Quantum Mechanics and Double Slit Experiments

- Particles exhibit wave interference
- Indeterminacy (pattern lost if measure which slit)
- One particle vs ensemble
- Interpretation: probability waves

\[ |\Psi_{TOT}\rangle = |\Psi_1\rangle + |\Psi_2\rangle \]

\[ I(\theta) = \frac{I_0}{I_0} \cos^2 \left( \frac{\phi}{2} \right) \]

\[ \frac{\phi}{2\pi} = \frac{\text{path}}{\lambda} = \frac{d \sin \theta}{\lambda} \]

What We Observe “at the Screen”: Lepton Number

• Why must the muon decay weakly?
  ❖ Long lifetime result of heavy $W$
  ❖ Lifetime $\tau \approx 2\mu s$

\[
\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu
\]

\[
\begin{array}{cccc}
L_\mu & +1 & 0 & 0 & +1 \\
L_e & 0 & +1 & -1 & 0 \\
\end{array}
\]

• More favorable decay

\[
\mu^- \rightarrow e^- \gamma
\]

\[
\begin{array}{cccc}
L_\mu & +1 & 0 & 0 \\
L_e & 0 & +1 & 0 \\
\end{array}
\]

❖ Electromagnetic interaction
❖ Should have lifetime $\sim 10^{-18}$ sec
❖ Observed rate $< 1.2 \times 10^{-11}$ of all $\mu$ decays

ν’s Have Lepton Number

- Nuclear β decay has e, reactors produce ν\textsubscript{e}
- Reines & Cowen exp’t to observe free \overline{\nu}_e

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


- Contrast to “failed” experiment by R. Davis

\[
\overline{\nu}_e + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar}
\]


NOT OBSERVED
ν’s Have Lepton Number (cont’d)

- In 1957, Brookhaven AGS and CERN PS first accelerators intense enough to make ν beam
  \[ p + Be \rightarrow \pi^+ + X, \quad \pi^+ \rightarrow \mu^+ \nu \]
- 1962: Lederman, Steinberger, Schwartz propose experiment to see
  \[ \nu_\mu + N \rightarrow \mu^- + X \]  
  (Phys.Rev.Lett. 9, 36 (1962))

Saw lots of...
\[ \nu_\mu + N \rightarrow \mu^- + X \]

Saw none of...
\[ \nu_e + N \rightarrow e^- + X \]
Weak Interactions
Conserve Lepton Number

- Many exp’t confirmations of Lepton number conservation ($\mu$, $\tau$ decays, etc)
- Neutrino interactions conserve lepton number too.
- But what happens to the neutrino in between creation/annihilation, while in flight?

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]

\[ \nu_\mu + N \rightarrow \mu^- + X \]
Neutrino Double Slit Experiment

- We create and observe $|\nu_\mu\rangle$ & $|\nu_e\rangle$ via weak interaction
- But suppose $\nu$’s have mass $\neq 0$. Can label them by
  $|\nu_1\rangle$ -- the heavier mass state with $m = m_1$.
  $|\nu_2\rangle$ -- the lighter mass state with $m = m_2$.
- We do not know in which mass state the neutrino propagates (it’s an unknown ‘slit’) – must assume both $\Rightarrow$ interference!

Suppose at $t=0$ have a state $|\psi(0)\rangle = |\nu_\mu\rangle$. Later…?

Probability $\{\nu_\mu \rightarrow \nu_e\}(t) \propto \sin^2[1.27\Delta m^2 L/E_{\nu}]$

To see the effect, must have $E_{\nu}/L \sim \Delta m^2$

$NB$: $\sin^2(x)$ because now talking about fraction of beam that disappears!
A Mixture of $\nu$ States

• How can a quantum state produced at $t=t_1$ appear as a different quantum state at $t=t_2$?

• Mass eigenstates need not coincide with weak eigenstates (two indep. bases)

$$|\nu_e\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle$$

$$|\nu_\mu\rangle = -\sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle$$

• Reminiscent of crossed polarizers.
Neutrinos have 3 slits

- The $\nu_\tau$ discovered $\Rightarrow$ $\geq 3$ lepton flavors must exist

- Measurements of $Z^0$ boson resonance $\Rightarrow$ only $2.983\pm0.009$
  lepton flavors participate in weak interaction

- With 3 $\nu$ families we expect
  - 3 mixing probabilities between flavor $i \rightarrow j$
  - 2 distinct mass splittings
ν Mixing Orthodoxy

- If you believe in flavor mixing, there must be a 3×3 unitary transformation to mass states:

\[ c_{ij} = \cos \theta_{ij}, \quad s_{ij} = \sin \theta_{ij} \]

- In the quarks, mixing matrix has phase \( \delta \neq 0 \) responsible for \( \mathcal{CP} \).

\[ \sin \theta_{\text{solar}} < 0.62 \quad (\text{Smirnov, hep/0309299}) \]

\[ \mathrm{CHOOZ} \quad 90\% \text{C.L.} \quad \sin \theta_{13} < 0.22 \]

\[ m_2 = 2 \times 10^{-3} \text{eV}^2 \]

\( \mathrm{Super-K} \quad 90\% \text{C.L.} \quad \sin^2 \theta > 0.58 \]

Is this \textit{non-zero}???
Large enough to measure \( \mathcal{CP} \) in \( \nu_\mu \to \nu_e \)

Is the mixing angle truly \textit{maximal}???

But hopefully this picture is wrong or incomplete!
(Peggy Lee: “Is that all there is?”)
Two Detector ν Experiments

FNAL CCFR experiment, 1982-83

- Near detector predicts ν energy spectrum and rate at far detector (assuming an absence of oscillations)
- Greatly reduces systematic uncertainties due to calculating beam flux.

CERN CHARM/CDHS experiments, 1982-83
Interpretation of Oscillation Results

\[ P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E_\nu} \right) \]

- Oscillations into unknown flavor causes dip in observed spectrum.
Long Baseline $\nu$ Oscillation Exp’s

- Reproduce atmospheric $\nu$ effect using accelerator beam
- $L \sim 100$’s kilometers to match oscillation frequency

K2K (KEK to SuperK)
$L = 250$ km  Concluded

MINOS (Fermilab to Minnesota)
$L = 735$ km  2005

CNGS (Cern to Gran Sasso, Italy)
$L = 750$ km  tested 2006, run 2008

Near Detector: 980 tons
Far Detector: 5400 tons

MINOS (Fermilab to Minnesota)
$L = 735$ km  2005

K2K (KEK to SuperK)
$L = 250$ km  Concluded
The Challenge of Long Baselines...

Neutrinos at the Main Injector

- MI ramp time ~1.5sec
- MI is fed 1.56μs batches from 8 GeV Booster
- Simultaneous acceleration & dual extraction of protons for
  - Production of $\bar{p}$ (Tevatron collider)
  - Production of neutrinos (NuMI)
- NuMI designed for
  - 8.67 μs single turn extraction
  - $4 \times 10^{13}$ ppp @ 120 GeV
- Antiproton Production:
  - Requires bunch rotation ($\Delta t \sim 1.5\text{nsec}$)
  - Merges two Booster batches into one batch (“slip-stacking”)
Lambertsons

Bend out of MI

Final bend to Soudan

NuMI Proton Beam Line
Target Hall

Target Hall after Contractor completion

Decay pipe

Target Hall shielding installation

Target/baffle Module installed
Focusing Horns

Main horn field between conductors

Horn 2 suspended from shielding module being lowered into shielding pit

Hall probe moving along horn axis

figure A. Marchiori, J. Hylen
To people who consider the Midwest flyover land, the BWCA Wilderness puts Minnesota on the map. National Geographic Traveler listed it as one of 50 Places of a Lifetime/The World’s Greatest Destinations, along with the Grand Canyon and Big Sur. In the book “1,000 Places to See Before You Die,” it’s the only Minnesota entry.
Neutrino Beams 101:

**Beam MC**

- Total
- Neck-Neck
- Neck-Horn2
- Underfocused
- Overfocused
- Horn1-Neck

![Energy Distribution Graph](image)

**Axis Labels:**
- Y-axis: #CC Events/GeV/kton/3.8x10^{20}pot
- X-axis: Energy (GeV)

**Legend:**
- Black: Total
- Red: Neck-Neck
- Orange Dashed: Neck-Horn2
- Orange Dotted: Underfocused
- Blue: Overfocused
- Blue Dashed: Horn1-Neck

**Graph Description:**
- The graph illustrates the distribution of neutrino events as a function of energy.
- Different colors and line styles represent various beam configurations and focus scenarios.

**Diagram Elements:**
- The diagram includes visual representations of beam configurations and energy-related annotations.
Consequence: Flux Uncertainty

Energy (GeV)

Error (Far/Near)

LE-10
- Total error
- Horn 1 Angle
- Horn 2 Angle
- Horn 1 Offset
- Horn 2 Offset
- Horn Current
- Horn Current Distribution
- Baffle Scraping
- Chase
- Protons on Target

figure courtesy Ž. Pavlović
Neutrino Beams 102

“Low” Energy
proton target
Horn 1

“High” Energy
target
Horn 1

Pions with
\[ p_T = 300 \text{ MeV/c} \] and
\[ p = 5 \text{ GeV/c} \]
\[ p = 10 \text{ GeV/c} \]
\[ p = 20 \text{ GeV/c} \]

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

Vary \( \bar{\nu} \) beam energy by sliding the target in/out of the 2nd horn

figure courtesy Ž. Pavlović
Opportunity: Flexible Beam Energy


figure courtesy Ž. Pavlović
Neutrino Beams 103:

- ND and FD spectra similar, but not identical

\[ E_\nu = \frac{0.43E_\pi}{1 + \gamma^2 \theta^2} \]

\[ \text{Flux} \propto \frac{1}{L^2} \left( \frac{1}{1 + \gamma^2 \theta^2} \right)^2 \]
Consequence: Extrapolating to the FD

- ND and FD spectra are similar, but *not* identical.

- If they were identical, (NuMI approximating a point source) could say

\[ N_{\text{Far}}^i = \mathcal{R}_{FN} N_{\text{Near}}^i \]

where

\[ \mathcal{R}_{FN} = \left( \frac{Z_{\text{near}}}{Z_{\text{far}}} \right)^2 \]
Extrapolating to the FD (cont’d)

- The ND sees the NuMI beam as an extended line source of neutrinos, while FD sees a point source, weighted by \( \pi \) lifetime.

\[
\mathcal{N}_{FN} = \frac{1}{\int_{48m}^{720m} (Z_{FD} - z)^2 dz} \int_{48m}^{720m} \frac{1}{(Z_{FD} - z)^2} e^{-0.43m_\pi z/E_\nu c\tau} dz
\]

where \( E_\nu \approx 0.43 E_\pi \).

- Better than this need a MC to evaluate \( \mathcal{N}_{FN} \):
  - Angular correlations in decay
  - Pi’s that interact before decaying

Fluka 2005
- Tuned MC
- Pion Lifetime

NuMI Beam MC
- Horn 1 neck
- Horn 2 neck
- Edge of Decay Pipe
MINOS Decided to Pursue a “Blind Analysis” Policy
Step 1: Look at ND Data

- Hope no gross disagreements with beam MC
- See if neutrino identification is OK
First Observed Neutrino Events in Near MINOS Detector

January 21, 2005

$\nu_\mu + \text{Fe} \rightarrow \mu^+ + X$
Neutral Current $\nu_\mu$ Backgrounds

- Analysis requires an energy spectrum measurement.

- In $\nu_\mu + \text{Fe} \rightarrow \mu^+ + X$ interaction, reconstruct $E_\nu = p_\mu + E_X$.

- Can’t see full neutrino energy in NC $\nu_\mu + \text{Fe} \rightarrow \nu_\mu + X$ interactions.
Coping with High Intensity

- 10-20 events/spill in the ND (cf 10^{-4}/spill in the FD!)
Beam is Stable

- June
- July
- August
- September
- October
- November
ND Compared to Beam MC

- These plots show the beam spectrum as “dead reckoned” by Fluka2005 + our tracking MC through the beam line.

- Errors bars from the beam systematics (dominated by $\pi/K$ production in the target).

- Some real apparent contradictions? MC is low in the LE beam, but high in the ME beam.
ND Spectra After Tuning

LE10/0kA

- MINOS ND Data
- Fluka 2005 $\chi^2=225$
- Tuned Hadron Production $\chi^2=119$

figure courtesy Ž. Pavlović, P. Vahle
Step 2: Decide How to Extrapolate
ND $\rightarrow$ FD

- FD Spectrum = (F/N ratio) $\times$ ND Spectrum

$$N_{E_\nu, FD}^i = \mathscr{R}_{FN}^i \times N_{E_\nu, ND}^i$$

$N_{E_\nu}$ = Number of events at given energy of neutrino in ND or FD
$i$ = particular energy bin

- Tests on "mock data" to ensure no biases, understand systematics
Alternative Extrapolation "Matrix Method"

Checks of the Fitting

- MC “Mock data sets”
  - 100 experiments
  - each $10^{20}$ POT exposure
- Studies of
  - biases
  - statistical precision

**Best Fit**

- $\Delta m^2$ (eV$^2$)
- $\sin^2(2\theta)$
- $\chi^2$

![Graphs of best fit points for 100 mock data sets with 1e20 POT exposure](image)
# Systematic Uncertainties

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Shift in $\Delta m^2$ ($10^{-3}$ eV$^2$)</th>
<th>Shift in $\sin^2(2\theta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near/Far norm. (livetime, fid vol) ±4%</td>
<td>0.065</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Absolute hadronic energy scale ±10%</td>
<td>0.075</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>NC contamination ±50%</td>
<td>0.010</td>
<td>0.008</td>
</tr>
<tr>
<td>All other systematic uncertainties</td>
<td>0.041</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Total systematic (summed in quadrature)</td>
<td>0.11</td>
<td>0.008</td>
</tr>
<tr>
<td>Statistical error (data)</td>
<td>0.17</td>
<td>0.080</td>
</tr>
</tbody>
</table>
Step 3: Peek at the Far Detector Data
(“Box is still closed”)

• In 2006 analysis, question was “Do ν’s disappear?”
  ❖ unknown “blinding function” to hide most of the data
  ❖ Collaborators given free access to “open” data set
  ❖ Only got to see full data set once “box was open”

• In 2007 analysis, want unbiased $\Delta m^2$, $\sin^2(2\theta)$ measurement
  ❖ Access to all the data, but complete blinding of all rates
  ❖ Did not look at energy spectrum, so couldn’t bias $\Delta m^2$
Checks on the FD Data

- These are all CC neutrino events
- Rates blinded – we don’t know the normalization
- MC has been scaled to agree with data
• Calibrations based on stopping cosmic ray $\mu$’s.
• Study ionization for 20-plane window upstream of stopping $\mu$ location.
Example Events (I)

- These events taken from the “open” data sample in the FD (which we are permitted to look at in detail).
- $E_v = 3.0$ GeV
- $y = E_{had}/E_v = 0.3$
Example Events (II)

- These events taken from the “open” data sample in the FD (which we are permitted to look at in detail).
- $E_{\nu} = 24.4$ GeV
- $y = E_{\text{had}}/E_{\nu}=0.4$
Example Events (III)

- These events taken from the “open” data sample in the FD (which we are permitted to look at in detail).
- $E_v = 10.0$ GeV
- $y = E_{\text{had}}/E_v = 0.3$
Example Events (IV)

- These events taken from the "open" data sample in the FD (which we are permitted to look at in detail).
- $E_\nu = 2.1$ GeV
- $y = E_{\text{had}}/E_\nu = 0.1$ ("quasi-elastic"?)
Example Events (V)

- These events taken from the “open” data sample in the FD (which we are permitted to look at in detail).
- $E_\nu = 18.7$ GeV
- $y = E_{had}/E_\nu = 0.9$
• These events taken from the “open” data sample in the FD (which we are permitted to look at in detail).
• $E_v = 3.3$ GeV
• $y = E_{had}/E_v = 0.6$
Example Events (VII)

- These events taken from the “open” data sample in the FD (which we are permitted to look at in detail).
- \( E_\nu = 25 \text{ GeV} \)
- \( y = E_{\text{had}} / E_\nu = 0.6 \)
Step 4: Look at All Events

“Open the Box”
FD Events are “In time” and Uniform
Neutrino Energy Spectrum

Null Oscillation Hypothesis

$\chi^2 / \text{n.d.f.} = 139.2 / 36 = 3.9$
Oscillation Hypothesis Fit

\[ |\Delta m_{32}^2| = 2.38^{+0.20}_{-0.16} \times 10^{-3} \text{ eV}^2 / c^4 \]

\[ \sin^2(2\theta_{23}) = 1.00_{-0.08} \]

\[ \chi^2 / \text{n.d.f.} = 41.2 / 34 = 1.2 \]

\[ P(\chi^2, \text{n.d.f}) = 0.18 \]
“One possible explanation for dark matter is a group of subatomic particles called neutrinos. Last week, researchers working on the MINOS experiment at Fermilab, near Chicago, confirmed these results. …”

“The researchers created a beam of muon neutrinos … The neutrinos then travelled 750km (450 miles) through the Earth to a detector in a former iron mine in Soudan, Minnesota.”

“By comparing how many muon neutrinos arrived there with the number generated, Fermilab's researchers were able to confirm that a significant number of muon neutrinos had disappeared—that is, they had changed flavour. Thus the neutrino does, indeed, have mass and a more accurate number can be put on it.”
Fitting into the Unphysical Region

\[ \Delta m^2 = 2.26 \times 10^{-3} \text{eV}^2 \]

\[ \sin^2 2\theta = 1.07 \]
Compare 1.3 \& 2.5 \times 10^{20} \text{POT Datasets}

- Reconstruction and selection method
  - Changes number of events
  - \( \sim 2\sigma \) change in \( \Delta m^2 \)

- Shower modeling
  - \( \Delta m^2 \) systematic decrease \( 0.06 \times 10^{-3} \text{eV}^2 \)

- New data set fluctuates down
Our Long-term Goal:

For $\Delta m^2 = 0.0020$ eV$^2$, $\sin^2 2\theta_{23} = 1.0$

Oscillated/unoscillated ratio of number of $\nu_\mu$
CC events in far detector vs $E_{\text{observed}}$

figure courtesy D. Petyt
Off-Axis Beam from NuMI

• Possible to measure rates $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$ due to...
  - CP violation
  - $\nu$'s propagating through matter
• Fermilab P929 (NOvA)
Competition in Japan
JHF-Kamioka neutrino project

< 1 GeV
\( \nu \mu \) beam

Super Kamiokande 295km JAERI (Tokai)

50 kton Water Cherenkov

0.75 MW 50 GeV PS

\sim 1\text{Mt} \text{“} \text{Hyper Kamiokande} \text{”}

4MW 50GeV PS
**1st Demonstration of Off-Axis Beam**

- NuMI ν’s sprayed in all directions.

- $K \rightarrow \mu \nu$ and $\pi \rightarrow \mu \nu$ decays lead to lower $E_\nu$ at large decay angle

$$E_\nu = \frac{0.43 E_\pi}{1 + \gamma^2 \theta^2}$$

- Opportunity to double-check our beam flux calculations using ‘mature’ neutrino detector

![Graph showing calculated neutrino flux from K and pi decays](image)
The Fermilab Neutrino Program

- Many ideas are now being discussed/proposed/built
  - MINOS – Precision oscillation parameters
  - NOvA – first observation of $\nu_\mu \rightarrow \nu_e$, matter effects?
  - MINErVA – precision scattering cross sections
  - MicroBooNE – Liquid Argon TPC R&D
  - NuSOnG – weak mixing angle
  - FNAL-DUSEL – CP Violation in neutrinos?
- Project X accelerator would enable diverse program
The path forward is crystal clear ...

...but very fragile indeed.

Prof. Thomas Coan, Fall 1993

SMU student Yurii Maravin, Summer 1994
The Blind Leading the Blind?

“Knowing in part may make a fine tale, but wisdom comes from seeing the whole.”

It Remains a World-Wide Effort to Interpret Neutrino Disappearance and the Possibilities of Neutrino Mass

- double-beta
- direct $m_\nu$
- atmospheric
- LSND/MiniBooNE
- solar
- reactor
- accelerator
Conclusions

• MINOS rapidly progressing
  - Construction complete after 6 years
  - $3.5 \times 10^{20}$ POT delivered
  - First result confirms $\nu$’s disappear
  - Under oscillation hypothesis,
    \[ \Delta m_{23}^2 = (2.38^{+0.20}_{-0.16}) \times 10^{-3} \, eV^2 \]
    \[ \sin^2 (2\theta_{23}) = 1.00^{+0.20}_{-0.16} \]

• Rich program of physics ahead
  - Results on oscillations $\nu_S$ other new physics
  - Search for rare osc. phenomena, like
    $\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_s$
  - Is $\nu_\mu \rightarrow \nu_\tau$ mixing maximal?
  - Future experiments: CP violation
Backup Slides
Alternatives for $\nu_\mu$ Disappearance

“Neutrinos actually decay to lighter states”
Barger et al., hep-ph/9907421

“Neutrinos propagating in Extra Dimensions”
Barbieri et al., hep-ph/9907421

“SuperK effect is combination of $\Delta m^2$(solar) and $\Delta m^2$(LSND)”
Barenboim et al., hep-ph/0009247

- Most think $\nu_\mu \rightarrow \nu_\tau$ looks like a good explanation of the atmospheric $\bar{\nu}$ depletion, but one must be open to other possibilities given
  - The 3 $\Delta m^2$ problem
  - Naturalness, attraction of a $\nu_{sterile}$ GUT’s
  - Due skepticism of jumping to conclusions in hard experiments

![Graphs and data plots related to neutrino decay and oscillations.](image)
Charged Current $\nu_\mu$ Selection

- Charged current events distinguished by
  - muon track
  - long event length
- Probability distribution function to reduce $\nu_\mu$-NC bckgd to $\nu_\mu$-CC sample.

\[ Y = 1 - \frac{p_\mu}{E_\nu} \]
Charged Current $\nu_\mu$ Selection (cont’d)

- In LE beam, expect 89% efficiency, 98% CC purity
“Tuning” the Beam Spectra in \((x_F, p_T)\)

- LE10/0kA
- LE10/170kA
- LE10/185kA
- LE10/200kA
- LE100/200kA
- LE250/200kA

Vary the horn current

Vary the target’s location
Several tunings of the \((x_F, p_T)\) spectra were attempted.

All can accommodate the ND neutrino spectra.

All yield similar tuned F/N ratio (within 2%)
Charged Current $\nu_\mu$ Selection Variables

- Track length (planes)
- Track length beyond Shower
- Curvature/Resolution
- Track Pulse Height / Plane
- $Y = 1 - \frac{p_\mu}{E_\nu}$
- Classification Parameter
Comparison with Unblinded MC

MINOS Preliminary

No Osc.

Osc. ($\Delta m^2 = 0.0024 \text{ eV}^2$)

MINOS Data

$\chi^2 / \text{n.d.f.} = 30.8 / 20 = 1.5$