IL NUOVO CIMENTO **47 C** (2024) 359
DOI 10.1393/ncc/i2024-24359-5

Colloquia: MAYORANA 2023

ICARUS short base-line neutrino oscillation search at Fermilab

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received 6 August 2024

Summary. — ICARUS liquid argon TPC detector was moved to Fermilab after a successful tree-years physics run at the INFN LNGS underground Laboratory. The detector is taking data exposed to Booster and NuMI off-axis neutrino beams to address, within the SBN experimental program, the longstanding puzzle of sterile neutrinos from the observed anomalies at accelerators, nuclear reactors and radioactive sources.

1. – Introduction

Neutrino oscillations represent today a major experimental evidence of a physics beyond the Standard Model of the fundamental interactions. Being some properties of neutrinos still unknown, they are naturally one of the main portals towards new physics. Despite the well-established description of three neutrino flavours mixing, several anomalies have been collected so far by the pioneering LSND experiment and in measurements of the (anti) neutrino flux from nuclear reactors and from intense radioactive sources [1] hinting to the existence of additional sterile neutrino states. Furthermore, an excess of electron-like events has been observed at the Neutrino Booster Beam accelerator (BNB) by MiniBooNE [2] at Fermilab. A large part of the oscillation parameters has been already investigated by the ICARUS and OPERA experiments at LNGS with the CNGS neutrino beam constraining the allowed oscillation parameters to $\Delta m^2 \sim 1$ eV^2 [3].

More recently, the Neutrino-4 experiment at Dimitrovgrad SM-3 reactor reported evidence of neutrino disappearance using a liquid scintillator detector moved from 6.4 to 11.9 m distance from the reactor core, observing a characteristic L/E modulation in the 1-3 m/MeV range [4]. The combined Neutrino-4 data with the flux measurements of GALLEX, Sage and BEST radioactive sources would result in 5.8 σ C.L. oscillation signal with $\Delta m^2 \sim 7.3$ eV^2 and $\sin(2\theta) \sim 0.36$. A 2.7 eV mass neutrinos could also be an obvious Dark Matter candidate if the high density of relic neutrinos is considered.

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2. – The SBN neutrino program at Fermilab

The FNAL Short-Baseline Neutrino (SBN) program is conducting a sensitive search for new physics beyond the Standard Model, recording millions of charged and neutral current neutrino interactions at the GeV energy to address ~ 1 eV mass-scale sterile neutrinos search and definitely clarify the long-standing puzzle of neutrino anomalies.

Three large Liquid Argon Projection Chambers (LAr-TPC) detectors are installed at shallow depth exposed to the ~ 0.8 GeV BNB neutrinos at different distances from the target: ICARUS-T600 (467 t active mass), MicroBooNE (89 t active mass) and SBND (82 t active mass) at 600 m, 470 m and 110 m respectively [5]. This multiple LAr-TPC configuration should provide a world-leading sterile neutrino search experiment with high sensitivity for $\nu_\mu \rightarrow \nu_e$ appearance signals by comparing neutrino interactions at the different distances from target. The initial BNB neutrino beam will be characterized by the SBND near detector, greatly reducing systematic uncertainties in the search for oscillation signals at the far sites.

The significant cancellation of neutrino flux and cross sections uncertainties in the near to far detectors' flux comparison combined with the huge event statistics will allow for a sensitive oscillation search in the ν_μ disappearance channel. Furthermore, the simultaneous analysis of ν_e and ν_μ CC events will allow to disentangle the effects of ν_μ disappearance and ν_e appearance at $\Delta m^2 \sim 1$ eV^2 mass-splitting.

The successful ICARUS-T600 detector installation, LAr filling, and commissioning phase, allowed for the start of the physics data taking in June 2022. SBND detector, in final stages of installation, will be ready for data-taking in early 2024, while MicroBooNE completed his run on 2020 addressing the anomalies observed by MiniBooNE [6].

ICARUS physics will also include the study of neutrino cross-sections and interaction topologies at energies of interest to the long baseline research program with the multi-kt DUNE LAr-TPC detector [7]. In addition to the BNB beam, ICARUS is also receiving higher-energy neutrinos at 6° off-axis from the Main Injector (NuMI) collecting a significant event statistics in the $0 \div 3$ GeV energy range with a $\sim 5\%$ ν_e enriched component from the dominant three body-decay of K produced at the target. Furthermore NuMI events will allows for a rich Beyond Standard Model search program including Higgs portal scalar, neutrino trident, heavy neutral leptons and light Dark Matter search.

3. – ICARUS as far detector for the SBN program

The ICARUS-T600 cryogenic detector is the first large-scale LAr-TPC containing 760 t of ultra-pure LAr, initially proposed by C. Rubbia [8] as an alternative to the Cherenkov detector to accurately identify any ionizing particle in complex topology neutrino events.

The detector consists of two identical modules each one housing two TPCs (~ 54000 wires in total) composed by three parallel readout wire planes, 3 mm pitch, placed 3 mm apart from each other and oriented at 0 and $\pm 60^0$ with respect to the longitudinal direction [9]. A semi-transparent central cathode produces a 500 V/cm uniform electric field to drift the ionization electrons, generated by the charged particles, to the TPC wire planes facing the drift volume. Through appropriate voltage biasing, the first two Induction 1, 2 planes provide a nondestructive measurement of charge, which is fully collected by the last Collection plane. The prompt VUV scintillation light emitted by ionizing particles traversing the liquid argon is detected by photo-multiplier tubes (PMT) coated with TetraPhenyl Butadiene (TPB) wavelength shifter, installed behind the TPC wires. This light detection system is used for the event trigger and for the absolute timestamp of recorded events, reconstructing the interaction position along the drift coordinate.

ICARUS took data at the underground LNGS exposed to CNGS neutrino beam concluding a successful 3 years long run in 2013 with several physics and technical achievements, demonstrating the effectiveness of the single-phase LAr-TPC technique and thus paving the way to future large LAr-TPC detectors:

- The liquid argon was kept at an exceptionally high purity level ($\leq$ 50 ppt of O_2) to avoid the absorption of ionization electrons by residual electron-negative impurities. The corresponding free electron lifetime $\tau \geq 7$ ms initially resulted in a few percent signal reduction in the 1.5 m drift path covered in $\sim$ 1 ms [10], reaching then $\tau \geq 15$ ms with an improved cryogenic system [11].

- The calorimetric measurement of the particle energy is performed by integration of electron charge signals in the last wires' plane. The detector demonstrated a remarkable e/γ separation and particle identification exploiting the measurement of dE/dx ionization *versus* range. The momentum of escaping muons has been measured via multiple Coulomb scattering with $\sim$ 15% resolution in the 1÷5 GeV/c range, depending on the muon momentum and track length [12]. The capabilities to reconstruct the interaction vertex, identify and measure e.m. showers generated by primary electrons and accurate measurement of the invariant mass of photon pairs for the π^0 recognition, allowed the strong rejection of the NC background in the study of the $\nu_\mu \to \nu_e$ transitions.

- ICARUS performed a sensitive search for the LSND anomaly, providing the limit on $\nu_\mu \to \nu_e$ oscillation probability $P \leq 3.86\ 10^{-3}$ at 90 % C.L. [3], and constrained the oscillation parameters to a narrow region with $\Delta m^2 \sim 1$ eV^2 to be definitely investigated.

Subsequently ICARUS-T600 detector underwent an intensive overhauling at CERN in view of its deployment at Fermilab, introducing several technological developments while maintaining the already achieved performance. A more detailed description can be found elsewhere [13]. The TPC chambers have been installed in new cold vessels surrounded by a new purely passive thermal insulation. Both liquid and gas argon are continuously recirculated and filtered by new cryogenics and purification systems. The light detection system has been upgraded with 360 new 8" PMTs TPB coated installed behind the TPC wires. The PMT gain equalization and timing is performed with the single electron response and by flashing them with 405 nm laser pulses via an optical fiber system. This will allow more precise event timing, exploiting also the Booster bunched beam structure ($\sim$ 2 ns FWHM bunches every 19 ns) to reject out-of-bunch cosmic events.

The TPCs are equipped with an upgraded "warm" read-out electronics which includes a front-end based on analog low noise - charge sensitive pre-amplifier, 400 ns synchronous sampling, with $\sim$ 1.3 μs shaping time to match the electron transit time in the wire plane spacing with a signal to noise ratio $\geq$ 10.

The detector is exposed to the abundant flux of cosmic rays that would overwhelm the TPC during the 1 ms window required to drift the ionization electrons to the TPC wires. To cope with this challenging condition, the detector is protected by a 2.85 m concrete overburden reducing cosmic rays by a factor 2, complemented by a segmented Cosmic Ray Tagger (CRT) system composed by plastic scintillation counters surrounding the TPCs, to tag the remaining incoming charged particles. The ICARUS DAQ relies on the

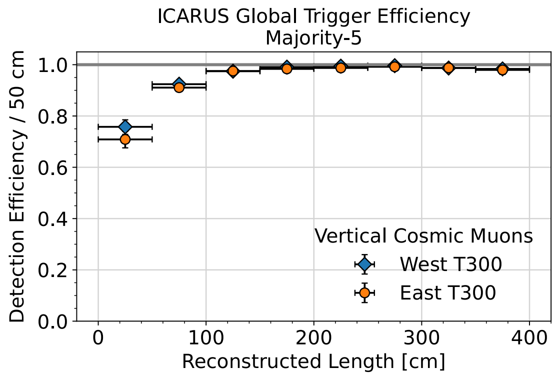

Fig. 1. – Preliminary trigger recognition efficiency as measured with almost vertical crossing cosmic muons as a function of the track length (1 m muon track $\simeq$ 200 MeV deposited energy).

architecture already deployed at LNGS, *i.e.*, a waveform recording of TPC/PMT/CRT signals triggered by the scintillation light signal in coincidence with the proton beam extraction, with ICARUS synchronized to the beam radio-frequency by an atomic clock locked to a GPS and the signals distributed by the White Rabbit system. The PMT signals are processed by fast digitizers to produce a majority trigger logic.

4. – ICARUS initial operation

The installation of the overburden completed the detector assembly and commissioning, marking the beginning of ICARUS physics data taking (further details in [13]).

Beam events are collected requiring at least 5 fired PMT pairs (PMTs in OR logic) inside one of the 6 m longitudinal detector slices, which includes 30 PMTs on the left TPC and 30 PMTs on the right TPC. A more stringent multiplicity of 9 PMT pairs is applied to record PMT signals within a 2 ms time window around the trigger time to recognize and tag cosmic rays crossing the detector during the $\sim$ 1 ms drift time. The recognition efficiency was measured selecting almost vertical cosmic muons by matching TPC tracks to CRT signals as a function of the deposited energy. An almost uniform event recognition capability $\geq$ 90% for $E_{DEP} \geq$ 100 MeV was reached (fig. 1).

In the first physics Run-1 from June 9^{th} to July 10^{th} 2022 ICARUS collected 4.1 10^{19} (6.8 10^{19}) pot for BNB (NuMI) with an efficiency exceeding 93%.Several tuning activities were performed during the summer beam shutdown to improve the detector performance. ICARUS was brought back to physics data taking by the end of 2022 and has successfully concluded Run-2 on July 2023, collecting 2.1 10^{20} (2.8 10^{20}) pot for BNB (NuMI).

The free electron lifetime has been monitored by measuring the charge signal attenuation along cosmic muon tracks. A stable value of $\tau \sim$ 4.5 ms was measured in the East cryostat during the whole commissioning phase and physics runs, whereas τ increased from 3 ms to 8.5 ms in the West one by regenerating the LAr cryogenic filters. The filter regeneration in the East cryostat is planned at the start of Run-3.

While SBND is preparing to join the SBN program, ICARUS-standalone phase is addressed to test the Neutrino-4 oscillation claim [4] in the same baseline over energy range (1 $\div$ 3 m/MeV), but collecting 100 times more energetic events. The Neutrino-4 oscillation-like signal can be initially addressed by ICARUS at the BNB studying the ν_μ

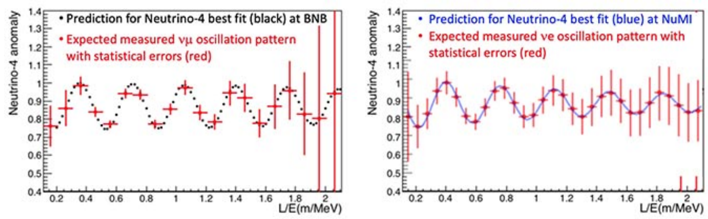

Fig. 2. – Expected survival oscillation probability in ICARUS according to Neutrino-4 hint, $\Delta m^2 = 7.5$ eV^2, $\sin^2 2\theta = 0.26$: contained Q.E. ν_μ CC at BNB ($\sim 8500 \sim 8.4\ 10^{19}$ p.o.t., left) and of ν_e CC at NuMI off-axis ($\sim 5200 \sim 9\ 10^{20}$ pot right).

disappearance channel channel as a function of the neutrino energy, to be followed by an analogous search exploiting the NuMI beam enriched ν_e-signal (see fig. 2).

For these purposes the studies on the collected BNB neutrinos are focused on CC quasi-elastic interactions looking for contained events with a single muon and at least a proton in the final state. The analysis of the quasi-elastic ν_e CC interactions from NuMI off-axis beam will benefit from the unique ICARUS electron *vs.* photon discrimination by the evolution of dE/dx signal along the trajectory of the shower. The genuine ν_e Q.E. CC is identified by a single primary mip electron producing a E.M. shower in association with at least a proton from the interaction neutrino vertex. The collected data is being analysed to better understand the detector performance and to develop a robust strategy to automatically select a pure sample of well reconstructed event topologies. Particle identification performance and kinematic reconstruction capability were investigated with visual selected neutrino interactions inside the active LAr. In 70% of the cases the reconstructed vertex and end position of the muon resulted within few cm from the scanned position. Particle identification tools are based on the energy loss by ionisation, relying on the comparison between the measured deposited energy along the track with theoretical expected profiles of different particles (see fig. 3) for muon and proton. Q.E. ν_μ CC events with only one muon and one single proton in the final state have been kinematically reconstructed. Muon and proton momenta were measured from their range as well as the total transverse momenta which should be dominated by the Fermi momentum in argon nuclei in genuine CC quasi-elastic events. Figure 4 left shows a typical CC quasi-elastic candidate from BNB that passed all selections, while the middle plot represents the reconstructed muon and proton momenta in the transverse plane. The distribution of the corresponding missing transverse momentum is in reasonable agreement with MC expectations despite the present limited data statistics (right).

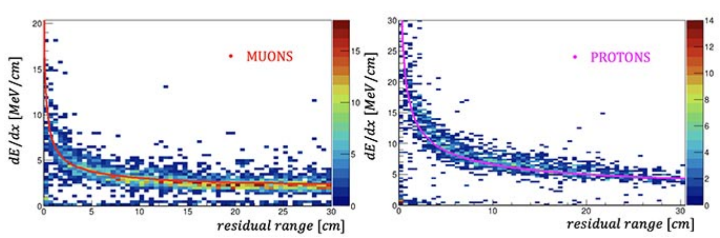

Fig. 3. – Deposited energy along the trajectory for muon and proton candidates compared with the corresponding Bethe-Block theoretical stopping power (red).

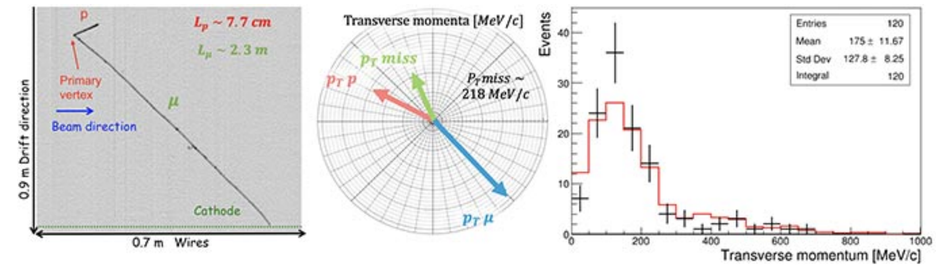

Fig. 4. – Left: ν_μ CC quasi-elastic event collected with BNB. Middle: transverse momentum reconstruction of the previous event. Right: neutrino transverse momenta distribution (black) for all well reconstructed events in comparison to MC expectations (solid red line).

5. – Conclusion

ICARUS detector installation and commissioning at FNAL were completed by mid 2022, starting data taking exposed to both Booster and NuMI beams with excellent performance. Collected events are actively studied to develop and tune automatic neutrino selection procedures while improving the actual reconstruction tools. Preliminary results proved ICARUS' capability on calorimetry and particle identification. ICARUS early phase focuses mainly on Neutrino-4 claim searching for a ν_μ disappearance with BNB and then ν_e disappearance in the NuMI off-axis beam. The SBND detector at shorter distance from the BNB target will join ICARUS effort to perform a definitive 5σ C.L. analysis of sterile neutrinos.

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