Outline

- Why?
- Neutrinos From the Sun
- Sudbury Neutrino Observatory (SNO)
- Observables
- Solar Neutrino Flux
- Mixing Parameters

A.Bellerive, CAP, June 2009
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- Mixing Parameters
- Solar Neutrino Flux
- Observables
- Sudbury Neutrino Observatory (SNO)
- Neutrinos From the Sun
- Why?
Evidence for Neutrino Mixing

First evidence of neutrino oscillation

$$\frac{\nu_\mu}{\nu_e} \neq 2$$

Atmospheric Neutrinos
high energies

Solar Neutrinos
low energies

Primary neutrino source

$$p + p \rightarrow D + e^+ + \nu_e$$

Neutrinos $\nu_e$, $\bar{\nu}_\mu$, and $\nu_\mu$

Neutralino detector

Beamstop Neutrinos
tunable energies

Future!
Neutrino Mixing

As in the quark sector one defines a neutrino mixing matrix which relates the mass and weak eigenstates

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= 
U_e
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
= 
U_\mu
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
= 
U_\tau
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Quark: \[\theta_{12} \approx \pi/14\] \[\theta_{23} \approx \pi/76\] \[\theta_{13} \approx \pi/870\] yes \[\theta_{13} < \pi/20\]

Neutrino: \[\theta_{12} \approx \pi/6\] \[\theta_{23} \approx \pi/4\] \[\theta_{13} \approx \pi/23\]

\[
U_{\alpha\beta} = 
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & e^{-i\delta}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} \\
0 & 1 & 0 \\
-s_{13} & 0 & \cos \theta_{13}
\end{pmatrix}
\]

where \(c_y = \cos \theta_y\), and \(s_y = \sin \theta_y\)
Mass hierarchy with $\Delta m_{12}^2 > 0$ is assumed.

Is it???

Note the small $\nu_e$ component in $\nu_3$ from atmospheric results.

$P(\nu_\mu \rightarrow \nu_\mu)$!!!

Neutrino can only mix (quantum effect) if there are mass differences between the states.

It implies neutrinos have masses which leads to physics beyond the Minimal Standard Model.
The First Piece

Solar Neutrino Flux

- The Sun produces $\nu_e$ in fusion nuclear reactions
- Solar neutrino oscillation occurs inside the Sun
- Survival probability depends on the neutrino energy
Solar Neutrinos

\[ p + p \rightarrow ^2\text{H} + e^+ + \nu_e \quad \text{99.75\%} \]

\[ p + e^- + p \rightarrow ^2\text{H} + \nu_e \quad \text{0.25\%} \]

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

\[ 85\% \rightarrow ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p \]

\[ \sim 15\% \rightarrow ^3\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e \]

\[ \sim 10^{-5}\% \rightarrow ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \]

\[ 15.07\% \rightarrow ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \gamma + \nu_e \]

\[ 0.02\% \rightarrow ^7\text{Be} + p \rightarrow ^8\text{B} + \gamma \]

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

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

\[ ^8\text{Be}^* \rightarrow ^4\text{He} + ^4\text{He} \]
Solar Neutrinos
Solar Neutrino Mixing

\[ P_{ee} \equiv P(\nu_e \rightarrow \nu_e) \]

\[ P_{ee} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\varphi) \]

\[ P_{ee} \approx \sin^2(2\theta_{12}) \sin^2(\varphi) \]

where \( \varphi = 1.27 \Delta m_{12}^2 \frac{L}{E} \)

**Physics:**
\( \Delta m_{12}^2 \) & \( \sin(2\theta_{12}) \)

**Experiment:**
Distance (\( L \)) & Energy (\( E \))

**Survival Probability**

3 Parameters!

\[ \Delta m_{12}^2 = m_2^2 - m_1^2 \]

signed quantity

\[ \theta_{12} = \text{solar mixing} \]

\[ \theta_{13} = \text{small} \]

*The state evolves with time or distance*
Combination of the Chlorine, Gallium, SK, and CHOOZ restricted the mixing parameters

Pre SNO

\[ \Delta m^2 = \Delta m_{12} \]

\[ \theta = \theta_{12} \quad \theta_{13} = 0 \]
Mixing Parameters

Combination of the Chlorine, Gallium, SK, and CHOOZ restricted the mixing parameters

Pre SNO

\[ \Delta m^2 = \Delta m_{12}^2 \]

\[ \theta = \theta_{12} \quad \theta_{13} = 0 \]

2\(\nu\) active oscillations

LMA

TODAY

SMA

LOW

VAC

JustSo2

Allowed Regions

Cl+Ga+SK rates + CHOOZ

Phys.Rev. D64 (2001) 093007
Matter-Enhanced Neutrino Oscillations

Neutrinos produced in weak state $\nu_e$ ⇒ High density of electrons in the Sun
⇒ Superposition of mass states $\nu_1, 2, 3$ changes through the MSW resonance effect
⇒ Solar neutrino flux detected on Earth consists of $\nu_e + \nu_{\mu,\tau}$

$\begin{align*}
\text{All neutrino flavors} & \quad \text{Only electron neutrinos} \\
\nu_x & \quad \nu_x \\
Z^0 & \quad W^+ \\
e^- & \quad e^- \\
e^- & \quad e^- \\
e^- & \quad \nu_e
\end{align*}$
Solar Neutrino Problem (Pre SNO)

Neutrino reactions

\[ \nu_e + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar} \]
\[ \nu_e + ^{71}\text{Ga} \rightarrow e^- + ^{71}\text{Ge} \]
\[ \nu_l + e^- \rightarrow \nu_l + e^- \]

\[ \sim 10^8 \text{ km} \]

Measured $\neq$ Predicted

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Medium</th>
<th>Threshold (MeV)</th>
<th>Measured/SSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake</td>
<td>Chlorine</td>
<td>0.814</td>
<td>0.34±0.03</td>
</tr>
<tr>
<td>SAGE+GALLEX/GNO</td>
<td>Gallium</td>
<td>0.2332</td>
<td>0.52±0.03</td>
</tr>
<tr>
<td>SuperK</td>
<td>H$_2$O</td>
<td>7.0</td>
<td>0.406±0.013</td>
</tr>
</tbody>
</table>

The Second Piece:

Observables

Sudbury Neutrino Observatory
Sudbury Neutrino Observatory

- 6000 mwe overburden
- 1000 tonnes D$_2$O
- 12 m Diameter Acrylic Vessel
- 1700 tonnes Inner Shield H$_2$O
- Support Structure for 9500 PMTs, 60% coverage
- 5300 tonnes Outer Shield H$_2$O

Image courtesy National Geographic
Neutrino reactions within SNO

Elastic-scattering (ES):
\[ \nu_x + e^- \rightarrow \nu_x + e^- \]

Charged-currents (CC):
\[ \nu_e + d \rightarrow p + p + e^- \]

Neutral-currents (NC):
\[ \nu_x + d \rightarrow p + n + \nu_x \]

- \( \nu_e \) mainly strong directional sensitivity
- \( \nu_e \) only \( E_e \) well correlated with \( E_\nu \)
- All flavors equally
- Total neutrino flux
Key signatures for $\nu$ mixing with SNO

Flavor change? $P_{ee}(E_{\nu}) \neq 1$?

\[
\frac{\Phi_{CC}}{\Phi_{ES}} = \frac{\nu_e}{\nu_e + 0.154(\nu_\mu + \nu_\tau)}
\]

\[
\frac{\Phi_{CC}}{\Phi_{NC}} = \frac{\nu_e}{\nu_e + \nu_\mu + \nu_\tau}
\]
Three methods to detect neutrons

<table>
<thead>
<tr>
<th>Phase I (D$_2$O)</th>
<th>Phase II (Salt+D$_2$O)</th>
<th>Phase III ($^3$He+D$_2$O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov. 99 - May 01</td>
<td>July 01 - Sep. 03</td>
<td>Nov. 04 - Nov. 06</td>
</tr>
</tbody>
</table>

- **n captures on Deuterium**
  - $^2$H(n,$\gamma$)$^3$H
  - $\sigma = 0.0005b$
  - 6.25 MeV single $\gamma$
  - PMT array readout

- **n captures on Chlorine**
  - $^{35}$Cl(n,$\gamma$’s)$^{36}$Cl
  - $\sigma = 44b$
  - 8.6 MeV multiple $\gamma$s
  - PMT array readout

- **n captures on $^3$He**
  - $^3$He(n,p)$^3$H
  - $\sigma = 5330b$
  - 0.764 MeV(p,$^3$H)
  - NCD readout

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

```
\nu_x + d \rightarrow \nu_x + P + n
```

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

PMT array measurement:

- Position
- Time
- Charge

Čerenkov photons

e\(^-\) from CC or ES reaction

Compton-scattered

e\(^-\) of \(\gamma\)'s from \(n\)-capture from NC reaction

Pattern Recognition
Neutrino Observables $\text{D}_2\text{O}$ Phase

Kinetic Energy Distribution

Radial Distribution ($R^3$, $R_{AV}=1$)

Solar Direction Distribution
Advantages of Salt: more sensitive

- Neutrons capturing on $^{35}\text{Cl}$ provide higher neutron energy above threshold.
- Higher capture efficiency
- Gamma cascade changes the angular profile.
Advantages of salt: event isotropy

Isotropy variable, $\beta_{14}$, function of angles between each pair of hit PMTs ($\theta_{ij}$) in event [similar to thrust in collider physics]

$\beta_{14}$ powerful discriminating variable between NC and CC/ES events
Neutrino Observables Salt Phase

Radial Distribution ($R^3, R_{AV}=1$)

Energy Distribution (MeV)

Solar Direction Distribution

Isotropy Distribution

NC changed due to larger $\sigma_{n\gamma}$

NC shifted to higher energy

Unchanged

All new due to multiple $\gamma$'s
Physics Motivation

Event-by-event separation. Measure NC and CC in separate data streams – break the statistical correlation

Different systematic uncertainties than neutron capture on deuteron or NaCl
Neutrino Observable NCD Phase

Events per 10 keV

Ni wall

$^3\text{He}:\text{CF}_4$ gas

Cu anode wire

191 keV

573 keV

Shaper Energy (MeV)
SNO Phase III with NCD’s

**Blind data set of the NCD events**

- Data from $^3$He NCD-Strings
- Alpha Background
- Characteristic $^3$He(n,p)$^t$ Spectrum from Calibration

**Improve Separation**
- Pulse-Shape-Disc.
- String-by-String
- Ring-by-Ring Symmetry
- Pulse-Evolution & MC Model

**Counts vs. Energy (MeV)**
Arranging the Pieces:

Solar Neutrino From the Sun
- Simultaneous fit of all the phases
- Lower energy threshold for the D$_2$O and Salt phases
- CC and ES spectrum for the NCD phase
- Consistently fit for P$_{ee}$ with no model assumption
Update – improvement – new stuff

- Tune up the Monte Carlo on calibration data based on 5 years of operational experience
- Improve optics (especially at large radii)
- New energy estimator (improve energy resolution by 6%)
- Reduced the energy thresholds
  \[ \text{D}_2\text{O} \ (5 \rightarrow 3.5 \text{ MeV}) \text{ and Salt} \ (5.5 \rightarrow 3.5 \text{ MeV}) \]
- Improve CC statistics by \(~40\%\) & NC by \(~70\%\)
- Allow to fit the background wall
- Investigate Pulse Shape Discrimination NCD
- Implement signal extraction to permit simultaneous 3-phase fitting which propagate all the systematic uncertainty to likelihood space
What SNO is all About

SNO is a unique opportunity to study both particle physics and astrophysics.

Sun \( \nu_e \) \rightarrow \text{Vacuum} \rightarrow \text{Earth} \( \nu_e, \nu_\mu, \nu_\tau \)

Neutral Current (NC): \( \nu_x \), astrophysics.
Measurement of the total rate of solar neutrinos.
Solar neutrino flux, understanding of stars, nuclear fusion rates...

Charged Current (CC): \( \nu_e \), particle physics.
Measurement of the survival probability of electron neutrinos.
Weak interactions, lepton flavor conversion, neutrino mass...
What SNO is all About

SNO performs a combined analysis of the 3 phases with lower threshold

CC/NC: shown to be different than 1.0
Proof of oscillations, neutrino mass, new physics...

CC/NC: turn into measurement of the survival probability
Experimentally, function of neutrino energy.

\[
P_{\nu_e \rightarrow \nu_e} \equiv P_{ee}
\]

\[
\frac{dCC}{dT} = \int P_{ee}(E_\nu) \frac{d\Phi(\nu_e)}{dE_\nu} dE_\nu \int \frac{d\sigma}{dT_e}(E_\nu, T_e) \frac{dR}{dT}(T_e, T) dT_e
\]

\(P_{ee}\): use the measurement to understand its functional form.
Phenomenological study of the neutrino oscillation parameters.
Going A Step Further (Down)

Kinetic Energy Spectrum

3 neutrino signals

Threshold = 3.5 MeV
Going A Step Further (Down)

Kinetic Energy Spectrum

3 neutrino signals
+ 17 backgrounds

Threshold = 3.5 MeV
Going A Step Further (Down)

Kinetic Energy Spectrum

3 neutrino signals
+ 17 backgrounds

internal (D₂O)

Threshold = 3.5 MeV
Going A Step Further (Down)

Kinetic Energy Spectrum

3 neutrino signals
+ 17 backgrounds

internal (D$_2$O)

external (AV + H$_2$O)

Threshold = 3.5 MeV
Going A Step Further (Down)

Kinetic Energy Spectrum

3 neutrino signals
+ 17 backgrounds
  internal \((\text{D}_2\text{O})\)
  external \((\text{AV} + \text{H}_2\text{O})\)
  PMT \(\beta-\gamma\)s

Threshold = 3.5 MeV
Approach

Charged Current (CC)
Elastic Scattering (ES)
Neutral Current (NC)

Energy

$P_{ee}$

CosThSun

Position

Isotropy
Global View:

Why !? 
CC Spectrum Uncertainties

- Salt phase spectrum
- NEW spectrum

PRELIMINARY
NC Flux Uncertainties

~ 4 %

Preliminary
Polynomial Survival Probability

**SNO ‘fake’**
Monte Carlo sample data set
1σ statistical error band

**Pe_e**

Survival Prob

Asymmetry

Neutrino energy (MeV)
Global Fit

- 7 experiments, ~150 observables, ~80 systematics and 1 common model (8 fluxes, 21 systematics).

Borexino (Italy):
1 flux, 1 obs., 1 syst.

GALLEX/GNO (Italy):
8 fluxes, 1 obs., 1 syst.

SAGE (Russia):
8 fluxes, 1 obs., 1 syst.

Super-Kamiokande (Japan):
2 fluxes, 77 obs., 30 syst.

KamLAND (Japan):
0 flux (reactor), 16 obs., 4 syst.

SNO (Canada):
2 fluxes, 69 obs., >40 syst.

Homestake (USA):
7 fluxes, 1 obs., 1 syst.
Leading Effect: $\tan^2 \theta_{12}, \Delta m^2_{21}$

- SNO data from two first phases.
- Uncertainty on $\tan^2 \theta_{12}$ decreases compared to previous analyses, even with the effect of $\sin^2 \theta_{13}$.
- Precision on $\Delta m^2_{21}$ dominated by KamLAND.
**Sub-leading Effect:** $\sin^2 \theta_{13}$

- SNO data from two first phases.
- Precision on $\tan^2 \theta_{12}$ allows to see the effect of $\sin^2 \theta_{13}$.
- Signs of $\sin^2 \theta_{13} > 0$. 
Conclusion & Future

- First paper (2001)
- Direct evidence of solar neutrino flavour transformation (2002)…but assumed $P_{ee} = 1$
- Confirmation of solar neutrino oscillations in 2005 with full salt results and 2008 with first NCD paper
- Total flux in agreement with SSM and at more than 5σ level:

\[ \phi_{\mu\tau} > 0 \quad \Delta m_{12}^2 > 0 \quad P_{ee} < 1 \quad \phi_{e\mu\tau} = \phi_{SSM} \]

- Great physics out of SNO
- Archival solar physics publications in 2009 with a consistent 3-phase fit of all SNO data
- From solving SNP to precision physics