Urca processes in stellar degenerate cores

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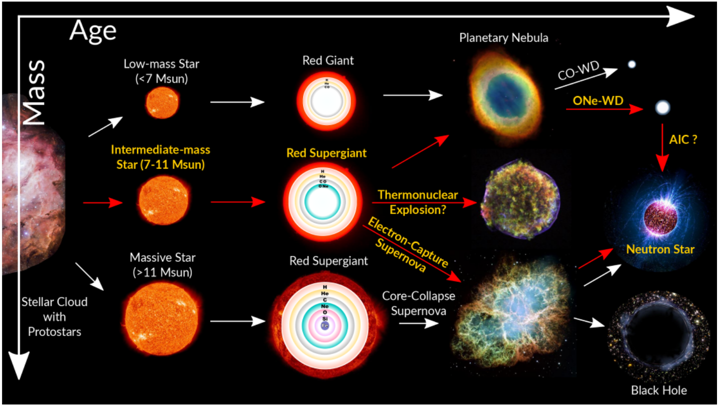
The fate of stars



Heiko Möller, PhD Thesis (2017)

Degenerate ONe cores

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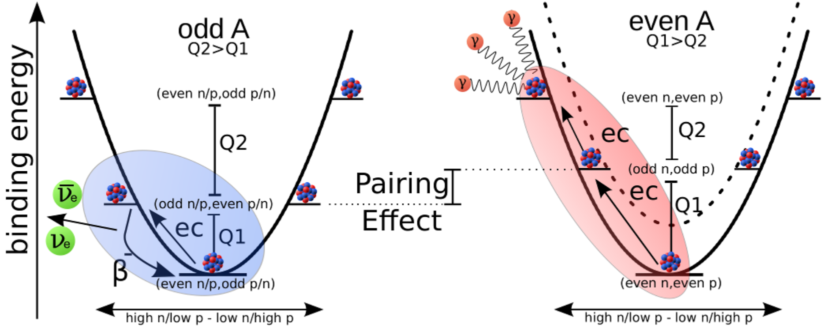
- Main content after carbon burning: ^{16}O, ^{20}Ne, ^{23}Na, ^{24}Mg and ^{25}Mg.
- Mainly supported by degeneracy pressure
- Electron Fermi energy $E_F \sim \rho^{1/3}$ increases when the core contracts
- Electron capture (EC) when E_F is larger than the Q value
- This corresponds to a specific density threshold ρ
- Thresholds (Arnett, *Supernovae and Nucleosynthesis*):

Nucleus	E_F [MeV]	$2Y_e\rho$ [g $\cdot$ cm^{-3}]
^{25}Mg	3.833	1.17×10^9
^{23}Na	4.374	1.67×10^9
^{24}Mg	5.513	3.16×10^9
^{20}Ne	7.026	6.20×10^9
^{16}O	10.42	1.90×10^{10}

Urca and double electron capture processes



Heiko Möller, PhD Thesis (2017)

Urca cooling in acreeting ONe white dwarfs

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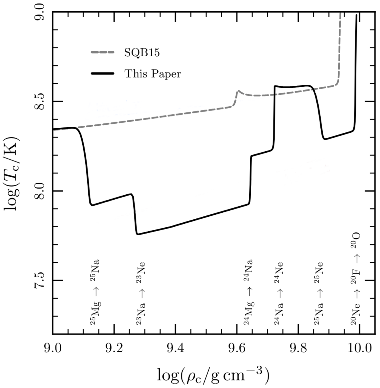
- We study the evolution of acreeting ONe white dwarfs up to oxygen ignition
- Conditions at ignition important for final outcome
- Heating from double electron capture: ^{20}Ne and ^{24}Mg
- Schwab et al. (2017): Urca pairs ^{25}Mg & ^{25}Na, ^{23}Na & ^{23}Ne and ^{25}Na & ^{25}Ne
- This was also studied in Heiko Möller's PhD thesis
- Both used the MESA (Modules for Experiments in Stellar Astrophysics) stellar evolution code

Urca cooling in acreeting ONe WD

Schwab et. al, 2017.



Unexplored: Effect of metallicity in ONe cores

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- Non-zero metallicity in the progenitor $\Longrightarrow$ additional nuclei in ONe core
- Piersant et al. (2017):
  - Studied effects of initial metallicity on SNe Ia (i.e. acreeting CO white dwarfs)
  - Included EC processes on the corresponding nuclei
  - Simulation: increased density and neutronization at thermal runaway
  - Thus: metallicity affects light curve of SNe Ia
- But the effects of metallicity in ONe cores remain unexplored
- This is what we are currently investigating,
  i.e. including EC procceses on additional nuclei from initial metallicity

Nuclei considered in Piersanti et al.

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URCA Pairs (Lines 1–8) and Double Electron-capture Triplets (Lines 9–10) Considered in the Present Work

Isobars	ρ_{URCA} or ρ_{2EC} in 10^9 g cm^{-3}	$X_{\odot}$ [a]	Source
^{19}F–^{19}O	2.43	1.07×10^{-7}	Suzu2016
^{21}Ne–^{21}F	3.78	3.74×10^{-5}	Suzu2016
^{23}Na–^{23}Ne	1.86	1.42×10^{-4}	Suzu2016
^{25}Mg–^{25}Na	1.31	3.84×10^{-5}	Suzu2016
^{27}Al–^{27}Mg	0.104	5.60×10^{-5}	Suzu2016
^{31}P–^{31}Si	1.09	6.68×10^{-6}	Oda1994
^{37}Cl–^{37}S	2.19	3.03×10^{-6}	Oda1994
^{39}K–^{39}Ar	0.012	3.39×10^{-6}	Oda1994
^{32}S–^{32}P–^{32}Si	0.144	3.14×10^{-4}	Oda1994
^{56}Fe–^{56}Mn–^{56}Cr	1.27	1.05×10^{-3}	Lang2001

Note. Suzu2016 : Suzuki et al. (2016), Oda1994 : Oda et al. (1994), Lang2001: Langanke & Martínez-Pinedo (2001).
[a] Mass fraction abundance of the β-stable isotope in the initial ZSUN model.

Additional nuclei for ONe cores

- Nuclei above should also matter for ONe cores
- But: Oxygen ignites at higher densities than carbon
- Consequently: EC on larger set of nuclei prior to runaway
- Rough selection: Order by abundance and choose most abundant

Weak interaction rates

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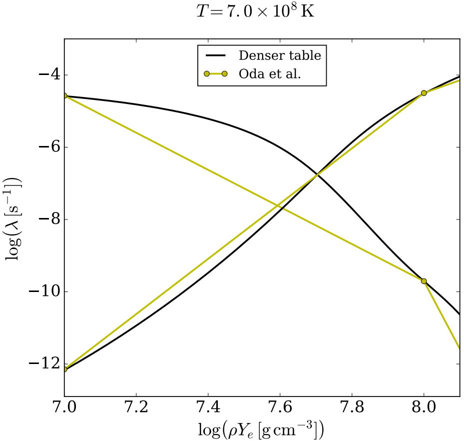
- To include these effect we need accurate weak interaction rates
- Traditional way: Tables of interaction rates, e.g.
  - Fuller, Fowler, and Newman (1980, 1982, 1985): sd & pf shells
  - Oda et al. (1994): sd shell
  - Langanke and Martínez-Pinedo (2001): pf shell
  - Suzuki et al. (2016): sd shell
- Tables based on experimental data + shell model calculations
- Problem: interpolation errors
  - Rates can quickly change several orders of magnitude
  - Newer tables (e.g. Suzuki et al.) have denser data points
  - But we still get issues at low temperatures (see Schwab et al. (2017))

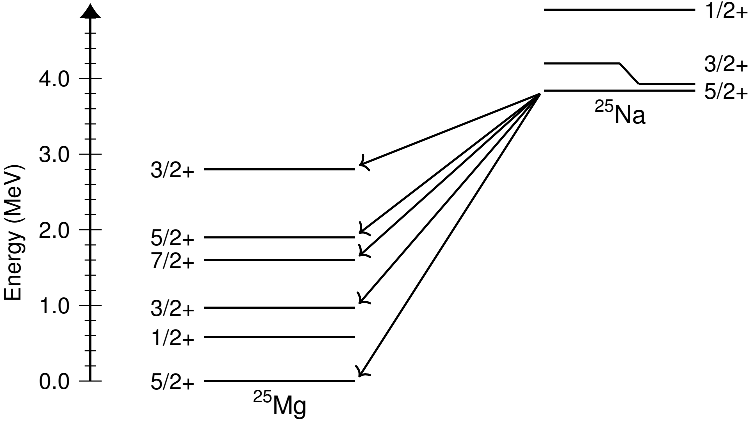
Example: The Urca pair ^{31}P and ^{31}Si



Alternative: Analytical determination

- At these temperatures only low-lying excited states are relevant
- Consequently the rates are typically determined by a few transitions
- This means that we can compute the rates during the simulation
- Phase space integrals can be approximated as an analytical expression (see Fuller, Fowler, and Newman (1985))
- This functionality has been implemented in the MESA stellar evolution code
- We must identify relevant transitions

Urca pair ^{25}Mg and ^{25}Na: Experimental data



Urca pair ^{25}Mg and ^{25}Na: Relevant transitions

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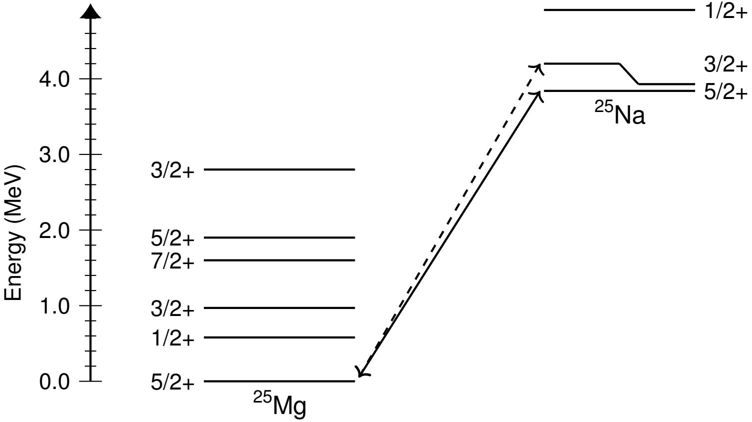

^{25}Mg and ^{25}Na: What is the difference?

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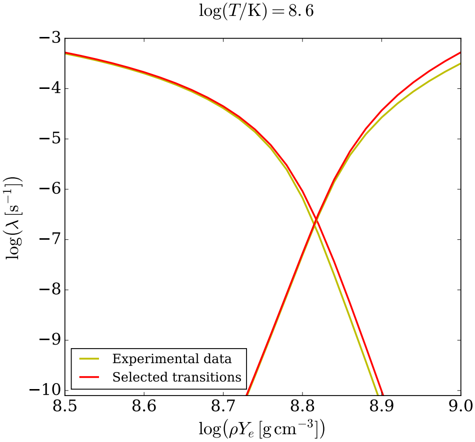

^{25}Mg and ^{25}Na: Are other transitions important?

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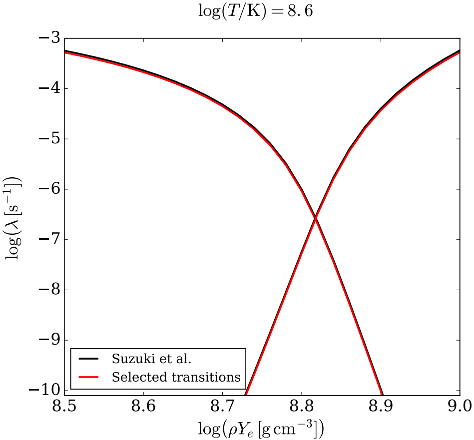
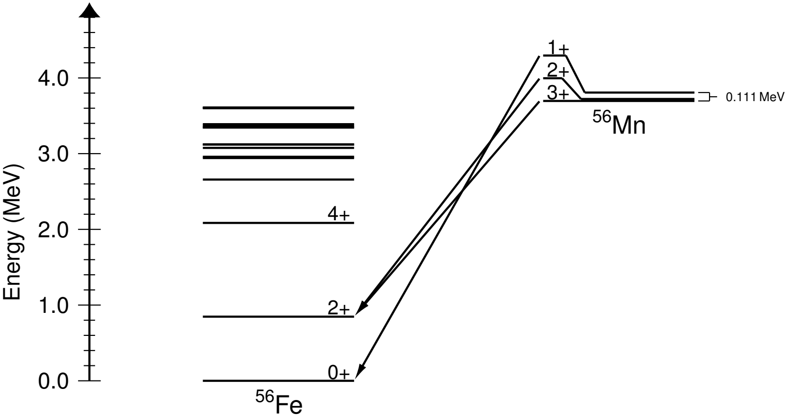
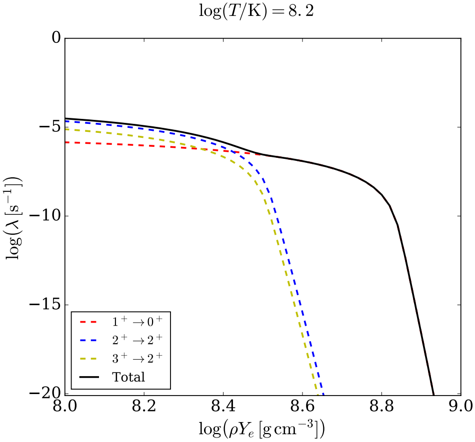


Beta decay of ^{56}Mn

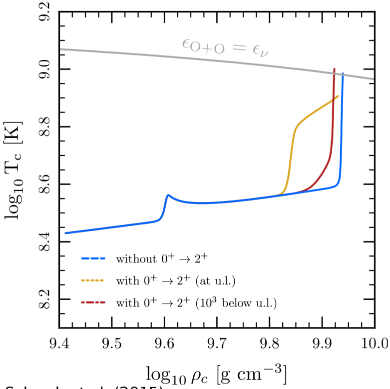


Beta decay of ^{56}Mn

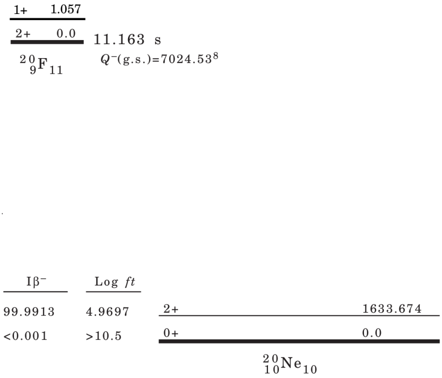


Forbidden transition from ^{20}Ne

- Martinez-Pinedo et al. (2014): forbidden transition important for EC on ^{20}Ne



Schwab et al. (2015)



Conclusions

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- Urca processes are important for the evolution of degenerate stellar cores
- Rates are typically determined by few transitions — analytic determination of the rates
- Accounting for initial composition of the star (metallicity) allows for additional EC processes that are currently being investigated
- Second forbidden transition from ^{20}Ne still needs to be determined

Appendix

$$\lambda^{EC} = \sum_{if} P_{if} \lambda_{if}^{EC} \qquad P_{if} = \frac{(2J_i + 1)\exp(-E_i/kt)}{\sum_j (2J_j + 1)\exp(-E_j/kt)}$$

$$\lambda_{if}^{EC} = \frac{\ln 2}{K} B_{if} \phi^{EC}(q_{if}) \qquad B_{if}(GT) = g_A^2 \frac{\langle \psi_f | \sum_k \sigma^k t_k^+ | \psi_i \rangle}{2J_i + 1}$$

$$\phi^{EC}(q_{if}) = \int_{w_l}^{\infty} wp(q_{if} + w)^2 F(Z, w) S_e(w) dw$$