Nuclear Physics and Supernova Dynamics

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Tribute to Gerry - Stony Brook, November 26, 2013
Hans Bethe’s Centennial at Caltech
How a Supernova Explodes

When a large star runs out of nuclear fuel, the core collapses in milliseconds. The subsequent \textit{"bounce\textquotedbl} of the core generates a shock wave so intense that it blows off most of the star's mass.

by Hans A. Bethe and Gerald Brown
EQUATION OF STATE IN THE GRAVITATIONAL COLLAPSE OF STARS

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Received 12 February 1979

Abstract: The equation of state in stellar collapse is derived from simple considerations, the crucial ingredient being that the entropy per nucleon remains small, of the order of unity (in units of k), during the entire collapse. In the early regime, \( \rho \sim 10^{10} - 10^{13} \text{ g/cm}^3 \), nuclei partially dissolve into \( \alpha \)-particles and neutrons; the \( \alpha \)-particles go back into the nuclei at higher densities. At the higher densities, nuclei are preserved right up to nuclear matter densities, at which point the nucleons are squeezed out of the nuclei. The low entropy per nucleon prevents the appearance of drip nucleons, which would add greatly to the net entropy.

We find that electrons are captured by nuclei, the capture on free protons being negligible in comparison. Carrying the difference of neutron and proton chemical potentials \( \mu_n - \mu_p \) in our capture equation forces the energy of the resulting neutrinos to be low. Nonetheless, neutrino trapping occurs at a density of about \( \rho = 10^{12} \text{ g/cm}^3 \). The fact that the ensuing development to higher densities is adiabatic makes our treatment in terms of entropy highly relevant.

![Fig. 1. Shell-model description of the electron capture. In the capture, protons will go to the \( \psi \) level of the daughter nucleus, which then decays by \( \gamma \)-emission down to the \( 2p \) orbitals.](image)

What we are saying in shell-model language is that ground-state to ground-state or low excited-state transitions are hindered through admixture of the giant Gamow–Teller state, whereas in the electron capture process the transition occurs to the giant Gamow–Teller state itself.

In its role of hindering low-lying \( \beta \)-transitions, the Gamow–Teller state is analogous to the giant dipole state, admixture of which retards low-lying E1 transitions by factors of \( \sim 100 \) to \( 1000 \). On the other hand, the Gamow–Teller strength has not been found in one relatively concentrated state, as in the case of the giant dipole resonance. This should not matter for the discussion here, since the strength, even if fragmented, should play the same role in hindering low-lying transitions.
Supernova: collapse phase

Important nuclear input:
- Electron capture on nuclei
- Neutrino-nucleus reactions

H.-Th. Janka
Supernova: explosion

Important nuclear input
Equation of state
Neutrino processes
Closer look on

- electron capture in presupernova phase
  (nuclear composition $A \sim 60$)

- electron capture during collapse
  (nuclear composition $A > 65$)

- nuclear deexcitation by neutrino pairs
Capture is dominated by Gamow-Teller transitions
During collapse, electrons are described by Fermi-Dirac distribution with chemical potentials of order a few MeV
Parent nuclei are described by thermal ensemble
Calculating stellar capture rates

Capture on nuclei in mass range A~45-65 calculated by large-scale shell model

Capture rates are noticeably smaller than assumed before!
Shell model electron capture rates

Shell model rates are noticeably smaller than rates from independent particle model (Fuller, Fowler, Newman)
Consequences of capture rates

Shell model rates for Fe-Ni nuclei slower by order of magnitude

Important changes in collapse trajectory

Heger
Woosley
Martinez
Pinedo
Digression: Type Ia supernovae

Universe expands!

Content of universe:

- Type Ia standard candle
- Schmidt vs Perlmutter
- Riess

Universe expands
Abundances in Type Ia’s

Type Ia’s have produced about half of the abundance of nickel-iron range nuclei in the Universe

Modern electron capture rates solve inconstency problem in Type Ia supernova abundance production

Martinez-Pinedo, Thielemann
Iron-nickel mass range under control

With increasing density, less sensitivity to details of GT distribution -> models less sophisticated than shell model suffice, e.g. QRPA
Electron Capture on 20Ne

- Important for late evolution of O-Ne-Mg cores of 8-10 solar mass stars

Rate determined by experimental data from beta-decay and (p,n) data!

except for ground-state ground-state-transition where only limit exists

Martinez-Pinedo, Lam,
Effect of screening

- Beta decay rate enhanced, but electron capture rate reduced

\[ \text{beta: } 20F \rightarrow 20Ne \]
\[ \text{e-capture: } 20Ne \rightarrow 20F \]

shifts URCA process to higher densities

Martinez-Pinedo, Lam
Abundance distribution during collapse

Electron captures drive nuclear composition towards neutron-rich unstable nuclei
Unblocking GT for nuclei with neutron numbers N>40

In Independent Particle Model, GT are Pauli-blocked for N>40. In reality, blocking does not occur due to correlations and finite T. Calculations of rates by SMMC/RPA model.
B(GT) strengths for 76Se

34 protons, 42 neutrons

Zhi, Martinez-Pinedo, Sieja, Nowacki
Experimental GT distributions

courtesy Dieter Frekers
Neutron occupancies

Data from transfer reactions: J.P Schiffer and collaborators
Cross-shell correlations converge slowly. Hence, models like thermofield dynamics model or finite temperature QRPA, which consider only 2p-2h correlations, do not suffice. (Zhi et al.)
Inelastic neutrino-nucleus scattering

validation of nu-nucleus cross sections from precision (e,e') M1 data

Martinez-Pinedo, Richter, Neumann-Cosel

neutrino scattering on nuclei acts as additional obstacle – in particular for high-energy neutrinos

supernova neutrino spectrum shifts to lower energies

smaller event rates for earthbound supernova neutrino detectors

Janka, Hix, Martinez-Pinedo, Juogadalvis, Sampaio
Consequences for supernova detectors

Change in supernova neutrino spectra reduces neutrino detection rates

<table>
<thead>
<tr>
<th>Detector</th>
<th>Material</th>
<th>$\langle \sigma \rangle$ ($10^{-42}$ cm$^2$)</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>SNO</td>
<td>d</td>
<td>5.92</td>
<td>16%</td>
</tr>
<tr>
<td>MiniBoone</td>
<td>$^{12}$C</td>
<td>0.098</td>
<td>43%</td>
</tr>
<tr>
<td></td>
<td>$^{12}$C (N$_{gs}$)</td>
<td>0.089</td>
<td>41%</td>
</tr>
<tr>
<td>S-Kamiokande</td>
<td>$^{16}$O</td>
<td>0.013</td>
<td>58%</td>
</tr>
<tr>
<td>Icarus</td>
<td>$^{40}$Ar</td>
<td>17.1</td>
<td>20%</td>
</tr>
<tr>
<td>Minos</td>
<td>$^{56}$Fe</td>
<td>8.8</td>
<td>27%</td>
</tr>
<tr>
<td>OMNIS</td>
<td>$^{208}$Pb</td>
<td>147.2</td>
<td>27%</td>
</tr>
</tbody>
</table>
Inelastic neutrino-nucleus scattering

Potential consequences:
- thermalization of neutrinos during collapse
- preheating of matter before passing of shock
- nucleosynthesis, $\nu p$-process
- supernova neutrino signal

- neutrino cross sections from $(e, e')$ data
- validation of shell model
- G. Martinez-Pinedo, P. v. Neumann-Cosel, A. Richter
Nuclear de-excitation

Fuller and Meyer (1991):

In hot stellar environment nuclei can de-excite by emission of neutrino pairs

- additional cooling mechanism, besides electron capture
- source of neutrinos other than electron neutrinos
De-excitation rates

- Neutral current process.
- At collapse conditions dominated by Gamow-Teller and first-forbidden transitions

Two different approaches:

**Fuller+Meyer:**
Independent particle model, „Brink hypothesis“

**Fischer, Martinez-Pinedo:**
Phenomenological Gaussians for excitation (guided by data)
„Brink hypothesis“
De-excitation by detailed balance
De-excitation strength

excitation strength

level density
cuts strength
tails
De-excitation rates

\[ T = 0.7 \text{ MeV} \]

\[ \langle Z \rangle = 32, \ \langle A \rangle = 83 \]

\[ T = 1.5 \text{ MeV} \]

\[ \langle Z \rangle = 42, \ \langle A \rangle = 124 \]
Role of nuclear de-excitation in supernova simulation

11.2 solar mass progenitor

spherical symmetry, full neutrino transport (AGILE Boltztran code)

NUCLEAR DEEXCITATION HAS NO EFFECT ON SUPERNOVA DYNAMICS!

Source of other neutrino types
Thanks Gerry

Visit of Gerry and Hans Bethe
January 1993, Pasadena
The RIB Chance: New Horizons