Prospectives Nationales 2020-2030
Physique Nucléaire et Astrophysique Nucléaire

Compact stars and matter at extreme conditions

1. General context

One of the big challenges of nuclear physics is to understand matter at extreme conditions of density, isospin asymmetry, and temperature, as they prevail in compact stars, core-collapse supernova explosions, and neutron-star mergers. This includes questions which are directly relevant for our understanding of atomic nuclei, for instance concerning the symmetry energy of nuclear matter, but also very fundamental questions, for instance whether dense matter undergoes a phase transition to deconfined quark matter. One hopes to find answers to these questions by studying compact astrophysical objects, which in this sense can be considered as nuclear physics laboratories.

Vice versa, stunning astrophysical observations such as X-ray outbursts, pulsar glitches, supernova neutrinos, and very recently even gravitational waves from neutron-star mergers, call for explanations which require modeling from scales ranging from km down to fm. On the smallest scales, input from nuclear theory is needed. This field is therefore characterized by an intense exchange between observers, theorists working on the macroscopic models, nuclear theorists, and nuclear experimentalists.

2. Astrophysical observations

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Neutron stars, supernovae and kilonovae are observed in a large variety of different signals: electromagnetic waves ranging from radio frequencies to gamma, neutrinos, and most recently also gravitational waves. A strong effort is also made to combine the different signals. This “multimessenger astrophysics" turned out to be very powerful. For instance, it revolutionized our understanding of the nucleosynthesis of heavy elements through the r-process.

In the next ten years, a lot of progress can be expected from gravitational waves with present interferometers (LIGO, Virgo), which allowed already to extract from a single observed neutron-star merger information on the masses, radii and tidal deformability of the two neutron stars. The upgrades of the LIGO and Virgo interferometers, as well as the joining of future ones (KAGRA and LIGO India) will increase the number of detected events. A second revolution is expected from the third generation of interferometers (cosmic explorer and Einstein Telescope). Furthermore, future observations in X rays with XMM-Newton and NICER, later also Athena X-IFU, will continue to improve the current constraints on neutron-star radii based on existing and promising methods. Precise radius measurements are very important since the mass-radius relation contains information on the equation of state of dense matter.

Finally, radio timing of binary pulsars has enabled dozens of neutron star mass measurements, some of them with very high accuracy, and will continue to do so, especially in the advent of MeerKAT and SKA. The accurate measurement of millisecond pulsar spin periods and spin down rates also provides unique input for gravitational wave emission searches at twice the spin frequency with ground based interferometers. Those searches have already put stringent constraints on the oblateness of neutron stars. Many more pulsars (rotating neutron stars) will be discovered in radio (SKA) and gamma (Fermi) and precise timing measurements will allow one, e.g., to extract information on their magnetic field and age. Observation of more pulsar glitches (sudden speed-up of the rotation) will help to constrain pairing in neutron-star matter via the moments of inertia of the superfluid neutrons.

3. Macroscopic modeling

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The birth of a neutron stars is the consequence of the contraction of the stellar core of massive stars, which liberates sufficient gravitational energy to power the supernova explosion. In consequence, the properties of the explosion and its outcome depend crucially on the equation of state of neutron rich matter at nuclear densities and neutrino interactions which determine the efficiency of energy extraction. Direct signatures of this process are expected from the detection of gravitational waves and neutrinos. Later signatures include the distribution of newly synthesized nuclei and the mass, kick, spin properties of the compact remnant. The modeling of the engine of supernova explosion is now progressing towards a systematic exploration of the huge parameter space of initial conditions with ab-initio 3D simulations which are numerically challenging complemented with 1D modelling based on carefully chosen physical prescriptions.

Once formed, the evolution of the proto-neutron star (PNS) can be constrained from the observation of emitted gravitational waves and neutrinos. For older, isolated neutron stars, the surface temperature can be observed. Those stars have been modeled in some details now but still, new ingredients need to be added: in particular global models of elastic crust seem very important for star oscillations, which can be seen in gravitational waves, and for most of observable electromagnetic properties. Such crustal models may be coupled to the dynamics of the magnetic field to model bursts from magnetars, for instance. Another important motivation for cold neutron star models comes from the observation of glitches (sudden spin-up in the rotation observed in pulsars). These models require either the inclusion of a superfluid component, coupled with the crust or, again, the dynamics of the crust.

Binary neutron star mergers are now extensively studied, yet there are several improvements that need to be made. First viscosity effects must be identified and numerical viscosity separated from physical one. Then, magnetic field effects (again) have to be taken into account in a realistic way. Finally, post-merger object, which is supposed to be a super- or hyper-massive neutron star in strong differential rotation, must be studied with more emphasis on the microphysics happening there: viscosity, neutrino transport, etc. The kilonova signal depends strongly on conditions for r-process nucleosynthesis, dependent among others on ejecta composition, and on rates for the r-process itself.

4. Microscopic theory

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The macroscopic models require input from microscopic nuclear theory, such as in particular the equation of state. It directly determines the mass-radius relation of neutron stars and the tidal deformability of binary mergers, and it is an important ingredient of the hydrodynamic evolution of a supernova or neutron-star merger, etc. The recent measurement of gravitational waves helps to further constrain the equation of state, and extra constraints from the after-merger GW signals are expected in the future. Concerning densities up to roughly saturation density, it may be expected that within the next decade, important progress will be made within ab-initio theory (starting from realistic NN and 3N interactions). An important open problem is to produce consistent equations of state that describe at the same time the non-uniform phases of the neutron-star crust and the uniform matter in the core. In this density range, an efficient technique consists in using a meta-modeling of microscopic density functionals, because the parameters of the meta-models are better constrained by ab-initio, experimental and observational data than the much larger number of free parameters in typical phenomenological nuclear energy density functionals. At higher density, deeper in the core, one expects that additional particles such as hyperons should be present in matter, which tend to soften the equation of state too much unless a repulsive hyperon interaction is added. However, the in-medium properties and interactions of the hyperons need further investigations and have to be constrained also by data from hypernuclei. At even higher density, quark matter may appear. Since lattice QCD is not applicable at finite density, one has to rely on effective quark models. For the modeling of supernovae and neutron-star mergers, it will be necessary to extend all equations of state to finite temperatures (in the core collapse and in the post-merger phase of binary mergers, the temperature can reach up to 100 MeV) and out of beta equilibrium. The observable signals of the different phase transitions need to be identified. Besides the equation of state, also the viscosity is an important ingredient of hydrodynamic simulations and needs to be studied from the microscopic point of view.

Other aspects that will be investigated in the next decade are electroweak cross sections. Electron capture and neutrino transport play a crucial role in supernova simulations. Neutrino reactions determine also the ejecta composition of binary neutron-star mergers, and neutrino emission is the most efficient cooling mechanism in neutron stars. The most important electron capture processes in the collapse phase concern exotic nuclei for which no microscopic calculation of the rate is available. Moreover in dense matter, the cross sections are strongly modified by nuclear many-body effects. In the case of Cooper pairing of neutrons, also the direct production of neutrino-antineutrino pairs is possible, and this process needs further investigations.

Pairing in neutron and neutron-rich matter has also other observable consequences, such as modified cooling curves due to suppressed specific heat, and pulsar glitches as a consequence of superfluidity. The density dependence of the pairing gaps is a long-standing open problem and we hope that detailed neutron-star observations will help to solve it. Furthermore, the superfluid density in the inner crust, which directly affects pulsar glitches, may be suppressed by entrainment between superfluid neutrons and clusters. But the strength of the entrainment is still under debate and we hope that a consensus can be reached in the next years.

In order to test the different theoretical scenarios, it is extremely important that the theoretical results for all the microscopic properties of dense matter mentioned above are provided in a form that makes them easy to use by the community of macroscopic modelers. In the case of the equations of state, a lot of effort in this direction has recently been made (COMPOSE data base https://compose.obspm.fr). This needs to be generalized also to the other properties (electron capture and neutrino cross sections, superfluidity, etc.).

5. Nuclear physics experiments

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The characterization of the equation of state of nuclear matter is one of the main research subjects of the nuclear-physics community and a crucial ingredient to any neutron-star or supernova simulation. In astrophysical situations, matter is typically very asymmetric (neutron rich). Therefore, the isovector dependence of the equation of state, in particular the symmetry energy and its density dependence, needs to be studied. In-medium properties of clusters need also to be measured since clusters are expected to affect the neutrino mean free path in

astrophysical media. This will be done with the help of heavy-ion collisions at energies around the Fermi energy (<100 MeV per nucleon) and higher. The measurement of exclusive data with high resolution (charge, mass, energy) will allow us to provide much more stringent experimental constraints for the parametrization of the symmetry energy as a function of the density than it is the case today, in particular at subsaturation densities as they prevail in the neutron-star crust. This research field is complementary to the studies of the symmetry energy at higher energies (beyond 100 MeV per nucleon) and thus higher densities, as done at accelerators such as GSI or RIKEN. Conditions of density and temperature corresponding to neutron-star mergers are for instance studied by the HADES collaboration (see GT03).
Another key ingredient of core-collapse simulation is the deleptonization rate, which is governed by the electron capture rate on extremely exotic nuclei close to the N=50 shell closure around ^{78}Ni. Microscopic calculations of these quantities need crucial inputs from experimental physics, notably the Gamow-Teller strength that can be measured in beta decay and charge exchange reactions.
Valuable inputs come also from studies of giant (GR) or pygmy (PR) resonances, in particular of the isoscalar giant monopole resonance (GMR) and of isovector giant and pygmy dipole resonances (GDR/PDR). Their properties can not only be used as a robust test for modern density-functional approaches, but they also constrain the equation of state of asymmetric matter. GMR energies in nuclei with increasing N/Z ratio are sensitive to the symmetry energy through their dependence on the incompressibility of the neutron-rich matter. In the case of dipole excitations (GDR or PDR), two observables are crucial for nuclear matter studies as they are sensitive to the density dependence of the symmetry energy: the electric dipole polarizability and the neutron-skin thickness. Both GDR and PDR need in particular good knowledge of the dipole strength at low energy and for all the cases, monopole or dipole resonances, a study should be done along an isotopic chain in order to understand how their properties develop.
It is clear that many links can be found between the topics "compact stars and matter at extreme conditions" and "nucleosynthesis". These aspects, X-ray bursts for example, are presented in the contribution "Nucleosynthesis".

6. Needs of the community for the next decade

As discussed in the preceding sections, this field is strong interdisciplinary. Even if astrophysical observations are somewhat at the limit of the activities of IN2P3, there are close collaborations with theoretical and experimental groups from IN2P3. It is important to maintain and extend these collaborations, e.g., by hiring researchers across the boundaries of the institute, as it was done when there was the interdisciplinary section 47.

To make the link between microphysics and observations, the field of macroscopic modeling is of crucial importance. However, compared to other countries such as Germany, USA, and Japan, this community in France is very small and clearly needs to be reinforced. For instance, the topic of global simulations of nucleosynthesis is not covered at all, and the efforts to understand the hydro-dynamics of core-collapse supernovae and mergers (kilonovae) rely on very few people. We believe that it would be beneficial for IN2P3 to get more strongly involved in the field of these simulations since it gives also more importance and visibility to (experimental and theoretical) microphysics results if they are included in global models and compared with observations.

Concerning the microscopic modeling, we realize that the open questions require research activities in many different directions and using also very different theoretical approaches. We therefore rely on IN2P3 to hire young permanent researchers, postdocs, and PhD students in support of this community. We also need infrastructures for high-performance computing (cf. GT09).

From the experimental point of view, exotic beams are required, especially of neutron rich nuclei, both at low energies for beta-decay studies and in the Fermi-energy domain (10-100A MeV) for scattering and reaction experiments. For the low energies some beams of interest are available at the ALTO facility which would need however to be complemented by a beam purification device such as a double penning trap and a total absorption spectrometer (TAS) for the beta-decay studies. Phase 2 of SPIRAL2 coupled to DESIR would be the dream facility for such studies.
SPIRAL2 Phase 2 (or alternatively SPES or HIE-ISOLDE) could also provide re-accelerated neutron-rich beams for reactions, albeit at energies below 10A MeV, too low for most of the studies proposed here, in particular symmetry energy, giant resonance and charge-exchange measurements. As of today no ISOL facility plans re-acceleration above 10A MeV, so in-flight facilities such as FAIR and RIKEN will have to be used. Both of these facilities plan specific beam lines to deliver beams in the Fermi-energy domain. Detectors such as FAZIA/INDRA and ACTAR are well suited for these studies.
The EURISOL facility would cover all the above requirements but hope for constructing someday this facility has dwindled in recent years.