Neutrinos and Nucleosynthesis

A.B. Balantekin
Big Bang

He, H, Li, D

Supernova of Pop III stars and formation of Pop II stars

C, N, O, Mg, Si, Ca, Fe, Sr, Ti, ...

Pop II stars going supernova

U, Eu, Th, ... (via r-process)

AGB stars

Ba, La, Y, ... (via s-process)

Neutrinos play a crucial role in many nucleosynthesis scenarios.
Neutrinos not only play a crucial role in the dynamics of these sites, but they also control the value of the electron fraction, the parameter determining the yields of the r-process.
A > 100 abundance pattern fits the solar abundances well.

Observations

Model calculations for neutron-star mergers

Coalescence timescale = 1 Myr

Average merger rate = 20/Myr

Average merger rate = 2/Myr

Star formation rate?

Yield of neutron star mergers

SDSS Data from Aoki et al., arXiv: 1210.1946 [astro-ph.SR]
Development of 2D and 3D models for core-collapse supernovae: Complex interplay between turbulence, neutrino physics and thermonuclear reactions.
Neutrinos from core-collapse supernovae

- $M_{\text{prog}} \geq 8 M_{\odot} \Rightarrow \Delta E \approx 10^{53} \text{ ergs} \approx 10^{59} \text{ MeV}$
- 99% of the energy is carried away by neutrinos and antineutrinos with $10 \leq E_{\nu} \leq 30 \text{ MeV} \Rightarrow 10^{58}$ neutrinos
Neutrinos dominate the energetics of core-collapse SN

Total optical and kinetic energy = \(10^{51}\) ergs

Total energy carried by neutrinos = \(10^{53}\) ergs

Explosion only 1% of total energy

10% of star’s rest mass

\[
E_{\text{grav}} \approx \frac{3}{5} \frac{GM_{ns}^2}{R_{ns}} \approx 3 \times 10^{53} \text{ ergs} \left(\frac{M_{ns}}{1.4M_{\odot}}\right)^2 \left(\frac{10 \text{ km}}{R_{ns}}\right)
\]

Neutrino diffusion time, \(\tau_\nu\) \(\sim 2-10\) s

\[
L_\nu \approx \frac{GM_{ns}^2}{6R_{ns}^2} \frac{1}{\tau_\nu} \approx 4 \times 10^{51} \text{ ergs / s}
\]
For example understanding a core-collapse supernova requires answers to a variety of questions some of which need to be answered by nuclear physics, both theoretically and experimentally.

Balantekin and Fuller, Prog. Part. Nucl. Phys. 71 162 (2013)
This reaction is background to the dark matter searches with nuclear targets.
Nuclear form factors need to be included. McLaughlin, Engel.

\[
\frac{d\sigma}{d \cos \theta} = \frac{G_F^2}{8\pi} \left\{ Z^2 \left( 4 \sin^2 \theta_W - 1 \right) + N \right\}^2 E_\nu^2 (1 + \cos \theta)
\]

\[
T_{\text{av. recoil}} = \frac{2}{3A} \left( \frac{E_\nu}{\text{MeV}} \right) \text{keV}
\]

Understanding neutrino cross sections better is crucial to astrophysics!

See talks by Suzuki and Suhonen.
\( \lambda_p \): proton weak loss rate (rate for \( \bar{\nu}_e + p \rightarrow e^+ + n \) and \( e^- + p \rightarrow \nu_e + n \) reactions)

\( \lambda_n \): neutron weak loss rate (rate for \( \nu_e + n \rightarrow e^- + p \) and \( e^+ + n \rightarrow \bar{\nu}_e + p \) reactions)

\[
\frac{dN_p}{dt} = -\lambda_p N_p + \lambda_n N_n \quad \frac{dN_n}{dt} = +\lambda_p N_p - \lambda_n N_n
\]

Electron fraction: \( Y_e = \frac{\text{Net number of electrons}}{\text{Number of baryons}} \)

Neutral medium, only protons and neutrons: \( Y_e = \frac{N_p}{N_p + N_n} \)

\[
\frac{d}{dt} Y_e = \lambda_n - (\lambda_p + \lambda_n) Y_e \quad \text{At equilibrium} \quad \frac{d}{dt} Y_e = 0 \Rightarrow Y_e^{(\text{equilibrium})} = \frac{\lambda_n}{\lambda_n + \lambda_p}
\]
The potential is provided by the coherent forward scattering of $\nu_e$'s off the electrons in dense matter.

\[ E^2 = p^2 + m^2 \]

In matter:
\[ (E - V)^2 = (p - A)^2 + m^2 \Rightarrow E^2 = p^2 + m_{\text{eff}}^2 \]

$V \propto$ background density

$A \propto J_{\text{background}}$ (currents) or $A \propto S_{\text{background}}$ (spin)

In the limit of static, charge-neutral, and unpolarized background

$V \propto N_e$ and $A = 0$

\[ m_{\text{eff}}^2 = m^2 + 2EV + O(V^2) \]

There is a similar term with Z-exchange. But since it is the same for all neutrino flavors, it does not contribute to phase differences unless we invoke a sterile neutrino.
Recall the MSW effect

In vacuum: \( E^2 = p^2 + m^2 \)

In a potential: \((E - \Phi)^2 = p^2 + m^2 \Rightarrow E^2 = p^2 + m_{\text{eff}}^2, \ m_{\text{eff}}^2 \approx m^2 + 2E\Phi\)

The potential is provided by the coherent forward scattering of \( \nu_e \)'s off the electrons in dense matter.

There is a similar term with Z-exchange. But since it is the same for all neutrino flavors, it does not contribute at tree level to phase differences unless we invoke a sterile neutrino.

If the neutrino density itself is also very high then one has to consider the effects of neutrinos scattering off other neutrinos. This is the case for a core-collapse supernova.

Fuller, Qian, Raffelt, Smirnov, Duan, Balantekin, Pehlivan, Friedland, ...
The second term makes the physics of a neutrino gas in a core-collapse supernova a very interesting many-body problem, driven by weak interactions.

Neutrino-neutrino interactions lead to novel collective and emergent effects, such as conserved quantities and interesting features in the neutrino energy spectra (spectral “swaps” or “splits”).

Energy released in a core-collapse SN: \( \Delta E \approx 10^{53} \) ergs \( \approx 10^{59} \) MeV

99% of this energy is carried away by neutrinos and antineutrinos!

\( \sim 10^{58} \) Neutrinos!

This necessitates including the effects of \( \nu\nu \) interactions!

\[
H = \sum a^\dagger a + \sum (1 - \cos \theta) a^\dagger a^\dagger a a
\]

- \( \sum a^\dagger a \) describes neutrino oscillations
- \( \sum (1 - \cos \theta) a^\dagger a^\dagger a a \) describes neutrino-neutrino interactions

The second term makes the physics of a neutrino gas in a core-collapse supernova a very interesting many-body problem, driven by weak interactions.
See the talk by Pehlivan
Many neutrino system

This is the only many-body system driven by the weak interactions:

Table: Many-body systems

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>Strong</th>
<th>at most $\sim 250$ particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensed matter</td>
<td>E&amp;M</td>
<td>at most $N_A$ particles</td>
</tr>
<tr>
<td>$\nu$'s in SN</td>
<td>Weak</td>
<td>$\sim 10^{58}$ particles</td>
</tr>
</tbody>
</table>

Astrophysical extremes allow us to test physics that cannot be tested elsewhere!
Evolution of neutrino fluxes ($1/r^2$-dependence removed)

Balantekin and Yuksel, 2005

$\nu_e$, $\nu_e$, $\nu_x$, $\nu_x$

$L^{51}$: luminosity in units of $10^{51}$ ergs s$^{-1}$
Equilibrium electron fraction with the inclusion of $\nu\nu$ interactions

$L^{51} = 0.001, 0.1, 50$

$X_\alpha = 0, 0.3, 0.5$ (thin, medium, thick lines)

Balantekin and Yuksel, 2005

$\theta_{13} \sim \pi/10$

$\theta_{13} \sim \pi/20$

$\theta_{13} \sim \pi/20$ with $\alpha$ effect
$\lambda_p$: proton weak loss rate (rate for $\bar{\nu}_e + p \rightarrow e^+ + n$ and $e^- + p \rightarrow \nu_e + n$ reactions)

$\lambda_n$: neutron weak loss rate (rate for $\nu_e + n \rightarrow e^- + p$ and $e^+ + n \rightarrow \bar{\nu}_e + p$ reactions)

$$\frac{dN_p}{dt} = -\lambda_p N_p + \lambda_n N_n$$

Electron fraction: $Y_e \equiv \frac{\text{Net number of electrons}}{\text{Number of baryons}}$

Neutral medium, only protons and neutrons: $Y_e = \frac{N_p}{N_p + N_n}$

Neutral medium, with protons, neutrons and alphas: $Y_e = \frac{N_p + 2N_\alpha}{N_p + N_n + 4N_\alpha}$

Mass fraction of alphas: $X_\alpha = \frac{4N_\alpha}{N_p + N_n + 4N_\alpha}$

$$\frac{d}{dt} \left[ Y_e - \frac{1}{2} X_\alpha \right] = \lambda_n - \left( \lambda_p + \lambda_n \right) Y_e + \frac{1}{2} \left( \lambda_p - \lambda_n \right) X_\alpha$$

Vanishes if weak interactions of alphas are ignored
\[
\frac{dY_e}{dt} = 0
\]

If alpha particles are present:

\[
Y_e = \frac{\lambda_n}{\lambda_p + \lambda_n} + \frac{1}{2} \frac{\lambda_p - \lambda_n}{\lambda_p + \lambda_n} X_\alpha
\]

If alpha particles are absent:

\[
Y_e^{(0)} = \frac{1}{1 + \frac{\lambda_p}{\lambda_n}}
\]

If \( Y_e^{(0)} < 1/2 \), non-zero \( X_\alpha \) increases \( Y_e \). If \( Y_e^{(0)} > 1/2 \), non-zero \( X_\alpha \) decreases \( Y_e \). Non-zero \( X_\alpha \) pushes \( Y_e \) to 1/2

Alpha effect

Alpha effect

Active-sterile mixing
Does the reactor-flux anomaly imply active-sterile neutrino mixing?

Can we know the reactor neutrino flux ever as well as we need?

Are Light Sterile Neutrinos Consistent with Supernova Explosions?

Meng-Ru Wu, Tobias Fischer, Gabriel Martínez-Pinedo, and Yong-Zhong Qian

1Institut für Kernphysik (Theoriezentrum), Technische Universität Darmstadt, Schloßgartenstraße 2, 64289 Darmstadt, Germany
2GSI Helmholtzzentrum für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany
3School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455

(Dated: May 13, 2013)

We point out that for sterile neutrinos of the eV mass scale with mixing parameters suggested by the reactor neutrino anomaly, substantial flavor transformation occurs in both $\nu_e$-$\nu_s$ and $\bar{\nu}_e$-$\bar{\nu}_s$ channels near a supernova core where the electron-to-baryon ratio is $\approx 1/3$. We show that the rate of heating by neutrino reactions in the shocked material is significantly reduced for $\sim 100$ ms after the launch of the shock in spherically symmetric models of 8.8 and 11.2 $M_\odot$ supernovae. While the exact
Sterile neutrino decay and Big Bang Nucleosynthesis

\[ \Gamma_{i \rightarrow j} = \frac{|\mu|^2}{8\pi} \left( \frac{m_i^2 - m_j^2}{m_i} \right)^3 = 5.308 \text{s}^{-1} \left( \frac{\mu_{\text{eff}}}{\mu_B} \right)^2 \left( \frac{m_i^2 - m_j^2}{m_i^2} \right)^3 \left( \frac{m_i}{eV} \right)^3 \]

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul$^{1,2}$, Maxim Markevitch$^2$, Adam Foster$^1$, Randall K. Smith$^1$ Michael Loewenstein$^2$, and Scott W. Randall$^1$

1 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
2 NASA Goddard Space Flight Center, Greenbelt, MD, USA.


<table>
<thead>
<tr>
<th>Sterile neutrino mass</th>
<th>How it asserts itself</th>
<th>What does it solve?</th>
</tr>
</thead>
<tbody>
<tr>
<td>~ 1 eV</td>
<td>Mixing with active flavors</td>
<td>Reactor anomaly, IceCube data</td>
</tr>
<tr>
<td>~ 7 keV</td>
<td>Electromagnetic decay</td>
<td>Gammas rays from the galactic centers</td>
</tr>
<tr>
<td>~ 4-5 MeV</td>
<td>Electromagnetic decay</td>
<td>$^7$Li problem in BBN</td>
</tr>
</tbody>
</table>

Are we cooking up a separate magic potion for each malady?
Black hole or neutron star?

Black hole or neutron star?

\[ \frac{^{232}\text{Th}}{^{151}\text{Eu} + ^{153}\text{Eu}} \]
Truncated r-process

Aoki et al., APL 766, L13 (2013)
If we want to catch a supernova with neutrinos we’d better know what neutrinos do inside a supernova.
Thank you very much!