Experiments on neutrino oscillation & OPERA

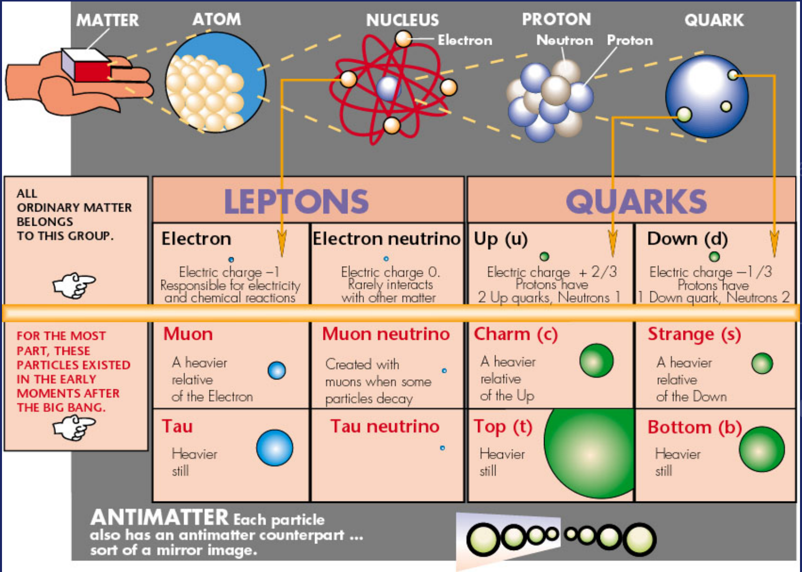
Benjamin Janutta

Hamburg student seminar
Institut für Experimentalphysik
Universität Hamburg

25.04.2005

Overview

A brief history



	LEPTONS		**QUARKS**	
ALL ORDINARY MATTER BELONGS TO THIS GROUP.	**Electron** Electric charge −1 Responsible for electricity and chemical reactions	**Electron neutrino** Electric charge 0. Rarely interacts with other matter	**Up (u)** Electric charge +2/3 Protons have 2 Up quarks, Neutrons 1	**Down (d)** Electric charge −1/3 Protons have 1 Down quark, Neutrons 2
FOR THE MOST PART, THESE PARTICLES EXISTED IN THE EARLY MOMENTS AFTER THE BIG BANG.	**Muon** A heavier relative of the Electron	**Muon neutrino** Created with muons when some particles decay	**Charm (c)** A heavier relative of the Up	**Strange (s)** A heavier relative of the Down
	Tau Heavier still	**Tau neutrino**	**Top (t)** Heavier still	**Bottom (b)** Heavier still

ANTIMATTER Each particle also has an antimatter counterpart ... sort of a mirror image.

A brief history

- first indirect “detection” already in 1914 by Chadwick, measuring a continuus β-decay spectrum.
- explaining the continuus β-decay spectrum, Wolfgang Pauli postulated “Neutronen” in 1930.
- in 1947 Powell *et al.* observed ν_μ in a balloonborne emulsion experiment.
- Cowan and Reines observed $\overline{\nu}_e$ in a reactor neutrino experiment in 1956, which motivated Pontecorvo to discuss $\nu_e \rightarrow \overline{\nu}_e$ oscillations.
- in 1964 Davis started the Homestake Experiment which gave rise to the so called “Solar Neutrino Problem”.

A brief history

- first indirect “detection” already in 1914 by Chadwick, measuring a continuus β-decay spectrum.
- explaining the continuus β-decay spectrum, Wolfgang Pauli postulated “Neutronen” in 1930.
- in 1947 Powell *et al.* observed ν_μ in a balloonborne emulsion experiment.
- Cowan and Reines observed $\bar{\nu}_e$ in a reactor neutrino experiment in 1956, which motivated Pontecorvo to discuss $\nu_e \rightarrow \bar{\nu}_e$ oscillations.
- in 1964 Davis started the Homestake Experiment which gave rise to the so called “Solar Neutrino Problem”.

A brief history

- first indirect “detection” already in 1914 by Chadwick, measuring a continuus β-decay spectrum.
- explaining the continuus β-decay spectrum, Wolfgang Pauli postulated “Neutronen” in 1930.
- in 1947 Powell *et al.* observed ν_μ in a balloonborne emulsion experiment.
- Cowan and Reines observed $\overline{\nu}_e$ in a reactor neutrino experiment in 1956, which motivated Pontecorvo to discuss $\nu_e \rightarrow \overline{\nu}_e$ oscillations.
- in 1964 Davis started the Homestake Experiment which gave rise to the so called “Solar Neutrino Problem”.

A brief history

- first indirect “detection” already in 1914 by Chadwick, measuring a continuus β-decay spectrum.
- explaining the continuus β-decay spectrum, Wolfgang Pauli postulated “Neutronen” in 1930.
- in 1947 Powell *et al.* observed ν_μ in a balloonborne emulsion experiment.
- Cowan and Reines observed $\overline{\nu}_e$ in a reactor neutrino experiment in 1956, which motivated Pontecorvo to discuss $\nu_e \longrightarrow \overline{\nu}_e$ oscillations.
- in 1964 Davis started the Homestake Experiment which gave rise to the so called “Solar Neutrino Problem”.

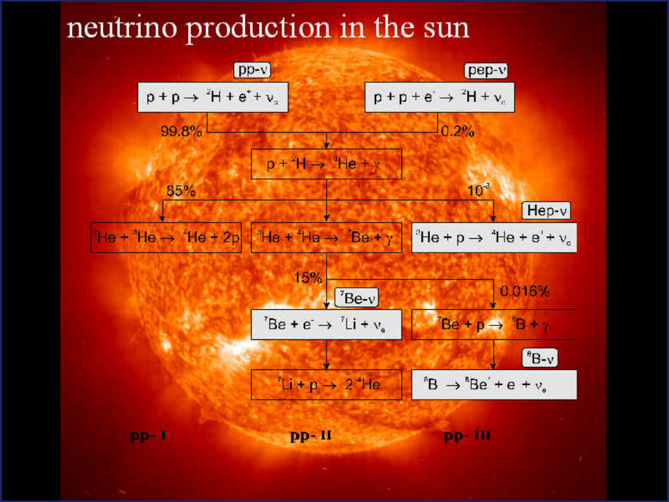
A brief history

- first indirect “detection” already in 1914 by Chadwick, measuring a continuus β-decay spectrum.
- explaining the continuus β-decay spectrum, Wolfgang Pauli postulated “Neutronen” in 1930.
- in 1947 Powell *et al.* observed ν_μ in a balloonborne emulsion experiment.
- Cowan and Reines observed $\overline{\nu}_e$ in a reactor neutrino experiment in 1956, which motivated Pontecorvo to discuss $\nu_e \longrightarrow \overline{\nu}_e$ oscillations.
- in 1964 Davis started the Homestake Experiment which gave rise to the so called “Solar Neutrino Problem”.

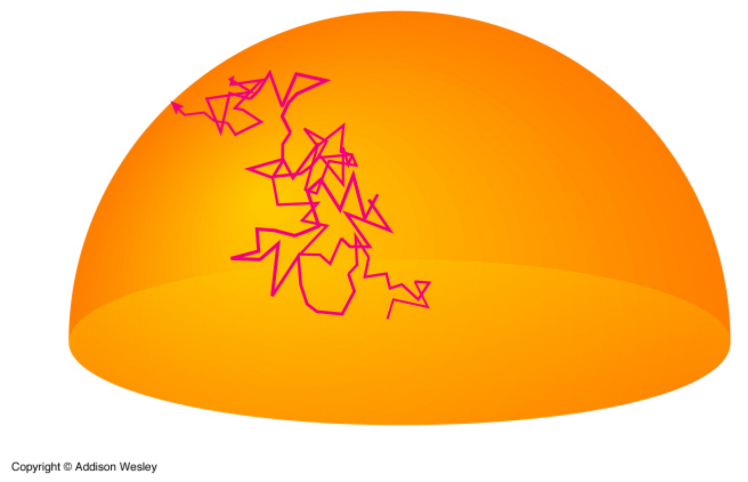
Overview of Neutrinosources

- The sun as a neutrino source
- The earth’s atmosphere as neutrino source
- Nuclear powerplants as neutrino sources
- Beamlines as neutrino sources
- The Big Bang as source of the relic neutrino background
- Super Novae as source neutrinos

Mechanisms of neutrino production in the sun



What about gammas??



Copyright © Addison Wesley

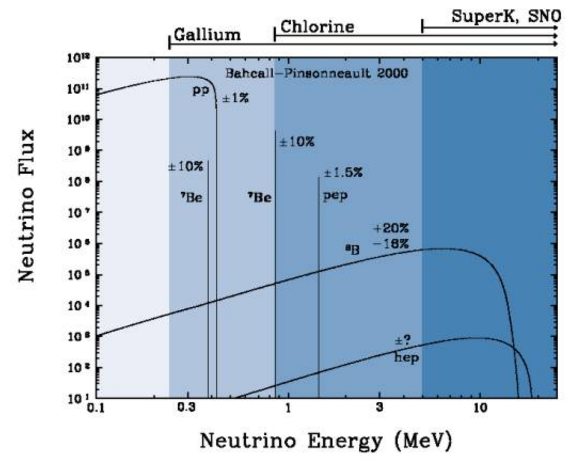
Mechanisms of neutrino production in the sun

Since the 1960’s John Bahcall and others perform calculations to predict the solar ν_e flux on the earth. In this Standard Solar Model (SSM), there are basically 5 nuclear reactions that contribute to the solar ν-flux. Those are:

Reaction	Label	Flux($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
$p+p \rightarrow {}^2H + e^+ + \nu_e$	pp	$5.95 \cdot 10^{10}$
$p+e^- + p \rightarrow {}^2H + \nu_e$	pep	$1.40 \cdot 10^{8}$
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	hep	$9.3 \cdot 10^{3}$
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	${}^7Be$	$4.77 \cdot 10^{9}$
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$	${}^8B$	$5.05 \cdot 10^{6}$

The spectrum of these reactions looks as follows.

Expected flux of solar neutrinos



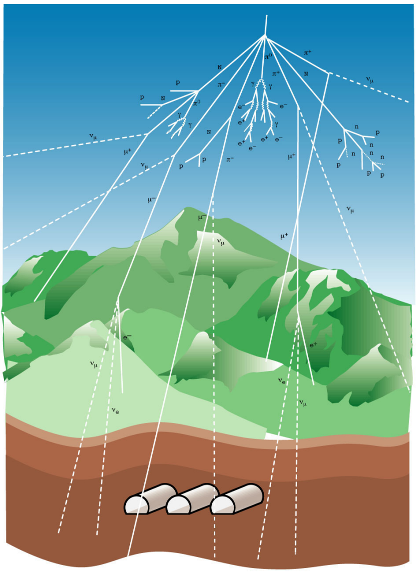
Overview of Neutrinosources

- The sun as a neutrino source
- The earth’s atmosphere as neutrino source
- Nuclear powerplants as neutrino sources
- Beamlines as neutrino sources
- The Big Bang as source of the relic neutrino background
- Super Novae as source neutrinos

Atmospheric neutrino production

The atmospheric neutrinos emerge from the following reaction in the earth's atmosphere:

$$\pi \longrightarrow \mu + \nu_\mu$$

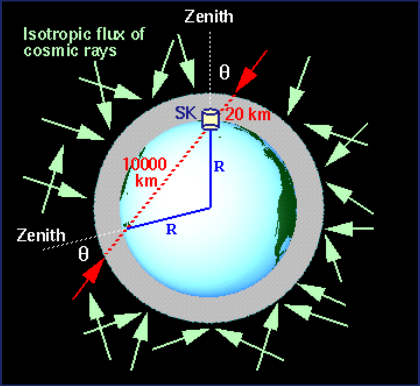


Atmospheric neutrino production

The atmospheric neutrinos emerge from the following reaction in the earth's atmosphere:

$$\pi \longrightarrow \mu + \nu_\mu$$

Taking into account matter effects one can show that the propability of detecting certain νs depends on the zenith angle θ.



Overview of Neutrinosources

- The sun as a neutrino source
- The earth’s atmosphere as neutrino source
- Nuclear powerplants as neutrino sources
- Beamlines as neutrino sources
- The Big Bang as source of the relic neutrino background
- Super Novae as source neutrinos

Neutrinos emerging from nuclear powerplants

On of the typical decays in nuclear power plants is for example:

$$^{235}_{92}\mathrm{U} + \mathrm{n} \rightarrow ^{94}_{40}\mathrm{Zr} + ^{140}_{58}\mathrm{Ce} + 2\mathrm{n} + 6\overline{\nu}_e + 6e^-$$

Thus we have 6 $\overline{\nu}_e$ for each nuclear fission. For a powerplant with a thermal power of $P_{\mathrm{therm}} = 3.8GW$ and energy release of $E \approx 200MeV/\mathrm{fission}$ in fissions of ^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu one then gets $7.1 \cdot 10^{20}$ neutrinos per second. Thus we get a very strong, isotrop source of $\overline{\nu}_e$.

Overview of Neutrinosources

- The sun as a neutrino source
- The earth’s atmosphere as neutrino source
- Nuclear powerplants as neutrino sources
- Beamlines as neutrino sources
- The Big Bang as source of the relic neutrino background
- Super Novae as source neutrinos

Neutrino Beams

Overview of Neutrinosources

- The sun as a neutrino source
- The earth’s atmosphere as neutrino source
- Nuclear powerplants as neutrino sources
- Beamlines as neutrino sources
- The Big Bang as source of the relic neutrino background
- Super Novae as source neutrinos

Overview of Neutrinosources

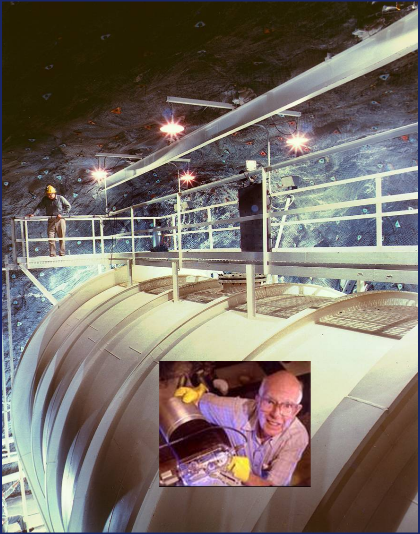
- The sun as a neutrino source
- The earth’s atmosphere as neutrino source
- Nuclear powerplants as neutrino sources
- Beamlines as neutrino sources
- The Big Bang as source of the relic neutrino background
- Super Novae as source neutrinos

Solar Neutrinos: pioneer experiment Homestake

Since about 1970 R. Davis and his collaborants detect ν_e in the Homestake experiment through the following radiochemical reaction:

$$\nu_e + Cl^{37} \rightarrow Ar^{37} + e^-$$
$$E_\nu > 814\,\mathrm{keV}$$

The deficite of solar ν_e gave rise to the idea of neutrino oscillations.



Neutrinooscillations in the vacuum

Oscillations can occure if flavour eigenstates for the active neutrino types (l = e, μ, τ) are related to mass eigenstates (i) via the MNSP [1] mixing matrix U_{li}: with

$$|\nu_l\rangle = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 0 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} |\nu_i\rangle$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$ and δ is called the CP-violating angle. The θ_{ij} are the so calles mixing angles.

---

[1] Maki-Nakagawa-Sakata-Pontecorvo

Neutrino oscillation in the 2 Flavour case

Taking into account only 2 neutrino flavours, we get:

$$\begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{23} & s_{23} \\ -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} \nu_2 \\ \nu_3 \end{pmatrix}$$

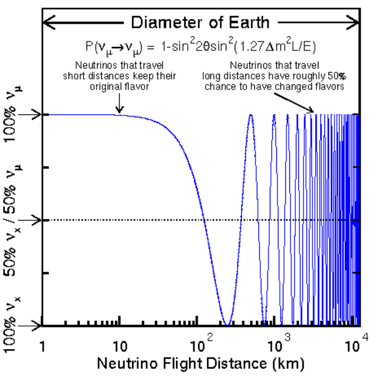
Where θ_{12} is the solar mixing angle θ_{sol}. The oscillation probability for $\nu_\mu \longrightarrow \nu_\tau$ oscillations is given by:

$$P_{\mu\to\tau} = \sin^2 2\theta \, \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

where $\Delta m \equiv m_3^2 - m_2^2$.

Neutrino oscillation in the 2 Flavour case

Taking into account onl



Where θ_{12} is the solar r robability for

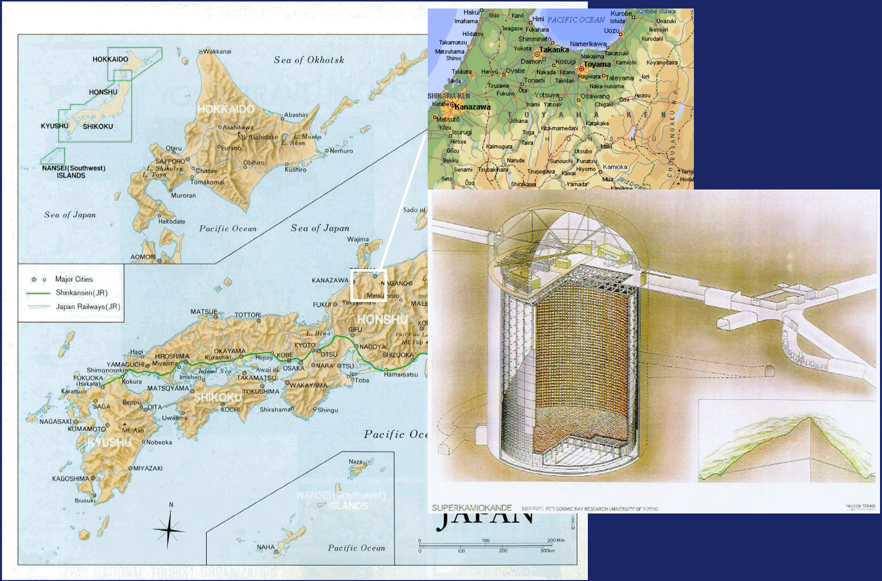
$\nu_\mu \longrightarrow \nu_\tau$ oscillations is g

where $\Delta m \equiv m_3^2 - m_2^2$.

The location

The location

The location



SuperKamiokande

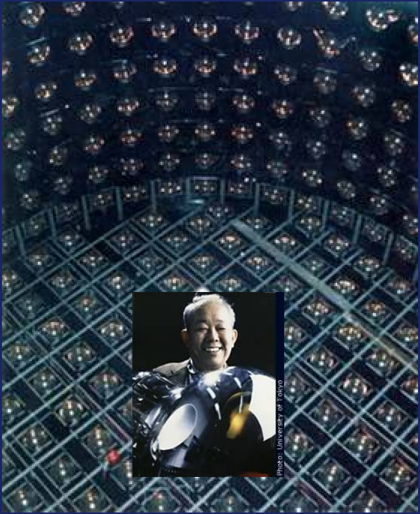
- SuperK is the follow-up of the KamiokaNDE[2] and located in a mine near Kamioka close to the old KamiokaNDE facility.
- Just like KamiokaNDE, SuperK uses PMTs to detect Cerenkov light rings. The number of PMTs has been increased to 13000, the target mass was increased to 50kt of ultra pure H_2O, compared to 2140t used at KamiokaNDE.

---

[2] Kamioka nucleon decay experiment

Kamiokande

The KamiokaNDE is one of the pioneerexperiments in neutrino-physics. Originally build to detect the proton decay, it was the first real time neutrino experiment, using photo multiplier tubes (PMT) to detect the cherenkov lightcones produced elastically scattered electrons/muons. In 2002 Masatoshi Koshiba was rewarded the noble price for the realtime meadurement of neutrinos.



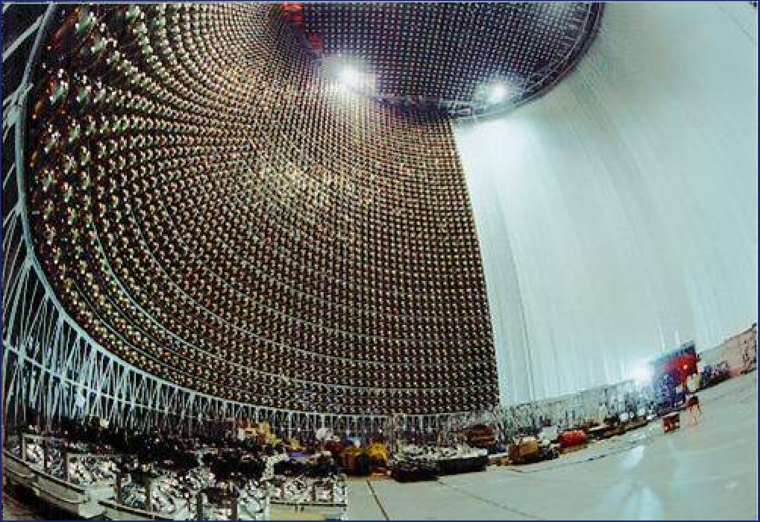
SuperKamiokande

- SuperK is the follow-up of the KamiokaNDE[2] and located in a mine near Kamioka close to the old KamiokaNDE facility.
- Just like KamiokaNDE, SuperK uses PMTs to detect Cerenkov light rings. The number of PMTs has been increased to 13000, the target mass was increased to 50kt of ultra pure H_2O, compared to 2140t used at KamiokaNDE.

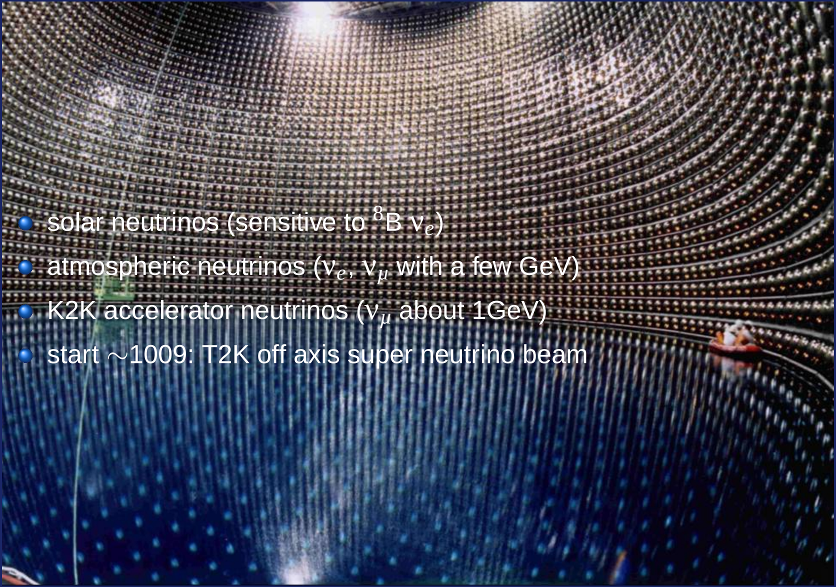
---

[2] Kamioka nucleon decay experiment

SuperK interieur



SuperK physics



- solar neutrinos (sensitive to ^{8}B ν_e)
- atmospheric neutrinos (ν_e, ν_μ with a few GeV)
- K2K accelerator neutrinos (ν_μ about 1GeV)
- start ∼1009: T2K off axis super neutrino beam

Solar neutrinos at SuperK

The solar neutrinos are observed through elastic scattering (ES) reaction:

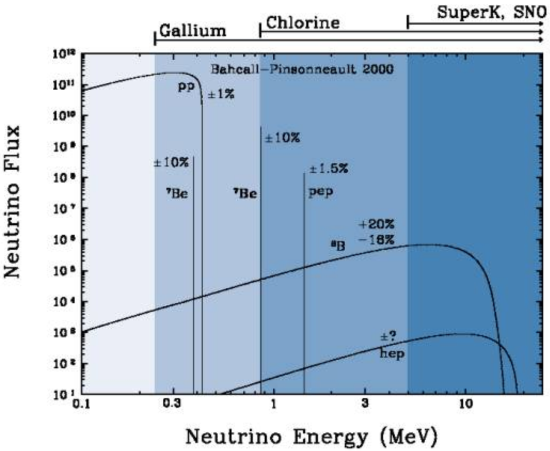
$$\nu_x + \mathrm{e}^- \longrightarrow \nu_x + \mathrm{e}^-$$

Light water detectors like SuperK are thereby mainly sensitive to ν_e because of the reduced cross-section of

$$\sigma(\nu_{\mu,\tau} + \mathrm{e}^- \longrightarrow \nu_{\mu,\tau}\mathrm{e}^-) \approx 0.15\sigma(\nu_e + \mathrm{e}^- \longrightarrow \nu_e + \mathrm{e}^-).$$

SuperK could detect νs with an energy as low as 5 MeV (^{8}B neutrinos).

Expected flux of solar neutrinos



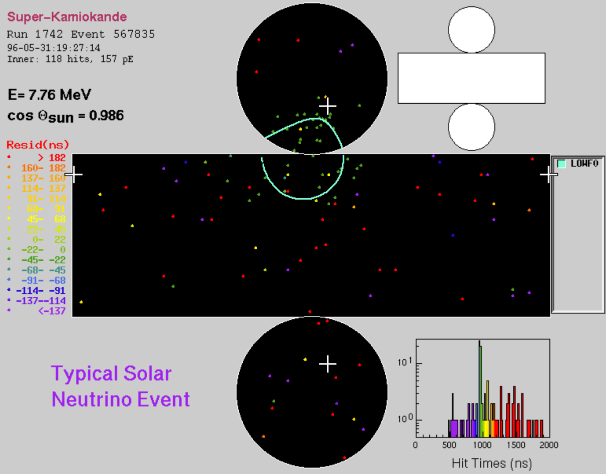
Solar neutrinos at SuperK

- What does a solar ν_e look like in the detector, what does it tell us?
- How could one distinguish actual solar ν events from possible background[3]?
- So what do we learn from SuperK??

---

[3] e.g. radioactive spalations, spalation products from cosmic rays

Solar ν_e seen by SuperK



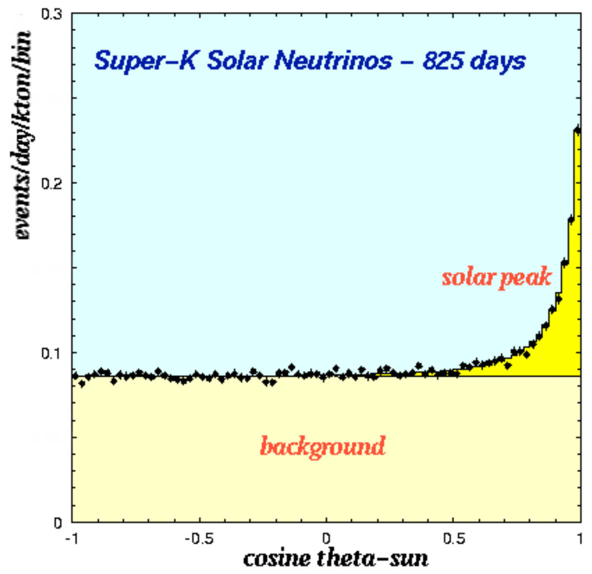
Solar neutrinos at SuperK

- What does a solar ν_e look like in the detector, what does it tell us?
- How could one distinguish actual solar ν events from possible background[3]?
- So what do we learn from SuperK??

---

[3] e.g. radioactive spalations, spalation products from cosmic rays

Distinguishing solar ν_e from background signals



Solar neutrinos at SuperK

- What does a solar ν_e look like in the detector, what does it tell us?
- How could one distinguish actual solar ν events from possible background[3]?
- So what do we learn from SuperK??

---

[3] e.g. radioactive spalations, spalation products from cosmic rays

SuperK solar results

The SuperK data allows the precise determination of the ES neutrino flux

$$\Phi_{\mathrm{ES}} = (2.35 \pm 0.02 \pm) \cdot 10^6 \mathrm{cm}^{-2} \mathrm{s}^{-1}$$

While the shape of the spectrum agrees well with the one predicted from the ν-spectrum of the ^{8}B β-decay. The measurements of the absolute flux, however, is about 46.5% of that predicted by the SSM.

Atmospheric neutrinos at SuperK

Allthough the higher energy of the atmospheric νs leeds to the production of pions or numerous hadrons in the final state on again looks for the ES events.

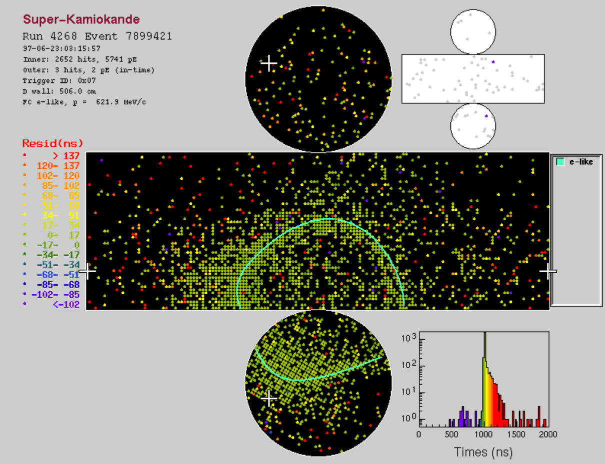
- What does an atmospheric ν look like in the detector, what does it tell us?
- How could one distinguish ν_μ from ν_e
- So what do we learn about atmospheric ν from SuperK??

Atmospheric neutrinos at SuperK

Allthough the higher energy of the atmospheric νs leeds to the production of pions or numerous hadrons in the final state on again looks for the ES events.

- What does an atmospheric ν look like in the detector, what does it tell us?
- How could one distinguish ν_μ from ν_e
- So what do we learn about atmospheric ν from SuperK??

Atmospheric ν seen by SuperK



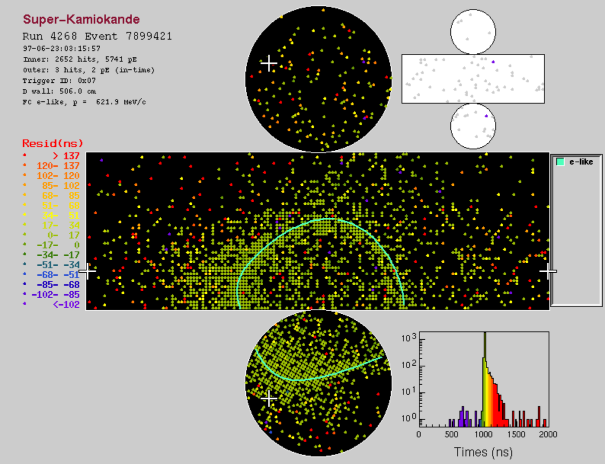
```
Super-Kamiokande
Run 4268 Event 7899421
97-06-23:03:15:57
Inner: 2652 hits, 5741 pE
Outer: 3 hits, 2 pE (in-time)
Trigger ID: 0x07
D wall: 506.0 cm
FC e-like, p =  621.9 MeV/c
```

Atmospheric neutrinos at SuperK

Allthough the higher energy of the atmospheric νs leeds to the production of pions or numerous hadrons in the final state on again looks for the ES events.

- What does an atmospheric ν look like in the detector, what does it tell us?
- How could one distinguish ν_μ from ν_e
- So what do we learn about atmospheric ν from SuperK??

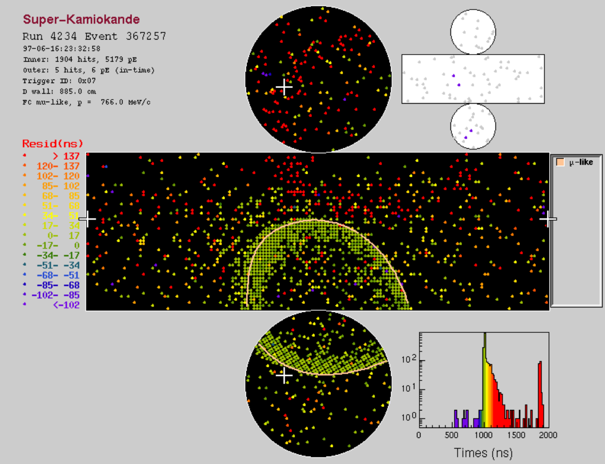
Atmospheric ν seen by SuperK



Super–Kamiokande

```
Run 4268 Event 7899421
97-06-23:03:15:57
Inner: 2652 hits, 5741 pE
Outer: 3 hits, 2 pE (in-time)
Trigger ID: 0x07
D wall: 506.0 cm
FC e-like, p =  621.9 MeV/c
```

Solar ν seen by SuperK



Super-Kamiokande
Run 4234 Event 367257
97-06-16:23:32:58
Inner: 1904 hits, 5179 pE
Outer: 5 hits, 6 pE (in-time)
Trigger ID: 0x07
D wall: 885.0 cm
FC mu-like, p = 766.0 MeV/c

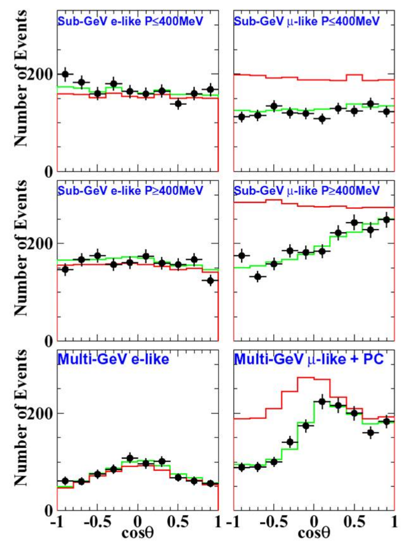
Atmospheric neutrinos at SuperK

Allthough the higher energy of the atmospheric νs leeds to the production of pions or numerous hadrons in the final state on again looks for the ES events.

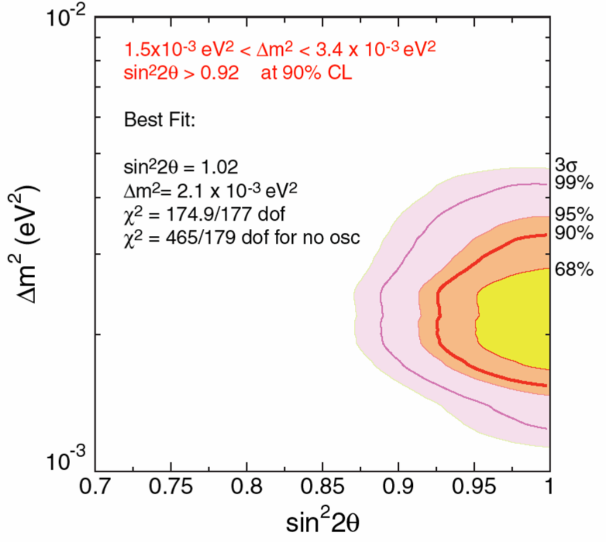
- What does an atmospheric ν look like in the detector, what does it tell us?
- How could one distinguish ν_μ from ν_e
- So what do we learn about atmospheric ν from SuperK??

SuperK atmospheric results

Thegreen lines show the the Monte Carlo for a model with oscillations and the red line shows the Monte Carlo results for a model without oscillations.



SuperK atmospheric results



The K2K beamline at KEK

- K2K[4] uses a ν_μ-beam from the KEK facility to SuperK.
- It was build to confirm the hypothesis of neutrino-oscillations.
- To analyze the outgoing beam, a second near detector was build. This detector consists of a small scaled down replica of the SuperK detector and a muon spectrometer.

---

[4] KEK to Kamiokande Long Baseline Neutrino Oscillation Experiment

The K2K beamline at KEK

- K2K[4] uses a ν_μ-beam from the KEK facility to SuperK.
- It was build to confirm the hypothesis of neutrino-oscillations.
- To analyze the outgoing beam, a second near detector was build. This detector consists of a small scaled down replica of the SuperK detector and a muon spectrometer.

---

[4] KEK to Kamiokande Long Baseline Neutrino Oscillation Experiment

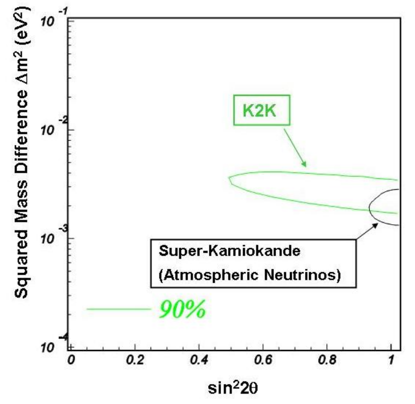
The K2K beamline at KEK

- K2K[4] uses a ν_μ-beam from the KEK facility to SuperK.
- It was build to confirm the hypothesis of neutrino-oscillations.
- To analyze the outgoing beam, a second near detector was build. This detector consists of a small scaled down replica of the SuperK detector and a muon spectrometer.

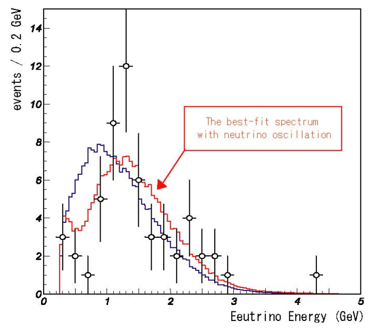
---

[4] KEK to Kamiokande Long Baseline Neutrino Oscillation Experiment

K2K results


K2K
Super-Kamiokande
(Atmospheric Neutrinos)
90%
Squared Mass Difference Δm^2 (eV^2)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1
$\sin^2 2\theta$

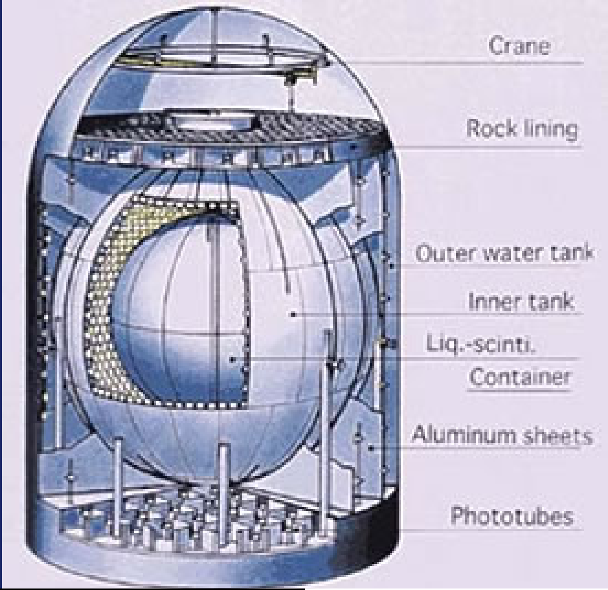
K2K results


events / 0. 2 GeV
0
2
4
6
8
10
12
14
0
1
2
3
4
5
Eeutrino Energy (GeV)
The best-fit spectrum
with neutrino oscillation

KamLAND

- The KAMioka Liquid scintillator antineutrino detector was build at the place of the old KamiokaNDE experiment.
- Instead of water it uses 1000t of liquid scintillator.
- KamLANDs physics

KamLAND scematic



KamLAND

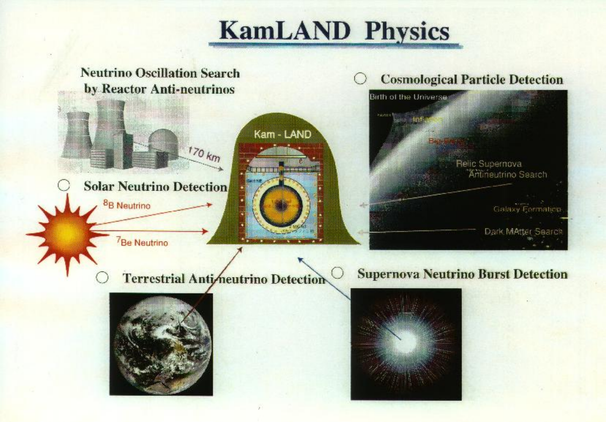
- The KAMioka Liquid scintillator antineutrino detector was build at the place of the old KamiokaNDE experiment.
- Instead of water it uses 1000t of liquid scintillator.
- KamLANDs physics

KamLAND

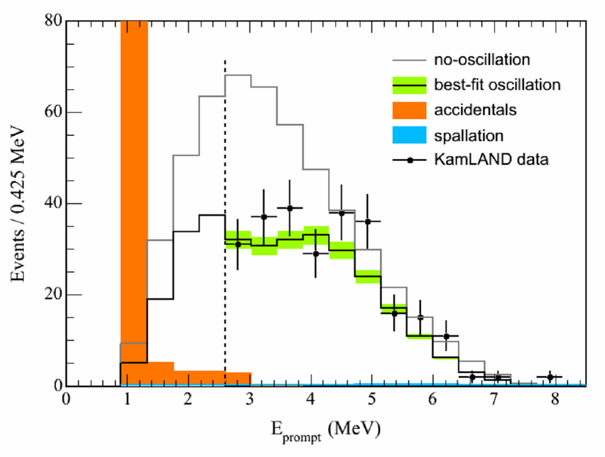
KamLAND

- The KAMioka Liquid scintillator antineutrino detector was build at the place of the old KamiokaNDE experiment.
- Instead of water it uses 1000t of liquid scintillator.
- KamLANDs physics

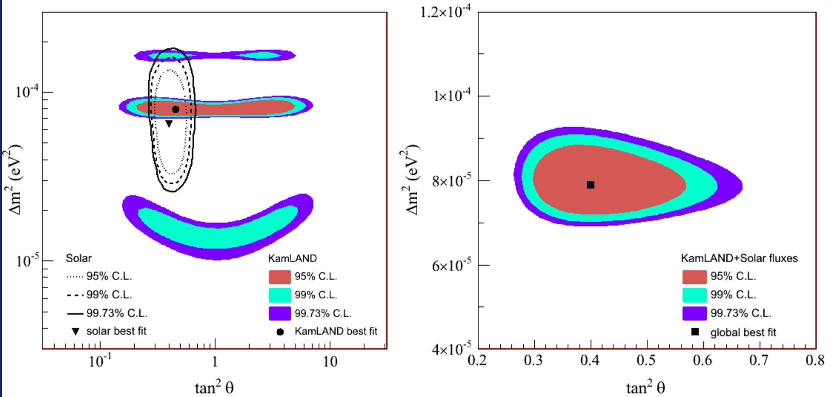
KamLAND physics program



KamLAND results

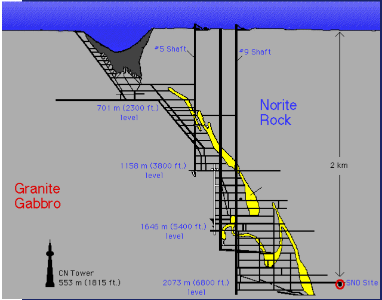


KamLAND results



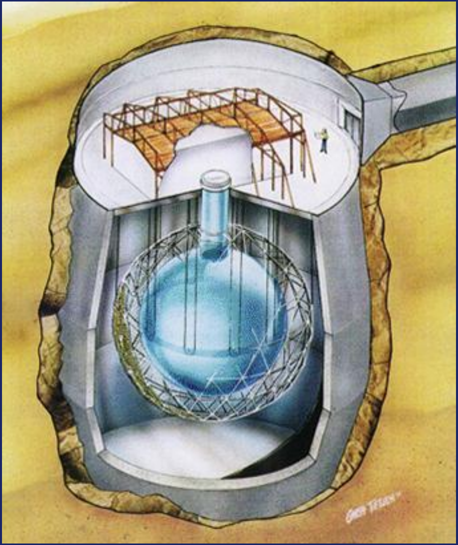
Location of the sudbury neutrino observatory

Location of the sudbury neutrino observatory



Sudbury Neutrino Observatory (SNO)

- Like SuperK SNO is a water Cerenkov light detector.
- There will be at least three different configurations of the detector.
    - starting in Mai 1999 with 1000t ofD_2O in SNO's acrylic vessel
    - in June 2001 there was an addition of $\sim$2000kg NaCl to SNO's $\sim$1000t of D_2O
    - in october 2003 the NaCl was removed and additional drifttubes were installed in the acrylic vessel
- SNO observes 3 different kind of interactions:



Sudbury Neutrino Observatory (SNO)

- Like SuperK SNO is a water Cerenkov light detector.
- There will be at least three different configurations of the detector.
  1. starting in Mai 1999 with 1000t ofD_2O in SNO's acrylic vessel
  2. in June 2001 there was an addition of $\sim$2000kg NaCl to SNO's $\sim$1000t of D_2O
  3. in october 2003 the NaCl was removed and additional drifttubes were installed in the acrylic vessel
- SNO observes 3 different kind of interactions:

Sudbury Neutrino Observatory (SNO)

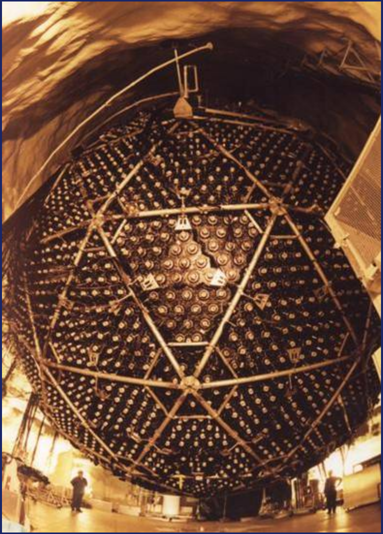
- Like SuperK SNO is a water Cerenkov light detector.
- There will be at least three different configurations of the detector.
  1. starting in Mai 1999 with 1000t ofD_2O in SNO's acrylic vessel
  2. in June 2001 there was an addition of $\sim$2000kg NaCl to SNO's $\sim$1000t of D_2O
  3. in october 2003 the NaCl was removed and additional drifttubes were installed in the acrylic vessel
- SNO observes 3 different kind of interactions:

Sudbury Neutrino Observatory (SNO)

- Like SuperK SNO is a water Cerenkov light detector.
- There will be at least three different configurations of the detector.
  1. starting in Mai 1999 with 1000t ofD_2O in SNO's acrylic vessel
  2. in June 2001 there was an addition of $\sim$2000kg NaCl to SNO's $\sim$1000t of D_2O
  3. in october 2003 the NaCl was removed and additional drifttubes were installed in the acrylic vessel
- SNO observes 3 different kind of interactions:

Sudbury Neutrino Observatory (SNO)

- Like SuperK SNO is a water Cerenkov light detector.
- There will be at least three different configurations of the detector.
    1. starting in Mai 1999 with 1000t ofD_2O in SNO's acrylic vessel
    2. in June 2001 there was an addition of $\sim$2000kg NaCl to SNO's $\sim$1000t of D_2O
    3. in october 2003 the NaCl was removed and additional drifttubes were installed in the acrylic vessel
- SNO observes 3 different kind of interactions:



Sudbury Neutrino Observatory (SNO)

- Like SuperK SNO is a water Cerenkov light detector.
- There will be at least three different configurations of the detector.
  1. starting in Mai 1999 with 1000t ofD_2O in SNO’s acrylic vessel
  2. in June 2001 there was an addition of $\sim$2000kg NaCl to SNO’s $\sim$1000t of D_2O
  3. in october 2003 the NaCl was removed and additional drifttubes were installed in the acrylic vessel
- SNO observes 3 different kind of interactions:

Observed interactions at SNO

- The NC interactions are equally sensitiv to all non sterile ν

  $$\nu_x + d \longrightarrow p + n + \nu_x - 2.224 MeV.$$

  This interaction is observed through 3 different techniques in the separated phases of the experiment.

- The CC interactions are specific to ν_e interactions,

  $$\nu_e + d \longrightarrow p + p + e^- - 1.442 MeV$$

  where the e$^-$ energy is strongly correlated to the ν_e energy, which makes SNO sensitiv to possible spectral distortions.

- The ES reaction has a substantial lower cross section and as mentioned before is predominantly sensitiv to ν_e.

Observed interactions at SNO

- The NC interactions are equally sensitiv to all non sterile ν

  $$\nu_x + d \longrightarrow p + n + \nu_x - 2.224 MeV.$$

  This interaction is observed through 3 different techniques in the separated phases of the experiment.
- The CC interactions are specific to ν_e interactions,

  $$\nu_e + d \longrightarrow p + p + e^- - 1.442 MeV$$

  where the e$^-$ energy is strongly correlated to the ν_e energy, which makes SNO sensitiv to possible spectral distortions.
- The ES reaction has a substantial lower cross section and as mentioned before is predominantly sensitiv to ν_e.

Observed interactions at SNO

- The NC interactions are equally sensitiv to all non sterile ν

  $$\nu_x + d \longrightarrow p + n + \nu_x - 2.224 MeV.$$

  This interaction is observed through 3 different techniques in the separated phases of the experiment.
- The CC interactions are specific to ν_e interactions,

  $$\nu_e + d \longrightarrow p + p + e^- - 1.442 MeV$$

  where the e$^-$ energy is strongly correlated to the ν_e energy, which makes SNO sensitiv to possible spectral distortions.
- The ES reaction has a substantial lower cross section and as mentioned before is predominantly sensitiv to ν_e.

SNO-results

An extended maximum-likelihood fit to the fluxes of active-flavor neutrinos from ^{8}B yields:

$$\begin{aligned}\Phi_{CC} = &\quad 1.68^{+0.06\,+0.08}_{-0.06\,-0.09}\cdot 10^6\mathrm{cm}^{-2}\mathrm{s}^{-1}\\ \Phi_{ES} = &\quad 2.35^{+0.22\,+0.15}_{-0.22\,-0.15}\cdot 10^6\mathrm{cm}^{-2}\mathrm{s}^{-1}\\ \Phi_{NC} = &\quad 4.94^{+0.21\,+0.38}_{-0.21\,-0.34}\cdot 10^6\mathrm{cm}^{-2}\mathrm{s}^{-1}\end{aligned}$$

These results are consistent with those expected for neutrino oscillations with the so called Large Mixing Angle parameters and also with an undistorted ^{8}B spectrum.

Summary

The best fits at the Moment are:

$$\begin{aligned}\Delta m^2_{\mathrm{sol}} &= 8.2^{+0.6}_{-0.5} \cdot 10^{-5} eV^2 \\ \tan^2\theta_{\mathrm{sol}} &= 0.40^{0.09}_{-0.07}\end{aligned}$$

$$\begin{aligned}\Delta m^2_{\mathrm{A}} &= 2.1 \cdot 10^{-3} eV^2 \\ \sin^2\theta_{\mathrm{A}} &= 1.0\end{aligned}$$

What's left to do??

- ν_τ appearance needed
- precision on Δm^2 and mixing angles
- unknown mixing angle θ_{13}
- sign of Δm_{13}
- CP violation

Summary

The best fits at the Moment are:

$$\begin{aligned} \Delta m^2_{\mathrm{sol}} &= 8.2^{+0.6}_{-0.5} \cdot 10^{-5} eV^2 \\ \tan^2\theta_{\mathrm{sol}} &= 0.40^{0.09}_{-0.07} \end{aligned}$$

$$\begin{aligned} \Delta m^2_{\mathrm{A}} &= 2.1 \cdot 10^{-3} eV^2 \\ \sin^2\theta_{\mathrm{A}} &= 1.0 \end{aligned}$$

What's left to do??

- ν_τ appearance needed
- precision on Δm^2 and mixing angles
- unknown mixing angle θ_{13}
- sign of Δm_{13}
- CP violation

Summary

The best fits at the Moment are:

$$\begin{aligned} \Delta m^2_{\mathrm{sol}} &= 8.2^{+0.6}_{-0.5} \cdot 10^{-5} eV^2 \\ \tan^2\theta_{\mathrm{sol}} &= 0.40^{0.09}_{-0.07} \end{aligned}$$

$$\begin{aligned} \Delta m^2_{\mathrm{A}} &= 2.1 \cdot 10^{-3} eV^2 \\ \sin^2\theta_{\mathrm{A}} &= 1.0 \end{aligned}$$

What's left to do??

- ν_τ appearance needed
- precision on Δm^2 and mixing angles
- unknown mixing angle θ_{13}
- sign of Δm_{13}
- CP violation

Summary

The best fits at the Moment are:

$$\begin{aligned} \Delta m^2_{\mathrm{sol}} &= 8.2^{+0.6}_{-0.5} \cdot 10^{-5} eV^2 \\ \tan^2\theta_{\mathrm{sol}} &= 0.40^{0.09}_{-0.07} \end{aligned}$$

$$\begin{aligned} \Delta m^2_{\mathrm{A}} &= 2.1 \cdot 10^{-3} eV^2 \\ \sin^2\theta_{\mathrm{A}} &= 1.0 \end{aligned}$$

What's left to do??

- ν_τ appearance needed
- precision on Δm^2 and mixing angles
- unknown mixing angle θ_{13}
- sign of Δm_{13}
- CP violation

Summary

The best fits at the Moment are:

$$\begin{aligned} \Delta m^2_{\text{sol}} &= 8.2^{+0.6}_{-0.5} \cdot 10^{-5} eV^2 \\ \tan^2\theta_{\text{sol}} &= 0.40^{0.09}_{-0.07} \end{aligned}$$

$$\begin{aligned} \Delta m^2_{\text{A}} &= 2.1 \cdot 10^{-3} eV^2 \\ \sin^2\theta_{\text{A}} &= 1.0 \end{aligned}$$

What's left to do??

- ν_τ appearance needed
- precision on Δm^2 and mixing angles
- unknown mixing angle θ_{13}
- sign of Δm_{13}
- CP violation

Summary

The best fits at the Moment are:

$$\begin{aligned} \Delta m^2_{\mathrm{sol}} &= 8.2^{+0.6}_{-0.5} \cdot 10^{-5} eV^2 \\ \tan^2\theta_{\mathrm{sol}} &= 0.40^{0.09}_{-0.07} \end{aligned}$$

$$\begin{aligned} \Delta m^2_{\mathrm{A}} &= 2.1 \cdot 10^{-3} eV^2 \\ \sin^2\theta_{\mathrm{A}} &= 1.0 \end{aligned}$$

What's left to do??

- ν_τ appearance needed
- precision on Δm^2 and mixing angles
- unknown mixing angle θ_{13}
- sign of Δm_{13}
- CP violation

You wanna know more???

- A. B. McDonald, Nucl. Phys. A **751**, 53 (2005) [arXiv:nucl-ex/0412005].
- B. Aharmim *et al.* [SNO Collaboration], arXiv:nucl-ex/0502021.
- T. Araki *et al.* [KamLAND Collaboration], Phys. Rev. Lett. **94**, 081801 (2005) [arXiv:hep-ex/0406035].
- Y. Ashie *et al.* [Super-Kamiokande Collaboration], Phys. Rev. Lett. **93**, 101801 (2004) [arXiv:hep-ex/0404034].