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THE PAST, PRESENT AND FUTURE OF LAr-TPC NEUTRINO EXPERIMENTS*

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Liquid Argon Time Projection Chambers (LAr-TPCs) is an exciting class of detectors designed for registration of very rare events, such as neutrino interactions or nucleon decay. They offer a good detection efficiency, excellent background rejection, bubble chamber quality images, very good particle identification and calorimetric reconstruction of particle's deposited energy. These capabilities made LAr-TPCs a very promising choice for neutrino physics experiments. In this paper, an overview of past, present and future neutrino experiments based on LAr-TPC technology is presented.

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1. Introduction

The idea of a Liquid Argon Time Projection Chamber (LAr-TPC) was first proposed by Rubbia in 1977 [1] as a powerful detection technique providing a three-dimensional (3D) imaging of any ionizing event. In this type of detectors, liquid argon serves also as the neutrino target. Neutrinos passing through LAr interact with argon atoms and produce, among others, ionization particles and light. Charged particles propagate in an electric field through liquid argon and leave a path of ionization electrons. The ionization electrons induce current in the anodes wire planes, and finally their charge is collected. The measurements of: (1) the wires signals, and (2) ionization electrons drift time exploiting scintillation light prompt signal and electrons velocity provide all the information needed for the 3D reconstruction of an event. The usage of argon seems to be optimal, since it is dense (larger neutrino cross sections), inert (ionization electrons can be drifted through it), and relatively cheap (for example, much cheaper than

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liquid xenon). However, the LAr must be kept extremely pure, allowing the ionization electrons to drift across the TPC without significant attenuation, as was recently shown by ICARUS Collaboration [3]. In addition, LAr-TPC provide a very good discrimination between electron and photon interactions, what is of great importance for neutrino experiments.

2. Working principle of LAr-TPC

The ICARUS Collaboration pioneered the LAr-TPCs and demonstrated their feasibility for long term underground operation, therefore, a short description of the working principle of this detection technique will be based on their T600 detector. It is the largest LAr-TPC ever built, with four TPC chambers and cryogenic system containing about 760 tons of LAr. The ICARUS T600 detector is composed of two identical T300 half-modules with internal dimensions of 3.6 m (width) $\times$ 3.9 m (height) $\times$ 19.6 m (length). Each half-module houses two TPCs with centrally placed cathode, the electric field shaping system and photomultipliers for the LAr scintillation light detection. Two induction and one collection parallel planes of anode wires (53248 wires in total), oriented at 60 degrees with respect to each other, are placed along the walls opposite to the cathode. With the nominal voltage of 75 kV, the drift time of ionizing electron is about 1 ms over the maximum electron drift length of 1.5 m. The drifting electrons induce a signal in the first two induction planes, whereas their charge is collected in the last collection plane. Thanks to the 3 mm pitch of anode wires and signal time sampling of 400 ns, a resolution of about 1 mm^3 in the three-dimensional reconstruction of an ionizing event has been achieved. Particle identification is obtained by exploiting the dE/dx *versus* range measurement. This allows for complete event reconstruction. Due to the absence of magnetic field, muons momenta are measured with the use of multiple scattering method exploiting the Kalman filter technique [4]. The working principle of the ICARUS T600 LAr-TPC is schematically presented in Fig. 1, whereas the

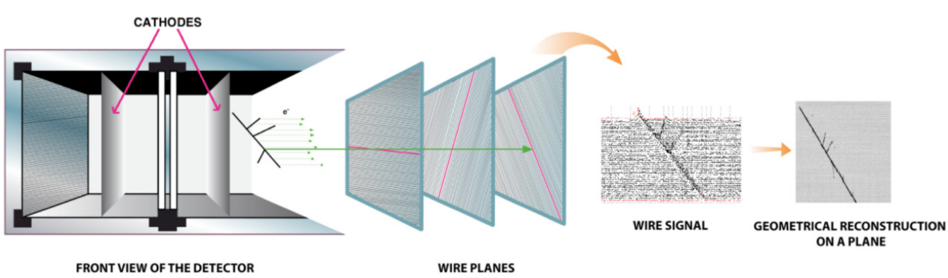

Fig. 1. Illustration of the ICARUS T600 working principle: a charged particle ionization path in LAr and its geometrical reconstruction [6].

detailed description of the detector can be found in [5]. The ICARUS T600 detector was taking data in INFN Gran Sasso underground National Laboratory (LNGS) in 2010–2013, proving the maturity of this detection technique and paving the way for the next generation LAr-TPCs.

3. Selected past, present and future LAr-TPC experiments

In Table I, a selection of past, present and planned experiments exploiting LAr-TPC detection technique is listed, together with the used/planned neutrino beam location and energy. Details of some of them are presented below.

TABLE I

Table 1. Summary of past, present and future LAr-TPC neutrino experiment. Updated table of [2].

Experiment	LAr mass	Physics goals	Baseline [km]	E_ν [GeV]	Detector location	Current status
ArgoNeuT	175 l	R&D, cross sections, accelerator ν	1	$\sim$ 0.1–10	Fermilab (NuMI beam)	Completed data under analysis
LArIAT	550 l	Study of char. particle interaction in LAr	—	0.2–1.2	Fermilab (dedicated tertiary char. beam line)	Running since 2015
MicroBooNE	170 t 89 t active	R&D, sterile ν, short baseline	0.470	$\sim$ 0.1–3	Fermilab (BNB)	Starting 2015
CAPTAIN	2 t — prototype 10 t	ν interaction		$<$ 0.05, 1.5–5	LANL Fermilab (NuMI)	Letter of Intent 2014
SBND (LAr1-ND)	220 t 112 t active	Sterile ν, short baseline	0.110	$\sim$ 0.800	Fermilab (BNB)	Design phase Start $\sim$ 2017
ICARUS	760 t 476 t active	R&D, Sterile ν, Atm. ν, Long baseline, Short baseline	732 0.600	$\sim$ 5–25	Gran Sasso (CNGS), Fermilab (BNB)	2010–2013 Start $\sim$ 2016
MODULAr	5000 t	Long baseline	730	$\sim$ 5–25	Gran Sasso	Proposed
GLADE	5000 t	Long baseline	810	$\sim$ 0.5–2	Fermilab (NuMI beam)	Letter of Intent
DUNE (LBNE)	34000 t	Long baseline	1300	$\sim$ 0.5–5	Fermilab, SURF	Planned $\sim$ 2021
LAGUNA\ LBNO	40000 t	Long baseline	2300	$\sim$ few	Europe	R&D, future

ArgoNeuT was a project at Fermilab to expose a small-scale (175 l) detector to the NuMI neutrino beam. Data taking was concluded in March 2010 whereas the analysis is ongoing. Detector collected thousands of neutrino and anti-neutrino events between 0.1 and 10 GeV. Among other issues, the experiment measured the cross section of the neutrino and anti-neutrino Charged Current Quasi-Elastic (CCQE) interaction on Ar target, and analyzed the vertex activity associated with such events [7].

LArIAT: Liquid Argon In A Testbeam program aims at accurate measurements of known particle species, and to characterize LAr-TPC performance in the range of energies relevant to the upcoming short- and long-baseline experiments for neutrino physics and for proton decay searches. To achieve this, the LArIAT uses dedicated tertiary charged beam line at Fermilab [8]. The beam line producing low momenta, 0.2–2.0 GeV particles extracted from a high energy pion beam. Knowledge from this research will be used in construction of very large-scale (multi kilotons) future LAr detectors. The first physics run was competed from April 30^{th} to July 8^{th}, 2015.

One of the closest programs which will come into force in the neutrino physics is a Short-Baseline Neutrino (SBN) program of three LAr-TPC detectors located along the Booster Neutrino Beam (BNB) at Fermilab. It mainly aims to answer definitively the "sterile neutrino puzzle", *i.e.* resolve a class of experimental anomalies in neutrino physics, and to perform the most sensitive search for sterile neutrinos at eV mass-scale through both, appearance and disappearance oscillation channels. The experiment will consist of three detectors: SBND (112 tons of LAr active mass; in conceptual design phase), MicroBooNE (170 t; 89 tons active mass) and ICARUS T600 (760 t; 476 t active mass) installed at 100, 470 and 600 meters from target, respectively. In absence of anomalies, signals from all three detectors should be a copy of each other [9].

SBND: Short-Baseline Near Detector (LAr-TPC), formerly known as LAr1-ND. It will be the nearest-to-target detector, with TPC dimensions of 4 m long, 4 m high and 4 m wide, with 2 m drift distance. SBND uses three wire planes, with 3 mm wire pitch. It includes also UV laser based calibration system, light collection system for detection of scintillation light and external cosmic ray tagging system [10].

MicroBooNE: Micro Booster Neutrino experiment is a large LAr-TPC detector located along the Booster neutrino beam line, where it will collect data for a total of 6.6×10^{20} POT, in neutrino running mode. In July 2015, the detector for the first time was filled with liquid argon and a month later first UV laser tracks have been seen in TPC. The detector dimensions are 2.5 m $\times$ 2.3 m $\times$ 10.2 m, with 2.5 m maximum drift distance. MicroBooNE holds, the same as SBND and ICARUS T600, 3 planes of wires with 3 mm wire spacing, with 8256 wires total and 30 PMT's which provide the absolute event time and triggering information [11].

DUNE: Although ICARUS experiment with long-base completed operation, the idea of Long-Base Neutrino Experiments (LBNE) has not been abandoned. As a part of LBNE it will be to design and execute a high capable Long-Base Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE; formerly — before January 2015 — known as Long Base Neutrino Experiment (LBNE)). DUNE will be a dual-site experiment focused around three central components: a high intensity neutrino source and two detectors spaced apart about 1300 km. First detector serves as near detector just downstream of the ν source, located in Fermilab, and second one as far massive LAr-TPC detector deep underground at the Sanford Underground Research Facility (SURF; site of the former Homestake Mine in Lead, South Dakota). The distance (baseline) 1300 km delivers optimal sensitivity for neutrino charge-parity symmetry violation and mass ordering effects [12].

CAPTAIN: Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrino detector. CAPTAIN employs two detectors: a primary detector with approximately 10 tons of LAr designed for physics measurements and a prototype detector with 2 tons of LAr for configuration testing. It is deployed in a portable cryostat designed to accommodate as large a TPC as possible (with considerations for shape) allowing for optical access to the liquid argon volume for laser calibration. The physics programs includes neutrino interaction measurements in low (< 0.05 GeV) energy range, at stopped pion sources for supernova neutrino studies, and medium energy range (1.5–5 GeV) at Fermilab's NuMI beam [13].

4. Conclusions

The capabilities presented above make the LAr-TPC detectors perfect tools for investigation of various aspects of very rare events physics. An increase of LAr volume (ktons range) might be important in investigation of CP violation in the leptonic sector, neutrino mass hierarchy measurement and baryon number violating processes. However, substantial increase of volume may cause problems with LAr purification and stability of electric field. Despite of the so far success of the LAr-TPC, a worldwide efforts are taken or planned to develop this detection technique. Should one think of increasing the size of a single phase (tens of kton) huge LAr container or about a modular structure with several separate vessels, each of a few kton, like it was proposed for the MODULAr detector [14]? Another solution is a double phase LAr-TPC detector in which ionizing electrons are extracted from the liquid phase, and their signal is amplified in the gaseous phase, as proposed by the LAGUNA/LBNE Collaboration [15]. In any case, the LAr-TPC detectors future should be very exciting.

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