Thermal protoneutron stars with hyperons*

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Abstract The properties of thermal protoneutron star matter including hyperons are investigated in the framework of the relativistic mean field theory (RMFT). In protoneuron star matter, with the increase of the temperature, the critical densities of hyperons decrease, the sequence for appearances of hyperons change, the abundances of hyperons as well as neutrinos increase, and the strong interactions between baryons get weaker. Meanwhile, the abundances of isospin multiple states for nucleons, Σ, and Ξ become identical, leading to isospin saturated symmetric matter, respectively. Moreover, if a protoneutron star is born with higher temperature, it is less likely to convert to a black hole.

Key words neutron star, finite temperature, hyperons

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A protoneutron star is now believed to be born as a result of the gravitational collapse of a massive evolved progenitor star ($M \sim 8-25\ \mathrm{M}_\odot$) in Type-II supernova[1, 2]. Neutrinos of this star are prevented by their short mean free paths from running away on dynamical timescales. On a timescale of 10−20s, neutrinos diffuse from the star, but leave behind much of their energy which causes significant heating of the ambient matter[3, 4]. Following the heating, the star cools by radiating neutrino pairs of all flavors and after several minutes its temperature falls below 1 MeV[5]. Finally, the star slowly cools via neutrino and photon emission after about 10^7 years[6, 7]. The presence of hyperons can soften the equation of state and hence it is reasonable to include them in protoneutron stars. On the other hand, protoneutron star matter is thermal matter. An interesting issue is how the system temperature influences the hyperonization and isospin asymmetry in protoneutron star matter. Moreover, baryons interact on each other mainly through strong interactions. The strong interactions between baryons in protoneutron star matter should also depend on the temperature. Thirdly, a massive protoneutron star with hyperons may convert to a low mass black hole after its neutrinos diffuse[8]. To know the effect of the temperature on the stable maximum mass with which a protoneutron star can evolve into a cold neutron star is important. The above mentioned questions will be answered in this paper. In the relativistic mean field theory (RMFT), the lagrangian density is,

$$L = \sum_{\mathrm{B}} \overline{\psi}_{\mathrm{B}}[\mathrm{i}\gamma_u\partial^u - (M_{\mathrm{B}} - g_{\sigma\mathrm{B}}\sigma) - g_{\omega\mathrm{B}}\gamma_u\omega^u - g_{\rho\mathrm{B}}\gamma_u \boldsymbol{\tau}\boldsymbol{b}^u]\psi_{\mathrm{B}} + \frac{1}{2}(\partial_u\sigma\partial^u\sigma - m_\sigma^2\sigma^2) - U(\sigma) + \frac{1}{2}m_\omega^2\omega_u \omega^u + \frac{1}{2}m_\rho^2\boldsymbol{b}_u\boldsymbol{b}^u - \frac{1}{4}F^{uv}F_{uv} - \frac{1}{4}G^{uv}G_{uv} + L_{\mathrm{l}}.$$

Here $U(\sigma)$ is the nonlinear term proposed by Boguta and Bodmer[9]. The sum on B is over all baryon octet $(\mathrm{p},\mathrm{n},\Lambda,\Sigma,\Xi)$. $\mathrm{L_l}$ represents the contribution of leptons (e and $\mathrm{v_e}$). In neutron stars, chemical equilibrium among baryons and leptons implies the relation, $\mu_{\mathrm{B}} = \mu_{\mathrm{n}} - q_{\mathrm{B}}\mu_{\mathrm{e}} + q_{\mathrm{B}}\mu_{\mathrm{ve}}$. The lepton fraction is defined as $Y_{\mathrm{L}} = (\rho_{\mathrm{e}} + \rho_{\mathrm{v_e}})/\rho_{\mathrm{B}} = 0.4$. In the calculation, the GL85 set[10] is used. The hyperon couplings are expressed as a ratio to the nucleon couplings. Here, we set $x_\sigma = x_\rho = 0.6$, $x_\omega = 0.66$[11].

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Figure 1 presents the fractions of baryons at ρ_B=0.8 fm^{-3} in protoneutron star matter versus temperature. At other densities the similar behaviour can be obtained. At 0.8 fm^{-3}, the abundances of hyperons increase with the temperature. This implies the neutrino abundance in the star core increases with temperature because hyperons can contribute negative electric charges. On the other hand, abundances of isospin multiple states for nucleons, Σ and Ξ become identical, leading to isospin saturated symmetric matter. Fig. 2 shows the critical densities for hyperons versus temperature. With the increase of temperature, the critical densities of hyperons become lower. This means protoneutron star matter at higher temperature may contain more hyperon species. In particular, some hyperons can appear at $\rho_B = 0$ if the temperature exceeds some critical values. The critical value of temperature is 26 MeV for Λ, 33 MeV for Σ^-, 37 MeV for Σ^0, 42 MeV for Σ^+ and 49 MeV for Ξ^-. Moreover, the sequence for the appearances of hyperons also changes with temperature. For example, the Λ appears earlier than the Σ^- in protoneutron star matter at the temperature lower than 5 MeV but the case is converse in other temperature region. The similar phenomenon also appears between Σ^+ and Ξ^-.

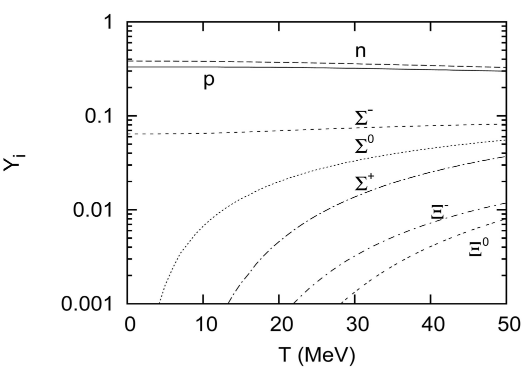

Fig. 1. Fractions of baryon octet versus temperature at ρ_B=0.8 fm^{-3}.

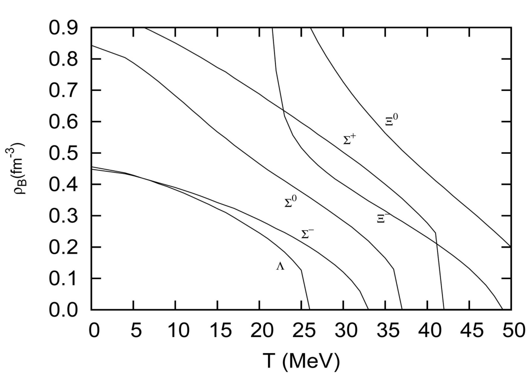

Fig. 2. The critical densities for hyperons versus temperature.

Figure 3 shows the meson potentials versus baryon density at different temperatures. All meson potentials decrease with temperature. So, the attractive (σ), repulsive (ω), and isospin (ρ) interactions decrease with temperature. Moreover, the σ-meson potential directly relates to the baryon effective mass and the ρ-meson potential describes the isospin asymmetry of nuclear matter. Therefore, baryon effective masses decrease with the temperature. So does the asymmetry of nuclear matter. From Fig. 3 one can conclude that in protoneutron star matter the strong interactions among baryons get smaller with the temperature. This is because particles move faster and become quite free at higher temperature condition.

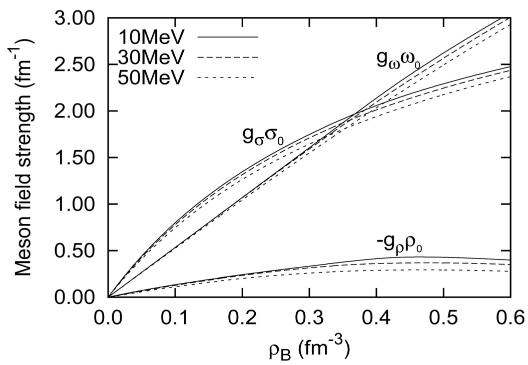

Fig. 3. Field strengths for the σ, ω and ρ mesons versus baryon density at different temperatures.

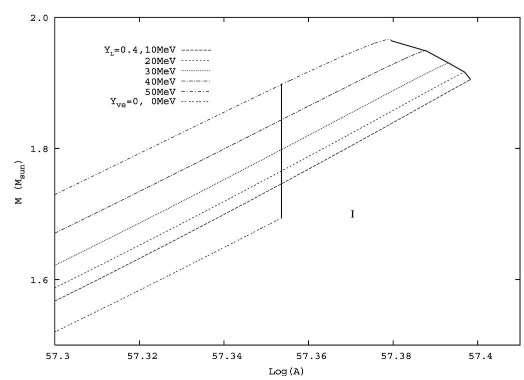

Fig. 4. protoneutron star masses versus total baryon numbers A at different temperatures. Cold neutron star masses versus numbers A are also shown. The vertical line denotes the maximum total baryon number ($A = \sim 10^{57.35}$) for the stable cold neutron star.

Figure 4 presents the protoneutron star masses versus the total baryon numbers for protoneutron stars at different temperatures. The maximum total baryon number of the stable cold neutron star is $\sim 10^{57.35}$, which is smaller than that of protoneutron stars at finite temperature. It means there exists two possible ways of evolutions for a hyperonized protoneutron star. When neutrinos of a protoneutron star whose baryon numbers exceed $\sim 10^{57.35}$ diffuse, a further collapse happens and then a low mass black hole will be formed. Alternatively, a protoneutron star with number $< 10^{57.35}$ can eventually evolve into a cold and lepton poor neutron star. The stable maximum mass with which a protoneutron star can evolve into a stable neutron star is denoted by the vertical solid line which stands for $A =\sim 10^{57.35}$ in Fig. 5. The solid line on the right side represents the maximum masses which are obtained by solving Tolman-Oppenheimer-Volkoff (TOV) equations[12]. Both of the solid lines bound a region denoted as I. Once a protoneutron star falls into the region I, it will transit to a black hole. In fact, the case of SN1987A is a potential proof for the transition from the protoneutron star to the black hole due to the commence of the hyperons[13]. Here, we also present the influences of temperature on this transition. When the temperature rises from 10 to 50 MeV, the stable maximum mass increases from 1.74 $M_\odot$ to 1.90 $M_\odot$, namely, increasing by $\sim 9\%$. The mass range in which a protoneutron star converts to a black hole decreases from ~ 0.16 $M_\odot$ (10 MeV) to ~ 0.06 $M_\odot$ (50 MeV), decreasing by $\sim 60\%$. Therefore, if a protoneutron star formed in the SN1987A gains lower temperature, it is more likely to convert to a black hole.

In summary, the properties of protoneutron star matter at finite temperature are investigated in the framework of the RMFT. The system temperature has a great impact on the hyperonization process of protoneutron star matter. With the increase of the temperature, the critical densities of hyperons decrease, whereas their abundances increase. A protoneutron star with higher temperature have larger amount of neutrinos. The interaction potentials between baryons get smaller with the temperature. Moreover, the increase of the temperature suppresses the isospin asymmetry and leads to isospin saturated matter. That a protoneutron star evolve into a cold stable neutron star or a low mass black hole also depends on the system temperature. If a protoneutron star is born with higher temperature, its converting to a low mass black hole is less likely to happen.

References

1 Bethe H A. Rev. Mod. Phys., 1990, **62**: 801

2 Burrows A, Hayes J, Fryxell B A. ApJ., 1995, **450**: 830

3 Burrows T J, Mazurek A, Lattimer J M. ApJ., 1981, **251**: 325

4 Burrows A, Lattimer J M. ApJ., 1986, **307**:178

5 Keil W, Janka H Th. A&A., 1995, **296**:145

6 Tsuruta S, Cameron A G W. Can. J. Phys., 1966 **44**: 1863

7 Schaab C, Weber F, Weigel M K et al. Nucl. Phys. A, 1996, **605**: 531

8 Glendenning N K. Compact Stars. New York: Springer-Verlag, 1997

9 Boguta J, Bodmer A R. Nucl. Phys. A, 1977, **292**: 413

10 Glendenning N K. ApJ., 1985, **293**: 470

11 Knorren R, Prakash M, Ellis P J. Phys. Rev. C, 1995, **52**: 3470

12 Oppenheimer J R, Volkoff G., Phys. Rev., 1939, **55**: 374

13 Madappa Prakash, Ignazio Bombaci, Manju Prakash. Phys. Rep., 1997, **280**: 1