Composition and EOS of $b-$stable Charge neutral $n+p+e+m$ Matter at Finite Temperature

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Introduction: In supernovae matter the internal temperature is as high as of the order T ~10-40 MeV and the proton fraction $Y_P(r,T) \approx 1/3$. The heavy element core of massive star inside the supernova matter undergoes a gravitational collapse resulting into either directly to a black hole or to a metastable proto neutron star (PNS). The newly formed stars have a quite large proton fraction and as a result copious amount of neutrinos are produced. The PNS cools rapidly via emission of neutrinos (URCA process), within few seconds and reaches a temperature less than 1 MeV. Proton fraction controls the rapid cooling mechanism of the neutron star and is a strong function of temperature. In typical neutron stars, proton fraction is solely determined from the nuclear symmetry energy together with the charge neutrality condition. But in the early stage of PNS the internal temperature ranges between 40-50 MeV, where entropy plays a crucial role in the total free energy of the system. The process of formation and cooling of the PNS can be basically considered as isentropic process where the free energy plays the crucial role. Out of the limited numbers of works on the neutron star calculation at finite temperature available in the literature, some have used symmetry energy at finite temperature in their calculations and others have used free symmetry energy. We shall calculate in this work the equilibrium proton fraction in hot charge neutral $b-$stable $n+p+e+m$ matter that constitutes the bulk of supernovae matter and PNS core, by using the free symmetry energy.

The work will be carried out in the frame work of non-relativistic mean field theory using finite range effective interaction. For the purpose we have used the effective interactions which depends only on the inter nucleon separation distance 'r' and the total nucleon density $r = r_n + r_p$ of the medium. Such effective interactions have been used with successfully in the study of properties of symmetric and asymmetric nuclear matter[1,2]. Under this formalism, the momentum and temperature dependence of neutron and proton mean fields as well as temperature dependence of the interaction part of EOS of asymmetric nuclear matter (ANM) are simulated through the finite range exchange parts of the effective interaction $v_{ex}^{l,ul}(r)$ operating between pairs of like (l) and unlike (ul) nucleons. In view of this, a correct knowledge of the momentum dependence of the neutron (n) and proton (p) mean fields in neutron rich ANM is very crucial while deciding the temperature dependence of various nuclear matter properties. The momentum dependence of neutron and proton mean fields in ANM is related to the existing problem of $n-p$ effective mass splitting in neutron rich matter. So far, from different theoretical and empirical studies, an almost consensus opinion has emerged on the fact that neutron effective mass goes above that of the proton in neutron rich ANM. However, the magnitude of the $n-p$ effective mass splitting is yet to be decided [3]. In view of this, we shall also examine the influences of effective mass splitting on the composition of hot $b-$stable charge neutral $n+p+e+m$ matter and bulk properties neutron stars at finite temperature, i.e., PNS. However, the results obtained are qualitative in the sense that we have not considered the possible hyperonic and quark degrees freedom that may be present at high density and temperature conditions.

Formalism: The condition for $n+p+e+m$ matter under $b-$ equilibrium at a given density r and temperature T is given by

$$m_n(r,T) - m_p(r,T) = m_e(r,T) = m_m(r,T), \quad \ldots(1)$$

where, m_i, $i = n, p, e, m$ are the respective chemical potentials. For quadratic approximation of free energy density the quantity in left hand side of eq.(1) can be expressed as,

$$m_n(r,T) - m_p(r,T) = 4(1-2Y_p(r,T))F_{sym}(r,T), \quad (2)$$

$F_{sym}(r,T)$ being the free symmetry energy and m_i, with $i = n, p$. The charge neutrality condition of the b -equilibrated matter is given by the relation

$$Y_p(r,T) = Y_e(r,T) + Y_m(r,T), \quad \ldots(3)$$

where, $Y_i = r_i / r$, $i = n,p,e,m$ are the respective particle fractions. Equation (1) in conjunction with eq.(2) and eq.(3) are solved simultaneously to obtain the respective particle fractions and chemical potentials. Once the particle fractions as a function of density at a given temperature are known, the EOS of nucleonic part and leptonic parts can be calculated. The EOS of nucleonic part can be calculated from the EOS of ANM obtained with the finite range effective interaction. The leptonic EOSs are calculated from non interacting relativistic Fermi gas model. The EOS of b -stable neutron star matter (NSM) thus obtained are used to study the bulk properties of PNS.

Results and Discussion: The equilibrium proton fractions obtained at different temperatures $T = 0,20,40$ *and* 60 *MeV* for different splittings of finite range exchange strength parameter $(e^{l}_{ex} + e^{ul}_{ex})$ into like and unlike e^{l}_{ex} and e^{ul}_{ex}, respectively, leading to different neutron-proton effective mass splitting are shown as functions of density r in the Figs 1 (a), (b) and (c). The proton fraction $Y_P(r,T)$ increases in a region of density r where $F_{sym}(r,T)$ decreases at a rate slower than $m(r,T)$ with increasing temperature. On the other hand $Y_P(r,T)$ can decrease with increase in temperature T in a region of density r where $F_{sym}(r,T)$ decreases at a faster rate than $m(r,T)$ with increase in temperature. However, in the low density region, proton fraction increases sharply with temperature. At a given temperature the rate of increase of the particle fractions in NSM increase as e^{l}_{ex} increase from $e^{l}_{ex} = (e^{l}_{ex} + e^{ul}_{ex})/6$ (Case A) to $e^{l}_{ex} = (e^{l}_{ex} + e^{ul}_{ex})/2$ (Case B) as may be seen in Fig-2. Although the compositions of NSM for the three cases of different $n-p$ effective mass splittings show marked differences, it is found from calculations that it has little effect on the bulk properties of PNS. In the three cases the mass and radius of the neutron star calculation at finite temperature give almost same results. Thus different momentum dependences of neutron and proton mean fields in ANM has affect on the composition of protoneutron stars without any remarkable effect on its bulk properties.

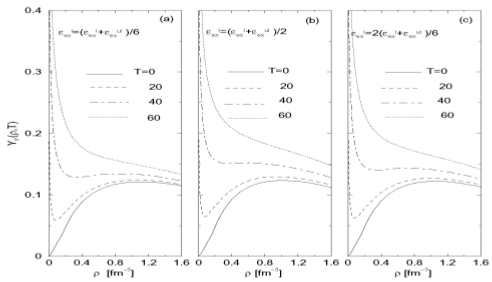

Fig.1(a) , (b) &(c): Equilibrium proton fraction for different cases of e^{l}_{ex} at temperatures, T=0, 20, 40 and 60 MeV.

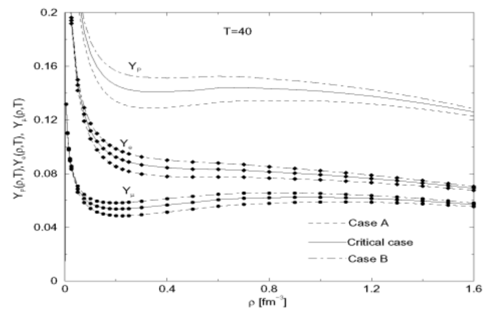

Fig.2: Equilibrium fractions Y_p, Y_e, Y_m for different cases of e^{l}_{ex} at temperature, T=40 MeV.

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