Bulk viscosity of Hot Neutron star Matter

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Introduction

The study of binary neutron star merger (BNSM) has gained importance with the upcoming facilities for detection of gravitational waves. The numerical simulations of the BNSM [1,2] have shown that there are density oscillations in large scale in the post-merger remnants. These oscillations will be damped eventually by the dissipative processes which are, of course, not known to any reasonable extent. It has been suggested [3] that the urca processes, modified (MU) and direct (DU), can produce significant dissipations in the time scale relevant to the neutron star merger and post-merger evolution. If the temperature of the merged matter rises up to several MeV, where the neutrinos produced in the weak decay processes can also be trapped. In this work we shall consider the neutrino-free hot isothermal neutron star matter (NSM) under the consideration of neutron (n), proton (p), electron (e) and muon (μ) composition.

Formalism

The neutrino-free n + p + e + μ matter in equilibrium under the weak interaction is subject to the condition

$$\mu_n - \mu_p = \mu_e = \mu_\mu \ , \qquad (1)$$

where μ_i , i= n, p, e, μ, is the respective chemical potential at equilibrium and the charge neutrality condition is

$$Y_p = Y_e + Y_\mu \ , \qquad (2)$$

with $Y_i=\rho_i/\rho$, i= e, μ, is the lepton fractions and $\rho=\rho_n+\rho_p$ being the total density of the NSM.

Under the density oscillations, there is deviation from the equilibrium value of the density that results in to a difference in the rates of the direct, $n \rightarrow p + e + \bar{\nu}_e$, and reverse, $p + e \rightarrow n + \nu_e$ processes. Under the small amplitude oscillations, the bulk-viscosity resulting from the direct and reverse rate difference is given by [4]

$$\xi = \frac{C^2}{A}\frac{\lambda A}{\omega^2+\lambda^2 A^2} \ , \qquad (3)$$

where C and A are the beta disequilibrium susceptibilities corresponding to the deviations from equilibrium density and equilibrium proton fraction respectively and are determined from the equation of state of NSM; ω is the oscillation frequency and λ is the decay constant that is determined from the difference in direct and reverse rates. The explicit expression for C_l and A_l are given by

$$A_l = -\frac{1}{\rho}\left(\frac{\partial\mu_\Delta}{\partial Y_p}\right)_p = (A_{nn} - A_{pn}) + (A_{pp} - A_{np}) + A_{ll} \quad (4)$$

$$C_l = \rho\left(\frac{\partial\mu_\Delta}{\partial\rho}\right)_{Y_p} = \rho_{n0}(A_{nn} - A_{pn}) - \rho_{p0}(A_{pp} - A_{np}) - \rho_{l0}A_{ll} \quad (5)$$

with l=e,μ and $A_{ij} = \left(\frac{\partial\mu_i}{\partial\rho_j}\right)_0$, where the index 0 refers to the static equilibrium state [4]. In this work we have computed the bulk viscosity of neutrino-free hot neutron star matter using the finite range simple effective interaction (SEI) model which has been used in the study of bulk viscosity at zero-temperature [5].

Results and Discussion

The EoS of SEI used in the present calculation is the same as has been used in the recent work of Ref. [6]. The particle fraction is computed by solving together the beta-equilibrium condition Eq. (1) and charge neutrality condition Eq. (2) simultaneously. At finite temperature T the presence of the anti-particles, positrons and anti-muons, become mandatory. We have taken the anti-particles into account in our calculation, where the charge neutrality condition gets modified as,

$$Y_p = (Y_e - Y_{e^+}) + (Y_\mu - Y_{\mu^+}) \ . \qquad (6)$$

The equilibrium particle fractions thus computed are shown as a function of density at temperatures T=5-50 MeV in different panels of Fig. 1 where the fractions of the anti-leptons, positrons and anti-muons, are also shown. In the calculation of bulk viscosity from Eq. (3) the factor $\frac{C_l^2}{A_l}$ is solely determined from the EoS. The plot $\frac{C_l^2}{A_l}$ as a function of density is shown at different temperatures for electrons and muons in the two panels of Fig. 2. The dip in the curves in the panel (b) corresponds to the onset of muon production threshold density. The bulk viscosity is computed under the considerations of both MU and DU processes, and the total bulk viscosity

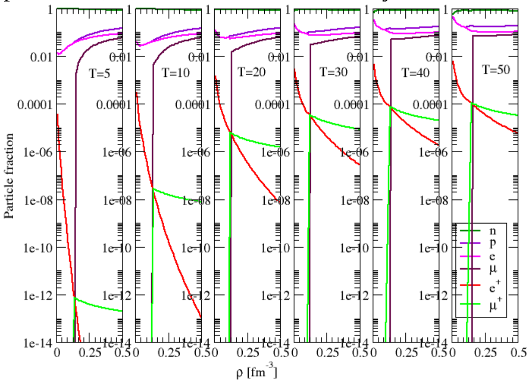

Fig. 1 : Particle fractions as a function of ρ for temp. T= 5-50 MeV.

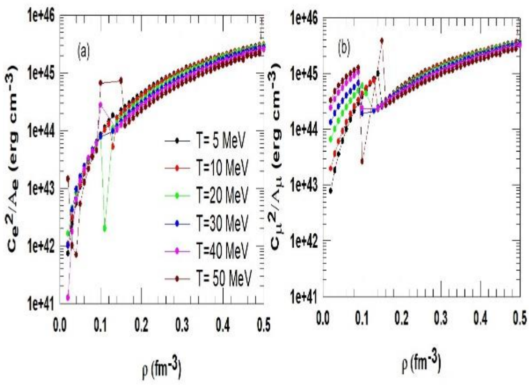

Fig. 2 : C^2 /A as a function of ρ for e (panel(a)) and for μ (panel (b)) for T=5-50 MeV.

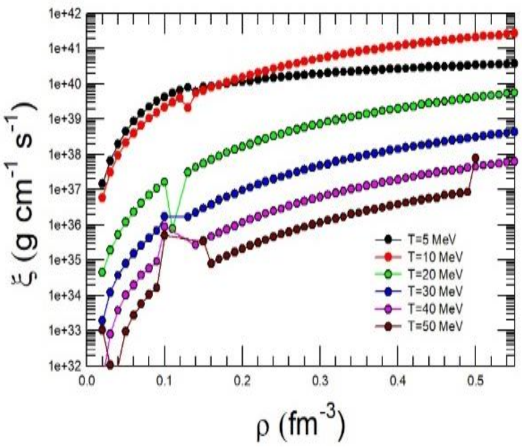

Fig. 3 : Bulk-viscosity ξ as a function of ρ for temperatures in the range T= 5-50 MeV.

is given by $\xi = \xi_{MU} + \xi_{DU}$. The MU contribution has four parts, $\xi_{MU} = \xi_{MU}^{ne} + \xi_{MU}^{pe} + \xi_{MU}^{n\mu} + \xi_{MU}^{p\mu}$, where n and p in the superscript refer to the neutron and proton branches of the MU processes. The DU contribution to bulk viscosity has two parts $\xi_{DU} = \xi_{DU}^{e} + \xi_{DU}^{\mu}$, corresponding to the two leptons, e and μ. The oscillation frequency is taken as $\omega=10^4$ s^{-1} which is the typical frequency in the stellar events of BNSM. The decay constants for the partial processes of the DU and MU have been derived in the work of Haensel et al. [7]. Using these decay constants the partial bulk viscosities of the MU and DU processes have been calculated. The total bulk viscosity thus obtained for the neutrino-free NSM has been shown as a function of density at temperatures T=5-50 MeV and shown in Fig. 3. The bulk viscosity increases at a higher rate from low density and slows down around density ρ~0.1 fm^{-3} but maintains the monotonical increasing trend except at the muon production threshold densities where deviations from the monotonically increasing behaviour occur. This occurs at all temperatures. However, the magnitude of the bulk viscosity in the NSM decreases with increase in temperature in agreement with the findings of the earlier works [3,4]. In the present calculation the bulk viscosity decreases from ~10^{41} g cm^{-1} s^{-1} to ~10^{36} g cm^{-1} s^{-1} by a factor of five as T increases from 5 to 50 MeV.

Conclusion

The bulk viscosity in neutrino-free hot NSM has been computed where the particle fractions and the quantities of the EoS have been obtained in a thermodynamically consistent manner. The bulk viscosity in neutrino-free NSM is found to be decreasing as temperature increases which also agrees with the earlier findings.

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