TITLE: **Modelling dense matter at finite temperature in compact stars**

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The present contribution concerns the following research fields (check the relevant boxes, multiple if needed):

☒ Nuclear astrophysics

☐ Nuclear structure and reactions

☐ Hadronic physics

☐ Particle physics

☐ Astro-particle physics

☐ Cosmology and gravitation

Abstract:

The theoretical description of matter as found in compact objects, such as core-collapse supernovae and neutron stars, is extremely challenging because of the extreme conditions encountered in these objects. A unified and consistent treatment of the different phases of matter is however certainly needed and crucial to provide more realistic astrophysical models thus more reliable interpretation of astrophysical observables.

In this contribution, we focus on the modelling of finite-temperature matter at sub-saturation densities, such as that typically found in the outer layers of the proto-neutron star and in most of the dynamical evolution of the supernova cores. The current state-of-the-art and the different challenges to be addressed in the near future will be discussed.

TEXT (max 5 pages):

Introduction and motivations

Compact objects, such as core-collapse supernovae and neutron stars, are extraordinary laboratories to explore matter in extreme conditions that cannot be currently reproduced on Earth. These astrophysical objects are also thought to be the most probable sites for the origin of stable neutron-rich elements (plus some radioactive elements with long half-life) heavier than iron, produced by the rapid neutron-capture process (so-called r-process) [Arn07].

Despite enormous progress has been done in the last decades to understand and model compact stars, many questions still remain open. From the observational point of view, more and more precise (multi-messenger) observations of these objects are expected in the upcoming years. Therefore, it is timely to develop models of compact objects as realistic and precise as possible, based on up-to-date nuclear (theoretical and experimental) data, in order to correctly interpret astrophysical observations. This requires the development of global reliable microscopic models, that allow a consistent calculation of the different nuclear inputs (such as the equation of state, transport coefficients, etc…) needed for supernovae and neutron-star macroscopic modelling.

The importance of a unified treatment of finite nuclei and infinite matter

The main microscopic ingredients for the description of compact stars are the equation of state and composition of dense matter, and the electro-weak processes (in particular, electron capture), entering neutrino transport[1]. Most of these data currently employed in several numerical simulations are based on nuclear models which are in tension with astrophysical observations, nuclear-physics experimental measurements, and/or ab-initio calculations of homogeneous nuclear matter [Oer17, Bur18]. Therefore, more reliable and as microscopic as possible nuclear inputs, compatible with both nuclear physics and astrophysical constraints, have to be developed. Treating in a unified and consistent way the different phases of matter that are expected to be present in compact stars is a notably challenging task, because of the extreme range of temperature, density, and isospin asymmetry encountered in these objects. However, it is important to stress that a unified treatment, meaning that the same nuclear model is employed for the different regions of the star, is essential to avoid spurious non-physical effects in numerical modelling [For16]. Although several calculations of different nuclear inputs (some of which employing unified modelling) exist at zero temperature[2] and in beta equilibrium, which is an approximation applicable in the description of mature neutron stars, a much smaller number of them are currently available at finite temperature and off equilibrium. In particular, the effects of temperature cannot be neglected in proto-neutron stars, binary neutron-star merger remnants, and in core-collapse supernovae, while off-(beta-)equilibrium conditions can be met in both supernova and merger environments, as well as in accreting neutron-star crusts, introducing additional complications to the calculations. A theoretical consistency between the calculations of the different microscopic inputs is not only important for the equation of state, but also for the nuclear processes that critically depend on the matter composition. This is the case for electron-capture rates in core-collapse supernova[3], for nuclear processes related to the heat released in accreting neutron stars [Fan18, Lau18], and for

[1] More details on the equation of state above nuclear saturation and its connection with the constraints coming from gravitational-wave observations are given in the contribution to these "prospectives" by J. Margueron et al., and aspects related to the weak interaction processes are discussed in the contribution by M. Oertel et al.

[2] A more thorough discussion on the current approaches at zero temperature for the crust of neutron stars, and related challenges, are discussed in the contribution by M. Urban et al.

[3] See contribution by M. Oertel et al.

neutrino interactions that govern the transport properties during the proto-neutron-star formation and cooling [Sch18]. In the latter scenario, a crucial ingredient in the modelling is represented by transport coefficients, that need to be calculated consistently with the employed equation of state, i.e. within the same nuclear model. In particular, in current cooling simulations, the presence of the different nuclear species is taken into account in an approximated way through an "impurity parameter", taken as a free parameter adjusted on cooling observational data.

Sub-saturation nuclear matter at finite temperature

In this contribution, we concentrate on the modelling of finite-temperature matter at densities below the saturation density of symmetric nuclear matter, such as that found in the outer layers of the proto-neutron star as well as in most of the dynamical evolution of the supernova cores. From the astrophysical point of view, although the (proto-)neutron-star crust contributes only about one percent to the stellar mass, it is essential for many astrophysical phenomena associated with neutron stars, such as glitches[4], X-ray bursts, thermal radiation of soft X-ray transients in quiescence, and (proto-)neutron-star cooling [Cha08]. From the theoretical point of view, the description is particularly challenging because matter is clusterised and finite temperature implies a thermodynamically consistent consideration of all the possible microstates. Ab-initio methods such as quantum Monte-Carlo calculations employing realistic nucleon-nucleon interactions from chiral perturbation theory can bring powerful constraints for homogeneous matter, but are currently not affordable to describe inhomogeneous matter. Therefore, one has to rely on more phenomenological approaches, rooted on the nuclear energy density functional theory, which can in principle be applied in the wide thermodynamic conditions spanned in different compact-object scenarios (isolated and accreting neutron stars, and supernova). The use of sets of functionals, whose parameters are adjusted on the most up-to-date experimental and astrophysical constraints, allows to perform systematic sensitivity studies taking into account our current nuclear-physics knowledge, thus addressing the question of the model dependence and quantifying the uncertainties in the predictions of astrophysical observables.
Within this general theoretical framework, different aspects need to be addressed in the near future:

- The presence of a ***statistical distribution of nuclei*** at finite temperature requires to go beyond the standard Wigner-Seitz approximation. Though extensive microscopic calculations with quantum molecular dynamics or Time Dependent Hartree-Fock are in principle possible [Nan18], the most flexible possibility is to switch to cluster degrees of freedom [Gul15, Gra18, Pai20, Fan20, Car20]. The drawback of the approach is that beyond mean-field effects such as pairing are not easily accounted for, and nuclei have to be treated as open systems in the medium of their continuum states. The simultaneous presence of bound and unbound states leads to a modified statistical counting, and to ***in-medium modifications of the nuclear energies***, both due to the Pauli-blocking effect of the continuum states. All these effects can be easily addressed for few-body systems [Rop15] or in the bulk approximation [Mal21], but a systematic microscopic evaluation of the energy shifts requires both theoretical and numerical developments, as well as collaborations with the nuclear structure theorists.
- Complementary to the previous point, in-medium modifications to the nuclear energies can be constrained through extensive ***comparisons of different mean-field models with cluster degrees of freedom to experimental measurements***. Heavy-ion collisions in the

[4] See contribution by M. Urban et al.

Fermi energy domain, where these clusters are copiously produced, are ideal tools for this purpose [Pai20].

- The presence of a distribution of nuclei at finite temperature might also lead to impurities in the catalysed as well as accreted crust, with potential important consequences on a number of astrophysical phenomena. This happens if the composition of the crust is frozen at temperatures higher than the crystallization temperature. To settle the issue, the ***crystallization of a multi-component plasma*** has to be calculated with realistic nuclear inputs in order to evaluate the crystallization temperature and the associated impurity factor. At the same time, hydrodynamical calculations of the cooling process including the different reactions rates must be performed to compare the cooling and reaction time, and estimate the freeze-out time of the crust composition.
- The study of the crystallization of the neutron-star crust in a multi-component approach has a theoretical interest in itself, because of the difficulties related to the determination of the ***phase diagram*** and the associated latent heat [Med10, Med11]. The latter issue has been long investigated in the context of white dwarfs, because of the direct connection with astrophysical observations and cosmochronology [Fon01, Tre19]. However, in the case of neutron stars, the situation is expected to be very different considering the more massive nucleides involved and possible ***influence of magic numbers and their modification*** in very neutron-rich matter.

- Weak processes involving electrons and neutrinos play a major role in transport properties of compact stars[5]. In the thermodynamic conditions where matter is clusterised, those processes can occur on finite nuclei as well as non-spherical cluster shapes collectively known as nuclear "pasta". When the dynamics occurs over very short time scales as it is the case of core-collapse supernova, early proto-neutron star cooling and binary mergers, the Boltzmann equation should be directly simulated coupled to the hydrodynamical evolution, which is a very hard theoretical and numerical task. However, in many other phenomena associated to slower time scales, such as isolated neutron-star cooling, X-ray transients and relaxation after accretion, the ***relaxation time approximation*** can be safely employed, and the dynamical evolution is ruled by ***transport coefficients*** such as thermal and electrical conductivity and viscosity [Sch18]. Depending on the temperature domain, the effect of matter inhomogeneities can be recast in a global ***impurity factor***, or it requires the computation of the ***static and dynamic structure factor of the nuclei or pasta structures,*** together with the distribution of the different nuclear species. Self-consistent and more microscopic calculations of the impurity parameter have started [Fan20, Car20], but consistent calculations of transport properties and their implementation in numerical simulations of (proto-)neutron-star cooling have still to be performed.
- Quantitative advance in our understanding of the complex astrophysical phenomena involving compact stars will only be achieved if the microscopic inputs are consistently implemented in macroscopic hydrodynamical simulations[6]. To this aim, an important and collective effort must be undertaken to produce sets of data in an open data format that can be directly exploited in hydrodynamical simulations and/or in the analysis of observational data. A huge progress in this direction has already been achieved through the creation of ***open access repositories such as the CompOSE repository*** [CompOSE]. The international visibility of the research of the French community in

[5] See contributions by M. Oertel et al. and J. Margueron et al.
[6] See contribution by J. Novak et al.

the next decade clearly depends on our collective capability of improving and promoting the database for a generalised use in the astrophysical community.

Conclusions

The strongly interdisciplinarity of this field requires collaborations among researchers in nuclear physics and astrophysics. Indeed, the microscopic inputs needed for compact-star modelling have to be implemented in numerical simulations in order to extract reliable predictions on global astrophysical observables (both static and dynamical properties) thus to be able to compare with observations. Such collaborations already exist, both at national and international level, and it is certainly important to strengthen and extend these cross-field collaborations.

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