Probing the symmetry energy and asymmetric dense nuclear matter properties in light of neutron skin thickness of ^{208}Pb

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Introduction

Neutron stars, some of the most dense and asymmetric nuclear systems in the universe, exhibit central densities reaching five -six times the nuclear saturation density. Their internal structure may host exotic components, including hyperons and quarks, adding complexity to their study. Understanding key properties of neutron stars such as their maximum mass, radius, and tidal deformability requires robust models of the equation of state (EoS). One such model, the Relativistic Mean Field (RMF) formalism, is widely employed to describe the interactions between nucleons through the exchange of mesons like σ, ω, ρ and δ. Recent astrophysical discoveries, such as neutron stars with maximum masses around $2M_\odot$ PSR J0740+6620, have placed significant constraints on the EoS at high densities. Additionally, gravitational wave observations, particularly from the GW170817 event, have driven a deeper focus on tidal deformability, prompting refinements in EoS models. The recent PREX-II experiment [1], which provided model-independent measurements of neutron skin thickness through parity-violating electron scattering, has also shown significant impact on our understanding of symmetry energy critical for describing the EoS. This work aims to propose relativistic interactions capable of predicting neutron star masses close to $2M_\odot$, while also aligning with neutron skin thickness data for ^{208}Pb within PREX-II measurements, thus integrating recent observational and experimental constraints into a refined EoS model.

Theoretical model

The RMF model's effective Lagrangian density represents the interaction of baryons through the exchange of σ, ω, ρ, and δ mesons up to quartic order. The Lagrangian density for the RMF model [2] of the nucleon system is given as

$$\begin{aligned}
\mathcal{L} &= \sum_{N\,=\,n,p} \overline{\Psi}_N [i\gamma^\mu \partial_\mu - (M_N - g_\sigma \sigma - g_\delta \delta.\tau_N + g_\omega \gamma^\mu \omega_\mu \\
&+ \frac{1}{2} g_\rho \gamma^\mu \tau_{3N}.\rho_\mu + e\gamma_\mu \frac{1+\tau_{3N}}{2} A_\mu)]\Psi_N \\
&+ \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) - \frac{\overline{\kappa}}{3!} g_{\sigma N}^3 \sigma^3 - \frac{\overline{\lambda}}{4!} g_{\sigma N}^4 \sigma^4 \\
&- \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + \frac{1}{4!}\zeta g_\omega^4 (\omega_\mu \omega^\mu)^2 - \frac{1}{4}\rho_{\mu\nu}\rho^{\mu\nu} \\
&+ \frac{1}{2} m_\rho^2 \rho_\mu \rho^\mu + \frac{1}{2}\Lambda_v g_\omega^2 g_{\rho N}^2 \omega_\mu \omega^\mu \rho_\mu \rho^\mu + \frac{1}{2}(\partial_\mu \delta \partial^\mu \delta - m_\delta^2 \delta^2) \\
&+ \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \sum_{\ell=e,\mu} \overline{\Psi}_\ell \left(i\gamma^\mu \partial_\mu - M_\ell\right) \Psi_\ell
\end{aligned} \tag{1}$$

The equation of motion for nucleons and mesons can be obtained by solving the standard Euler-Lagrange equation of motion [2, 5] as:

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)}\right) - \frac{\partial \mathcal{L}}{\partial \phi} = 0 \tag{2}$$

From Lagrangian density, one can also obtain energy-momentum ($\mathcal{T}^{\mu\nu}$) tensor, which can be used to find pressure ($\mathcal{P}$) and energy density ($\mathcal{E}$) [5]

$$\mathcal{T}^{\mu\nu} = \sum_{\phi_a} \frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_a)} \partial^\nu \phi_a - g^{\mu\nu}\mathcal{L} \tag{3}$$

$$\mathcal{P} = \frac{1}{3}\sum_{j=1}^{3} \left\langle \mathcal{T}^{jj} \right\rangle \tag{4}$$

$$\mathcal{E} = \left\langle \mathcal{T}^{00} \right\rangle \tag{5}$$

Results and Discussion

In the present work, we investigate the effect of neutron skin thickness of ^{208}Pb from PREX-II on nuclear matter and neutron star properties. To aim this, six sets of relativistic interactions named as S20, S22, S24, S26, S28 and S30 are generated by reproducing the ground state properties like binding energies, charge radii of some closed/open shell nuclei and simultatneously fitting the various values of neutron skin thickness (Δr_{np}) which range from 0.20 to 0.30 fm within PREX-II limits 0.283±0.071 fm in fiiting data used for model optimization. We use simmulated annealing

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TABLE I: The symmetric nuclear matter observables at saturation density and neutron star properties for various parameter sets.

Model	ϵ(MeV)	K(MeV)	J(MeV)	L(MeV)	M^*/M	$\rho_0(fm^{-3})$	$\Lambda_{1.4}$	$R_{1.4}$(Km)	$M_{max}(M_\odot)$
S20	-16.08	240.57	32.10	57.16	0.602	0.147	614.87	13.06	2.00
S22	-16.03	234.37	33.50	64.82	0.608	0.148	616.46	13.08	2.01
S24	-16.10	227.50	34.47	74.04	0.606	0.148	638.50	13.20	2.02
S26	-16.13	228.90	35.85	86.46	0.602	0.148	683.16	13.39	2.02
S28	-16.15	224.18	37.07	97.70	0.601	0.146	749.88	13.61	2.02
S30	-16.17	230.49	38.29	122.85	0.601	0.148	974.96	14.18	2.08

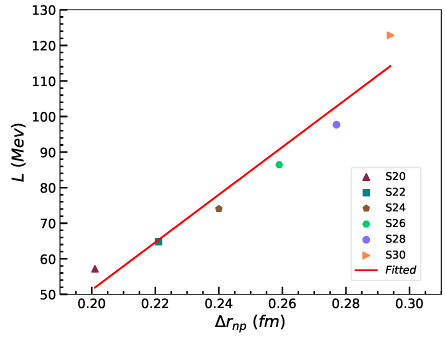

FIG. 1: (color online) Plot between density dependence of symmetry energy (L) and the neutron skin thickness (Δr_{np}) of ^{208}Pb.

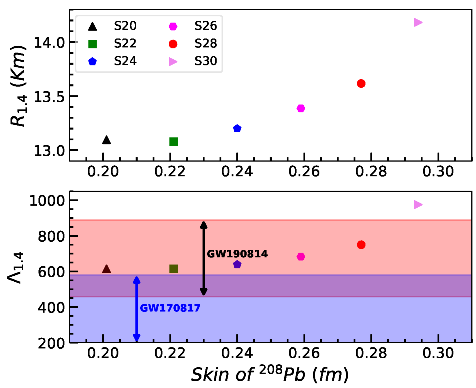

FIG. 2: (color online) Variation of radius and dimensionless tidal deformability of canonical $1.4M_\odot$ neutron star with skin thickness (Δr_{np}) of ^{208}Pb.

technique to observe the χ^2 minimisation for optimization of model parameters.
In Fig. 1, we display the plot between the linear density dependence of symmetry energy (L) and Δr_{np} of ^{208} Pb. It can be observed from the figure that L shows strong dependence on Δr_{np} of ^{208} Pb and are strongly correlated to each other. Also smaller value of Δr_{np} gives softer L while its larger value leads to stiffer value of L. It can be concluded that Δr_{np} can well constrain the symmetry energy J and its slope L which in turn can constrains the coupling parameters g_ρ, g_δ and Λ_v in isovector sector. In Table.I we have depicted the nuclear matter properties at saturation density and neutron star properties obtained for the parameter sets S20 to S30. The maximum mass of neutron star lies in the range 2.00 to 2.08 $M_\odot$ which satisfies the mass constraints of PSR J0740+6620 [3] and neutron star radius ($R_{1.4}$) coresponding to canonical mass 1.4 $M_\odot$ lies in the range 13.06 to 14.18Km which satisfies the radius constraints from NICER measurements [4]. In Fig. 2 we depict the values of neutron star radius ($R_{1.4}$) (upper panel) and dimensionless tidal deformability ($\Lambda_{1.4}$) (lower panel), versus neutron skin thickness of ^{208}Pb. It can be noticed from the figure that the values of $R_{1.4}$ changes by $\approx$ 1 Km as we proceed from S20 to S30 interactions. The value $\Lambda_{1.4}$ also shows significant change (from 614.87 to 974.96) as can be notiiced from the figure. This might be attributed to the fact that as we proceed from S20 to S30 interaction, the L becomes more and more stiffer resulting into stiffer EoS and hence large value of $R_{1.4}$ and $\Lambda_{1.4}$.

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