The many facets of the (non-relativistic) nuclear equation of state

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A nucleus is a quantum many body system made of strongly interacting Fermions, protons and neutrons (nucleons). This produces a rich Nuclear Equation of State whose knowledge is crucial to our understanding of the composition and evolution of celestial objects. The nuclear equation of state displays many different features; first neutrons and protons might be treated as identical particles or nucleons, but when the differences between protons and neutrons are spelled out, we can have completely different scenarios, just by changing slightly their interactions. At zero temperature and for neutron rich matter, a quantum liquid gas phase transition at low densities or a quark-gluon plasma at high densities might occur. Furthermore, the large binding energy of the α particle, a Boson, might also open the possibility of studying a system made of a mixture of Bosons and Fermions, which adds to the open problems of the nuclear equation of state.

Many aspects of the Nuclear Equation of State (NEOS) have been studied in large detail in the past years. Finite nuclei resemble classical liquid drops, the crucial difference is that the nucleus in its ground state, or zero temperature, does not `solidify' similarly to a drop at low temperatures. This is due to the quantum nature of the nucleus: more specifically its constituents, neutrons (n) and protons (p), are Fermions. They obey the Pauli principle which forbids two equal Fermions, two protons with the same spin or two neutrons with the same spin (either both up or both down), to occupy the same quantum state. Thus at zero temperature, two or more Fermions cannot be at rest (a solid) when confined in a finite volume. In order to constrain the NEOS, we need to use the thermodynamic concepts, therefore we need to create in laboratory equilibrated systems at temperature T and density ρ.

In this review paper [1], the starting point of the NEOS is the understanding of the nucleus in its ground state. The paradigm of the nuclei is the liquid drop model and the Weizsäcker mass formula. Using a simple Fermi gas formula which takes into account finite sizes and neutron-proton asymmetries, we discussed the finite effects and symmetry energy. Then we review the approach to extract symmetry energies with isobaric analog states. After this, we proposed a Skyrme type NEOS at zero temperature assuming the interaction is local and there is a second order phase transition from nuclear matter to quark gluon plasma. We study the physical quantities, S (symmetry energy), L (slope of symmetry energy) and Ksym (curvature of symmetry energy) with different assumptions. We demonstrate that these quantities are coupled. We also review the NEOS with momentum dependence and effective mass of nucleons at zero temperature. Then we extend our NEOS at zero temperature to temperature dependence assuming the nucleons system is in Fermi case or classical case. The results show we need to be careful for both cases since the behavior of nuclear matter might seem reasonable in a given region but not so in another. Then we review the finite size effects of one of temperature dependence NEOS and compare the results with ones from experiments and percolation model. The knowledge of the NEOS is necessary to explain observed celestial objects and events. We briefly review the relevance of NEOS in case of neutron stars. We test our NEOS and 150 Skyrme NEOS with the mass and radius relation of neutron stars. A good correlation between the mass and radius with Ksym has been shown. The simulation models have played an important role helping us understand what happened in heavy ion collisions. We recall some features and differences of the popular simulation models. Boltzmann-Nordheim-Vlasov (BNV) and Constraint Molecular Dynamics (CoMD) models have been used to study the neutron skin and Giant Resonances (GR) with different NEOS. The models's results are compared with the experimental measurements. At the end, we review the different methods which used to extract the temperature and density from heavy ion collisions, eg. the Saha equation, coalescence model and quantum fluctuation method. The comparison of the results extracted with different methods from CoMD has been shown. The popular Fisher model, Landau approach to extract free energy, isoscaling and m scaling are also covered.

[1] G. Giuliani, H. Zheng, and A. Bonasera, Prog. Part. Nucl. Phys. **76**, 116 (2014).