Detectors in Neutrino Physics

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Disclaimer & Acknowledgements

• Disclaimer
  – Cannot show or explain every neutrino detector. This will be a selection of detectors and their principles.
  – Will try to convey principles and important considerations in detector design and neutrino measurements.

• Acknowledgements
Outline

• world of neutrino detectors
• neutrino sources
• historical perspective
  – lessons from the pioneers
• neutrinos as a probe - probing neutrinos
• experimental challenges
  – cross-sections
  – detector segmentation and backgrounds
• detectors in neutrino physics
  – detection channels
  – particle signatures
  – present and future
Neutrino physics: problems and methods

- Mass
- Dirac/Majorana
- Magnetic moments
- Oscillation/sterile neutrinos
- Astronomy
- Cosmology
- Geology
- Radioactive sources
- Reactor
- Accelerator
- Atmospheric
- Solar
- Astro-objects
- Relic-neutrino
- Earth
- Semiconductor/crystals/gaseous/scintillator
- Liquid scintillator
- Liquid Argon
- Sampling detector
- Emulsion
- Water Cerenkov
- Nuclear chemistry

Y. Wang
Neutrinos from the Big Bang  ~330 neutrinos per cm³

Supernova Neutrinos

Atmospheric Neutrinos

Geo Neutrinos

Accelerator & Reactor Neutrinos

High Energy Cosmic Neutrinos

Solar Neutrinos
Neutrino Energies

Big-Bang neutrinos $\sim 0.0004$ eV

Neutrinos from the Sun $< 20$ MeV depending on their origin.

Atmospheric neutrinos $\sim$ GeV

Antineutrinos from nuclear reactors $< 10.0$ MeV

Neutrinos from accelerators up to GeV ($10^9$ eV)
Neutrino Energy Spectrum

Detectors must match requirements of v source
Neutrino Detector Spectrum

energy - volume correspondence
Neutrino Detector Spectrum

from the very small to the very big

energy - volume correspondence
Historical Perspective:
Lessons from the Pioneers
Postulate of the Neutrino

Chadwick, 1914

\[ N \rightarrow N' + e^- \text{ some nuclei emit electrons!} \]

Reines and Cowan, 1956

“Observation of the Free Antineutrino”

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

Be patient. It is hard and takes a long time.
First Proposal For Direct Detection of Neutrino

Need an intense source of neutrinos
First Antineutrino Detector

Reines and Cowan 1956

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
Observation of the Free Antineutrino

1959 The Savannah River Detector - A new design

*Backgrounds!*

*Second version of Reines’ experiment worked!*

inverse beta decay

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

positron annihilation

n capture
Reines-Cowan Experiment

### Coincidence Event Signature

- **Incident antineutrino**
- **Gamma rays**
- **Positron annihilation**
- **Neutron capture**
- **Inverse beta decay**

**Liquid scintillator and cadmium**

### Event Signal

- **Electric noise**
- **Cosmic ray**

**Ideal to turn off neutrino source!**

Karsten Heeger, Univ. of Wisconsin  
FNAL, February 16, 2012
Fermi’s Theory of Beta Decay

existence of a point-like four fermion interaction

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

Lagrangian of the interaction:

\[ L(x) = -\frac{G_F}{\sqrt{2}} [\bar{\phi}_p(x)\gamma^\mu\phi_n(x)][\bar{\phi}_e(x)\gamma_\mu\phi_\nu(x)] \]

\[ G_F = \text{Fermi coupling constant} = (1.16637 \pm 0.00001) \times 10^{-5} \text{ GeV}^{-2} \]

Fermi’s theory still stands (parity violation added in the 50s).
Fermi’s Idea for Measuring $m_\nu$

**Fig. 5.** Energy distribution curve of the beta-rays.

*Fig. 1.2. Graph from Fermi’s famous paper on the theory of beta decay, showing how the shape of the emitted electron’s energy spectrum varies with neutrino mass.*
Beta Decay

\[ ^6\text{He} \rightarrow ^6\text{Li} + e^- + \nu \]

imaging events

Fig. 1.2. Cloud chamber picture of the decay of He$^6$ (Csikai et al. [1958]).
Neutrinos from Accelerators

High energy $\nu$ from accelerators to study weak interactions

Discovery of Muon Neutrino

1962

\[ \bar{\nu}_\mu + p \rightarrow n + \mu^+ \]
\[ \nu_\mu + n \rightarrow p + \mu^- \]

\( \nu_\mu \) produce nice tracks as they go through the chamber (29 events)
\( e^- \) produce showers as they cross Al (0 events)
Neutral Current Discovery (1973)

Major triumph for the Standard Model

Gargamelle bubble chamber at CERN showing how an invisible neutrino has jogged an electron

Table 1

<table>
<thead>
<tr>
<th></th>
<th>$\nu$-exposure</th>
<th>$\bar{\nu}$-exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of neutral-current candidates</td>
<td>102</td>
<td>64</td>
</tr>
<tr>
<td>No. of charged-current candidates</td>
<td>428</td>
<td>148</td>
</tr>
</tbody>
</table>
Number of Active Neutrinos

Precision studies of Z-line shape, determine number of active light neutrinos

Each separate $\nu_l$ adds to total Z-width.

$$Z^0 \rightarrow q\bar{q}, l\bar{l} \quad N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_\ell} \left( \frac{\Gamma_\ell}{\Gamma_\nu} \right)_{\text{SM}}$$

From LEP, one finds:

$$N_\nu = 2.984 \pm 0.008$$

which argues strongly for only having 3 generations

Big bang nucleosynthesis gives a constraint on the effective number of light neutrinos at $T \sim 1$ MeV:

$$1.2 < N_\nu^{\text{eff}} < 3.3 \quad [99\% \text{ CL}]$$
Search for tau Neutrino

Discovery of \(\tau\) lepton at SLAC (Martin Pearl, 1975)

\[ \rightarrow \text{there should be a corresponding neutrino.} \]

In 1989, indirect evidence for the existence of \(\nu_\tau\) in measurement of \(Z\)-width

\[ \rightarrow \text{no one had directly observed the tau neutrino.} \]

The tau neutrino interact and form a tau that has an 18% probability of decaying to

- a muon and two neutrinos (long event)
- an electron and two neutrinos (short event)

86% of all tau decays involve only 1 charged particle (a kink) which is the particle physicists are looking for in DONUT experiment
Discovery of tau Neutrino

2000

An 800 GeV beam of protons from the TeVatron collides with a block of tungsten

$D_s$ decay into $\tau$ and $\nu_\tau$ neutrino

$$D_s \rightarrow \nu_\tau + \tau$$

$$\tau \rightarrow \nu_\tau + X$$

Experimental Challenges:
- Very short lifetime of the $\tau$.
- $\nu_\tau$ is extremely non-interacting
  (detector must have a very fine resolution).

Detecting a $\tau$ Neutrino

6,000,000 candidate events on tape

4 clean tau events
A $\nu_\tau$ interacted with a nucleon in a steel layer, producing a $\tau$.

Long tau decay because it decays to one charged particle, the electron, and the decay vertex occurs several sheets downstream from the neutrino interaction vertex.

Short tau decay to an electron in less than the distance it takes to traverse an emulsion layer.
“Standard Model” Neutrino Physics

1914  Electron Spectrum in β decay is continuous
1930  Pauli postulates that a new particle is emitted
1933  Fermi names the new particle neutrino and introduces four-fermion interaction
1956  Reines and Cowan discover the neutrino
1962  At least two neutrinos: νe ≠ νμ
1973  Discovery of neutral currents at CERN
1983  Discovery of the W and Z
1989  Measurement of Z width at CERN → Nν=3
2002  tau neutrino discovered.
Production Thresholds and \( \nu \) Source energies

\[ l = e \quad m_e = 0.511 \text{ MeV} \quad P_{\text{thresh}} = 0.511 \text{ MeV} \]
\[ l = \mu \quad m_\mu = 106 \text{ MeV} \quad P_{\text{thresh}} = 112 \text{ MeV} \]
\[ l = \tau \quad m_\tau = 1.78 \text{ GeV} \quad P_{\text{thresh}} = 3.47 \text{ GeV} \]
Neutrinos Properties

Neutrinos in the Standard Model
- point-like
- no charge
- 3ν flavors
- massless ν (ad hoc assumption in Standard Model)
- upper limits on m_ν from kinematic studies.
- weak and gravitational interactions

neutrinos as a clean probe

Discovery of ν_μ and ν_τ
Accelerator studies of ν
Neutrinos Properties

Neutrinos in the Standard Model

- pointlike
- no charge
- 3ν flavors
- massless ν (ad hoc assumption in Standard Model)
- upper limits on $m_ν$ from kinematic studies.
- weak and gravitational interactions

**probing neutrinos = probing new physics beyond SM**

Beyond the Standard Model

- number of mass states?
- Dirac vs Majorana mass?
- magnetic moment?
- mixing parameters
- CP violation?
Neutrinos as a Probe – Probing Neutrinos
Neutrinos as a Probe

Understanding Matter and Interactions with Neutrinos

- Reines-Cowan $\nu$ discovery and the BNL $2\nu$ experiment
- fundamental $\nu$ properties

- hadronic weak currents
- observation of neutral currents
- cross sections

Bubble Chambers: BNL, ANL, FNAL, CERN, Serpukhov

counter experiments: CDHS, CHARM, CCFR, NuTEV

- structure functions ($F_2, F_3$)
- parton universality
- electroweak studies $\sin^2(\theta_W)$
- strange sea studies
- QCD measurements
- cross sections

Neutrinos as probes to understand matter and interactions
Neutrinos as a Probe

Understanding Astrophysics

Reines-Cowan \( \nu \) discovery and the BNL 2\( \nu \) experiment

fundamental \( \nu \) properties


solar neutrinos

SN1987A observation of astrophysical neutrinos
Probing Neutrinos

Neutrino Masses and Mixing, Non-Standard Effects

searches for neutrino oscillation with intense sources of $v_e, \bar{v}_e, v_\mu, \ldots$
Experimental Challenges:

Cross-Sections
Detector Segmentation and Backgrounds
First Neutrino Cross-Section Calculation

1934 Bethe-Peirls: calculation of first cross-section for inverse beta

\[ \bar{\nu}_e + p \rightarrow n + e^+ \quad \text{or} \quad \nu_e + n \rightarrow p + e^- \]

using Fermi theory

\[ \sigma \approx 5 \times 10^{-44} \, \text{cm}^2 \quad \text{for} \quad E(\bar{\nu}) = 2 \, \text{MeV} \]

Accurate to factor 2

Conversion from natural units:

\[ \hbar c = 197.3 \, \text{MeV} \cdot \text{fm} \]

Cross-section: multiply by \( (\hbar c)^2 = 0.3894 \times 10^{-27} \, \text{GeV}^2 \cdot \text{cm}^2 \)

Mean free path of antineutrino in water:

\[ \lambda = \frac{1}{n \sigma} \approx 1.5 \times 10^{21} \, \text{cm} \approx 1600 \, \text{light - years} \]

\[ n = \frac{\text{num. free protons}}{\text{volume}} \approx 2 \frac{N_A}{A} \rho \]

In water:

\[ n = \frac{2 \times 6 \times 10^{23}}{18} = 6.7 \times 10^{22} \, \text{cm}^{-3} \]

- Probability of interaction:

\[ P = 1 - \exp \left( - \frac{L}{\lambda} \right) \approx \frac{L}{\lambda} = 6.7 \times 10^{-20} \, (\text{m water})^{-1} \]

Need very intense source of antineutrinos to detect inverse beta reaction.
Neutrino Cross Section is Small

Weak interactions are weak because of the massive W and Z boson exchange

\[ \sigma^{\text{weak}} \propto G_F^2 \propto \left(\frac{1}{M_W \text{ or } Z}\right)^4 \]

\[ G_F = \frac{\sqrt{2}}{8} \left(\frac{g_W}{M_W}\right)^2 = 1.166 \times 10^{-5} / \text{GeV}^2 \quad (g_W \approx 0.7) \]

For 100 GeV neutrinos:

\[ \sigma(\nu e) \approx 10^{-40} \]
\[ \sigma(\nu p) \approx 10^{-36} \text{ cm}^2 \]
\[ \sigma(pp) \approx 10^{-26} \text{ cm}^2 \]

Mean free path length in steel \( \sim 3 \times 10^9 \) m

→ Need big detectors and lots of \( \nu \)'s
Energy dependence

- target description is different depending on the $\nu$ energy

- $\nu$-nucleon elastic scattering (nucleon form factors)
- can also create resonances

- $\nu$-quark inelastic scattering (parton density functions)

10 MeV 50 MeV 100 MeV 1 GeV 100 GeV TeV
Energy dependence

- solar, reactor
- supernova
- atmospheric
- accelerator
- galactic or extra-galactic

- also, treatment of **nuclear effects** is energy dependent …

  - shell model, 
  - RPA, EFT
  - impulse approximation
  - quark parton model
  - (Fermi Gas, spectral functions, etc.)
Energy Dependence of Neutrino Interactions

Searching for new effects (Coherent $v$-$A$ scattering)

Coherent $v$-$A$ elastic $\sigma \sim 10^{-39}$ cm$^2$

Max Energy of recoil nucleus $\sim 2E_{\nu}^2 / M$

SM process

Understanding neutrino oscillations and cross-sections
Detector Segmentation

Detectors are often homogeneous due to large size requirement

Geometries

- **Segmented (sampling):** Instrumented in small volumes. Target may not be the active detector element.
- **Unsegmented (fully active):** Volume instrumented as a whole. Target is active detector element

Background Suppression

- Passive shielding from cosmic rays at ~200Hz/m² on surface
  - segmented may be OK on surface
  - unsegmented go underground
- Time correlation with neutrino source (e.g. beam)
- Active background discrimination
Detectors in Neutrino Physics:

Detection Channels
Particle Signatures
Neutrino Detection and Particle Signatures

Detect particles when neutrinos interact with nuclei or electrons bound to nuclei

Neutral Current (NC)

Charged Current (CC)

Elastic Scattering (ES)
Elastic Scattering (ES)

Cross-sections for nucleons turn off below 200 MeV. At low energies we can use target containing free nucleons, or neutrino-electron elastic scattering.

**Elastic Scattering**
- electron sent primarily in forward direction
- energy of electron $\sim$ uniformly distributed between 0 and $E_v$
- $\sigma_{CC}/\sigma_{NC} \sim 1/6$
Charged Current (NC) and Neutral Current (NC)

**Charged Current**
- outgoing lepton tags incoming $\nu$ flavor
- nearly all $\nu$ energy is deposited in the detector
- rates affected by (active) neutrino oscillations

**Neutral Current**
- only hadrons present, no information on incident neutrino flavor
- NC rates not affected by oscillation
- in many cases NC events are background to the CC processes
Neutrino Detection and Particle Signatures

- **dE/dx from Bethe Bloch**
- e⁻ will create Bremsstrahlung, e⁺e⁻

**Ionization loss**

**Electromagnetic showers**

- Similar to EM shower but different interactions
- π⁰ are produced which decay to photons, which the proceed electromagnetically
- Neutrons may be made in shower which show no visible energy

**Hadronic showers**
Neutrino Detection and Particle Signatures

Cherenkov Light

- Electron neutrino $\nu_e$
- Electron $e^-$
- Protons $p$
- Deuteron $n_p$
- Neutrino $\nu$
- Electron $e^-$

The Cherenkov radiation from a muon produced by a muon neutrino event yields a well-defined circular ring in the photomultiplier detector bank.

The Cherenkov radiation from the electron shower produced by an electron neutrino event produces multiple cones and therefore a diffuse ring in the detector array.

Lattice of photomultipliers

Shielded and optically transparent medium
TeO₂ Bolometer: Source = Detector

For $E = 1$ MeV: $\Delta T = E/C \approx 0.1$ mK

Signal size: 1 mV

voltage signal $\propto$ energy deposited

Time constant: $\tau = C/G = 0.5$ s

Energy resolution: $\sim 5-10$ keV at 2.5 MeV
Neutrino Detection and Physics Goals

- **Neutrino Oscillation Measurement**
  - identify flavor of neutrino
    - unique flavor channels (e.g. SNO)
    - lepton identification (e.g. accelerator)
  - measure energy

- **Neutrino Interaction Measurement**
  - measure different interaction channels
  - measure total energy of events (all final states)
  - identify neutrino vs antineutrinos
  - initial and final nucleus (for nuclear effects)
Detectors in Neutrino Physics: Present and Future
Cl-Ar Solar Neutrino Experiment at Homestake

$\nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^-$

only sensitive to $\nu_e$

SSM

Karsten Heeger, Univ. of Wisconsin

FNAL, Fermilab
Neutrino Detection in SNO

Neutrino Interactions on Deuterium and their Flavor Sensitivity

**Charged-Current (CC)**

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

\[ E_{\text{thresh}} = 1.4 \text{ MeV} \]

*Measurement of energy spectrum*

**Neutral-Current (NC)**

\[ \nu_x + d \rightarrow \nu_x + n + p \]

\[ E_{\text{thresh}} = 2.2 \text{ MeV} \]

*Measures total $^8$B flux from Sun*

**Elastic Scattering (ES)**

\[ \nu_x + e^- \rightarrow \nu_x + e^- \]

*sensitivity to all neutrino flavors*
Neutrino Detection in SNO
Super-Kamiokande

atmospheric neutrinos
Super-Kamiokande

atmospheric neutrinos

40% coverage

20% coverage
Super-Kamiokande

atmospheric neutrinos

$\nu_e$ CC

2 GeV visible energy

one is signal, one is background

$\pi^0$ decay at high energy

NC $\pi^0$
Super-Kamiokande

solar neutrinos

Through electron scattering
MiniBoone

total volume: 800 tons (6 m radius)
fiducial volume: 445 tons (5 m radius)
1280 PMTs in detector at 5.5 m radius
10% photocathode coverage
240 PMTs in veto

electron ring

μ ring

Events courtesy G. Zeller

Cherenkov events in oil
A common issue: photo detection for large water/scintillator/LAr detectors

low cost, single PE, low background,…

- **Large area, low cost MCP**

  - All (cheap) glass
  - Anode is silk-screened

R&D project by Henry Frisch et al.
Reactor Neutrino Experiments

KamLAND

inverse beta decay
\[ \nu_e + p \rightarrow e^+ + n \]

Near-Far Concept

multiple detectors cancel systematics

distance \( L \sim 1.5 \text{ km} \)
Sampling detectors for neutrino beams

- **Absorber:** Pb, Fe, …
- **Sensitive detectors:** Emulsion Films (OPERA), Plastic (MINOS) and Liquid (NOVA) Scintillators, RPC (INO), …
- **Near detector issues:** hybrid detector system to monitor neutrino/muon flux & beam profile
Tracking Calorimeters
# Neutrino Detectors

<table>
<thead>
<tr>
<th>Exp’t</th>
<th>$\nu$ Energy (GeV)</th>
<th>Detector Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>MINOS</td>
<td>2-6</td>
<td>Steel Scintillator</td>
</tr>
<tr>
<td>MINERvA</td>
<td>1-20</td>
<td>Solid Scintillator</td>
</tr>
<tr>
<td>OPERA</td>
<td>15-25</td>
<td>Emulsion-Lead</td>
</tr>
<tr>
<td>ICARUS</td>
<td>15-25</td>
<td>Liquid Argon TPC</td>
</tr>
<tr>
<td>T2K</td>
<td>0.7</td>
<td>Water Cerenkov</td>
</tr>
<tr>
<td>NOvA</td>
<td>2</td>
<td>Segmented Scintillator</td>
</tr>
</tbody>
</table>

**Super-K**

$v_e CC$  

**ICARUS**

$\nu_e + A \rightarrow p \pi^+$  

$\nu_e CC$  

**NOvA**

$\nu_e + A \rightarrow \pi^+ e^-$  

**MINERvA**

$e^+ 15 \text{ GeV}, p_t=1.16 \text{ GeV}$

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

**OPERA**

$1\pi^0, 2\gamma, 2\pi_\text{vis}$
To be applicable to neutrino experiments higher density is required. Use liquid Ar instead of gas. Has potential to reach very large masses (100 kt) with ~mm granularity.

- Boiling point: 87 K (compare to N₂ 77 K)
- Density 1.4 g/cc
- Interaction length: 114 cm
- Radiation length: 14 cm
- Moliere radius: 7 cm

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

Icarus T300

ArgoNeut, FNAL
LAr Detectors - Lots of Event Information

for a single event, see $dE/dx$ versus momentum (range)
Detector Comparison

Technology Choice is a Trade-Off

<table>
<thead>
<tr>
<th>Detector Technology</th>
<th>Largest Mass to Date (kton)</th>
<th>( \nu_e )</th>
<th>( \nu_\mu )</th>
<th>( \nu_\tau )</th>
<th>+/-?</th>
<th>Ideal ( \nu ) Energy Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAR TPC</td>
<td>0.6</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>Not yet</td>
<td>huge</td>
</tr>
<tr>
<td>Water Cerenkov</td>
<td>50</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>&lt;2GeV</td>
</tr>
<tr>
<td>Emulsion/Pb/Fe</td>
<td>0.27</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>&gt;.5GeV</td>
</tr>
<tr>
<td>Scintillator++</td>
<td>1 or less</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>huge</td>
</tr>
<tr>
<td>Steel/Scint.</td>
<td>5.4</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
<td>&gt;.5GeV</td>
</tr>
</tbody>
</table>

requirements for next-generation detectors
- signal efficiency
- background rejection (NC)
- probe new/other physics
TPC Experiments

EXO - Search for $0\nu\beta\beta$ in $^{136}\text{Xe}$

Presently have 200 kg of 80% enriched $^{136}\text{Xe}$

LXe TPC

- Symmetric anode planes with charge collection X and Y wire grid (ground)
- 468 avalanche photodiodes (APDs) collect scintillation light
- Field-shaping rings
- Cathode plane (-75 kV)
- Teflon reflectors

One half of TPC during assembly

R&D on Barium tagging
What about a Neutrino Magnetic Moment?

\[ \frac{d\sigma}{dT_e} = \text{weak int} + \frac{\pi\alpha^2 \mu^2}{m_e^2} \left( \frac{1}{T_e} - \frac{1}{E_\nu} \right) \]

Electron Recoil \( T \) (MeV)

\( \nu_e^- - e^- \) from U\(^{235}\) at a reactor
TPC Experiments

Low Electron Recoil Energy Experiment

Experiment at Nuclear Reactors (low energy source of $\nu_e$)

Time Projection Chamber

- $V = 1 \, \text{m}^3$
- $L = 1.6 \, \text{m}$
- $D = 0.9 \, \text{cm}$

High density, relatively low $Z$, good drifting properties

3bar CF$_4$ gas
thank you