Bulk viscosity of superfluid Neutron Stars under the influence of Direct URCA and Modified URCA reactions

S. P. Pattnaik[1,3], S. K. Padhihari[1], K.Madhuri[1,4], and T. R. Routray[1,*],
[1]School of Physics, Sambalpur University, Jyotivihar-768 019, India.
[2]Departament de FísicaQuànticaiAstrofísica and Institut de CiènciesdelCosmos(ICCUB),
Facultat de Física, Universitat de Barcelona, Martí i Franquès 1, E-08028 Barcelona, Spain
[3]G.M. H.S. School, Sambalpur, Odisha-768004, India
[4]Women's College, Sambalpur, Odisha-768001, India
* email: trr1@rediffmail.com

Introduction

Theoretically, the r-mode oscillation in pulsar neutron stars (NSs) is hypothesized to constitute a constant source of Gravitation Wave (GW) released by these pulsars. The r-modes are the neutral circular currents on the surface of non-rotating NSs, while the Coriolis force provides the true dynamics in the case of pulsars [1,2]. The resulting instability in the pulsar star as a result of continuous GW emission is mitigated by viscous processes in the NS, and the r-mode oscillation is subjected to the condition $e^{i\omega t-t/\tau}$, where ω is the real part of the r-mode frequency given by $\omega=\frac{(l-1)\,(l+2)}{(l+1)}\,\Omega$, where Ω is the angular velocity of the pulsar. Contribution to the r-mode comes from the emission of GW that tries to render the r-mode unstable and the viscous effects that counter balances the instability due to GW emission. So, the reciprocal of the resultant time-scale $\frac{1}{\tau}=\frac{1}{\tau_G}+\frac{1}{\tau_{vis}}$, with τ_G being the gravitational time-scale and $\frac{1}{\tau_{vis}}$ is the sum of the reciprocal of all the different viscous time-scales. Shear viscosity and bulk viscosity are well known components out of the various viscous effects. At high temperatures, $T > 10^9$ K, bulk viscosity is dominating, and thus critical for hot new-born NSs. It prevails when the pulsation modes cause fluctuations in pressure and density that push the star out of equilibrium [3,4,5].

In this work we focus mainly on the bulk viscosity of the superfluid matter of the NS using simple effective interaction (SEI). Here we have limit ourselves to the case of npeμ matter.

Formalism

The bulk viscosity of sufficiently hot npeμ matter is mostly determined by URCA neutrino processes associated with electron and muon emission and capture by nucleons. The neutrino processes under consideration are classified as direct Urca and modified Urca processes [3,4,5,6]. A direct URCA is a sequence of two reactions,

$$n\rightarrow p+l+\overline{\nu}_l\ ,\ p+l\rightarrow n+\nu_l \qquad \text{... (1)}$$

where, lepton l is either e or μ and ν_l is the associated neutrino. In modified URCA processes an additional nucleon required to conserve momentum,

$$n+N\rightarrow p+N+l+\overline{\nu}_l\ ,\ \ p+N+l\rightarrow n+N+\nu_l, \qquad \text{...(2)}$$

where, N is an additional nucleon required to conserve momentum of the reacting particles.
The direct URCA and modified URCA are subject to the condition $p_{Fn} \le p_{Fp}+p_{Fl}$, and $p_{Fn} \le 3p_{Fp}+p_{Fl}$, respectively, where p_{Fn} and p_{Fp} are the Fermi momenta of the neutron and proton, respectively and p_{Fl} is the Fermi momentum of the lepton, either e or μ.

The total bulk viscosity of non-super fluid matter is written as a sum of the partial bulk viscosities associated with each URCA reaction [3,4,5,6,7],

$$\xi = \xi_{DURCA} + \xi_{\mathrm{MURCA}} \qquad \text{...(3)}$$

This bulk viscosity is strongly affected by the superfluidity of nucleons in the core of a NS. As a result, the bulk viscosity is reduced, since superfluidity introduces energy gap in momentum dependence of the nucleon energy, and the total bulk viscosity can be expressed as

$$\xi' = \xi\, R, \qquad ...(4)$$

where, R is the reduction factor, which is 1 for non-superfluid matter and less than 1 for superfluid matter as discussed in Refs. [3] and [4]. The total bulk viscosity is calculated using the finite range simple effective interaction (SEI), that is given by [8 and references therein],

$$v_{eff} = t_0(1 + x_0 P_\sigma)\delta(r) + \frac{t_3}{6}(1 + x_3 P_\sigma) \left(\frac{\rho}{1+b\rho}\right)^{\gamma} \delta(r) + (W + BP_\sigma - HP_\tau - MP_\sigma P_\tau) f(r) \quad (5)$$

where, *f(r)* is the functional form of the finite range part and in this work, we have taken it to be of Gaussian form. The other terms have their usual meanings. It has in total 11 parameters. For the study of ANM, however, nine combinations, namely, b, γ, α, ϵ_0^l, ϵ_0^{ul}, ϵ_γ^l, ϵ_γ^{ul}, ϵ_{ex}^l and ϵ_{ex}^{ul} of these 11 parameters are required. The connection of the new parameters to the interaction parameters and their determinations has been discussed in Ref.[9].

Results and Discussion

We have studied three different superfluidity types, $^1S_0$, $^3P_2$ (m_j=0), and $^3P_2$ (m_j=2) that are denoted by A, B and C, respectively. The superfluidity of type A may be attributed to any protons, while superfluidity of types B and C may be attributed to neutrons[3]. The bulk viscosity is calculated by computing the reduction factors, R, for the three cases, and the results are compared with the bulk viscosity of the non-superfluid case. The results are shown in the Figure 1 as a function of temperature, T, for the equation of state of SEI corresponding to γ =1/2, that has incompressibility $K(\rho_0)$=245 MeV and slope L= 76.26 MeV. The results in the Fig.1 is for density $\rho=4\rho_0$, where ρ_0 is the saturation density, where we have used $\omega = 10^4$ s^{-1}, the critical temperature T_c to be 10^{10} K

It is found that stronger reduction in bulk viscosity is provided by the type A and B superfluidity in comparison to type C for temperature less than 10^9 K. However, above this temperature, the three curves get closure asymptotically approaching the non-superfluid curve as the critical temperature T_c is reached

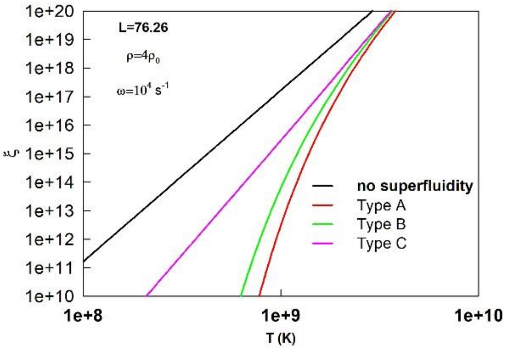

Fig. 1. The total bulk viscosity of non-superfluid matter (black solid line), total bulk viscosity of superfluid matter (Type A (red solid line), Type B (green solid line), and Type C (pink solid line)) as a function of temperature (T).

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