Neutron-Proton effective mass splitting and thermal evolution of Nuclear matter

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Introduction: Finite temperature calculation of nuclear matter equation of state (EOS) has emerged as an important area of nuclear research in the recent years for its implications not only in nuclear physics but also in nuclear astrophysics. In this work we restrict to effective interactions which depend only on the inter nucleon separation distance 'r' and the total nucleon density $r = r_n + r_p$ of the medium. 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. Theoretical predictions of different models on the momentum dependence of neutron and proton mean fields in ANM can be divided into two distinct groups depending on whether the neutron effective mass goes above that of the proton one or the other way around. In the formalism used in the present work it is possible to reproduce effective mass splittings of both kinds depending on the relative splitting of the total exchange strength into like and unlike channels. The present status on this important issue is that the nature of $n-p$ effective mass splitting is more or less resolved and there is almost a consensus opinion that neutron effective mass goes above that of the proton in neutron rich ANM. However, the magnitude of the effective mass splitting is yet to be decided [1] and it is still an open problem. In view of this, we examine the influence of effective mass splittings of different magnitudes on the thermal evolution of various properties of neutron rich matter.

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. Under the quadratic approximation on $(1-2Y_p)$-dependence, which is valid not only at $T=0$ but also at finite T [2], the entropy density, energy density, free energy density and pressure take the simple form,

$$S(r,Y_p,T) = S_0(r,T) + (1-2Y_p)^2 S_s(r,T), \quad \ldots(1)$$

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

$$F(r,Y_p,T) = F_0(r,T) + (1-2Y_p)^2 F_s(r,T), \quad \ldots(3)$$

$$P(r,Y_p,T) = P_0(r,T) + (1-2Y_p)^2 P_s(r,T). \quad \ldots(4)$$

Since pure neutron matter (PNM) and symmetric nuclear matter (SNM) at same T and r constitute the two extremes of ANM, it is necessary that $S_s(r,T)$ $H_s(r,T)$, $F_s(r,T)$ and $P_s(r,T)$ be identified as,

$$S_s(r,T) = S_n(r,T) - S_0(r,T) \quad \ldots(5)$$

$$H_s(r,T) = r\,E_S(r,T) = H_n(r,T) - H_0(r,T) \quad \ldots(6)$$

$$F_s(r,T) = F_n(r,T) - F_0(r,T) \quad \ldots(7)$$

$$P_s(r,T) = P_n(r,T) - P_0(r,T), \quad \ldots(8)$$

where, the indices n and 0 refer to that of PNM and SNM respectively, and $E_S(r,T)$ is the nuclear symmetry energy as a function of r and T. It is evident from the eqs.(1)-(8) that a complete description of EOS of ANM amounts to separate descriptions of EOSs of PNM and SNM at same T and r. The formalism is valid for any model where calculation of EOSs of SNM and PNM is possible.

Results and Discussion: The thermal evolution of nuclear matter properties relative to their zero temperature values have been calculated for our finite range interaction used in Ref.[3], where, $f(r)$ is the Yukawa form of the finite short range interaction, specified by a single parameter, a , the range of the interaction. The present study requires only the exchange parts of the interaction and independent of how the density dependent parts of the EOSs in SNM and PNM are constrained at zero-temperature. The values of the range a and exchange strength $e_{ex} = \left(e_{ex}^{l} + e_{ex}^{ul}\right)/2$ in SNM are obtained in our earlier work [4] to be 0.4044 fm and - 243.6 MeV. In absence of a correct knowledge of splitting of e_{ex} into like and unlike channels, e_{ex}^{l} and e_{ex}^{ul} respectively, which also determines the $n-p$ effective mass splitting in ANM, we have studied the thermal evolution of nuclear matter properties like, entropy density, energy density, free energy density, pressure, etc., for representative splittings of e_{ex} into e_{ex}^{l} and e_{ex}^{ul} within its possible range $0 \le e_{ex}^{l} \le e_{ex}$. The entropy density $S_i(r,T)$, $i = 0,n$, in SNM and PNM respectively are shown as a function of density in Figures 1(a) and (b) for the representative values of e_{ex}^{l} in the range 0.15 $(e_{ex}^{l} + e_{ex}^{ul})$ to 0.45 $(e_{ex}^{l} + e_{ex}^{ul})$ at two different temperatures, T = 40 and 60 MeV. The results obtained show that there is a critical value of e_{ex}^{l} close to $2(e_{ex}^{l} + e_{ex}^{ul})/6$ on either side of which the density dependence of entropy density in PNM relative to the value in SNM exhibit two contrasting behaviours. For e_{ex}^{l} weaker than this critical value, the symmetry entropy density can be positive at higher value of density. Now the question arises whether the entropy density in the one component system of PNM can surpass to that of SNM which is a two component system. For e_{ex}^{l} stronger than the critical value $2(e_{ex}^{l} + e_{ex}^{ul})/6$ the symmetry entropy density is negative at any density. This is true at any T .

For the critical value, $e_{ex}^{l} = 2(e_{ex}^{l} + e_{ex}^{ul})/6$ the entropy density in PNM approaches to that of SNM asymptotically in the high density region which is true at all temperatures. The thermal evolution in the cases of other nuclear matter properties, such as, energy density and free energy density for the different values of e_{ex}^{l} show the same characteristic feature. Thus, on the basis of two different behaviours obtained with the thermal evolution of nuclear matter properties, the whole range of possible splitting of exchange strength parameter, $(e_{ex}^{l} + e_{ex}^{ul})$, into like and unlike channels are sub-divided into two smaller regions narrowing down the magnitude of possible $n-p$ effective mass splitting in neutron rich asymmetric matter. The n and p effective masses calculated as a function of neutron-proton asymmetry $(1-2Y_p)$ in ANM at normal density r_0 for the critical value, $e_{ex}^{l} = 2(e_{ex}^{l} + e_{ex}^{ul})/6$, agrees well with the ab initio DBHF results [5]. However, more theoretical and experimental efforts are needed in order to further constraining the $n-p$ effective mass splitting.

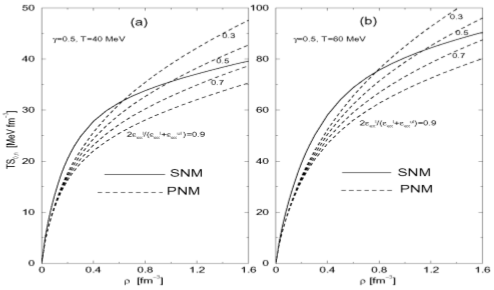

Fig.1(a) & (b): (a) Entropy density as a function of density in SNM (solid curve) and different cases in PNM (dotted curves) fot different cases of e_{ex}^{l} at temperature, T=40 MeV, (b) same as (a) at T=60 MeV.

Acknowledgments : Work is supported by UGC-DAE CSR/KC/2009/NP06/1354 dated 31-7-09.

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