Neutrino-driven wind

\[ \langle E_\nu \rangle \approx 11 \text{ MeV} \]
\[ \langle E_\bar{\nu} \rangle \approx 16 \text{ MeV} \]
\[ \frac{n}{p} \approx 1.5 \]

\[ \nu + n \rightarrow p + e^- \]
\[ \bar{\nu} + p \rightarrow n + e^+ \]
But the $\nu$ is a double-edged sword...

The $\alpha$ effect

Equilibrium neutron/proton ratio not stable!!!

Protons are captured and stuck into $\alpha$ particles as soon as they’re created!!!

$n/p$ shrinks!!!

The upshot:

Must... get away... from neutrinos...
Neutrinos do everything

- power an expansion that causes $T$ and $\rho$ to fall (varying the conditions)
- set the neutron/proton ratio via
  \[
  \nu + n \to p + e^- \\
  \bar{\nu} + p \to n + e^+. 
  \]
  The $\bar{\nu}$'s have higher energy and give an excess of neutrons.
- eject $\approx 10^{-5} M_\odot$ of stuff.

not to mention exploding the star!
Calculating \( \beta \)-decay is hard!
Usual Approach

\[ \frac{1}{n} = 1 + 1 - 0 + \frac{1}{0} \]
Our goal:

Completely self consistent HFB + QRPA calculation, so that daughter states correspond to collective spin-isospin oscillations of ground-state density.

Steps:
1. Coordinate-space HFB
2. p-n QRPA in "canonical basis" for energies of and transitions to daughters

Self consistency means using the same interaction everywhere in the steps above. We use one from the "Skyrme class"
Skyrme Interaction:

\[ N_{12} = t_0 (1 + x_0 \rho_0) S^2 (\nabla - \Sigma) + \frac{1}{2} t_2 (1 + x_2 \rho_0) \left( S \cdot \frac{\rho}{\rho_0} \right) \]

\[ + t_2 (1 + x_2 \rho_0) \left[ \nabla \cdot \frac{\rho}{\rho_0} \right] + \frac{1}{2} t_3 (1 + x_3 \rho_0) \frac{\rho}{\rho_0} \cdot \frac{\rho}{\rho_0} \]

\[ + i \nabla_0 (\nabla \times \frac{\rho}{\rho_0}) \cdot \nabla \times \frac{\rho}{\rho_0} \]

\[ \overline{\nabla} = \nabla_1 - \nabla_2 \]

\[ \rho_0 = \frac{1}{2} (1 + \overline{\nabla} \cdot \overline{\rho} ) \]

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Skyrme Energy functional

\[ \mathcal{H} (\rho) = \frac{t_0}{2} \left[ (1 + x_0 \rho_0) \rho^2 - (x_0 + 2) (\rho^2 + \rho_0^2) \right] \]

\[ + \frac{1}{2} t_1 \left[ (1 + x_1 \rho_0) \rho^2 + 34 (\nabla_0 \rho)^2 \right] - (x_1 + 2) \left[ \rho_0^2 + 3 \nabla_0 (\rho_0^2) \right] \]

+ lots more ...

\[ \int \ldots \]

including "time odd currents"

(like the spin density)
Unfortunately, predictions of most Skyrme interactions for the Gamow-Teller distribution bear no resemblance to reality.

Can easily see this by looking at Landau parameter \( g_0' \):

\[
\begin{align*}
V_{12} & \rightarrow f_0 \delta^2 \left( r - r'_2 \right) + f_1 \delta^3 \left( r - r'_2 \right) \frac{\vec{r}_1 \cdot \vec{r}_2}{r_1 r_2} \\
& + g_0 \delta^3 \left( r - r'_2 \right) \frac{\vec{r}_1 \cdot \vec{r}_2}{r_1 r_2} \\
& + g_0' \delta^3 \left( r - r'_2 \right) \frac{\vec{r}_1 \cdot \vec{r}_2}{r_1 r_2}
\end{align*}
\]

\( g_0' \) determines energy & strength of GT resonance in nuclear matter.
Force

SG II  0.93
SKM*  0.94
SKP   0.06
SLy4  0.90
SLy5  -0.15
SLy6  0.90
SLFU  0.88
SK0'  0.80

Empirical ~ 1.80
FIG. 1. Summed GT strength up to 20 MeV as a function of excitation energy for the closed-shell nucleus $^{90}$Zr, calculated with the SkO', SLy5, and SkP Skyrme forces. We also plot the measured strength reported in Ref. [59] The calculated strength, as is customary, is multiplied by $(1/1.26)^2$; the quenching corresponds to setting $g_A$ to 1.0 in our calculations of beta decay.
$I=0$ pairing

This interaction enters the QRPA, shifting intermediate strength down. Ignoring it leads to lifetimes that are systematically too long.

In this channel we use a simple $2$-Gaussian force, though a simple Skyrme interaction would do just as well, provided it contains some derivatives.

The strength of the interaction in this channel is the only free parameter.
reports half-lives only when the predicted deformation $\beta_2$ is less than 0.1. The PDNS collaboration reports only the lower bound, which is marked here with arrows pointing up. The PDNS collaboration reports only the lower bound, which is marked here with arrows pointing up. When predicted half-lives are larger than 10 possible values of the predicted half-lives are shown as well. When predicted half-lives are larger than 10 possible values of the predicted half-lives are shown as well. When predicted half-lives are larger than 10 possible values of the predicted half-lives are shown as well.

![Graph](image-url)

**Figure 6.** Comparison of calculated half-lives for $^{13}$N, $^{14}$C, and $^{29}$Zn with the experimental values taken from Refs. [12] (HFR+QPA+SDS), [13] (PRISM+QPA), [14] (HFR+QPA+SDS), and [15] (HFR+QPA+SDS) only for the $^{12}$N isotope, with experimental values taken from Refs. [12] (HFR+QPA+SDS), [13] (PRISM+QPA), [14] (HFR+QPA+SDS), and [15] (HFR+QPA+SDS).
Results of Ref. [12] (PRD+QPA), red [19] (ETP1+QPA), and experimental data where available. Also plotted are the predictions of Ref. [20] (HFB+QPA+SKO) without (HFB+QPA+SKO, \( V = 0 \)) and with (HFB+QPA+SKO, \( V = 0 \)) the nuclear-particle interaction. Our results appear to be in agreement with predictions for the half-lives of closed neutron-shell nuclei along the R-process path.
FIG. 10. Predicted abundances in a simulation of the r-process. The solid line corresponds to the rates of Ref. [12], and the dotted line to the rates obtained here around $N=82$ and 126. All other nuclear and astrophysical parameters are the same for the two lines. The crosses are observed solar-system abundances.

The whole process can speed up by a factor of 2 or so. *say something here
The near future

1. Decoupling the time-even and time-odd terms in the Skyrme energy functional. This has never been done because people haven't cared enough about states with non-zero angular momentum.

2. A more comprehensive investigation of $T=0$ pairing in the Skyrme framework.

3. Deformed nuclei and full $r$-process simulations.

The far future: Beyond RPA?
Conclusions

1) Neutrinos cause problems for the "hot-bubble" r-process. It would be nice if the nucleosynthesis took less time.

2) It actually does take a little less time than usually thought because \( \beta \)-decay rates have been systematically underestimated. How much less? Don't really know yet.

3) Peaks could form just prior to "freeze-out". This would really shorten the time.