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Nuclear Symmetry Energy for Dense Hadronic Matter in the Era of Advanced Gravitational Wave Detectors

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Abstract

Recent developments of gravitational wave detectors like LIGO and Virgo provide us an optimistic opportunity of expecting first few events in near future. One of the exciting possibilities is that we can probe the inner structure of compact objects like neutron star by analyzing the observed pattern of gravitational waves. Among the characteristic features of the equation of state(EoS), the symmetry energy of dense hadronic matter is discussed. A model which implements a new scaling law of physical parameters of hadronic matter is briefly sketched to demonstrate how it affects the equation of state and the outcome for the mass and radius estimation is discussed for an n-p asymmetric configuration.

1. Introduction

The detection of gravitational waves is one of the remaining direct tests of Einstein's theory of general relativity, which is believed to be the theory for the gravity of our Universe. The recent development of gravitational wave detectors seem to be promising such that we can expect first few events in coming years. Among the leading observatories are LIGO and Virgo, for which the advanced detection systems are going to be completed soon [1, 2]. With increasing detection efficiency, the distance to the observable gravitational source is expected to be increasing by factor of ten to reach as further as few hundreds Mpc, which corresponds to an increase of the number of events by thousand times [3]. It implies that the event rate of observation is expected to be ∼ 40/year for gravitational waves from binary mergers(for example neutron star-neutron star or black hole-neutron star), which is compared to the estimated rate of present machine(less than one event per year [3]). Together with future observatories, like KAGRA [4] in Japan and LIGO India [5], they will be giving additional information such as the location of gravitational wave sources for identifying the astrophysical process of emitting gravitational waves.

There have been intensive researches on how the gravitational wave forms are related to the physics of materials of the merging stars or on how the observational data can be used to infer the structure and EoS of compact stars. Particularly the high density aspect of EoS is relevant to the core of the compact stars like neutron stars. The core density of neutron star is believed to be higher than normal nuclear matter density, $n_0 = 0.16/fm^3$, up to which most of physics for nuclear phenomena has been considered to be understood very well. For example, the average density of neutron star of $1.4M_\odot$ with radius 10km can be estimated as $0.3/fm^3 \sim 2n_0$. Thus it is very likely the core density is much higher than n_0. Recent observations of $\sim 2M_\odot$ pulsars [6, 7] do not exclude the possibility of high core density up to $\sim 9n_0$. Then one naturally asks whether EoS developed in the low density nuclear matter can be simply extrapolated up to more than $3n_0$.

So far it remains as one of the open questions. Theoretically the treatment of strongly interacting dense nuclear matter (hadronic matter) has been considered to be a difficult task. In contrast to the finite temperature case, where finite temperature field theory and lattice calculations have been successfully applied, there have been

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no such scheme developed up to now for dense matter system. On the other hand there have been other approaches of adopting effective theories, which however show very different features of EoS beyond normal nuclear density. They differ from each other basically due to their different assumptions on density dependent interactions as well as on particles involved in EoS. Of course they are subjected to be verified or supported directly or indirectly by the experiments and astrophysical observations.

The heavy-ion collision is one of the terrestrial tools to obtain information on how the strong interactions between hadrons (nuclear interaction) are modified with varying densities. For this purpose, such laboratories as RAON at IBS/Korea, FAIR at GSI/Darmstadt, FRIB at MSU/Michigan, and NICA at JINR/Dubna are in project. They will probe the ranges of temperature up to 50 − 60 MeV and of density up to $(3-4)n_0$. Although the density is expected to be not much higher than $3n_0$ according to their present experimental design, we can expect direct information from the controlled experiments, which will provide the test of microphysics of dense matter beyond normal nuclear density.

The observation of pulsars mostly from the binary systems provides the information on the masses of neutron stars. The information on their radii is not directly attainable but one can infer the radii from the determined mass through the Tolmann-Oppenheimer-Volkov(TOV)equation [8]. Given EoS for pressure, P, and energy density, ϵ, the radius and mass can be obtained by integrating TOV equation,

$$\begin{aligned} \frac{dM}{dr} &= 4\pi\epsilon\, r^2, \\ \frac{dP}{dr} &= -\frac{GM\epsilon}{r^2}\left(1+\frac{P}{\epsilon}\right)\left(1+\frac{4\pi r^3 P}{M}\right) \\ &\quad \times\left(1-\frac{2GM}{r}\right)^{-1}, \end{aligned} \tag{1}$$

where $M(r)$ is the mass enclosed inside the radius r. This equation is integrated up to the radius R, where $P = 0$, and the mass of the star is determined by $M(R)$.

One can see that given EoS, pressure and energy density, the radius can be determined in connection to the mass measurement. However EoS is not well known especially for the dense core of the compact star and the radius determination in this theoretical procedure is not so promising. Without having a theoretically well grounded model of EoS at present, it is necessary to have other types of observation, for example gravitational wave observation. The gravitational waves radiated during merger depends on EoS. During this period, the wave form depends mainly on the radius and mass, which are determined by EoS through TOV Eq. (1). When they come closer or collide, it becomes dependent more directly on the detailed structure of EoS deep inside the core of neutron star. Hence it is expected that the gravitational wave can carry along the direct information of EoS to the observer at a distance, which otherwise can be only inferred indirectly by electromagnetic wave observations. Ring-down process is also dependent on EoS, since the stiffness of EoS determines whether the final stage becomes black hole or not [9]. Thanks to the development of numerical relativity [10], a number of predictions is possible, which might be tested by the improved gravitational wave detectors. The more reliable calculations in numerical relativity is expected provided with more realistic EoS. It will answer one of the important questions: how the central core of neutron star is formed, hyperon matter or quark matter.

For the hadronic matter dominated by neutrons and protons, the nuclear symmetry energy plays a very important role since it determines the fraction of proton in compact star as well as the threshold of new hadronic degrees of freedom. Hence it is a very important variable for highly dense matter in the core of compact stars but as mentioned above it is one of the quantities which has not been explored yet up to the density of compact star core. In section 2, The nature of symmetry energy, which is not well explored beyond the normal nuclear density but is very important in deciding what kind of new degrees of freedom should be taken into account in the star matter other than nucleon, will be discussed. In section 3, we discuss a model with new scaling [11, 12, 13] for nuclear matter which is compatible with recently observed high mass($\sim 2M_\odot$) neutron stars [14, 15]. The discussions will be given in section 4.

2. Nuclear Symmetry Energy of Dense Nuclear Matter

Neutron star as it is called is dominated by the neutron. But because of the symmetry energy that drives the system into neutron-proton symmetric state there must be some fraction of protons and as well as electrons to make the system electrically neutral as the density is increasing. The system is in weak equilibrium with neutrons, protons and electrons. As density is increasing muons are emerging via the weak interaction and the system includes a finite fraction of muons as well. The threshold density of muon is determined by the symmetry energy, which will be elaborated below.