Study of tidal deformability as a function of iso-scalar and iso-vector nuclear matter parameters

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The Neutron star(NS) matter up to 2-3 times the saturation density ($\rho_0 = 0.16$ fm^{-3}) is expected predominantly to be composed of nucleons in β-equilibrium. The equation of state(EoS) for such matter can be expressed using iso-scalar and iso-vector nuclear matter parameters(NMPs) which characterize the symmetric nuclear matter (SNM) and density-dependent symmetry energy, respectively. Also NS properties like radius, tidal deformability(Λ) strongly depend upon the EoS. The iso-scalar NMPs are binding energy per nucleon (e_0), incompressibility coefficient (K_0), skewness (Q_0), and kurtosis (Z_0) to describe the EoS for the SNM. The density dependent symmetry energy that accounts for the deviation from the SNM is governed by the iso-vector NMPs such as symmetry energy coefficient (J_0), its slope (L_0), curvature ($K_{\rm sym0}$), skewness ($Q_{\rm sym0}$), kurtosis ($Z_{\rm sym0}$) evaluated at ρ_0. In order to demonstrate our approach, we use the $\frac{n}{3}$ expansion of the EoS with expansion coefficients depending on the linear combination of the NMPs considered[1]. In the present work, we perform systematic statistical analysis and multi-parameter correlation studies to identify the minimal set of essential iso-scalar and iso-vector nuclear matter parameters that predominantly determine tidal deformability of neutron stars.

We express tidal deformability for a given NS mass using linear (Λ_{L_n})[2] and quadratic (Λ_{Q_n})[2] functions of n number of NMPs as, $\Lambda_{L_n} = c_0 + \sum_{i=1}^{n} c_i(x_i - \hat{x}_i)$, $\Lambda_{Q_n} = \Lambda_{L_n} + \sum_{i=1}^{n}\sum_{j=i}^{n} c_{ij}(x_i - \hat{x}_i)(x_j - \hat{x}_j)$ where, $x \in \{e_0, K_0, Q_0, Z_0, J_0, L_0, K_{\rm sym0}, Q_{\rm sym0}, Z_{\rm sym0}\}$ for $n = 9$; and $\hat{x}$ corresponds to the median value of parameter x. The coefficients c_i and c_{ij} are obtained by fitting the values of Λ_{TOV}(M) to above defined functions Λ_{L_n}, Λ_{Q_n}. We consider Λ_{L_n}, Λ_{Q_n} with $n = 2$ and $n = 4$ which correspond to $x \in \{L_0, K_{\rm sym0}\}$ and $x \in \{K_0, Q_0, L_0, K_{\rm sym0}\}$, respectively. We also consider Λ_{L_9} which includes all the nine NMPs considered and $\Lambda_{Q_4+L_5}$[2] with Q_4 denotes contribution up to quadratic order for $x \in \{K_0, Q_0, L_0, K_{\rm sym0}\}$ and L_5 denotes the linear contributions from the remaining 5 NMPs (e_0, Z_0, J_0, $Q_{\rm sym0}$, $Z_{\rm sym0}$). We referred these fitted functions as Λ_{Func}.

Parameter	min	max	med
K_0	200	300	231.96
Q_0	-800	800	-418.89
L_0	20	120	52.26
K_{sym0}	-250	250	-67.44
J_0	27	37	31.87
e_0	-16.3	-15.7	-16.0
Z_0	1400	2500	1638.14
Q_{sym0}	300	900	726.49
Z_{sym0}	-2000	-1000	-1622.35

TABLE I: Priors for the nuclear matter parameters used in our analysis. All the parameters are uniformly distributed within the minimum ('min') and maximum ('max') bounds. The median ('med') values are also listed [1]. All values are in the units of MeV.

We performed an extensive analysis aimed at identifying the key nuclear matter parameters that primarily influence the tidal de-

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formability values of neutron stars. Among these parameters, both the iso-scalar parameters K_0 and Q_0, as well as the iso-vector parameters L_0 and K_{sym0}, emerged as the most significant contributors which I have shown in figure(1). We fit the values of tidal deformabilities obtained by solving the TOV equations to the linear and quadratic functions of these nuclear matter parameters. To validate these functions, we compared them with the tidal deformability values obtained from TOV equations applied to equations of state constructed with varying all the nuclear matter parameters. Our analysis showed that the predictions for $\Lambda_{Q_4+L_5}$ deviate within 10% from the Λ_{TOV} up to higher masses (in figure (3) I have shown the prediction of Λ_{Func} over Λ_{TOV} for higher mass $1.8M_{sun}$) for EoSs constrained with energy per particle of PNM within 90% confidence interval up to $2\rho_0$ derived from χEFT. It also has an additional constraint on the central density of $1.8M_{sun}$ NS ($\rho_c(1.8)$) which is below $3.5\rho_0$. We show a direct mapping between tidal deformability values and nuclear matter parameters, enabling quick estimations without recourse to the solution of TOV equations. Consequently, it will facilitate efficient Bayesian statistical inference of relevant nuclear matter parameters directly from astrophysical observations.

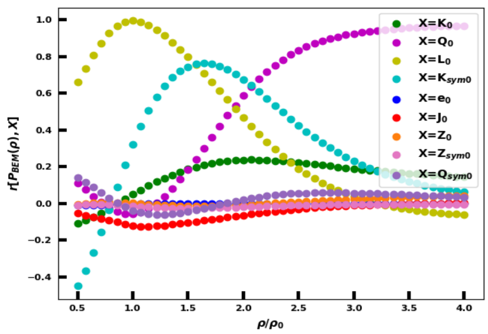

FIG. 1: Plots for the correlations of the β- equilibrium pressure at a given density ($P_{BEM}(\rho)$) with the nuclear matter parameters . The results are obtained by varying all the nuclear matter parameters.

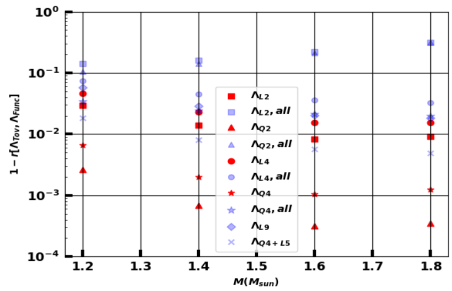

FIG. 2: Variations of the correlation coefficients r[Λ_{TOV},Λ_{Func}] as a function of neutron star mass is shown. The red color denotes the case when only the NMPs involved in the Λ_{Func} are varied (e.g. (L_0 and K_{sym0}) for Λ_{L2} or Λ_{Q2}; and (K_0, Q_0, L_0, K_{sym0}) for Λ_{L4} or Λ_{Q4}) and the light blue color denotes the case where all the nine NMPs are varied (with an extra label 'all') within their respective ranges.

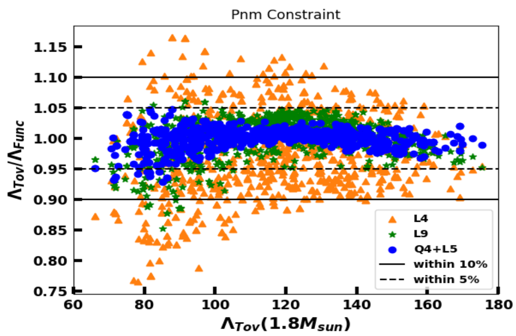

FIG. 3: The ratio $\Lambda_{TOV}/\Lambda_{Func}$ for the neutron star mass $1.8M_{sun}$. The Λ_{TOV} is obtained by varying all the nuclear matter parameters. The dashed and solid horizontal lines represent 5% and 10% deviations of Λ_{Func} from Λ_{TOV}, respectively.

References

[1] N. K. Patra, S. M. A. Imam, B. K. Agrawal, A. Mukherjee, and T. Malik, Phys. Rev. D 106, 043024 (2022).

[2] S. M. A. Imam, A. Mukherjee, B. K. Agrawal, and G. Banerjee, (2023), arXiv:2305.11007 [nucl-th].