Present status and future prospect of the solar neutrino measurements for completing the PMNS picture and beyond

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Contents

- Introduction of Solar neutrino
- Current experiments
  - Super-Kamiokande
  - Borexino
- Future prospects
  - Hyper-Kamiokande
Solar neutrino

**How does the Sun shine?**

Nuclear fusion reactions can occur deep inside the Sun.

\[ 4p \rightarrow ^{4}\text{He} + 2\ e^{+} + 2\ \nu_{e} + 26.7\text{MeV} \]

\(~\sim6.6\times10^{10}\ \text{neutrinos}/\text{sec}/\text{cm}^{2}\)  

Particle physics: Neutrino oscillations  
Astrophysics: Still open issues on our Sun

Photon-measured luminosity

\(\rightarrow \sim10^{7}\text{years radiated from the center to the surface.}\)
Solar neutrino

**pp-chain**

Dominant process in the Sun (~99% of the energy)

W. Fowler

**CNO cycle**

Small ratio (<1%) in the Sun, poorly known yet

H. A. Bethe
Standard Solar Model

Flux (cm\(^{-2}\) sec\(^{-1}\) MeV\(^{-1}\))

- pp: ±0.5%
- \(^{13}\)N: +15% - 14%
- \(^{15}\)O: +16% - 15%
- \(^{17}\)F: +19% - 17%
- \(^{7}\)Be: ±5.8%
- pep: ±1.1%
- \(^{8}\)B: ±11.3%
- hep: ±15.5%

Neutrino energy (MeV)

(Bahcall-Pena-Garay-Serenelli 2008)

Super-K, SNO

BOREXINO

Hyper-K

J.N. Bahcall

Rencontres du Vietnam
Solar neutrino in PMNS picture

\[
\begin{align*}
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
&=
\begin{pmatrix}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} e^{-i\delta} & 0 & \cos \theta_{13}
\end{pmatrix}
\begin{pmatrix}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\end{align*}
\]

Atm. and Acc. \hspace{1cm} Reactor and Acc. \hspace{1cm} Solar and KamLAND

\(\theta_{23} \sim 45 \pm 5^\circ\) \hspace{1cm} \(\theta_{13} \sim 9^\circ\) \hspace{1cm} \(\theta_{12} \sim 34 \pm 3^\circ\)

\[\Delta m_{21}^2 = 7.54 \hspace{1cm} \text{for KamLAND}\]
\[\Delta m_{21}^2 = 4.82 \hspace{1cm} \text{for Solar}\]

~2 \(\sigma\) tension
Spectrum predicted by non-standard models

Sterile neutrino


MaVaN


Non-standard interaction


Unparticle

## Astrophysics : Metallicity puzzle

<table>
<thead>
<tr>
<th>Flux (cm(^{-2}) s(^{-1}))</th>
<th>GS98 (HZ)</th>
<th>AGSs09met (LZ)</th>
<th>diff. (HZ-LZ)/HZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp (10(^{10}))</td>
<td>5.98(1±0.006)</td>
<td>6.03(1±0.005)</td>
<td>-0.8%</td>
</tr>
<tr>
<td>pep (10(^{8}))</td>
<td>1.44(1±0.01)</td>
<td>1.46(1±0.009)</td>
<td>-1.4%</td>
</tr>
<tr>
<td>(^{7})Be (10(^{9}))</td>
<td>4.94(1±0.06)</td>
<td>4.50(1±0.06)</td>
<td>8.9%</td>
</tr>
<tr>
<td>(^{8})B (10(^{6}))</td>
<td>5.46(1±0.12)</td>
<td>4.50(1±0.12)</td>
<td>17.6%</td>
</tr>
<tr>
<td>(^{13})N (10(^{8}))</td>
<td>2.78(1±0.15)</td>
<td>2.04(1±0.14)</td>
<td>26.6%</td>
</tr>
<tr>
<td>(^{15})O (10(^{8}))</td>
<td>2.05(1±0.17)</td>
<td>1.44(1±0.16)</td>
<td>29.7%</td>
</tr>
<tr>
<td>(^{17})F (10(^{6}))</td>
<td>5.29(1±0.20)</td>
<td>3.261±0.18</td>
<td>38.3%</td>
</tr>
</tbody>
</table>

Metallicity determines the opacity of the solar plasma, which affects the central temperature of the sun.
Super-Kamiokande (1996~)

50000 tons of Water Cherenkov detector

- Neutrino-electron elastic scattering
  $\nu^+ + e^- \rightarrow \nu^+ + e^-$

- Find solar direction
- Realtime measurements
  - day-night flux differences
  - seasonal variation
- Energy spectrum

41.4 m
39.3 m

Cherenkov light
Charged particle

Neutrino
Super-Kamiokande (1996~)

Typical event

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

- Find solar direction
- Realtime measurements
  - day-night flux differences
  - seasonal variation
- Energy spectrum

Detector performance

<table>
<thead>
<tr>
<th>resolution (10 MeV)</th>
<th>information</th>
</tr>
</thead>
<tbody>
<tr>
<td>vertex</td>
<td>55cm</td>
</tr>
<tr>
<td>direction</td>
<td>23deg.</td>
</tr>
<tr>
<td>energy</td>
<td>14%</td>
</tr>
<tr>
<td>~ 6 hits/MeV</td>
<td># of hits.</td>
</tr>
</tbody>
</table>

well calibrated by LINAC and DT within 0.5% precision

E_e = 8.6 MeV (kin.)
\[ \cos \theta_{sun} = 0.95 \]
Motivation of the measurement

See the neutrino oscillation MSW effect directly

Spectrum distortion

Day-Night flux asymmetry

Super-K can search for the spectrum “upturn” expected by neutrino oscillation MSW effect
Neutrino oscillation

\[ \sin^2(\theta_{12}) = 0.316^{+0.034}_{-0.026} \]
\[ \Delta m^2_{21} = 7.54^{+0.19}_{-0.18} \]

\[ \sin^2(\theta_{12}) = 0.310 \pm 0.014 \]
\[ \Delta m^2_{21} = 4.82^{+1.20}_{-0.60} \]

\[ \sin^2(\theta_{12}) = 0.310 \pm 0.012 \]
\[ \Delta m^2_{21} = 7.49^{+0.19}_{-0.17} \]

The unit of \( \Delta m^2_{21} \) is \( 10^{-5} \) eV\(^2\)

\[ \sin^2 \theta_{13} = 0.0219 \pm 0.0014 \]
Day/Night asymmetry

expected time variation as a function of $\cos\theta_z$

Day/Night Amplitude was fitted to $-3.3\pm1.0\pm0.5\%$

Non-zero significance was $2.9\sigma$

in SK-I to IV (4499 days)
Recoil electron spectrum

Solar+KamLAND parameter
Solar global parameter
Quadratic spectrum best-fit
Exponential spectrum best-fit

SK spectrum data is consistent within 1σ for the Solar best fit parameters, while marginally consistent within 2σ for the Solar+KamLAND best fit parameters.
BOREXINO (2007~)

**Liquid scintillator:**
270 t PC+PPO (1.5g/l) in a 150 \( \mu \)m thick *Inner nylon vessel* (R=4.25m)

**Buffer region:**
PC+DMP quencher (5g/l) 4.25m<R<6.75m

**Outer nylon vessel:**
R=5.50m (*\(^{222}\)Rn Barrier)

**Stainless Steel Sphere:**
R=6.75m 2212 8” PMTs with light guide cone. 1350m\(^3\)

Experimental target:
- Solar Neutrinos
- Geo Neutrinos
- SuperNova neutrinos
- Long/Short base line neutrinos
- etc…

The wide energy range in real time are measurable.
Solar neutrinos in BOREXINO

Detection principle

Elastic scattering (ES)

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

✓ High light yield (~500 p.e./MeV)
  - lowering energy threshold
  - good energy resolution
✓ Realtime measurements
✓ No neutrino directional inf.
  - background reduction and understanding are critical

Radiopurity is crucial
Recent results in BOREXINO

B. Caccianiga, DOI: 10.5281/zenodo.2672266

Energy spectrum (TFC subtracted)
**Recent results in BOREXINO**

B. Caccianiga, DOI: 10.5281/zenodo.2672266

<table>
<thead>
<tr>
<th>Solar $\nu$</th>
<th>Borexino results Rate [cpd/100 t]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp$</td>
<td>$134 \pm 10^{+6}_{-10}$</td>
</tr>
<tr>
<td>$^7$Be</td>
<td>$48.3 \pm 1.1^{+0.4}_{-0.7}$</td>
</tr>
<tr>
<td>$pep$ (HZ)</td>
<td>$2.43 \pm 0.36^{+0.15}_{-0.22}$</td>
</tr>
<tr>
<td>$pep$ (LZ)</td>
<td>$2.65 \pm 0.36^{+0.15}_{-0.24}$</td>
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</table>

Total uncertainties 2.7%  
5 $\sigma$ evidence

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<tr>
<th>Solar $\nu$</th>
<th>Borexino results Flux $[\text{cm}^{-2}\text{s}^{-1}]$</th>
<th>Expected-HZ Flux $[\text{cm}^{-2}\text{s}^{-1}]$</th>
<th>Expected-LZ Flux $[\text{cm}^{-2}\text{s}^{-1}]$</th>
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<td>$pp$</td>
<td>$(6.1 \pm 0.5)^{+0.3}_{-0.5}) \times 10^{10}$</td>
<td>$5.98 (1 \pm 0.006) \times 10^{10}$</td>
<td>$6.03 (1 \pm 0.005) \times 10^{10}$</td>
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<tr>
<td>$^7$Be</td>
<td>$(4.99 \pm 0.13)^{+0.07}_{-0.10}) \times 10^{9}$</td>
<td>$4.93 (1 \pm 0.06) \times 10^{9}$</td>
<td>$4.50 (1 \pm 0.06) \times 10^{9}$</td>
</tr>
<tr>
<td>$pep$ (HZ)</td>
<td>$(1.27 \pm 0.19)^{+0.08}_{-0.12}) \times 10^{8}$</td>
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</tbody>
</table>
Survival probability

(averaged) vacuum oscillation dominant

Matter effect is dominant

$P_{\nu_e}$

$\Delta m^2_{21}$

$\sin^2 \theta_{12} = 0.308$

$\Delta m^2_{21} = 7.50 \times 10^{-5} \text{eV}^2$

$\sin^2 \theta_{12} = 0.311$

$\Delta m^2_{21} = 4.85 \times 10^{-5} \text{eV}^2$

M. Ikeda, Neutrino 2018
DOI: 10.5281/zenodo.1286857
Metallicity puzzle

B. Caccianiga, DOI : 10.5281/zenodo.2672266

BX results seem to give a hint towards the HZ hypothesis in spite of the large theoretical error
Hyper-Kamiokande

(See also “Hyper-Kamiokande Design Report”, arXiv: 1805.04163)

Next generation of large water Cherenkov detector

(~2027 - )

- 190 kton Fiducial volume:
  ~10 x Super-K
- 40% photo coverage with high-efficiency PMTs:
  ~2 x Super-K
  (~40,000 for inner detector)
Solar neutrinos in Hyper-K

Sensitivity of Day/Night flux asymmetry

- b/w zero D/N and Solar of $\Delta m_{21}^2$
- b/w Solar and KamLAND of $\Delta m_{21}^2$

Systematic error:
- 0.3 %
- 0.1 %
- 0.3 %
Solar neutrinos in Hyper-K

Sensitivity of spectrum upturn

- 3.5MeV energy threshold
- 4.5MeV energy threshold
Summary

- Solar neutrino experiments are important for both particle physics and astrophysics.
- Current running detectors of solar neutrino experiment are Super-Kamiokande and Borexino.
  - Indication of Day-Night asymmetry has been found in Super-K at 3σ level.
  - Precise measurements of pp, ⁷Be, pep has succeeded in Borexino. Metallicity puzzle is still remaining.
  - 2σ tension between solar and KamLAND Δm²¹² is seen. Future experiments, Hyper-K, JUNO, DUNE etc., are possible to solve this problem.