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<td>✉ Inverse Beta Decay</td>
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<td>- Discovery of the $\nu_K$</td>
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<td>✉ Tracking Detectors</td>
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<td>- Two $\nu$ Experiment</td>
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<td>- NuTeV, MINOS, CHARM II</td>
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<td>✉ Bubble Chambers</td>
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<td>- Discovery of Tau Neutrino</td>
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<td>- ICARUS &amp; future experiments</td>
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Mixed throughout: fundamental physics of particle interactions, principles of operation of detector elements. Lots of diagrams, photos, and event displays.
All particle detectors rely on the electromagnetic interaction of the particle with the detector material.

Neutrinos do not have electromagnetic interactions.

Ergo, there is no such thing as a neutrino detector.

However, one can detect the products of neutrino interactions.

The design choices for each detector are very much determined by the properties of the $\nu$ interactions under study, as well as other constraints such as the beam, backgrounds, etc. But in the end, it is the final state particles that are detected through their EM interactions.
Large Mass Required

\[ \text{Rate} = \Phi \times \sigma \times N_{\text{targets}} \]

\[ \Phi(8 \text{~B solar } \nu) = 6 \times 10^6 \text{~cm}^{-2}\text{s}^{-1} \]
\[ \Phi(\text{atm. } \nu) \approx 1 \text{~cm}^{-2}\text{s}^{-1} \]
\[ \sigma(\nu e) \sim 10^{-43} \text{~cm}^2 \text{ (10 MeV)} \]
\[ \sigma(\nu N) \sim 10^{-38} \text{~cm}^2 \text{ (1 GeV)} \]

\[ \Rightarrow 10\text{’s events per day in 22.5 kton Super-K detector} \]

Equivalently, \[ \lambda = \frac{1}{n_{\text{targets}} \sigma} \]: famous light year of lead

Neutrino Detectors - Ed Kearns - Fermilab/KEK Neutrino Summer School - 2007
Neutrino Flavor Identification

**Neutrino Flavors**

- **$\nu_e$**
  - showering
  - Recoiling hadrons (maybe single nucleon)

- **$\nu_\mu$**
  - penetrating
  - threshold $E_\nu > 110$ MeV

- **$\nu_\tau$**
  - challenging
  - threshold $E_\nu > 3.5$ GeV

- **$\nu_{e,\mu,\tau}$**
  - annoyed (frequently background)
  - Recoiling hadrons (maybe single $\pi^0$)

**Reactions**

- $\tau \rightarrow e\nu\nu$ 18%
- $\rightarrow \mu\nu\nu$ 18%
- $\rightarrow 3\pi\nu$ 14%
- $\rightarrow \pi\nu$ 11%
- ...

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Energy Regimes

example: $\text{CC } \nu_\mu$

- **Quasi-elastic**
  - $E < \text{GeV}$

- **Single-pion**
  - $E \sim \text{GeV}$

- **Multi-pion and Deep Inelastic Scattering**
  - $E > \text{several GeV}$

$\nu_\mu$ interaction with a proton:
- Muon
- Pion
- Hadrons: $p,n,\pi,K,\ldots$

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Energy Regimes

example events

$\nu_\mu \rightarrow \mu^+ + p$  
Quasi-elastic  
$E < GeV$

$\nu_\mu \rightarrow \pi^+ + p$  
single-pion  
$E \sim GeV$

Deep Inelastic Scattering  
$E > several GeV$

Note: “World’s First Neutrino Observation in a Bubble Chamber” Nov. 13, 1970, ANL
Interactions with Electrons

Elastic Scattering
[both CC & NC diagrams contribute]

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

Inverse Muon Decay

\[ \nu_\mu + e^- \rightarrow \nu_e + \mu^- \]

Both characterized by very forward scattering angle
Inverse Beta Decay Detectors

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

Excellent detection opportunities

- \(E_{\text{thresh}} = 1.8\text{ MeV}\)
- \(E_{\text{prompt}} = E_\nu - 0.8\text{ MeV}\)
- \(E_{\text{capture}} = 2.2\text{ MeV} \) (on proton, 10-several 100 \(\mu\text{s}\) later)

\[
\sigma = 0.0952 \left( \frac{E_e p_e}{1\text{MeV}^2} \right) \times 10^{-42}\text{ cm}^2 \sim 5 \times 10^{-43}\text{ cm}^2
\]
Discovery of the Neutrino

1956  

1995 Nobel Prize: F. Reines

Data acquisition: oscilloscope traces!
Principle of Detection: Scintillation

Emission of a pulse of light in response to ionization.
10,000-50,000 photons/MeV

Organic liquids & plastics

Inorganic crystals - NaI, CsI, BaF2, BGO

Nobel liquids - Ne, Ar, Xe
KamLAND

30% photo-coverage
1869 PMTs

Liquid scintillator:
80% dodecane
20% psuedocumene
1.5g/l PPO
~8000 photons/MeV
(500 pe/MeV detected)

U/Th purified to below
$10^{-17}$ g/g
KamLAND Event

3.2 MeV e+ 2.2 n capture
$\Delta t = 110$ ms
$\Delta x = 34$ cm

Important detector characteristic:
good fiducial volume determination

$\sigma_{vtx} = 21 \text{cm}/\sqrt{E(\text{MeV})}$
Goal: $\bar{\nu}_e$ appearance in beam of $\bar{\nu}_\mu$.

Beam energy:
$E_\nu \sim 50$ MeV

Dilute mineral oil-based scintillator
0.031 g/l of b-BPD

Allows for Cherenkov light pattern for particle identification

$\sim 30$ pe/MeV

$n = 1.47$

Scint./Cherenkov $\sim 5:1$
Remember the Time Domain

SNO pure $D_2O$ phase
0.5 mb cross section
capture time few 100 $\mu$s
6.3 MeV gamma
capture on $^1H$ is 0.33b

SNO salt-phase
44 b cross section
capture time 5.3 $\mu$s
8.6 MeV total gammas

Gadolinium
49,700 b cross section
Used for $n$-capture in Chooz reactor experiment
Proposal to put 0.5% Gd in Super-K

We will also later see that the $t=2.2$ $\mu$s lifetime of muon decay is a valuable experimental handle for water Cherenkov detectors.
Tracking (Plane) Detectors

Layers of target: eg. steel, marble, glass

Layers of ionization detector:
- spark chambers
- proportional counters
- scintillator strips
- drift tubes
- resistive plate chambers (RPCs)

CDHS - CERN
Two Neutrino Experiment

1962

10× 1-ton modules
1” Aluminum plates with spark gap
Coincidence counters (A) and
Anticoincidence counters (B,C,D)

34 single muon events and only 6 showers ⇒ π→µν is ν_µ not ν_e

1988 Nobel Prize: Lederman, Schwartz, Steinberger
Energy Determination

1. Range
2. Magnetic Tracking
3. Shower Calorimetry
\( \frac{-dE}{dx} \) --- Range

\[ \frac{-dE}{dx} = K z^2 \frac{Z}{A} \beta^2 \ln \left( \frac{2m_ec^2 \beta^2 \gamma^2 T_{max}}{I^2} \right) - \beta^2 - \delta(\beta \gamma) \]

\( \frac{1}{\beta^2} \)

Minimum ionizing

\(~1.5\) MeV g\(^{-1}\) cm\(^2\)

for most materials; multiply by density

(but water \(~2\) MeV/cm)

Relativistic rise

Fermi plateau
density effect

Bethe-Bloch

Fluctuations due to \(\delta\)-rays cause high energy tail in sampling detector: "Landau tails"

Combined with momentum measurement:
effective particle ID handle

Neutrino Detectors - Ed K
Muon Ranger

Simple, no magnetic field; limited by size.
Reconstructed energy: build range table, integrating Bethe-Bloch; incorporate each layer of differing material. (ask GEANT for help)

K2K Fine-Grained Detector
Run 2279 Spill 18568 TRGID 1

Quasi-elastic: \( \nu \mu n \rightarrow \mu^- p \)

Note increasing ionization density as proton stops: “Bragg peak”

\[(dE/dx)_\text{Fe}= 1.45 \text{ MeV g}^{-1}\text{cm}^2 \times 7.9 \text{ gm cm}^{-3}= 90 \text{ MeV/cm} \ldots 1 \text{ GeV muon travels } \sim 1 \text{m} \]
(careful use of range chart, eg. in PDG, gives 80 cm)
Magnetic Tracking

\[ p_t[\text{GeV}] = 0.3 \ B[\text{T}] \ r[\text{m}] \]

\[ p_t \approx 0.3B \frac{l^2}{8s} \quad \frac{\delta p_t}{p_t} = \frac{\delta s}{s} \]

\[ \frac{\sigma_{p_t}}{p_t} = \frac{\sigma_x p_t}{0.3Bl^2} \sqrt{\frac{720}{N + 4}} \quad \text{for } N \geq 10 \text{ equidistant} \]

Gluckstern NIM24(1963) 381

- Increase \( l \) (more leverage)
- Increase \( B \) (more curvature)
- Decrease \( \sigma_x \) (hit resolution) or increase \( N \) hits
Electromagnetic Showers

- Characterized by radiation length: $X_0 \sim 180 \text{ } \text{A/Z}^2$
- Longitudinal profile $\sim x^\alpha e^{-\beta x}$
- Logarithmic growth of shower max. (i.e. calorimeter depth)
- Energy resolution: $\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b$
- Photon conversion probability: $\Phi(x) = \Phi_0 e^{-\frac{7}{9}x X_0}$

Photon has significant chance of traveling one to several radiation lengths before converting to $e^+e^-$

Will be important in next lecture

To see shower shape: $\sim 1X_0$ per plane
### Relevant for hadronic showers

<table>
<thead>
<tr>
<th>Material</th>
<th>( \rho ) [g cm(^{-3})]</th>
<th>( X_0 ) [cm]</th>
<th>( \lambda_{int} ) [cm]</th>
<th>dE/dx [MeV/cm]</th>
</tr>
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<tbody>
<tr>
<td>H(_2)O</td>
<td>1.00</td>
<td>36</td>
<td>83.6</td>
<td>1.99</td>
</tr>
<tr>
<td>LAr</td>
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<tr>
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<td>11.35</td>
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**Neutrino Detectors**

**Neutrino Summer School**

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**6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS**

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<tr>
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**Relevant for hadronic showers**

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**PDG: Review of Particle Properties**

Table 6.1: Revised May 2002 by D. E. Groom (LNSU). Gases are evaluated at 30°C and 1 atm (as parameters): for \( \rho \), \( X_0 \), and \( \lambda_{int} \). Data for hadronic showers are from Refs. 1 and 2. Further data and properties are given in Ref. 3 and at http://pdg.lbl.gov/atomdata/properties.
Paschos-Wolfenstein

\[
\frac{\sigma(NC,\nu) - \sigma(NC,\bar{\nu})}{\sigma(CC,\nu) - \sigma(CC,\bar{\nu})} = \frac{1}{2} - \sin^2 \theta_W
\]
MINOS

- 5.4 kton far detector, 1 kton near
- 484 steel/scintillator planes
- 2.54 cm thick steel plates ($1.4X_0$)
- 1.2 T solenoidal magnetic field
- peak neutrino energy ~ 3 GeV
- 92% $\nu_\mu$, 1.5% $\nu_e/\bar{\nu}_e$-bar
MINOS - neutrino appearance

If early atmospheric results had held up, $\Delta m^2 > 10^{-2}$ eV$^2$. MINOS originally envisioned for statistical study of $\tau$-appearance.

MINOS has some sensitivity for $\nu_e$ appearance but detector is not optimum.

But for now-- it is the only running experiment that can extend beyond Chooz limit.
CHARM-II
CERN-Hamburg-Amsterdam-Rome-Moscow
1988-1991

Target material: 692 tons of glass
$Z\sim11$ $\rho=2.2 \text{ g/cm}^3$ $X_0=12 \text{ cm}$ $\lambda=44 \text{ cm}$ inexpensive
One plane: 4.8 cm thick plate + 1 cm streamer tube

Detector for Neutrino-Electron Scattering (and Inverse Muon Decay)

- Isolated electromagnetic shower: low $Z$
- Strongly peaked in neutrino direction - want good angular resolution (low density)
- Backgrounds: $\nu$-nucleon scattering
  neutral current $\pi$ production

Ideas bouncing around to revisit this at Fermilab

Neutrino Detectors - Ed Kearns - Fermilab/KEK Neutrino Summer School - 2007
Quiz: what would Inverse Muon Decay look like?
Bubble Chambers

ne plus ultra of particle imaging

Single event discoveries

Limitations led to extinction

But principles being revived for dark matter

New detectors vie for claim of “electronic bubble chamber”

Neutrino Detectors - Ed Kearns - Fermilab/KEK Neutrino Summer School - 2007
Discovery of Neutral Currents

Gargamelle bubble chamber
- CERN, 1973
- $E_\nu \sim 1\text{-}2 \text{ GeV}$
- 15 tons freon

\[
\begin{align*}
\nu_\mu + N &\rightarrow \nu_\mu + \text{hadrons} \quad \text{(NC)} \\
\nu_\mu + N &\rightarrow \mu^- + \text{hadrons} \quad \text{(CC)} \\
\nu_e + N &\rightarrow e^- + \text{hadrons} \quad \text{(CC)} \\
\nu_\mu + e^- &\rightarrow \nu_\mu + e^- \quad \text{(NC)} \\
n + N &\rightarrow \text{hadrons} \quad \text{(contamination)} \\
\end{align*}
\]
also antineutrino beam ($\bar{\nu}_\mu$)

Single event discovery
BG estimate $0.03 \pm 0.02$

$E_e = 385 \pm 100 \text{ MeV}$
angle w. beam $1.4^\circ \pm 1.5^\circ$
Gargamelle
\[ \nu N \rightarrow \nu N \pi^0 \]

**Figure 7.** NC 1\(\pi\) cross section \(\sigma(\nu_\mu p \rightarrow \nu_\mu p \pi^0)\). Shown are the free nucleon cross section predictions from NUANCE and NEUGEN with \(m_A = 1.032\) GeV, \(m_\pi = 0.84\) GeV, and \(\sin^2 \theta_W = 0.233\).

G.P. Zeller, hep-ex/0312061

---

Not much data! Actually, there are many more measurements of NC/CC ratios. These reactions are the dominant background to T2K, NO\(\nu\)A and other \(\nu_e\) appearance experiments.
Principle of Operation: Bubble Chamber

- Liquified gas, H₂, D₂, Ne, Ar, Freon, Xe kept close to boiling.
- After trigger, piston expands volume, gas bubbles form along track.
- Bubble growth stops when piston pushed back.
- Illuminate with flash and photograph.
- Last experiments used holographic illumination, achieved ~100µm bubbles.

FIG. 2. Side view of the 15-ft bubble chamber.
But...

- Fixed target only.
- High energy particles not contained; $\oint B \cdot dl$ only 10 T m.
- Photograph scanning difficult (some automation developed).
Hybrid Detectors

More like a collider detector than a detector of nearly monolithic design:

- Vertex detector
- Tracking region
- Particle identification
- EM calorimeter
- Hadron calorimeter
- Muon spectrometer
MINERνA

- νN scattering
- nuclear effects
- single-π production
- coherent-π production
- parton distributions
- strange particle production

8.3 ton high resolution (1.7cm x 3.3cm) segmented scintillator target

+ 40% × 6.2 ton nuclear target
Simulated MINERνA Events

Quasielastic event
\[ \nu_\mu \ n \rightarrow \mu^- \ p \]

Neutral Current \( \pi^0 \)
\[ \nu_\mu \ A \rightarrow \nu_\mu A \pi^0 \]

Resonance production
\[ \nu_\mu \ p \rightarrow \mu^- \Delta^{++} \rightarrow \mu^- p \pi^+ \]

J. Nelson, NuINT07
NOMAD

- $\nu_\tau$ appearance at small $\sin^2 2\theta$ - comparable to quarks
- $\Delta m^2$ range 1-1000 eV$^2$ motivated by Hot Dark Matter
- $E_\nu \sim 20-40$ GeV, $L = 600$ m at CERN SPS
- Also CHORUS detector, similar goals, emulsion-based
Later version, NOMAD-STAR, had Si tracking target

“electronic bubble chamber”
Transition Radiation

EM radiation (X-rays) emitted when a relativistic charged particle crosses boundaries of differing indices of refraction.

- $N_\gamma \sim 1/137$ per boundary $\Rightarrow$ stacks of foils
- X-rays counted by gaseous detector e.g. Xe

- Radiated energy $\propto \gamma = \frac{E}{m}$

$\Rightarrow$ Identify high energy (GeV) electrons ($\gamma > \text{few} \ 1000$)
    rejecting charged pions (which can shower early in EM calorimeter)

Also can be used to estimate energy of high energy muons, eg. 0.1-1 TeV cosmic ray muons in MACRO experiment.
$\nu_\tau$ was detected ... but not by oscillation*
DONUT Detector

Identification of muons coming from tau decay

Calorimeter determines energy of decay products

Drift chambers decay particle

Magnet spreads tracks of charged particles

Emulsion target with planes of scintillation fibers

Steel shield to block particles other than neutrinos

Neutrino beam

DONUT Detector for direct observation of tau neutrinos ($\nu_\tau$)

15 meters (about 50 feet)
Nuclear Emulsions

Photograph of emulsion tracks (from CHORUS)
Neutrino Detectors - Ed Kearns - Fermilab/KEK Neutrino Summer School - 2007

$\nu_\tau$ Event $\nu_\tau N \rightarrow \tau X \rightarrow 3h \nu_\tau (X)$
Multiple Coulomb Scattering

\[
\theta_{RMS}^{plane} = \frac{13.6}{\beta cp} z \sqrt{\frac{x}{X_0}} \left[ 1 + 0.038 \ln \left( \frac{x}{X_0} \right) \right]
\]

Important experimental constraint:

- He in $\nu$ decay volume
- Low Z (Be) collider beam pipe
- Kalman filter for improved track reconstruction
- Momentum estimate (DONUT, MACRO)

Tested with $\pi$ tracks in test beam -
Resolution $\sim 30\%$
OPERA

$\nu_\tau$ appearance in $\nu_\mu$ beam
(atmospheric $\Delta m^2$)

The OPERA detector
(~200,000 bricks)
1.8 kton

M. Dracos, VCI2007

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What have I skipped?

- Highest energy detected - neutrino telescope AMANDA, IceCube (see F. Halzen lecture)

- Lowest energy detected - $pp$ solar (GALLEX/GNO, SAGE) also $^7$Be: Ray Davis Homestake Mine experiment

1995 Nobel Prize: R. Davis & M. Koshiba (Kamiokande)

615 tons of $C_2Cl_4$
(dry cleaning fluid)

1500 meters depth

Individual Ar atoms extracted and counted by radioactive decay ($\tau \sim 35$ days)

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

Back to inverse beta decay again!