Characteristics of proton in nuclear matter at low proton concentration

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Introduction

Equation of state(EOS) of asymmetric nuclear matter with low proton fractions at finite temperature is one of the relevant issues in the theory of neutron star calculation particularly for the calculation of outer crust of neutron star. In this outer crust, non uniform structures of nuclear matter is expected[1], where the matter is supposed to be consistent with low proton fractions Y_p. Calculations are also available for proton fractions $Y_p(0.05 \le Y_p \le 0.4)$ within nuclear matter densities ρ in the range $(0.03 \le \rho \le 0.1)$[2]. In this respect, our aim is to study the pressure, generated by protons for various values of low proton fractions $Y_p = 0.06$, 0.08, 0.1 and 0.12 at different values of densities at temperature T=5MeV. Nucleon effective mass also plays an important role in understanding many interesting physical quantities and phenomena in nuclear physics and astrophysics[3]. Determination of proton-neutron effective mass splitting in neutron rich nuclear matter is receiving more and more attention. We have calculated effective mass of proton at various values of proton fractions at densities 0.10, 0.15, 0.20, 0.25 and $0.30 fm^{-3}$ at temperature T=5MeV.

Model

A non-relativistic microscopic formulation is developed in frame work of Brueckner Goldstone expansion at finite temperature[4]. In this formalism, zero temperature Brueckner theory is extended to finite temperature. In our calculation, density dependent two body Sussex interaction is used which produces correct saturation property in symmetric nuclear matter. Basing upon this formalism, we have performed the calculation for isothermal [5] and isentropic[6] EOS of nuclear matter and supernova matter. Starting point of our formalism is to write grand thermodynamic potential per unit volume.

$$\Omega = -P = -T ln Tr e^{-(H-\mu n)} \qquad (1)$$

Where H and n are Hamiltonian and number density operators. P, T and μ are Pressure, Temperature and Chemical potential respectively. We have introduced proton fraction Y_p defined as $Y_p = n_+/n$. Where n_+=density of proton. n=n_++n_-=nuclear matter density. n_-=number density of neutron. Effective mass is calculated using the formula

$$\frac{m^*_\tau}{m_\tau} = \left(1 + \frac{2m_\tau}{\hbar^2}\frac{dU_\tau}{dk^2}\right)^{-1} \qquad (2)$$

U_τ is the single particle potential and it is calculated using the formula

$$U_\tau \ (\ k_1) = \frac{1}{2\pi^2}\int_0^\infty dk_2[n_+(k_2)g_{++} \qquad (3)$$
$$(\ E_s, k_1, k_2) + n_-(k_2)g_{-+}(E_s, k_1, k_2)]$$

$n_\tau(k)$=Fermi distinction function.
$g_{\tau\tau}(E_s, k_1, k_2) \rightarrow$ Interaction matrices.
$\tau \rightarrow$ '+' for proton and '-' for neutron.
$E_s \rightarrow$ starting energy for two particles. Pressure generated by protons is calculated using the formula

$$P_\tau = \frac{1}{\pi^2}\int_0^\infty dk k^2 n_\tau(k)\left(\frac{1}{3}k\frac{d\epsilon_\tau}{dk} + \frac{1}{2}U_\tau(k)\right) \qquad (4)$$

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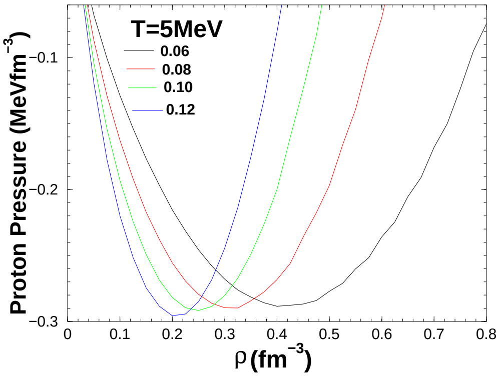

FIG. 1: Proton pressure at various various values of densities at Y_p = 0.06, 0.08, 0.10 and 0.12 at temperature T = 5MeV.

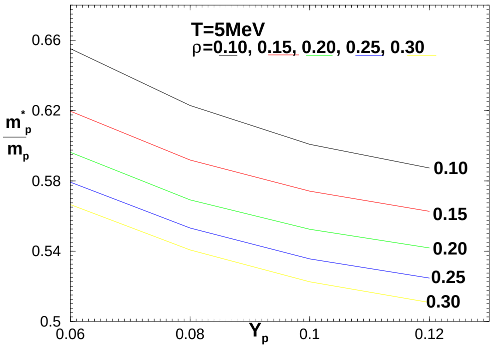

FIG. 2: Effective mass of proton at various values of proton fractions at densities ρ = 0.10, 0.15, 0.20, 0.25 and 0.30fm^{-3} at temperature T = 5MeV.

Single particle potential takes into accounts the scattering into intermediate states properly and self consistency is satisfied with respect to single particle potential and chemical potential.

Results

Effective mass of proton is plotted in Fig-1, at various values of proton fractions for densities ρ=0.10, 0.15, 0.20, 0.25 and 0.30fm^{-3} at temperature T=5MeV. It is found that at low density, for a given proton fraction say 0.06, effective mass of proton is larger. When the fraction of proton as well as density increase, effective mass is reduced. It may be due to mean field effect which depends on nucleon-nucleon interaction. However effective mass is model dependent.

In Fig-2, pressure generated by protons for proton fractions Y_p = 0.06, 0.08, 0.1 and 0.12 are plotted for various values of densities at temperature T=5MeV. It is found that for all the values of given proton fractions, the generation of pressure due to protons is -ve and of parabolic in nature. Each curve is having a minimum value. But the width of the parabola decreases as the proton fraction is enhanced. However, this -ve pressure generated by protons at these fractions gives the idea that the nuclear matter with these proton fractions is unstable even at high densities.

References

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