Neutrino Physics

Takashi Kobayashi
Institute for Particle & Nuclear Studies
High Energy Accelerator Research Organization (KEK)
20 yrs ago

- 1987 Feb 23
- 16:35:35
- (+170,000 yr)

Takashi Kobayashi (KEK), PAC07
20 yrs ago

- 1987 Feb 23
  16:35:35
  (+170,000yr)
20 yrs ago

- 1987 Feb 23
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- Supernova exploded
  - Large Magellanic Cloud

Takashi Kobayashi (KEK), PAC07
20 yrs ago

- 1987 Feb 23 16:35:35 (+170,000yr)
- Supernova exploded
  - Large Magellanic Cloud
- Neutrino detected by Kamiokande
20 yrs ago

- 1987 Feb 23 16:35:35 (+170,000yr)
- Supernova exploded in Large Magellanic Cloud
- Neutrino detected by Kamiokande

Start of new exciting era of neutrino physics?
Introduction

The Growing Excitement of Neutrino Physics

- K2K confirms atmospheric oscillations
- KamLAND confirms solar oscillations
- Nobel Prize for neutrino astroparticle physics!
- SNO shows solar oscillation to active flavor
- Super K confirms solar deficit and "images" sun
- Super K sees evidence of atmospheric neutrino oscillations
- Nobel Prize for v discovery!
- LSND sees possible indication of oscillation signal
- Nobel Prize for discovery of distinct flavors!
- Kamioka II and IMB see supernova neutrinos
- Kamioka II and IMB see atmospheric neutrino anomaly
- SAGE and Gallex see the solar deficit
- LEP shows 3 active flavors
- Kamioka II confirms solar deficit

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>1930</td>
<td>Pauli predicts the Neutrino</td>
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Introduction

The Growing Excitement of Neutrino Physics

- Neutrino was least known matter particle 20yrs ago
  - Standard model ASSUMES: mass=0, No flavor mixing
- Great progress since then
- Still neutrino is least known particle now in 2007
  - Many unanswered fundamental questions
- New era of “Neutrino Flavor Physics” just opened
  - Many new projects
- This talk
  - Progress made in last ~20yrs (masses&mixings)
    - Solar v/Atm v/Acc/Reactor
  - unanswered questions
  - (not all) future projects

1930  1955  1980  2005

Pauli predicts the Neutrino
Fermi’s theory of weak interactions
Reines & Cowan discover (anti)neutrinos
2 distinct flavors identified
Davis discovers the solar deficit
K2K confirms atmospheric oscillations
KamLAND confirms solar oscillations
Nobel Prize for neutrino astroparticle physics!
SNO shows solar oscillation to active flavor
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Kamioka II and IMB see supernova neutrinos
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LEP shows 3 active flavors
Kamioka II confirms solar deficit
Neutrino Oscillation (in 2-flavor approx.)

- **Neutrino Mixing**
  \[
  \begin{pmatrix}
  \nu_\mu \\
  \nu_e
  \end{pmatrix} =
  \begin{pmatrix}
  \cos \theta & -\sin \theta \\
  \sin \theta & \cos \theta
  \end{pmatrix}
  \begin{pmatrix}
  \nu_1 \\
  \nu_2
  \end{pmatrix}
  \]

- **Mass**
  \[
  m_1, m_2
  \]

- **Mass difference**
  \[
  \Delta m^2 \equiv |m_1^2 - m_2^2|
  \]

Weak eigenstates \quad Mass eigenstates

- **Probability to change flavor**
  \[
  P(\nu_\mu \rightarrow \nu_e) = |\langle \nu_e | \nu_\mu (t) \rangle|^2 = \sin^2 2\theta \cdot \sin^2 \left( \frac{\Delta m^2 [eV^2] \cdot L [km]}{E_\nu [GeV]} \right)
  \]

- **Signature**
  - Decrease of orig flavor ("Disappearance")
  - Appearance of diff flavor ("Appearance")
  - Characteristic energy (or L/E) distortion

- **Example**
  \[
  \Delta m^2 = 3 \times 10^{-3} eV^2
  \]
  \[
  L = 250 km
  \]

-takaaki kajita (kek), pac07
3 flavor mixing

\[ |\nu_i\rangle = \sum U_{li} |\nu_i\rangle \]

Weak Mass eigenstates

\[ m_i: 3 \text{ masses,} \]

**Maki-Nakagawa-Sakata Matrix**

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

\[ U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} \]

LBL acc. experiments

(Solar LBL reactor)

(Atm \nu)

\[ \Delta m_{ij}: 2 \text{ independent differences} \]

3 mixing angles and 1 CPV phase

Takashi Kobayashi (KEK), PAC07
Solar Neutrino Problem ('70~'90)

\[ \sim 7 \times 10^{10} \nu_e / \text{s/cm}^2 \]
Solar Neutrino Problem (’70~’90)

"Radio-Chemical"

Homestake
615ton C_2Cl_4
1970~1994

ν_e + ^37Cl → ^37Ar + e^-

Galium exp’s
Gallex+SAGE

ν_e + ^71Ga → ^71Ge + e-

~7x10^{10} \nu_e/\text{s/cm}^2

Takashi Kobayashi (KEK), PAC07
Solar Neutrino Problem (’70~’90)

"Radio-Chemical" Homestake
615 ton C₂Cl₄
1970~1994

νₑ⁺³⁵Cl → ³⁷Ar+e⁻

Galium exp’s
Gallex+SAGE

νₑ⁺⁷¹Ga → ⁷¹Ge+e⁻

~7x10¹⁰ νₑ/s/cm²

Chlorine
SuperK
Kamionkande
(1983~1996)

νₑ+e⁻ → νₑ+e⁻
Real time, Energy
Dir. Info.

Takashi Kobayashi (KEK), PAC07
Solar Neutrino Problem ('70~'90)

“Radio-Chemical”

Homestake
61.5 ton C₂Cl₄
1970~1994

$\nu_e + ^{71}\text{Cl} \rightarrow ^{71}\text{Ge} + e^-$

Gallex's
Gallex+SAGE

$\nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^-$

Kamiokande
(1983~1996)

~$7 \times 10^{10} \ nu_e / \text{s/cm}^2$

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

Real time, Energy
Dir. Info.

Takashi Kobayashi (KEK), Fall 2007
Solar Neutrino Problem (’70~’90)

“Radio-Chemical”

Homestake
61.5 ton C₂Cl₄
1970~1994

~7x10⁻¹⁰ νₑ/s/cm²

Kamiokande
(1983~1996)

Significant Deficit Observed!!

νₑ¹³⁷Cl → ¹³⁷Ar⁺e⁻

Galium exp’s
Gallex+SAGE

νₑ+e⁻ → νₑ+e⁻

Real time, Energy Dir. Info.

Takashi Kobayashi (KEK), Feb 2007
Super-Kamiokande (1996~)

- 50,000ton Water Cherenkov
  - >10x(all solar $\nu$ experiments)!
- Elastic Scatt (ES): $\nu_x + e^- \rightarrow \nu_x + e^-$
  - $\nu_e + 0.15 (\nu_\mu + \nu_\tau)$
- Observed deficit, spectrum, etc

SK-I (1996~2001)

5-20 MeV

$\text{Event/day/bin} = 0.41 \pm 0.02$

Data/SSM

Takashi Kobayashi (KEK), PAC07
SNO @Ontario, Canada (1999~2006)

- 1000ton D$_2$O Cherenkov
- 6000m w.e. UG
- 12m$^3$ Acrylic Vessel
- 9,500 20cm-PMTs (60% coverage)

Sensitive to

- NC: $\nu_x + d \rightarrow p + n + \nu_x$
- ES: $\nu_x + e^- \rightarrow \nu_x + e^-$
- CC: $\nu_e + d \rightarrow p + p + e^-$

# of evts

$\Phi_{e+\mu+\tau} \propto \Phi_{e+\mu+\tau}$
$\Phi_{e} + 0.15\Phi_{\mu+\tau} \propto \Phi_{\mu+\tau}$
$\Phi_{e} \propto \Phi_{e}$

$\Phi_{e+\mu+\tau} = 4.94 \pm 0.21^{+0.38}_{-0.34} (stat) \pm 0.09 (syst)$
$\Phi_{e} + 0.15\Phi_{\mu+\tau} = 2.35 \pm 0.22 (stat) \pm 0.15 (syst)$
$\Phi_{e} = 1.68 \pm 0.06 (stat) \pm 0.08 (syst) \times 10^5 / \text{cm}^2 / \text{sec}$

Takashi Kobayashi (KEK), PAC07 PhysRevC72,055502(2005)
Evidence of non-$\nu_e$ components

SK
$\propto \Phi_{e} + 0.15 \Phi_{\mu+\tau}$

SNO CC $\propto \Phi_{e}$

SNO NC $\propto \Phi_{e+\mu+\tau}$

9$\sigma$ effect!
KamLAND reactor neutrino exp. (2002~)

- 1000 ton liq. Scint.
  - In spherical balloon 13 m dia., 135 µ thick
- 1325 17inch PMT
- <L~180 km, <Eν~> few MeV
  - Attact Sol. ν of Δm²~10⁻⁵ eV

Detect \( \bar{\nu}_e \) from reactor

\[ \bar{\nu}_e + p \rightarrow e^+ + n, \quad e^+ + e^- \rightarrow 2\gamma \text{ (prompt)} \]

\[ n + p \rightarrow d + \gamma \text{ (2.2 MeV) (delayed)} \]
KamLAND reactor neutrino exp. (2002~)

- 1000 ton liq. Scint.
  - In spherical balloon 13 m dia., 135μ thick
- 1325 17 inch PMT
- \( <L> \sim 180\text{km}, <E_\nu> \sim \text{few MeV} \)
  - Attack Sol. \( \nu \) of \( \Delta m^2 \sim 10^{-5}\text{eV} \)

Detect \( \bar{\nu}_e \) from reactor

\[
\bar{\nu}_e + p \rightarrow e^+ + n, \quad e^+ + e^- \rightarrow 2\gamma \quad \text{(prompt)}
\]

\[
n + p \rightarrow d + \gamma \quad \text{(2.2 MeV)} \quad \text{(delayed)}
\]

Significant deficit & Distortion Observed!

---

Takashi Kobayashi (KEK), PAC07
KamLAND reactor neutrino exp. (2002~)

- 1000 ton liq. Scint.
  - In spherical balloon 13 m dia., 135 μ thick
- 1325 17 inch PMT
- \( L \approx 180 \text{ km}, \quad <E_\nu> \approx \text{ few MeV} \)
  - Attack Sol. \( \nu \) of \( \Delta m^2 > 10^{-5} \text{eV}^2 \)

Detect \( \bar{\nu}_e \) from reactor

\[
\bar{\nu}_e + p \rightarrow e^+ + n, \quad e^+ + e^- \rightarrow 2\gamma \text{ (prompt)} \\
n + p \rightarrow d + \gamma \text{ (2.2 MeV) (delayed)}
\]

Oscillatory Behavior Observed!

\[
\begin{align*}
P_{ee} &= 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right) \\
&\text{oscillation} \\
\end{align*}
\]

\[
\begin{align*}
P_{ee} &= (\cos^2 \theta + \sin^2 \theta \exp(-\frac{m_2 L}{2\tau E}))^2 \\
&\text{decay} \\
\end{align*}
\]

\[
\begin{align*}
P_{ee} &= 1 - \frac{1}{2} \sin^2 2\theta (1 - \exp(-\frac{\gamma L}{E})) \\
&\text{decoherence} \\
\end{align*}
\]

\[
\begin{align*}
\text{Ratio} = \frac{\text{KamLAND data}}{\text{best-fit oscillation}} \\
\text{with real reactor distribution} \\
\text{Ideal oscillation pattern} \\
L_0/E (\text{km}/\text{MeV}) \\
L_0 = 180 \text{ km is used for KamLAND}
\end{align*}
\]

No osc. excluded @ 99.999995%
Constraints on $\Delta m_{12}^2$, $\theta_{12}$

$$P = \sin^2 2\theta_{12} \cdot \sin^2 \left( 1.27 \frac{\Delta m_{12}^2 [\text{eV}^2] \cdot L [\text{km}]}{E_v [\text{GeV}]} \right)$$

SK
Constraints on $\Delta m_{12}^2$, $\theta_{12}$

\[ P = \sin^2 2\theta_{12} \cdot \sin^2 \left( 1.27 \frac{\Delta m_{12}^2 [eV^2] \cdot L [km]}{E_{\nu}[GeV]} \right) \]
Constraints on $\Delta m_{12}^2$, $\theta_{12}$

$$P = \sin^2 2\theta_{12} \cdot \sin^2 \left( 1.27 \frac{\Delta m_{12}^2 [eV^2] \cdot L [km]}{E_{\nu} [GeV]} \right)$$

SK+SNO

All Solar + KamLAND

Takashi Kobayashi (KEK), PAC07
Constraints on $\Delta m_{12}^2$, $\theta_{12}$

$$P = \sin^2 2\theta_{12} \cdot \sin^2 \left( 1.27 \frac{\Delta m_{12}^2 [eV^2] \cdot L [km]}{E_{\nu} [GeV]} \right)$$

“Solar Neutrino Problem” is now understood as neutrino oscillation
Altitude 10-20 km

Cosmic ray (proton, He)

\( p, \text{He} \)

\[
\frac{(\nu_\mu + \bar{\nu}_\mu)}{(\nu_e + \bar{\nu}_e)}
\]

Takashi Kobayashi (KEK), PAC07
Atmospheric neutrino

Altitude 10–20 km

Cosmic ray (proton, He)
p, He

\[ \frac{\nu_{\mu} + \bar{\nu}_{\mu}}{\nu_e + \bar{\nu}_e} \]

\[ \nu_{\mu}, \mu^\pm, \pi^\pm, K^\pm \]

L = 10–30 km

L = 13,000 km

Roughly \( \sim 1 \nu / \text{cm}^2 / \text{sec} \)
“Atmospheric neutrino anomaly” before SK

Kamiokande
3kt Water,
1000 50cm PMTs

IMB (US, 1982–1991)


MACRO (Gran Sasso)
8kt Water,
2000 20cm PMTs

Takashi Kobayashi (KEK), PAC07
“Atmospheric neutrino anomaly” before SK

μ/e ratio

Smaller than exp’ed significantly
Some agree w/ exp’ed
Clarification was desired

Kamiokande

3kt Water,
1000 50cm PMTs

IMB (US, 1982–1991)

Soudan-2


8kt Water,
2000 20cm PMTs

L.M. (Gran Sasso)

Takashi Kobayashi (KEK), PAC07
Super-Kamiokande Observations (1996~)

- "Evidence of neutrino oscillation"

\[ R_{\text{sub-GeV}} = 0.658 \pm 0.016 \pm 0.035 \]

\[ R_{\text{multi-GeV+PC}} = 0.7024^{+0.032}_{-0.030} \pm 0.101 \]
Constraint on $\Delta m_{23}^2$, $\theta_{23}$ from SK

Allowed parameter region

$\Delta m^2$ (eV$^2$)

$\sin^2 2\theta_{23}$

99% C.L.

90% C.L.

68% C.L.

L/E analysis

Data/Prediction (null osc.)

L/E (km/GeV)

90% CL allowed region:

$\sin^2 2\theta_{23} > 0.93$

$1.9 < \Delta m_{23}^2 < 3.1 \times 10^{-3}$ eV$^2$

Clear oscillatory behavior

$P \approx \sin^2 2\theta_{23} \cdot \sin^2 \left(1.27 \frac{\Delta m_{23}^2 \text{[eV}^2]\cdot L\text{[km]}}{E_\nu\text{[GeV]}}\right)$

Takashi Kobayashi (KEK), PAC07
Confirmation by accel. long baseline (LBL) experiments

- \( p+X \rightarrow \pi^+ \rightarrow \nu \mu + \mu \)
  - Pure (~99%) \( \nu_\mu \), ~1% \( \nu_e \)
- Confirm SK atm \( \nu \) w/ different, well-controlled systematics
  - \( L, \) dir. Known
  - Ev can be measured
    - Spectrum distortion
  - Initial spec/flavor contents measured
- **K2K (1999~2004)** FINISHED!
  - \( \nu \mu \) disapp/ \( \nu e \) app
- **MINOS (2005~)** ON-GOING
  - \( \nu \mu \) disapp/( \( \nu e \) app)
- **OPERA (2006~)** Commissioning
  - \( \nu \tau \) appearance
  - Beam: 1\textsuperscript{st} comm: Aug 2006, 2\textsuperscript{nd} comm: Sep 2007
  - 60~70k/154k emulsion bricks when 2\textsuperscript{nd} comm.

**CERN 400GeV SPS**

\[ \langle E_\nu \rangle \sim 17\text{GeV} \]

\[ L = 732\text{km} \]

**OPERA (2006~)**

1.7kt emulsion based \( \nu_L \) (KEK), PAC07

**MINOS (2005~)**

50 kton Water Cherenkov detector
K2K final results (2006)

- # of events
  - Exp’ed: $158.1_{-8.6}^{+9.2}$
  - Obs’ed: 112
- Spectrum shape
  - $2.8\sigma$ distortion

Consistent w/ SK
Definitely confirmed
SK atm υ results!
MINOS 1st yr results

- Best-fit spectrum for $1.27 \times 10^{20}$ POT

\[ |\Delta m^2_{32}| = 2.74 \pm 0.44 \text{ (stat + syst)} \times 10^{-3} \text{ eV}^2 \]
\[ \sin^2 2\theta_{23} = 1.00 \pm 0.13 \text{ (stat + syst)} \]
Normalizat ion = 0.98
MINOS 1st yr results

- Best-fit spectrum for 1.27x10^{20} POT

\[ |\Delta m_{32}^2| = 2.74^{+0.44}_{-0.26} \text{ (stat + syst)} \times 10^{-3} \text{ eV}^2 \]

\[ \sin^2(2\theta_{23}) = 1.00 \text{ (stat + syst)} \]

“Atmospheric Neutrino Anomaly” is now understood as neutrino oscillation
$\nu_\mu \leftrightarrow \nu_e$ osc. Search around atm $\nu$ $\Delta m^2$:
Constraint on $\Delta m_{13}^2$, $\theta_{13}$

$$P \approx \sin^2 2\theta_{13} \cdot \sin^2 \left(1.27 \frac{\Delta m_{13}^2 [eV^2]}{E_\nu [GeV]} \cdot L [km] \right)$$

- $\nu_\mu \rightarrow \nu_e$ appearance search
  - Atm $\nu$
  - K2K
- $\bar{\nu}_e$ disappearance search in reactor
  - $E_\nu \sim$ MeV, $L \sim$ km
- No evidence so far
- $\sin^2 2\theta_{13} < 0.15$ at $\Delta m^2$
  - $= 2.5 \times 10^{-3}$ eV$^2$
  - From Chooz reactor exp

Takashi Kobayashi
LSND Issue

- **LSND observe \( \nu_e \) excess in \( \nu_\mu \) beam (2001)**
  - \( \sim 30 \text{MeV} \) \( \nu_\mu \) from \( \mu^+ \) decay at rest det’ed \( \sim 30 \text{m} \)
  - If oscillation: \( \Delta m^2 \sim 1 \text{eV}^2 \), \( \sin^2 2\theta \sim 10^{-2} \sim 10^{-3} \)
- If true
  - 3 mass diff. (sol\( \sim 10^{-4}/\text{atm} \sim 2.5 \times 10^{-3}/\text{LSND} \sim 1 \))
  - \( \Rightarrow >3 \nu \text{’s?} \), Sterile? (LEP says # of active vs. \( \leq 3 \))
  - CPTV?
- Definite confirmation necessary
  - w/ **different systematics**
  - \( \Rightarrow \) MiniBooNE
- **MiniBooNE Experiment (2002~)**
  - \( \sim \text{GeV} \) wideband \( \nu_\mu \) beam from 8GeV Booster @ FNAL
  - 800ton pure mineral oil, R=6m, Cherenkov det @ 500m, 1280 PMT
  - Search for \( \nu_e \) events

Excess of candidate \( \nu_e \) events
\[ 87.9 \pm 22.4 \pm 6.0 \text{ events (3.8}\sigma) \]
\[ P(\ \bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 0.264 \pm 0.081 \% \]
MiniBooNE First Result (Apr. 2007)

- Observed NO excess beyond background
- LSND allowed region mostly excluded (90% CL)

Takashi Kobayashi (KEK), PAC07
What are known and unknown

**NEUTRINOS**

\[
U_{MNSP} \approx \begin{pmatrix}
0.8 & 0.5 & ? \\
0.4 & 0.6 & 0.7 \\
0.4 & 0.6 & 0.7
\end{pmatrix}
\]

- **Unknowns (not all)**
  - Mixing angle $\theta_{13}$
  - Mass Hierarchy (sign($\Delta m_{23}^2$))
  - CP violation
    - Baryon asymmetry in universe?
  - Absolute Neutrino Mass
  - Dirac or Majorana?
  - New physics??
  - Whole understanding
    - Hint of Phys Beyond $\mathcal{SM}$

---

**Legend**
- $\nu_e$
- $\nu_\mu$
- $\nu_\tau$

**Axes**: $m^2$ vs $m^2$

- $m_1^2$:
  - $\sim 0.08 \times 10^{-3} \text{ eV}^2$
  - $\sim 2.5 \times 10^{-3} \text{ eV}^2$
- $m_2^2$:
  - $\sim 0.08 \times 10^{-3} \text{ eV}^2$
  - $\sim 2.5 \times 10^{-3} \text{ eV}^2$
- $m_3^2$:
  - $\sim 0.08 \times 10^{-3} \text{ eV}^2$
  - $\sim 2.5 \times 10^{-3} \text{ eV}^2$

---

**Notes**:
- $\theta_{12} \sim 34^\circ$
- $\theta_{23} \sim 45^\circ$
- $\theta_{13} < 10^\circ$
- $\Delta m_{12}^2 \sim \Delta m_{23}^2$
- $\delta \sim 2 \pi$

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**References**:
PAC07
What are known and unknown

Unknowns (not all)
- Mixing angle $\theta_{13}$
  - Acc LBL/Reactor
- Mass Hierarchy
  (sign($\Delta m_{23}^2$))
  - Acc LBL/Atm
- CP violation
  - Baryon asymmetry in universe?
  - Acc LBL
- Absolute Neutrino Mass
  - $0n2\beta/\beta$ decay spec
  - Cosmology
- Dirac or Majorana?
  - $0\nu2\beta$
- New physics??

Whole understanding
⇒ Hint of Phys Beyond $\mathcal{SM}$

PAC07
What are known and unknown

**NEUTRINOS**

\[ U_{\text{MNSP}} \approx \begin{pmatrix} 0.8 & 0.5 & ? \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \]

**Unknowns (not all)**

- **Acc LBL/Reactor**
- **Acc LBL/Atm**
- Baryon asymmetry in universe?
- **Acc LBL**
  - Absolute Neutrino Mass
  - \(0\nu2\beta/\beta\) decay spec
  - Cosmology
- **Dirac or Majorana?**
  - \(0\nu2\beta\)
- New physics??

Whole understanding

⇒ Hint of Phys Beyond SM

PAC07
Next most important step: $\theta_{13}$. Why?

CPV & $\text{sign}(\Delta m^2)$ will be probed thru $\nu_e$ appearance in accel LBL

$$
P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2 S^2_{13} S^2_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E} \times \left( 1 + \frac{2a}{\Delta m^2_{31}} (1 - 2S^2_{13}) \right)$$

$$+ 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos \delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m^2_{32} L}{4E} \sin \frac{\Delta m^2_{31} L}{4E} \sin \frac{\Delta m^2_{21} L}{4E}$$

$$- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin \delta \sin \frac{\Delta m^2_{32} L}{4E} \sin \frac{\Delta m^2_{31} L}{4E} \sin \frac{\Delta m^2_{21} L}{4E}$$

+ other terms.

$$\delta \rightarrow -\delta, a \rightarrow -a \text{ for } \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

Matter eff.: $a = 7.56 \times 10^{-5} [\text{eV}^2 \cdot \rho / [\text{g/cm}^3] \cdot E / [\text{GeV}]]$

CP-odd term $\propto \sin \delta \cdot S_{12} \cdot S_{23} \cdot S_{13}$

(where $\sin \theta_{12} \sim 0.5$, $\sin \theta_{23} \sim 0.7$, $\sin \theta_{13} < 0.2$)

- If $\theta_{13}$ is large ($\sin^2 2\theta_{13} > 0.01$)
  - $\nu_e$ app. seen in next gen acc exp
  - CPV may be seen in (upgraded) next gen exp’s

- If $\theta_{13}$ is too small ($\sin^2 2\theta_{13} << 0.01$)
  - may need to wait vFact to see CPV

Takashi Kobayashi (KEK), PAC07
Next most important step: $\theta_{13}$. Why?

$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}^2S_{13}^2S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} (1 - 2S_{13}^2)\right)$

$+ 8C_{13}^2S_{13}S_{23}(C_{12}C_{23} \cos \delta - S_{12}S_{13}S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$

$- 8C_{13}^2C_{12}C_{23}S_{13}S_{23} \sin \delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E}$

+ other terms.

$\delta \rightarrow -\delta, a \rightarrow -a$ for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Matter eff.: $a = 7.56 \times 10^{-3} [eV^2] \cdot \left(\frac{\rho}{[g/cm^3]}\right) \cdot \left(\frac{E}{[GeV]}\right)$

**CP-odd term** $\propto \sin \delta \cdot s_{12} \cdot s_{23} \cdot s_{13}$

(where $\sin \theta_{12} \sim 0.5, \sin \theta_{23} \sim 0.7, \sin \theta_{13} < 0.2$)

- If $\theta_{13}$ is large ($\sin^2 2\theta_{13} > 0.01$)
  - ve app. seen in next gen acc exp
  - CPV may be seen in (upgraded) next gen exp’s
- If $\theta_{13}$ is too small ($\sin^2 2\theta_{13} << 0.01$)
  - may need to wait vFact to see CPV

Takashi Kobayashi (KEK), PAC07
Tokai-to-Kamioka (T2K) experiment

(See TUXKI03 Ishida’s talk)

- Main goals
  - Discovery of $\nu_e$ appearance
  - Precise measurements on $\nu_\mu$ disapp.
- Highest intensity J-PARC PS (750kW)
  - Commissioning: May 2008 ~
- $\nu$ beamline in J-PARC
  - Off-axis narrow band beam tuned at osc. max
  - Construction 2004 ~ 2008
  - Commissioning: Apr. 2009 ~
- SK full recovery done in 2006

Takashi Kobayashi (KEK), PAC07
T2K possible extension: CPV search

1Mton (0.54Mton fiducial mass)
Hyper-Kaqmiokande

2 years of $\nu$ run + 7 years of anti-$\nu$ run $\Rightarrow$ $O(10^6)$ events for both runs
T2K possible extension: CPV search

2 years of $\nu$ run + 7 years of anti-$\nu$ run $\Rightarrow$ $O(10^6)$ events for both runs

$3\sigma$ CP sensitivity: $|\delta| > 20^\circ$ for $\sin^2 2\theta_{13} > 0.01$
- **Existing NuMI Off-axis beam**
  - 200kW ($\rightarrow$ 320 $\rightarrow$ 700 $\rightarrow$ 1200kW upgrade plan)

- **New** Full active liq. Scint fine grained
  - 15kton
  - @~810km, ~15mr-off

Takashi Kobayashi (KEK), PAC07
NOvA (2011?)

- **Existing NuMI Off-axis beam**
  - 200kW (→ 320 → 700 → 1200kW upgrade plan)
- **New Full active liq. Scint fine grained**
  - 15kton
  - @~810km, ~15mrad-off
- **$\nu_e$ appearance**
  - Comparable to T2K

Takashi Ko

Feldman
PAC@Aspen,07
NOvA (2011~)

- **Existing NuMI Off-axis beam**
  - 200kW \(\rightarrow\) 320 \(\rightarrow\) 700 \(\rightarrow\) 1200kW upgrade plan
- **New Full active liq. Scint fine grained**
  - 15kton
  - \(\sim\) 810km, \~15mr-off

- **\(\nu_e\) appearance**
  - Comparable to T2K

- **Sign(\(\Delta m^2_{13}\)) thru matt. eff.**
  - Unique feature of NOvA
  - cf. longer dist. higher E than T2K

Takashi Ko
Reactor Experiments for $\theta_{13}$

- Disapp. of $\sim 3$MeV $\nu_e$ bar at $\sim$ km
- Purely sensitive to $\theta_{13}$
  - No sensitivity on CPV & matter effect ($\text{sign}\Delta m^2$)
  - Complementary to acc. LBL exp's
- Small signal $\rightarrow$ syst limited
  - Identical near/far det

![Double Chooz 90% CL](image)

$$\sin^2 2\theta_{13} \sim 0.025$$

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Optimistic start date</th>
<th>Detectors (ton@km)</th>
<th>GW-t-yr (yr)</th>
<th>90% CL $\sin^2 2\theta_{13}$ sensitivity</th>
<th>Far event rate</th>
<th>Funding Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Chooz</td>
<td>2009?</td>
<td>10.2@0.15, 10.2@1.067</td>
<td>80(4)</td>
<td>0.025</td>
<td>15,000/yr</td>
<td>Partially funded</td>
</tr>
<tr>
<td>RENO</td>
<td>Late 09</td>
<td>20@0.15, 20@1.5</td>
<td>340(1)</td>
<td>0.03</td>
<td>18,000/yr</td>
<td>Funded</td>
</tr>
<tr>
<td>Daya Bay</td>
<td>08(fast), 09(full)</td>
<td>40@0.36, 40@0.5, 40x2@1.75</td>
<td>3700(3)</td>
<td>0.008</td>
<td>70,000/yr, 110,000/yr</td>
<td>Proposed</td>
</tr>
<tr>
<td>ANGRA</td>
<td>2013(full)</td>
<td>1@0.05, 50@0.3, 500@1.5</td>
<td>15000(5)</td>
<td>0.0055</td>
<td>350,000/yr</td>
<td>Proposed</td>
</tr>
</tbody>
</table>

Takashi Kobayashi (KEK), PAC07
If $\theta_{13}$ is (unfortunately) very small?

**Neutrino Factory**

- Proton Driver Target Station
- 16 GeV
- 50m decay/drift
- 100m Ind Linac
- 60m bunching
- 140m cooling
- $1.6 \text{ GeV, 200 MHz}$
- Linac $0.2 \rightarrow 3 \text{ GeV}$
- RLA 1: $3 \rightarrow 11 \text{ GeV}$
- RLA 2: $11 \rightarrow 50 \text{ GeV}$
- 7.5 MeV/m average Accel Freq: 400 MHz
- Turns: 4
- p: 80 m
- Arc: 100 m
- Linac: $2 \times 150 \text{ m}$

**Beta Beam**

- $\nu_e$ from accelerated radioactive nuclei

- EURISOL
- SPL
- Linac 3
- PSB
- PS
- Decay Ring
- B rho = 1500 Tm
- B = 5 T
- L_{off} = 2500 m

$\nu_e/\bar{\nu}_e$ from accelerated muons
- No ambiguity in flux
- High intensity
- $\nu_e \rightarrow \nu_\mu$
- Need magnetized det.

**Need to establish basic technologies**

Takashi Kobayashi (KEK), PAU
If $\theta_{13}$ is (unfortunately) very small.

$\nu_e$ from accelerated radioactive nuclei.
Summary

The Growing Excitement of Neutrino Physics

- K2K confirms atmospheric oscillations
- KamLAND confirms solar oscillations
- Nobel Prize for neutrino astroparticle physics!
- SNO shows solar oscillation to active flavor
- Super K confirms solar deficit and "images" sun
- Super K sees evidence of atmospheric neutrino oscillations
- Nobel Prize for v discovery!
- LSND sees possible indication of oscillation signal
- Nobel Prize for discovery of distinct flavors!
- Kamioka II and IMB see supernova neutrinos
- Kamioka II and IMB see atmospheric neutrino anomaly
- SAGE and Gallex see the solar deficit
- LEP shows 3 active flavors
- Kamioka II confirms solar deficit

Pauli predicts the Neutrino
Fermi's theory of weak interactions
Raines & Cowan discover (anti)neutrinos
2 distinct flavors identified
Davis discovers the solar deficit

1930 1955 1980 2005

Takashi Kobayashi (KEK), PAC07
Continuing Excitement of Neutrino Physics

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2000
2030
2010
2020

Takashi Kobayashi (KEK), PAC07
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Now!

MiniBooNE no excess
MINOS confirmed SK
CNGS/OPERA started

Takashi Kobayashi (KEK), PAC07
Summary

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T2K start Apr. 2009
Reactor $\theta_{13}$

$\theta_{13}$ discovery race!

NOvA

1980  2005  2010  2020  2030

Takashi Kobayashi (KEK), PAC07
Summary

Continuing Excitement of Neutrino Physics

The Growing Excitement of Neutrino Physics

1980

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2010

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2020

- T2K-II (CP)? if $\theta_{13}$ large

Takashi Kobayashi (KEK), PAC07
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Takashi Kobayashi (KEK), PAC07
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- 0v2$\beta$ (CUORE, etc)
- Abs mass
- Majorana?

Takashi Kobayashi (KEK), PAC07
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Takashi Kobayashi (KEK), PAC07
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Takashi Kobayashi (KEK), PAC07
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Takashi Kobayashi (KEK), PAC07
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Takashi Kobayashi (KEK), PAC07
Continuing Excitement of Neutrino Physics

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Summary

Continuing Excitement of Neutrino Physics

The Growing Excitement

- Neutrino has now
  - Finite mass!!
  - Large mixing!!
- First evidence of physics not accounted by SM
- Still many fundamental questions
- Could be clue to Physics Beyond SM
- Neutrino Physics will continue to be exciting for > several 10yrs
  - (like last 40yrs of quarks)

T2K start Apr. 2009
MINOS confirmed SK
CNGS/OPERA started

$\theta_{13}$ discovery race!

NOvA

T2K-II(CP)? if $\theta_{13}$ large
$v$Fact? $\beta$-beam (if $\theta_{13}$ small?)

KATRIN $\beta$-decay
$0\nu \beta$ (CUORE, etc)

Abs mass Majorana?

R&D

2010 2020 2030

Takashi Kobayashi (KEK), PAC07
Abs. mass & Majorana?

- Tritium $\beta$-decay experiments
  - Shift of end-point of $\beta$-ray spectrum
  - $m_{ee}^2 = \sum |U_{ei}|^2 m_i^2$
  - Present: $m_\nu < 2.2\text{eV}$ (Mainz, Troitk)
  - Potential: $m_\nu < 0.3\text{eV}$ (KATRIN, 2010~)

- $0\nu 2\beta$ decay experiments
  - Only if Majorana ($\nu = \bar{\nu}$) & massive
  - Peak in energy spec at Q-value
  - Present: $< ~ 0.35\text{eV}$
  - Potential: $0.03\text{eV}$ (CUORE, Gerda, Majorana, EXO..)

- Cosmology
  - Large scale structure, CMB
  - $\Sigma = m_1 + m_2 + m_3$
  - Present: $0.7\text{eV}$

Takashi Kobayashi (KEK), PAC07
Backup
MW Proton Facility : J-PARC

Unique facility
3GeV+50GeV
Multi-purposes
•Materials and life sci.
•Nucl. and part. phys.
•Nucl. transmutation

Construction
2001~2008

Materials and Life Science Experimental Facility
Hadron Experimental Facility
Nuclear Transmutation
J-PARC = Japan Proton Accelerator Research Complex

Linac (350m)
3 GeV Synchrotron (25 Hz, 1MW)
50 GeV Synchrotron (0.75 MW)

Neutrino to Kamiokande

Takashi Kobayashi (KEK), PAC07
3 GeV Tunnel
(Beam injection in the fall of 2007)

Linac
(Beam Test is underway)
3 GeV Tunnel
(Beam injection in the fall of 2007)

Linac
(Beam Test is underway)

Takashi Kobayashi (KEK), PAC0
3 GeV Tunnel (Beam injection in the fall of 2007)

Neutron Source (Beams in the Spring of 2008)

Linac (Beam Test is underway)

Takashi Kobayashi (KEK), PAC0
Linac beam on Jan. 24, 2007

Accelerated up to design energy of 181MeV

Takashi Kobayashi (KEK), PAC07
Linac beam on Jan. 24, 2007

Accelerated up to design energy of 181 MeV

Takashi Kobayashi (KEK), PAC07
T2K status (photo album)

- Primary line tunnel
- Target station
- TS Helium vessel
- 3rd Horn
- 1st Horn
- April, 2007
- Decay volume
- Beam dump core
T2K status (photo album)

Primary line tunnel

Target station

TS Helium vessel

3rd Horn

1st Horn

April, 2007

Decay volume

Beam dump core

In short, on schedule.
Other ideas of future acc. experiments

- CPV and matter effect
- All needs multi-MW + ~Mton detector

T2Kamioka + Korea?: sensitivity on both $\delta$ & sign($\Delta m^2$)

Based on: M. Ishitsuka et al., PRD 72, 033003 (2005), hep-ph/0504026
(see also K. Hagiwara et al., hep-ph/0504061)