Hyperon Puzzle with Simple Effective Interaction

P. Bano[1], T. R. Routray[1,]*, S. P. Pattnaik[1], D. Behera[1], D. N. Basu[2], Z. Naik[1],
S. Pasayat[1] and B. Behera[1]
[1]School of Physics, Sambalpur University, Jyoti Vihar-768019, Burla, Sambalpur, Odisha, INDIA
[2]Variable Energy Cyclotron Center, 1/AF Bidhan Nagar, Kolkata, 700064, INDIA
* email: trr1@rediffmail.com

Introduction

The Hyperon puzzle in the study of Neutron star (NS) properties is a prevailing uncertainty remained unanswered till date. The problem has been examined using various existing models [1-4] by different groups and their findings are the same, i. e., if the hyperons are considered then the equation of state (EoS) becomes soft predicting relatively smaller value for the pressure of the Neutron star matter (NSM). Thus by considering hyperons in the NSM, it becomes difficult to predict the highest measured NS mass PSR J0348+0432 which is 2.01 ± 0.04 $M_\odot$ [4]. However the maximum mass is covered in the predictions of the same model calculations for (npeμ) matter of the NS core composition. This naturally raises a doubt, whether hyperons are present in the NS core or not. This is the Hyperon puzzle.

The problem has been studied by using realistic Paris and Argonne V18 [3] interaction along with three body forces, in the microscopic Brueckner-Hartree-Fock (BHF) model [1,3] and also in the Dirac-Brueckner-Hartree-Fock (DBHF) model [1]. In the non-relativistic calculation using realistic interactions as well as BHF model calculations the Nucleon-Hyperon (NY) interaction is also taken into considerations in a phenomenological manner. Since, the constraints available for NY interactions are associated with large uncertainty, the DBHF calculation in [1] has been performed under the consideration of non-interacting Fermi gas model for the hyperons. So, in this work our objective is to examine the Hyperon puzzle using our Simple Finite range effective interaction (SEI) [5] for nucleon-nucleon and hyperons are considered as free as has been done in DBHF calculations of [1].

Formalism

Here, we consider all the six hyperons Λ^0, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0 in our study. The chemical equilibrium condition for the core matter comprising of neutron (n), proton (p), electron (e^-), muon (μ^-) and all the six hyperons is given by

$$\mu_i = \mu_n b_i - q_i \mu_e \qquad (1)$$

where, μ_i and q_i are respectively, the chemical potential and electric charge of baryon species i, μ_n and μ_e are the chemical potentials of neutron and electron respectively. In absence of neutrinos, equilibrium require $\mu_e = \mu_\mu$. The charge neutrality is maintained at all points in the core,

$$Y_p + Y_{\Sigma^+} = Y_{e^-} + Y_{\mu^-} + Y_{\Sigma^-} + Y_{\Xi^-} \quad , \qquad (2)$$

where, Y_i, i= p, Σ^+, e^-, μ^-, Σ^- and Ξ^- is the respective particle fraction, i.e., $Y_i = \rho_i/\rho$, ρ_i being the corresponding particle density and ρ is the total baryonic density given by,

$$\rho = \rho_n + \rho_p + \rho_{\Lambda^0} + \rho_{\Sigma^-} + \rho_{\Sigma^0} + \rho_{\Sigma^+} + \rho_{\Xi^-} + \rho_{\Xi^0}. \qquad (3)$$

The chemical potentials of the leptons and six hyperons are given under non-interacting relativistic Fermi gas model as,

$$\mu_i = (c^2\hbar^2 k_i^2 + m_i^2 c^4)^{1/2} \quad , \qquad (4)$$

where, i= e, μ, Σ^-, Λ^0, Σ^0, Σ^+, Ξ^-, Ξ^0. The nucleonic parts, μ_n and μ_p are obtained considering interaction, where we have used SEI [5]. The SEI is given by

$$V_{eff}(r) = t_0(1 + x_0 P_\sigma)\delta(r) + \frac{t_3}{6}(1 + x_3 P_\sigma)\left(\frac{\rho(\mathbf{R})}{1 + b\rho(\mathbf{R})}\right)^\gamma \delta(r) + (W + BP_\sigma - HP_\tau - MP_\sigma P_\tau)f(r) \qquad (5)$$

where, f(r) is the functional form of the finite range interaction which depends on a single parameter α, the range of the interaction and in the present case taken as of Yukawa form. The SEI in Eqn. (5) contains 11-parameters namely t_0, x_0, t_3, x_3, b, W, B, H, M, γ and α that will be determined from nuclear matter (NM) and finite nuclei properties. The SEI is used widely in the studies of nuclear matter and finite nuclei.

Result and discussion

The Baryon and lepton fractions are calculated at a given Baryon density (ρ) from Eqn. (1) subject to the conservation of charge neutrality in Eqn. (2) and total Baryon density in Eqn. (3). The results of the particle fractions are shown in Fig.1 as a function of baryon density ρ. The results in Fig.1 corresponds to the EoS of SEI for $\gamma=1/2$, that predicts the incompressibility $K(\rho_0)= 240$ MeV.

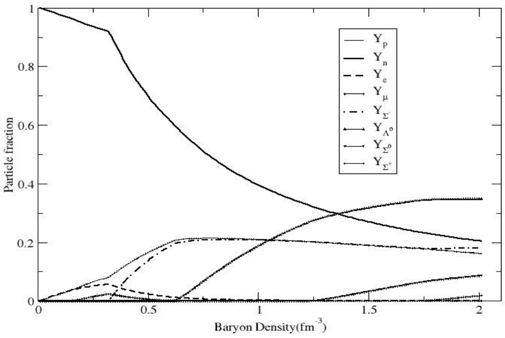

Fig. 1 Particle fractions as a function of baryon density.

From Fig.1 it may be seen that, Σ^- is produced first at density 0.33 fm^{-3}, thereafter Λ^0 appears at 0.62 fm^{-3}, Σ^0 at 1.23 fm^{-3}, and Σ^+ at 1.74 fm^{-3}. The lepton fractions, which are produced in the region of low density gradually decreases and becomes zero after density 1 fm^{-3}. Thereafter, the role of leptons in maintaining charge neutrality is taken over by the Σ^-. After the production of hyperons the neutron fraction starts decreasing with a relatively rapid rate. At density 1.36 fm^{-3}, the Λ^0 fraction exceeds the neutron fraction. The Σ^- fraction and proton fraction maintains the same ratio beyond the density where lepton fractions become zero in order to maintain charge neutrality till the production of Σ^+. The proton fraction starts decreasing when the Σ^+ emission starts. In the present EoS there is no Cascade formation up to density 2 fm^{-3}. The particle fraction curve in Fig.1 of the present study has close similarity with that of the DBHF results in [1] and results for realistic interaction in [2]. With the equilibrium particle fractions thus determined as a function of baryon density ρ, the EoS of the NSM is calculated. In order to compare the consequence of inclusion of hyperons, we have also calculated the EoS of NS core for (npeμ) composition. The Mass-Radius relation for the two cases, baryonic matter composition and (npeμ) matter composition, is shown in Fig. 2.

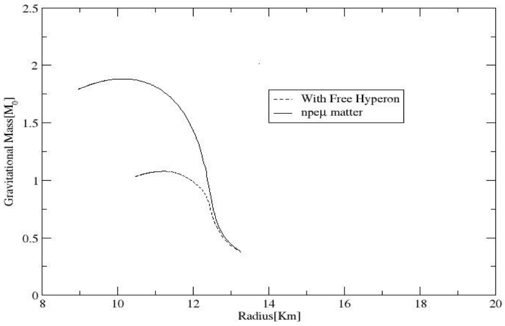

Fig. 2 Mass-Radius relation for the two cases, baryonic matter composition and (npeμ) matter composition.

The maximum mass predicted for the (npeμ) core is 1.89 $M_\odot$ that decreases to a value 1.1 $M_\odot$ when the hyperons are considered. The result is qualitatively similar to the findings on the subject by other model calculations. In summary, our analysis reaffirm the problem of strong softening of the EoS, and consequently large reduction in Neutron star maximum mass, due to the presence of hyperon, which seems to be model independent. Leaving behind the same fascinating questions open concerning phase transitions and degrees of freedom appropriate for NSM.

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