Liquid Argon Detectors for SuperNNe II Physics

D. Cline
UCSB

1. Development of ICA1000 → 600τ → 1800τ
2. The LANNUDD Concept and DU56
3. Nova II at Numi off Axis
4. LANND0-50m Experiment at LENS & WPP
5. Physics Goals of CAR Detector
   a) Proton Decay
   b) SN II νe, νx → νe oscillation
   c) Relic νe Detection from Past SNII (will not discuss θ13 from LB)

Summary
Liquid Argon TPC Properties

- 3D tracking + total-absorption calorimetry.
- Pixel size: 3 mm × 3 mm (wire planes) × 0.6 mm (via 400 ns time sampling).
- \( \rho = 1.4 \text{ g/cm}^3 \), \( T = 89\text{K at 1 atm.} \), \( X_0 = 14 \text{ cm} \), \( \lambda_{\text{int}} = 80 \text{ cm} \).
- A minimum ionizing particle yields 50,000 \( \text{e/cm} \).
- Drift velocity of 1.5 m/msec at 500 V/cm \( \Rightarrow \) 5 m drift in 3 msec.
- Diffusion coef. \( D = 6 \text{ cm}^2/\text{s} \) \( \Rightarrow \sigma = 1.3 \text{ mm after 3 msec} \).
- Can have only 0.1 ppb of \( \text{O}_2 \) for a 5 m drift, \( \Rightarrow \) Purify with Oxisorb.
- Liquid argon costs \$0.7M/kton – and is “stored” not “used”.

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**Liquid Argon Detector for DUSEL**

- Early work
  - [AUI](#)
  - H. Chen...
  - P. Doe

**First Rev Proposal**
- 1983
- Harvard, WICE, CERN

**TRACE THIS IDEA BACK TO L. ALVAREZ**

Energy Resolution:

\[ 11 \% \sqrt{E (\text{MeV})} \]

from \( \mu \rightarrow e \) studies - I CARDS
Technical Feasibility:
History of prototype work on ICARUS

R&D Program

3 ton prototype


24 cm drift wires chamber


50 litres prototype 1.4 m drift chamber

1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

10 m³ industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.
50 l prototype in the CERN WANF neutrino beam

$\nu_\mu + X \rightarrow \mu^- + \text{many prongs}$

$\nu_\mu + n \rightarrow \mu^- + p$
The success of the ICARUS T600

One of the two T300 modules

tested above ground in Pavia in 2001
now below ground in Gran Sasso
Allows for high resolution imaging like bubble chambers, but with calorimetry and continuous digital readout (no deadtime) 31,000 $\text{Trues}$ at Pavia

Data

Full study of electrons from $\mu \rightarrow e + \nu + \bar{\nu}$

$\langle E_0 \rangle \approx 30\text{MeV}$

ICARUS images

MC simulation
T600 Transport to LNGS

Total weight 2×45 ton
Transport from Pavia to LNGS-Hall B
approved (110 K€)

Tender completed and company chosen
Trolley ready
Distance: 732 km / Time: 4 days/300T
Date: 15 June 2004

SAGENAP Meeting – Washington – April 14-16, 2004

Franco Sergiampietri – 1, 6
The T3000 configuration

- T1200/B
- T1200/A
- T600

CRYOGENIC FACILITY

Note: "UNDER CONSTRUCTION" and "OPERATE LATE SPRING 2006" are handwritten.
CNGS $\nu_\tau$ interaction, $E_\nu=18.7$ GeV

$e^- 9.5$ GeV, $p_t=0.47$ GeV/c

$\tau \rightarrow e^- + \nu_e + \nu_\tau$

280 cm

105 cm

290 cm

$e^- 15$ GeV, $p_t=1.16$ GeV/c

Vertex: $1\pi^0, 2p, 3n, 2\gamma, 1e$

CNGS $\nu_e$ interaction, $E_\nu=16.6$ GeV

120 cm

Review CNGS presentation

POWERFUL REJECTION OF $\pi^0$s
LANNDD—a massive liquid argon detector for proton decay, supernova and solar neutrino studies and a neutrino factory detector

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Abstract

We describe a possible Liquid Argon Neutrino and Nucleon Decay Detector (LANNDD) that consists of a 70 kT magnetized liquid Argon tracking detector. The detector is being designed for the Carlsbad Underground Laboratory. The major scientific goals are:

1. Search for {p → K^{-} + \nu_{e}} to 10^{15} years lifetime;
2. Detection of large numbers of solar neutrino events and supernova events;
3. Study of atmospheric neutrinos;
4. Use as far detector for Neutrino Factories in the USA, Japan or Europe.

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Keywords: Neutrino; Nucleon decay; Liquid argon

1. Introduction

One option for next generation nucleon decay search instrument is a fine-grained detector, which can resolve kaons as well as background from cosmic ray neutrinos that are below the threshold for water Cerenkov detectors such as Super-Kamiokande (SK). One option for a next generation nucleon decay search instrument is a fine-grained detector, which can resolve kaons as well as background from cosmic ray neutrinos that are below the threshold for water Cerenkov detectors such as Super-Kamiokande (SK). Such a detector can make progress beyond the few \times 10^{14} yr limits from SK for SUSY favored modes because the reach improves linearly with the time and not as...
- Large modules ($\geq 100$ kton) can be built using technology of liquid methane storage. (Total cost of a 100-kton detector is estimated to be $200M$.)

- Detector is continuously “live” and can be “self-triggered” using pipelined, zero-suppression electronics.

- Operates at the Earth’s surface with near zero overlap of cosmic ray events.

- Detector is compatible with operation in a magnetic field.
200-kton Cryogenic Tanks Used for LNG Storage

Chicago Bridge & Iron: can build 100-kton LAr tank for < $20M.
Extrapolation to Very Large Modules

Preliminary cost estimate for a liquid argon detector of 100 kton total mass.

<table>
<thead>
<tr>
<th>Component</th>
<th>Scaling</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid argon (industrial grade)</td>
<td>$M$</td>
<td>$70M$</td>
</tr>
<tr>
<td>Cryo plant, including Oxisorb purifiers</td>
<td>$M$</td>
<td>$10M$</td>
</tr>
<tr>
<td>Surface site preparation</td>
<td>$M^{2/3}$</td>
<td>$10M$</td>
</tr>
<tr>
<td>Cryogenic storage tank</td>
<td>$M^{2/3}$</td>
<td>$20M$</td>
</tr>
<tr>
<td>Electronics (300k channels)</td>
<td>$M^{2/3}$</td>
<td>$30M$</td>
</tr>
<tr>
<td>Computer systems</td>
<td>$M^{2/3}$</td>
<td>$10M$</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td></td>
<td><strong>$150M</strong></td>
</tr>
<tr>
<td><strong>Contingency</strong></td>
<td></td>
<td><strong>$50M</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>$200M</strong></td>
</tr>
</tbody>
</table>

*Can be re sold after the experiment finishes*
Very Low Cost of excavation $\sim 25\$/tons

WIPP
An Underground Science Center
Near Carlsbad, New Mexico
Made available by the
U.S. Department of Energy

DOE Property

WIPP's Low-Background Characterization
- The self-luminous surrounding WIPP provides extremely low levels of naturally occurring radioactive materials
- $\sim 10^{-7}$ roentgens
- $T^2 \sim 50$ years
- $9.4 \times 10^{11}$ protons
- $\sim 10^4$ holes

Oblivious Living Organisms Found at WIPP
In 1990, the oldest living organisms ever found were collected in the WIPP underground. These bacterial bacteria micromes were collected from interstitial water inclusions left over from fluid precipitation of the Permian Sand hundreds of millions of years ago.
What a difference a new director makes!

2002 - Several NUMI off axis workshop
DBC/Kirk MacDonald/Francesco Bergerzuch
all purpose LAR detectors for
all axis NUMI
designs for a SO1, 50kT and 40 ton
detector were put forward

All REJECTED BY THE FINAL DIRECTOR

2005 - NuSAG Charge includes
a large LAR Detectors ??
- First tell by Poddem
endorse the path - NOVA II
Collaboration a rapid journey for
a 15 \( \rightarrow \) 50kT Detector
Endorsement from NuSAG towards realization of very large liquid Argon TPCs will keep effort on time to contribute to Fermilab's NuMI long baseline program
Overview

6 Wire Sectors, each containing 6 Wire Planes

7 Cathode Planes

Active volume
Diameter: 40m
Height: 30m

Scalable → 15-50 kTons
4 - 6 wire planes
Liquid Argon as a commodity

- Byproduct of air liquefaction
- Annual production ~ 1,000,000 tons/year (mostly at the coasts, East Chicago)
- Delivery: truck (20 t) or railroad car (70 t)
- Cost (delivered) $0.60/kg

<table>
<thead>
<tr>
<th>grade</th>
<th>O2 content [ppm]</th>
<th>application</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>20.</td>
<td>General Industrial, shield gas</td>
</tr>
<tr>
<td>D</td>
<td>10.</td>
<td>Heat treating, sintering</td>
</tr>
<tr>
<td>E</td>
<td>5.</td>
<td>High purity applications</td>
</tr>
<tr>
<td>F</td>
<td>2.</td>
<td>Semiconductor applications</td>
</tr>
</tbody>
</table>
Many large LNG tanks in service

Excellent safety record

Last failure in 1940 understood
Electrons versus $\pi^0$'s at 1.5 GeV

Dot indicates hit color indicates collected charge green=1 mip, red=2 mips

Electrons
Single track (mip scale) starting from a single vertex

$\pi^0$
Multiple secondary tracks can be traced back to the same primary vertex
Each track is two electrons - 2 mip scale per hit

Use both topology and dE/dx to identify interactions
LArTPCs

- Total absorption calorimeter
- 5mm sampling
  - $\rightarrow$ 28 samples/rad length
- energy resolution

$\nu_e$ efficiency
NC rejection

First pass studies using hit level MC show
$\sim 80 \pm 7\% \nu_e$ efficiency and
NC rejection factor $\sim 70$

(only need rejection factor of 20 to knock background
down to $\frac{1}{2}$ the intrinsic $\nu_e$ rate)

Studies from groups
working on T2K LAr indicate 85-95% $\nu_e$ efficiency
in documents submitted to NuSAG
Efficiency is substantial even for high multiplicity events
Efficiency is $\sim 100\%$ for $y < 0.5$, and $\sim 50\%$ above this

$$y = \frac{E_{\text{had}}}{E_{\nu}}$$
Baseline Concept presented in two day "mini-Review"
Fermilab Particle Physics Division

No show stoppers in scaling up liquid argon technology as per Fermilab mechanical, cryogenic, and electronics engineers

Large detector can be built at a reasonable cost

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Cost Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 kton TPC</td>
<td>~100M</td>
</tr>
<tr>
<td>15 kton TPC</td>
<td>~54M</td>
</tr>
</tbody>
</table>

*Preliminary Costing*

*Notes:
- N2A 25kT: $160M
- But eff 2 LRT ~ 80%
- eff? N2A ~ 25%*
R&D efforts underway

at FNAL

at UCLA/CERN

at Yale
Pisa/ UCLA
HV Lab at
CERN
ICARUS HV Construction

CANNOD-5m
At CERN Now
Test in Summer 2005
The detector

TPC with parallelepiped drift volume confined between a cathode and a wire chamber 5m apart.

Front Chimney
Signal Feedthrough
In Argon
LN2 Heat Exchanger
View Port

Back Chimney
HV Feedthrough
Out Argon
LN2 Heat Exchanger

Field Shaping Electrodes
- N 333
- Thickness: 10 mm
- Pitch: 15 mm
- Material: Aluminum

Wire Chamber
- HW: 64
- VW: 64
- Pitch: 3 mm

Centering Rings
- N 10
- Material: G10

Cathode

Electric field kept uniform through a stack of equally spaced field shaping electrodes, biased at linearly decreasing voltages from the cathode voltage to ground.

UCLA Meeting - CERN, September 17th, 2004
LANNDD-5mD, F. Sergiampietri, 8
Double wall, vacuum insulated cryostat.

Inner cold cylinder \((D = 400 \text{ mm} \times L = 5.8 \text{ m})\) hanging from the outer warm cylinder by stainless steel (or Kevlar) ropes.

Two chimneys \((D = 200 \text{ mm})\) positioned at the two ends \((d = 5.1 \text{ m})\), used for \(a)\) signal and control feedthrough, \(1^{\text{st}}\) heat exchanger, argon input/output and \(b)\) high voltage feedthrough, \(2^{\text{nd}}\) heat exchanger.

Chimney's volume used as argon expansion buffer (~2% of the liquid volume).

Heat input (including conduction through signal cables and HV feedthrough) reduced to few watts (due to hanging system, warm/cold mechanical connection via stainless steel diaphragm bellows, super-insulation wrapping of the cold cylinder). Foreseen \(\text{LN}_2\) consumption < 10 l/24h.
Figure 6. Arrival of the cryostat crate at CERN (top-left); mounting the wheels (top-right), positioning inside the laboratory (bottom-left); the UHV pumping group (bottom-right).
Progresses: The wire chamber

NEW FUNDING FROM DIE

UCLA Meeting - CERN, September 17th, 2004
LANNDD-5mD, F. Sergiampietri, 20
LANNDD Collaborations

LANNDD – 5M

Collaboration:
C. Cerri, F. Sergiampietri, R. Pazzi
INFN – Sezione di Pisa
D.B. Cline, Y. Seo, X. Yang, H. Wang
UCLA – Department of Physics and Astronomy
A. Bueno, S. Navas, 5 students
Universidad de Granada
Departamento de Física Teórica y del Cosmos – Física de Altas Energías

LANNDD – WIPP Site Study

Collaboration:
UTD: Ervin Fenyves, Robert Burkart, Alicia Kiefer, William Burgett
UCLA: D. Cline, K. Lee, Y. Seo
University of Hawaii: John Learned
### Nucleon decay

<table>
<thead>
<tr>
<th>Channel</th>
<th>Efficiency (%)</th>
<th>Background (5 kT̅on×year)</th>
<th>$\pi/B$ Limit $\times10^{30}$ yrs (5 kT̅on×year)</th>
<th>PDG limit $\times10^{30}$ yrs</th>
<th>Needed Exposure to reach PDG (kT̅on×year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow e^+ \pi^0$</td>
<td>45.30</td>
<td>0.005</td>
<td>265</td>
<td>1600</td>
<td>30.24</td>
</tr>
<tr>
<td>$p \rightarrow e^+ (\pi^0)$</td>
<td>15.10</td>
<td>9.73</td>
<td>30.0</td>
<td>1600</td>
<td>8263.3</td>
</tr>
<tr>
<td>$p \rightarrow K^+ \pi^-$</td>
<td>96.75</td>
<td>0.005</td>
<td>565</td>
<td>670</td>
<td>5.93</td>
</tr>
<tr>
<td>$p \rightarrow K^+ (\pi^0)$</td>
<td>97.55</td>
<td>0.005</td>
<td>570</td>
<td>245</td>
<td>215</td>
</tr>
<tr>
<td>$p \rightarrow e^- (\pi^+ K^+)$</td>
<td>18.60</td>
<td>0.125</td>
<td>109</td>
<td>82</td>
<td>3.78</td>
</tr>
<tr>
<td>$p \rightarrow e^- (\pi^- K^+)$</td>
<td>29.50</td>
<td>6.01</td>
<td>72.4</td>
<td>82</td>
<td>5.93</td>
</tr>
<tr>
<td>$p \rightarrow e^+(\pi^+ K^+)$</td>
<td>16.30</td>
<td>19.68</td>
<td>24.5</td>
<td>82</td>
<td>41.5</td>
</tr>
<tr>
<td>$p \rightarrow \pi^+ \pi^-$</td>
<td>41.85</td>
<td>3.91</td>
<td>117</td>
<td>25</td>
<td>0.52</td>
</tr>
<tr>
<td>$p \rightarrow \pi^+ (\pi^+)$</td>
<td>44.80</td>
<td>0.04</td>
<td>262</td>
<td>473</td>
<td>9.04</td>
</tr>
<tr>
<td>$p \rightarrow \mu^+ \pi^0$</td>
<td>17.85</td>
<td>20.81</td>
<td>26.6</td>
<td>473</td>
<td>1113.5</td>
</tr>
<tr>
<td>$n \rightarrow e^- K^+$</td>
<td>95.95</td>
<td>0.000</td>
<td>685</td>
<td>32</td>
<td>0.24</td>
</tr>
<tr>
<td>$n \rightarrow e^- \pi^-$</td>
<td>44.35</td>
<td>0.040</td>
<td>317</td>
<td>158</td>
<td>2.50</td>
</tr>
<tr>
<td>$n \rightarrow e^- (\pi^-)$</td>
<td>25.55</td>
<td>26.73</td>
<td>41.6</td>
<td>158</td>
<td>55.26</td>
</tr>
<tr>
<td>$n \rightarrow \mu^- \pi^-$</td>
<td>44.75</td>
<td>0.12</td>
<td>319</td>
<td>100</td>
<td>1.57</td>
</tr>
<tr>
<td>$n \rightarrow \mu^- (\pi^-)$</td>
<td>21.05</td>
<td>14.56</td>
<td>43.1</td>
<td>100</td>
<td>19.68</td>
</tr>
<tr>
<td>$n \rightarrow \pi^0$</td>
<td>45.10</td>
<td>2.37</td>
<td>199</td>
<td>112</td>
<td>2.43</td>
</tr>
</tbody>
</table>

Also: $p \rightarrow e^+ \nu \nu \ [\text{like } n \rightarrow 3 \nu] \text{ for } 10^{32} \text{ year}$

NuFact05, Frascati, 21-26.06.2005
# Proton Decay Search

## Limits on proton mean life ($\tau_p$)

### Exposure: 300 kTon $\times$ year

<table>
<thead>
<tr>
<th></th>
<th>$p \rightarrow e^+ \pi^0$</th>
<th>$p \rightarrow K^+ \bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Efficiency (%)</td>
<td>$\tau_p$ (years)</td>
</tr>
<tr>
<td>4.5 years @ LANNDD</td>
<td>No nuclear reinteractions</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Nuclear reinteractions (FLUKA)</td>
<td>19</td>
</tr>
</tbody>
</table>

### Exposure: 1000 kTon $\times$ year

<table>
<thead>
<tr>
<th></th>
<th>$p \rightarrow e^+ \pi^0$</th>
<th>$p \rightarrow K^+ \bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Efficiency (%)</td>
<td>$\tau_p$ (years)</td>
</tr>
<tr>
<td>15 years @ LANNDD</td>
<td>No nuclear reinteractions</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Nuclear reinteractions (FLUKA)</td>
<td>19</td>
</tr>
</tbody>
</table>
Advantages of LAR for SN \( \nu_e \) Detection:

1) No Free H (no \( \nu_e \tau p \rightarrow e^+ \nu_\tau \).\footnote{By}

2) Very sensitive to \( \nu_e + Ar \rightarrow e^- + k \)

3) \( K^+ \rightarrow 0 \) ... gives powerful event signature

4) Very good pattern and energy information (\( \mu \rightarrow e \) study with ICARUS T300)

5) Good pointing for \( 2 \mu + e \rightarrow 2 \mu + e \) events back to SN II

Detector: ICARUS 1800T at CNGS
LAUNDO at 70kT? (DUSEL NRU?)
NOA II at Fermi 15-50kT 2014?
Nucleon decay searches

$p \rightarrow \nu K^+$ decay

$n \rightarrow \nu K^0$ decay

$p \rightarrow e^+ \pi^0$ decay

Thanks to excellent tracking and particle id capabilities

LAr unique tool for

Extremely efficient background rejection

High detection efficiency

Bias-free, fully exclusive channel searches!
Solar neutrinos detection in ICARUS

- Two reactions can be measured independently:
  - Elastic scattering on atomic electron:
    \[ \nu_x + e^- \rightarrow \nu_x + e^- \]
  - \( \nu \) absorption on Argon nuclei:
    \[ \nu_e + ^{40}\text{Ar} \rightarrow ^{40}\text{K}^* + e^- \]

- **Signature**: primary electron track eventually surrounded by low energy secondary tracks (\(^{40}\text{K}^*\) de-excitation).
- Electron track threshold = 5 MeV (needed to reduce background contribution and to establish the \( e^- \) direction in elastic scattering).
- Sensitive to \(^8\text{B}\) component of the solar spectrum.
Cosmic Neutrinos: SN, Neutron star collapse, AGN, GRB

ICARUS T1800 is a unique instrument, with sensitive mass, able to detect $\nu$ in a wide energy region of interest (from one to thousands MeV):

Inverted Hierarchy
Normal

<table>
<thead>
<tr>
<th>reaction</th>
<th>oscillation (SN at 10 kpc)</th>
<th>oscillation (SN in the Large Magellanic cloud)</th>
</tr>
</thead>
<tbody>
<tr>
<td>elastic</td>
<td>24 (24)</td>
<td>1 (1)</td>
</tr>
<tr>
<td>CC</td>
<td>460 (600)</td>
<td>19 (24)</td>
</tr>
<tr>
<td>NC</td>
<td>546 (546)</td>
<td>22 (22)</td>
</tr>
<tr>
<td>total</td>
<td>1030 (1170)</td>
<td>42 (47)</td>
</tr>
</tbody>
</table>

UCLA Group Meeting
S. Otwinowski, April 25, 2005
$\nu_e$ from SN II

LANEHD or NWA II

Assume a SOKT DETECTOR
SN II 10 km away

$N_{\nu e} = 15,000$ events for Normal mass hierarchy

$N_{\nu e} = 11,000$ events for Inverted mass hierarchy

Difference 4000 events will largely be above 25 MeV

Neutrino energy - easy to measure with good energy resolution by EAR

For LANEHD this is on 2024 sec

To measure - near $\sim 10$ sec

For NWA II these may be difficult -
Detector on surface - enormous cosmic ray flux (100 $\mu$ per beam spill/sec)

A special trigger would have to be devised - there could still be many back ground events
Detect of Relic $\nu_e$

From Past SN II

1. MSW effect could give $\nu_e$ a harder spectrum ($\nu_x \rightarrow \nu_e$ in SN)

2. $\nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K} \rightarrow ^{40}\text{Ca}$

   gives a unique signature — perhaps (1-e) events could be detected per year

   $E_\nu \sim 20 - 30$ MeV

For Icarus T180D $\langle \text{event} \rangle = 10^4 \text{cm}^{-2}$

LANMDD, Nova II $\langle \text{event} \rangle = 10^2 \text{cm}^{-2}$

Summary

After years of R&D LAR detectors have arrived:

- CNS/ ICARUS T180D (2008)
- DUSEL LANMDD $\sim$ TOKT (?)
- FNAL Numi off axis Nova II $\sim$ 50 KT (2014)

Beyond Long Base line LBNF, there are other important goals, p decay, SN...