Probing the equation of state beyond the saturation density

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Introduction

The accurate knowledge of the equation of state(EOS) is important in understanding the structure of finite nuclei as well as critical issues in astrophysics. The EOS for an arbitrary asymmetry can be decomposed into two parts, namely, the EOS for the symmetric nuclear matter (SNM) and the density dependent symmetry energy.

$$e(\rho, \delta) = e(\rho, 0) + J(\rho)\delta^2 \qquad (1)$$

where ρ is baryon number density, $\delta = (\rho_n - \rho_p)/\rho$ is the asymmetry parameter and $J(\rho)$ is the density dependent symmetry energy.

The knowledge of the EOS for the SNM and the symmetry energy around the saturation density($\rho_0 \sim 0.16\ fm^{-3}$) comes from the various nuclear observables. For instance, the incompressibility coefficient and the symmetry energy at the saturation density are determined by the iso-scalar giant monopole resonance energy and the binding energy for the neutron-rich nuclei, respectively. The behaviour of these quantities at densities beyond the saturation densities are however poorly known till date. The neutron stars being dense object with the central densities around a few times of the saturation density , it is natural to expect that their bulk property to be governed predominantly by the high density behaviour of the EOS. In other words, the bulk properties of the neutron stars may be strongly correlated with the key properties of the nuclear matter at the densities beyond saturation density. Thus the properties of dense object like neutron star might give some information about these quantities at high density.

In the present contribution we would like to look into these correlations in some detail .The key properties of the nuclear matter we have considered are the incompressibility coefficient K, its derivative M, the nuclear symmetry energy J and the slope parameter L defined as, $K(\rho) = 9\frac{dP}{d\rho}$, $M(\rho) = 3\rho\frac{dK(\rho)}{d\rho}$, $J(\rho) = \frac{1}{2}\left(\frac{\partial^2 e}{\partial \delta^2}\right)_{\delta=0}$, $L(\rho) = 3\rho\frac{\partial J(\rho)}{\partial \rho}$ where P is the pressure.

We calculate the Pearson's correlation coefficient $C[A, B]$ which enables one to understand quantitatively the linear correlation between a pair of observables A and B. The value of $C[A, B]$ lie in the range of -1 to 1. If $\|C[A, B]\|$ is 1, then the quantities A and B are totally linearly correlated and $C[A, B] = 0$ if A and B are statistically independent.

Theoretical Models

Different type of relativistic and non relativistic models are used for this work. We have chosen relativistic mean field (RMF) models BSP, BSR2, BSR6, BSR9, BSR13, NL3, TM1, GM1, non relativistic Skyrme models Ska, Sly4 together with the realistic model proposed by Akmal, Pandharipande and Ravenhall(APR) for our calculation. The Lagrangian for the field theoretical relativistic mean field model where the baryons interacting through the exchange of mesons is explained explicitly in Refs.[1]. The non relativistic Skyrme Hartree-Fock model is discussed in Refs.[2] and the detail of APR model is in Refs.[3]. These models can successfully produce the finite nuclei properties like binding energy per nucleon, incompressibility coefficient and symmetry energy at saturation density and effective mass of nucleons. The properties of neutron stars are calculated by solving Tolman-Oppenheimer-Volkoff equations.

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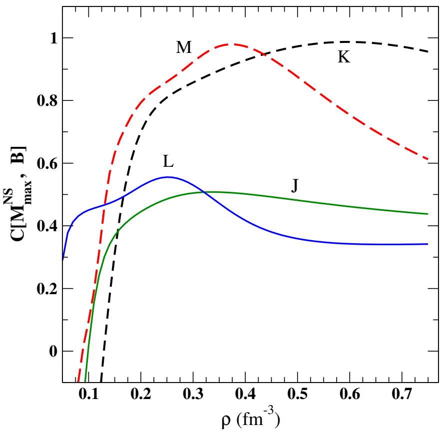

FIG. 1: (Color online) Results for the correlation coefficient C[M^{NS}_{max},B] as a function of density where B = J, L, K, M as labeled along the curves.

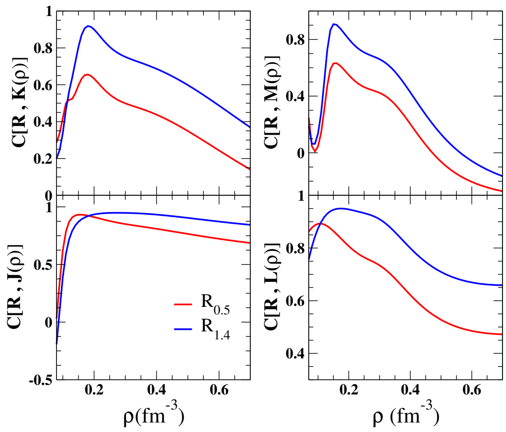

FIG. 2: (Color online) Results for the correlation coefficient C[R,B] as a function of density where $R = R_{0.5}$, $R_{1.4}$ and B = J, L, K, M . Here $R_{0.5}$ and $R_{1.4}$ represents the neutron star radius corresponding to neutron star of mass $0.5M_{\odot}$ and $1.4M_{\odot}$, respectively.

Results and Discussions

Figure 1 shows the correlation coefficients of maximum mass of neutron star with nuclear properties J, L, K, M as a function of density. From this figure it is clear that the maximum mass of neutron star is poorly correlated with the iso-vector quantities J and L but very well correlated with incompressibility coefficient K and its slope M. The correlation coefficients $C[M^{NS}_{max}, K(\rho)]$ and $C[M^{NS}_{max}, M(\rho)]$ gives maximum value st densities $\rho \sim 3.8\rho_0$ and $\rho \sim 2.3\rho_0$ respectively.

Now, in figure 2 the correlation coefficients of neutron star radius (corresponding to a fixed neutron star mass) with J, L, K, M is plotted as a function of density. The correlation coefficients of neutron star radius with K and M are stronger for higher values of neutron star mass. The value of $C[R, K(\rho)]$ is peaking around density $\rho = 1.1\rho_0$. Same thing happens for M but in this case the density at which correlation become maximum is $\rho \sim \rho_0$. Very recently, it has been shown that the M is correlated with iso-scalar giant resonance energy at the sub-saturation density ($\rho \sim 0.1 fm^{-3}$). So, the present result certainly provides the information on EOS beyond that density. The correlation coefficients of neutron star radius with density dependent symmetry energy J are maximum at density $\rho \sim \rho_0$ for $R_{0.5}$ and $\rho \sim 1.7\rho_0$ for $R_{1.4}$. Similarly we find that the value of $C[R, L(\rho)]$ is maximum at density 0.11 fm^{-3} for $R_{0.5}$ and $\sim 1.1\rho_0$ for $R_{1.4}$. These results shows that the maximum value of correlation coefficients are shifting towards the higher density for higher value of neutron star mass.

From this work, we can conclude that the properties of neutron stars are better correlated to the key properties of nuclear matter at densities which are higher than the saturation density. So the knowledge of the global properties of neutron star can put some constraints on the nuclear observables at high density.

References

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