Neutrino Physics: On Earth and in the Heavens

- The discovery of neutrino mass
- Challenges in the lab: double beta decay, long baseline neutrinos
- Challenges in the heavens: the composition of the Sun
Introduction

A great deal of effort and expense has been consumed in recent searches for new physics at the energy frontier

But so far, the specific evidence we have that there is physics beyond the standard model has come primarily from low-energy tests

**Neutrino mass and mixing:** oscillations of solar and atmospheric neutrinos

**Cosmological dark matter:** a variety of observations showing that the amount of gravitating mass at various scales is about 7 times the baryonic mass

The former is today’s theme, a story with
- exquisitely precise, clean experiments
- persistence, which will continue to be needed …
The Standard Solar Model: Davis to SNO

- Origin of solar neutrino physics: desire to test a model of low-mass, main-sequence stellar evolution
  - local hydrostatic equilibrium: gas pressure gradient counteracting gravitational force
  - hydrogen burning: pp chain, CN cycle
  - energy transport by radiation (interior) and convection (envelope)
  - boundary conditions: today’s mass, radius, luminosity

- The implementation of this physics requires
  - electron gas EOS
  - low-energy nuclear cross sections
  - radiative opacity
  - some means of fixing the composition at ZAMS, including the ratios X:Y:Z
Model tests:

- **Solar neutrinos**: direct measure of core temperature to $\sim 0.5\%$ – once the flavor physics has been sorted out

- **Helioseismology**: inversions map out the local sound speed, properties of the convective zone

As sound speed measurements reached 1% in the 1990s, it became apparent that the SSM was marvelously predictive …

But the story with neutrinos was complicated
1. INTRODUCTION

In 1958, Holmgren & Johnston (1958, 1959) found that the cross section for \( ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma \) was about 1,000 times larger than anticipated, so that in addition to the simplest \( ^3\text{He} + ^3\text{He} \rightarrow ^4\text{He} + 2p \) proton-proton (pp) I termination of the pp chain (see Figure 1), there might be significant branches to the pp II and pp III cycles and, thus, significant fluxes of \(^7\text{Be}\) and \(^8\text{B}\) solar neutrinos. Despite the uncertainties that existed in 1958—the solar core temperature was poorly constrained by theory, and other nuclear physics important to the pp chain had not been resolved—both Cameron (1958) and Fowler (1958) pointed out that it might be possible to detect solar neutrinos using a radiochemical method Ray Davis had developed at Brookhaven (Davis 1955). Although the endpoint of the main source of neutrinos from the pp I cycle, \( p + p \rightarrow d + e^- + \bar{\nu}_e \), is below the 811-keV threshold for \( \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- + \text{m} \), most \(^7\text{Be}\) and \(^8\text{B}\) neutrinos are sufficiently energetic to drive this reaction. In 1962 Fowler organized a team of young Caltech researchers—John Bahcall, Icko Iben, and Dick Sears—to begin the development of a solar model to more accurately predict the central temperature of the Sun and to estimate the rates of neutrino-producing reactions (Bahcall et al. 1963). The history of these early developments is summarized in several sources (Bahcall & Davis 1982, Haxton 2010, Lande 2010). By early 1964, following significant advances in the solar model and in the understanding of the nuclear physics of the pp chain and the \(^{37}\text{Cl}(\nu_e, e^-) ^{37}\text{Ar} \) reaction, Davis (1964) and Bahcall (1964) concluded that a measurement of solar neutrinos would be possible, were Davis to mount a detector 100 times larger than that he built at Brookhaven, in a site sufficiently deep to reduce backgrounds from high-energy cosmic-ray muons to an acceptable level. In April 1968, Davis, Harmer & Hoffman (1968) announced an upper bound on the solar neutrino capture rate for \(^{37}\text{Cl} \) of 3 SNU (1 SNU = \( 10^{-36} \) captures target \(-1 \).
By mid-1990s model-independent arguments developed showing that no adjustment in the SSM could reproduce observed ν fluxes (Cl, Ga, water exps.).

Hata et al.

Castellani et al.

(and Heeger and Robertson)
SNO, Super-Kamiokande, Borexino
the “solar $\nu$ problem” was definitively traced to new physics by SNO flavor conversion $\nu_e \rightarrow \nu_{\text{heavy}}$

requires an extension of the SM -- Majorana masses or $\nu_R$
… we will return to this story latter

A very similar problem arose in studies of atmospheric neutrinos — which led to discovery of a second oscillation occurring at shorter distances scales
Neutrino oscillations require a mass (massless particles travel at the speed of light and thus have no “clock”)

And they require mixing

\[ m_1, m_2, m_3 \neq m_{\nu_e}, m_{\nu_\mu}, m_{\nu_\tau} \]

mass eigenstates \( \neq \) flavor eigenstates
(eigenstates of free propagation) (production eigenstates)

\[ |\nu_e\rangle = \sum_i U_{ei} |\nu_i\rangle \]

e.g., for the mixing of just two flavors

\[ |\nu_e\rangle = \cos \theta_{12} |\nu_1\rangle + \sin \theta_{12} |\nu_2\rangle \]
\[ |\nu_\mu\rangle = -\sin \theta_{12} |\nu_1\rangle + \cos \theta_{12} |\nu_2\rangle \]
Then it is straightforward to show, for a coherent localized neutrino wave packet

\[ |\nu(t = 0) = |\nu_e \rangle \implies P_{\nu_{\mu}}(t) = |\langle \nu(t)|\nu_{\mu} \rangle|^2 \sim \sin^2 2\theta_{12} \sin^2 \frac{\pi ct}{L_0} \]

\[ L_0 = \frac{4\pi \hbar c E_{\nu}}{\delta m_{21}^2 c^4} \]

\[ \delta m_{21}^2 = m_2^2 - m_1^2 \]

It was also discovered (the MSW mechanism) that in matter

\[ \delta m_{21}^2 \implies \delta m_{21}^2(\rho) \]
Then it is straightforward to show, for a coherent localized neutrino wave packet

\[ |\nu(t = 0) = |\nu_e\rangle \quad \Rightarrow \quad P_{\nu_\mu}(t) = |\langle \nu(t)|\nu_\mu\rangle|^2 \sim \sin^2 2\theta_{12} \sin^2 \frac{\pi ct}{L_0} \]

\[ L_0 = \frac{4\pi \hbar c E_{\nu}}{\delta m_{21}^2 c^4} \quad \delta m_{21}^2 = m_2^2 - m_1^2 \]

It was also discovered (the MSW mechanism) that in matter

\[ \delta m_{21}^2 \quad \Rightarrow \quad \delta m_{21}^2(\rho) \]

makes the $\nu_e$ heavier in matter
Then it is straightforward to show, for a coherent localized neutrino wave packet

\[ |\nu(t = 0) = |\nu_e\rangle \Rightarrow P_{\nu_\mu}(t) = |\langle \nu(t)|\nu_\mu\rangle|^2 \sim \sin^2 2\theta_{12} \sin^2 \frac{\pi ct}{L_0} \]

\[ L_0 = \frac{4\pi \hbar c E_\nu}{\delta m_{21}^2 c^4} \quad \delta m_{21}^2 = m_2^2 - m_1^2 \]

It was also discovered (the MSW mechanism) that in matter

\[ \delta m_{21}^2 \Rightarrow \delta m_{21}^2(\rho) \]

\[ e^- \rightarrow Z_0 \rightarrow \nu_e, \nu_\mu \]

| alters \delta m_{12}^2(\rho) | e^- \rightarrow W^+ \rightarrow \nu_e |
\[ \theta = \frac{\pi}{12} \]

\[ F' = 1 - \sin(2\theta) \]

\[ F'_{x=1} = 1 - \frac{1}{4} \sin^2(2\theta) \]

\[ x_{\text{start}} = -20 \]

\[ \text{Plot} \left( F'_{x}, \right) \text{ from } x_{\text{start}} \text{ to } -x_{\text{start}} \]

\[ G' = \sqrt{\frac{2}{\pi}} \arctan \left( \frac{x}{5} \right) - 1 + \cos(2\theta) \]

\[ \Theta' = \frac{1}{2} \arccos \left( \sqrt{\frac{2}{\pi}} \arctan \left( \frac{x}{5} \right) - 1 + \cos(2\theta) \right) \]

\[ \text{N} \left( \Theta'_{x_{\text{start}}} \right) \]
\[
\theta = \pi - \frac{12}{\pi}
\]

\[
F(x) = 1 - \sin(2\theta) \cos(2\theta) + \sin(2\theta)^2
\]

\[
F(1) = 1 - \frac{1}{4} \sin^2(2\theta)
\]

\[
x_{\text{start}} = -20
\]

\[
\text{Plot} \ F(x), \ x = x_{\text{start}}, \ x = -x_{\text{start}}
\]

\[
G(x) = \sqrt{\left(\frac{2}{\pi} \arctan\left(\frac{x}{5}\right) + 1 - \cos(2\theta)\right)^2 + \sin(2\theta)^2}
\]

\[
\Theta(x) = \frac{1}{2} \arccos\left(\sqrt{\left(\frac{2}{\pi} \arctan\left(\frac{x}{5}\right) - 1 + \cos(2\theta)\right)^2 + \sin(2\theta)^2}\right)
\]

\[
\Theta(x_{\text{start}}) = 76.461
\]

\[
\text{Plot} \ G(x), \ x = x_{\text{start}}, \ x = -x_{\text{start}}
\]
Why is the discovery of neutrino mass important?

The answers weave together several issues, and a bit of history

- Neutrinos are different from other standard-model fermions in lacking a charge or other additively conserved quantum number. What distinguishes $\nu$ from $\bar{\nu}$?

- Now that we know they have a mass, why is that mass so much smaller than other masses?

- A related long-lived nuclear decay mode, double beta decay
1930: Pauli’s suggests a “neutrino” accompanies the electron in β decay

1932: Chadwick’s discovery of the “neutron”

1934: Fermi’s incorporation of both in his “effective theory” of β decay

\[ n_{\text{bound}} \rightarrow p_{\text{bound}} + e^- + \bar{\nu}_e \]

1935: M. Goppert-Mayer describes “double β disintegration”

\[ 2n_{\text{bound}} \rightarrow 2p_{\text{bound}} + 2e^- + 2\bar{\nu}_e \]

1937: Majorana suggests that

\[ \nu_e \equiv \bar{\nu}_e \]
In the same year Giulio Racah pointed out that Majorana’s new theory would lead to a second form of $\beta\beta$ decay -- a neutrinoless type

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\[ 2n \rightarrow 2p + 2e^- \]
Lepton Number: Are the Neutrino and Antineutrino distinct?

For many years it was thought that this issue was decided:

despite the lack of an obvious distinguishing quantum number, \( \nu \downarrow \bar{\nu} \)

we do a “thought” experiment (implicitly assumes a massless neutrino)

\[ e^+ \rightarrow \nu_e \]

this defines the \( \nu_e \)
then allow it to interact in a target

this defines the $\nu_e$

finding an $e^-$ is produced
and then a second experiment

this defines the $\bar{\nu}_e$
allow it to interact in a target

this defines the $\bar{\nu}_e$

finding an $e^+$ is produced
- with these definitions of the $\nu_e$ and $\bar{\nu}_e$, they appear operationally distinct, producing different final states.

- introduce a lepton “charge” to distinguish the neutrino states and to define the allowed reactions, by the additive conservation law

$$\sum_{\text{in}} l_e = \sum_{\text{out}} l_e$$

\[
\begin{array}{c|c}
\text{lepton} & l_e \\
\hline
\text{e}^- & +1 \\
\text{e}^+ & -1 \\
\nu_e & +1 \\
\bar{\nu}_e & -1 \\
\end{array}
\]

- $\nu_e \perp \bar{\nu}_e \Rightarrow$ Dirac neutrino
- $\nu_e = \bar{\nu}_e \Rightarrow$ Majorana neutrino

Dirac neutrino
Odd N and Z nuclei: two broken pairs

Even N and Z nuclei: attractive pairing force

Nuclear physics is a “filter” to isolate $\beta\beta$ decay

Implications for $\beta\beta$ decay?
First-order 
$^{76}$Ge $\beta$ decay energetically forbidden
About 50 cases where nuclear physics isolates very rare, second-order weak interactions.
About 50 cases where nuclear physics isolates very rare, second-order weak interactions
$2\nu$ $\beta\beta$ decay occurs regardless of whether $\nu = \bar{\nu}, \; \nu \perp \bar{\nu}$

\[(N, Z) \rightarrow (N - 1, Z + 1) + e^- + \bar{\nu}_e\]
\[(N - 1, Z + 1) \rightarrow (N - 2, Z + 2) + e^- + \bar{\nu}_e \Rightarrow\]
\[(N, Z) \rightarrow (N - 2, Z + 2) + 2e^- + 2\bar{\nu}_e\]

lepton-number conserving

$0\nu$ $\beta\beta$ decay is effectively the experiment we just finished describing

\[(N, Z) \rightarrow (N - 1, Z + 1) + e^- + \bar{\nu}_e\]
\[\bar{\nu}_e + (N - 1, Z + 1) \not\rightarrow (N - 2, Z + 2) + e^- \Rightarrow\]
\[(N - 1, Z + 1) \not\rightarrow (N - 2, Z + 2) + 2e^-\]

lepton-number violating - and ruled our experimental “results”
spectrum of summed energy for the two outgoing electrons:

with good detector energy resolution, the 0ν and 2ν modes can be separated

The two ββ decay modes can be distinguished in experiments.
The Discovery of Parity Violation

This simple picture — that the absence of neutrinoless double beta decay implies the neutrino must be Dirac — changed in 1957.

Lee and Yang pointed out the likelihood that parity was violated, and that violation was quickly confirmed in experiments.

In particular, Goldhaber, Grodzins, and Sunyar showed that the neutrino had a definite handedness, to the accuracy this could be measured (*maximal* parity violation).

Reconsider our experiments with massless neutrinos.
If there is a conserved lepton number

forbidden by lepton number conservation
Remove the restriction of an additively conserved lepton number

\[ \text{allowed, with a rate proportional to } G_F^4 \]

conflicts with experimental upper bounds on rates
But if the $\nu$ and anti-$\nu$ have distinct handedness, nothing about lepton number can be concluded.

![Diagram showing electron decay and neutrino exchange](image)

Sadly, then, this process would tell us nothing about the $\nu$’s Dirac/Majorana character.
ββ Decay with Massive Neutrinos

If neutrinos have mass, helicity is not a particle label: it can be reversed by jumping to a moving frame.

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The Majorana neutrino mass plays two roles, removing helicity as a label and providing the source of the lepton number violation.

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Neutrino mass restores ββ decay as a definitive test of lepton number violation, though with a rate suppressed by $(m_\nu/E_\nu)^2$ where $E_\nu \sim 1/R_{\text{nuclear}}$. 

The Majorana neutrino mass plays two roles, removing helicity as a label and providing the source of the lepton number violation.
We have been discussing two limits for describing massive neutrinos.

- **Majorana:**
  - \( \nu_{LH} \) to \( \nu_{RH} \) via boost followed by CPT.
  - \( \nu_{RH} \) to \( \nu_{LH} \) via CPT and boost.

- **Dirac:**
  - \( \nu_{LH} \) to \( \nu_{RH} \) via boost and CPT.
  - \( \nu_{RH} \) to \( \nu_{LH} \) via CPT and boost.

Lorentz invariance is indicated by the arrows.
We expect both kinds of mass to exist: what is not forbidden is required

Dirac equation mass term \( \bar{\Psi} M_D \Psi \), project out the L/R and \( \nu/\bar{\nu} \) DoFs

\[
L_M = [ \bar{\Psi}_R M_D \Psi_L + \bar{\Psi}_L^c M_D^T \Psi_R^c + \bar{\Psi}_L M_D^\dagger \Psi_R + \bar{\Psi}_R^c M_D \Psi_L ] + h.c.
\]

\[
= ( \bar{\Psi}_L^c, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}_R^c ) \left( \begin{array}{cccc} 0 & 0 & M_D^T & 0 \\ 0 & 0 & M_D & 0 \\ M_D^\dagger & M_D & 0 & 0 \\ M_D^* & 0 & 0 & 0 \end{array} \right) \left( \begin{array}{c} \Psi_L^c \\ \Psi_R \\ \Psi_L \\ \Psi_R^c \end{array} \right)
\]
The Majorana mass terms complete this matrix

\[ L_M = \left[ \bar{\Psi}_R M_D \Psi_L + \bar{\Psi}_L^c M_D^T \Psi_R^c + \bar{\Psi}_L^c M_L \Psi_L + \bar{\Psi}_R^c M_R \Psi_R \right] + \text{h.c.} \]

\[ = \left( \bar{\Psi}_L^c, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}_R^c \right) \left( \begin{array}{cccc}
0 & 0 & M_L & M_D^T \\
0 & 0 & M_D & M_R^T \\
M_L^\dagger & M_D^\dagger & 0 & 0 \\
M_D^* & M_R^* & 0 & 0 \\
\end{array} \right) \left( \begin{array}{c}
\Psi_L^c \\
\Psi_R \\
\Psi_L \\
\Psi_R^c \\
\end{array} \right) \]
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\[ = \left( \bar{\Psi}_L^c, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}_R^c \right) \left( \begin{array}{cccc} 0 & 0 & M_L & M_D^T \\ 0 & 0 & M_D & M_R^\dagger \\ M_L^\dagger & M_D^\dagger & 0 & 0 \\ M_D^\dagger & M_R & 0 & 0 \end{array} \right) \left( \begin{array}{c} \Psi_L^c \\ \Psi_R \\ \Psi_L \\ \Psi_R^c \end{array} \right) \]

The SM:
1) has no RHed \( \nu \) fields \( \Rightarrow \) no Dirac masses
2) assumes conserved lepton no. \( \Rightarrow \) no Majorana masses

so massless SM neutrinos
The Majorana mass terms complete this matrix

\[ L_M = \left[ \bar{\Psi}_R M_D \Psi_L + \bar{\Psi}_L M_D^T \Psi_R^c + \bar{\Psi}_L^c M_L \Psi_L + \bar{\Psi}_R^c M_R \Psi_R \right] + h.c. \]

\[ = \left( \bar{\Psi}_L^c, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}_R^c \right) \left( \begin{array}{cccc}
0 & 0 & M_L & M_D^T \\
0 & 0 & M_D & M_R^T \\
M_L^T & M_D^T & 0 & 0 \\
M_D^* & M_R & 0 & 0 \\
\end{array} \right) \left( \begin{array}{c}
\Psi_L^c \\
\Psi_R \\
\Psi_L \\
\Psi_R^c \\
\end{array} \right) \]

But
1) might anticipate \( M_D \sim \) other SM Dirac masses
2) know \( M_L \ll M_D \) (no \( \beta \beta \) decay), reasonably \( M_R \gg M_D \)

so with these assumptions can diagonalize this matrix
The Majorana mass terms complete this matrix

\[ L_M = \left[ \bar{\Psi}_R M_D \Psi_L + \bar{\Psi}_L^c M_D^T \Psi_R^c + \bar{\Psi}_L^c M_L \Psi_L + \bar{\Psi}_R^c M_R \Psi_R \right] + h.c. \]

\[ = \left( \bar{\Psi}_L^c, \bar{\Psi}_R, \bar{\Psi}_L, \bar{\Psi}_R^c \right) \left( \begin{array}{cccc}
0 & 0 & M_L & M_D^T \\
0 & 0 & M_D & M_R^T \\
M_L^T & M_D^T & 0 & 0 \\
M_D^* & M_R & 0 & 0 \\
\end{array} \right) \left( \begin{array}{c}
\Psi_L^c \\
\Psi_R \\
\Psi_L \\
\Psi_R^c \\
\end{array} \right) \]

\[ m_{\nu}^{\text{light}} = M_D \left( \frac{M_D}{M_R} \right) \text{ seesaw} \]

SM fermion mass scale needed “small parameter” specific to vs
Murayama’s $\nu$ mass cartoon

standard model fermion masses

standard model $\nu$ and mass=0
2 Neutrinos meet the Higgs boson

Murayama’s $\nu$ mass cartoon

standard model fermion masses

standard model $\nu$ and mass=0

light Dirac neutrino mass
Murayama’s $v$ mass cartoon

- Standard model fermion masses
- Standard model $v$ and mass = 0
- Light Dirac neutrino mass
- Light LHed Majorana neutrino mass
Murayama’s $\nu$ mass cartoon

standard model fermion masses

light Dirac neutrino mass

light LHed Majorana neutrino mass

← the anomalous $\nu$ mass scale, connected with the seesaw?
Has led to a “standard scenario” that is used to discuss $\beta\beta$ decay and other experiments

Three very heavy
$\sim$ Majorana vs

$M_R \sim M_{GUT} \sim 10^{15}$ GeV

Three very light
$\sim$ Majorana vs

$\nu_e, \nu_\mu, \nu_\tau$
Has led to a “standard scenario” that is used to discuss $\beta\beta$ decay and other experiments, properties being probed in low energy experiments, cosmology.

With

$$M_R \sim M_{\text{GUT}} \sim 10^{15} \text{GeV}$$

Three very heavy $\sim$ Majorana vs

Three very light $\sim$ Majorana vs

$\nu_e, \nu_\mu, \nu_\tau$
We have learned a lot about the pattern of the light masses from the solar, atmospheric, reactor, and accelerator experiments - but two hierarchies remain.

Normal hierarchy

\[ m_{\nu} \]

\[ \delta m_{solar}^2 \]

\[ \delta m_{atmos}^2 \]

\[ m_{\nu}^1 \sim 0 \]

Inverted hierarchy

\[ m_{\nu} \]

\[ \delta m_{solar}^2 \]

\[ \delta m_{atmos}^2 \]

\[ m_{\nu}^1 \sim 0 \]
We have learned a lot about the pattern of the light masses from the solar, atmospheric, reactor, and accelerator experiments - but two hierarchies remain.

Add matter, measure oscillations over \( \delta m_{\text{atmos}} \) scale of \( \sim 1000 \text{ km} \).
LBNF: mass hierarchy (and CP violation)

1.2 MW beam, on axis, to a 10→40 kton LiAr detector at Sanford Lab

1300 km of matter: sign of matter effects ⇔ normal/inverted;

5 years of $\nu_\mu$, $\bar{\nu}_\mu$ running $\nu_\mu \rightarrow \nu_e$ vs $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (also CP)
Particle tracks created by a neutrino interaction in liquid argon in the Argon Neutrino Test project (ArgoNeuT). Deep underground placement of a neutrino detector will shield it from cosmic rays, which are abundant and would generate signals in the detector that serve only to complicate the data analysis. Most cosmic rays will get absorbed by the matter above the detector. The DUNE LArTPC is planned for installation at 4850 feet (1,475 m) below the surface.

Much enlarged ICARUS-like LiAr far detector

with a near-detector at FermiLab to help characterize the initial beam
Absolute Neutrino Masses?

Oscillations measure mass differences: $\delta m^2_{21} = \delta m^2_{\text{solar}}$, $\delta m^2_{31} = \delta m^2_{\text{atmos}}$

The absolute scale is not fixed

how do we measure absolute masses?
From tritium $\beta$ decay:

![Graph showing relative decay amplitude vs. electron energy.]

**Mainz/Troitsky limit:**

$$\langle m_\nu \rangle_{\text{tritium}} = \sum_i |U_{ei}|^2 m_\nu^2(i) \lesssim 2.2 \text{ eV}$$

Major new effort on tritium $\beta$ decay is underway, but lab experiments are running into intrinsic limits due to feasible source intensities and detector resolution.
KATRIN at Karlsruhe

Leopoldshafen, 25.11.06

goal: $\langle m_v \rangle_{\text{tritium}} \lesssim 250 \text{ meV}$
Alternatively, cosmology:

Neutrinos start off relativistic in the early universe, where they suppress the growth of structure on large scales.

Transition to nonrelativistic

Effects scale and redshift dependent

Current limits

\[
\frac{1}{3} \sum_i m_i \lesssim 80 \text{ meV}
\]
Mass scenarios critical to next-generate $\beta\beta$ decay efforts

![Graph showing mass scenarios](image-url)
Mass scenarios critical to next-generate $\beta\beta$ decay efforts

- Degenerate
- Inverse
- Normal

$\beta\beta$ decay at the inverted hierarchy level

Minimum neutrino mass $m_{\nu_{\text{min}}}$ (eV) vs. effective mass $\langle m_{\beta\beta} \rangle$ (eV)
Current-generation timelines for project construction and running

From NSAC Subcommittee on 0ν ββ decay
GERDA I, Gran Sasso; Majorana, SL

GERDA I \(^{76}\text{Ge},\) 21.6 kg-y

\[ \tau_{1/2} > 2.1 \times 10^{25} \text{y} \quad 90\% \text{ c.l.} \]

EXO-200, WIPP

\(^{136}\text{Xe}, 99.8\ \text{kg-y}\)

\[ \tau_{1/2} > 1.1 \times 10^{25} \text{y} \quad 90\% \text{ c.l.} \]

KamLAND-Zen, Kamioka

\(^{136}\text{Xe}, 89.5\ \text{kg-y}\)

\[ \tau_{1/2} > 1.9 \times 10^{25} \text{y} \quad 90\% \text{ c.l.} \]
CUORE-0/Cuoricino, Gran Sasso

$^{130}\text{Te}, \ 29.6\text{kg-y}$

$\tau_{1/2} > 4.0 \times 10^{24}\text{y} \ 90\% \ c.l.$

NEXT, Canfranc Laboratory

Gaseous $^{136}\text{Xe}$ TPC, final state i.d.

SNO+, SNOLab

$^{130}\text{Te}$-loaded scintillator, to begin in 2016
The benchmarks

1. where we are now

GERDA + other Ge: $\tau_{1/2} > 3.0 \times 10^{25} \text{y} \; 90\% \; \text{c.l.} \quad \langle m_{\beta\beta} \rangle < 460 \; \text{meV}$
The benchmarks

2. where the demonstrator experiments will take us

5-year ‘demonstrator’ experiments: $\sim 1.6 \times 10^{26}$ y to reach 200 meV
Majorana and GERDA joint effort (using the best ‘demonstrator’ technology) a 1-ton enriched $^{76}$Ge detector

desirable attributes: excellent resolution, nearly free of backgrounds, feasible costs, final-state tagging, scalability ...
The benchmarks

3. probe the inverted hierarchy mass band of 19-49 meV

ton+ experiments reaching $10^{28}$ y after a decade of running
Back to the Beginning: Neutrinos as a Probe of Astrophysics

Ray Davis’s initial goal was to use neutrinos to determine the temperature and nuclear physics of the solar core.

The SSM tested in these early experiments assumes the Sun was homogeneous when it first formed: gas cloud collapse.

The initial conditions include the Sun’s metallicity, determined in part from analyses of photo-absorption lines in the solar atmosphere.
- Early analyses modeled the photosphere in 1D, without explicit treatments of stratification, velocities, inhomogeneities.

- New 3D, parameter-free methods were recently introduced, significantly improving consistency of line analyses: MPI-Munich.

**Dynamic and 3D due to convection**
• Spread in abundances from different C, O lines sources reduced from \( \sim 40\% \) to \( 10\% \)

• But abundances significantly reduced \( Z: \ 0.0169 \Rightarrow 0.0122 \)

• Makes sun more consistent with similar stars in local neighborhood

• Lowers SSM \(^8\)B flux by 20\%
But adverse consequences for helioseismology
Table 1  Standard solar model characteristics are compared to helioseismic values, as determined by Basu & Antia (1997, 2004)

<table>
<thead>
<tr>
<th>Property</th>
<th>GS98-SFII</th>
<th>AGSS09-SFII</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>((Z/X)_{S})</td>
<td>0.0229</td>
<td>0.0178</td>
<td>–</td>
</tr>
<tr>
<td>(Z_{S})</td>
<td>0.0170</td>
<td>0.0134</td>
<td>–</td>
</tr>
<tr>
<td>(Y_{S})</td>
<td>0.2429</td>
<td>0.2319</td>
<td>0.2485 ± 0.0035</td>
</tr>
<tr>
<td>(R_{CZ}/R_\odot)</td>
<td>0.7124</td>
<td>0.7231</td>
<td>0.713 ± 0.001</td>
</tr>
<tr>
<td>(\langle\delta c/c\rangle)</td>
<td>0.0009</td>
<td>0.0037</td>
<td>0.0</td>
</tr>
<tr>
<td>(Z_{C})</td>
<td>0.0200</td>
<td>0.0159</td>
<td>–</td>
</tr>
<tr>
<td>(Y_{C})</td>
<td>0.6333</td>
<td>0.6222</td>
<td>–</td>
</tr>
<tr>
<td>(Z_{ini})</td>
<td>0.0187</td>
<td>0.0149</td>
<td>–</td>
</tr>
<tr>
<td>(Y_{ini})</td>
<td>0.2724</td>
<td>0.2620</td>
<td>–</td>
</tr>
</tbody>
</table>

\(X\), \(Y\), and \(Z\) are the mass fractions in H, He, and metals, respectively. The subscripts \(S\), \(C\), and \(ini\) denote current photospheric, current core, and zero-age values, respectively.

\(R_{CZ}\) is the radius to the convective zone, and \(\langle\delta c/c\rangle\) is the average fractional discrepancy in the sound speed, relative to helioseismic values.

Properties of two SSMs we use in this review are listed in Table 1. The models differ in the values assumed for the photospheric metallicity \((Z/X)_{S}\), with the GS98-SFII SSM being more metal rich than the AGSS09-SFII SSM. The table gives the model photospheric helium \(Y_{S}\) and metal \(Z_{S}\) abundances, the radius of the convective zone \(R_{CZ}/R_\odot\), the and deviation of the sound speed \(\langle\delta c/c\rangle\) from the helioseismic profile, the core helium and heavy element abundances \(Y_{C}\) and \(Z_{C}\), and the Sun's presolar abundances \(Y_{ini}\) and \(Z_{ini}\).
Solar abundance problem: A disagreement between SSMs that are optimized to agree with interior properties deduced from our best analyses of helioseismology (high $Z$), and those optimized to agree with surface properties deduced from the most complete 3D analyses of photoabsorption lines (low $Z$).

Difference is a deficit of $\sim 40 \ M_{\oplus}$ of metal, integrating over the Sun’s convective zone (which contains about 2.6% of the Sun’s mass).

One set of measurements might be wrong…. or…
Did the Sun form from a homogeneous gas cloud?

Galileo data, from Guillot AREPS 2005

Standard interpretation: late-stage planetary formation in a chemically evolved disk over ~ 1 m.y. time scale
Contemporary picture of metal segregation, accretion

~ 5% of nebular gas

Dullemond and Monnier, ARA&A 2010
This has led to the suggestion that planetary formation scrubbed metals from the last 5% of nebular gas.

The depleted gas, deposited on the solar surface, would be sufficient to dilute the Sun’s thin convective envelope, while leaving the interior unaltered.

\[ \Rightarrow \text{a metal-poor surface, a metal-rich interior} \]

Numerically the mass of metals extracted from the protoplanetary disk (40-90 M_⊕) is sufficient to account for the needed dilution.

Can we use neutrinos to directly measure core metallicity?

The Sun generates 1% of its energy through the CNO cycle: catalysts for CN cycle are the primordial C, N of the solar core.
Can we use neutrinos to directly measure core metallicity?

The Sun generates 1% of its energy through the CNO cycle: catalysts for CN cycle are the primordial C, N of the solar core
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The Sun generates 1% of its energy through the CNO cycle: catalysts for CN cycle are the primordial C, N of the solar core
solar core

CN burning in equilibrium
@ $T_7 \sim 1.5$

$\nu(^{13}\text{N})+\nu(^{15}\text{O})$

primordial C burned:
$^{14}\text{N}(p, \gamma)$ bottleneck

present day burning of primordial C
$\nu(^{13}\text{N}) - \nu(^{15}\text{O})$
measurable neutrino fluxes

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

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

depending on both C+N and C (the principal solar metals)

these fluxes depend on the core temperature T (metal-dependent) but also have an additional linear dependence on core metallicity
dependence of the CN neutrino flux on the abundance of C+N can be exploited to relate solar neutrino measurements to the Sun's primordial C and N abundances (Serenelli, Haxton & Pena-Garay 2012).

\[
\frac{\phi(^{15}\text{O})}{\phi(^{15}\text{O})_{\text{SSM}}} = \left[ \frac{\phi(8\text{B})}{\phi(8\text{B})_{\text{SSM}}} \right]^{0.729} x_{C+N} \\
\times [1 \pm 0.006(\text{solar}) \pm 0.027(\text{D}) \pm 0.099(\text{nucl}) \pm 0.032(\theta_{12})]
\]
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\]

a thermometer for the solar core: measured to 2% by SuperKamiokande
what we want to know: the primordial core abundance of C + N (in units of SSM best value)

\[
\frac{\phi(^{15}\text{O})}{\phi(^{15}\text{O})_{\text{SSM}}} = \left[ \frac{\phi(\text{8B})}{\phi(\text{8B})_{\text{SSM}}} \right]^{0.729} x_{C+N}
\]

\[
\times \left[ 1 \pm 0.006(\text{solar}) \pm 0.027(\text{D}) \pm 0.099(\text{nucl}) \pm 0.032(\theta_{12}) \right]
\]
The dependence of the CN neutrino flux on the abundance of C+N can be exploited to relate solar neutrino measurements to the Sun's primordial C and N abundances (Serenelli, Haxton & Pena-Garay 2012):

\[
\frac{\phi(^{15}\text{O})}{\phi(^{15}\text{O})_{\text{SSM}}} = \left[ \frac{\phi(^{8}\text{B})}{\phi(^{8}\text{B})_{\text{SSM}}} \right]^{0.729} x_{C+N} \times [1 \pm 0.006(\text{solar}) \pm 0.027(D) \pm 0.099(\text{nucl}) \pm 0.032(\theta_{12})]
\]

the entire solar model dependence: luminosity, metalicity, solar age, etc., eliminated -- except for small residual differential effects of heavy element diffusion (necessary to relate today's neutrino measurements to core abundance 4.7 b.y. ago)
dependence of the CN neutrino flux on the abundance of C+N can be exploited to relate solar neutrino measurements to the Sun's primordial C and N abundances (Serenelli, Haxton & Pena-Garay 2012).

\[ \frac{\phi(^{15}\text{O})}{\phi(^{15}\text{O})^\text{SSM}} = \left[ \frac{\phi(^{8}\text{B})}{\phi(^{8}\text{B})^\text{SSM}} \right]^{0.729} x_{C+N} \times [1 \pm 0.006(\text{solar}) \pm 0.027(\text{D}) \pm 0.099(\text{nucl}) \pm 0.032(\theta_{12})] \]

some work needed here: \( ^{7}\text{Be}(p, \gamma), \quad ^{14}\text{N}(p, \gamma) \)
The dependence of the CN neutrino flux on the abundance of C+N can be exploited to relate solar neutrino measurements to the Sun's primordial C and N abundances (Serenelli, Haxton & Pena-Garay 2012). The expression is:

\[
\frac{\phi(15\text{O})}{\phi(15\text{O})_{\text{SSM}}} = \left[ \frac{\phi(8\text{B})}{\phi(8\text{B})_{\text{SSM}}} \right]^{0.729} x_{\text{C+N}} \\
\times [1 \pm 0.006(\text{solar}) \pm 0.027(\text{D}) \pm 0.099(\text{nucl}) \pm 0.032(\theta_{12})]
\]

SNO's marvelous measurement of the weak mixing angle
dependence of the CN neutrino flux on the abundance of C+N can be exploited to relate solar neutrino measurements to the Sun's primordial C and N abundances (Serenelli, Haxton & Pena-Garay 2012)

\[
\frac{\phi(15\,\text{O})}{\phi(15\,\text{O})_{\text{SSM}}} = \left[ \frac{\phi(8\,\text{B})}{\phi(8\,\text{B})_{\text{SSM}}} \right]^{0.729} x_{\text{C+N}}
\]

\[
\times [1 \pm 0.006(\text{solar}) \pm 0.027(\text{D}) \pm 0.099(\text{nucl}) \pm 0.032(\theta_{12})]
\]

a future neutrino measurement: Borexino, SNO+, Jinping....?
Both SNO+ and Borexino have considered such a measurement. Depth crucial: SNO+/Borexino $^{11}$C ratio is 1/70.
SNO+ simulation

(from Mark Chen)
this measurement is fundamental

- probes the most pristine primordial gas from which our solar system formed, at an interesting level of precision (10%)

- the first opportunity in astrophysics to directly compare surface and deep interior (primordial) compositions

- a first step in developing a “standard solar system model” that would link solar v physics, solar system formation, planetary astrochemistry
summary

1960s

test the solar model: precise determination of core temperature
summary

1990s

new neutrino physics: precise weak interaction parameters

solar and atmospheric neutrinos
summary

2000s

lab verification:
KamLAND
Daya Bay, RENO
T2K, NOVA,
...


2020: challenges

- Long baseline experiments to determine hierarchy, CP phase
- Double beta decay to test neutrino Dirac/Majorana character
- Precise cosmological tests to determine absolute mass
Using neutrinos as a precise probe of our Sun, other astrophysics in the 2020s.
The spectrum, showing its approximate flavor content, is solar, atmospheric, accelerator, reactor experiments.