Neutrino Experiments
Sources

SUN

SUPERNova

Other: GRB, ...
Solar pp chain reactions

\[ p + p \rightarrow ^2H + e^+ + \nu_e \]  
99.75%

\[ p + p + e^- \rightarrow ^2H + \nu_e \]  
0.25%

\[ ^2H + p \rightarrow ^3He \]  
86%

\[ ^3He + ^3He \rightarrow \alpha + 2p \]  
14%

\[ ^3He + \alpha \rightarrow ^7Be \]  
2.4×10⁻⁵

\[ ^7Be + e^- \rightarrow ^7Li + \nu_e \]  
99.89%

\[ ^7Li + p \rightarrow \alpha + \alpha \]  
0.11%

\[ ^8Be \rightarrow ^8Be + e^+ + \nu_e \]  
8Be → α + α
Solar CNO chain reactions
Solar neutrino energy spectrum

Neutrino Spectrum (+1σ)

- pp → ±1%
- $^7\text{Be} \rightarrow ±10.5\%$
- $^{13}\text{N} \rightarrow ±2\%$
- $^{15}\text{O} \rightarrow ±2\%$
- $^{17}\text{F} \rightarrow ±10.5\%$
- $^8\text{Be} \rightarrow ±16\%$
- hep → ±16%

Neutrino Energy in MeV

Flux (cm$^{-2}$ s$^{-1}$)

Bahcall–Serenelli 2005
SN neutrinos

B. Dasgupta et al. PRL 103, 051105, 2009
Also, all supernovae may not be alike, and the DSNB results issues raised which cannot be answered without new data. Consistent with each other and theory; still, there are puzzling for DSNB studies is undesirable.

Supernovae, possibly more relevant for cosmological applications.

Flux $\nu_i$ minosity

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PHYSICAL REVIEW C

$\nu_e$ is excluded. (We assumed a thermal emission energy of $3 \times 10^{52}$ erg, assumed shared equally among the six flavors, and an effective received $\bar{\nu}_e$ angular distributions of the detected events.

$\nu_e$ is roughly $18$ MeV as $1.2$ cm$^{-1}$

We show only the 90% C. L., which is appropriate for model-independent tests of the neutrino emission parameters of supernovae.

At least three puzzling features of the SN 1987A data still stand out. First, the fits to the Kam-II and IMB data for the neutrino emission per supernova, taking into account the core-collapse rate. We see roughly a factor of two discrepancy at the peak region. We also consider a point primarily on the GALEX star formation rate data.

Additionally, it is important to keep an open mind about what the true parameters are, given that (a) numerical supernova calculations for models with a lower neutrino emission per supernova. Indeed, this is part of the motivation for lowering the SK energy threshold, so that the detected events would be detected by the inverse beta Cerenkov muon decay background shown in Fig. 2. (Color online) DSNB detection spectra for selected bins in Fig. 3.

We emphasize that the Kam-II and IMB results are precisely and unambiguously measured through direct data on the core-collapse rate.

Beyond the two supernova neutrino emission parameters $\nu_i$ $(\text{canonical values})$ of the figures, there are largest. Indeed, this is part of the motivation for lowering the SK limit is thus based on energies large background rates.

One can get more insight by examining three points, which was shown to be consistent with the latest SK Analysis. The points are chosen just with respect to what is allowed by the true parameters are, given that (a) numerical supernova calculations for models with a lower neutrino emission per supernova. With dissolved gadolinium, $\nu_e$ on free protons.

$\nu_e$ would be detected by the inverse beta Cerenkov tagging could allow a rate-limited, instead of background-limiting sensitivity.

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Borexino observed *pep* neutrinos (PRL 108, 051302, 2012):
- First hint at observation with 97% C.L. significance

SNO published final analysis of *$^8$B* neutrinos (arXiv:1109.0763):
- Most precise measurement of the metallicity of the Sun’s core
- Most precise measurement of $\theta_{12}$

SNO presented most sensitive search *hep* neutrinos:
- Sensitivity of $13 \times 10^3 \, \text{cm}^{-2}\text{s}^{-1}$ (90% CL upper limit) is close to the predicted flux of $8.0 \times 10^3 \, \text{cm}^{-2}\text{s}^{-1}$

Borexino measured rate of *$^7$Be* neutrinos (PRL 107, 141302, 2011):
- Measured with a precision of 4.6%
7Be solar neutrino flux

Borexino collaboration, PRL 107, 141302, 2011
$^{8}$B solar neutrino flux

\[ 5.25 \pm 0.16^{+0.011}_{-0.013} \]
Solar neutrino oscillations

$P_{\nu_e \rightarrow \nu_e}$

Relative to expected flux

Directly measured

arXiv:1109.0763

arXiv:1109.3230
Outstanding solar neutrino questions

- What is the solar core metallicity?
- What is the total solar luminosity measured with neutrinos (measure *pp* or *pep* neutrinos)?
- Are there non-standard neutrino oscillations?
- What is the Sun’s CNO neutrino flux?
- Can we see a day/night effect due to interactions with matter?
Metallicity

<table>
<thead>
<tr>
<th>Source</th>
<th>BPS08(GS)</th>
<th>BPS08(AGS)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pp$</td>
<td>5.97(1 ± 0.006)</td>
<td>6.04(1 ± 0.005)</td>
<td>1.2%</td>
</tr>
<tr>
<td>$pep$</td>
<td>1.41(1 ± 0.011)</td>
<td>1.45(1 ± 0.010)</td>
<td>2.8%</td>
</tr>
<tr>
<td>$hep$</td>
<td>7.90(1 ± 0.15)</td>
<td>8.22(1 ± 0.15)</td>
<td>4.1%</td>
</tr>
<tr>
<td>$^7$Be</td>
<td>5.07(1 ± 0.06)</td>
<td>4.55(1 ± 0.06)</td>
<td>10%</td>
</tr>
<tr>
<td>$^8$B</td>
<td>5.94(1 ± 0.11)</td>
<td>4.72(1 ± 0.11)</td>
<td>21%</td>
</tr>
<tr>
<td>$^{13}$N</td>
<td>2.88(1 ± 0.15)</td>
<td>1.89(1 ± 0.14)</td>
<td>34%</td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>2.15(1 ± 0.17)</td>
<td>1.34(1 ± 0.16)</td>
<td>31%</td>
</tr>
<tr>
<td>$^{17}$F</td>
<td>5.82(1 ± 0.19)</td>
<td>3.25(1 ± 0.16)</td>
<td>44%</td>
</tr>
<tr>
<td>Cl</td>
<td>8.46$^{+0.87}_{-0.88}$</td>
<td>6.86$^{+0.69}_{-0.70}$</td>
<td></td>
</tr>
<tr>
<td>Ga</td>
<td>127.9$^{+8.1}_{-8.2}$</td>
<td>120.5$^{+6.9}_{-7.1}$</td>
<td></td>
</tr>
</tbody>
</table>
Non-standard $\nu$ oscillations

Outstanding SN neutrino questions

- What is the temperature and luminosity for $\nu_e$, anti-$\nu_e$, and $\nu_x$?
- Can we see evidence of collective oscillations?
- Can we determine the neutrino mass hierarchy?
- Can we see evidence of neutronization?
Future solar opportunities

- **SK: Currently operating**
  - Continues to measure $^8$B solar neutrinos, may observe day/night asymmetry

- **Borexino: Currently operating**
  - Improved measurement of pep and $^7$Be solar neutrinos
  - Plan to improve purity and go after CNO solar neutrinos

- **SNO+: Under construction**
  - Hopefully sensitive to pep, $^7$Be, and CNO solar neutrinos

- **LENS: Currently running μLENS (100 liter)**
  - 60ton LENS could measure the pp solar neutrino flux to ~2%

- **CLEAN: Currently building miniCLEAN**
  - 10ton fiducial liquid Ne detector could measure pp solar neutrino flux to 1%
Assuming Borexino-level backgrounds are reached.
LENS

Fitted Solar $\nu$-Spectrum
Signal + Background (S/N = 3)

- pp
- Indium Bgd
- $^7$Be
- CNO
- pep

Signal Electron Energy (Ev-Q) [MeV]

Events $\times 10^3$ vs. $20\text{keV}\cdot5\text{y} \cdot 10^3$
Future SN opportunities

- **SK**
  - Sensitive to anti-$\nu_e$ spec. and flux neutron inverse beta decay, $\nu_e$ spec. and flux from $e^-$ scattering

- **SNO+, KamLAND, Borexino**
  - Sensitive to $\nu_x$ spec. and flux via proton scattering

- **Gadzooks: Under investigation**
  - Sensitive to SN relic neutrinos

- **ICE cube: Currently operating**
  - Sensitive to time spectrum of neutrinos from SN

- **LBNE**
  - If located underground would be sensitive to $\nu_e$ spec. and flux
  - Would also be somewhat sensitive to SN relic neutrinos
Figure 2: Galactic SN neutrino-proton elastic scattering event yield in the absence of a SN burst. The yield of events is shown as a function of quenched kinetic energy $T'$ (in MeV) for all flavors and for each individual flavor. The yield is integrated over the entire event yield in the absence of a SN burst (at KamLAND). Above that threshold, the background is negligible. It is comprised of the entire event yield in the absence of a SN burst, and there are mostly from the Po peak. The background rates are known very well, and the expected fluctuations in the Po peak are reported to be $5\%$ at 1 MeV and $3\%$ at 2 MeV, respectively from laboratory tests of the detector material. Again, the quenching factor was reported to be $9\%$ for protons with recoil energies (1-10) MeV.

Figure 3: Galactic SN neutrino-proton elastic scattering event yield above $T' = 0.2$ MeV. The yield of events is shown as a function of quenched kinetic energy $T'$ (in MeV) for all flavors and for each individual flavor. The yield is integrated over the entire event yield in the absence of a SN burst (at KamLAND). Above that threshold, the background is negligible. It is comprised of the entire event yield in the absence of a SN burst, and there are mostly from the Po peak. The background rates are known very well, and the expected fluctuations in the Po peak are reported to be $5\%$ at 1 MeV and $3\%$ at 2 MeV, respectively from laboratory tests of the detector material. Again, the quenching factor was reported to be $9\%$ for protons with recoil energies (1-10) MeV.

The SNO+ fiducial volume is taken to be 4 m sphere of the detector. The detector material is a mixture of 80% (by volume) of dodecane (C$_{12}$H$_{26}$), 20% pseudocumene (C$_{9}$H$_{12}$), and a small amount of water. The density of the inner 5% by volume of the detector is $1.5\times10^3$ kg/m$^3$. The detector material is linear alkyl benzene (C$_{9}$H$_{10}$) with 20% pseudocumene (C$_{9}$H$_{12}$) and 80% dodecane (C$_{12}$H$_{26}$). The Birks constant for the scintillator in SNO+ is reported to be $0.5\times10^3$ cm/MeV and the effective scintillation energy is $0.875$ MeV.

Ref. [49] reports that these are marginally different from the values in the pre-purification scintillator. Again, the quenching factor was reported to be $9\%$ for protons with recoil energies (1-10) MeV. In recent laboratory tests of the detector material, the Birks constant for the scintillator in SNO+ is reported to be $0.5\times10^3$ cm/MeV and the effective scintillation energy is $0.875$ MeV.

Note that this is lower than the number of free proton targets is thus $5\times10^5$ for a SN burst, corresponding to the size (C$_{9}$H$_{12}$)$_n$ and pseudocumene (C$_{9}$H$_{12}$). The energy resolution at KamLAND is determined by a photoelectron quenched to 4 and a photoelectron quenched to 4 $\times$ (0 $\times$ 1). The mean energy of the Po peak is $9\%$ and $86\%$ respectively from which we estimate an energy resolution at KamLAND of $0.5\times10^3$ cm/MeV which we have determined to be $0.875$ MeV.
The true hierarchy is inverted in the right plots. The top plots show the expected spectral shapes for normal and inverted hierarchies for the Duan model. The comparison in the bottom plots is for total event rates for normal and inverted hierarchies on a particular spectrum at late time slice, not the full spectrum. The relative distance sensitivity of a single-detector module to a distance of one 17 kt LAr module is assigned. The results are reported in the last column of Table XVI. The number of events per 0.5 MeV of the total flux, we cannot evaluate the full statistical sensitivity. However, we have done the following: we have assumed that fluxes with oscillation signatures are at this time only available representing a fraction of the total flux provided by Huaiyu Duan. While information about the hierarchy is clearly present in the water and tagging different flavors of the supernova neutrino events is less than optimal. Assuming that the fraction of muons producing radioisotopes which decay in the supernova neutrino range is less than 100%, we can assume that cosmic ray muons will not be a significant issue for burst neutrinos, and backgrounds will be well known and can be statistically subtracted from a burst signal. We can assume that cosmic ray muons will not be a significant issue for burst neutrinos.
Summary

- Neutrino experiments have confirmed our basic model of solar fusion but there is more we need to understand about the metallicity, and total luminosity.
- Solar neutrino experiments have also allowed us to understand neutrino oscillations. They could be a sensitive test of non-standard interactions.
- It is not possible to build a dedicated SN burst detector as it is not certain when the next SN neutrinos will reach earth, but we should have as many detectors that are sensitive to these as possible to not only learn about SN physics, but also neutrino physics.