Supernova Neutrinos: Challenges and Prospects
Sanjay Reddy, Institute for Nuclear Theory, Seattle

- Introduction to supernova - a nuclear physics perspective
- Supernova neutrinos - why they are so relevant
- Neutrino interactions - how neutrino’s see dense matter
- The neutrino sphere - correlated matter at low density
- Charged current reactions
- Neutron star tomography
- Outlook.
Inevitability of Collapse of Massive Stars

- Successive stages of nuclear burning produces an inert core.
- The inner core is supported by electron-degeneracy pressure.
- It becomes unstable to gravitational collapse at the Chandrashekar mass.
Core Collapse Supernova

Core collapse \( t_{\text{collapse}} \sim 100 \text{ ms} \)

Shock wave \( E_{\text{shock}} \sim 10^{51} \text{ ergs} \)

1500 km

neutrinos diffuse out of the dense newly born neutron star to carry away almost all of the \( \sim 3 \times 10^{53} \text{ ergs} \)
Supernova Neutrinos

Past:
SN 1987a: ~ 20 neutrinos in support of supernova theory

Future:
Can detect ~10,000 neutrinos from galactic supernova

\[ 3 \times 10^{53} \text{ ergs} = 10^{58} \times 20 \text{ MeV Neutrinos} \]

\[ \overline{\nu}_e + p \rightarrow n + e^+ \text{ or } \nu + e^- \rightarrow \nu + e^- \]

\[ \frac{dN_{\text{detect}}}{dt} \sim \frac{\sigma_{\text{ref}} \times n_p \times M_{\text{tons}}}{4\pi D^2} \frac{E_{\nu}^2}{m_e^2} \frac{dN_{\text{emit}}}{dt} \]

Pons et al. (2002)
A Neutron Star is Born

- **Core**:
  - Temperature: $T \approx 10-20$ MeV
  - Number density: $n \approx 1-2 \times n_0$
  - Electron fraction: $Y_e \approx 0.3$

- **Hot Mantle**:
  - Temperature: $T \approx 5-40$ MeV
  - Number density: $n \approx 10^{-3}-10^{-1} \times n_0$
  - Electron fraction: $Y_e \approx 0.1-0.2$

- **Neutrino Sphere**:

- **Shock Wave**

Radius:
- $R = 10$ km
- $R = 100$ km
- $R = 150$ km
Protoneutron Star Evolution

- Gravitational binding energy is stored as internal energy: Thermal and neutrino degeneracy energy.

- Typical timescale for energy and lepton number loss in the core is 30-50 s.
• Neutrino diffusion drives the evolution.
• Star contracts and heats up during deleptonization.
• Interior cooling begins at $t \sim 15$ s.
• Cooling of the outer regions occurs at early times.

Neutrino diffusion and possibly convection sets the time scale.
Supernova Neutrino Emission

Neutrino interactions here determine the energy spectrum
Neutrino interactions here determine the time scale

\[ \langle \epsilon \rangle \approx \langle \epsilon \rangle_{\nu_e} \]

This is in contrast to the difference between the electron neutrino and antineutrino luminosities. In fact, the antineutrino flux is positive everywhere.

After the PNS has contracted to close to the cold neutron star radius, the neutrino flux is positive everywhere. This is the Joule heating discussed above. In contrast, the large negative equilibrium chemical potential gradient (and positive equilibrium chemical potential gradient for the anti-electron neutrinos) into the lower entropy core. This is the Joule heating discussed above. In contrast, the large negative equilibrium chemical potential gradient for the electron neutrinos overwhelms the positive radial temperature gradient and the electron neutrino luminosity has increased relative to the electron neutrino luminosity.

During the mantle contraction phase, there is the inward directed anti-electron, energy out to a significantly larger radius via scattering. The anti-electron neutrinos, and the dot-dashed lines are for electron neutrinos, the dashed lines are for electron antineutrinos, and the solid lines are for muon neutrinos. These neutrinos decouple further inside the core. This is the Joule heating discussed above. In contrast, the large negative equilibrium chemical potential gradient for the anti-electron neutrinos) into the lower entropy core. This is the Joule heating discussed above. In contrast, the large negative equilibrium chemical potential gradient for the electron neutrinos overwhelms the positive radial temperature gradient and the electron neutrino luminosity has increased relative to the electron neutrino luminosity.

Neutrino number and energy luminosities at infinity are shown in figure 4. Within the inner regions, the neutrino species. These neutrinos decouple further inside the core. This is the Joule heating discussed above. In contrast, the large negative equilibrium chemical potential gradient for the anti-electron neutrinos) into the lower entropy core. This is the Joule heating discussed above. In contrast, the large negative equilibrium chemical potential gradient for the electron neutrinos overwhelms the positive radial temperature gradient and the electron neutrino luminosity has increased relative to the electron neutrino luminosity.

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The emitted neutrino spectra at two representative times are shown in figure 5 for reference. The top panel is at 100 ms after the start of the simulation. The bottom panel is the spectrum at 5 seconds into the simulation so that they have a larger scale. In fact, the anti-electron neutrinos become transparent to neutrinos and the luminosity drops significantly.

Between thirty and forty seconds the PNS begins to cool and the temperature, resulting in a larger number and energy luminosity. In fact, the anti-electron neutrinos become transparent to neutrinos and the luminosity drops significantly.

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Neutrino Interactions

Neutrinos couple to matter through neutral and charged current reactions

\[ \mathcal{L}_{\text{int}}^{cc} = \frac{G_F}{\sqrt{2}} \, l_\mu j^{\mu}_W \quad \text{for} \quad \nu_l + B_2 \rightarrow l + B_4 \]

\[ \mathcal{L}_{\text{int}}^{nc} = \frac{G_F}{\sqrt{2}} \, l_\nu j^{\mu}_Z \quad \text{for} \quad \nu_l + B_2 \rightarrow \nu_l + B_4 \]

\[ \frac{\partial f(E_1)}{\partial t} = \int \frac{d^3k_3}{(2\pi)^3} \, R(E_1, E_3, \cos \theta) \, f_3(1 - f_1) \rightarrow \text{scattering-in} \]

\[ -R(E_3, E_1, \cos \theta) \, f_1(1 - f_3) \rightarrow \text{scattering-out} \]

\[ +R(E_1, -E_3, \cos \theta) \, (1 - f_1)(1 - f_3) \rightarrow \text{pair-production} \]

\[ -R(-E_1, E_3, \cos \theta) \, f_1 \, f_3 \rightarrow \text{pair-annihilation} \]
Correlations & Neutrino Scattering

- Neutrinos “see” more than one particle in the medium.
- Nature of spatial and temporal correlations between nuclei, nucleons and electrons affect the scattering rate.

\[
q_0 = E_1 - E_3
\]
\[
q = k_1 - k_3
\]

At small \( q_0 \) and \( q \) the neutrino cannot resolve single particles.

Sawyer (1975, 1989)
Iwamoto & Pethick (1982)
Horowitz & Wherberger (1991)
Raffelt & Seckel (1995)
Neutrinos Scatter From Fluctuations of Density & Spin

Differential Scattering/Absorption Rate:

\[
\frac{d\Gamma(E_1)}{d \cos \theta \ dq_0} = \frac{G_F^2}{4\pi^2} (E_1 - q_0)^2 \left[ (1 + \cos \theta) S_V^{\text{RPA}}(q_0, q) + (3 - \cos \theta) S_A^{\text{RPA}}(q_0, q) \right]
\]

- spectrum of density fluctuations
- spectrum of spin fluctuations
The Camera Analogy

The neutrino takes pictures of the plasma

\[ q_0 = E_1 - E_3 \quad \text{shutter speed} \]

\[ q = k_1 - k_3 \quad 1/\text{aperture} \]
Ground State & Fluctuations

Low temperature and density:

- Uniform matter
- Nuclear attraction
- One large neutron-rich nucleus + electrons
- Coulomb repulsion
- Several small neutron-rich nuclei + electrons

High temperature and density:

- Entropy or Pauli exclusion
- Nuclear repulsion
- One large neutron-rich nucleus + electrons

n > p=e
Nuclear pasta

At intermediate temperature and density complex structured phases are likely: \( \rho = 10^{13} - 10^{14} \text{ g/cm}^3 \) and \( T = 1 - 3 \text{ MeV} \).

Figures from: Schneider, Horowitz, Hughto & Berry (2013)
Composition and fluctuations in the neutrino sphere:

\[ \rho = 10^{11} - 10^{13} \text{ g/cm}^3 \text{ and } T=3-8 \text{ MeV} \]

How does the competition between density, entropy and nuclear binding energy resolve under these conditions?

This is the reason we are here at the ECT workshop.

What is the free energy difference between these configurations?

\[ F = E - TS \]
Experimental Tests
Can we reliably predict and measure the reduced effective nuclear binding?

\[ K_c(\alpha) = \frac{n_\alpha}{n_n^2 n_p^2} \]

Typel, Ropke et al. (2010)

Nuclear Symmetry Energy

The energy difference between neutrons and protons in neutron-rich matter is related to symmetry energy $S(\rho)$.

$$E(\rho_n, \rho_p) = E(\rho) + S(\rho) \left( \frac{\rho_n - \rho_p}{\rho} \right)^2 + \cdots$$

$$S(\rho) = a^V + \frac{L}{3} (u - 1) \quad u = \frac{\rho}{\rho_o}$$

Correlations play a key role in increasing $S(\rho)$ at densities and temperatures relevant to the neutrino sphere.
Is the binding relevant for supernova neutrinos?

For charged current reactions difference between neutron and proton binding is relevant.

Final state electron blocking is strong for the reaction:

\[ q_0 \approx \Delta U = U_n - U_p \]

Large \( q_0 \) crucial to overcome blocking

In neutron rich matter protons are deeply bound. Extent of binding depends on correlations and clusters.
Charged Current Reactions at Low Density

\[ \frac{d\Gamma}{\cos \theta dE_e} = \frac{G_F^2}{2\pi} p_e E_e (1 - f_e(E_e)) \times \left[ (1 + \cos \theta) S_T(q_0, q) + g_A^2 (3 - \cos \theta) S_{\sigma_T}(q_0, q) \right] \]

- Energy shift helps overcome electron final state blocking.
- Enhances $\nu_e$ absorption
- Larger energy needed to produce neutrons suppresses anti-$\nu_e$ absorption.

Roberts, Reddy & Shen (2012)
Neutrino Spectra are Sensitive to Symmetry Energy

Time evolution of electron neutrino spectrum could be a useful diagnostic

Robert, Reddy & Shen (2012)
Implications of modifying $\delta \epsilon = \langle \epsilon_{\bar{\nu}_e} \rangle - \langle \epsilon_{\nu_e} \rangle$

- Large $\delta \epsilon$ favors production of neutron-rich nuclei in supernova.
- Large $\delta \epsilon$ drives collective neutrino flavor oscillations closer to the neutron star.
- Large $\delta \epsilon$ should be detectable and its time evolution can constrain the low density symmetry energy.
Convection and equation of state

- Convection is driven by composition gradients.
- Buoyancy of matter depends on composition through the density dependence of the symmetry energy.
- Low L drives convection and large values suppress it.

Roberts, Cirigliano, Pons, Reddy, Shen, Woosley (2012)
Observable signatures of convective transport

• Neutrino flux is enhanced during convection.

• There is break in the light curve (when convection ends).

• Fraction of events between 3–10 s provides good discrimination.

Count rate in Super-Kamiokande for galactic supernova at 10 kpc.

Roberts, Cirigliano, Pons, Reddy, Shen, Woosley (2012)
Final rapid plunge of neutrino luminosity could reveal the most exciting information about neutron star interiors.
Hypothetical weakly interacting particles

Since neutrinos are trapped for ~20 s other light particles with weaker coupling to matter can change the cooling timescale.

$E_{\text{other}} > 10^{19}$ ergs/g/s -shortens the neutrino signal by a factor of 2

Axions

KK Gravitons

$R_2 = 0.44 \, \mu m$

$R_2 = 1.4 \, \mu m$

Raffelt (1996)

Pons et al (2001)
Outlook

• Neutrino interactions at supra and sub nuclear densities shape supernova neutrino emission.
• Neutrino cross-sections at sub-nuclear density are likely to be affected by correlations and clustering.
• Charged current rates are key to understanding spectral differences between different neutrino types. Sensitive to nuclear symmetry energy at low density.
• Models of warm low density matter remain poorly constrained by experiment.
• Detailed modeling supernova neutrino emission can unravel deep mysteries. Good chance your grandchildren will be proud.