Results from the ICARUS experiment and future of the T600 detector

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for the ICARUS Collaboration

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Outline

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The ICARUS Collaboration

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The ICARUS detector (T600)

The Liquid Argon Time Projection Chamber (electronic bubble chamber) [C. Rubbia: CERN-EP/77-08 (1977)] capable of providing a 3D imaging of any charged particle with:

• high granularity (spatial resolution of the detector ~ 1 mm³);
• excellent calorimetric properties.

• Total LAr mass 600 t, active mass 476 t
• Two identical T300 modules
  (2 TPC chambers for each module).

• TPC characteristics:
  ▪ (17.9 x 3.1 x 1.5 for each TPC) m³;
  ▪ drift length = 1.5 m;
  ▪ $E_{\text{drift}} = 0.5 \text{kV/cm}; v_{\text{drift}} = 1.6 \text{ mm/μs}$.

• 3 readout wire planes/chamber at 0°, ±60°,
  3 mm plane and wire spacing:
  ▪ ~ 53000 wires;
  ▪ two induction planes and one collection

• ionization and scintillation signals are exploited,
• PMTs signal is used for triggering,
• continuous probing of wire signals as a function of time allows 3D reconstruction.
• very pure argon : $\tau_{\text{ele}} > 7 \text{ ms}$

• PMTs for scintillation light (128 nm):
  ▪ (20+54) PMTs.
CNGS – CERN Neutrinos to Gran Sasso

Conventional beam based on protons from the SPS accelerator at CERN

- CNGS data useful for analyzes (01.10.2010 - 03.12.2012)
- detector live-time > 93%
- total $8.6 \times 10^{19}$ pot collected

$E \rightarrow 10 - 30 \text{ GeV}, \quad L \approx 730 \text{ km}$

$\nu_e/\nu_\mu \sim 0.8\%, \quad \nu_\mu/\nu_\mu \sim 2.1\%, \quad \nu_e/\nu_\mu \sim 0.07\%$
The electron lifetime $\tau_{\text{ele}}$ is crucial for LAr TPC performance and strongly depends on the LAr purity.

ICARUS has operated with $\tau_{\text{ele}} > 7$ ms.

After installation of new pumps on April 4th 2013 $\tau_{\text{ele}} > 14$ ms.

ICARUS has demonstrated the effectiveness of the single phase LAr-TPC technique, paving the way to huge detectors with ~5 m drift length.
LAr T600 reconstruction performance

Tracking:
- The 3D tracking is done with high spatial resolution (~1 mm³)
- Muon momentum via multiple scattering (Δp/p ~16% in the 0.4-4 GeV/c range).

Total energy reconstruction from charge integration

ENERGY RESOLUTIONS:
- Low energy electrons $\sigma(E)/E = 11%/\sqrt{E}$ (MeV) + 2%
- Electromagnetic showers $\sigma(E)/E = 3%/\sqrt{E}$ (GeV)
- Hadron shower (pure LAr) $\sigma(E)/E \approx 30%/\sqrt{E}$ (GeV)

Measurement of local energy deposition dE/dx:
- Very good e/π⁰ separation by means of dE/dx in the first part of the cascade
- Particle identification by dE/dx vs range
Unique detection properties of Lar-TPC technique allow to identify unambiguously individual e-events with high efficiency.

The evolution of the actual $dE/dx$ from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires.
Main results of the ICARUS experiment

- "Operation and performance of the ICARUS-T600 cryogenic plant at Gran Sasso underground Laboratory", (2015), sub. to JINST,
- "Experimental observation of an extremely high electron lifetime with the ICARUS-T600 Lar-TPC", (2014), JINST 9 P12006,
- "The trigger system of the ICARUS experiment for the CNGS beam", (2014), JINST 9 P08003,
- "Precise 3D track reconstruction algorithm for the ICARUS T600 liquid argon time projection chamber detector", (2013), Advances in High Energy Physics, AHEP, Volume 2013, Article ID 260820,
- "Experimental search for the 'LSND anomaly' with the ICARUS LAr-TPC detector in the CNGS beam", (2013), Eur. Phys. J. C 73:2345,
- "Measurement of the neutrino velocity with the ICARUS detector at the CNGS beam", (2012), Physics Letters B 713 17-22,
- "Precision measurement of the neutrino velocity with the ICARUS detector in the CNGS beam", (2012) JHEP 11 (2012) 049
- "A search for the analogue to Cherenkov radiation by high energy neutrinos at superluminal speeds in ICARUS", (2012), Physics Letters B 711 (2012) 270-275,
Superluminal speeds of neutrinos

The main measurement error for OPERA experiment concerned the optical fiber connector which was not functioning correctly when the measurements were taken.
Sterile neutrinos

- Sterile neutrinos were hypothesized in 1957 by B. Pontecorvo as particles not interacting via fundamental interactions except gravity.
- They are extremely difficult to detect. If they are heavy enough, they may also contribute to the dark matter.
- Sterile neutrinos may mix with standard neutrinos via a mass term. The „LSND anomaly“ and results from the MiniBooNE experiment may be considered as the experimental hints for sterile neutrinos.
- There are also disappearance anomalies in the anti-$\nu_e$ signal from the reactor experiments, and from the Mega-Curie sources in the solar neutrino experiments.
LSND (Liquid Scintillator Neutrino Detector) anomaly

LSND found an excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
Excess: $87.9 \pm 22.4 \pm 6.0 \ (3.8 \sigma)$

Oscillation probability: $0.264 \pm 0.067 \pm 0.045$

$\Delta m^2$ : $0.2 - 10 \text{ eV}^2$

Based on the data 1993 - 1998
Search for the LSND/MiniBooNE effect in the ICARUS T600

- Search for $\nu_\mu \rightarrow \nu_e$ appearance in CNGS beam neutrinos
  - $L = 730$ km, $E = 10 – 30$ GeV

- Differences w.r.t. the LSND experiment:
  - $L/E \approx 1$ m/MeV at LSND
  - $L/E \approx 36.5$ m/MeV at CNGS
  - LSND-like short distance oscillation signal averages to:
    $$\sin^2(1.27\Delta m^2 L/E) \approx \frac{1}{2}$$
  - $\langle P \rangle_{\nu_\mu \rightarrow \nu_e} \approx \frac{1}{2} \sin^2(2\theta)$

- ICARUS operates in a L/E region in which contributions from standard neutrino oscillations are not yet too relevant
Search for sterile neutrinos - results

- New analysis w.r.t. the previously published result in Eur. Phys. J. C73:2599 (2013) and based on 1995 $\nu$ interactions ($6.0 \times 10^{19}$ pot).

- An additional sample of 455 $\nu$ interactions, corresponding to $1.2 \times 10^{19}$ pot., has been added and the result based on 2450$\nu$ events and $7.2 \times 10^{19}$ pot (fully collected statistics - $8.6 \times 10^{19}$ pot) is presented below.

The expected number of $\nu_e$ events due to conventional sources:
- $4.8 \pm 0.6$ events due to $\nu_e$ beam contamination,
- $2.0 \pm 0.5$ events due to the oscillations $\nu_\mu \rightarrow \nu_e$
- $1.1 \pm 0.1$ events due to the oscillations $\nu_\mu \rightarrow \nu_\tau$ with $\tau \rightarrow e$

- Total number of expected $\nu_e$ events: $7.9 \pm 1.0$ (syst. only)
- 6 $\nu_e$ events observed in the data
ICARUS results on the LSND/MiniBooNE anomaly

- 6 $\nu_e$ events have been observed in agreement with the expectations $7.9 \pm 1.0$ due to the conventional sources.

- Limits on number of events due to LSND/MiniBooNE anomaly: 5.2 (90% CL) and 10.3 (99% CL).

- The corresponding limits on oscillation probability are:
  - $P(\nu_\mu \rightarrow \nu_e) \leq 3.9 \cdot 10^{-3}$ (90% CL)
  - $P(\nu_\mu \rightarrow \nu_e) \leq 7.6 \cdot 10^{-3}$ (99% CL)

ICARUS result strongly limits the window of possible parameters for LSND/MiniBooNE anomaly indicating a narrow region:

$\Delta m^2 \approx 0.5 \text{ eV}^2$, $\sin^2(2\theta) \approx 0.005$
Future of the ICARUS T600 detector

Part of the international Short Baseline Neutrino Oscillation Program at FNAL’s BNB (and NuMI off-axis beam) with three detectors (near: Lar1-ND, mid: MicroBooNE, far: ICARUS at shallow depths) which will measure both $\nu_\mu$ disappearance and $\nu_\tau$ appearance. The LSND 99% CL region will be covered at the $\sim 5\sigma$ level in 3 years data taking.

- The T600 was moved to CERN in Dec 2014 and is being upgraded within the WA104 experiment,
- The detector will be ready for the transportation to FNAL before the end of 2016
- The muon tagging system will be designed and constructed,
- Fully automatic tools for event reconstruction have to be developed,
- Start of the data taking with the beam is planned in Apr 2018
The ICARUS/WA104 Collaboration

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Colorado State University, USA
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FermiLab, USA
University of Pittsburgh, USA
SLAC National Accelerator Laboratory, USA
Proposed layout of SBN detectors at FNAL

- **SBN FD (~600m)**
- **MicroBooNE (470m)**
- **NuMi Beam**
- **SBN ND (110 m)**
- **ICARUS T600**: 476 t
- **MicroBooNE**: 89 t
- **LAr1-ND**: 112 t

- $E_\nu \approx 0.8 \text{ GeV}$
Physics program for the SBN

- The search for sterile neutrinos and exploration of the LSND/MiniBooNE anomalies using $\nu_\mu$ disappearance and $\nu_e$ appearance ($\nu_e$ appearance calculated sensitivity: $\sim5\sigma$ for the LSND allowed (99% C.L.) region for $6.6 \times 10^{20}$ pot,

- Precision measurements in the few hundred MeV to few GeV energy range – the world’s best measurement of $\nu_\mu$-Ar and $\nu_e$-Ar scattering,

- MicroBooNE and ICARUS will also record large samples of events from the off-axis flux of the NuMI Baseline neutrino beam (Long Baseline Neutrino Oscillation Program).
Conclusions

- ICARUS T600 detector has successfully completed the CNGS experiment conclusively demonstrating that LAr-TPC is a leading technology for future short/long baseline accelerator neutrino projects,

- Presently the ICARUS T600 detector is being overhauled at CERN,

- The detector will run again in 2018, this time as the far detector of the Short Baseline Neutrino Oscillation experiment at FNAL,

- The main aim of the SBN experiment is the definitive clarification of the LSND signal in terms of neutrino oscillations.
BACK-UP
The search for sterile neutrinos

- The experiment will likely clarify both LSND/MiniBooNE and Gallex/reactor anomalies by precisely and independently measuring both $\nu_e$ appearance and $\nu_{\mu}$ disappearance
- Disappearance analysis can profit from high rates and correlations between the three LAr-TPC detectors
LSND (Liquid Scintillator Neutrino Detector)

1993 - 1998

$p \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$

$\nu_\mu \rightarrow \nu_\mu \text{ (flavour oscillation)}$

$\overline{\nu}_e + p \rightarrow e^+ + n$

$\tau = 186 \mu s$

$p(n,\gamma)d (2.2 \text{ MeV})$

DAR: decay-at-rest

Michel spectra

$\nu_e$

$\overline{\nu}_\mu$

$\nu_\mu$

$\nu_e$

$\nu_\mu$

167 t diluted scintillator

30 m from beam stop

Cerenkov-Cone of positron

1220 PMT (8-inch)

Scintillation sphere of positron

Water target

Lower beam stop

Protons beam from LANSE accelerator
• Test the LSND anomaly
• Keep L/E same, change beam and energy
• 8 GeV proton beam (Be target)

neutrino energy (E): baseline (L):
MiniBooNE: ~700 MeV  MiniBooNE: ~540 m
LSND: ~30 MeV  LSND: ~30 m

• Mineral Oil Cherenkov Detector
• 800 tons, 12 m diameter sphere
• 1280 eight-inch PMT’s
• 240 PMT for VETO
• 611,000 \( \nu \) events
LSND and MiniBooNE

LSND has observed an excess of $\nu_e$ events in $\nu_\mu$ beam, $87.9 \pm 22.4 \pm 6.0$ (3.8 $\sigma$)

Experiments showing negative evidence:
KARMEN, NOMAD, BUGEY, NUTEV

for $200 < E_{QE} < 1250$ MeV
- antineutrino: $78.4 \pm 28.5$ (2.8 $\sigma$)
- neutrino: $162 \pm 47.8$ (3.4 $\sigma$)

for neutrinos the energy distribution is marginally compatible with a two neutrino oscillation formalism

MiniBoone results do not fully confirm the „LSND anomaly”
# Positive hints

<table>
<thead>
<tr>
<th>Anomaly</th>
<th>Source</th>
<th>Type</th>
<th>Channel</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>Short baseline</td>
<td>Decay at rest</td>
<td>-νμ →νe CC</td>
<td>3.8 σ</td>
</tr>
<tr>
<td>MiniBoone</td>
<td>Short baseline</td>
<td>Neutrino beam</td>
<td>-νμ →νe CC</td>
<td>3.4 σ</td>
</tr>
<tr>
<td>MiniBoone</td>
<td>Short baseline</td>
<td>Anti-Neutr. beam</td>
<td>anti-νμ →νe CC</td>
<td>2.8 σ</td>
</tr>
<tr>
<td>Gallium</td>
<td>Electron capture</td>
<td>Source</td>
<td>ν disapp.</td>
<td>2.7 σ</td>
</tr>
<tr>
<td>Reactors</td>
<td>Fission</td>
<td>Beta decay</td>
<td>ν disapp.</td>
<td>3.0 σ</td>
</tr>
</tbody>
</table>

Zhang, Qian, Vogel: „*Reactor antineutrino with known θ_{13}”* → 1.4 σ  
(arXiv:1303.0900), Mar 2013
1997 - 2001

KARMEN

- 50 t scintillator (5.6 x 3.2 x 3.5) m³
- L ≈ 18 m
- E < 50 MeV
- L/E = 0.4 - 1
KARMEN – no oscillation excess

- candidate events: 15
- background: $15.8 \pm 0.5$
  - cosmic: $3.9 \pm 0.2$
  - $\nu_e$ from CC: $9.9 \pm 0.4$
  - $-\nu_e$ contamination: $2.0 \pm 0.2$

- oscillation limit:
  - for $\Delta m^2 > 1 \text{ eV}^2$: $\sin^2 \theta < 0.0017$
  - $0.2 < \Delta m^2 < 1 \text{ eV}^2$
    $10^{-3} < \sin^2 \theta < 3 \cdot 10^{-2}$
LSND anomaly area

KARMEN – negative evidence
1997 - 2001

- 50 t scintillator (5.6 x 3.2 x 3.5) m$^3$
- $L \approx 18$ m       $E < 50$ MeV
- background : 15.8 ± 0.5
- candidate events : 15

Other exp. with the negative evidence:
NOMAD, BUGEY, NUTEV

MiniBooNE : PRL 110, 161801 (19 April 2013)