The effect of hyperon-meson coupling in infinite nuclear matter

M. Bhuyan[1],* S. K. Singh[2], S. K. Patra[2], and Shan-Gui Zhou[1]†
[1]*State key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China and*
[2]*Institute of Physics, Sachivalaya Marg, Bhubaneswar 751005, India*

Introduction

According to Baade and Zwicky [1], the supernova explosion could be a transition from star to a neutron star consisting of closely packed neutrons in a compact size object. After a few years, the general relativistic equation of hydrostatic equilibrium for spherically symmetric objects, now-a-days called as *Tolman-Oppenheiemer-Volkoff* (TOV) equation [2] come into figure, assuming the matter consists of non-interacting neutrons and obtained the maximal allowed mass to be 0.71 $M_{\odot}$. Later on the inclusion of nuclear energy from the interaction of neutrons increases this value substantially. In general at high densities, there might be the substantial population of heavy baryons (i.e. hyperons), because these become energetically favorable once the Fermi energy of neutrons becomes of the order of their rest mass. There were large number of systematic study including hyperon in the nuclear matter carried out *before* & *after* the recent observation of the neutron stars [3] (see the Ref. for review), predicting the masses not larger than the order of 1.8 $M_{\odot}$, which is significantly less in comparison to the modern observations [3].

In this work, we provide the relativistic mean field investigation of the neutron star properties by using various hyperon-meson coupling to the recently developed G2 force parameter [4]. It is to be noted that the model used here for the study of the EoS of the hyper-nuclear matter is the effective Lagrangian (E-RMF) [4], the extension of the standard relativistic mean field (RMF) model [5]. From the Lagrangian, we derive the equation of motion for σ, ω and ρ-mesons fields and solve it in the mean field approximation self consistently. Further, we derive the energy and pressure density along with all meson field equations analytically by self-consistent numerical iterative methods.

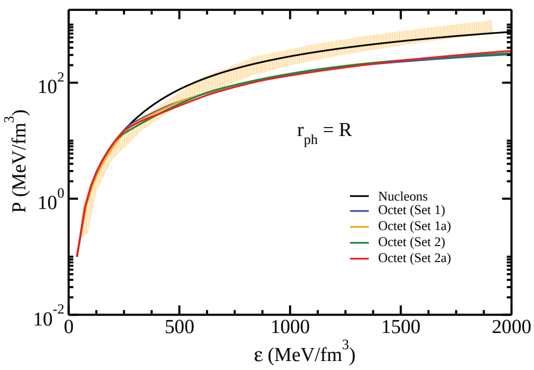

FIG. 1: The EoS for nucleon and octet systems for four different hyperon-meson coupling from E-RMF (G2) force parameter along with the empirical data (shaded area in the graph) by Steiner *et al.* [10].

Calculations and Discussions

Up to this point, we have considered the composition of a neutron star to comprise only the neutron, proton and electron. As we know, the core of the neutron stars have a very high density (~ 7–$8\ \rho_0$), other baryons of the octet family (Λ^0, Σ^0, Σ^+, Σ^-, Ξ^0, and Ξ^-) apart from the neutron and proton become important in the EoS of neutron star [6]. The electron e and muon μ are included for maintaining the charge neutrality and the $\beta-$ equilib-

*Electronic address: bunuphy@itp.ac.cn
†Electronic address: sgzhou@itp.ac.cn

TABLE I: The hyperon-meson coupling ratios for baryon octet family for four different parametrisation.

Parameter	$x_{\sigma\Lambda}$	$x_{\sigma\Sigma}$	$x_{\sigma\Xi}$	$x_{\omega\Lambda}$	$x_{\omega\Sigma}$	$x_{\omega\Xi}$	$x_{\rho\Lambda}$	$x_{\rho\Sigma}$	$x_{\rho\Sigma}$	$M/M_\odot$	$r_\odot$
Set 1 [8]	0.4800	0.4800	0.0000	0.5600	0.0000	0.0000	0.0000	0.0000	0.0000	2.02	11.8
Set 1a [8]	0.5800	0.5800	0.5800	0.6600	0.0000	0.3333	0.7500	0.0000	2.0000	2.05	11.5
Set 2 [9]	0.6104	0.6104	0.6104	0.6666	0.6666	0.6666	0.6104	0.6104	0.6104	2.06	11.5
Set 2a [9]	0.6106	0.4046	0.3195	0.6666	0.6666	0.3333	1.000	1.000	1.000	2.08	11.7

rium condition for the baryon octet system under the weak interaction [7], $B_1 \rightarrow B_2 + l + \overline{\nu}_l$ and $B_2 + l \rightarrow B_1 + \nu_l$. Here, B_1, B_2, l, ν and $\overline{\nu}$ are for the baryons, leptons, neutrino and anti-neutrino respectively. On the basis of the quark model, one can assume that the hyperons in the octet system interact with the mesons with distinct coupling constants (or coupling ratio). Hence, here we have taken two different ways of parametrisations: (1) same coupling ratios as assumed by the quark model [8] and (ii) different couplings strength for different baryons [9] to deal the octet in the EoS of compact star (see Table 1).

The equation of state for nuclear system and the octet system (i.e.. p, n, Λ^0, Σ^0, Σ^+, Σ^-, Ξ^0 and Ξ^-) are shown in Fig. 1. In the figure, we have shown five different EoSs for neutron star, one of them from nucleonic matter only and other four from the baryons of the octet family. From the figure, it is clear that the EoS from the nucleonic matter is a little stiffer than the octet family at high density. In other word, with the inclusion of baryons of the octet, the EoS becomes a little softer with respect to the baryon density. The obtained results from our calculations are compared with the empirical data for $r_{ph} = R$ with the uncertainty 2σ of Steiner *et. al.* [10]. Here R and r_{ph} are for the neutron radius and the photospheric radius, respectively. From these, one can conclude that the inclusion of these other octet families with the neucleon system makes the neutron star EoS softer as shown in figure. However it is quite important for the prediction of neutron star mass [3].

Summary and Conclusions

In this present study, we applied an chiral effective field theory relativistic mean filed approach to nuclear matter, where we investigated the impact of the hyperon-meson couplings on the EoS of hyper-nuclear matter. For all these coupling ratios, we found the range of EoSs are satisfactory to reproduce compact stars of mass $\sim 2.1\ M_\odot$ and the radii in the range of 12-14 km [11]. The affluence of hyperon in our EoSs are widely consistent with the recent predictions from other models. Further, we have calculated the yields and their location as a function of density for four coupling ratios, which is essential for nuclear and hyper-nuclear systems at high density [11].

References

[1] W. Baade and F. Zwicky, Phys. Rev. **46**, 76 (1934).
[2] R. Tolman, Phys. Rev. **55**, 364 (1939).
[3] J. Antoniadis et al., Science **340**, 6131 (2013).
[4] R. J. Furnstahl, B. D. Serot and H. B. Tang, Nucl. Phys. A **598**, 539 (1996).
[5] J. Meng, H. Toki, S. G. Zhou, S. Q. Zhang, W. H. Long, and L. S. Geng, Prog. Part. Nucl. Phys. **57**, 470 (2006).
[6] S. Weissenborn, D. Chatterjee and J. Schaffner-Bielich, Nucl. Phys. A **881**, 62 (2012).
[7] B. K. Sharma, P. K. Panda and S. K. Patra, Phy. Rev. C **75**, 035808 (2007).
[8] J. Boguta and S. Bohrmann, Phys. Lett. B **102**, 93 (1981).
[9] M. Chiapparini, M. E. Bracco, A. Delfino, M. Malheiro, D. P. Menezes and C. Providencia, Nucl. Phys. A **826**, 178 (2009).
[10] A. W. Steiner, J. M. Lattimer and E. F. Brown, Astrophys. J. **722**, 33 (2010).
[11] M. Bhuyan, S. K. Singh, S. K. Patra and Shan-Gui Zhou, *to be appeared in Phys. Rev. C.*