Abstract for the general public

The macro world around us that is under the scope of low-energy physics is a complex composition that includes several structure levels. The fundamental particles on the lowest level are called quarks. They combine to form neutrons and protons, nucleons (including up and down quarks), which make nuclei. These nuclei surrounded by electrons construct atoms that join together to make molecules and other chemical substances. The scientific achievements in physics have been always surprising and opened new windows in probing the universe. The standard model of fundamental particles is one of them that revealed the existence of particles that we were less familiar with. All different elements interact with each other in different ways through the exchange of particles. Over short distances gluons, mesons, and other types of bosons are the relevant mediators of the forces. Photons and gravitons describe the long-range electromagnetic and gravitational interaction. The most compacted matter on the earth is found in heavy nuclei which can be studied in heavy-ion collision (HIC) experiments. These high densities are interesting to investigate because exotic forms of matter and particles with one or two strange quarks can potentially appear while they are not found in ordinary matter. Therefore, the standard model, by proposing a surprising quantum number, strangeness, made it possible for us to have other states of the hadron classification that nucleons are also a part of them: hyperons. These amazing particles with "strange" flavor open new windows for our understanding of matter at higher energy and the extreme conditions of density and high temperature. One of the best places to explore matter under extreme conditions with densities higher than the density produced in HIC is astrophysical object called neutron star (NS). Recent astrophysical observations have shown us signatures for the appearance of hyperon in the core of NS, which are a natural laboratory for such extreme conditions. In the core of NS, not only we expect the appearance of substantial amounts of hyperons but also there is evidence for appearing deconfined quark matter accompanied by a phase transition from hadronic to quark matter when the density increases.

It is worth mentioning that hyperons have found their footprint in the earth's nuclei, and nuclei which contain hyperons have been discovered called hypernuclei. Besides the rich physics that is responsible to study them called hypernuclear physics, in a simple view, their importance in nuclear physics can be compared with muonic atoms in atomic physics. Although about 70 years have passed since the discovery of the first hypernucleus in 1952, still we encounter a lot of unknowns about them and there are several puzzles and questions that have to be answered in this field. One of the main questions is related to the full understanding of nucleon-hyperon and hyperon-hyperon interactions. Using experimental data from HIC, more accurate hyperonic potentials will be provided. Those potentials will be employed in many-body approaches to obtain the equation of state (EoS) of hypernuclear matter. Microscopic calculations of the EoS of dense matter profoundly affect our understanding of the origin and the thermodynamic properties of matter. During this project, I will obtain a more comprehensive EoS within two different theoretical approaches. One of them is based on the baryon-meson interaction in the mean-field approximation which includes the chiral partner of baryons for realizing the chiral symmetry restoration in the hadronic sector called the parity doublet model. The second approach is a potential-based method called the lowest order constrained variational (LOCV) method which employs the realistic potentials for each pair of baryons. I will compare their results to investigate the main capabilities of each approach in reproducing the experimental and observational data. Moreover, the obtained EoSs will be employed to construct either a first-order or crossover phase transition from hypernuclear matter to deconfined quark matter to investigate the required situations for this transition. It has been demonstrated that NS observational constraints can be used to narrow down the variation of predictions for the onset of this phase transition. Including hyperonic degree of freedom deeply affects the thermodynamic properties of the matter in the core of NS or hot and dense quantum chromodynamics (QCD) matter. From the physical point of view, this degree of freedom is expected at high densities therefore, the new results obtained from the updated EoSs would be more reliable for predicting the QCD phase diagram which describes strongly interacting matter over the whole range of density and temperature. The new EoS should be able to reproduce the nuclear saturation properties at low densities and the observational constraints for the mass and radius of NS at high densities. Such an EoS could be used in both astrophysical and HIC applications and its results will be probed in future HIC at FAIR, NICA, and the low-energy relativistic HIC facilities.