Bulk viscosity of the neutron star matter under the influence of Direct URCA reactions

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Introduction

The bulk viscosity in the neutron star matter (NSM), usually referred to as the n+p+e+μ matter, partly arises from the particle scattering which is small in comparison to the shear viscosity. The main contribution to bulk viscosity comes from the URCA reactions in which electrons (e) and muons (μ) are emitted and absorbed by the nucleons. The URCA reactions are of two types, direct URCA and modified URCA processes. A direct URCA is a sequence of two reactions,

$n \rightarrow p + l + \bar{\nu}_l$, $p + l \rightarrow n + \bar{\nu}_l$ ...(1)

where, lepton l is either e or μ and ν_l is the associated neutrino. The direct URCA are subject to the condition $p_n \leq p_p + p_l$, where p_n and p_p are the momentum of the neutron and proton, respectively and p_l is the momentum of the lepton, either e or μ. If the direct URCA is not allowed by momentum conservation then the bulk viscosity is determined by the modified URCA processes,

$n + N \rightarrow p + N + l + \bar{\nu}_l$, $p + N + l \rightarrow n + N + \bar{\nu}_l$, ...(2)

where, N is an additional nucleon required to conserve momentum of the reacting particles. In this work we shall restrict to the direct URCA reaction examining its impact on the bulk viscosity ζ of the non-superfluid (npeμ) matter.

Formalism

The system of n+p+e+μ, in equilibrium with respect to the beta and muon decay and capture processes, is in fully thermodynamical equilibrium, refer to as chemical equilibrium of the system. If the chemical equilibrium is achieved then $\mu_n - \mu_p = \mu_e = \mu_\mu$, μ_i, i=n,p,e are the respective chemical potentials. Under these conditions the rates of the direct and inverse reactions Γ_l and $\bar{\Gamma}_l$ (l= e or μ), of any URCA process are equal. In the case of the particle reactions, if the particle fractions $Y_i = \frac{\rho_i}{\rho}$, i=n,p,e,μ, ρ_i being the respective particle fractions where $\rho = \rho_n + \rho_p$ is the total nucleon density, deviates from their instantaneous equilibrium values, which may be caused by pulsation in NS or due to any other perturbing mechanism, then this will produce non-zero difference of instantaneous μ_i :

$\eta_e = \mu_n - \mu_p - \mu_e$, $\eta_\mu = \mu_n - \mu_p - \mu_\mu$ ...(3)

This causes an asymmetry of the direct and inverse direct URCA reactions expressed under the linear approximation $\Gamma_l - \bar{\Gamma}_l = -\lambda_l \eta_l$, ...(4)

where, λ_l is the asymmetry coefficient of the given type l= e or μ. The non-equilibrium URCA reactions provide the energy dissipation that damp out the stellar perturbation and contribute to the bulk viscosity ζ. The bulk viscosity has contributions from the two types of leptons in (npeμ) matter, l= e or μ, $\zeta = \zeta_e + \zeta_\mu$, where, ζ_l can be given as [1,2], $\zeta_l = \frac{|\lambda_l|}{\omega^2} C_l^2$, ...(5)

with, ω being the frequency of the perturbation and C_l is given by,

$$C_l = -\rho \frac{\partial^2 e\,(\rho, Y_p)}{\partial\rho\partial\, Y_p} - \frac{c^2 p_{fl}^2}{3\mu_l}, \quad \dots(6)$$

where, $e\,(\rho, Y_p)$ is the energy per nucleon with Y_p being the equilibrium proton fraction and p_{fl} is the Fermi-momentum of the lepton considered under relativistic Fermi gas model. Upon evaluating λ_l by computing the direct and inverse reaction rates, Γ_l and $\bar{\Gamma}_l$ the expression for ζ_l in equation (5) results into [1]

$$\zeta_l = \frac{17 G^2 (1+3g_A^2)}{240\pi \hbar^{10} C^3 \omega^2} C_l^2 m_n^* m_p^* m_e^* (k_B T)^4 \theta_{npl} \quad \dots(7)$$

where, G= G_F cos θ_C, G_F being the Fermi coupling constant and θ_C is the Cabibbo angle, g_A is the axial vector normalization constant, m_n^*, m_p^*, m_e^* are the respective effective masses and the step function θ_{npl} is equal to 1 if URCA process is on and 0 otherwise.The evaluation of bulk viscosity ζ requires the knowledge of C_l, m_n^*, m_p^* which can be obtained from the equation of state (EOS) of the asymmetric nuclear matter (ANM). Here we have obtained the EOS of ANM from the finite range simple effective interaction (SEI) [3]. The fixation of parameters of SEI along with the predictions in NM and finite nuclei can be seen in [Ref [4] and references therein]. The bulk viscosity has been calculated here for the EOS covering the range of slope parameter $L(\rho_0)$= 70 MeV-110 MeV.

Results and Discussion

The equilibrium proton fraction Y_p is calculated from the beta stability, $\mu_n - \mu_p = \mu_e = \mu_\mu$, and charge neutrality $Y_p = Y_e + Y_\mu$, conditions for the two EOSs of SEI having $L(\rho_0)$= 70 MeV and 110 MeV, referred to as EOS1 and EOS2, respectively. The results of the proton and lepton fractions as a function of density are shown in Figure 1. Using the EOS of SEI the energy per nucleon $e(\rho, Y_p)$ in the (npeμ) matter is computed and the quantity C_l is evaluated for the two EOSs. The n- and p- effective masses m_n^* and m_p^* are evaluated as a function of density from the expression

$$\frac{m_{n(p)}^*}{m} = \left[1 + \frac{m}{\hbar^2 k}\frac{\partial u^{n(p)}(k,\rho)}{\partial k}\right]_{k=k_{n(p)}}^{-1}$$

, where $u^{n(p)}$ is the neutron (proton) single particle potential and $k_{n(p)}$ is the neutron (proton) Fermi momentum. The electron effective mass, $m_e^* \approx \frac{p_{fe}}{c}$, obtained from the relativistic Fermi gas model. By knowing the quantities C_l, m_n^* and m_p^* as a function of ρ, the bulk viscosity ζ of the (npeμ) matter given in equation (7) can be studied for any typical temperature T and perturbing frequency ω, where one use the standard values of G=1.436 x 10^{-49} erg cm^3 and g=1.23. The bulk viscosity ζ has been calculated as a function of density ρ, for T= 10^9 K and ω= 10^4 s^{-1} and the results are shown in Figure 2 for the two EOSs of SEI corresponding to $L(\rho_0)$= 70 MeV and 110 MeV. The curve for EOS1 shows a smooth slowly increasing behavior with increase in density. However, the curve for EOS2 shows sudden jumps at densities ρ=0.26 fm^{-3} and 0.30 fm^{-3}. The first jump corresponds to the onset of electron direct URCA and the subsequent one is from muon direct URCA processes. This can also be verified from the electron and muon fraction curves in figure 1 that at these density values the condition $p_n \leq p_p + p_l$, is satisfied for EOS2. But for EOS1 this is not satisfied at any density and hence no sudden rise in the bulk viscosity is predicted for it.

Figure1: Particle fractions Y_p,Y_e and Y_μ in NSM as a function of density, ρ for EOS1 and EOS2 in panel (a) and (b), respectively.

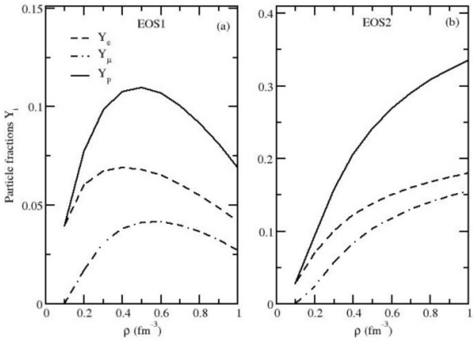
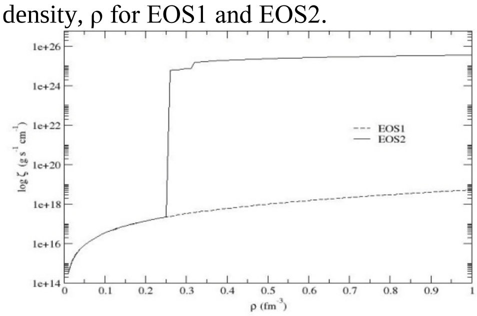


Figure 2: The bulk viscosity, ζ as a function of density, ρ for EOS1 and EOS2.



Conclusion

A large increase in the bulk viscosity takes place as the direct URCA process become operative and if it happens then the bulk viscosity becomes the dominating damping mechanism to the perturbation in NSs. Whether direct URCA takes place in NSs or not is yet to be answered with definiteness. Under such a circumstance one should include the modified URCA contribution that can take place at almost all densities inside the NS which is our subsequent work.

References

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