Impact of nuclear physics in astrophysics

Past activities and some open questions

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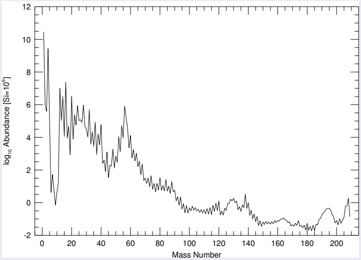
Big questions

We want to understand

1. What are the nuclear processes which drive the evolution of stars, galaxies and the Universe ?
2. Where do the different elements come from forming the building blocks for life ?

- H ($\approx$ 75%) and ^{4}He ($\approx$ 25 %) by far the most abundant baryons known in the Universe
- Different groups of nuclei
  - Light elements up to B (rare)
  - C,N,O, Ne, Mg, Si, iron peak nuclei (much more abundant)
  - Heavy nuclei
- Different sites for the production of these elements (nucleosynthesis)

Solar system abundances [Hix & Thielemann 1999]



1. What is the nature of matter under extreme conditions not reachable in present laboratories ?

French community

Naturally interdisciplinary nuclear physics, astrophysics and theoretical physics → IN2P3, INP, INSU

Nucleosynthesis

- Experiments for key reactions : IJCLab, GANIL, CENBG, IPHC
- Stellar abundance observations : GEPI, CENBG
- Modelling : IAP, LUPM

Compact objects

- Dense matter modelling : LPC, IP2I, GANIL, IJCLab, LUTH
- Experiments (heaby-ion collisions) : GANIL, Subatech, LPC
- Observations : Nançay, IRAP, IPAG, CENBG, Obs. Strasbourg, AIM
- Modelling : LUTH, AIM, IP2I, IAP

Strong connection with gravitational waves (GdR OG), detection of binary neutron star mergers by Virgo/LIGO

Working group activities since 2018

Many activities in common with nuclear physics working group from GdR OG

2018

- September 2018 : around 50 participants at the first group meeting (Observatoire de Paris) ; overview of different subjects

2019

- Workshop on nuclear equations of state in Virgo $\longrightarrow$ negotiations for a neutron star physics group entering the collaboration
- Meeting on possibilities of experiments in nuclear astrophysics with lasers

2020 : covid-19 restrictions strongly impact the activities

- June 2020 : Working group meeting with webinars on Einstein Telescope project, unified equations of state and holographic models for neutron stars

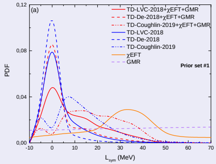
Short review and perspectives

Dense matter properties

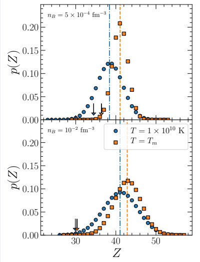
What do we know about the EoS ?

- Constraints from
  - NS masses ($M_{\rm NS} > 1.97 M_\odot$)
  - GW170817 tidal deformability $\tilde{\Lambda}$
  - Nuclear masses, experiments for nuclear matter parameters, . . .
  - Ab-initio neutron matter calculations
  - NS radii (NICER results)

Bayesian analysis with semi-agnostic EoS [Güven 2020]



Inner crust in MCP approach [Carreau2020b]



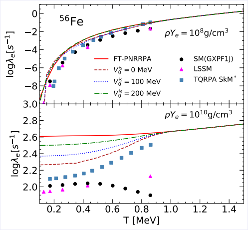
- Some remarks on EoS modelling
  - Meta-modelling approach to the nuclear EoS [Margueron2018,Carreau2020a] developped in addition to phenomenological or ab-initio approaches
  - Importance of unified treatment (homogeneous $\leftrightarrow$ clusterised) matter
  - Still many uncertainties for central part : non-nucleonic degrees of freedom (hyperons, mesons, quarks) might exist
  - CCSN and BNS mergers : need finite T and out of β-equilibrium matter

Reaction rates

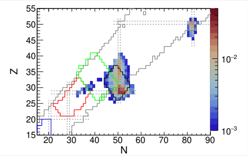
- Different (weak) interaction rates are extremely important ! Neutrino emission for (P)NS cooling, CCSN neutrino signal, BNS merger ejecta composition, ...

  - Overall reaction rates : matter composition + individual rates
    - Homogeneous matter : calculate individual rates in hot and dense medium $\longrightarrow$ collective response
    - Clusterised matter : rates on nuclei far from stability (up to now mostly shell model, some others, e.g. RPA [Ravlic2020,Fantina2012])

EC rates on ^{56}Fe [Ravlic2020]



EC during infall, identification of most important nuclei [Pascal2020]



- Impact on dynamics of CCSN [Pascal2020] : electron fraction at bounce, shock propagation in early post-bounce, $\cdots$

Perspectives

Equation of state

- Much recent progress with NS masses, GW170817, NICER, flexible parameterisations, new data expected from Virgo/LIGO, SKA, ATHENA, ...
- Importance of measuring nuclear matter properties (K,L,...) at $n_B > n_0$ to improve parameterisations
- Better understanding of clusteriseed matter for NS crust and core collapse
- Determine composition and interactions at high densities/temperatures

EoS is not all !

- Neutrino reaction rates consistent with matter composition (CCSN, NS cooling, BNS ejecta composition)
- Nuclear superfluidty (Glitches, NS oscillations)
- Transport properties (NS cooling, oscillations, magnetic field structure)

Many open questions and much work needed, theory, experiment, observations and simulations

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