Effective mass splitting and Neutron Star properties at finite temperature

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Introduction

Finite temperature calculation of equation of state (EOS) of charge neutral b-stable $n+p+e+m$ matter (NSM) at finite temperature T is crucial in the study of formation mechanism of neutron stars (NS) which have temperature as high as ~50 MeV in the core at when they born. In the present work, our objective is to calculate the NS properties at finite T with particular emphasis on the momentum dependence of nucleonic mean fields. We have used the Yukawa effective interaction (YEI) in our study that has been successfully used in the calculations of EOS of NSM at finite temperature [1] and themal evolution of properties of nuclear matter (NM) [2]. The temperature dependence of the mean fields and the interaction parts of the energy densities are simulated through the Fermi-Dirac momentum distribution functions while the interaction itself is temperature independent. Hence, in order to have the correct thermal evolution it is necessary to know the correct momentum dependence of the nucleonic mean fields. But this aspect of the nucleonic mean field has remained as an open problem in nuclear research as evident from the predictions of effective mass splitting ($(m_n^* - m_p^*)$ splitting) by different theoretical models which not only diverge but also contradicting. In a recent work [2] it has been shown that the whole range of allowed momentum dependence of nucleonic mean field in NM can be divided into two distinct regions. The actual momentum dependence can be constrained to either of these two smaller regions subject to the answer to the question: Whether entropy density in pure neutron matter (PNM) can exceed to that of symmetric matter (SNM) or not? The calculation of NS properties at $T \neq 0$ is therefore expected to give different results for varying momentum dependence of nuclear mean fields.

Formalism

The b-equilibrium condition for NSM at $T \neq 0$ can be given by

$$4\left[1-2Y_P(r,T)\right] F_{sym}(r,T) = m(r,T) \qquad (1)$$

where, $m(r,T)$ is the b-equilibrated chemical potential and $F_{sym}(r,T)$ is the free symmetry energy defined as ,

$$F_{sym}(r,T) = [\{H_n(r,T) - H_0(r,T)\} - T\{S_n(r,T) - S_0(r,T)\}]/r \qquad (2)$$

with, H_i, S_i, $i = n,0$, are the energy densities and entropy densities in PNM and SNM, respectively. The equilibrium proton fraction $Y_p(r,T)$ under the charge neutrality condition is given by,

$$Y_P(r,T) = \frac{1}{p^2 r} \sum_{i=e,m} \int_0^\infty \frac{k^2 dk}{\exp\{[(c^2\hbar^2 k^2 + m_i^2 c^4)^{1/2} - m(r,T)]/T\} + 1} \qquad (3)$$

where, the leptons (electron e and muon m) are considered as relativistic ideal Fermi gases. If the density dependence of $F_{sym}(r,T)$ is known then the equations (1) and (2) can be solved iteratively to obtain b-equilibrium chemical potential, lepton fractions and proton fraction. Thus the composition of NSM at different T and r is essentially determined by the density and temperature dependence of $F_{sym}(r,T)$. The EOS of NSM can now be described by

$$H^{NSM}(r,Y_p,T) = H^N(r,Y_p,T) + H^e(r,Y_e,T) + H^m(r,Y_m,T)$$
$$P^{NSM}(r,Y_p,T) = P^N(r,Y_p,T) + P^e(r,Y_e,T) + P^m(r,Y_m,T)$$

where, H^i and P^i, $i = NSM, N, e, m$ are the energy density and pressure of NSM, nucleonic part, electronic and muonic parts respectively. Calculation of the EOS of NSM and hence the finite temperature properties of NS has been done for the YEI given by

$$v_{eff}(\vec{r}) = t_0(1+x_0P_s)d(\vec{r}) + \frac{1}{6}t_3(1+x_3P_s)\left[\frac{r(\vec{R})}{1+br(\vec{R})}\right]^g d(\vec{r})$$

$$+\left(W + BP_s - HP_t - MP_s P_t\right) f(r) \qquad \ldots(4)$$

The energy density, entropy density and free symmetry energy density in SNM and PNM are discussed in Refs.[1,2]. Altogether 9 parameters, $a, b, g, e_0^l, e_0^{ul}, e_g^l, e_g^{ul}, e_{ex}^l$ and e_{ex}^{ul} are involved and their determination from various constraints is also discussed in Refs.[1, 2].

Results and discussion

The results of the EOSs of NSM for three representative values of e_{ex}^l, namely, $e_{ex}^l = e_{ex}/3$, $2e_{ex}/3$, e_{ex}. where the two extreme values corresponds to two different regions of momentum dependence and the middle one is the boundary value dividing the two regions [2] are shown in the Fig. 1 at temperature T=40 MeV.

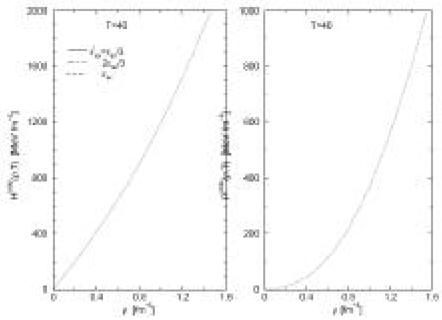

Fig.1. EOSs of NSM

It is found from the figure that thermal evolution of different magnitude resulting from varying momentum dependence has no appreciable effect on the EOS of NSM. It is therefore expected that different choices of e_{ex}^l will also show marginal difference on finite temperature NS results and the possibilities of using it in resolving the problem of $(m_n^* - m_p^*)$ splitting is bleak. The TOV equation is solved for the three cases of momentum dependence of nuclear mean fields for the NS results at different temperatures. The mass versus radius results are shown in Fig. 2 at T=5 and 10 MeV. The results are as expected from the EOSs of NSM showing marginal difference for different choices of e_{ex}^l. Therefore, specializing to the boundary value, $e_{ex}^l = 2e_{ex}/3$, mass versus the central density and radius versus the central density are shown in Figs. 3 and 4, respectively, for T=5 and 10 MeV. The results show that the central density of NS decreases, whereas, the radius increases with increase in temperature. The findings are in agreement with the microscopic BHF calculations using realistic interaction [3].

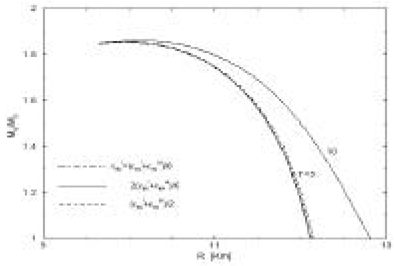

Fig.2. M~R relation of NS

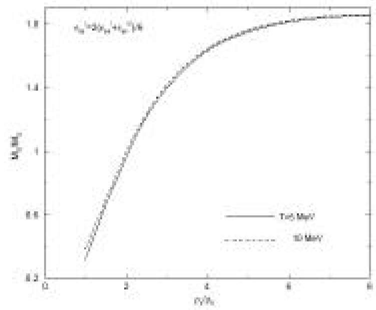

Fig.3. Mass~Central density of NS

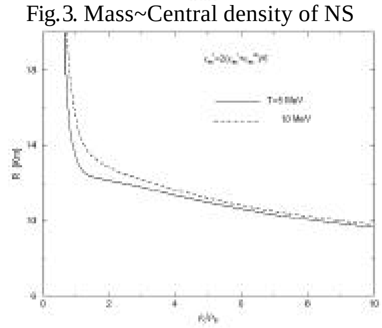

Fig.4. Radius~Central density of NS

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