Nuclear Matter and Neutron Star Observables Post CREX-PREX-II Results

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Introduction

Neutron skin thickness (Δr_{np}) is the difference between the neutron and proton RMS radii in a nucleus, influenced by the Coulomb repulsion among protons and the strong nuclear interactions. It is vital for understanding nuclear structure and the equation of state (EoS) of asymmetric nuclear matter in neutron stars [1, 2]. Recent experiments, PREX-II for ^{208}Pb [3] and CREX for ^{48}Ca [4] , provide precise, model-independent measurements of Δr_{np}, revealing different neutron skin thicknesses: 0.283 ± 0.071 fm for ^{208}Pb and 0.121 ± 0.026 fm for ^{48}Ca. PREX-II suggests a stiff EoS with high symmetry energy slope ($L = 106 \pm 37$MeV)[5], leading to larger neutron star radii and tidal deformability, while CREX indicates a softer EoS. This disparity poses challenges for current nuclear models to reconcile both results simultaneously. Relativistic mean-field (RMF) models are explored to address these discrepancies by extending interactions, including mesonic couplings, to better align with nuclear and astrophysical observations, predicting neutron star properties such as mass, radius, and deformability.

THEORETICAL MODEL

The Lagrangian density model that has been modified recently within the RMF approximation is suitable for building the Equation of State (EoS) that pertains to nuclear and neutron star matter. Nucleon interactions are captured by this effective Lagrangian density through the interchange of isoscalar (σ and ω_μ), isovector (ρ_μ), and δ mesons, with terms up to quartic order.

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

RESULTS AND DISCUSSION

In the current work, a new parameter set, HPD (Table(I)), is obtained for the Relativistic Mean Field (RMF) model by modifying the model's parameters to precisely fit the experimental data that is currently available, including charge rms radii and total binding energies [6] for a few closed shell nuclei, including ^{16,24}O, ^{40,48}Ca, ^{56,68,78}Ni, ^{88}Sr, ^{90}Zr, ^{100,116,132}Sn, ^{144}Sm, and ^{208}Pb. The value of the neutron skin thickness of ^{208}Pb from the PREX-II and for ^{48}Ca from CREX Experimental data is also included in our fitting.

The properties of symmetric nuclear matter and neutron stars for HPD parameterization are presented in Table (II). The properties of nuclear matter as determined by HPD parameterization agree with both observed and empirical values.

In Fig. 1, we display the prediction of neutron skin thickness (Δr_{np}) for ^{208} Pb and ^{48} Ca nucleus for HPD and some other models. The HPD do quite well as compared to other models considered and fall well within the 67% confidence ellipse satisfying the CREX and PREX-II results simultaneously. In Fig. 2, we present the results for the gravitational mass of non-rotating neutron stars and their radius for HPD model considered in the present work. It is observed that the maximum gravitational mass of the non-rotating neutron star for HPD parameter is 2.25 $M_\odot$ which is in good agreement with the mass constraints reported for heaviest

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TABLE I: Model parameters for various proposed HPD's models of RMF Lagrangian given in Eq. (1). The parameter $\overline{\kappa}$ is in fm^{-1}. The values of $\overline{\kappa}$ and $\overline{\lambda}$ are multipled by 10^2. The mass m_σ is in the unit of MeV. The mass for nucleon, ω, ρ and δ meson is taken as M_N =939 MeV, m_ω=782.5 MeV and $m_\rho = 763$ MeV and $m_\delta = 980 MeV$.

Model	g_σ	g_ω	g_ρ	g_δ	$\overline{\kappa}$	$\overline{\lambda}$	ζ	Λ_v	m_σ
HPD	10.11147	13.09473	25.72259	14.93641	2.25447	-1.35465	0.01355	0.00332	491.03
BSRV-CPREX	10.44536	13.43408	10.28003	1.70338	1.66238	-0.20868	0.024293	0.02257	501.93
FSUGarnet	10.51131	13.71679	13.87880	-	1.64884	-0.352992	0.02348	0.08600	496.73
FSUGOLD2	10.39532	13.55413	8.97026	-	1.52185	-0.05362	0.02560	0.00165	497.48

TABLE II: Properties of symmetric nuclear matter at Saturation Density (ρ_0). The values of neutron skin thickness Δr_{np} (in fm) for ^{48}Ca and ^{208}Pb nucleus obtained for various RMF models are also shown.

	Nuclear matter and Neutron star properties									Δr_{np} (Neutron skin)	
	ρ_0	m^*/m	E/A	K	J_0	L	M_{max}	$R_{1.4}$	$\Lambda_{1.4}$	^{48}Ca	^{208}Pb
HPD	0.154	0.588	-16.22	201.86	34.41	87.87	2.25	14.29	1155.47	0.138	0.214
BSRV-CPREX	0.148	0.602	-16.10	226.99	34.99	82.32	2.03	13.32	681.52	0.215	0.251
FSUGarnet	0.153	0.578	−16.23	229.62	30.96	51.06	2.06	12.92	628.80	0.166	0.161
FSUGold2	0.150	0.593	-16.28	237.86	37.58	112.70	2.07	13.85	853.87	0.231	0.285

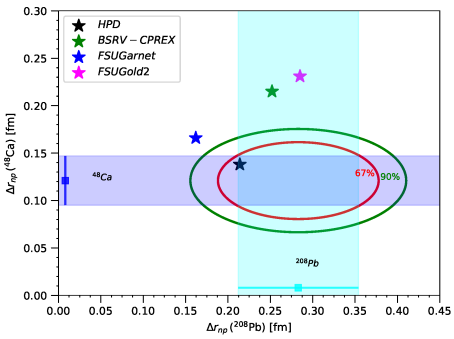

FIG. 1: (color online) Neutron skin thickness (Δr_{np}) for ^{208}Pb and ^{48}Ca nucleus.

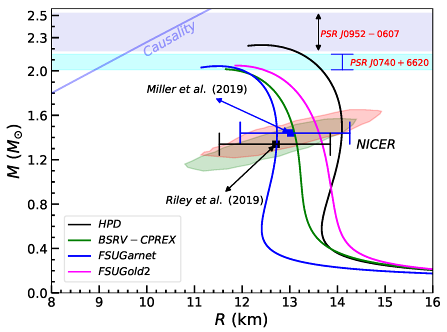

FIG. 2: (color online) Relationship between neutron star mass and its radius.

neutron star M_{max} =2.35± 0.17 M$_\odot$ for black widow pulsar PSR J0952-0607 [7]. The radius $R_{1.4}$ corresponding to 1.4 M$_\odot$ neutron star for HPD model which simultaneously satisfy the CREX and PREX constraints is 14.29 Km and is well consistent with the inferences on the radius constraints from NICER [8]. The larger values of parameters g_ρ and g_δ obtained for the HPD model, which are necessary to simultaneously reproduce the CREX and PREX-II results, may lead to a stiffening of the equation of state (EoS). This stiffening could result in neutron stars with larger radii and, consequently, a higher tidal deformability ($\Lambda_{1.4}$). However, this outcome is inconsistent with astrophysical observations ($\Lambda_{1.4} \leq 580$) [9] from the GW170817 event.

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