Effect of shear viscosity on antikaon nucleation bubbles in neutron star

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Introduction

In the past few years there has been a growing interest in the study of nucleation process of bubbles of a new phase in first order phase transitions. The goal is to compute the probability that a bubble of a new phase, such as quark matter [1], kaon condensed phase [2], appears in a system of initial (hadron)phase near the critical temperature. It was shown that the shear viscosity might control the initial growth rate of a bubble of the quark phase [3, 4]. Recently we carried out calculations of shear viscosity involving antikaon condensation in neutron star matter [5]. This motivates us to investigate the effect of shear viscosity on the nucleation process of bubbles of K^- condensed phase in neutron stars, which has not been investigated so far.

Formalism

We consider a first order phase transition from charge neutral and beta-equilibrated nuclear matter to K^- condensed phase in a hot neutron star after the emission of trapped neutrinos. The bubbles consisting of antikaon condensed matter are formed in the hadron phase at temperature $T < T_c$ because of thermal fluctuations, where T_c is the critical temperature. The modern theory of homogeneous nucleation via thermal activation pioneered by Langer [6], yields the following formula for the nucleation per unit time per unit volume

$$I = \frac{\kappa}{2\pi}\Omega_0 \exp(-\frac{\Delta F}{T}), \qquad (1)$$

where ΔF is the excess free energy of the system due to formation of the critical bubble. The prefactor in I is the product of two terms: Ω_0 is the statistical prefactor which measures the available phase space volume, κ is the dynamical prefactor, which determines the exponential growth rate of critical droplets given by [3]

$$\kappa = \frac{2\sigma}{R_*^3(\Delta w)^2}\left[\lambda T + 2\left(\frac{4}{3}\eta + \zeta\right)\right] \qquad (2)$$

where Δw is the difference of the enthalpy of the two phases, λ is the thermal conductivity, η and ζ are the shear and bulk viscosity respectively, σ is the surface tension for the surface separating the two phases. However, the dominant contribution to dynamical prefactor comes from the shear viscosity term, so we take ζ and λ to be zero [3]. The change in free energy of the system is

$$\Delta F = -\frac{4\pi}{3}\left(P^K - P^H\right)R^3 + 4\pi\sigma R^2 \qquad (3)$$

where R is the radius of the droplet, P^H and P^K are the pressure in nucleon and antikaon condensed phases respectively. The bubble would grow whenever its radius is larger than a critical value (R_*) and collapse otherwise. The free energy is maximum at this critical radius given by

$$R_*(T) = \frac{2\sigma}{(P^K - P^H)}. \qquad (4)$$

The thermal nucleation time τ_{th}, relative to innermost stellar region $[V_{nuc} = (4/3)R_{nuc}^3]$, $R_{nuc} \sim 100\,m$ where almost constant pressure and temperature occur, can thus be written as

$$\tau_{th} = (V_{nuc} I)^{-1}. \qquad (5)$$

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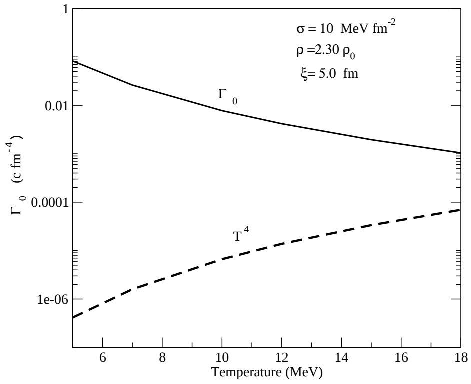

FIG. 1: Prefactor as a function of temperature

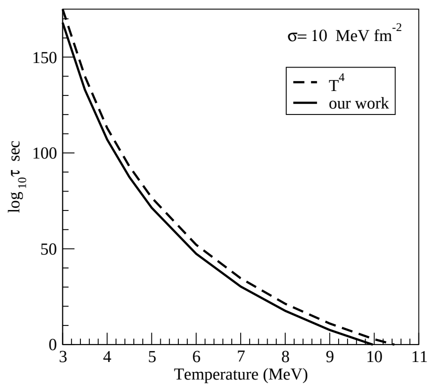

FIG. 2: Thermal nucleation time with temperature compared with the calculation of T^4 approximation.

It is evident from Eq. 5 that the thermal nucleation time is inversely proportional to the shear viscosity. The shear viscosity which is an input to Eq. 2 has recently been calculated [5] in the presence of an antikaon condensate. The shear viscosity of individual carrier is given by

$$\eta_i = \frac{n_i p_{F_i}^2 \tau_i}{5 m_i^*} \qquad (6)$$

where n_i is the number density of the carrier, p_{F_i} its Fermi momentum, m_i^* the effective mass and τ_i is the relaxation time. The total shear viscosity is given by $\eta = \sum_i \eta_i$ where $i = e, \mu, p, n$.

We adopt the relativistic field theoretical model at finite temperature [7] for the calculation of the equation of state (EOS), shear viscosity and nucleation rate.

Results

The prefactor of Eq. 2 in previous calculations was approximated by T^4 according to the dimensional analysis [1, 3]. The prefactor calculated with this approximation differs by several orders of magnitude from the actual calculation, which is evident from Fig. 1. However, this difference between two calculations is reduced appreciably at higher temperatures, where the effect of shear viscosity is not much pronounced.

We find that this difference in prefactor at lower temperature is reflected in the results of thermal nucleation time. A comparison of our results with that of T^4 approximation shows that the T^4 approximation overestimates our results of thermal nucleation time. For example in Fig.2 the thermal nucleation time is 1s at T=10 MeV in our case whereas it is $\sim 10^3$ s at the same temperature. This highlights the importance of shear viscosity in our calculation. Finally, thermal nucleation of the antikaon condensed phase may be possible when the thermal nucleation time is less than the cooling time $t_{cool} \sim 10^2$ s.

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