# A Systematic Study of Nuclear Matter: Finite Nuclei to Neutron Star

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The classification of nuclear matter, characterization of its properties, and analysis of various phenomena emerging from or happening in nuclear matter remain an area of intense activity. In a broad prospect, the nuclear matter is categorized as finite nuclei and infinite nuclear matter. Since the discovery of an atomic nucleus by Rutherford and his collaborators through the famous gold-foil scattering experiment in 1911, the pursuit of understanding the structure of a nucleus is continued yet. An atomic nucleus exhibits a variety of nuclear phenomena, e.g., fission, fusion, and radioactivity. The infinite nuclear matter is defined as an ensemble of infinite (practically, very large) number of constitute particles. A neutron star is a good example of an asymmetric infinite nuclear matter that have a mysterious nature.

Nuclei lie away from $\beta-$ stability line with large neutron to proton asymmetry are of great importance. One of the quests among the nuclear physics community is how to synthesis the exotic and superheavy nuclei and to explore their applications. Since the matter at extreme density and temperature is impossible to create in a laboratory, a study of neutron-rich nuclei is treated as a tool to understand it. Due to the great importance of naturally available and neutron-rich thermally fissile nuclei, it is worth studying their properties. Besides nuclear bulk properties, it is worth knowing the nuclear symmetry energy that is directly connected with the isospin asymmetry of the system; either infinite nuclear matter or finite nuclei. It is an important quantity having significant role in different areas of nuclear physics, for example, in structure of ground-state nuclei, physics of giant collective excitation, dynamics of heavy-ion reactions, and physics of neutron star.

Neutron stars (NSs) are fascinating objects that are born from the collapse of massive stars and reach central densities that may exceed those found in atomic nuclei by up to an order of magnitude. They are considered to be unique cosmic laboratories to explore properties of ultra-dense matter under extreme conditions of density and neutron-proton asymmetry. One of the most chaotic and enthralling conundra in physics is the problem of dark matter in the Universe. Besides, a lot of theoretical studies have been done to find the nature of DM particles or to constrain the DM variables by applying different assumptions. In this thesis, we have considered WIMP as a DM candidate and have tried to constrain its parameters with the help of gravitational-waves data, emitted from binary neutron star merger.

The main aim of the thesis is to study the properties of nuclear matter, i.e., finite nuclei to infinite nuclear matter, at zero and finite temperature within effective field theory motived relativistic mean-field model by using some of the recent parameter sets. For this, we have chosen exotic, superheavy, and natural/neutron-rich thermally fissile nuclei and studied ground as well as excited-state bulk and surface properties of nuclei. We have also tried to figure out the possible constraints on the DM variables by considering WIMP, a DM candidate, inside the NS core and using gravitational-wave data GW170817.

We have studied the fission parameters of hot natural thermally fissile $^{234,236}$U and $^{240}$Pu nuclei [1], and neutron-rich thermally fissile $^{244-262}Th$ and $^{246-264}U$ nuclei [2] within the temperature-dependent axially-deformed effective field theory motivated relativistic mean-field (E-TRMF) formalism by using the

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recently developed FSUGarnet, and IOPB-I parameter sets. The results obtained by these two forces are compared with the results of the well known and widely accepted NL3 parameter set. The excitation energy $E^*$, shell correction energy $\delta E_{shell}$, single-particle energy for neutrons and protons $\epsilon_{n,p}$, level density parameter $a$, neutron skin-thickness $\Delta R$, quadrupole and hexadecapole deformation parameters, two neutron separation energy $S_{2n}$, and asymmetry energy coefficient $a_{sym}$ of these natural/neutron-rich thermally fissile nuclei are calculated at finite temperature. The dependency of level density parameter and other observables on the temperature and the force parameters (interaction Lagrangian) are discussed there.

We have also studied the effective surface properties such as the symmetry energy, neutron pressure, and symmetry energy curvature that are calculated using the coherent density fluctuation model [3]. The isotopic chains of $O$, $Ca$, $Ni$, $Zr$, $Sn$, $Pb$, and $Z = 120$ are considered in the present analysis, which covers nuclei over the whole nuclear chart. The matter density distributions of these nuclei along with the ground-state bulk properties are calculated within the spherically symmetric E-RMF model by using the recently developed IOPB-I, FSUGarnet, and G3 parameter sets and compared with the results of the NL3 set. This investigation is quite relevant for the synthesis of exotic nuclei with high isospin asymmetry including superheavy and also to constrain an equation of state of nuclear matter.

Furthermore, we show the temperature-dependent symmetry energy and its relevant quantities for $^{234,236,250}U$, and $^{240}Pu$ nuclei. The temperature-dependent relativistic mean-field (TRMF) model with FSUGarnet, IOPB-I, and NL3 parameter sets is used to obtain the ground and excited-state bulk properties of finite nuclei and the energy density, pressure, and the symmetry energy of infinite nuclear matter. The nuclear matter observables at the local density of the nuclei serve as an input to the local density approximation to obtain the effective symmetry energy coefficient, neutron pressure, and the symmetry energy curvature of $^{234,236,250}U$ and $^{240}Pu$ nuclei [4].

Moreover, we have investigated for the first time the effects of DM inside an NS adopting the $\sim 10$ $GeV$ WIMP hypothesis as suggested by the results of the DAMA/LIBRA collaboration, which can be realized e.g. in the framework of the Next-to-Minimal Supersymmetric Standard Model (NMSSM). The dark matter particles interact with the baryonic matter of a neutron star through the Higgs bosons. The dark matter variables are essentially fixed using the results of the DAMA/LIBRA experiment, which are then used to build the Lagrangian density for the WIMP-nucleon interaction inside a neutron star. We have used the E-RMF model to study the equations of state in the presence of dark matter. The predicted equations of state are used in the Tolman-Oppenheimer-Volkoff equations to obtain the mass-radius relations, the moment of inertia, and effects of the tidal field on a neutron star. The calculated properties are compared with the corresponding data of the GW170817 event [5].

## Acknowledgments

I am thankful to Dr. Shakeb Ahamd (supervisor) and Prof. S. K. Patra (co-supervisor) for their guidance through out this work. Financial support provided by DST as INSPIRE fellowship is greatly acknowledged.

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