SEARCH FOR STERILE NEUTRINOS INCLUDING RECENT RESULTS FROM THE ICARUS DETECTOR IN THE CNGS NEUTRINO BEAM*

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The ICARUS T600 detector at the LNGS Gran Sasso underground Laboratory is the first large mass Liquid Argon Time Projection Chamber (LAr-TPC) designed to study the oscillations of neutrinos from the CERN–CNGS beam, the atmospheric neutrinos and matter stability. In stable conditions, the detector has been collecting data since October 2010 to December 2012. The results, presented here, relate to the search for $\nu_\mu \to \nu_e$ signal due to the LSND anomaly. The LSND anomaly would manifest itself as an excess of ν_e events in ν_μ beam. The present analysis is based on a total sample of 1995 events of CNGS neutrino interactions corresponding to 6×10^{19} pot. Four clear ν_e events have been identified, compared with an expectation of 6.4 ± 0.9 events from conventional sources. The result is compatible with the absence of a LSND anomaly. At 90% and 99% confidence levels, the limits of 3.7 and 8.3 events correspond to oscillation probabilities 3.4×10^{-3} and 7.6×10^{-3}, respectively. The result strongly limits the LSND anomaly to a narrow region around $(\Delta m^2,\ \sin^2(2\theta_{\rm new})) = (0.5\,{\rm eV}^2,\ 0.005)$, where there is an overall agreement (90% C.L.) among the present ICARUS limit, the published limits of KARMEN, and the published positive signals of LSND and MiniBooNE collaborations.

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1. Introduction

The possible presence of neutrino oscillations into sterile states has been proposed by Pontecorvo [1]. An experimental search for an anomalous $\bar{\nu}_e$ production at short distances has been performed by the LSND experiment [2].

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This experiment has reported an anomalous excess of $\bar{\nu_e}$s among $\bar{\nu_\mu}$s originating from pion decays at rest with $E_\nu \approx 30$ MeV and $L \approx 30$ m. The LSND signal $\langle P(\bar{\nu_\mu} \to \bar{\nu_e})\rangle = (2.64 \pm 0.67 \pm 0.45) \times 10^{-3}$ corresponds to a excess of $(87.9 \pm 22.4 \pm 6.0)$ events (3.8σ effect) at $L/E_\nu \sim 0.5$–1.0 m/MeV. These results may imply the presence of additional mass-squared differences as compared with two for three standard model neutrinos.

A recent result from MiniBooNe [3], performed with neutrinos from the 8 GeV FNAL-Booster in an energy ranges L/E_ν has confirmed in both the neutrino (3.4σ) and antineutrino (2.8σ) channels an LSND-like anomalies signal. However, for neutrinos the energy distribution is marginally compatible with a two-neutrino oscillation formalism.

In addition, apparent ν_e or $\bar{\nu_e}$ disappearance anomalies have been recently detected from nuclear reactors (3.0σ) [4] and from Mega-Curie k-capture calibration sources (2.7σ) [5, 6], originally developed for the gallium experiments to detect solar ν_e. However, taking into account the known θ_{13} value, the reactor antineutrino anomaly decreases to 1.4σ [7].

In the ICARUS experiment, anomalies due to the ν_e appearance in a ν_μ beam are studied at much larger values of L/E_ν, centered around $L/E_\nu \approx 36.5$ m/MeV. These hypothetical anomalies will, therefore, produce very fast oscillations as a function of E_ν, averaging over the observed spectrum to $\sin^2(1.27 \times \Delta m^2_{\mathrm{new}} \times L/E) \approx 1/2$ and $\langle P(\nu_\mu \to \nu_e)\rangle \approx 1/2 \times \sin^2(2\theta_{\mathrm{new}})$. The $\Delta m^2_{\mathrm{new}}$ and θ_{new} are parameters corresponding to the new anomalies oscillations.

2. The ICARUS T600 experiment

The LAr-TPC was proposed by Rubbia in 1977 [8]. This detection technique is capable to provide both high granularity 3D imaging of any charged particle (the spatial resolution of the detector is about 1 mm^3) and excellent calorimetric properties. It is based on the collection of the ionization signal ($\sim 6\,000$ electrons per mm) and scintillation light ($\sim 5\,000$ photons per mm at 128 nm), the latter being used for trigger purposes and for t_0 determination. The ICARUS T600 LAr-TPC detector was taking data in Hall B of the Gran Sasso underground National Laboratory (LNGS). It was shielded from cosmic rays by about 1400 m of rock.

2.1. The detector layout

The ICARUS T600 detector [9, 10] (Fig. 1), filled with about 760 tons of ultra-pure liquid argon, consists of two identical, adjacent and independent half-modules, with internal dimensions $3.6 \times 3.9 \times 19.6$ m^3. Each half-module has two TPCs sharing a common cathode. The anode of each TPC is made of three parallel wire planes, 3 mm apart, oriented at 0° and $\pm 60^\circ$

with respect to the horizontial direction. The operation of the detector is based on ionization electrons which are transported in a uniform electric field ($E_d = 500$ V/cm) over macroscopic distances up to 1.5 m (a distance between the cathode and anode wires planes). The first two wire planes are almost transparent to drifting electrons (Induction 1 and 2) which are finally collected by the third one (Collection). The measurement of the time of ionizing event, combined with the electron drift velocity information ($v_d \sim 1.6$ mm/μs), provides the absolute position of the track along the drift direction. The absolute time of the ionizing events is determined by the prompt detection of the scintillation light ($\lambda = 128$ nm). For this purpose, Photo Multiplier Tubes (PMTs) are installed behind the wire planes [11].

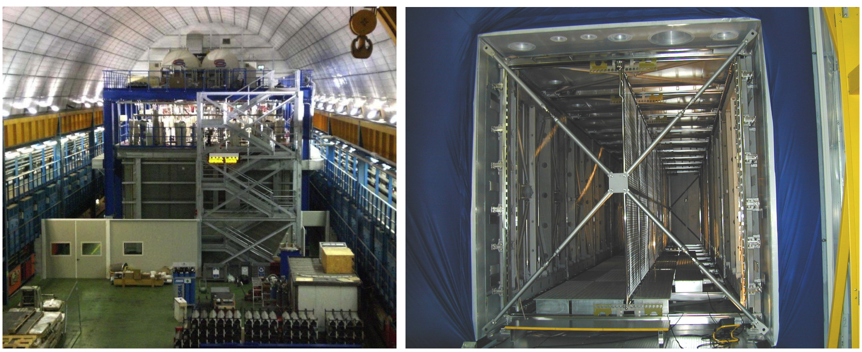

Fig. 1. The ICARUS T600 detector in Hall B at the LNGS underground laboratory (left) and the half-module with two TPCs sharing a common cathode (right).

2.2. CERN Neutrinos to Gran Sasso — CNGS

The CNGS project aims at directly detecting $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillations. A ν_μ beam ($10^{17}\nu$/day) is produced at CERN and directed towards the LNGS Laboratory, 732 km away. The beam is generated from collisions of protons with nucleons in a graphite target. The products of such interactions, mainly pions and kaons, in most cases decay to ν_μ and muons. The CNGS neutrino facility provides an almost pure ν_μ beam peaked in the energy range $10 \leq E_\nu \leq 30$ GeV, with a spectral contamination from muon anti-neutrino of about 2% and an electron neutrino component of less than 1% [12].

2.3. CNGS data collecting

The ICARUS T600 started to take data in stable conditions on October 1st, 2010 collecting a total of neutrino data corresponding to 8.6×10^{19} pot (400 GeV protons on target) until December 2012. The detector lifetime in this period was about 93%. The results presented in this paper are based on 1995 neutrino events corresponding to 6×10^{19} pot.

2.4. Physics potential

The main goal of the ICARUS T600 programme [13] is the search for $\nu_\mu \to \nu_\tau$ oscillation in the CNGS beam. A very important channel for this search is $\tau \to e\nu\nu$, where the accurate measurement of electron energy and kinematical selection criteria based on the missing transverse momentum allow to fully reject background, keeping $\sim 50\%$ efficiency for signal selection. The search for sterile neutrinos within LNSD parameter space is also performed by looking for an excess of ν_e CC events in the CNGS beam. Moreover, in the ICARUS T600 experiment atmospheric neutrinos are analyzed for the first time in the LAr detector, and the search for the proton decay in exotic channels not accessible to the Cherenkov detectors is conducted.

3. Results and discussion

In the ICARUS experiment, the neutrino interaction vertex and 2D projections of tracks and showers are identified visually. The event reconstruction is based on the signals recorded by the three TPC wire planes [10, 14]. After hit finding and fitting, the energy deposition is computed in the charge collecting view. A correction is introduced based on the (small) electron signal attenuation due to the drift distance directly measured with the help of cosmic ray muons. The high density of sampling — corresponding to $\sim 2\%$ of a radiation length — and the remarkable signal/noise ratio of about 10/1 allow us to measure the specific ionisation on each wire. It is also possible to perform precise calorimetry and particle identification for stopping particles [14] and obtain a powerful e/γ separation [12]. The total visible energy of the events has been determined from the total charge collected by the TPC wires, corrected for the electronic response [10] and for the dE/dx recombination of the signals in LAr [14]. The detailed description of the data selection and the Monte Carlo simulation is presented in [12, 15].

The expected number of ν_e events after taking into account the efficiency [12] due to conventional background sources in the energy range and fiducial volume is:

- 3.7 ± 0.6 events due to the estimated ν_e beam contamination;
- 1.7 ± 0.4 ν_e events due to the $\nu_\mu \to \nu_e$ oscillations for $\sin^2(\theta_{13}) = 0.0242 \pm 0.0026$;
- $1.0 \pm 0.1\nu_\tau$ with $\tau \to e$ events due to the oscillations $\nu_\mu \to \nu_\tau$;

giving a total of 6.4 ± 0.9 (syst. error only) expected events. A thorough discussion on the estimate of the systematic uncertainties on the predicted number of ν_e events have already been presented in [12].

In the total sample of 1995 events of CNGS neutrino interactions, four electron neutrino events have been found. This is compatible with the expectation of 6.4 ± 0.9 due to conventional sources: the probability of observing a statistical under-fluctuation resulting in four or fewer ν_e events is 25%.

One of these four observed events is shown in Fig. 2. It has a total energy of 11.5 ± 2.0 GeV and an electron of the energy of 10 ± 1.8 GeV, taking into account a partially missing component of the e.m. shower. The electron transverse momentum is 1.8 ± 0.4 GeV$/c$. There is also shown the dE/dx evolution starting with a single ionising electron to e.m. shower.

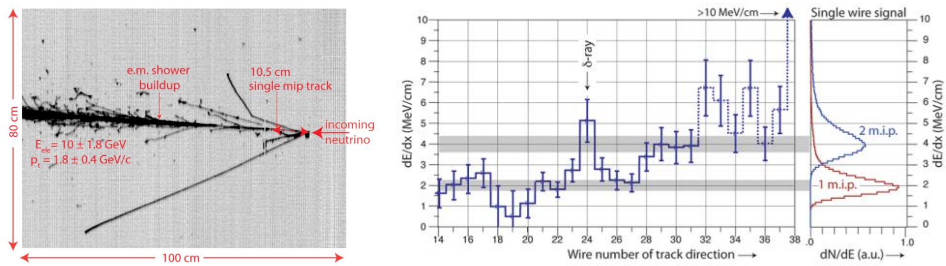

Fig. 2. One of four observed events with a clear electron signature (left). The evolution of the actual dE/dx from a single track to an e.m. shower for electron (right).

At confidence levels of 90% and 99%, the limits are respectively 3.7 and 8.3 events [16]. The corresponding limits on the oscillation probability are $\langle P(\nu_\mu \to \nu_e)\rangle \leq 3.4 \times\ 10^3$ and $\langle P(\nu_\mu \to \nu_e)\rangle \leq 7.6 \times 10^3$ respectively.

The LSND result [2] was based on anti-neutrino events. A small 2% muon anti-neutrino event contamination was also present in the CNGS beam. In the limiting case in which the whole effect is due to $\bar{\nu_\mu} \to \bar{\nu_e}$, the absence of an anomalous signal gives a limit of 4.2 events at 90% C.L. The corresponding limit on the oscillation probability is $\langle P(\bar{\nu_\mu} \to \bar{\nu_e})\rangle \leq 0.32$.

As shown in Fig. 3, a major fraction of the initial two dimensional plot $[\Delta m^2_{\rm new}, \sin^2(2\theta_{\rm new})]$ of the main published experiments sensitive to the $\nu_\mu \to \nu_e$ anomaly [2, 3, 17–19] is excluded by the present result. The ICARUS result allows to define a much smaller, narrower region centered around $(\Delta m^2_{\rm new}, \sin^2(2\theta_{\rm new})) = (0.5{\rm eV}^2, 0.005)$ in which there is 90% C.L. agreement between the present ICARUS limit, the limits of KARMEN and the positive signals of the LSND and MiniBooNE collaborations.

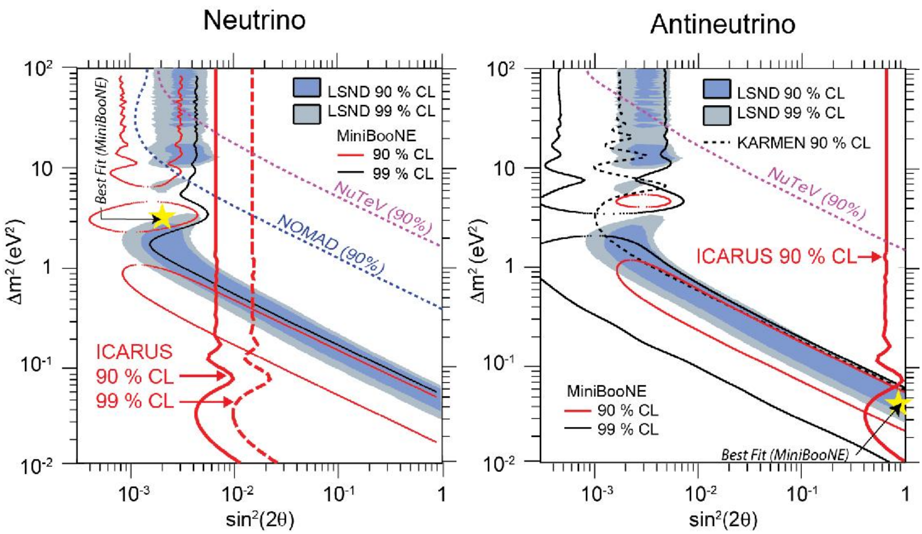

Fig. 3. Neutrino (left) and antineutrino (right) with Δm^2 as a function of $\sin^2(2\theta_{\rm new})$ for the main experiments sensitive to the $\bar{\nu_\mu} \to \bar{\nu_e}$ and $\nu_\mu \to \nu_e$ anomalies [2, 3, 17–19] and for the ICARUS results (dark gray/red lines). The stars (yellow) mark the best fit points of MiniBooNE [3]. The ICARUS limits on the oscillation probability for $\nu_\mu \to \nu_e$ are $\langle P(\nu_\mu \to \nu_e)\rangle \leq 3.4 \times 10^3$ and $\langle P(\nu_\mu \to \nu_e)\rangle \leq 7.6 \times 10^3$ at 90% and 99% C.L. respectively and for $\bar{\nu_\mu} \to \bar{\nu_e}$ is $\langle P(\bar{\nu_\mu} \to \bar{\nu_e})\rangle \leq 0.32$ at 90% C.L.

In the MiniBooNE energy range $200 < E_\nu < 475$ MeV below the sensitive E_ν/L region of LSND, a new effect and a significant additional anomaly has been reported [3], both for neutrino and antineutrino data. The neutrino result may be compared with the present experiment.

Recently, a similar search performed at the same CNGS beam by the OPERA experiment has confirmed the ICARUS finding and the absence of anomalous oscillations with an independent limit $\sin^2(2\theta_{\rm new}) < 7.2 \times 10^{-3}$ [20].

In conclusion, the LSND anomaly appears to be still alive and further experimental efforts are required to prove the possible existence of sterile neutrinos. The recently proposed ICARUS/NESSiE experiment at the CERN-SPS neutrino beam [21], based on two identical LAr-TPC detectors, complemented with magnetized muon spectrometers and placed at two different distances from proton target ($\sim$ 300 m and $\sim$ 1.6 km), has been designed to definitely settle the origin of the LSND-like anomalies.

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