Shell Model and Supernova

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supernova: general picture
the quest for nuclear input
shell model and applications
...
Core-collapse supernova.
Electron captures in core collapse.

- $T = 0.5–2.0$ MeV, $\rho = 10^8–10^{13}$ g cm$^{-3}$.
- The dynamical time scale set by electron captures: 
  
  \[ e^- + (N, Z) \rightarrow (N + 1, Z - 1) + \nu_e \]
- Evolution decreases number of electrons ($Y_e$) and Chandrasekhar mass
  \[ M_{Ch} \approx 1.4(2Y_e)^2 M_\odot \]

- Capture rates on individual nuclei computed by:
  - Shell Model ($A < 65$)
  - Shell Model Monte Carlo ($A > 65$)
Gamow-Teller strength distributions in pf-shell nuclei.

(n,p) experiments, TRIUMF

(d,²He) experiments, KVI Groningen

Shell model results agree after overall quenching by (0.77)²
GT strength in multi-shell calculations

- No-core shell model calculation of $^{12}\text{C}$
- Gamow-Teller strength shifted to higher excitation energies

M1 and GT strengths in $^{12}\text{C}$

E. Caurier, G. Martinez-Pinedo, F. Nowacki
Pauli blocking of Gamow-Teller transition

- Unblocking mechanism: correlations and finite temperature
- Calculation of rate in SMMC + RPA model
Correlations across $N = 40$ shell gap

- strong deformation in $N \sim Z \sim 40$ nuclei
- SMMC ($(fp gds)$ model space)
- deformation due to $g_{9/2}$ orbital
- W. Nazarewicz, D. Dean

- B(E2) strength in $^{68}\text{Ni}$
- most strength in excited states
- neutron pair excitation across shell gap
- shell model (F. Nowacki)
Electron capture: nuclei vs protons

Capture rate and average energy

\[ R_{ec} \text{ (s}^{-1}) \]

\[ \langle E_{\nu e} \rangle \text{ (MeV)} \]

\[ \rho \text{ (g cm}^{-3}) \]

protons

nuclei

Mass abundances

\[ T= 9.01 \text{ GK, } \rho= 6.80 \times 10^9 \text{ g/cm}^3, \ Y_e= 0.433 \]

\[ T= 17.84 \text{ GK, } \rho= 3.39 \times 10^{11} \text{ g/cm}^3, \ Y_e= 0.379 \]

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Consequences

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Consistent treatment of supernova dynamics coupled with a nuclear network.

Essential neutrino reactions in the shock heated region:

\[ \nu_e + n \leftrightarrow p + e^- \]
\[ \bar{\nu}_e + p \leftrightarrow n + e^+ \]

Ye evolution of a mass element
Comparison with observations.

Carla Fröhlich et al., astro-ph/0410208

![Graph showing comparison of [X/Fe] ratios for various elements: Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn. The graph compares different studies: Cayrel et al., Gratton & Sneden, Thielemann et al., and This work. Each element is plotted with error bars indicating variability.]
Effect of neutrinos on nucleosynthesis.

G. Martínez-Pinedo, C. Fröhlich

Without neutrinos flow stops at $^{64}\text{Ge}$ ($t_{1/2} = 64\text{ s}$)

With neutrinos:

$\bar{\nu}_e + p \rightarrow e^+ + n; \quad n + ^{64}\text{Ge} \rightarrow ^{64}\text{Ga} + p; \quad ^{64}\text{Ga} + p \rightarrow ^{65}\text{Ge}$; \ldots
Determining inelastic neutrino-nucleus cross sections

\[ T(M1) = (L_p - L_n) + (g_p - g_n) \sum_{i} t_z(S_i \mu_N) \]

INELASTIC NEUTRINO SCATTERING ON NUCLEI

\((v, v'), GT_0 \) (e, e'), ... DATA YIELD GT_0 INFORMATION

IF ORBITAL PART CAN BE REMOVED

ISOVECTOR PIECE DOMINATES

\[ T(GT_0) \sim \sum_{i} t_z(S_i) \]

\[ T(M1) = \left\{ \frac{1}{2} (L_p - L_n) + (g_p - g_n) \sum t_z(S_i) \right\} \mu_N \]

M1 DATA YIELD GT_0 INFORMATION IF ORBITAL PART CAN BE REMOVED

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Neutrino cross sections from electron scattering

- high-precision SDalinac data
- large-scale shell model

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

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large-scale shell model (allowed transitions), finite-T effects
random phase approximation (forbidden transitions)
A. Juodagalvis, G. Martinez-Pinedo, J.M. Sampaio
Summary

Improved nuclear ingredients for supernova simulations

- Electron capture rates on nuclei
- Neutrino-nucleus cross sections
- Level densities; partition functions
- Equation of state; matter composition

The future of nuclear astrophysics is FAIR