**TITLE: Weak interaction rates in compact star physics**

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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:** Neutrinos play an important role in compact star astrophysics: neutrino-heating is one of the main ingredients in core-collapse supernovae, neutrino-matter interactions determine the composition of matter in binary neutron star mergers and have among others a strong impact on conditions for heavy element nucleosynthesis, and neutron star cooling is dominated by neutrino emission except for very old stars. The corresponding weak interaction rates have to be determined for conditions very different from terrestrial laboratories, since compact star matter is very neutron rich and can reach densities far above nuclear matter saturation density. Many astrophysical simulations use analytic approximations for the interaction rates which are often far from reproducing more complete calculations. A collective effort shall be undertaken to perform the latter calculations for the different relevant thermodynamic conditions and provide the corresponding data for simulations.

**Context:** The first detection of gravitational waves (GWs) from a binary neutron star (BNS) merger (GW170817) by the LIGO-Virgo collaboration (LVC) [Abbott2017] together with an electromagnetic counterpart has brilliantly given birth to multi-messenger astronomy. During the O3 campaign of LVC which started in April 2019, many new detections have been reported, in particular one BNS merger GW190425 [Abbott2020a], and another event with an object which could be the heaviest neutron star (NS) ever measured [Abbott2020b], thus challenging all our present theories on the NS equation of state (EoS). In the coming years, the GW detector network sensitivity will be further increased making this rapidly evolving new astronomy revolutionize the exploration of the Universe and address fundamental questions on the nature of gravity, of dark matter, the origin of elements heavier than iron, the properties of dense matter in NSs and the structure of these compact stars themselves. In addition to binary mergers, future multi-messenger observations include the possibility of a galactic core-collapse supernova (CCSN), where the GW and neutrino signal carry in particular the imprint of the yet poorly understood explosion mechanism and dense matter properties. A complete understanding of these exciting observations will be achieved once they can be modeled successfully. Many questions still remain open, among others about microphysics properties including neutrino reaction rates. The latter play an essential role for astrophysics of compact objects :

1. The dynamics of BNS mergers only marginally depend on neutrino interactions. However, ejecta composition and nucleosynthesis conditions are very sensitive to the neutrino treatment and neutrino interactions.
2. The heating by neutrinos of the stalled shock wave represents a crucial element for CCSN dynamics, contributing to the explosion mechanism
3. (Proto)-neutron star cooling is dominated by neutrino emission for about a million of years.

Simulations of these processes are computationally very expensive, such that currently mostly analytic expressions for the relevant reaction rates [Bruenn1985, Rosswog2003,Schmitt2018] are applied, which are, however, based on very crude approximations. Several corrections have been added to the original expressions, such as weak magnetism and recoil [Burrows1998, Horowitz2002], nuclear structure corrections [Horowitz1997, Bruenn1997], effective masses and chemical potentials for nucleons in dense matter [Roberts2012, Martinez-Pinedo2012], additional reactions [Hannestad1998, Fischer2020] and superfluidity in cooling neutron stars older than several minutes [Yakovlev2001]. Nuclear physicists have, however, pointed out since decades that in dense matter different effects can modify the neutrino matter interaction rates and neutrino emissivities by orders of magnitude, in particular collective effects [Reddy1999]. (Special) relativistic effects can play an important role, too [Leinson2001, Leinson2002].

The conditions for BNS mergers, CCSN and early (proto)-neutron star cooling are thereby rather similar: hot and dense nuclear matter with different asymmetries, i.e. proton to neutron ratios. In the central and hot parts, matter is homogeneous, whereas the outer regions, containing more dilute and cold matter, nuclear clusters are found and form a crust in older neutron stars. For the latter, conditions are different, since starting at several minutes after birth in a CCSN, matter can be considered as cold and superfluid components appear which strongly influence the interactions. For the actual observed neutrino signal, in addition (collective) neutrino oscillations are important, see the contribution by C. Volpe and references therein.

In order for astrophysical simulations of compact objects to be reliable, state-of-the art nuclear physics input should be included. The EoS data base, Compose[1], initiated by the European Compstar network is a recent example of efforts undertaken to provide realistic nuclear physics data to the community. In view of the

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[1] https://compose.obspm.fr

importance of neutrinos in the above mentioned scenarios, it is essential to extend this effort and provide state-of-the-art neutrino-matter interaction rates under conditions relevant for the three above mentioned scenarios in a way such that they can be directly applied to simulations. This work is necessary to predict reliably the gravitational wave and correlated neutrino signal from these compact star sources, preparing the next science runs of LIGO/Virgo and the third generation detector Einstein Telescope in a multi-messenger context together with the neutrino detectors.

**Neutrino-matter reaction rates under conditions of BNS mergers and CCSN**. Among the dominant reactions to be considered in the core up to the neutrinosphere are neutrino-nucleon scattering (neutral current, NC) and neutrino absorption and creation (charged current, CC) reactions on nucleons (neutrons and protons). As mentioned above, the aim is to provide results for the interaction rates going beyond the simple analytic approximations. Full (special) relativistic kinematics and in particular collective effects are important in this context. For CC reactions, these collective effects have been incorporated in publicly available rate tables, tested within CCSN simulations [Oertel2020]. They have been treated with the so-called “random phase approximation” (RPA) which has been proven very successful in nuclear physics, e.g. for describing giant resonances. Much effort has been devoted, too, to determine the nucleonic response function -basis of the calculation of the neutrino reaction rates- in dense matter and hot matter in RPA, see e.g. [Pastore2014] for a review. The first simulations with improved rates show noticeable differences in the location of the neutrinospheres in the early post-bounce phase. On the technical side, computing time is only slightly increased with respect to employing analytical rates. It is, however, extremely important to treat scattering and absorption/creation reactions on the same footing to correctly determine neutrino luminosities and propagation and thus among others the conditions for establishing weak equilibrium in the center, the position of the neutrinosphere, and matter composition. The formalism shall thus be extended to neutrino scattering reactions. Under some thermodynamic conditions, the basic reactions are kinematically suppressed and the presence of so-called “spectator” nucleons is required for the respective process to take place. Technically this is described by including at least two-particle-two-hole states in the response of nuclear matter. Another issue is that many models predict in addition to nucleons the presence of hyperons (strange baryons) or quarks in the core of neutron stars and in the hot central regions of BNS mergers and CCSN. Neutrino reactions on these particles have to be considered, too, among others to determine the conditions for establishing weak strangeness changing equilibrium. Holographic QCD techniques can thereby help to improve our knowledge of weak processes and transport phenomena in dense quark matter, see the contribution by F. Nitti.

Concerning inhomogeneous matter, it has been pointed out in CCSN simulations [Pascal2020] that the uncertainties on the electron capture (EC) rates on individual nuclei during infall induce stronger modifications on the mass of the inner core at bounce and the maximum of the neutrino luminosity peak than the progenitor model or the EoS. The results indicate that the simulations are most sensitive to the EC rates for neutron-rich nuclei near the N=50 closed shell and to less extent to the next closed shell at N=82. The main difficulty is that for the relevant nuclei not much information is available, neither experimentally nor from microscopic calculations. The situation is nevertheless expected to improve in the near future due to dedicated experimental research programs. On the theoretical side, total EC rates are influenced as well by the nuclear distribution given by the EoS, as by the rates on individual nuclei, suffering both from strong uncertainties. Uncertainties in matter composition mainly stem from the definition of clusters in a hot nuclear environment and nuclear properties far from the stability valley. Uncertainties in rates on individual nuclei are mainly due to nuclear structure and finite temperature effects and only for a few relevant nuclei microscopic results exist, either from the shell model [Langanke2001], from (Q)RPA [Fantina2012,Ravlic2020] or from the finite temperature response theory [Litvinova2018,Litvinova2020], taking into account the coupling between single-nucleon and collective degrees of freedom. A correct treatment of nuclear correlation is crucial in this context, since electron capture rates can be considerably modified, see e.g. [Litvinova2021]. Similar problems appear for nuclei relevant for r-process nucleosynthesis: the r-process path is determined by the competition between (rapid) neutron capture [Sieja2021] and the subsequent beta-decay of very neutron rich nuclei.

**Cooling of neutron stars** The cooling of NSs during the first 50-100 years, when the crust stays hotter than the core, and the afterburst relaxation in x-ray transients are dominated by processes in the neutron star crust. Reactions on the electron gas were long supposed to be largely dominant, since in particular in the inner crust superfluidity strongly suppresses reactions on individual neutrons. However, as shown for the specific heat [Grasso2008, DiGallo2011, Martin2014, Durel2018], considering collective excitations is important in this context, too (see also contribution by M. Urban). For older neutron stars, neutrino emissivities from the homogeneous matter in the core are essential. As discussed above for the case of hot matter present in CCSN and BNS merger remnants, here again, collective excitations of the dense matter are important and can considerably change the resulting rates. They should therefore be included in the neutrino rates and heat transport properties for older neutron stars, too. Very quickly NSs cool down to temperatures where they contain superfluid components (neutrons, protons and potentially quarks). This gives rise to an additional neutrino emission mechanism, the pair breaking and formation (PBF) process, with an important impact on cooling phenomenology. Therefore, the formalism has to be extended within the quasi-particle RPA (QRPA), see e.g. [Baldo2017] for an application to matter in the neutron star core and [Khan2005, Grasso2008, Martin2014] for the crust. Although not as computationally demanding as CCSN and BNS merger simulations, modeling NS cooling is expensive, such that currently mainly analytic expressions for the reaction rates [Schmitt2018] are applied which do not always consider state-of-art knowledge about nuclear correlations in the dense medium.

**Outlook:** On the experimental and observational side, many projects are underway or planned for the near future which will give us information about compact stars, combining different signals from a multi-messenger perspective. These include neutrino detectors (e.g. DUNE, Kamiokande, KM3NeT), gravitational wave detectors (LIGO/Virgo/Kagra and the 3rd generation detectors EinsteinTelescope and Cosmic Explorer), the radio telescope SKA and x-ray observatories (NICER, eXTP). In the light of these more and more precise and complete data, we need to improve the theoretical models of the nuclear microphysics input in relation with the global numerical modeling (see contribution by J. Novak). Concerning weak interaction rates, in the French community a lot of expertise is availaible to provide as a common effort these rates including nuclear effects for neutron rich nuclei and dense (and hot) neutron rich matter coherently with an underlying EoS, ready for use in simulations, and translate the outcome to reliable predictions for the observable neutrino signal.

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