Lecture notes version: some annotations added and slides/overlays condensed with respect to the version shown during the school.
<table>
<thead>
<tr>
<th>Lecture I: Broad Survey of Past Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>✨ <strong>Inverse Beta Decay</strong></td>
</tr>
<tr>
<td>- <em>Discovery of the</em> $\nu$</td>
</tr>
<tr>
<td>- <em>KamLAND, LSND</em></td>
</tr>
<tr>
<td>✨ <strong>Tracking Detectors</strong></td>
</tr>
<tr>
<td>- <em>Two $\nu$ Experiment</em></td>
</tr>
<tr>
<td>- <em>NuTeV, MINOS, CHARM II</em></td>
</tr>
<tr>
<td>✨ <strong>Bubble Chambers</strong></td>
</tr>
<tr>
<td>- <em>Discovery of Neutral Currents</em></td>
</tr>
<tr>
<td>✨ <strong>Hybrid Detectors:</strong></td>
</tr>
<tr>
<td>- <em>MINER$\nu$A, NOMAD</em></td>
</tr>
<tr>
<td>- <em>Discovery of Tau Neutrino</em></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lecture II: The Challenges for $\nu_e$ Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>✨ <strong>Water Cherenkov</strong></td>
</tr>
<tr>
<td>- <em>Super-Kamiokande</em></td>
</tr>
<tr>
<td>✨ <strong>Segmented Scintillator</strong></td>
</tr>
<tr>
<td>- <em>NO$\nu$A</em></td>
</tr>
<tr>
<td>✨ <strong>Liquid Argon TPC</strong></td>
</tr>
<tr>
<td>- <em>ICARUS &amp; future experiments</em></td>
</tr>
</tbody>
</table>

*Mixed throughout: fundamental physics of particle interactions, principles of operation of detector elements. Lots of diagrams, photos, and event displays.*
So, you want to build a neutrino detector?

- How many events do you need to detect?
  This determines detector mass.
- What kind of interaction? $\nu_e$, $\nu_\mu$, $\nu_\tau$, NC?
- What do you want to measure: Energy? Final states?
  This influences detector technology.
- What sorts of backgrounds do you expect?
  How much can you tolerate?
  More influence on detector technology, maybe conflicting.
- How much money do you have?
  Detector technology, mass, time...
Challenge of $\nu_e$ Appearance

- Accelerator beam flux: $100 \times 10^6 \, \nu /\text{cm}^2/\text{5 yr}$
- Oscillation Probability: 1-10%
- Event rates: CC $\nu_\mu / \text{NC} / \nu_e$: 10K / ~800 / 200 events
- Signal Efficiency / BG: 40% / 20 events
- Mass of detector: 22.5 kt

... and something comparable for NO$\nu_A$.

And then... let’s in the future try to measure a difference in $\nu_e$ versus anti-$\nu_e$ appearance to demonstrate CP violation. Need more intense beam and bigger detector. See strategy lectures.
Neutrino Interactions

![Graph showing neutrino interactions with energy distribution and oscillation effects.](Image)
**Water Cherenkov**

**SK-I: 1996-2001**
22.5 kton fiducial volume (2m from wall)
11146 50-cm inner PMTs, 40% coverage
1885 20-cm outer PMTs

**SK-II: Jan 2003-Oct 2005**
Recovery from accident
5182 50-cm inner PMTs
Acrylic + FRP protective
Outer detector fully restored

**SK-III: May 2006-**
Restored 40% coverage
Outer detector segmented (top | barrel | bottom)

**SK-future:**
Replace all electronics - 2008
Add Gadolinium - 20??
Super-Kamiokande III  (newly rebuilt, filling in May 2006)
Cherenkov Effect

Applications:
- Calorimetry - water, lead glass
- Threshold counters (adjust n)
- Air Cherenkov - gamma ray astronomy
- Particle ID by Cherenkov angle + momentum

Cherenkov Radiation in Water (n = 1.33)

\[ \cos \theta = \frac{1}{\beta n} \]
\[ \beta \text{ threshold } = 0.75 \]
\[ \theta \rightarrow 41^\circ = \theta_c \text{ as } \beta \rightarrow 1 \]

at $\beta=1 \sim 770$ photons/cm emitted ($\lambda$ 300-600 nm)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Cherenkov Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p$(MeV/c)</td>
</tr>
<tr>
<td>electron</td>
<td>0.58</td>
</tr>
<tr>
<td>muon</td>
<td>119.</td>
</tr>
<tr>
<td>pion</td>
<td>158.</td>
</tr>
<tr>
<td>kaon</td>
<td>560.</td>
</tr>
<tr>
<td>proton</td>
<td>1063.</td>
</tr>
</tbody>
</table>

Neutrino Detectors - Ed Kearns - Fermilab/KEK Neutrino Summer School - 2007
“Tracking”

Vertex, direction, momentum

- Find position where $t_i$-TOF($x,y,z$) is most peaked
- Correct for length of muon track
- Correct for PMT acceptance (#photons) and attenuation
- Incorporate PID by expected light pattern
- Assign momentum by #pe and fit Cherenkov angle
Particle Identification

Compare observed and expected light pattern and Cherenkov angle using likelihood

N.B. This is an SK-II event (from K2K)
Ring Finding

Hough transform

Becomes peak finding problem

b) Tube hits in \( \theta - \phi \) space

- Number of events vs. \( L \):
  - Sub-GeV-like
  - Single-ring
  - Multi-ring

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Signal and Background

Further cuts:

<table>
<thead>
<tr>
<th></th>
<th>CC $\nu_\mu$</th>
<th>NC</th>
<th>signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>no decay e</td>
<td>14%</td>
<td>19%</td>
<td>76%</td>
</tr>
<tr>
<td>E window</td>
<td>1%</td>
<td>16%</td>
<td>58%</td>
</tr>
<tr>
<td>pi0 likelihood</td>
<td>0.40%</td>
<td>10%</td>
<td>42%</td>
</tr>
</tbody>
</table>
Muon Decay

0 20 40 60 80 100 120 140 500 1000 1500 2000
timing (nsec)

μ → e 崩壊が起きる期待値
(τ ~ 2 μs)

測定結果

time difference (μsec)

Neutrino Detectors - Ed Kearns - Fermilab/KEK Neutrino Summer School - 2007
Super-Kamiokande
Run 999999 Sub 113 Ev 31624
03-05-19 03:45:00 0030 0000 0002
Inner: 3641 hits, 13498 pM
Outer: 3 hits, 2 pM (in-time)
Trigger ID: 0x03
D wall: 769.0 cm
PC e-like, p = 1483.6 MeV/c

Charge (pe)
- 21.8
- 19.1-21.8
- 16.5-19.1
- 14.2-16.5
- 12.0-14.2
- 10.0-12.0
- 8.2-10.0
- 6.5-8.2
- 5.1-6.5
- 3.8-5.1
- 2.7-3.8
- 1.8-2.7
- 1.1-1.8
- 0.5-1.1
- 0.2-0.5
- < 0.2

Times (ns)
Super-Kamiokande

Run 999999 Sub 113 Ev 31624
03-05-19:09:45.09 0000 0000 0000
Inner: 3641 hits, 13490 pC
Outer: 3 hits, 3 pC (in-time)
Trigger ID: 0x03
D wall: 789.0 cm
FC e-like, p = 1483.6 MeV/c
Super-Kamiokande

Run 999999 Sub 113 Ev 31624
03-05-19:09:45:09 0000 0000 0002
Inner: 3641 hits, 13490 pM
Outer: 3 hits, 3 pM (in-time)
Trigger ID: 0X03
D wall: 789.0 cm
PC e-like, p = 1483.6 MeV/c

$t_{PMT} - TOF(x, y, z)$

Resid(ns)
- > 137
- 120 - 137
- 102 - 120
- 85 - 102
- 68 - 85
- 51 - 68
- 34 - 51
- 17 - 34
- 0 - 17
- -17 - 0
- -34 - -17
- -51 - -34
- -68 - -51
- -85 - -68
- -102 - -85
- < -102

1-ring e-like

Times (ns)
Monte Carlo Vectors

<table>
<thead>
<tr>
<th>Particle</th>
<th>Energy (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>691</td>
</tr>
<tr>
<td>pi0</td>
<td>1442</td>
</tr>
<tr>
<td>gamma</td>
<td>245</td>
</tr>
<tr>
<td>gamma</td>
<td>1204</td>
</tr>
</tbody>
</table>

1-ring e-like
E reconstructed 1.7 GeV

Note: this event is well above the T2K reconstructed energy window (350-850 MeV). But it is in the range for the first maximum at T2KK or FNAL-DUSEL.
Segmented Scintillator

(nearly) *fully active target* and tracking medium
high spatial resolution
SciBath  FINeSSE

Vertex Detector side view:

- Liquid scintillator
- WLS fiber array
- PMTs + on-board electronics

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NOvA

Off-axis from NuMI beam
810 km baseline
E ~ 2.2 GeV narrow band

~20 kton totally active detector
(build as much as can afford)

Planes of liquid scintillator (mineral oil) read by WLS fiber and APD
Surface detector with small overburden (below)
One is Signal, One is Background

\[ \nu_e + p \rightarrow e^- + p + \pi^+ \]

\[ \nu_\mu + N \rightarrow \nu_\mu + p + \pi^0 \]
Liquid Argon TPC
Principle of Operation: LAr TPC

Charge yield ~ 6000 electrons/mm
(~ 1 fC/mm)

UV Scintillation Light: L

Light yield ~ 5000 γ/mm

Drift direction

Low noise Q-amplifier

Continuous waveform recording

Neutrino Detectors - Ed Kearns - Fermilab/KEK Neutrino Summer School - 2007
...an electronic bubble chamber

Gargamelle bubble chamber

Bubble diameter ~ 3 mm (diffraction limited)

ICARUS electronic chamber

Bubble size ~ 3x3x0.4 mm³

<table>
<thead>
<tr>
<th>Medium</th>
<th>Heavy freon</th>
<th>Liquid Argon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitive mass</td>
<td>3.0 ton</td>
<td>Many ktons</td>
</tr>
<tr>
<td>Density</td>
<td>1.5 g/cm³</td>
<td>1.4 g/cm³</td>
</tr>
<tr>
<td>Radiation length</td>
<td>11.0 cm</td>
<td>14.0 cm</td>
</tr>
<tr>
<td>Collision length</td>
<td>49.5 cm</td>
<td>54.8 cm</td>
</tr>
<tr>
<td>dE/dx</td>
<td>2.3 MeV/cm</td>
<td>2.1 MeV/cm</td>
</tr>
</tbody>
</table>
ICARUS
ICARUS T300 prototype

C. Rubbia at Fermilab October 2005 “20 years of liquid Argon technology”

Neutrino Detectors - Ed Kearns - Fermilab/KEK Neutrino Summer School - 2007
LAr at T2K 2KM (proposed)

A 100 ton detector for the 2 km site of the T2K experiment

Number of interactions per $10^{21}$ p.o.t. on a 100 ton LAr detector

<table>
<thead>
<tr>
<th>Flavour</th>
<th>CC (QE)</th>
<th>NC</th>
<th>TOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>190763 (121859)</td>
<td>26253</td>
<td>217016</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$</td>
<td>8023 (2764)</td>
<td>2063</td>
<td>10086</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>3704 (1372)</td>
<td>725</td>
<td>4429</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>372 (96)</td>
<td>100</td>
<td>472</td>
</tr>
</tbody>
</table>

Neutrino Detectors - Ed Kearns - Fermilab/KEK Neutrino Summer School - 2007
One is signal the other is background
<table>
<thead>
<tr>
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<tr>
<td>gamma</td>
<td>245 MeV/c</td>
</tr>
<tr>
<td>gamma</td>
<td>1204 MeV/c</td>
</tr>
</tbody>
</table>
Challenges for Huge LAr TPC

Goal is ~100 kton for CP-violation class experiments

Highly desirable to be underground to also search for proton decay ($p \rightarrow K^+ \nu$ especially promising).

Largest existing detector is 600t ICARUS at Gran Sasso

R&D needed to develop multi-kton detector.
Purification, long drift, (optional) operation in magnetic field, charge amplification, safety …

It is generally assumed that 100 kton LAr and 300 kton water Cherenkov are competitive for CP-violation class neutrino experiments. Higher efficiency makes up for lower mass. Water Cherenkov signature performance is good sub-GeV, but becomes worse at higher energies (above few GeV).

Monte Carlo
Megaton Scale
Water
Cherenkov
Detectors
Hyper-Kamiokande

2 detectors 48m x 50m x 250 m
1 Mton total mass
What’s stopping us from making even bigger water Cherenkov detectors?

(1) PMT fabrication time dominates the schedule

(2) Cost: scaling from SK with no savings, 100K tubes ~ 300M$

Preliminary and hypothetical
## 40% or 20% Photon Coverage?

<table>
<thead>
<tr>
<th></th>
<th>Super-K I (40% coverage)</th>
<th>Super-K II (20% coverage)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sub-GeV vertex resolution</strong></td>
<td>26 cm (e-like) / 23 cm (μ-like)</td>
<td>30 cm (e-like) / 29 cm (μ-like)</td>
</tr>
<tr>
<td><strong>Sub-GeV particle mis-ID</strong></td>
<td>0.81% (e-like) / 0.70% (μ-like)</td>
<td>0.69% (e-like) / 0.96% (μ-like)</td>
</tr>
<tr>
<td><strong>Sub-GeV momentum resolution</strong></td>
<td>4.8% (e-like) / 2.5% (μ-like)</td>
<td>6.3% (e-like) / 4.0% (μ-like)</td>
</tr>
<tr>
<td>p→e⁺π⁰ signal efficiency</td>
<td>40.8±1.2 ±6.1%</td>
<td>42.2±1.2 ±6.3%</td>
</tr>
<tr>
<td>p→ e⁺π⁰ background</td>
<td>0.39(±35%) events/100kty</td>
<td>0 events/100kty</td>
</tr>
<tr>
<td>p→ K⁺ν, γ tag signal efficiency</td>
<td>8.4±0.1 ±1.7%</td>
<td>4.7±0.1 ±1.0%</td>
</tr>
<tr>
<td>p→ K⁺ν, γ tag background</td>
<td>0.72(±28%) events/100kty</td>
<td>1.4(±30%) events/100kty</td>
</tr>
<tr>
<td>p→ K⁺ν, π⁺π⁰ signal efficiency</td>
<td>5.5±0.1 ±0.7%</td>
<td>5.7±0.1 ±0.4%</td>
</tr>
<tr>
<td>p→ K⁺ν, π⁺π⁰ background</td>
<td>0.59(±28%) events/100kty</td>
<td>1.0(±30%) events/100kty</td>
</tr>
<tr>
<td><strong>T2K CCνₑ likelihood effic.</strong></td>
<td>83.7% (±0.1% stat)</td>
<td>84.8%</td>
</tr>
<tr>
<td><strong>T2K BG likelihood effic.</strong></td>
<td>21.3 %</td>
<td>21.5 %</td>
</tr>
</tbody>
</table>

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F. Dufour, T2KK Workshop (2006)

Preliminary numbers, for comparison purposes. Final published efficiencies and BG may differ.
# Hybrid Avalanche Photodiode


<table>
<thead>
<tr>
<th>Parameters</th>
<th>13-inch HPD</th>
<th>20-inch PMT (R3600-02)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order of Gain</td>
<td>$10^5$</td>
<td>$10^7$</td>
</tr>
<tr>
<td>Single Photon Time Resolution ((\sigma))</td>
<td>190ps</td>
<td>2300ps</td>
</tr>
<tr>
<td>Single Photon Energy Resolution</td>
<td>44% (preliminary)</td>
<td>150%</td>
</tr>
<tr>
<td>Rise Time</td>
<td>1ns</td>
<td>10ns</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>2.2ns</td>
<td>20ns</td>
</tr>
<tr>
<td>Dynamic Range (Signal intensity in P.E.)</td>
<td>3000 p.e.</td>
<td>1000 p.e.</td>
</tr>
</tbody>
</table>
Conclusions

Neutrino detectors:

What do you want from the final state?
What does your experiment demand in terms of signal, background, event reconstruction?

Design based on interplay of:
Mass - Granularity - Cost

Next generation (+100 kton) will likely be:
Water Cherenkov (cheap, so to speak)
Liquid Argon (if we can learn how)

Thanks for all the good questions,
let's go to the barbecue!

Special thanks to: