Adam Para

NEUTRINO DETECTORS
ART AND SCIENCE OF NEUTRINO DETECTORS

Or rather

Stories about neutrino detection
Lecturing in XXI Century

Many of these talks/lectures are very thoughtful. Many of them are quite complete. Many of them are unbiased. Many of them are very interesting and inspiring.

I have borrowed most of my materials from some of them.
An intricate Web of Neutrino Physics and Experiments

- Mass
- Dirac/Majorana
- Magnetic moments
- Oscillation/sterile neutrinos
- Astronomy
- Cosmology
- Geology
- Reactor
- Accelerator
- Atmospheric
- Solar
- Astro-objects
- Relic-neutrino
- Earth
- Nuclear chemistry
- Water
- Cerenkov
- Emulsion
- Liquid Argon
- Sampling detector
- Liquid scintillator
- Semiconductor crystals
- Gaseous scintillator
- Liquid scintillator
- Semiconductor crystals
- Gaseous scintillator
Neutrino industry
Neutrino Experiments: A Confluence of Multiple Disciplines

- High Energy Physics
- Nuclear Physics
- Radiochemistry
- Chemistry
- Computing
- Electrical Engineering
- Structural Engineering
- Civil Engineering
- Optics
- Photonics
- Geophysics
- Mining
- Nuclear Power Engineering
- Safety
- Cryogenics
- Material Science
- Quality Control
- Helioseismology
Theory of Neutrino Experiment
According to Boris Kayser

\[
\sum_{i}^{\sum_{i}}
\]
Theory of Neutrino Experiment According to Boris Kayser - An Example

John Bahcall

Ray Davies
How the Sun Burns?

- The Sun emits light because nuclear fusion produces a lot of energy.

\[ p + p \rightarrow D + e^+ + \nu_\alpha \]
\[ p + e^- + p \rightarrow D + \nu_\alpha \]
\[ p + D \rightarrow ^3\text{He} + \gamma \]

\[
\begin{array}{c|c|c}
\text{Reaction} & \text{Neutrino endpoint energy (MeV)} \\
\hline
pp & 0.42 \\
pep & 1.44 \\
^7\text{Be} & 0.86 \\
^8\text{B} & 15 \\
\end{array}
\]
Cl-Ar Solar Neutrino Experiment at Homestake

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

1970 - 1994

only sensitive to $\nu_e$
25 years of 'Solar Neutrino Anomaly' – an Amazing Story of Professional Persistence

- Calculated the expected rate of events related to a minute (~$10^{-4}$) fraction of the solar neutrino flux
- 600 tons of a washing powder solution
- 15 unstable atoms produced per month ($\tau=34$ days)
- Atoms extracted and counted with known efficiency

- Experimental results and theoretical calculations agree within a factor of three: given the complexity of a problem a huge success for mere mortals
- Unbelievable confidence in the correctness of the prediction and the understanding of the experiment: trademark of highest level of science
Evolving Physics of/with Neutrinos

- Do neutrinos exist?
- How many different kinds?
- Theory of weak interactions? V-A? Neutral currents?
- Neutrinos as a probe of a nucleon structure and the theory of strong interactions
- Precision tests of the Standard Model
- How many families? Does the $\nu_\tau$ really exist?
- Nature of neutrinos? Dirac vs Majorana?
- Neutrinos as a probe of astrophysical objects: supernovae
- Neutrinos as a probe of the Earth interior
- Neutrinos as a probe of physics beyond the standard model
Neutrino Experiments

- Neutrino source (man-made or natural)
- Neutrino flux (measure, monitor, calculate)
- Neutrino detector

All these elements are quite specific to the physics problem in question. Examples of dual/triple purpose experiments are exceptions rather than a rule.
Neutrino Experiments: What do we Want to Measure?

- Counting neutrino interactions (== cross section)
- Identify the flavor (CC reactions)
- Identify the interaction (NC, CC)
- Measure the parent neutrino energy/spectrum
- Details of the final state (inclusive, exclusive)

Depending on the physics requirements AND the neutrino source AND the neutrino energy range the detectors are completely different.

Not to mention dedicated experiments for neutrino mass measurement and double beta decay experiments.
Neutrinos as a Probe

Understanding Matter and Interactions with Neutrinos

Reines-Cowan ν discovery and the BNL 2ν experiment

fundamental ν 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(θ_w)
strange sea studies
QCD measurements
cross sections

Neutrinos as probes to understand matter and interactions
Probing Neutrinos

Neutrino Masses and Mixing, Non-Standard Effects

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

fundamental $\nu$ properties

searches for neutrino oscillation with intense sources of $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, ...
Sources for neutrino detectors

- double-beta decay
- nuclear reactors
- super-novas
- the sun

- atmospheric neutrinos
- extra galactic sources?
- beta beams?
- neutrino factories?
- particle accelerators

Energy [eV]

10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15}

1 keV 1 MeV 1 GeV 1 TeV 1 PeV

- primarily \( \nu_e \) or anti-\( \nu_e \)
- primarily \( \nu_\mu \) or anti-\( \nu_\mu \)
- mixed \( \nu_e + \nu_\mu \)

at source

- duty cycle \( \approx 1 \)
- duty cycle \( << 1 \)
PRODUCING NEUTRINOS
Comments on Neutrino Beams/Sources

For a precision experiment one needs to know:

- Neutrino beam composition (neutrino/antineutrino contamination)
- Flavor composition (electron neutrino background, tau neutrino component of the beam)
- Total flux of neutrinos (measured or calculated, see the reactor neutrino ‘anomaly’)
- Energy distribution
Conventional Neutrino Beam

Variable Energy Neutrino Beam

Low Energy Beam

proton \rightarrow \text{Target} \rightarrow \text{Horn 1}

Pions with
\begin{align*}
  p_T &= 300 \text{ MeV/c} \quad \text{and} \\
  p &= 5 \text{ GeV/c} \\
  p &= 10 \text{ GeV/c} \\
  p &= 20 \text{ GeV/c}
\end{align*}

Vary \nu beam energy by sliding the target in/out of the 1st horn

High Energy Beam

proton \rightarrow \text{Target} \rightarrow \text{Horn 1}

\text{MINOS Data}

\begin{align*}
  \text{pME} &\quad \text{pHE} & \quad \text{LE}
\end{align*}

\# / 0.5 GeV

\begin{align*}
  700 &\quad 600 & \quad 500 \\
  400 & \quad 300 & \quad 200 \\
  100 & \quad 200 & \quad 300 \\
  10 & \quad 20 & \quad 30
\end{align*}

\begin{align*}
  E_\nu \text{ (GeV)}
\end{align*}

\text{figure courtesy Ž. Pavlović}
For a number of reasons the far and near detectors ‘see’ a different energy spectrum of the ‘same’ beam.

Both beam spectra are correlated: they come from the same parent hadron beam.

Far detector spectrum can be constructed from the event spectrum observed in the near detector.
Off-axis Neutrino Beams

- An un-avoidable consequence of the beam production procedure.
- With some luck could provide a highly optimized (intensity and energy spectrum) beam
Spallation Neutron Source

\( \pi^- \) absorbed by target

\( \pi^+ \) DAR

Target Area

Accelerator based Decay at Rest

E range up to 52.8 MeV

\( \nu_\mu = 29.8 \) MeV

\( \tau \approx 2200 \) nsec

\( \tau \approx 26 \) nsec

\( \sim 99\% \) capture

\( \sim 1 \) GeV

\( \text{Mono-Energetic!} \)
## V-source Proposal Overview

<table>
<thead>
<tr>
<th>Type</th>
<th>channel</th>
<th>Background</th>
<th>Source</th>
<th>Production</th>
<th>Activity (Mci)</th>
<th>Proposal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>$\nu_e e \rightarrow \nu_e e$</td>
<td>radioactivity (managable)</td>
<td>$^{51}\text{Cr}$</td>
<td>$n_{th}$ irradiation in Reactor</td>
<td>in</td>
<td>$&gt;3$</td>
</tr>
<tr>
<td></td>
<td>Compton edge</td>
<td>Solar $\nu$ (irreducible)</td>
<td></td>
<td></td>
<td>out</td>
<td>5-10</td>
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<tr>
<td></td>
<td>$5% E_{res}$</td>
<td>$\nu$ -Source (out ok but in ?)</td>
<td>$^{37}\text{Ar}$</td>
<td>$n_{fast}$ irradiation in Reactor (breeder)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 cm $R_{res}$</td>
<td></td>
<td></td>
<td></td>
<td>out</td>
<td>5</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>$\bar{\nu}_e p \rightarrow e^+ n$</td>
<td>reactor $\nu$ &amp; $\nu$ -Source</td>
<td>$^{144}\text{Ce}$</td>
<td>spent nuclear fuel reprocessing</td>
<td>in</td>
<td>0.005-0.05</td>
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<tr>
<td></td>
<td>$E_{th}=1.8$ MeV</td>
<td>(e$^+$,n) Coincidence</td>
<td></td>
<td></td>
<td>out</td>
<td>0.5</td>
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<tr>
<td></td>
<td>$5% E_{res}$</td>
<td>Background free</td>
<td>$^{90}\text{Sr}$</td>
<td></td>
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<td>-</td>
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<tr>
<td></td>
<td>15 cm $R_{res}$</td>
<td></td>
<td>$^{106}\text{Rh}$</td>
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Th. Lasserre - Neutrino 2012
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DETECTING NEUTRINOS
Experimenting with Neutrinos (especially lately)

- Interacting neutrino flavor of primary importance, charged current reactions a principal detection channel

\[
\begin{align*}
    l &= e \quad m_e = 0.511 \text{ MeV} \quad P_{\text{thresh}} = 0.511 \text{ MeV} \\
    l &= \mu \quad m_\mu = 106 \text{ MeV} \quad P_{\text{thresh}} = 112 \text{ MeV} \\
    l &= \tau \quad m_\tau = 1.78 \text{ GeV} \quad P_{\text{thresh}} = 3.47 \text{ GeV}
\end{align*}
\]
Energy Regimes Available for Studies

- double-beta decay
- nuclear reactors
- super-novas
- the sun
- atmospheric neutrinos
- beta beams?
- extra galactic sources?
- neutrino factories?
- particle accelerators

Energy [eV]

- $10^3$: 1 keV
- $10^4$: 1 MeV
- $10^5$: 1 GeV
- $10^6$: 1 TeV
- $10^7$: 1 PeV

- primarily $\nu_e$ or anti-$\nu_e$
- primarily $\nu_\mu$ or anti-$\nu_\mu$
- mixed $\nu_e + \nu_\mu$

- duty cycle $\approx 1$
- duty cycle $<< 1$
Detection and Measurement of Neutrino Interactions

- **E < 100 MeV**
  - Electron neutrinos and antineutrinos CC only
  - Neutral currents
  - Rate
  - Energy spectra
  - Electron direction

- **100 MeV < E < 1 GeV** (enter muon neutrinos CC)
  - Mostly quasi-elastic interactions, low multiplicity
  - Neutrino energy from kinematics

- **E>1 GeV** (enter, slowly, tau neutrinos CC)
  - Increasingly complex final states
  - Calorimetric measurement of neutrino energy

- **E > 1 TeV**: surprisingly clean separation of neutrino flavors
CC Low Energy Physics

- CC: $\nu_e, \mu + ^{12}\text{C}_{gs} \rightarrow + ^{12}\text{N}_{gs}$
- CC: $\nu_e, \mu + ^{12}\text{C}_{gs} \rightarrow + ^{12}\text{N}^*$
- CC: anti-$\nu_e + p \rightarrow + n$
  - $n + p \rightarrow d + 2.2$ MeV photon

neutron thermalization mean time = 200 $\mu$s

happens so quickly you only see 1 light flash!

two 0.511 MeV photons

one 2.2 MeV photon

- $\nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{N}_{gs}$
- $^{12}\text{N}_{gs} \rightarrow ^{12}\text{C} + e^+ + \nu_e$
- 11 ms half life
Antineutrino Detectors

6 ‘functionally identical’ detectors:
Reduce systematic uncertainties

Target mass measured to 3 kg (0.015%) during filling.

All detectors filled from common GdLS tanks.

192 8” PMTs detect light in target, ~163 p.e./MeV.

Calibration robots insert radioactive sources and LEDs.

Reflectors improve light collection uniformity.
Principal Challenges

- Light yield (⇒ energy resolution)
- Radiopurity (⇒ low detection thresholds)
- Gd loading
- Transparency (light attenuation)
- Photodetector coverage (⇒ affordable photodetectors)
Neutrino detection channels

**Charged-current**

- $v_e$ -> electron shower
- $v_\mu$ -> hadrons
- $v_\tau$ -> tau decay

**Neutral-current**

- $v_{e,\mu,\tau}$ -> hadrons

- In charged-current (CC) events outgoing lepton tags incoming neutrino flavor.
  - In the case of $v_\tau$, the presence of a $\tau$ must be deduced from the $\tau$ decay products.

- In CC events nearly all the neutrino energy is deposited in the detector.

- In neutral-current events, only hadrons are present and no information about the incident neutrino flavor is available.

- CC rates are affected by oscillations.

- NC rates are not affected by oscillations.
  - In only a few analyses are NC events considered to be signal. In most cases NC events are backgrounds to the CC processes.
Discovery of the muon neutrino (1962)

Leon M. Lederman
Melvin Schwartz
Jack Steinberger

[Nobel prize 1988]

Melvin Schwartz in front of the spark chamber used to discover the muon neutrino

Single muon event from original publication
A Bubble Chamber: Ultimate Tracking Detector

The 'Neutrino Event'
Nov. 13, 1970 — World’s first observation of a neutrino in a hydrogen bubble chamber
A Perfect Experiment: GGM at PS

A single event a tantalizing hint.

Three events a major discovery

Precision view of the final state of critical importance.
Difficult Experiment: Search for NC with GGM at PS

- Exquisite view of the final state.
- Clear interaction of a neutral particle with no muon or electron in the final state.
- Neutrino or neutron?
- It is not detector alone which decides about the quality of the experiment. Beam and environment is an important factor too.
High Energy Neutrino Era: Decline of the Bubble Chambers

Leakage of hadronic shower
Muon identification
Confusion caused by electromagnetic showers form pi-zeros
(typical) Detector Requirements

- Large volume (inexpensive, please)
- Identify the flavor of the neutrino (i.e. identify the charged lepton)
- Measure the total energy of the event (~ estimator of the neutrino energy)
- Provide some kinematical information about the event (direction of a hadronic jet)
- Determine the direction of the incoming neutrino
Quasi-elastic reconstruction \( \nu_\mu + n \rightarrow \mu^- + p \)

\[
E_\nu = \frac{m_N E_l - m_l^2/2}{m_N - E_l + p_l \cos \theta_l}
\]

From 2 body kinematics

Figure 2: (left) The scatter plots of the reconstructed neutrino energy versus the true one for \( \nu_\mu \) events. The method of the energy reconstruction is expressed in Equation 14. (right) The energy resolution of \( \nu_\mu \) events for 2 degree off-axis beam. The shaded (red) histogram is for the true QE events.
Cherenkov detectors

Super-Kamiokande

**SNO**
- 6000 mwe overburden
- 1000 tonnes $\text{D}_2\text{O}$
- 12 m Diameter Acrylic Vessel
- 1700 tonnes Inner Shield $\text{H}_2\text{O}$
- Support Structure for 9500 PMTs, 60% coverage
- 5300 tonnes Outer Shield $\text{H}_2\text{O}$

**Ice Cube**

**MiniBooNE Detector**
- Signal Region
- Veto Region

**ANTARES**

**NEMO**
Why Take This Approach?

- **Large Size**: for rare events, low fluxes
- **Low Threshold**: 3 MeV with high efficiency
- **Excellent e/μ**: >99% νμ rejection in T2K νe data
- **Low cost/kton**
- **Free protons**
- **Mature technology**: short development time
- **Safety, Maintenance, Accessibility**
Particle ID Using Cerenkov Light

From side
short track, no multiple scattering

electrons: short track, mult. scat., brems.

muons: long track, slows down

neutral pions: 2 electron-like tracks

Ring
Sharp Ring
Fuzzy Ring
Sharp Outer Ring with Fuzzy Inner Region
Two Fuzzy Rings
Water Cherenkov: e/μ identification

- At low momenta one can correlate the particle visible energy with the Cherenkov angle. Muons will have "collapsed" rings while electrons are almost always at 42°.

- At higher momenta, look at the distribution of light around Cherenkov angle. Muons are "crisp", electron showers are "fuzzy". See plots and figures at the right.

Figures from M. Earl's PhD Thesis

Figures from http://hep.bu.edu/~superk/amnu/
MiniBoone

total volume: 800 tons (6 m radius)
iducial 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
Challenges of High Energies
Tracking Calorimeters
CDHS(W): magnetized iron-scintillator calorimeter

CHARM: marble - drift tubes

Fig. 13. Pattern of tube hits for two typical events: (a) electron-induced, (b) pion-induced.
MINOS Event

\[ \nu_\mu \rightarrow \nu_\mu \]
Interactions Classification with Iron-Scintillator Tracking Calorimeter (MINOS)
The Ultimate Tracking Calorimeter

- Fully active
- Good energy resolution
- Excellent electron identification
- Good electron-pizero rejection
Sample signal and background events in NOvA

\[ \nu_\mu N \rightarrow \nu_\mu p \pi^0 \]
\[ E_\nu = 10.6 \text{ GeV} \]
\[ E_p = 1.04 \text{ GeV} \]
\[ E_{\pi^0} = 1.97 \text{ GeV} \]

\[ \nu_e p \rightarrow e^- p \pi^+ \]
\[ E_\nu = 2.5 \text{ GeV} \]
\[ E_e = 1.9 \text{ GeV} \]
\[ E_p = 1.1 \text{ GeV} \]
\[ E_{\pi^+} = 0.2 \text{ GeV} \]
$\nu_\mu$ (1.4 GeV) + N $\rightarrow$ $\mu$ (1.0 GeV) + X (QEL)

Color code for hits:
e $\mu$ p $\pi$

Proton ID from dE/dx

$\nu_\mu$ Quasi-Elastic Event
Searching for tau neutrinos
With Nuclear Emulsions

Exquisite spatial resolution and granularity
The New Principle

- Intense, high-energy long baseline muon-neutrino beam
- Massive active target with micrometric space resolution
- Detect tau-lepton production and decay
- Underground location
- Use electronic detectors to provide “time resolution” to the emulsions and preselect the interaction region
Proof of the Pudding
An Alternative Approach: Kinematical Reconstruction

νμ CC event in the NOMAD detector

1. Veto wall
2. Drift chambers
3. Trigger plane
4. Transition radiation tracker
5. Trigger plane
6. Preshower region
7. Electromagnetic calorimeter
8. Hadron calorimeter
9. Muon tracking
10. Forward calorimeter
11. Magnet return yoke
12. Magnet
A $\bar{\nu}_e$ CC candidate in NOMAD
NOMAD’s Search of $\nu_\mu \rightarrow \nu_\tau$

- Understanding the Control-samples
  - Data-simulator technique: Control-Data/MC provide the calibration
  - x2 more hits along Z-axis (No $\tau^+$)

- Completely blind analysis
  - Divide search into Low- and High-background regions

- Multivariate analysis: Pt-balance, track-reconstruction, missing-particles

- Improved $4\pi$ $\mu$-ID
  - 4TT-Coverage: min-$P_\mu \geq 0.3$ GeV

Fig. A.1. Definition of the NOMAD kinematics for a $\nu_\tau$ CC event.
The MINERvA Detector

MINOS steel/scintillator detector used as muon ranger
Very High Granularity Tracking Detector

\[
\frac{\sigma}{E} = a \oplus \frac{b}{\sqrt{E}} \oplus \frac{c}{E}
\]

- \(a = 0.119\)
- \(b = 0.268\)
- \(c = 0.0\)
ULTRA HIGH ENERGY NEUTRINOS
10 TeV neutrino induced muon neutrino in Ice Cube

Times differ by roughly 2.5 usec. For PMT with ~10 ns time resolution this gives an up vs. down discrimination of > 250 sigma!
Particle ID in Ice Cube

10 TeV muon neutrino induced upward muon

375 TeV electron neutrino
Ultimate Heavy Liquid Bubble Chamber: Liquid Argon Detectors

- ICARUS T600@LNGS
- ArgoNEUT@FNAL
- MicroBOONE@FNAL
- 250L@JPARC
- LBNE (USA)
- GLACIER (dual phase) (Europe)

- Exquisite granularity/tracking resolution
- Good hadron energy resolution $\Delta E/E \sim 10\%$
ICARUS, LNGS beam
Instead of Summary

- After all these years of experimentation and R&D we have developed experimental techniques which allow us most of the conceivable questions regarding neutrinos.
- However not all the solutions may be affordable.
- Even affordable solutions may not be available all/many at the same time. Global collaboration/coordination may be called for.
- For man-made neutrino beams: physics potential = beam intensity $\times$ detector mass. Careful optimization is necessary.
- Optimization is considerably more difficult if multi-purpose facilities are considered.
- For subtle effects a careful inclusion of systematics: background and efficiencies, calibrations, etc.. is critical..
- We live in a golden age of neutrino physics. Let’s convince others (i.e. funding agencies) about it.