Neutron stars in a Skyrme Model with Λ hyperons

Neelam Guleria[1],[*] Shashi K. Dhiman[1,2], and Radhey Shyam[3]
[1] *Department of Physics, H. P. University, Shimla 171005, India*
[2] *University Institute of Natural Sciences and Interface Technologies,*
Himachal Pradesh Technical University, Hamirpur 177001, India
[3] *Theory Division, Saha Institute of Nuclear Physics,*
1/AF Bidhan Nagar, Kolkata - 700064, INDIA

In order to calculate neutron-star properties, it is necessary to have an Equation of State (EOS) linking pressure to the total energy density of the dense matter. At densities closer to the the nuclear saturation density ($\rho_0 = 0.17 fm^{-3}$), the matter is mostly composed of neutrons, protons and leptons (electrons and muons) in β equilibrium. As density increases, new hadronic degrees of freedom may appear. Hyperons are one of them as the equilibrium conditions in neutron stars makes the formation of hyperons energetically favorable. The role of hyperons on the neutron star properties have been studied by several authors (see, e.g. Refs. [1–9]).

In this paper, we employ the best fit ΛN interactions obtained by us [10] to discuss the implications of hyperons on the EOS and structure of neutron stars. Unlike several other authors, we have included only the Λ hyperons into our calculations as this study is restricted to the interactions obtained in this work. In that sense our work may appear to be less complete in comparison to studies present by other authors who include other hyperons as well. Nevertheless, in all likelihood the ΣN interaction is repulsive because no stable Σ hypernucleus other than that of mass 4, is known to exist. Therefore, Σ appears at much higher densities [8] as compared to Λ. The Ξ hyperon, on the other hand, could appear at densities comparable to those of Λ. However, there is considerable amount of uncertainty about the strength of ΞN interaction as no bound Ξ hypernucleus has been detected so far. The threshold of the appearance of the Ξ hyperons is pushed to higher densities with increasing ΞN potential.

In our calculations of the EOS we have closely followed the methods reported in Ref. [11–14]. The energy density in homogeneous matter in the presence of Λ hyperons is

$$\begin{aligned}\mathcal{E} &= \mathcal{E}_{NN} + \mathcal{E}_{N\Lambda} + \mathcal{E}_{\Lambda\Lambda} + \mathcal{E}_e + \mathcal{E}_\mu \\ &+ n_n m_n c^2 + n_p m_p c^2 + n_\Lambda m_\Lambda c^2 \end{aligned} \quad (1)$$

where the energy density functional $\mathcal{E}_{NN}$, $\mathcal{E}_{N\Lambda}$, $\mathcal{E}_{\Lambda\Lambda}$ are taken from Ref. [13]. The Leptonic contribution $\mathcal{E}_e$ and $\mathcal{E}_\mu$ to the energy density is calculated as discussed in Refs. [13, 14]. The equations for the equality of chemical potentials (represented by μ in the following)

$$\begin{aligned}\mu_n - \mu_p &= \mu_e, \quad \mu_\mu = \mu_e \\ \mu_n + m_n &= \mu_\Lambda + m_\Lambda, \end{aligned} \quad (2)$$

where chemical potentials are defined as

$$\mu_j = \frac{\partial \mathcal{E}}{\partial n_j} \quad (3)$$

where $\mathcal{E}$ is total energy density and n_j the particle number density. The total baryon number density is $n_b = n_n + n_p$ and the charge neutrality requires $n_p = n_e + n_\mu$, where n_e and n_μ are the number densities of electrons and muons, respectively. The EOS is defined by the expressions

$$\rho(n_b) = \frac{\mathcal{E}(n_b)}{c^2}, \quad P(n_b) = n_b^2 \frac{d(\mathcal{E}/n_b)}{dn_b}, \quad (4)$$

where $\rho(n_b)$ is the mass density of the matter. To obtain the relation between neutron

---

[*] Electronic address: `neelam.phy@gmail.com`

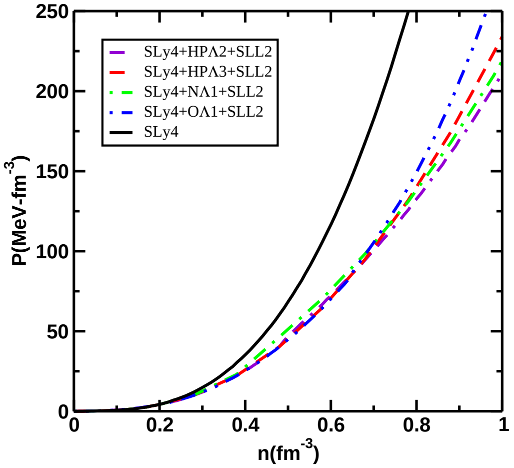

FIG. 1: The equation of state (pressure as a function of baryon number density) obtained by using ΛN interactions HPΛ2 (dot-double dashed line), HPΛ3 (dashed line), NΛ1 (dash-dotted line) and OΛ1 (dash-double dotted line).

star mass and its radius, we have solved the Tolmann-Oppenheimer -Volkoff equation [10].

In Fig. 1 we show the equation of state of the for ΛN interactions HPΛ2, HPΛ3, NΛ1, OΛ1. We see that in each case the inclusion of hyperons makes the EOS much softer with respect to the pure nucleonic case. Since hyperon can be accommodated in the lower momentum states, their kinetic energies are decreased which leads to the softening of the EOS. We note from Fig. 1 that the degree of softness of the EOS obtained with HPΛ2 and NΛ1 interactions are almost identical. However, with HPΛ3 the softness is comparatively smaller and with OΛ1 the softening of the EOS is relatively the lowest. The predicted maximum mass and corresponding radius are listed in table 1 also the radius corresponding to mass 1.4 [measured in solar mass $M_\odot$] are also listed in the same table. We note from table 1 that with interactions HPΛ2, HPΛ3, and NΛ1 maximum mass is similar (around 1.5 $M_\odot$). However, with OΛ1 interaction the maximum mass is 1.80 $M_\odot$. This result can be understood from the fact that a stiffer EOS leads to a larger neutron mass.

TABLE I: Neutron star properties for NN force SLy4.

NN	NΛ	ΛΛ	R(1.4$M_\odot$)	M_{max}	R(M_{max})
SLy4	-	-	11.62	2.02	9.84
SLy4	HPΛ2	SLL2	10.23	1.50	8.07
SLy4	HPΛ3	SLL2	10.24	1.54	9.23
SLy4	NΛ1	SLL2	10.97	1.52	9.97
SLy4	OΛ1	SLL2	10.03	1.80	9.34

References

[1] N. K. Glendenning, Astrophys. J. **293** (1985) 470.

[2] N. K. Gledenning and S. Moszkowski, Phys. Rev. Lett. 67 (1991) 2414.

[3] S. Balberg and A. Gal, Nucl. Phys. **A625** (1997) 435.

[4] M. Baldo, G. F. Burgio and H.-J. Schulze, Phys. Rev. C **61** (2000) 055801.

[5] I. Vidana, A. Polls, A. Ramos, L. Engvik, and M. Hjorth-Jensen, Phys. Rev. C **62** (2000) 035801.

[6] H.-J. Schulze, A. Polls, A. Ramos and I. Vidana, Phys. Rev. C **73** (2006) 058801.

[7] H.-J. Schulze, and T. Rijken, Phys. Rev. C **84** (2011) 035801.

[8] S. Weissenborn, D. Chatterjee and J. Schaffner-Bielich, arXiv:1111.6049 [astro-ph.HE].

[9] D. L. Whittenbury, J. D. Carroll, A. W. Thomas, K. Tsushima, and J. R. Stone, arXiv:1204.2614 [nucl-th].

[10] N. Guleria, S. K. Dhiman, and R. Shyam, Nucl. Phys. A **886** (2012) 71.

[11] E. Chabanat, P. Bonche, P. Haensel, J. Meyer and R. Schaeffer, Nucl. Phys. **A 627** (1997) 710.

[12] J. Rikovska Stone, J. C. Miller, R. Koncewicz, P. D. Stevenson, and M. R. Strayer, Phys. Rev. C **68** (1993) 034324.

[13] L. Mornas, Eur. Phys. J. A **24** (2005) 293.

[14] B. K. Agrawal, S. K. Dhiman, and R. Kumar, Phys. Rev. C **73** (2006) 034319.

[15] G. Baym, C. Pethick and P. Sutherland, Astrophys. J. **170** (1971) 299.