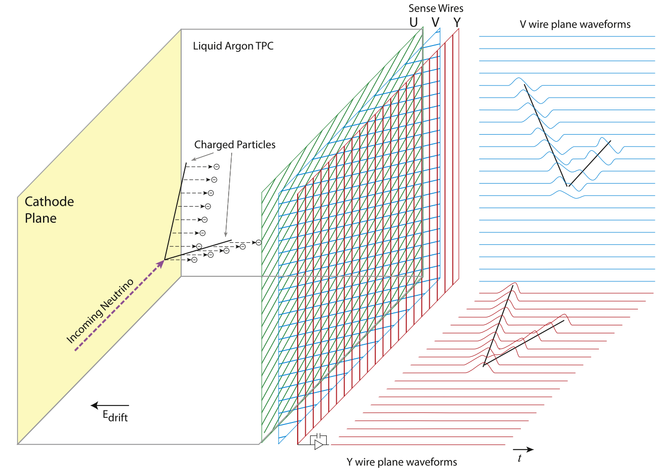

Fig. 1. Schematic of drifting charge in an LAr TPC.

2. Experience with LAr TPCs

Already in the ’70s the use of particle physics sampling-calorimeters employing cryogenic noble liquids combined was recognized as a viable option for the realization of large apparatus at accelerator experiments [2]. Following then the pioneering effort of the ICARUS program, most of the distinctive features of the LAr TPC technique were assessed with a series of seminal studies and R&D projects [3–6]. The ICARUS T600 detector realized in Italy [7] might be considered the culmination of this early effort. The device, which is still the largest LAr TPC ever built with its 600 tons of purified liquid argon, was firstly used in 2001 for a series of engineering runs on surface that provided several interesting technology and physics results with exposure to cosmic rays [8]. In a second phase, the detector located deep underground was exposed from 2010–2013 to the CERN to Gran Sasso CNGS neutrino beam [9].

On a much smaller scale, the USA ArgoNeuT (Argon Neutrino Test) experiment operated a 0.25 ton LAr TPC from 2009–2010 in the NuMI neutrino beam at Fermilab [10]. The experiment performed a series of accurate studies on neutrino interactions in the few-GeV energy range, among which the first neutrino cross section measurements on an argon target [11–16].

The ArgoNeuT detector layout was later modified and refurbished and is now the running LArIAT (Liquid Argon in a Testbeam) experiment [17] on the test beam line at Fermilab. Here measurements of known particle species at defined energies are being made towards characterization of events in LAr TPCs [18], including large statistics studies of Kaon interactions on argon target as well as reconstruction of first ever collected antiproton annihilations — both relevant for matter stability searches with the DUNE large underground LAr TPC. LArIAT is now serving as a test stand for future developments of LAr TPC design, such as the PixLAr experiment, where the pixel readout developed in the framework of the ArgonCube project is being tested with charged particle beams (see below), and the SBND program for qualification of new cold electronics solutions.

More R&D activities were carried out with prototypes of increasing size and complexity in Europe, notably in Bern [19–21], and at CERN by the ETHZ group [22–26], as well as in the US at FERMILAB [27–30]. In particular, quite an extensive work was conducted in the framework of the LBNE [31] and LBNO [32,33] long baseline proposals, the first in US, based on the single phase approach, the second in Europe exploiting the double phase readout technology. The two projects eventually generated the DUNE project, based on the use of both charge readout techniques.

A major milestone was represented by the construction and operation of MicroBooNE (or Micro Booster Neutrino Experiment), the first experiment to run on in the Short Baseline Neutrino (SBN) program based in the US, at Fermilab [34]. MicroBooNE’s physics goal is to study short baseline neutrino oscillations, in particular to address the nature of the LSND/MiniBooNE data [35,36], possibly pointing to the existence of additional (sterile) neutrino states in nature. MicroBooNE has been specifically designed to clarify if the observed excess of low energy electromagnetic-like events observed in the MiniBooNE experiment [36] is actually due to electrons, and hence to a potential signal of new physics, or to single photons. This goal well illustrates the power of this technology for large scale neutrino oscillation physics in general. While large Cerenkov imaging detectors such as the Super-Kamiokande Detector [37] have driven many results in accelerator neutrino physics thus far, these detectors cannot differentiate electrons from photons and cannot achieve precision topology at the level of LAr TPCs. These capabilities translate beyond oscillation physics to enable precision neutrino interaction cross section measurements, and searches for astro-particle and exotic physics phenomena. Fig. 2, showing one of the first neutrino interactions in the MicroBooNE detector, well illustrates LAr TPCs fine-grained topological resolution and calorimetry for neutrino physics.

MicroBooNE combines its physics program with R&D studies for novel LAr TPC detectors. The detector [39] design follows a “classical” implementation of the LAr TPC technique. A large cylindrical cryostat holding ~170 tons of LAr houses the rectangular 2.3 m (height) × 2.6 m (drift) × 10.4 m (length) TPC with an active volume of ~85 tons. A −70 kV field drifts the ionization electrons over 2.3 m from the cathode plane to three wire-chamber readout planes. Cold front end electronics immersed in LAr readout the charge signals from the wires and an array of 32 8-inch photomultiplier tubes facing into the TPC volume from behind the wire chamber planes record scintillation light produced in argon.

Two more LAr TPC detectors, SBND and ICARUS presently under construction and assembly, will complete the Short Baseline Neutrino (SBN) program [40] at Fermilab. SBND with about 110 t active LAr mass near the Booster Neutrino Beam target and ICARUS with its 430

Please cite this article in press as: F. Cavanna, et al., Advances in liquid argon detectors, Nuclear Inst. and Methods in Physics Research, A (2018), https://doi.org/10.1016/j.nima.2018.07.010.