UNIT1: Experimental Evidences of Neutrino Oscillation
Atmospheric and Solar Neutrinos

Stefania Ricciardi
HEP PostGraduate Lectures 2016
University of London
Neutrino Sources

• Artificial:
  – nuclear reactors
  – particle accelerators

• Natural:
  – Sun
  – Atmosphere
  – SuperNovae
  – fission in the Earth core (geoNeutrinos)
  – Astrophysical origin (Old supernovae, AGN, etc.)

Expected, but undetected so far,: 
  – relic neutrinos from BigBang (~300/cm³)

Neutrinos are everywhere!
Neutrino Flux vs Energy

The Sun is the most intense detected source with a flux on Earth of $6 \times 10^{10} \, \nu/cm^2s$

Detection of solar and atmospheric neutrino has provided the first compelling evidence of neutrino oscillations.

Below detection threshold of current experiments

Abundant but challenging detection

Atmospheric Neutrinos
Neutrino Production in the Atmosphere

Absolute $\nu$ flux has ~10% uncertainty. But muon/electron neutrino ratio is known with ~3% uncertainty. Expected:

$$\frac{\phi(\nu_\mu + \bar{\nu}_\mu)}{\phi(\nu_e + \bar{\nu}_e)} \approx 2$$
Cosmic Flux Isotropy

We expect an isotropic Flux of neutrinos at high energies (earth magnetic field deviate path of low-momentum secondaries only: East-West effects)

For $E_\nu >$ a few GeV, and a given $\nu$ flavour (Up-going / down-going) $\sim 1.0$ with $<1\%$ uncertainty

Note the baseline (= distance $\nu$production-$\nu$detetection) spans 3 order of magnitudes!
Atmospheric neutrino detectors

Neutrinos in 100 MeV – 10 GeV energy. Flux ~ 1 event/(cm$^2$ sr sec) ⇒ *Quasi-elastic interaction region*

**Small cross-section ⇒ Massive Detector (kTons)**
Background from charged cosmic rays ⇒ deep underground location: mines, caverns under mountains, provide >1 Km rock overburden necessary to reduce the muon flux by 5-6 orders of magnitude

2 detection techniques:
- Calorimetric - iron and tracking detectors (Nusex, Frejus, Soudan)
- Cherenkov - water (Kamiokande, IMB)

First detectors built to search for proton-decay. Atmospheric neutrinos studied as they constitute a background for this search. First “anomalies” seen in the flux ratio.

The first experiment to claim model-independent observation of oscillation (non-uniform zenith angle distribution) is SuperKamiokande (1998). Super = 20 times bigger than Kamiokande.
SUPER-KAMIOKANDE (SuperK)

Kamioka Mine in Japan
- 1400m underground
- 50 ktons of pure water
  (Fiducial volume for analysis 22.5 ktons)

- 10,000 PMT inner detector
- 2,000 PMT outer detector (cosmic ray veto)
SuperK: Water Filling

Fishing $\nu$ with 50 cm ØPMT

Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo
Detection Principle

Super-Kamiokande is a water Cherenkov detector. Charged particles traveling in water with speed higher than \( c/n \) (i.e., above threshold for Cherenkov light production) emit Cherenkov light.

Most important reaction: quasi-elastic \( \nu_e \ n \rightarrow p \ e^- \), \( \bar{\nu}_e \ p \rightarrow n \ e^+ \)
\( \nu_\mu \ n \rightarrow p \ \mu^- \), \( \bar{\nu}_\mu \ p \rightarrow n \ \mu^+ \)

Only leptons above Cherenkov threshold detected, charge not identified. Cherenkov light is detected by an array of light sensitive photomultipliers. The image is in the form of a ring (red tubes).

The cone aperture determines velocity. If we can identify the particle than we know its mass, and from velocity we can compute its energy or momentum: \( \beta = p/E \), \( E^2 = m^2 + p^2 \)
Upward-going muon
Movie frames of Cherenkov light propagating in SK
After 50 ns (Frame 2)
100 ns

Muon reaches SK bottom, light still travelling
Electron and Muon Identification

Electron ring is fuzzier than muon ring. Electron produces shower of gammas, electrons and positrons. Gammas don't produce Cherenkov light. Electrons and positrons do. In the shower each of them flies at a little bit different angle and each of them makes its own weak Cherenkov ring. All those rings added together produce the observed fuzzy ring. This difference in sharpness of muon and electron rings is used to identify muons and electrons in Super-Kamiokande.

From the Official SuperK WEBSITE: http://www-sk.icrr.u-tokyo.ac.jp/doc/sk/index.html
Zenith angle Distribution

Half of the $\nu_\mu$ are lost!
Up-down Asymmetry (SuperK)

The mechanism to produce the asymmetry must depend on the distance traveled and on $\nu$ energy

$\Rightarrow \nu$ Oscillations

The hatched region shows the theoretical expectation without neutrino oscillations. The dashed line for $\mu$-like events represents the fit of the data in the case of two-generation $\nu_\mu \rightarrow \nu_\tau$ oscillations with $\Delta m^2 = 3.5 \times 10^{-3}$ eV$^2$ and $\sin^2 2\theta = 1.0$. 

$FC = \text{fully contained}$  
$PC = \text{partially contained}$
Survival Probability

\[ P(\nu_\mu \rightarrow \nu_\mu) = 1 - P(\nu_\mu \rightarrow \nu_\tau) = 1 - \sin^2 2\theta \sin^2 (\Delta m^2 L/4E) \]

Using \( E = 1 \text{ GeV}, \sin^2 2\theta = 1 \)
\( \Delta m^2 = 10^{-2} (\text{eV}^2) \)
we obtain this oscillation pattern vs \( L \)

Zenith angle

Mixing angle

Losc = \( 4\pi E/\Delta m^2 \)

Up-going flux suppressed by about 50%

Down-going flux not suppressed
\[ \Delta m^2 - \sin^2 2\theta \text{ Plane} \]

Interpretation of Atmospheric neutrino results:

- \( \nu_e \) flux as expected \( \Rightarrow \) it is not \( \nu_\mu \rightarrow \nu_e \) oscillations
- 3 \( \nu \) generations \( \Rightarrow \) it must be \( \nu_\mu \rightarrow \nu_\tau \) oscillations, where \( \nu_\tau \) is not seen
  (most of \( \nu_\tau \) under threshold for \( \tau \) production in CC interactions \( (E_{th} > 3 \text{ GeV}) \))
- Oscillation to sterile neutrinos excluded by analysis of NC

\[ P_{\mu \tau} = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L / E) \]

- \( <L> \sim 10^3 \text{ Km}, <E>\sim 1\text{GeV} \)
- Max \( P_{\mu \tau} \) (=1)
  - \( \Rightarrow \sin^2(2\theta) = 1 \)
  - \( \Rightarrow \Delta m^2 \sim E/L \sim 10^{-3} \)

Need to take into account:

- Flux Spectrum,
- Baseline variations
- Detection Resolution

for a rigorous measurement

Assuming \( \nu_\mu \rightarrow \nu_\tau \) oscillation

1489 days

\[ \text{Best fit:} \quad \sin^2 2\theta = 1 \]
\( (\text{Max mixing}) \)
\( \Delta m^2 = 2 \times 10^{-3} \)

\[ \text{Allowed region} \]

- 68% C.L.
- 90% C.L.
- 99% C.L.
The “dip” in the L/E Analysis

First dip in $\mu$-like events deficit observed by SK!

Decay and decoherence disfavored at 4 and $5\sigma$ level, respectively.

$L = D_{\text{Earth}} \times \cos \theta_Z$

$\theta_Z$, zenith angle

Should observe first dip!
First confirmation with Man-made neutrino beam (K2K)

K2K experiment (1999-2004)
150±10 events if no oscillation
108 events observed
Deficit at ~4σ level
Solar Neutrinos
Standard Solar Model (SSM)

- Mass
- Luminosity
- Radius,
- Metal content of the photosphere
- Age

Inferences on solar interior ($\rho$, $P$, $T$)

SSM describes the evolution of an initially homogeneous solar mass $M_0$ up to the sun age $t$ so as to reproduce $L_0$, $R_0$ and $(Z/X)_{\text{photo}}$

$\Rightarrow$ Predicts solar neutrino flux (intensity and spectrum)

$M = 2 \times 10^{30}$ Kg
$R = 7 \times 10^8$ m
$L = 4 \times 10^{26}$ W

Hydrogen fusion in the Sun:

$\text{proton} \rightarrow \text{He}^4 + 2e^+ + 2\nu_e + 25\text{MeV}$
The pp-chain

99.77%  
\[ p + p \rightarrow d + e^+ + \nu_e \]

0.23%  
\[ p + e^- + p \rightarrow d + \nu_e \]

\[ d + p \rightarrow ^3\text{He} + \gamma \]

84.7%  
\[ ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \]

13.8%  
\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e \]

13.78%  
\[ ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \]

\[ ^3\text{He} + ^3\text{He} \rightarrow \alpha + 2p \]

7Li + p \rightarrow \alpha + \alpha

\[ ^8\text{B} \rightarrow ^8\text{Be}^* + e^+ + \nu_e \]

\[ ^3\text{He} + p \rightarrow \alpha + e^+ + \nu_e \]

\[ ^7\text{Li} + p \rightarrow \alpha + \alpha \]

\[ 2\alpha \]

\[ ^8\text{Be}^* \rightarrow 2\alpha \]

pp I  pp II  pp III  hep
Solar Neutrino Energy Spectrum

Sun luminosity: \( L = 8.6 \times 10^{11} \text{ MeV cm}^{-2} \text{ s}^{-1} \)

Total Neutrino flux (only \( \nu_e \)): \( \Phi(\nu_e) = 2 \times \frac{L}{26 \text{ MeV}} = 6.6 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \)

Small theoretical uncertainty (~1%): total flux is constrained by solar luminosity

Spectra and relative abundances have larger uncertainties

Small Uncertainty: Luminosity constrained

Large Uncertainty: Stronger dependence on \( T (\propto T^{24}) \)
Experiments and Detection methods

Solar $\nu$
- Small x-section
- Low energy
- Cosmic rays Background

Important detector parameters
- Big Target Mass, $O(kT)$
- Low Detection Threshold
- Deep underground

Radiochemical detectors (integrated flux)
- Homestake 1969-1999  $^{37}$CL  0.8
- Sage 1990  $^{71}$Ga  0.2
- Gallex/GNO 1991  $^{71}$Ga  0.2

Real-time detector (differential flux: time, E, $\theta$)
- Kamioka/SuperK 1985  $H_2O$  5
- SNO 1999  $D_2O$  5
- Kamland 2001  Liq Scint  5.5
- Borexino 2007  Liq Scint.  <1
Homestake (1969 ~99)

380,000 l of C$_2$Cl$_4$ (615 tons)

Homestake Mine, 1400 m deep

E$_V$ > 0.8 MeV
Sensitive to $^8$B + $^7$Be

Extract $^{37}$Ar once per month by flushing He together with small (known) amount of stable $^{36}$Ar to measure extraction efficiency

Data/SSM = 0.30 ± 0.03

$^{37}$Ar is radioactive and decays with half-life of 35 days

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

Predicted rate
8.5± 1.8 SNU

Observed rate
2.56± 0.23 SNU
~0.5 atoms/day!
Gallium Experiments

\[ \nu_e \rightarrow 71\text{Ga} \rightarrow 71\text{Ge} \ e^- \]

\[ \text{E}_{\nu} > 0.23 \text{ MeV} \]

Sensitive to pp

\[ \text{Gallex/GNO} \]
Calibrated with
High intensity
\[ ^{51}\text{Cr} \nu \text{ source} \]

- Observed (Data): 68.1 ± 3.75 SNU (GALLEX + GNO + SAGE)
- Predicted (SSM):
  \[ 131^{+12}_{-10} \text{ SNU} \]
- Data / SSM = 0.52 ± 0.03
Strong forward peak due to elastic scattering of solar $^8$B neutrinos with electrons. 
$E_{\text{threshold}} \sim 5$ MeV

22,400 ± 200 solar neutrino interactions were observed in 22,500 tons of water during 1496 live days. (~15 events/day)

Kamiokande & SuperK provided the first evidence of neutrino production in the core of the Sun with 
**Time, Direction, and Energy** information
SOLAR Neutrino PROBLEM

What can be wrong?
- Sun model
- Experiments
  – ν propagation from SUN to Earth

>30 years of debate!
A $\nu$ trick?

$\nu$ decay? Excluded by SN1987A

$$\gamma \tau = (E_\nu / m_\nu) \tau > 8 \text{ min}$$

Best bet: $\nu_e \rightarrow \nu_x$ oscillation

Flux suppression could have the right energy dependence according to chosen oscillation mechanism and parameters ($\Delta m^2, \sin^2 2\theta$)

Confirmation could come from an experiment equally sensitive to all $\nu$ flavor, via detection of NC interactions: SNO
Sudbary Neutrino Observatory (Ontario, 1999~2007)

Threshold energy for neutrino detection $5\text{MeV}$
\implies$\text{Sensitive to } ^8\text{B} \text{ neutrinos}$

$1 \text{ Kton } D_2O$

SNO can determine both:
$\Phi(\nu_e)$ and $\Phi(\nu_e + \nu_\mu + \nu_\tau)$
ν Detection at SNO

** Charged-Current**

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

- Measurement of \( \nu_e \) energy spectrum
- Weak directionality

** Neutral-Current**

\[ \nu_x + d \rightarrow p + n + \nu_x \]

- Measure total \(^{8}\text{B} \) \( \nu \)
- Equally sensitive to ALL \( \nu \)
  - \( \sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau) \)

** Elastic Scattering**

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

- Low Statistics
  - \( \sigma(\nu_e) \approx 7 \sigma(\nu_\mu) \approx 7 \sigma(\nu_\tau) \)
  - Strong directionality
First SNO RESULTS (April 2002)

• The measured total B neutrino flux is in excellent agreement with the SSM prediction.
SSM is right

• Only 1/3 of the B-neutrinos survive as $\nu_e$
All Experiments are right!

⇒ 2/3 of the produced $\nu_e$ transform into active neutrinos ($\nu_\mu$ or $\nu_\tau$, indicated as $\phi_{\mu\tau}$)
Evidence of flavour transformation!
(independent of SSM)

$\phi_{CC}(\nu_e) = \phi_e$
$\phi_{NC}(\nu_x) = \phi_e + \phi_{\mu\tau}$
$\phi_{ES}(\nu_x) = \phi_e + 0.15\phi_{\mu\tau}$
SNO solves it!
Borexino

• First real-time detection of $^7\text{Be}$, Gran Sasso Labs (Italy)
• 270t Extreme radio-purity liquid scintillator doped with PC+PPO in a 125$\mu$m thick nylon vessel

PC filling completed
May 15th, 2007
Borexino detector

**Scintillator:**
270 t PC+PPO in a 125 μm thick nylon vessel

**Nylon vessels:**
- Inner: 4.25 m
- Outer: 5.50 m

**Carbon steel plates**

**Stainless Steel Sphere:**
- 2212 photomultipliers
- 1350 m³

**Water Tank:**
- γ and n shield
- μ water Ch detector
- 208 PMTs in water
- 2100 m³

Design based on the principle of graded shielding

20 legs
Borexino observe low energy $\nu$ flux

$^7$Be flux, 5% accuracy
PRL 107,1411302, 2011

$pp\nu$ flux, 10% accuracy
Borexino results fit validate current $\nu$-oscillation framework

Borexino data validate the MSW-LMA model in the vacuum dominated region

Next:
- Look for CNO neutrinos. Important for solar models (constrain Sun metallicity)
- More precise measurements of $^8$B spectrum (1-5 MeV transition region sensitive to new physics effects)
SNO+ (SNO tank to be filled with \( \text{Te}^{130} \)-loaded scintillator)

Deepest detector \( \Rightarrow \) unique sensitivity to pep neutrinos \( \Rightarrow \) sensitivity in transition region

**SNO+ Physics Program**

- search for neutrinoless double beta decay
- neutrino physics
  - solar neutrinos
  - geo antineutrinos
  - reactor antineutrinos
  - supernova neutrinos

**SNO+ Physics Goals**
Summary

• Atmospheric neutrinos:
  – Flux properties: numu/nue, isotropic
  – Evidence of oscillation in SuperK:
    1. Numu/nue ratio
    2. Up-down asymmetry (cos theta distribution)
    3. Dip in L/E
  – Terrestrial (accelerator) confirmation: K2K experiment (and recently MINOS, OPERA, T2K, as we will see in the next lectures)
  – Detection techniques for GeV neutrinos
  – Benefit of Cerenkov: big mass, PID, works well in MeV-GeV range (elastic and quasi-elastic interactions)
Summary/2

- Solar Neutrinos
  - SSM
  - Detection techniques for solar neutrinos
  - Solar neutrino problem
  - SNO and solution to solar neutrino problem
  - Current/near future solar neutrino experiments