Transport coefficients of neutron star matter

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The densities found in the core of neutron stars can reach up to several times the normal nuclear density. Therefore, neutron stars are believed to be ideal astrophysical objects to study the properties of cold superdense matter. Various bulk properties of neutron stars depend directly on the internal structure of matter. But, the structure of matter and its equation of state(EoS) for such extreme densities are still poorly known. In the recent past, the detection of gravitational wave signals from neutron star mergers has come up as a new tool to study the superdense matter and uniquely determine its EoS. It is found that the transport properties of neutron star matter can play a significant role in the simulations of neutron star mergers[1]. Hence careful investigation for accurate understanding of the transport properties is highly required. In the present work, our aim is to investigate the density behavior of the transport coefficients like shear viscosity, electrical conductivity of the neutron star matter.

Nowadays, Relativistic Mean Field(RMF) model is largely used in describing properties of finite nuclei as well as neutron stars. In view of this, we have employed the same model for the description of matter present inside neutron stars. We have chosen the BSP[2] parameter set of the RMF model that yields reasonable values for both nuclear matter properties and the properties of finite nuclei. The maximum mass of neutron star resulting from this parameter set is also consistent with the 2 $M_\odot$ constraint.

In this work, the transport coefficients of the neutron star matter have been calculated within the framework of standard kinetic theory [3]. Considering the neutron star as a dissipative fluid, the macroscopic definition of shear viscosity says that it is a proportional constant between shear stress and velocity gradient. Whereas, ideal and dissipative parts of energy-momentum tensors can be microscopically expressed in terms of the equilibrium distribution function and non-equilibrium distribution respectively. The latter part can be assumed to be proportional to the velocity gradient, connected with shear viscosity and relaxation time τ_N, coming from the relaxation time approximation (RTA) of the Boltzman equation. Connecting macroscopic and microscopic picture, we will get a microscopic expression of shear viscosity:

$$\begin{aligned} \eta &= \frac{\gamma}{15}\int \frac{d^3\vec{k}}{(2\pi)^3}\frac{k^4}{E^2}\tau_N \delta(E-\mu) \\ &= \frac{\gamma}{30\pi^2}\tau_N \frac{(\mu^2-m^{*2})^{5/2}}{\mu} \end{aligned} \quad (1)$$

where equilibrium distribution function $f_0 = \theta(\mu - E)$ with $E = \sqrt{k^2 + m*^2}$ of nucleon medium at zero temperature and finite chemical potential μ is used and $m*$, γ are the effective mass and degeneracy factors of the constituent of the system respectively.

Similar to shear viscosity, electrical conductivity is another transport coefficient, which can be microscopically derived from the RTA based kinetic theory approach as

$$\begin{aligned} \sigma &= \frac{q^2\gamma}{3}\int \frac{d^3\vec{k}}{(2\pi)^3}\frac{k^2}{E^2}\tau_N \delta(E-\mu) \\ &= \frac{q^2\gamma}{6\pi^2}\tau_N \frac{(\mu^2-m^{*2})^{3/2}}{\mu} \end{aligned} \quad (2)$$

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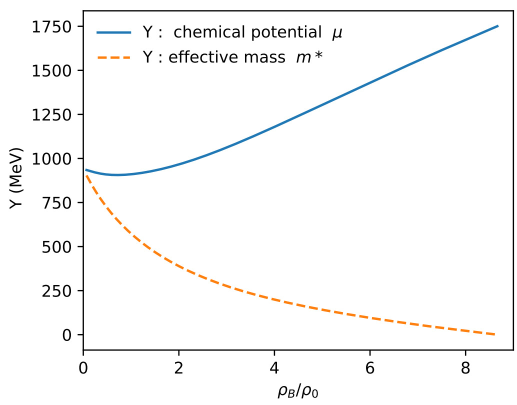

FIG. 1: Nucleon chemical potential μ and effective mass $m*$ versus scaled baryon density of NS matter.

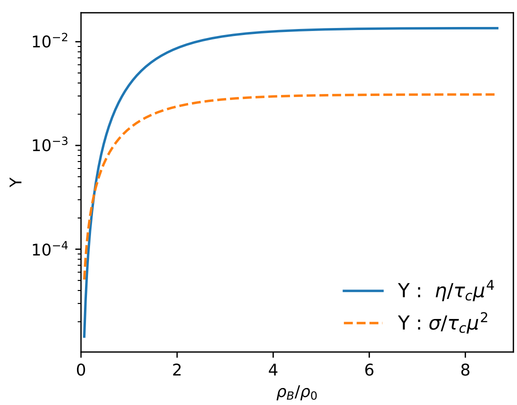

FIG. 2: Normalized shear viscosity and electrical conductivity as a function of scaled baryon density.

The main ingredient of the neutron star environment, which enter into the transport coefficients calculations, are nucleon chemical potential μ and effective mass $m*$. They are plotted in Fig. 1 as a function of scaled baryon number density ρ/ρ_0, where ρ_0 is the nuclear saturation density. At high densities, the chemical potential of the nucleons increases with density, whereas the trend is opposite for the effective nucleon mass.

Using these density dependent μ and $m*$ in Eqs. (1), (2), we have generated the density dependent profile of shear viscosity and electrical conductivity respectively. To make them dimensionless, we have normalized them as $\eta/(\tau_c\mu^4)$, $\sigma/(\tau_c\mu^2)$, and plotted in Fig. 2. As seen from the plot, at low density the values of the transport coefficients increase rapidly with density, but the rate of increments are low at high densities and their values almost saturate. The picture might be compared to the temperature dependence of normalized transport coefficients [4] and thermodynamical quantities like pressure, energy density and entropy density of QCD medium at $\mu = 0$, which saturate towards their Stefan-Boltzman (SB) limits. The detailed comparative analysis between normalized transport coefficients along density and temperature axis will be presented at the conference.

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