Symmetry energy effects on superfluidity of neutron stars

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Nuclear symmetry energy ($E_{\rm sym}$) affects interestingly the proton fraction (y_p) of neutron star (NS) matter (usually composed of n, p, e^- and μ^-) in β-equilibrium, i.e., larger $E_{\rm sym}$ generates larger y_p. Unfortunately at present, the behavior of $E_{\rm sym}(\rho)$ at high densities ($\rho > \rho_0$ with ρ_0 being the nuclear density) is not well known. So we consider the two cases, here called "small $E_{\rm sym}$" and "large $E_{\rm sym}$" cases. As a representative one, we take $E_{\rm sym}$ from a G-matrix calculation with Reid-soft-core NN potential for the former and $E_{\rm sym}$ from a Relativistic-Brueckner-Hartree-Fock approach for the latter. $E_{\rm sym}(\rho)$ in the former first increases and then saturates with ρ, whereas $E_{\rm sym}(\rho)$ in the latter increases monotonously with ρ. We discuss following points:

(i) We show how $E_{\rm sym}$ affects y_p (and hence $y_n = 1 - y_p$). For the small $E_{\rm sym}$ case, y_p is several % in the density regime of NS cores, but for the large $E_{\rm sym}$ case it increases with ρ and exceed 15% at $\rho \simeq 3.5\rho_0$. Then a dramtic effect on thermal property of NSs arises. Namely, a socalled Nucleon-Direct-URCA process (N-DUrca) with efficient ν-emission is made possible and opens a very fast cooling mechanism for NSs [1].

(ii) We discuss how the p-superfluid of ${}^1S_0$-type and the n-superfluid of ${}^3P_2$ type, existent in the limited density region of NS cores, are influenced through the y_p-difference between two cases, since the superfluid energy gap depends on the pairing attraction and the nucleon effective-mass, both of which are importantly linked to the fractional density (i.e., y_p and y_n) [2]. It is found that the density-region of the p-superfluid existence is pushed to lower density side for large $E_{\rm sym}$ case, althogh the effect is not remarkable for the n-superfluid.

(iii) As mentioned already, the N-DUrca process is operative for the large $E_{\rm sym}$ case and provides us with a candidate to explain the cooling scenario for the colder class NSs observed. However, when applied directly, it cause a problem of "too rapid cooling" and the coexistence with nucleon superfluidity to supress the ν-emission becomes essential. It is found that both of p- and n- superfluids are hard to be expected at densities where N-DUrca process is working. Therefore, we conclude that the N-DUrca process cannot be a fast cooling scenario responsible for the colder class NSs.

Finally, we extend our discussion to the case of NS matter with hyperon components (i.e., n, p, Λ, Σ^-, e^- and μ^-).

[1] J.M. Lattimer, C.J. Pethick, M. Prakash and P. Haensel, Phys. Rev. Lett. 66 (1991), 2701.

[2] T. Takatsuka and R. Tamagaki, Prog. Theor. Phys. Suppl. 112 (1993), 27.