DUNE: the Physics Potential of a Large, Underground, Liquid Argon Neutrino Detector

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- On behalf of the DUNE Collaboration -

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DUNE and LBNF

LBNF = Long-Baseline Neutrino Facility
(neutrino beam, site infrastructure, cryogen systems, etc.)

DUNE = Deep Underground Neutrino Experiment
(Near detector and deep underground far detector)
In the scope of the **2014 P5 report**, the international neutrino community aims to do the following with DUNE/LBNF:

- Exposure of at least 120 kt·W·year by 2035
- 1.2 MW beam power, upgradeable to a few MW power
- Underground far detector with at least 40 kt liquid argon fiducial volume
- Demonstrated capability to search for supernova bursts
- Demonstrated capability to search for proton decay with significant improvement over current bounds on the proton lifetime

**DUNE will be equipped for underground physics**
DUNE Far Detector at SURF

Sanford Underground Research Facility

Davis Campus

- MJD
  - Majorana Demonstrator
  - Neutrinoless double-beta decay
- LUX/LZ
  - Large Underground Xenon experiment
  - First and second generation dark matter
- CUBED
  - Center for Ultra-Low Background Experiments in the Dakotas
  - Low background counting

Ross Campus

- MJD
  - Majorana Demonstrator
  - Electroforming laboratory
- DIANA
  - Dual Ion Accelerators for Nuclear Physics
  - 4850 Level DIANA Laboratory

4850 ft depth
Two detector designs are being explored in parallel. Both will have the ability to detect scintillation light. Construction of four 10-kt modules will be phased over several years time.
Underground Physics Opportunities

With 40 kt of liquid argon at 4850 ft underground, there is significant potential for the following:

• Nucleon decay

• Atmospheric neutrinos

• Supernova burst neutrinos

Other physics involving solar neutrinos, diffuse supernova background neutrinos, indirect dark matter searches are also being studied
Some supersymmetric GUT models favor modes with kaons produced in the final state. DUNE has enhanced capability for detecting these modes, compared to water Cherenkov detectors.

Where does the matter-antimatter asymmetry come from? Baryon number should be violated, i.e. nucleon decay. GUT’s allow B number violation and give predictions for the lifetimes of nucleon decay.
Cosmogenic induced kaon decay candidate as seen in ICARUS:

\[ K \rightarrow \mu \nu_\mu \]
\[ \mu \rightarrow e\nu_e \nu_\mu \]

Proton decay will produce a single \( p = 340 \text{ MeV} \ K^+ \)

Backgrounds come from cosmic-rays and atmospheric neutrinos. Cosmic-rays mainly reduced by depth. Use energy threshold cut and strict PID \((dE/dx)\) to tag final state baryons from atmospheric neutrinos – containment of final state particles is key.
Expected Sensitivity to Nucleon Decay

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Water Cherenkov Efficiency</th>
<th>Cherenkov Background</th>
<th>Liquid Argon Efficiency</th>
<th>Argon Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p \rightarrow K^+\bar{\nu}$</td>
<td>19%</td>
<td>4</td>
<td>97%</td>
<td>1</td>
</tr>
<tr>
<td>$p \rightarrow K^0\mu^+$</td>
<td>10%</td>
<td>8</td>
<td>47%</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>$p \rightarrow K^+\mu^-\pi^+$</td>
<td>97%</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n \rightarrow K^+e^-$</td>
<td>10%</td>
<td>3</td>
<td>96%</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>$n \rightarrow e^+\pi^-$</td>
<td>19%</td>
<td>2</td>
<td>44%</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Background event rates are listed in events / (Mt\cdot year) for the nucleon decay channels of interest.

DUNE sensitivity depends on the phasing of the experiment. For a 20 year exposure with a 40 kt mass, upper limits on the proton lifetime will improve by an order of magnitude over limits set by Super-K for a 260 kt\cdot year exposure.
Oscillation Studies with Atmospheric Neutrinos

Oscillation parameters can be measured using atmospheric neutrinos (propagating through Earth) which cover a wide range of L/E.

Normal Hierarchy $\rightarrow \nu_e$ resonance
Inverted Hierarchy $\rightarrow \bar{\nu}_e$ resonance

The MSW resonance inside the Earth affects electron neutrinos of several GeV energy. Compare the effect on neutrinos and anti-neutrinos using statistical discrimination of event tagging features like p-recoil and decay electrons (nu or anti-nu?):
Oscillation Structure from MSW Effect

Summary of atmospheric neutrino interactions in DUNE (from detector simulation + GENIE). Relies on selecting high-resolution (energy and angle) events.

L/E distributions for a 350 kt-year exposure with ratio of oscillated and no oscillations – structure is very well-defined. Events from each containment sample are binned by energy and angle for oscillation analysis.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Event Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>fully contained electron-like sample</td>
<td>14,053</td>
</tr>
<tr>
<td>fully contained muon-like sample</td>
<td>20,853</td>
</tr>
<tr>
<td>partially contained muon-like sample</td>
<td>6,871</td>
</tr>
</tbody>
</table>

Expected sample for 350 kt-yr exposure
Atmospheric Neutrino Sensitivity to Mass Hierarchy

Relies mainly on electron neutrino appearance and muon neutrino disappearance. Differences between hierarchies appear when compared to ‘no-oscillation’ scenario. Unlike beam analysis, mass hierarchy sensitivity is essentially independent of $\delta_{CP}$.

Sensitivity of 40 kt DUNE is comparable to Hyper-K due to better angular and energy resolution of a LArTPC.
Supernova Burst Neutrinos

For core-collapse supernovae, about 99% of the gravitational binding energy is emitted in the form of neutrinos – on the order of $10^{58}$ over the course of the explosion!

Critical Fe core mass $\sim 1.4 \, M_\odot$

Below is the evolution of the burst for a specific flux model. Neutronization ($p + e^- \rightarrow n + \nu_e$) burst at early times is primarily electron flavor – only liquid argon detectors are sensitive to this component.
Supernova Neutrino Dynamics

Extreme conditions inside the supernova produce exotic effects, like neutrino-neutrino interactions, that are visible in the observed energy spectrum on Earth.

The ability to do physics with supernova neutrinos relies heavily on accurate reconstruction of the true neutrino energy. This is a non-trivial task.
Reconstructing true neutrino energy:

CC reaction: \( E_\nu = E_e + Q + K_{\text{recoil}} \)

We need to know dominant transition intensities very well (at least 28 levels observed)

Also need to know all the de-excitation gammas and their branching fractions

<table>
<thead>
<tr>
<th>Reaction Type</th>
<th>Events / 10 kt</th>
</tr>
</thead>
<tbody>
<tr>
<td>(CC) ( \nu_e + ^{40}\text{Ar} \rightarrow e^- + ^{40}\text{K}^* )</td>
<td>(~700 ) [1]</td>
</tr>
<tr>
<td>(CC) ( \bar{\nu}_e + ^{40}\text{Ar} \rightarrow e^+ + ^{40}\text{Cl}^* )</td>
<td>(~60 ) [1]</td>
</tr>
<tr>
<td>(ES) ( \nu_x + e^- \rightarrow \nu_x + e^- )</td>
<td>(~85 ) [1]</td>
</tr>
<tr>
<td>(NC) ( \nu_x + ^{40}\text{Ar} \rightarrow \nu_x + ^{40}\text{Ar}^* )</td>
<td>(~90 ) [2]</td>
</tr>
</tbody>
</table>

[1] K. Scholberg  
Supernova Neutrino Detection Challenges

Key aspects that must be addressed for energy reconstruction:

• Need to develop accurate model of energy levels and gamma/nucleon evaporation for excited states $^{40}$K*, $^{40}$Cl* and $^{40}$Ar*

• Model needs to address both the *bound and the unbound* states of the final nucleus (QRPA for example)

• One such model is currently under development:
  
  **MARLEY: Model of Argon Reaction Low Energy Yields**
  
  *(S. Gardiner, K. Bilton, C. Grant, R. Svoboda, E. Pantic)*

• Small scale LAr TPC near a source of <60 MeV electron neutrinos needs to demonstrate that the model is correct (or fine-tune it)

  **Example: CAPTAIN TPC (0.35 ton or 5 ton) near a source of electron neutrinos from muon decays at Fermilab**
Conclusions

• DUNE, with 40 kt of LAr at a depth of 4850 ft, has significant potential for exciting underground physics. Greatest potential from the following: nucleon decay, atmospheric neutrino oscillations, and SN burst neutrinos

• Nucleon decay sensitivity comes primarily in the form of modes with kaons, preferred by some SUSY GUT models
  – Particle ID, dE/dx, threshold cuts are very important for tagging a single kaon and rejecting events from atmospheric neutrinos
  – Sensitivity to lifetime bounds can improve from $\sim 6 \times 10^{33}$ (SK) to $\sim 6 \times 10^{34}$ using these modes

• Atmospheric neutrino oscillations provide complimentary physics to the beam source
  – MSW effect in the Earth can be used to obtain information on the neutrino mass hierarchy
Conclusions

- Sensitivity to the mass hierarchy strongly depends on $\theta_{23}$ but not so much on the value of $\delta_{CP}$

• Supernova burst at 10 kpc will yield $\sim$3000 electron neutrino CC interactions on $^{40}$Ar in DUNE (40 kt). Neutrinos can provide us with information on the dynamics of the burst and other exotic phenomena
  - Information comes from the SN neutrino energy, which needs to be accurately reconstructed
  - Complications arise in the energy reconstruction from lack of precision models of argon reactions at $< 60$ MeV and lack of direct measurements for comparison
  - Efforts are being made to study this problem with indirect beam sources and small-scale experiments
Thank you!

DUNE Collaboration at first meeting

Co-spokespersons

André Rubbia
Mark Thomson

DUNE is a multi-national collaboration is made up of 144 institutions from 26 countries.
Backup
# Single Phase TPC Concept

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reference Performance</th>
<th>Achieved Elsewhere</th>
<th>Expected Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal/Noise Ratio $^1$</td>
<td>9:1</td>
<td>10:1 [6, 7]$^2$</td>
<td>9:1</td>
</tr>
<tr>
<td>Electron Lifetime</td>
<td>3 ms</td>
<td>&gt; 15 ms [7]</td>
<td>&gt; 3 ms</td>
</tr>
<tr>
<td>Uncertainty on Charge Loss due to Lifetime</td>
<td>&lt; 1%</td>
<td>&lt; 1% [7]</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Dynamic Range of Hit Charge Measurement</td>
<td>15 MIP</td>
<td>15 MIP</td>
<td></td>
</tr>
<tr>
<td>Vertex Position Resolution $^3$</td>
<td>(2.5, 2.5, 2.5) cm</td>
<td>(1.1, 1.4, 1.7) cm [8, 9]</td>
<td></td>
</tr>
<tr>
<td>$e - \gamma$ separation $\epsilon_e$</td>
<td>0.9</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>$e - \gamma$ separation $\gamma$ rejection</td>
<td>0.99</td>
<td>0.99</td>
<td></td>
</tr>
<tr>
<td>Multiple Scattering Resolution on muon momentum $^4$</td>
<td>~18%</td>
<td>~18% [10, 11]</td>
<td>~18%</td>
</tr>
<tr>
<td>Electron Energy Scale Uncertainty</td>
<td>5%</td>
<td>2.2%[12]</td>
<td>From LArAT and CERN Prototype</td>
</tr>
<tr>
<td>Electron Energy Resolution</td>
<td>$0.15/\sqrt{E(\text{MeV})}$</td>
<td>$0.33/\sqrt{E(\text{MeV})}$ [12]</td>
<td>From LArAT and CERN Prototype</td>
</tr>
<tr>
<td>Energy Resolution for Stopping Hadrons</td>
<td>1–5%</td>
<td></td>
<td>From LArAT and CERN Prototype</td>
</tr>
<tr>
<td>Stub-Finding Efficiency $^5$</td>
<td>90%</td>
<td></td>
<td>&gt; 90%</td>
</tr>
</tbody>
</table>
Comparing to single-phase design:

- Higher gain and larger S/N
- Larger fiducial volume
- Lower detection threshold
- 3 mm pitch in x and y readout
- Fewer readout channels: 154k vs 384k for single phase
- Absence of dead material in LAr volume