Neutrino-nucleon interactions in dense and hot matter

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Outline

1. Introduction

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2. Some selected reactions
   - Direct Urca reactions
   - Modified Urca reactions
   - Neutrino-nucleon scattering
   - Electron capture on nuclei

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2. Some selected reactions
   - Direct Urca reactions
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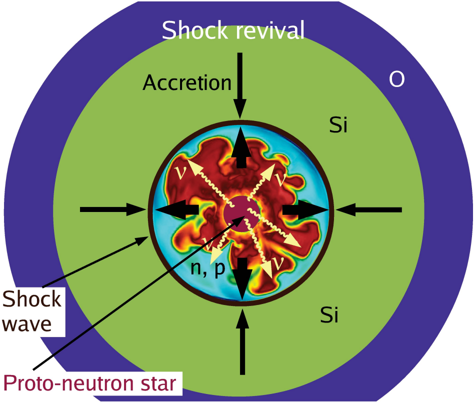
   - Electron capture on nuclei
3. Some results on proto-neutron star evolution
4. Summary

Neutrino interactions

Why are we wondering about ?

1. Core-collapse supernovae
   - Neutrino-driven explosion mechanism
   - Small changes in interactions rates can push explosions e.g. [Melson 2015]
   - Neutrino driven wind and nucleosynthesis
   - Proto-neutron star cooling by neutrino emission
   - Neutrino emissivities dominant for (P)NS cooling for $\lesssim 10^6$ yrs

Shock revival in a CCSN



[Janka 2012]

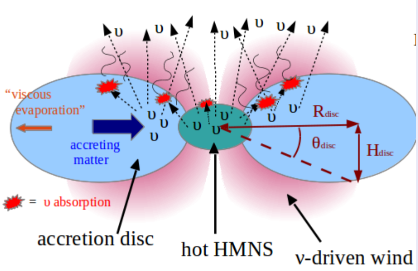
Neutrino interactions

Why are we wondering about ?

2. Binary neutron star mergers

- Neutron rich and hot environment → intense neutrino emission
- Determine neutron to proton ratio in the ejecta (conditions for heavy element nucleosynthesis)
- Release energy (cooling effect)
- Energy and momentum exchange with matter

Sketch of merger remnant



[Perego 2014]

Neutrino matter interactions

- Different types of interactions with matter (nucleons, nuclei and charged leptons, photons)
  - scattering (neutral current)
  - absorption/creation processes (charged current)
  - pair creation (neutral current)

Typical reactions

$$
\begin{aligned}
p + e^-(+N) &\leftrightarrow n + \nu_e(+N) \\
n + e^+(+N) &\leftrightarrow p + \bar{\nu}_e(+N) \\
(A,Z) + e^- &\leftrightarrow (A, Z-1) + \nu_e \\
N + N &\rightarrow \nu + \bar{\nu} + N + N \\
\nu + A &\rightarrow \nu + A \\
\nu + N &\rightarrow \nu + N
\end{aligned}
$$

- Will not treat them all here . . .

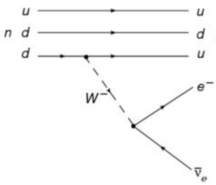
Outline

Neutrino-nucleon charged current reactions

Basic charged current weak interaction [Fermi 1934,...] :

$$G_F V_{ij} \bar{q}_i \gamma_\mu (1-\gamma_5) q_j \, \bar{\psi}_{l_1} \gamma^\mu (1-\gamma_5) \psi_{l_2}$$

Attention : interaction with quarks not nucleons !



- Governs the following reactions (not all of them are equally relevant)

Electron/positron capture

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

Neutron/proton decay

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

- Main problem : in medium nuclear response (matrix element + phase space)

General form (here : $p + e^- \to n + \nu_e$)

$$\frac{\partial f_\nu}{\partial t} \propto (1 - f_\nu) \int d_{q_0} \, n_e \int dq \, L^{\lambda\sigma} \, \mathrm{Im}\Pi_{\lambda\sigma}$$

Direct URCA reactions

- Governs the following reactions (not all of them are equally relevant)

Electron/positron capture

$$p + l^- \leftrightarrow n + \nu_l$$
$$n + l^+ \leftrightarrow p + \bar{\nu}_l$$

Neutron/proton decay

$$n \leftrightarrow p + l^- + \bar{\nu}_l$$
$$p \leftrightarrow n + l^+ + \nu_l$$

Different approximations to compute rates

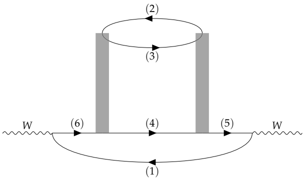
- Elastic approximation (neglect momentum transfer to nucleons and non-interacting nucleons) $\longrightarrow$ simple analytic expressions [Bruenn 1985]
- Include corrections to the nuclear matrix element (weak magnetism ...) $\longrightarrow$ slightly less simple expressions [Horowitz 2002]
- Include full phase space $\longrightarrow$ numerical computation [Roberts& Reddy 2017, Guo+2020,...]
- Include full phase space and nuclear interactions (mean field or RPA) [Reddy+1998, Burrows& Sawyer 1998,...]

- Analytic results widely used in simulations but crude approximations

Modified Urca reactions

Example : EC reaction

$p + e^- + N \leftrightarrow n + \nu_e + N$



- Spectator nucleon can lift kinematic restrictions of dUrca reactions
- Considered clearly subdominant to dUrca

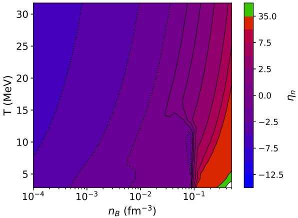
Common approximations

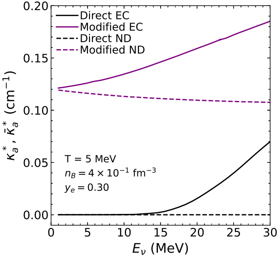
- All particles on respective Fermi surface $\longrightarrow$ cold matter [Friman & Maxwell 1979]
- Neglect momentum transfer $\longrightarrow$ low densities [Bacca+2012]
- Intermediate nucleon propagators as $\sim 1/E_e$ or $\sim 1/q_0$
- Only axial part

not adapted to PNS cooling, BNS merger remnant....

Results for Murca reactions

- Order of magntiude analytic estimate indicates a region in T, n_B where Murca is not necessarily suppressed
  - Low temperatures and high densities : $\frac{I_{mU}}{I_{dU}} \sim 10^{-6}$
  - High temperatures : $\frac{I_{mU}}{I_{dU}} \sim e^{\eta_i}$ $(\eta = (\mu^* - m^*)/T)$
    $\rightarrow$ mUrca not necessarily suppressed for $\eta \sim 0$!
- Numerical evalulation computed with confirms estimate
  - Full momentum dependence of matrix element and phase space
  - One pion exchange interaction
- Results confirm estimate

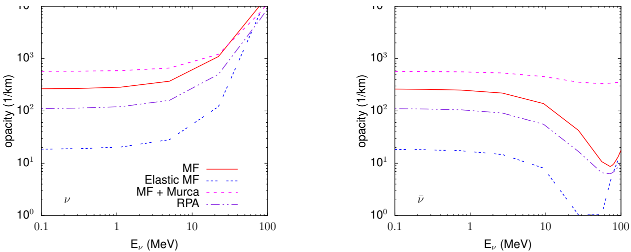




[Suleiman+ 2023]

Comparing different approximations

- Rates computed with RG(SLy4) EoS at $T = 16$ MeV, $n_B = 0.15$ fm^{-3}, $Y_e = 0.07$
- Murca reactions here as phenomenological finite life-time in Durca reactions



[Pascal+2022]

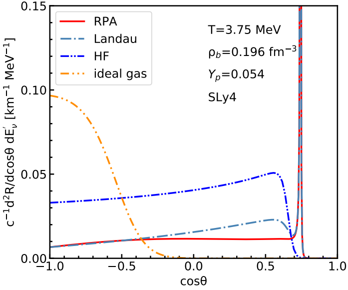
Neutrino-nucleon scattering

Different approximations to compute rates

- Inelastic (isoenergetic) scattering i.e. no energy transfer [Bruenn 1985]
- Treating nucleons as ideal non-interacting gas [Reddy+1998,Burrows&Sawyer1998, Thompson+2000]
- Include nuclear interactions

[Reddy+1998, Burrows& Sawyer 1998,Schwenk&Horowitz2006,...]

- Overall reduced rates with effects from nuclear interactions included
- Minimum scattering angle strongly depends on $m^{(*)}$ via $v_F \longrightarrow$ very EoS dependent and $v_F > c$ for many EoS

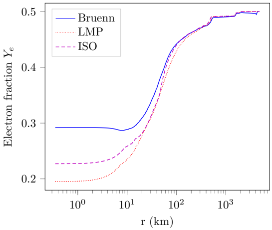


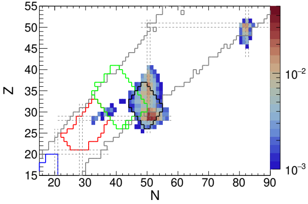
[Duan&Urban 2023]

Electron capture on nuclei

- Electron capture on nuclei main reaction to drive deleptonisation during CCSN infall

- Total rates : nuclear abundances and individual rates
- Mainly neutron rich nuclei far from stability →mainly shell model calculations
- Impact on dynamics of CCSN [Sullivan+2016, Pascal+2020, Johnston+2022,Giraud+2022] :
  - electron fraction and inner core mass at bounce,
  - shock propagation in early post-bounce, · · ·
- Experimental and theoretical effort underway to constrain main nuclei involved [Giraud+2023,Litvinova+2020,Dzhivoev+2022]



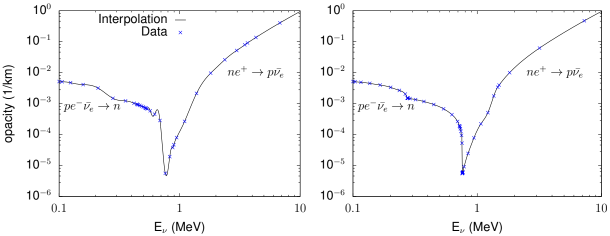


[Pascal+ 2020]

Outline

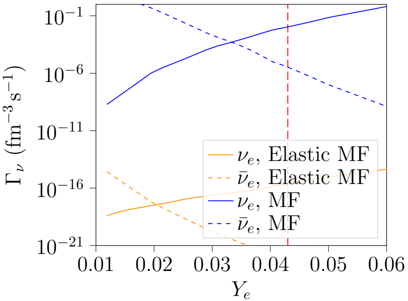
Neutrino tool kit

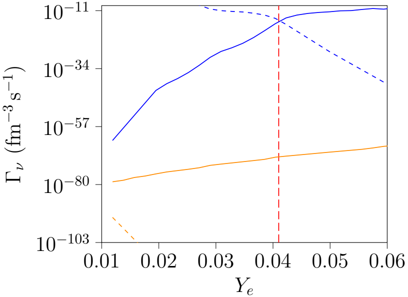
- Aim : provide numerically computed rates for use in simulations
  - Consistent with the underlying equation of state (EoS) model
  - Different levels of approximation : kinematics and nuclear interactions
  - Corrections are energy dependent (difficult to cast into a “gray” correction)
  - Polynomial fit (neutrino energy) to the opacities [Oertel+2020,Pascal+2022], see the data base https://compose.obspm.fr
  - Application to core-collapse supernova simulations (shift in position of neutrinosphere) [Oertel+2020] and proto-neutron star evolution [Pascal+2022]



Weak equilibrium during PNS evolution

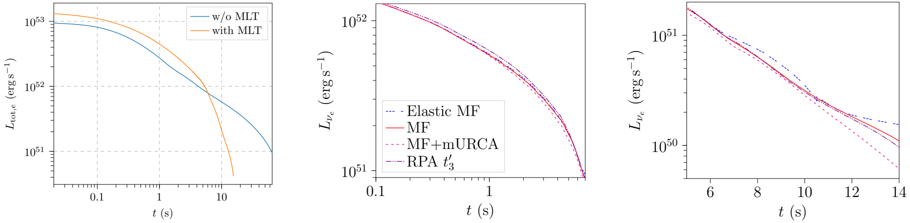
- Simulation of PNS evolution with quasi-static GR hydrodynamics + neutrino transport [Pascal+2022]





- β-equilibrium not correctly obtained $\rightarrow$ breakdown of the elastic approximation at high densities, need for numerical (pre-)computation of opacities

Influence of nuclear interactions



- Prevalent role of convection for dynamical proto-neutron star evolution, nuclear interactions in the opacities is subdominant effect
- Murca processes start to become important for late time evolution → better calculation needed

Outline

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Summary and outlook

Summary

- Collective effects important in dense matter → considerably modified neutrino opacities
- Microphysics effort since many years, some recent ones
  - Need to care about Murca type reactions at intermediate densities/temperatures
  - Role of the effective mass for νN scattering
  - Electron capture rates on nuclei
- State of the art rates need numerical computations → difficult to include on the fly

Outlook

- How to implement numerically computed rates with ongoing efforts in the nuclear physics community ? (Provided polynomial representations for CC rates)
- Do we need this for all applications ? Crude approximations might be good for some temperatures/densities