Topical questions in the experimental neutrino physics

Agnieszka Zalewska
Ustroń 2003

From the romantic era of great discoveries (1998-2002)
SuperKamiokande, K2K, SNO, KamLAND

to the realistic era of precise measurements (from 2003 onwards)
tens of experiments in the near or further future to study neutrino oscillations and properties

in order to answer a few fundamental questions and to help theorists to select good models (out of hundreds)

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Neutrino physics - outlook

1998 - 2002 - romantic era of great discoveries

1998 SuperKamiokande - atmospheric neutrinos anomaly explained by the $\nu_\mu \rightarrow \nu_\tau$ oscillations
2002 confirmed by the long base accelerator experiment K2K
2001-2002 SNO solves the 35 years old solar neutrino puzzle by the $\nu_e \rightarrow \nu_{\mu,\tau}$ oscillations
Dec 2002 KamLAND shows that reactor anti-$\nu_e$'s oscillate like solar $\nu_e$'s

from 2003 onwards - realistic era of precise measurements
- better determination of the oscillation parameters and neutrino mixing matrix elements
- determination of absolute mass scale
- neutrinoless double beta decay ($\beta\beta_{0\nu}$) down to 0.01 eV

LBL accelerator (on-, off-axis) and reactor expts, superbeams, niu-factories, underground cryogenic detectors, beta spectrometers, CMB surveys, ...

and still a bit of romanticism...
- searches for very high energy astrophysical neutrinos

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A few important questions

Seven questions of Murayama at EPS2003:
Dirac or Majorana?
Absolute mass scale?
How small is $\theta_{13}$?
CP Violation?
Mass hierarchy?
Verify Oscillation?
LSND? Sterile neutrino(s)? CPT violation?

Why?
To understand the mechanism given rise to neutrino masses and oscillations, the possible relation between CP-violation in the lepton sector at low energies and the generation of the baryon asymmetry of the Universe, new symmetries,...

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Neutrino sources

Three light active neutrinos: $\nu_e$, $\nu_\mu$, $\nu_\tau$ - result from LEP, others must be sterile

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Neutrino oscillations primer

In the two-neutrino oscillation scheme the probability that:

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \left( 1.27 \Delta m^2 \frac{L}{E} \right) \]

Appearance experiment:
\[ P(\nu_\alpha \rightarrow \nu_\beta) \geq 0 \]

Disappearance experiment:
\[ P(\nu_\alpha \rightarrow \nu_\alpha) \leq 1 \]

Matter effects: the same formulae for probabilities like for vacuum oscillations but effective masses and effective mixing angles
Neutrino oscillations after SNO

Two oscillation regions with a very solid experimental evidence:
  atmospheric region
  solar region

Third region:
  LSND
being checked by the dedicated MiniBOONE experiment

Note: SNO reduced the allowed oscillation space for solar neutrinos by 7 orders of magnitude
  CHOOZ excludes $\nu_{\mu} - \nu_e$ oscillations in the atmospheric region

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let us be more professional-three neutrino mixing

**U\(_{\text{MNSP}}\) - Neutrino Mixing Matrix**

<table>
<thead>
<tr>
<th>Solar</th>
<th>Chooz + Super-K</th>
<th>Atmospheric</th>
<th>0νββ decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\theta_{12} = 30.3^\circ)</td>
<td>(\tan^2 \theta_{13} &lt; 0.03 \text{ at } 90% \text{ CL})</td>
<td>(\theta_{23} = \sim 45^\circ)</td>
<td>To be determined</td>
</tr>
<tr>
<td><em>large</em></td>
<td><em>small, perhaps 0?</em></td>
<td><em>maximal</em></td>
<td></td>
</tr>
</tbody>
</table>

\[
U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\alpha_{\text{CP}}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\alpha_{\text{CP}}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i(\alpha/2 + i\beta)} \end{pmatrix}
\]

**Dirac phases**

- solar ν present
- reactor experiments + SK present
- atmospheric ν present
- 0νββ experiments present

**Majorana phases**

- Low E solar ν + SNO future
- reactor and accelerator ν future
- accelerator ν future
- 0νββ experiments future
Solar neutrinos primer

Most of the solar neutrinos in pp cycle

\[ 4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e + 2\gamma \]

Experiments measure the reactions:

\[ \nu_e + n \rightarrow p + e^- \quad \text{All} \]

In particular:

\[ \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- \]
\[ \nu_e + ^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + e^- \]
\[ \nu_\ell + e^- \rightarrow \nu_\ell + e^- \quad \text{SuperK, SNO} \]
\[ \nu_\ell + n \rightarrow \nu_\ell + n \quad \text{SNO} \]

--- Matter effects in the Sun are important for flavor conversion
--- We have to count on solar models to provide the needed input \( R = \frac{N_{\text{obs}}}{N_{\text{MC}}} \)
--- The distance to the Sun varies by about 7% during the year
--- During the night neutrinos pass through the Earth on their way to the detector, while during the day they do not \( \rightarrow \) the Earth matter effect provides further sensitivity to the neutrino parameters.

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SNO - oscillations of solar neutrinos

$\nu_e$ neutrinos produced in Sun
$\nu_e \rightarrow \nu_{\mu,\tau}$ on the way from the Sun core to the detector
total neutrino flux in agreement with the Standard Solar Model

Phase 1: 1000 tons of $D_2O$, 9456 photomultipliers, 7 kton $H_2O$, 2000 m. under surface, detection of the Cherenkov radiation

Phase 2: addition of two tons of salt to improve the neutron capture efficiency

Phase 3: addition of He detectors

Phase 1 publications
PRL 87, 071301 (2001) (SNO + SK)
PRL 89, 011301 (2002) (SNO only)

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Processes measured in the SNO experiment

CC: \[ \nu_e + d \Rightarrow p + p + e^- \]
only $\nu_e$'s, good energy measurement
weak dependence on the neutrino direction $1 - 1/3 \cos \theta$

NC: \[ \nu_x + d \Rightarrow p + n + \nu_x \]
all three types of neutrinos with
the same cross section,
measurement of the total neutrino flux

ES: \[ \nu_x + e^- \Rightarrow \nu_x + e^- \]
relatively small cross section,
sensitive mostly to $\nu_e$'s, sensitive
to the neutrino direction, reaction measured also by SuperK

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SNO Phase II - Salt

D$_2$O

**NC Sensitivity**

$\varepsilon_n \sim 24\%$

$n + ^2\text{H} \rightarrow ^3\text{H} + \gamma$

$E_\gamma = 6.25\text{ MeV}$

NC and CC separation by energy, radial, and directional distributions

Salt

**Enhanced NC Sensitivity**

$\varepsilon_n \sim 83\%$

$n + ^{35}\text{Cl} \rightarrow ^{36}\text{Cl} + \sum \gamma$

$E_{\sum \gamma} = 8.58\text{ MeV}$

NC and CC separation by event isotropy

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SNO Phase III
The Neutral Current Detectors

Array of $^3$He counters
- 96 Strings on 1-m grid
- 775 m total active length

Detection Principle

\[ ^2\text{H} + \nu_x \rightarrow p + n + \nu_x \text{-}2.22 \text{ MeV} \quad \text{(NC)} \]

\[ ^3\text{He} + n \rightarrow p + ^3\text{H} \]

Physics Motivation

Event-by-event separation. Measure NC and CC in separate data streams.

Different systematic uncertainties than neutron capture on NaCl.

NCD array as a neutron absorber.
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SNO - answers to the questions:

\[
\frac{\Phi_{cc}}{\Phi_{es}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)} = 1? 
\]

\[
\frac{\Phi_{cc}}{\Phi_{nc}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau} = 1? 
\]

\[
\Phi_{day} = \Phi_{night}? 
\]
2002 SNO results - solar flux analysis

\[ \Phi_{CC} = 1.76 \pm 0.05 \pm 0.09 \cdot 10^6 \text{ cm}^{-2} \text{ sec}^{-1} \]

\[ \Phi_{NC} = 5.09 \pm 0.43 \pm 0.46 \cdot 10^6 \text{ cm}^{-2} \text{ sec}^{-1} \]

\[ \Phi_{ssm} = 5.05 \pm 1.01 \]

\[ \Phi_{ES} \]

\[ \Phi_{CC} \]

\[ \Phi_{NC} \]

\[ \Phi_{SSM} \]
2002 SNO results - day/night asymmetry

It will be a very important measurement for Borexino and/or upgraded KamLAND!

\[ A_X = \frac{2(\Phi_{N,X} - \Phi_{D,X})}{(\Phi_{N,X} + \Phi_{D,X})} \]

\[ A_e = 12.8^{+6.2}_{-1.4}^{+1.5}_{-1.4} \]

\[ A_{\text{tot}} = -24.2^{+16.1}_{-2.5}^{+2.4}_{-2.5} \]

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2003 SNO results from phase 2

Phase 2

n capture efficiency almost doubled

\[
\phi_{CC}^{SNO} = 1.59^{+0.08}_{-0.07} \text{(stat)}^{+0.06}_{-0.08} \text{(syst)}
\]

\[
\phi_{ES}^{SNO} = 2.21^{+0.31}_{-0.26} \text{(stat)} \pm 0.10 \text{(syst)}
\]

\[
\phi_{NC}^{SNO} = 5.21 \pm 0.27 \text{(stat)} \pm 0.38 \text{(syst)}
\]

Phase 1

\[
\Phi_{cc}^{(v_e)} = 1.76^{+0.06}_{-0.05} \text{(stat)}^{+0.09}_{-0.09} \text{(syst.)} \times 10^6 \text{ cm}^2\text{s}^{-1}
\]

\[
\Phi_{es}^{(v_x)} = 2.39^{+0.24}_{-0.23} \text{(stat.)}^{+0.12}_{-0.12} \text{(syst.)} \times 10^6 \text{ cm}^2\text{s}^{-1}
\]

\[
\Phi_{nc}^{(v_x)} = 5.09^{+0.44}_{-0.43} \text{(stat.)}^{+0.46}_{-0.43} \text{(syst.)} \times 10^6 \text{ cm}^2\text{s}^{-1}
\]

Fig. 5: Global neutrino oscillation contours. (a) Solar global: D_2O day and night spectra, salt CC, NC, ES fluxes, SK, Cl, Ga. The best-fit point is \(\Delta m^2_{sol} = 6.5 \times 10^{-5}\), \(\tan^2 \theta = 0.40\), \(f_B = 1.04\), with \(\chi^2/\text{d.o.f.} = 70.2/81\). (b) Solar global + KamLAND. The best-fit point is \(\Delta m^2 = 7.1 \times 10^{-5}\), \(\tan^2 \theta = 0.41\), \(f_B = 1.02\). In both (a) and (b) the \(^8\text{B}\) flux is free and the hep flux is fixed.
Reactor antineutrinos

Long tradition, started by the first observation of neutrino interactions by Reines and Cowan

Typical power station gives $6 \times 10^{20}$ anty-$\nu$/s and 3GW of power

The Palo Verde reactor experiment

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KamLAND - very long baseline reactor experiment

Detector: inner detector - 1 kton of liquid scintillator, light registered by about 2000 photomultipliers, outer detector filled with oil, veto part filled with water,
Detector “looks” at more than 30 reactors in Japan and Korea at average distance of 180 km
reaction process: inverse-β decay ($\bar{\nu}_e + p \rightarrow e^+ + n$) + $p \rightarrow d + \gamma$

distinctive two-step signature

- prompt part: $e^+$

  $\bar{\nu}_e$ energy measurement
  
  $E_\nu \sim (E_\nu - \Delta) / I + \frac{E_\nu}{M_p} + \frac{\Delta^2 - m_e^2}{M_p}$
  
  $\Delta = M_u - M_p$

- delayed part: $\gamma$ (2.2 MeV)

- tagging: correlation of time, position and energy between prompt and delayed signal

$E_{th} = \frac{(M_n + m_e)^2 - M_p^2}{2M_p} = 1.806$ MeV
KamLand results - from Dec. 2002

54 observed events, 86.8$\pm$5.6 expected events if no oscillations

Fast signal of positron annihilation in coincidence with slower signal of neutron capture

\[
\frac{N_{obs} - N_{BG}}{N_{expected}} = 0.611 \pm 0.085\text{(stat)} \pm 0.041\text{(syst)}
\]
KamLand - oscillation study
combining rate and energy spectrum

Best fit:
\[ \Delta m^2 = 6.9 \times 10^{-5} \text{ eV}^2 \]
\[ \sin^2 2\theta = 1.01 \]

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6.9 x 10^{-5} \text{ eV}^2
\sin^2 2\theta = 1.01
Neutrino Oscillation Study, Using Rate & Energy Spectrum

A. Suzuki at Neutrino telescopes 2003

$E_{\text{prompt}} > 0.9 \text{ MeV}$

Best fit:

$\Delta m^2 = 6.9 \times 10^{-5} \text{eV}^2$

$\sin^2 2\theta = 0.91$

Note: Best fit (with SNO-phase 2):

$\Delta m^2 = 7.1 \times 10^{-5} \text{eV}^2$

$\tan^2 \theta = 0.41$
KamLAND - future

phase 1
after three years of data taking
much better $\Delta m^2_{12}$
small improvement on $\theta_{12}$

phase 2
studies of Be and pp neutrinos

2nd phase experiment
($E_{\text{th}} = 200$ keV)
$\nu_e + e^- \rightarrow \nu_e + e^-$

Solar neutrino Detection

$^7\text{Be}$ Neutrino

supernova-burst $\nu$, relic supernova $\nu$,
atmospheric $\nu$, Proton Decays, · · ·
SuperKamiokande - solar neutrinos flux modulation in time

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Atmospheric neutrinos primer

Primary cosmic rays
\[ p, \text{He} \ldots \]

Production height
10~30 km

Atmosphere

\[ \pi^-, K^- \]

\[ \nu_\mu, \nu_\mu, e^- \]

Travel length
10~30 km

Up to 13000 km

For \( E_\nu > \) a few GeV,
(Up-going / down-going) \(~ 1\)
Uncertainty of up/down ratio
\(< \) a few %
the detector rebuilt successfully and resumed data taking in Dec. 2002.

Inner detector

~5200 20inch PMTs with covers

Outer detector, 1885 8inch PMTs

from Hayato at EPS2003

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SuperKamiokande - oscillations $\nu_\mu \leftrightarrow \nu_\tau$

Measurement of energy and direction of muons and electrons from CC neutrino interactions

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SuperK - e and μ.
SuperK I - new analysis of the whole data

Up/Down double ratio \( R = \frac{N_{\text{obs}}_{\mu}/N_{\text{obs}}_{e}}{N_{\text{exp}}_{\mu}/N_{\text{exp}}_{e}} \)

and zenith angle distributions

for different event categories and energy subsamples

preliminary results presented at EPS03 in Aachen
Summary of the atmospheric $\nu$ events
1. contained events

(complete SK-I dataset)

**Sub GeV**

1 ring e-like

- **Data**: 3353
  - **MC (Honda)**: 3013.9

1 ring $\mu$-like

- **Data**: 3227
  - **MC (Honda)**: 4466.9

1 ring $\mu$-like + Partially Contained

- **Data**: 1562
  - **MC (Honda)**: 2098.0

**Multi GeV**

1 ring e-like

- **Data**: 746
  - **MC (Honda)**: 700.4

1 ring $\mu$-like

- **Data**: 208
  - **MC (Honda)**: 346.4

**Multi-GeV 1 ring $\mu$-like**

- **Data**: 439
  - **MC (Honda)**: 739.4

\[
\frac{\mu}{e}_{data} \quad \frac{\mu}{e}_{MC}
\]

\[
= 0.649 \pm 0.016 \quad (\text{stat.})
\]

\[
\pm 0.051 \quad (\text{syst.})
\]

\[
= 0.699 \pm 0.032 \quad (\text{stat.})
\]

\[
\pm 0.030 \quad (\text{syst.})
\]
Summary of the atmospheric ν events
2. up-going μ events

Up through going μ

Measured flux
\[ 1.70 \pm 0.02 \pm 0.04 \times 10^{-13} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]
(stat.) (syst.)

Theoretical calc. (Honda)
\[ 1.57 \pm 0.35 \times 10^{-13} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]
(theo.)

Up stopping μ

Measured flux
\[ 0.41 \pm 0.02 \pm 0.02 \times 10^{-13} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]
(stat.) (syst.)

Theoretical calc. (Honda)
\[ 0.61 \pm 0.14 \times 10^{-13} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]
(theo.)

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Preliminary!
Atmospheric $\nu$ zenith angle distribution

- Honda
- Best fit ($\sin^2 2\theta = 1.0, \Delta m^2 = 2.0 \times 10^{-3} \text{eV}^2$)

Sub GeV
- 1ring e-like
- 1ring $\mu$-like

Multi GeV
- 1ring e-like
- 1ring $\mu$-like + Partially Contained
- Multi ring ($\mu$)

Upward stopping $\mu$

Upward through going $\mu$
Comparison between old and new results from atmospheric $\nu$ data

- Neutrino flux
  (Honda 1995 $\rightarrow$ Honda 2001)
- Neutrino interaction models
  (several improvements, agree with K2K near data)
- Improved detector simulation
- Improved event reconstruction tools

Each change slightly shifted the allowed region to lower $\Delta m^2$

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K2K - first LongBaseLine accelerator experiment

Super-K (far detector)
50 kton Water
Cherenkov detector

Ev~1.3 GeV
νμ

50km

12GeV PS@KEK
• ν beam line
• Beam monitor
• Near detectors

< E_ν >~ 1.3GeV
almost pure ν_μ (~ 98%)
K2K - measurement principle

Near detector at KEK - K2K I
upgrade in 2003
for K2K II

Measurement of the muon momenta and directions in the near detector at KEK
-> neutrino flux and energy spectrum in the near detector
-> extrapolation of the flux and energy spectrum to the far detector, assuming
no oscillations
Measurement of the neutrino flux and energy spectrum in the far detector
-> conclusions concerning the oscillations based on the flux reduction and
modification of the energy spectrum

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K2K I - measurement results

- Flux disappearance:
  56 events observed
  80.1 ± 6.2 - 5.4 expected

- Modification of the energy spectrum

- Oscillation parameters compatible with the SuperK results for atmospheric oscillations

$\Delta m^2 = 1.5 \sim 3.9 \times 10^{-3}$ eV$^2$ @ $\sin^2 2\theta = 1$ (90% CL)

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Long BaseLine accelerator projects

In realisation:

♦ NuMi - neutrino beam from FNAL to the MINOS detector in the Soudan mine, start in 2005, near and far detector, $\nu_\mu$ disappearance

♦ CNGS - neutrino beam from CERN to CNGS, far detectors OPERA and ICARUS, start in 2006, $\nu_\tau$ appearance

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Long BaseLine accelerator projects

Optimisation of the experimental setup:

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

- a: CERN → GS
- b: Fermilab → MINOS
- c: KEK → SK
- d: Atmospheric \( \nu \)
MINOS experiment

- 5.4kt total
  - 484 planes in two ~14.5m long “super modules”, each plane 8m octagon
  - 2.54cm Fe, 1cm Scintillator
  - ~1.5T Magnetic field
MINOS experiment

5 years of data taking - $25 \times 10^{20}$ p.o.t in total

improved $\Delta m_{23}^2$

improved $\theta_{13}$

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CNGS programme

High energy neutrino beam, optimized for $\nu_\tau$ appearance
Two experiments: OPERA and ICARUS - small signal with no background

A “hybrid” experiment

Electronic detectors
$\to$ select $\nu$ interaction brick
$\to$ $\mu$ ID, charge and p

Emulsion scanning
$\to$ vertex search
$\to$ decay search
$\to$ e/\gamma ID, kinematics
LNSD effect

Excess of positrons above background interpreted as anty-$\nu_e$ appearance due to oscillations

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = (0.264 \pm 0.067 \pm 0.045)\%$$
Proton beam with momentum 800 MeV, data from 1993-1998, mostly pions at rest

Effect not confirmed by the KARMEN experiment

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MiniBOONE checks the LSND effect

Results: ~ 2005

Preliminary
let us be more professional-three neutrino mixing

$U_{MNSP}$ - Neutrino Mixing Matrix

**Solar**

$\theta_{12} = 30.3^{\circ}$

$tan^2 \theta_{13} < 0.03$ at 90% CL

*small, perhaps 0?*

**Chooz + Super- K**

**Atmospheric**

$\theta_{23} = \sim 45^{\circ}$

*maximal*

**$0\nu\beta\beta$ decay**

*Much discussion To be determined*

Dirac phases

$$U = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix} = \begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix} \times \begin{pmatrix}
\cos \theta_{13} & 0 & e^{-i\alpha_{\beta}} \sin \theta_{13} \\
0 & 1 & 0 \\
-e^{i\alpha_{\beta}} \sin \theta_{13} & 0 & \cos \theta_{13}
\end{pmatrix} \times \begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix} \times \begin{pmatrix}
1 & 0 & 0 \\
0 & e^{i\alpha/2} & 0 \\
0 & 0 & e^{i\alpha/2 + i\beta}
\end{pmatrix}$$

**Majorana phases**

**Reactor experiments + SK present**

$\nu$ present

**Atmospheric $\nu$ present**

**$0\nu\beta\beta$ experiments present**

**Low E solar $\nu$ + SNO future**

**Reactor and accelerator $\nu$ future**

**Accelerator $\nu$ future**

**$0\nu\beta\beta$ experiments future**

European Physical Society Meeting
Aachen, July 2003

Kevin Lesko
Subdominant oscillation $\nu_\mu - \nu_e$
measurement of $\theta_{13}$

The most important measurement at present:
  e.g. CP violation measurement possible, if $\theta_{13}$ not too small

Present limit for $\theta_{13}$ comes from CHOOZ $\sin^2 2\theta < 0.12$

Improved measurements require very massive detectors, intensive neutrino source and reduced background:
  NuMi off-axis experiment
  JHF (now J-PARC) superbeam - SuperKamiokande
dedicated LBL reactor experiment with two detectors and optimised baseline
  eventually LBL experiment at the neutrino factory

Very difficult measurement because depends on other oscillation parameters (->correlations) - dependence is quadratic for some parameters and trigonometric for others (->degeneracies) --> both neutrino and antineutrino beams are needed
**NuMi Off-Axis principle**

**Two body decay kinematics**

At this angle, 15 mrad, energy of produced neutrinos is 1.5-2 GeV for all pion energies ➔ very intense, narrow band beam

\[ \beta \theta + \gamma \theta = \text{Energy} \]

"On axis": \( E_n = 0.43E_p \)

\[ p_L = \gamma (p^* \cos \theta^* + \beta E^*) \]

\[ p_T = p^* \sin \theta^* \]
Two phase program

Phase I (running 2007 - 2014)
• 50 kton (fiducial) detector with $e \sim 40\%$
• $4 \times 10^{20}$ protons per year
• 1.5 years neutrino ($6000 \, n_{\mu} \, CC$, 70-80% 'oscillated')
• 5 years antineutrino ($7000 \, n_{\mu} \, CC$, 70-80% 'oscillated')

Phase II (running 2014-2020)
• 200 kton (fiducial) detector with $e \sim 40\%$ or 100 kton Liquid Argon
• $20 \times 10^{20}$ protons per year
• 1.5 years neutrino ($120000 \, n_{\mu} \, CC$, 70-80% 'oscillated')
• 5 years antineutrino ($130000 \, n_{\mu} \, CC$, 70-80% 'oscillated')
LBL accelerator projects - further future

Superbeams

High intensity conventional beams

Neutrino Factories

New type of accelerator

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Next generation LBL experiments in Japan
“J-PARC - Kamioka neutrino project”

First superbeam

Baseline ~295km
Conventional $\nu_\mu$ beam

Beam Energy ~1GeV
Will be adjusted to
the oscillation maximum

<table>
<thead>
<tr>
<th>Beam power</th>
<th>Far detector</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st phase</td>
<td>0.75MW</td>
<td>disappearance $\nu_\mu \rightarrow \nu_X$</td>
</tr>
<tr>
<td></td>
<td>Super Kamiokande(50kt)</td>
<td>appearance $\nu_\mu \rightarrow \nu_e$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NC measurements</td>
</tr>
<tr>
<td>2nd phase</td>
<td>~4MW</td>
<td>CP violation</td>
</tr>
<tr>
<td></td>
<td>Hyper Kamiokande(1Mt)</td>
<td>Proton decay</td>
</tr>
</tbody>
</table>
CERN concept of the neutrino factory

A possible layout of a neutrino factory
Sensitivity on the $\theta_{13}$ measurement

- NuMI and JHF-SK have a similar performance
- JHF-SK and NuMI statistics limited
- JHF-HK systematics limited
- NuFact far away from systematic limit
- Correlations and degeneracies require a clever setup
Complementary experiment: Reactors

- Long Baseline (~1 km from source)
- Disappearance $\nu_e \rightarrow \nu_e$
- Use near detector to measure reactor flux, spectrum and detector efficiency to cancel “all systematics”
- Look for small deviation from $1/r^2$ with plenty of reactor signal

\[
1 - P_{ee} \approx \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E} \right) + O(\alpha^2)
\]

- Very clean $\theta_{13}$ measurement (no ambiguities, no matter effects)

A.Zalewska, Ustron, 20.09.2003
Neutrino mass hierarchies

Two important questions:
How far from zero the whole picture is?
Normal hierarchy (above) or inverted hierarchy (w.r.t. $\Delta m^2_{\text{atm}}$)
Mass determination

Direct measurements based on end-point in the beta decays
the best measured $m_{\nu_e} < 2.2 \text{ eV}$ - from the end-point of the tritium beta decay by the Mainz and Tritsk experiments
future: KATRIN experiment with a sensitivity of 0.2 eV

Cosmological limits
recent cosmic microwave background measurements by the Wilkinson Microwave Anisotropy Probe (WMAP) together with earlier infrared survey experiment (2dF) give an upper limit of 0.71 eV for a sum of neutrino masses, hence 0.23 eV for a single neutrino.

Based on the lifetime measurements for the neutrinoless double beta decays
several experiments running or being prepared with an ultimate goal of achieving an accuracy of 0.01 eV
Mass determination from the $^3T$ endpoint

Ch. Kraus@EPS2003

- Final analysis of 6 data sets (119 days of data taking)
- No indication for disturbances, especially no Troitsk anomaly
- 2001 low and stable background due to careful preparation
- Standard analysis of data 98/99/01:
  \[ m_\nu^2 c^4 = -1.2 \pm 2.2_{\text{stat}} \pm 2.1_{\text{sys}} \text{ eV}^2 \]
  \[ \Rightarrow m_\nu c^2 \leq 2.2 \text{ eV} \quad (95\% \text{ C.L., unif. appr.}) \]
KATRIN - next generation experiment

start of data taking in 2007, big collaboration including Mainz and Troitsk

experimental observable in $\beta$-decay is $m_\nu$

aim: improve $m_\nu$ by one order of magnitude ($2 \text{ eV} \rightarrow 0.2 \text{ eV}$)

requires: improve $m_\nu$ by two orders of magnitude ($4 \text{ eV}^2 \rightarrow 0.04 \text{ eV}^2$)

problem: count rate close to $\beta$-end point drops very fast ($\sim \delta E^3$)

last 10 eV: $2 \times 10^{-10}$ / last 1 eV: $2 \times 10^{-13}$ of total $\beta$-activity

• improve statistics:
  • stronger tritium source (factor 80) (& larger analysing plane, $\Phi=10\text{m}$)
  - longer measuring period ($\sim 100 \text{ days} \rightarrow \sim 1000 \text{ days}$)

• improve energy resolution:
  - large electrostatic spectrometer with $\Delta E=1 \text{ eV}$ (factor 4 improvement)

• reduce systematic errors:
  - better control of systematics, energy losses (reduce to less than 1/10)

A. Zalewska, Ustron, 20.09.2003
Neutrino mass hierarchies

Effective neutrino mass in tritium beta decay as a function of the lightest neutrino mass

A. Zalewska, Ustron, 20.09.2003
Double beta decay primer

For some even-even nuclei the decay chain

\[(A, Z) \rightarrow (A, Z + 1) + e^- + \bar{\nu}_e \]
\[\rightarrow (A, Z + 2) + e^- + \bar{\nu}_e\]

is forbidden by energy conservation and one could have

\[(A, Z) \rightarrow (A, Z + 2) + 2e^- + 2\bar{\nu}_e\]
\[(A, Z) \rightarrow (A, Z + 2) + 2e^-\]
Double beta decay

\[ [T_{1/2}^{0\nu}]^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_\nu \rangle^2 \]

The nuclear matrix element
\[ |M^{0\nu}|^2 \]

Effective neutrino mass
\[ \langle m_\nu \rangle = \sum \phi_k m_k U_{e,k}^2 \]

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}^{0\nu}$ (y)</th>
<th>$T_{1/2}^{0\nu}$ (y)</th>
<th>$\langle m_\nu \rangle$ (eV)</th>
<th>$\langle m_\nu^1 \rangle$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>$(4.2 \pm 1.2) \times 10^{19}[16]$</td>
<td>$9.5 \times 10^{21}$ (76%) [17]</td>
<td>$&lt; 8.3$</td>
<td>$&lt; 16 - 30$</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>$(1.3 \pm 0.1) \times 10^{21}[37,18]$</td>
<td>$1.9 \times 10^{25}$[37]</td>
<td>$&lt; 0.35$</td>
<td>$&lt; 0.3 - 1$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$1.6 \times 10^{26}$ [19,38]</td>
<td>$&lt; 0.33 - 1.35$</td>
<td></td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>$(9.2 \pm 1.0) \times 10^{19}[20,21]$</td>
<td>$2.7 \times 10^{22}$ (68%) [20]</td>
<td>$&lt; 5$</td>
<td>$&lt; 4.6 - 14.4$</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>$(1.4^{+3.5}_{-0.5}) \times 10^{19}[22,23]$</td>
<td>$5.5 \times 10^{22}$[27]</td>
<td>$&lt; 2.1$</td>
<td>$&lt; 2.3 - 8.4$</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>$(8.0 \pm 0.6) \times 10^{18}[24,25,26]$</td>
<td>$7 \times 10^{22}$[29]</td>
<td>$&lt; 2.6$</td>
<td>$&lt; 2.6 - 8.2$</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>$(3.2 \pm 0.3) \times 10^{19}[28,29,30]$</td>
<td>Geoch. ratio [31]</td>
<td>$&lt; 1.1 - 1.5$</td>
<td></td>
</tr>
<tr>
<td>$^{128,130}$Te</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>$(7.2 \pm 0.3) \times 10^{24}[31,32]$</td>
<td>$7.7 \times 10^{24}$[31]</td>
<td>$&lt; 1.1 - 1.5$</td>
<td></td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>$(2.7 \pm 0.1) \times 10^{21}[31]$</td>
<td>$2.08 \times 10^{23}$</td>
<td>$&lt; 0.9 - 2.0$</td>
<td>$&lt; 0.85 - 5.3$</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>$8.1 \times 10^{20}[33]$</td>
<td>$4.4 \times 10^{23}$[34]</td>
<td>$&lt; 1.8 - 5.2$</td>
<td>$&lt; 2 - 5.2$</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>$7.0^{+11.8}_{-6.3} \times 10^{18}[25,35]$</td>
<td>$1.2 \times 10^{21}$[25]</td>
<td>$&lt; 3$</td>
<td>$&lt; 4.6 - 6.5$</td>
</tr>
<tr>
<td>$^{238}$U(3)</td>
<td>$(2.0 \pm 0.6) \times 10^{21}[36]$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Double beta decay

\[ [T_{1/2}^{0\nu}]^{-1} = G^{0\nu} |M^{0\nu}|^2 \langle m_\nu \rangle^2 \]

Theoretically evaluated $\beta\beta(0\nu)$ half-lives (units of $10^{28}$ years for $\langle m_\nu \rangle = 10$ meV).

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Isotope</th>
<th>$T_{1/2}^{0\nu}$</th>
<th>$\langle m_\nu \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>$^{130}\text{Te}$</td>
<td>7</td>
<td>27</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>$^{130}\text{Te}$</td>
<td>0.15</td>
<td>184</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>$^{136}\text{Xe}$</td>
<td>8</td>
<td>52</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>$^{76}\text{Ge}$</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>$^{76}\text{Ge}$</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>$^{76}\text{Ge}$</td>
<td>70</td>
<td>18</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>$^{100}\text{Mo}$</td>
<td>10</td>
<td>36</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>$^{136}\text{Xe}$</td>
<td>3</td>
<td>86</td>
</tr>
<tr>
<td>$^{160}\text{Gd}$</td>
<td>$^{130}\text{Te}$</td>
<td>0.01</td>
<td>240</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>$^{150}\text{Nd}$</td>
<td>0.15</td>
<td>190</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>$^{100}\text{Mo}$</td>
<td>0.04</td>
<td>560</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>$^{116}\text{Cd}$</td>
<td>&gt; 1</td>
<td>69</td>
</tr>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>$^{48}\text{Ca}$</td>
<td>1</td>
<td>158 [15]</td>
</tr>
</tbody>
</table>

Expected 5 y sensitivities of future projects. NME are from ref. [13] except when noted.

A.Zalewska, Ustron, 20.09.2003
NEMO3 experiment as an example

7.2 kg $^{100}$Mo
1 kg $^{82}$Se
0.4 kg $^{116}$Cd
0.6 kg $^{130}$Te
1 kg nat$^{75}$Te
0.6 kg Cu
48 g $^{150}$Nd
20 g $^{96}$Zr
7 g $^{48}$Ca

$^{0}\nu$, $^{2}\nu$

ββ0ν, ββ2ν

background

(ββ0ν)
Extremely High Energy neutrinos

Do they exist?
Where do they come from?

Boosted by the observation of EHE cosmic rays in the AGASA experiment

It is a part of the experimental program realized with big volume detectors (up to 1 km$^3$) based on a detection of Cherenkov radiation in ice
   Amanda, Icecube
or deeply in a sea or lake water
   Antares, Nestor, (pioneered by Baikal)

A.Zalewska, Ustron, 20.09.2003
AMANDA/ICECUBE - Antarctic experiments

- Dark sector
- Skiway
- South Pole
- Dome
- 80 Strings
- 4800 PMTs
- 1 km³
- 2004 - 2010

IceCube

Planned Location 1 km east
Neutrino Telescope in the Ice

1997:
AMANDA-B10
302 OMs on 10 Strings

2000:
AMANDA-II
677 OMs on 19 Strings
First results from AMANDA

Atmospheric neutrino spectrum

Search for extraterrestrial point sources

ICRC 2003: Geenen for AMANDA
Special role of tau neutrinos

Simulation of the PeV $\nu_{\tau}$ interaction in the ICECUBE detector

Shower due to $\nu_{\tau}$ interaction and shower due to $\tau$ decay separated by 500 meters!

1/3 of UHE neutrinos are $\nu_{\tau}$ neutrino (because of oscillations) not absorbed in the Earth (regeneration)

Also note: ICECUBE (and other exps) will be v. good laboratories for studies of h.e. atmospheric neutrinos.
Deep water neutrino telescopes

Close to Toulon, at a death of 2400 m., successful first tests, problems with bioluminescence
Deep water neutrino telescopes

At a death of 4000 m!

A. Zalewska, Ustron, 20.09.2003
Rate + Shape Analysis in 3 Generation Case

\[ P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx \sin^4 \theta_{13} + \cos^4 \theta_{13} \left[ 1 - \sin^2 2\theta_{12} \sin^2 \left( \frac{1.27 \Delta m_{12}^2 [eV^2] L [m]}{E [MeV]} \right) \right] \]

Sensitivity for \( \theta_{13} \) \( \Delta m_{12}^2 = 6.9 \times 10^{-5} \) eV\(^2\)

\[ \sin^2 2\theta_{13} \]

95\% C.L.

68\% C.L.

CHOOZ excluded
2003 SNO results from phase 2

-- higher efficiency for the neutron capture on Cl
-- greater isotropy of the Cherenkov light for NC events as compared to CC and ES samples -> better separation of event types
-- NC flux determined with almost twice smaller errors, CC and ES fluxes with errors comparable to phase 1 errors