Proto-neutron Star with trapped Neutrinos

S. K. Tripathy[1],* T.R.Routray[2] and B.Behera[2]
[1]*Govt. College of Engineering, Kalahandi, Bhawanipatna, Odisha, 766001, INDIA*
[2]*School of Physics, Sambalpur University, Jyotivihar, Sambalpur, Odisha, 768019, INDIA*
** email: tripathy_sunil@rediffmail.com*

Introduction

At the time of born, from gravitational collapse of a massive star, a neutron star (NS) commonly known as proto-neutron star (PNS), has a quite large temperature and proton fraction which initiates the direct URCA process. In this process abundant neutrinos are formed which are trapped inside during the early phase of evolution of the PNS. Within 10 to 20 seconds of formation, the PNS rapidly cools to practically zero temperature via neutrino emission as the mean free path of neutrino increases with decreasing energy. A cooled neutron star becomes practically free of the trapped neutrinos.

Studying the properties of neutron star allows us to test our knowledge on the equation of state (EOS) of nuclear matter. The composition and structure of NS depends on the nuclear symmetry energy whose high density behavior is still uncertain. There have been many attempts in recent times to constrain the high density behavior of nuclear symmetry energy.

In this work, we have considered the EOS and nuclear symmetry energy as has been constrained from universal high density behavior[1] to study the effect of trapped neutrinos on the composition and EOS of beta stable PNS. We have considered the nuclear symmetry energy at $T = 0\,MeV$ as a function of density for two different exchange strength parameters of the momentum dependent parts of the effective interaction acting between a pair of like nucleons corresponding to two different cases of neutron-proton effective mass splitting. It is worth to be mentioned here that, our present day knowledge on EOS is unable to ensure whether the neutron effective mass goes above the proton effective mass in a neutron rich matter. Even though, a consensus has been reached in favour of the neutron effective mass going above the proton one, there is still large uncertainty prevailing in constraining the magnitude of the splitting. The nuclear symmetry energies for the two cases considered here have been constrained from the universal high density behavior are neither very soft nor very stiff and do not allow the URCA process at T=0MeV for the whole range of densities.

Formalism

The work is carried out in the framework of non-relativistic mean field theory using a finite range effective interaction. For the purpose we have used the effective interactions which depend only on the inter nucleon separation distance r and the total nucleon density $\rho = \rho_n + \rho_p$ of the medium. Such effective interactions have been used successfully in the study of properties of symmetric and asymmetric nuclear matter [1, 2]. The effective interaction has also been successfully used to investigate the composition and EOS of beta stable charge neutral $n + p + e + \mu$ matter at finite temperature [3]. Under the formalism the momentum and temperature dependence of neutron and proton mean fields as well as the temperature dependence of the interaction part of EOS of asymmetric nuclear matter are simulated through the finite range exchange parts of the effective interaction.

The beta equilibrium conditions for the proto-neutron star with trapped neutrinos are

$$\rho_p = \rho_e \tag{1}$$

and

$$\mu_p + \mu_e = \mu_n + \mu_{\nu_e}, \tag{2}$$

where ρ_p and ρ_e are the densities of proton and electron. μ's are the chemical potentials of proton, electron, neutron and neutrinos. Muons are believed to be absent from the matter. Assuming a quadratic dependence of the EOS of asymmetric nuclear matter on the neutron-proton asymmetry, the difference in the neutron and proton chemical potentials is expressed through the free symmetry energy as

$$\mu_n - \mu_p = 4(1 - 2Y_p)F_{sym}(\rho, T) \qquad (3)$$

where, Y_p is the proton fraction and $F_{sym}(\rho, T)$is the free symmetry energy as a function of medium density and temperature. The free symmetry energy is related to the nuclear symmetry energy through entropy per nucleon.

The beta equilibrium conditions (1) and (2) are solved along with the constraint that in the early stage of evolution of the neutron star, the lepton fraction $Y_l = Y_e + Y_{\nu_e}$ is almost constant i.e around 0.35~ 0.4. In the calculation of composition and EOS of proto-neutron star, we have assumed the neutrinos to be mass less and ultra relativistic. In the neutrino free case, the beta equilibrium condition is reduced to that in an $n + p + e$ matter by taking the neutrino density and the neutrino chemical potential to be zero. During the calculation, it has been ensured that the baryonic density is conserved. Once the composition of beta stable matter for both the neutrino trapped and neutrino free cases, is known, the EOS can be calculated in usual manner. The structure and mass radius relation of the proton star can be calculated using the hydrodynamic TOV equation.

Results and Discussion

We have calculated the proton fraction and EOS of neutrino trapped and neutrino free beta stable neutron star matter at different temperatures [Fig.1]. It is found that, the composition of the matter becomes significantly different when the neutrinos are trapped. The neutrino trapping keeps the electron concentration high and hence the matter becomes proton rich in comparison to the case when neutrinos are diffused out. The proton fraction increases with increase in density. The temperature effect on the proton fraction is more prominent in case of the neutrino trapped case. Proton fraction increases with the increase in temperature. However, at low density region the increase in proton fraction with temperature is comparatively more than at high density region.

Corresponding to the different composition of the beta stable matter for the neutrino trapped and neutrino free cases, the EOS for neutrino trapped case is stiffer than the neutrino free case. Our results compare well with the calculation of Xu et al.[4].

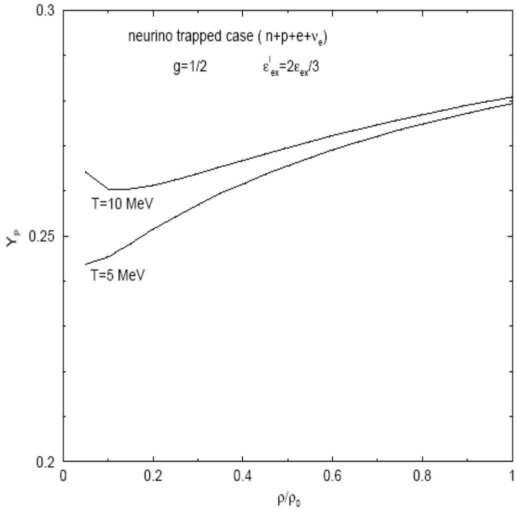

Fig.1. Proton fraction for neutrino trapped neutron star matter at two different temperautres.

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