Reaction rates in compact star physics

Dany Davesne (IP2I), Anthea Fantina (Ganil), Hubert Hansen (IP2I), Élias Khan (IJCLab), Elena Litvinova (GANIL), Jérôme Margueron (IP2I),Francesco Nitti (APC), Micaela Oertel (LUTH), Kamila Sieja (IPHC), Nadya Smirnova (CENBG), Michael Urban (IJCLab), Cristina Volpe (APC)

micaela.oertel@obspm.fr

Laboratoire Univers et Théories (LUTH)
CNRS / Observatoire de Paris/ Université Paris Diderot

Atelier Physique des Deux Infinis, June 7-8, 2021

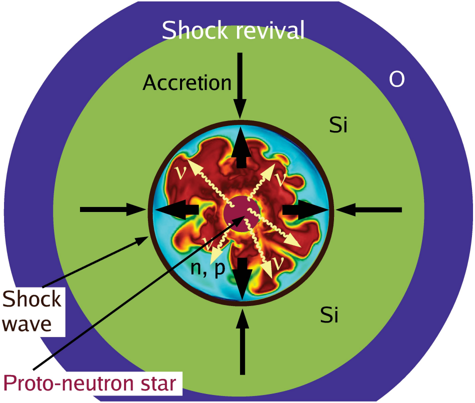
Outline

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

Shock revival in a CCSN



[Janka 2012]

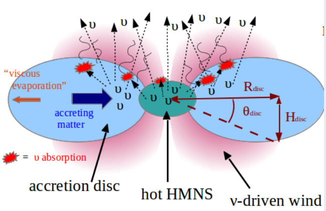
Neutrino interactions

Why are we wondering about ?

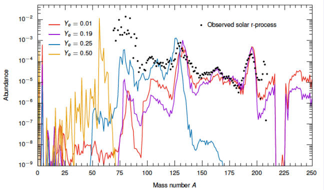
2. Binary neutron star mergers

- 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
- Source of viscosity

Sketch of merger remnant [Perego 2014]



r-process and neutrinos [Cristina Volpe]



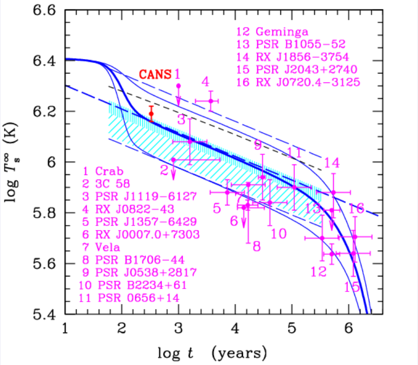
Neutrino interactions

Why are we wondering about ?

3. Neutron star cooling

- Energy loss by surface photon and neutrino emission
- Theory predicts essentially three cooling stages
  - Crust thermalisation ($\sim$ 10-50 yrs)
  - Neutrino cooling ($\sim 10^5 - 10^6$ yrs)
  - Photon cooling ($t \gtrsim 10^6$ yrs)
- Neutrino emissivities dominant for about 10^6 yrs

NS cooling



[Yakovlev 2011]

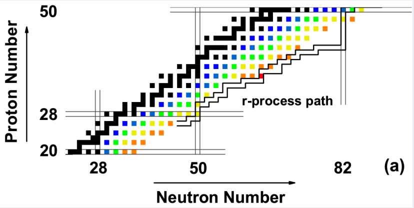
Particle capture reactions

Why are we wondering about ?

1. r-process nucleosynthesis and x-ray bursts/novae

- r-process : neutron capture fast compared with β-decay $\rightarrow$ operates at high neutron densities and on very neutron rich nuclei

TYPICAL r-PROCESS PATH



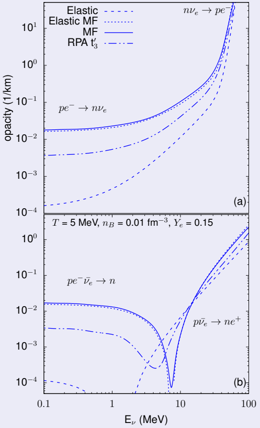
[Niu et al 2013]

- Astrophysical site long standing debate
  - CCSN ? Ejecta probably not neutron rich enough, weak r-process ?
  - Strong evidence for main r-process in BNS mergers (GW170817)
- x-ray bursts/novae produced by runaway nuclear fusion on the surface of an accreting NS/WD
- x-ray lightcurves sensitive to energy released in (α, p) and (γ, p) reactions

Neutrino matter interactions

- Different types of interactions with matter (nucleons, nuclei and charged leptons, photons), e.g. $p + e^- \to n + \nu_e$
- We are concerned with a hot and dense asymmetric matter
  $\to$ we need to consider nuclear correlations
- Overall reactions rates :
  matter composition + individual rates
  - Homogeneous matter : individual rates in dense (and hot) medium
    correlations (RPA) can considerably change rates at high density
- Need predictions for different reactions (absorption/creation via DURCA/MURCA, scattering) including reliably correlations

Neutrino opacities from CC reactions on nucleons

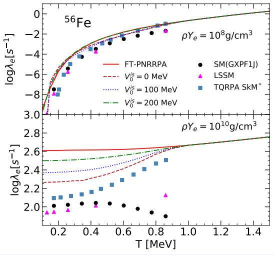


[Oertel 2020]

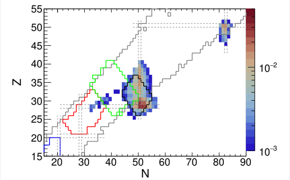
Electron capture on nuclei

- Individual EC rates dominant source of uncertainty during CCSN infall
  [Sullivan 2016,Pascal 2020]
- Fuller (1982) : EC on nuclei suppressed for $Z < 40$ and $N > 40 \rightarrow$ electron capture on free protons dominant
- This is not true !
  Thermal excitations, mixing of states, pairing correlations

EC rates on ^{56}Fe [Ravlic 2020]



Most relevant nuclei for EC [Pascal 2020]

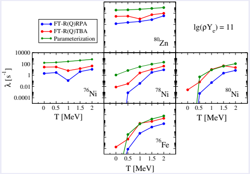


- Calculations using different approaches for nuclear interaction available
  - Shell-model rates [Langanke 2001,. . .]
  - (Q)RPA [Fantina 2012,Ravlic2020,. . .]
  - Finite temperature relativistic nuclear field theory [Litvinova 2018,2020,2021]
- Microscopic rates not available for all relevant nuclei

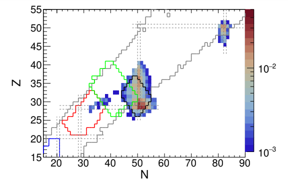
Electron capture on nuclei

- Individual EC rates dominant source of uncertainty during CCSN infall
  [Sullivan 2016,Pascal 2020]
- Fuller (1982) : EC on nuclei suppressed for $Z < 40$ and $N > 40 \rightarrow$ electron capture on free protons dominant
- This is not true !
  Thermal excitations, mixing of states, pairing correlations

EC rates on nuclei around ^{78}Ni [Litvinova 2021]



Most relevant nuclei for EC [Pascal 2020]

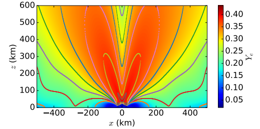


- Calculations using different approaches for nuclear interaction available
  - Shell-model rates [Langanke 2001,. . .]
  - (Q)RPA [Fantina 2012,Ravlic2020,. . .]
  - Finite temperature relativistic nuclear field theory [Litvinova 2018,2020,2021]
- Microscopic rates not available for all relevant nuclei

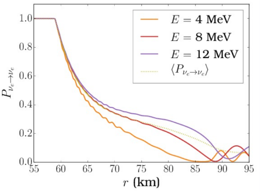
Neutrino flavor conversion phenomena

- Neutrinos modify their flavor in matter via various recently uncovered conversion mechanisms (MSW-like, multiple MSW, collective modes, ...)
- Flavor conversion in dense matter $\rightarrow$ spectral swapping, modified p/n rates $\rightarrow$ modified nucleosynthesis
- Open questions :
  - Interplay of different conversion mechanisms and with neutrino-matter interactions
  - Impact of neutrino flavor conversions on CCSN explosions
  - Impact on nucleosynthesis in CCSN and BNS mergers

Matter-neutrino resonances [Chatelain 2018]



ν_e survival probablity [Chatelain 2017]

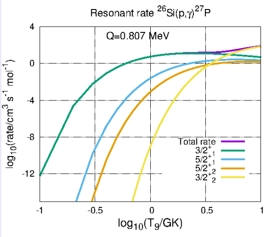


Particle capture reaction rates

Proton capture reaction rates for x-ray bursts and novae

- Large scale shell-model computations of spectra, proton and electromagnetic widths of states in proton-rich nuclei and nuclei along $N = Z$ line possible due to progress in computing and developments of effective charge-dependent interactions :
  - Reactions of high impact : ^{59}Cu$(p, \gamma)^{60}$Zn, ^{61}Ga$(p, \gamma)^{62}$Ge, etc [Cyburt 2016]
  - Evaluation of resonant proton capture rates with detailed nuclear structure input taking into account isospin-symmetry breaking
  - Systematic calculations of reaction rates on the pf-shell nuclei (update of the existing reaction database [Fisker 2001]

Proton capture rate ^{26}Si(p, γ)



[Smirnova et al in prep]]

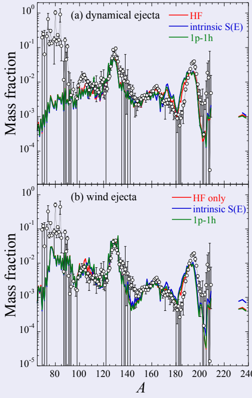
- Objectives : Update of important reaction rates as a more precise input for astrophysical x-ray burst (rp-process) and novae models

Particle capture reaction rates

Neutron capture reaction rates for r-process

- Large scale shell-model computations of spectra, spectroscopic factors and gamma-widths in very neutron-rich nuclei possible due to progress in computing and developments of effective interactions far from stability :
  - Benchmark for other theoretical models used for global modeling of nuclear structure for capture reactions [Goriély 2018]
  - Evaluation of direct neutron cpature rates with detailed nuclear structure input [Sieja 2021]
- Objectives : computation of resonant neutron capture using detailed structure input → reliable capture rates on exotic, neutron rich nuclei

Simulated r-process abundances



[Sieja 2021]]

Some final remarks

EoS is not all!

- Determine reaction rates consistently with matter composition is important(CCSN, NS cooling, BNS ejecta composition, nucleosynthesis, ...), strongly dependent on nuclear correlations
- Nuclear superfluidity (Glitches, NS oscillations, NS cooling) $\longrightarrow$ M. Urban's talk
- Transport properties (NS cooling, oscillations, magnetic field structure)
- Neutrino-Neutrino interactions and flavor conversions

Outlook

- On the experimental and observational side many projects (Super-Kamiokande,DUNE, KM3Net, LIGO/Virgo/Kagra, ET, SKA, NICER, eXTP, ATHENA)
  $\longrightarrow$ need for more precise and complete microphysics data as input for simulations
  $\longrightarrow$ reliable predictions and interpretations of experimental/observational data

Strong expertise in the french community!

Laboratoire Univers et Théories