Solar Neutrinos III: Unresolved Issues

• SNO: the low-energy and three-flavor analyses
• Borexino
• Metals and helioseismology
• What remains to be done
\[ \phi(8B) = \left( 5.046^{+0.169}_{-0.152} \text{(stat)}^{+0.107}_{-0.123} \text{(syst)} \right) \times 10^6 \text{ cm}^{-2}\text{s}^{-1} \]
FIG. 28: (Color online) Extracted a) CC and b) ES electron spectra as a fraction of one unoscillated SSM (BS05(OP)), from both signal extraction fits, with total uncertainties. The final 12–20 MeV bin in the kernel estimation fit is plotted at the mean of the spectrum in that range. Both spectra are consistent with the hypothesis of no distortion (a flat line).

As a result, the uncertainties are dominated by those due to statistics (which includes the ability to distinguish signal from background). This demonstrates the effect of the significant improvements made both in the determination of the individual systematic uncertainties, as presented in previous sections, and in the improved treatment of the dominant systematic uncertainties, whereby the self-consistency of the data itself was used to further constrain the allowed ranges of these parameters. It is worth noting that correlations between bins, which are not shown, tend to reduce the significance of any observed shape. Fitting to an undistorted spectrum (the flat line on Fig. 29) gives a \(\chi^2\) value of 21.52 for 15 degrees of freedom, which is consistent with the hypothesis of no distortion. The prediction for the \(T_{\text{eff}}\) spectrum for CC events taken from the best fit LMA point from a previous global analysis of solar data [9] is also overlaid on Fig. 29. The \(\chi^2\) value of the fit of the extracted spectrum to this prediction is 22.56 for 15 degrees of freedom, demonstrating that the data are also consistent with the LMA prediction.

FIG. 29: (Color online) Extracted CC electron spectrum as a fraction of one unoscillated SSM (BS05(OP)) from the binned-histogram signal extraction fit, with the uncertainties separated into statistical (blue bars) and systematic (red band) contributions. The predictions for an undistorted spectrum, and for the LMA point \(\Delta m^2 = 7.59 \times 10^{-5} \text{eV}^2\) and \(\tan^2 \theta_{12} = 0.468\) (taken from a previous global solar+KamLAND fit [9] and floating the 8B flux scale) are overlaid for comparison.

The one-dimensional projections of the fits in each observable parameter from the binned-histogram signal extraction are shown for each phase in Figures 30 and 31. Of particular note is the clear ES peak observed in the \(\cos \theta_{\odot}\) fits for both phases (Figs. 30(c) and 31(c)), demonstrating the extraction of ES events over the integrated energy spectrum, even with the low 3.5 MeV threshold. The error bars represent statistical uncertainties; systematic uncertainties are not shown. Figure 32 shows the one-dimensional projection in \(T_{\text{eff}}\) from Phase II (as in Fig. 31(a)) but with the fitted contributions from individual signal types separated into six categories: CC, ES, and NC neutrino events, internal backgrounds (within the D$_2$O volume), external backgrounds (in the AV, H$_2$O, and PMTs) and hep neutrino events. The \(\chi^2\) for the one-dimensional projections of the fit are given in Table XVIII. These were evaluated using statistical uncertainties only and are, therefore, a conservative test of goodness-of-fit in the one-dimensional projections. In all dimensions, the final result is a good fit to the data. Table XXII in Appendix A shows the extracted number of events for the neutrino fit parameters from the binned-histogram signal extraction fit, with total statistical plus systematic uncertainties. Table XIX shows the total number of background events extracted by each signal extraction in each phase, and a breakdown of the number of background neutron events occurring within each region of the detector. The two methods are in good agreement based on expectations from studies of Monte Carlo-generated 'fake' data sets. For comparison, the total number of events in each...
The survival probability was parameterized as a function of neutrino energy:

\[ P(E) = P_0 \times \sin^2(\theta \pm \phi) \]

where \( P_0 \) is the baseline survival probability, \( \theta \) is the mixing angle, \( \phi \) is the CP phase, and \( \pm \) indicates the flavor change (\( ee \) or \( \nu_x \)).

The advantage of this direct parameterization for \( \theta_13 \) is straightforward. We can test the goodness-of-fit to a model with no flavor conversion, \( \theta_13 = 0 \), and we can test the goodness-of-fit to a model with no \( CP \) violation, \( \phi = 0 \).

Under the assumption of unitarity (for example, no oscillations between active and sterile neutrinos), the NC, CC, and ES rates can be directly related. Based on this premise, a signal extraction fit was performed in which the free parameters directly described the total \( \nu \) flux and the \( \nu_x \) flux.

The dominant systematics in the fits were 'floated' from previous SNO analyses, which quoted a total uncertainty of 10% in \( \theta_13 \). The bands were computed by sampling the parameter space 1000 times, taking into account all relevant systematics.

The bands serve as a measure of the total flux of \( \nu_x \) from the Sun ever reported. In the unconstrained fit (Sec. 15.1), the total flux measured in this way was reduced in comparison to that from previous global solar+KamLAND fits.

The RMS spread in the best fit survival probability is that model testing becomes consistent with LMA. Requiring both simultaneously, we find a value consistent with LMA.

Figure 34 shows the RMS spread in the best fit survival probability is consistent with LMA. Under the assumption of unitarity (for example, no oscillations between active and sterile neutrinos), the NC, CC, and ES rates can be directly related. Based on this premise, a signal extraction fit was performed in which the free parameters directly described the total \( \nu \) flux and the \( \nu_x \) flux.

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between the solar and KamLAND experiments when contours explains the excellent agreement of \( \tan^{2}\theta_{12} \) oscillation analyses, respectively. When all solar experiment results from the various two- and three-flavor oscillation parameter analyses are allowed to vary in the fit, the best measurement of \( \Delta m^{2}_{12} \) and \( \sin^{2}\theta_{12} \) is extracted to a precision of \( 5 \times 10^{-5} \text{eV}^{2} \) from this fit is extracted to a precision of \( 5 \times 10^{-5} \text{eV}^{2} \).

The large-angle solution of the solar neutrino analysis (SNO, SK, CL, SAGE, Gallex/GNO, Borexino) combined with KamLAND the global two-flavor solar neutrino analysis (SNO, SK, Cl, SAGE, Gallex/GNO, Borexino) combined with KamLAND.
two-flavor
some tension?
At $\Delta m^2_{31} = 2.5 \times 10^{-3} \text{ eV}^2$, $\sin^2 2\theta_{13} < 0.15$

critically important to the CP-violation signal in future LB studies: $J_{CP} \sim 0.2 \sin 2\theta_{13} \sin \delta$
\[ P_{ee} \sim \cos^4 \theta_{13} \sin^2 \theta_{12} \]

\[ P_{ee} \sim \cos^4 \theta_{13} \left( 1 - \sin^2 2\theta_{12} \sin^2 \frac{\delta m_{12}^2 L}{4E} \right) \]

\( \sin 2\theta_{13} = 0.1 \)

\( \sin 2\theta_{13} = 0 \)

\( \sin 2\theta_{13} = 0.1 \)

\( \text{from Balantekin} \)

...or is it simply ignoring \( \theta_{13} \)?
between the solar and KamLAND experiments when contours explains the excellent agreement of tan
parameters are combined with data from the KamLAND re-
calibration analyses, respectively. When all solar experi-
ment results from the various two- and three-flavor os-
spectra.

The solar data includes: SNO's LETA survival probability
a) global solar data and b) global solar + KamLAND data.

Tables XX and XXI summarize the oscillation param-
Figure 40 shows the confidence regions in the

$$\sin^2 \theta_{12} \approx 0.02$$

$$\sin^2 \theta_{13} < 0.057 \ (95\%)$$

$$\sin^2 \theta_{13} = 2.00^{+2.09}_{-1.63} \times 10^{-2}$$
a hint of an effect

SNO 3-flavor global analysis
SNO, Super-K physics has been extracted from 0.01% of the available flux.
ppI

\[ p + p \rightarrow ^2\text{H} + e^+ + \nu \]

99.75%

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

86%

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

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

99.89%

\[ ^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu \]

99.89%

\[ ^7\text{Li} + p \rightarrow 2^4\text{He} \]

76%

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

14%

Borexino now making the first direct measurements of the low-energy flux

SNO, Super-K physics has been extracted from 0.01% of the available flux
Borexino
Detection reaction is $\nu_x + e \rightarrow \nu'_x + e'$

Use of scintillator allows one to see low energy events: $^{7}\text{Be}$ neutrinos produce scattered electrons with kinetic energy < 0.668 MeV

Resolution is good, $\sigma(T) \sim 0.8$ MeV $\sqrt{T/\text{MeV}}$, or 8-9% near 0.7 MeV

Can trigger on events with energy above $\sim 250$ keV

Thus in principal such detectors can do spectroscopy of the low-energy neutrino spectrum.

In practice this requires great care to reduce ambient backgrounds, which grow rapidly as the energy is lowered. This includes radon-associated (environmental) backgrounds as well long-lived activities produced by cosmic ray muons, e.g., $^{11}\text{C}$ -- a 20.4 minute beta source, 1.47 MeV kinetic energy release
in the high energy, matter enhanced regions. Borexino al-
target, neutrinos in the low energy, vacuum dominated- and
stringent test of the di-
neutrinos, at the energy of 0.862 MeV [9]. The distance
overall uncertainty on
assuming other 4 years of data taking, and to reduce the
energy neutrinos predicted by the MSW-LMA theory: as-
with the expected theoretical flux in the BPS09(GS98) MSW-

Using the above equation, we obtain
\[ P_{ee} = 1 - \frac{1}{2} \sin^2 2\theta_{12} \]

\[ \text{vacuum} \]

\[ \text{matter} \]

\[ \sin^2 \theta_{12} \]

\[ \]
Borexino volume is limited, \( \sim 300 \) tons

Just entering its calibration phase

Thus substantial improvement in precision is likely

an interesting technology that will be taken to the next level by SNO+ ... which has the reach to make a very new kind of neutrino check of the Sun
Recent Re-evaluations of Photospheric Abundances

- SSM requires as input an estimate of core metallicity at $t=0$

- Taken from meteoritic abundances or from photospheric absorption lines: the latter are the only practical way to determine the abundances of volatile heavy elements, such as C, N, O, Ne, Ar
  - SSM then assumes a homogeneous zero-age sun characterized by these abundances, for reasons previously described

- These metals influence solar dynamics: free-bound transitions important to opacity, influencing local sound speed: different metals dominate in different solar regions

- The once excellent agreement between SSM and helioseismology due in part to this input (Grevesse & Sauval 1998)
The classic analyses modeled the photosphere in 1D, despite stratification, velocities, inhomogeneities.

But new 3D, parameter-free methods have been introduced, significantly improving consistency of line analyses.

Dynamic and 3D due to convection
Spread in abundances from different C, O lines sources reduced from ~ 40% to 10%

But abundances significantly reduced Z: 0.0169 ⇒ 0.0122

Makes sun more consistent with similar stars in local neighborhood

Lowers SSM $^8$B flux by 20%
Fig. 1.— Relative sound-speed differences, $\delta c/c = (c_{\odot} - c_{\text{model}})/c_{\text{model}}$, between solar models and helioseismological results from MDI data. The vertical error bars show the 1σ error in the inversion due to statistical errors in the data. The horizontal error bars are a measure of the resolution of the inversions, defined as the distance between the first and third quartile points of the averaging kernels (approximately the half-width in radius of the measurement in regions of good resolution).

As discussed in Basu, Pinsonneault, and Bahcall (2001), the effect of mixing in the radiative zone of the Sun would be in the direction to reconcile the meteoritic and solar photospheric lithium abundances and to bring the computed surface helium slightly closer to the measured value. Such models have a somewhat shallower solar surface convection zone and the overall agreement with the sound speed data is comparable, or slightly less good, than models without extra mixing.

4.2. Comparisons for model BP04+ : new heavy element abundances

Figure 1 shows the dramatic lack of agreement between the helioseismological sound speeds and the values predicted by the BP04+ solar model, which uses the new heavy element abundance determinations (Allende Prieto, Lambert, & Asplund 2001; Allende Prieto, Lambert, & Asplund 2002; Asplund et al. 2004; Asplund et al. 2000; Asplund 2000). The Bahcall, Basu, Pinsonneault, Serenelli 2004 convective zone old (GS 1998) abundances new (AGS 2005) abundances

But adverse consequences for helioseismology

Tuesday, August 3, 2010
Discrepancy largest for $T \sim 2-5 \times 10^6 \text{ K}$: C, N, O, Ne, and Ar are partially ionized, with O and Ne particularly important to the opacity.

Troubling because the previous concordance between the SSM and helioseismology helped establish the credibility of the SSM, and thus the plausibility of a neutrino mixing solution to the solar $\nu$ problem.
Was the primordial Sun really homogeneous?

- Accept the photospheric and helioseismic results at face value: the convective zone (2.6% of the Sun's mass) has ~ 30% fewer metals than the radiative zone: deficit in the convective zone is 50 M⊕

- Galileo, Cassini, and subsequent planetary modeling show that significant metal differentiation occurred late in the evolution of the solar system, associated with formation of the gaseous giants
  - planets form late, involving the last ~ 5% of the gas
  - angular momentum transfer: that gas is in a thin disk
  - metal-rich grains and ice collect at the disk midplane
  - formation of the 10 M⊕ rock cores of the giant planet, which scour out this enriched material
  - rapid (1-few My) formation of gaseous envelopes, after the bulk of the nebular gas has already dissipated
  - timing: the sun already has developed its radiative core

- The observed atmospheric enrichments indicate a total metal excess of (40-90) M⊕, depending on planetary modeling uncertainties
Figure 5: Elemental abundances measured in the troposphere of Jupiter (circles) and Saturn (squares) in units of their abundances in the protosolar nebula. The elemental abundances for Jupiter are derived from the in situ measurements of the Galileo probe (e.g. Mahaffy et al. 2000; Atreya et al. 2003). Note that the oxygen abundance is considered to be a minimum value due to meteorological effects (Roos-Serote et al. 2004). The abundances for Saturn are spectroscopic determination (Atreya et al. 2003 and references therein). The solar or protosolar abundances used as a reference are from Lodders (2003). The arrows show how abundances are affected by changing the reference protosolar abundances from those of Anders & Grevesse (1989) to those of Lodders (2003). The horizontal dotted lines indicate the locus of a uniform 2- and 4-times solar enrichment in all elements except helium and neon, respectively.

Galileo data, from Guillot AREPS 2005

Standard interpretation: late-stage planetary formation in a chemically evolved disk over ~ 1 m.y. time scale.
Could a single mechanism be responsible for both problems? Did the process of planetary formation perturb and chemically segregate the last few percent of nebular gas, resulting in the enrichment of planetary atmospheres and dilution of the convective zone?

The matter in the disk’s “dead zone”--larger grains, ice concentrated in midplane--preferentially incorporated into the planets, reservoirs for 40-90 M\(_\oplus\) of excess metal.

The sun’s deep interior would reflect the composition of the primordial gas cloud; the planets and solar surface would be processed.
Several requirements

- processed gas remains in the solar system, not expelled

- because of the connection to planetary formation, the associated gas accretion rate would have to be on the order of $10^{-8} \times (1 \text{ My} / T_{\text{planets}})$ solar masses/year -- comparable to some observed T Tauri rates

- the Sun must have had a well-developed radiative core at the time of planetary formation (thus an isolated convective zone)
Experimental Possibilities?

- Solar neutrino experiments to date do not have the precision to address this problem. E.g., in the case of SNO:
  - SNO 391-day NCD-phase results: \((5.54 \pm 0.51) \times 10^6/cm^2s\)
  - SNO LET analysis: \((5.05 \pm 0.20) \times 10^6/cm^2s\)
  - SSM, 1998 GS abundances \((Z=0.0169)\): \(5.95 \times 10^6/cm^2s\)
  - SSM, 2005 AGS abundances \((Z=0.0122)\): \(4.72 \times 10^6/cm^2s\)

- Astronomical observations: there have been two recent studies of solar twins -- driven in part by the possibility that if the formation of planets alters a host star’s metallicity, a new tool for exo-planet hunting might develop.

- New neutrino measurements: there is one possibility for probing solar core metallicity directly.

systematic differences in heavy-element abundances between Sun and nearby solar twins, tightly correlated with the condensation temperature of the elements - so the mechanism is likely chemistry.

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**Israelian et al., Nature** 462 (2009) 189

established a direct correlation between solar twin abundance of Li and the presence of planets: otherwise identical systems with planets have roughly 1/10 the Li of those without planets - hypothesized a rather exotic “mechanical” explanation.
Condensation Temperatures of the Elements

Lodders (2003)

(PSRD graphic based on calculations done by Katarina Lodders, Washington University in St. Louis.)
Within the solar nebula, 98% of the material is hydrogen and helium gas that doesn’t condense anywhere.

Within frost line, rocks and metals condense, hydrogen compounds stay gaseous.

Beyond frost line, hydrogen compounds, rocks, and metals condense.

refractory elements condense

H₂O condenses
SNO+ as a possible test of a two-zone Sun

- pp chain (primary) vs CN cycle (secondary): catalysts for CN cycle are pre-existing metals (except in the interesting case of the first stars)

![Diagram showing the pp chain and CN cycle]
the CN-cycle contributes modestly to solar energy generation $\sim 1\%$

but produces measurable neutrino fluxes

$$^{13}\text{N}(\beta^+)^{13}\text{C} \quad E_\nu \lesssim 1.199 \text{ MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8 / \text{cm}^2\text{s}$$

$$^{15}\text{O}(\beta^+)^{15}\text{N} \quad E_\nu \lesssim 1.732 \text{ MeV} \quad \phi = (2.20^{+0.73}_{-0.63}) \times 10^8 / \text{cm}^2\text{s}.$$ 

these fluxes depend on the core temperature $T$, but also have an additional linear dependence on the total C+N in the Sun’s core

$$\phi_\nu^{\text{CN}} = F[S_\text{CN}; T; \theta_{12}; \text{CN}]$$

what we want to determine
the CN-cycle contributes modestly to solar energy generation \( \sim 1\% \)

but produces measurable neutrino fluxes

\[
\begin{align*}
13N(\beta^+)13C & \quad E_\nu \lesssim 1.199 \text{ MeV} & \phi &= (2.93^{+0.91}_{-0.82}) \times 10^8 / \text{cm}^2\text{s} \\
15O(\beta^+)15N & \quad E_\nu \lesssim 1.732 \text{ MeV} & \phi &= (2.20^{+0.73}_{-0.63}) \times 10^8 / \text{cm}^2\text{s}.
\end{align*}
\]

these fluxes depend on the core temperature \( T \), but also have an additional linear dependence on the total C+N in the Sun’s core

\[
\phi^\text{CN}_\nu = F[S_{14N+p}; \ T; \ \theta_{12}; \ \text{CN}]
\]

well enough measured by SNO and KamLAND
the CN-cycle contributes modestly to solar energy generation $\sim 1\%$

but produces measurable neutrino fluxes

$^{13}\text{N}(\beta^+)^{13}\text{C} \quad E_\nu \lesssim 1.199 \text{ MeV} \quad \phi = (2.93^{+0.91}_{-0.82}) \times 10^8 / \text{cm}^2\text{s}$

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$$\phi_{\nu}^{\text{CN}} = F[S_{14\text{N}_p}; \ T; \ \theta_{12}; \ \text{CN}]$$

a surrogate for 19 SSM parameters: calibrated to 0.5% by Super-Kamiokande
the CN-cycle contributes modestly to solar energy generation $\sim 1\%$

but produces measurable neutrino fluxes

$$^{13}\text{N}(\beta^+)^{13}\text{C} \ E_{\nu} \lesssim 1.199 \text{ MeV} \ \phi = (2.93^{+0.91}_{-0.82}) \times 10^8 / \text{cm}^2 \text{s}$$

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these fluxes depend on the core temperature $T$, but also have an additional linear dependence on the total $\text{C+N}$ in the Sun’s core

$$\phi_{\nu}^{\text{CN}} = F[S_{14}^{N+p}; \ T; \ \theta_{12}; \ \text{CN}]$$

a significant, limiting uncertainty until recently
Heroic efforts to make background-free measurements

LUNA and LENA measurements of $^{14}\text{N}(p,\gamma)$

Formicola (LUNA) et al. (2004); Imbriani et al. (2005); Bemmerer et al (2006); Lemut et al. (2006); Trautvetter et al. (2008); Runkle (TUNL) et al. (2005)

S-factor mapped down to 70 keV ⇒ event rate 1/mo
the CN-cycle contributes modestly to solar energy generation $\sim 1\%$ but produces measurable neutrino fluxes

$^{13}\text{N}(\beta^+)^{13}\text{C} \quad E_\nu \lesssim 1.199 \text{ MeV} \quad \phi = (2.93_{-0.82}^{+0.91}) \times 10^8/\text{cm}^2\text{s}$

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$$\phi^\text{CN}_\nu = F[S_{14\text{N}+p}; \ T; \ \theta_{12}; \ \text{CN}]$$

an experiment capable of measuring the fluxes
SNO+ will occupy the SNOLab cavity previously occupied by SNO

Three times larger and one kilometer deeper than Borexino
CN spectrum sits between the pep and 7Be line electrons

SNOLab’s 2 kilometer depth: factor-of-70 reduction in long-lived cosmogenic $^{11}\text{C}$, to 0.1 c/d/100 tons, compared to Borexino

$\rightarrow$ 7% CNO flux measurement appears possible
So the next solar neutrino experiment may have a different kind of impact

- It appears SNO+ and analysis could determine the core abundance of C+N to an accuracy of about 11% (with the error nominated by lab astrophysics, which could be improved with a bit of work) - this would check a key assumption of the SSM, that the metals are distributed uniformly throughout the Sun

- well motivated, as we have three apparent metallicity problems
  - SSM conflict between helioseismology, photospheric abundances
  - the anomalous abundances of Jupiter, Saturn
  - the systematic chemical anomalies in solar twins

- interesting that the solar neutrino problem has stimulated advances in two of the three available techniques for probing solar system interiors (solar neutrino detection, helioseismology)

- if C+N is anomalous, we will have to reconsider one of the central assumptions of the SSM
When will we be done with solar neutrinos?
When will we be done with solar neutrinos?

Not soon! ..... for example, there are sources we have not yet even discussed
FIG. 1. Representative diagrams for the various thermal neutrino pair processes considered here: a) Compton process; b) plasmon pole contribution to the Compton process; c) transverse plasmon decay; d) nuclear $Z^0$ emission; and e) pair production in free-bound atomic transitions.
FIG. 4. Natural neutrino sources. The terrestrial $\bar{\nu}_e$ flux and continuous flux of extragalactic supernova neutrinos of all flavors are from Krauss et al. [12]. The solar (fusion) $\nu_e$ flux is the standard solar result of Bahcall et al. [11]. The thermal solar neutrinos are for a single flavor.

These remarks are made because the most likely opportunity for measuring the thermal neutrino spectrum is a process that depends on flux density, not on total flux, and which samples that flux at a precise energy, the resonant reaction $\bar{\nu}_e + e^- \rightarrow (A, Z)$.

This reaction has been discussed previously in connection with terrestrial $\bar{\nu}_e$ sources [12]. Cross sections can be large in high $Z$ atoms, where the electron overlap with the nucleus is favorable. Because nuclear level widths are very narrow, this process samples the $\bar{\nu}_e$ flux density at a discrete energy. The are several possible candidate transitions with energies between 2 and 20 keV. (One that has been studied in connection with neutrino mass measurements is the decay of long-lived $^{163}$Ho to $^{163}$Dy, which has a positive q-value of less than 3 keV: either a neutrino mass or $\bar{\nu}_e$inducement of electron capture alters the atomic orbits that participate in the capture.)

The heavy-flavor neutrino flux also contains interesting information: if the existence of this flux were established, it would immediately impose kinetic mass limits of $\sim 1$ keV on $\nu_\mu$ and $\nu_\tau$. Unfortunately there is no obvious possibility for measuring these species. The problem could well prove as difficult as in the case of the cosmic microwave neutrinos, where existing experimental bounds exceed the expected flux by about 15 orders of magnitude [14].

As is the case with most sources of astrophysical neutrinos! CMB + LSS? bolometers? thermal $\nu_e/\bar{\nu}_e$ thermal $\nu_\tau/\bar{\nu}_\tau$ solar $\nu_e$ terrestrial $\bar{\nu}_e$ supernovae $\nu/\bar{\nu}$ (×100) scintillator and liquid noble gas detectors but matter effects? cosmic ray

Tuesday, August 3, 2010
supplementary slides
Can one extract from such a measurement the core metallicity?

- There are 19 SSM parameters $\beta_j$ with significant uncertainties

$$\alpha(i, j) \equiv \frac{\partial \ln \left[ \frac{\phi_i/\phi_i(0)}{\beta_j/\beta_j(0)} \right]}{\partial \ln \left[ \frac{\beta_j/\beta_j(0)}{\beta_j(0)} \right]} \implies \phi_i = \phi_i(0) \prod_{j=1}^{N} \left[ \frac{\beta_j}{\beta_j(0)} \right]^{\alpha(i,j)}$$

- Divide this dependence into environmental, nuclear, CN terms

$$\phi_i = \phi_i^{SSM} \left( \prod_{j \in \{Solar\}} \left[ \frac{\beta_j}{\beta_j(0)} \right]^{\alpha(i,j)} \prod_{j \in \{Metals\neq C,N\}} \left[ \frac{\beta_j}{\beta_j(0)} \right]^{\alpha(i,j)} \prod_{j \in \{Nuclear\}} \left[ \frac{\beta_j}{\beta_j(0)} \right]^{\alpha(i,j)} \prod_{j \in \{C,N\}} \left[ \frac{\beta_j}{\beta_j(0)} \right]^{\alpha(i,j)} \right)$$

- Bracketed “environmental” uncertainties: luminosity, radiative opacity, solar age, He and metal diffusion, fractional abundances of O, Ne, Mg, Si, S, Ar, and Fe -- not well controlled by lab constraints, but tend to affect all neutrino fluxes similarly

- What remains is a linear dependence on C, N -- our interest
Monte Carlo SSM studies of $^{8}\text{B}$, $^{15}\text{O}$ ν correlations

![Graphs showing correlations and residuals for $^{8}\text{B}$ and $^{15}\text{O}$ neutrino fluxes.](image)
Table 1. Partial derivatives $\alpha_{i,j}$ of neutrino fluxes with respect to solar environmental and nuclear cross section parameters.

<table>
<thead>
<tr>
<th>Source</th>
<th>Environmental $\beta_j$</th>
<th>Nuclear $\beta_j$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$L_\odot$</td>
<td>Opacity</td>
</tr>
<tr>
<td>$\phi(^8\text{B})$</td>
<td>7.16</td>
<td>2.70</td>
</tr>
<tr>
<td>$\phi(^{13}\text{N})$</td>
<td>4.40</td>
<td>1.43</td>
</tr>
<tr>
<td>$\phi(^{13}\text{N})/\phi(^8\text{B})^{0.599}$</td>
<td>0.11</td>
<td>-0.19</td>
</tr>
<tr>
<td>$\phi(^{15}\text{O})$</td>
<td>6.00</td>
<td>2.06</td>
</tr>
<tr>
<td>$\phi(^{15}\text{O})/\phi(^8\text{B})^{0.828}$</td>
<td>0.07</td>
<td>-0.18</td>
</tr>
</tbody>
</table>

**The point:** other neutrino measurements (SNO, Superk) have effectively calibrated the environmental uncertainties.
The bottom line is a primordial abundances $\leftrightarrow$ future experiment relation:

$$\frac{R_{exp}^{B/S}(CN)}{R_{cal}^{B/S}(^{15}O, \delta {m^2_{12}}, \theta_{12})} = \left( \frac{X(^{12}C)}{X(^{12}C)_{SSM}} \right)^{0.805} \left( \frac{X(^{14}N)}{X(^{14}N)_{SSM}} \right)^{0.199} \times (1.120 \pm 0.003)[1 \pm 0.03\,(SK) \pm 0.026\,(resid\,env) \pm 0.049\,(LMA) \pm 0.071\,(nucl)]$$

- diffusion: relating today’s metals to primordial ones
- errors that can be further improved in the laboratory:
  - nuclear physics
  - neutrino flavor physics

The net theory “error bar” in relating a SNO+ CN-$\nu$ measurement to primordial metallicity is thus about 9%