Temperature dependence of nuclear symmetry energy and equation of state of charge neutral $n+p+e+m$ matter in beta equilibrium

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Introduction: The temperature and density dependence of nuclear symmetry energy, $E_S(r,T)$, is a subject of current interest for its implications not only in various aspects of nuclear physics but also in astrophysics. In particular, in presupernovae explosions electron capture rate on nuclei and/or free protons is especially sensitive to the symmetry energy at finite temperature. While the effect of temperature on the kinetic energy part of $E_S(r,T)$ is well understood [1], the temperature dependence of interaction part of symmetry energy has received less attention [2]. In the framework of non-relativistic mean field theory the temperature dependence of the interaction part is simulated through finite range exchange interactions which also account for the momentum dependence of the mean field. A correct momentum dependence of the neutron (n) and proton (p) mean fields in asymmetric nuclear matter (ANM), an area quite less understood, is therefore very crucial while deciding the density dependence of symmetry energy [3]. The predictions of various microscopic models as well as effective theories on n and p effective mass splittings in ANM diverge which can be attributed to the deficiencies in our present day understanding on the subject. There have been attempts to constrain the n and p effective mass splitting in neutron rich asymmetric matter from the study of observables sensitive to the isovector features of the nuclear EOS [4], but the task has not been accomplished as yet and the magnitude of effective mass splitting is still an open problem.

Formalism: The basic quantities in the description of EOS of ANM are the energy density $H(r,Y_p,T)$ and pressure $P(r,Y_p,T)$ which can be extracted as functions of total nucleon density $r = r_n + r_p$, proton fraction $Y_p = (r_p / r)$ and temperature T in any theoretical model. In general, the energy density and pressure have very complicated dependence on r, Y_p and T. However, the isospin symmetry allows to decompose $H(r,Y_p,T)$ and $P(r,Y_p,T)$ in a series of even integral powers of $(1-2Y_p)$. The results have the crucial advantage that the Y_p- dependence of $H(r,Y_p,T)$ and $P(r,Y_p,T)$ have been separated out from their dependence on r and T. Under the quadratic approximation on $(1-2Y_p)$-dependence, which is valid not only at $T=0$ but also at finite T [5], the energy density and pressure take the simple form,

$$H(r,Y_p,T) = H_0(r,T) + (1-2Y_p)^2 H_s(r,T), \qquad \ldots(1)$$

$$P(r,Y_p,T) = P_0(r,T) + (1-2Y_p)^2 P_s(r,T). \qquad \ldots(2)$$

Since pure neutron matter (PNM) and symmetric nuclear matter (SNM) at same T and r constitute the two extremes of ANM corresponding to $Y_p = 0$ and $Y_p = 1/2$, respectively, it is necessary that $H_0(r,T)$ and $P_0(r,T)$ be identified with the energy density and pressure in SNM. Further, $H_s(r,T)$ and $P_s(r,T)$ are to be identified with the symmetry energy density and symmetry energy pressure respectively and defined in terms of the differences between the energy densities as well as pressure in PNM and SNM,

$$H_s(r,T) = r\,E_S(r,T) = H_n(r,T) - H_0(r,T), \qquad \ldots(3)$$

$$P_s(r,T) = P_n(r,T) - P_0(r,T), \qquad \ldots(4)$$

where, $E_s(r,T)$ is the nuclear symmetry energy as a function of r and T. It is evident from the eqs.(1)-(4) that a complete description of EOS of ANM amounts to separate descriptions of EOSs of PNM and SNM at same temperature T and same total nucleon density r. The calculation of EOS of charge neutral $n+p+e+m$ matter in $b-$equilibrium, i.e., neutron star matter (NSM), would require the additional conditions of charge neutrality

$$Y_p = Y_e + Y_m, \qquad \ldots(5)$$

and $b-$equilibrium, which for the quadratic approximation of the energy density becomes

$$4\,[1-2Y_P(r,T)]\,E_s(r,T) = m(r,T)\ldots.(6)$$

$m(r,T)$ in this equation is the $b-$equilibrium chemical potential corresponding to the equality $m_n(r,Y_p,T) - m_p(r,Y_p,T) = m_e(r,Y_e,T) = m_m(r,Y_m,T)$ where, m_i with $i = n, p, e$ and m are the neutron, proton, electron and muon chemical potentials and $Y_i = (r_i / r)$, with $i = e$ and m, are the electron and muon fractions.

Results and Discussion: The temperature evolution of nuclear symmetry energy relative to its zero temperature value,

$$Q(r,T) = [E_S(r,T) - E_S(r,T=0)], \quad \ldots(7)$$

and the proton fraction, $Y_p(r,T)$, in charge neutral $n+p+e+m$ matter in $b-$equilibrium are calculated for the two cases of splittings of finite range exchange strength parameters, $\left(e^{l}_{ex} + e^{ul}_{ex}\right)$, into interaction between a pair of like nucleons (l) and that of a pair of unlike nucleons (ul), namely, $e^{l}_{ex} = \left(e^{l}_{ex} + e^{ul}_{ex}\right)/6$ (Case A) and $e^{l}_{ex} = e^{ul}_{ex}$ (Case B). These two cases cover a wide range of magnitude of neutron and proton effective mass splittings in neutron rich asymmetric matter. In these calculations the EOS of ANM has been obtained by using the finite range effective interaction,

$$v_{eff}(\vec{r}) = t_0(1+x_0P_s)\,d(\vec{r}) + \frac{1}{6}t_3(1+x_3P_s)[\,r(\vec{R})/(1+br(\vec{R}))]^{g}\,d(\vec{r}) + (W + BP_s - HP_t - MP_s P_t)\,f(r) \quad ,\ldots(8)$$

where, $f(r)$ is the functional form of a short range interaction, considered in the work to be of Yukawa form, specified by a single parameter, a, the range of the interaction. The remaining symbols in eq.(8) have their usual meaning. The results are shown in the figures given below.

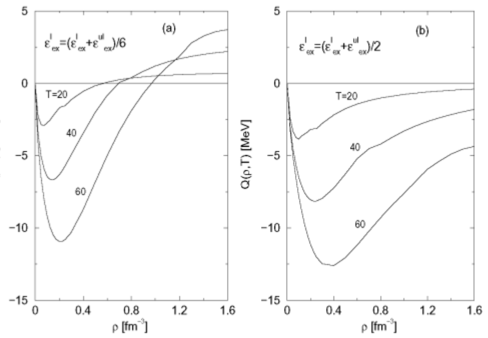

Figure 1(a) & (b): (a) Nuclear symmetry energy at temperature T relative to its zero temperature results, $Q(r,T)$, shown as a function of density for case A at three different temperatures, T=20, 40 and 60 MeV. (b) Same as (a) for case B.

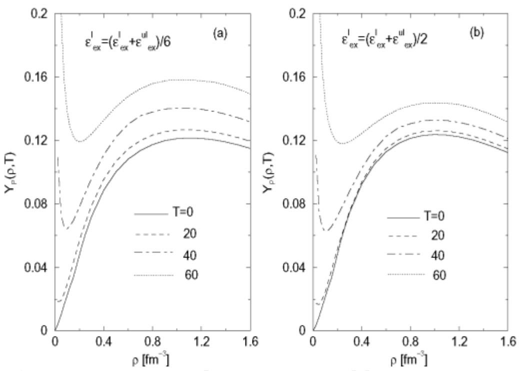

Figure 2(a) & (b): (a) Equilibrium proton fraction $Y_P(r,T)$ in NSM shown as a function of density for case A at four different temperatures, T=0, 20, 40 and 60 MeV. (b) Same as (a) for case B.

References

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