# THE MASS CALCULATIONS FOR THE NEUTRON STAR PSR J1614-2230

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*(Received March 6, 2012)*

The mass of the neutron star PSR J1614-2230 is calculated in the framework of relativistic mean field theory. In our calculations, we choose nine nucleon coupling constants (*i.e.* CZ11, DD-MEI, GL85, GL97, NL1, NL2, NLSH, TM1 and TM2), assuming that the neutron star only consists of neutrons, protons and electrons. It is found that the NLSH set give the hardest equation of state and the largest mass of neutron star. It is also found that, corresponding to the CZ11 set, the neutron star mass is $1.9702\,M_{\odot}$ which is approximate the mass of the neutron star PSR J1614-2230. Thus, we may obtain a possible model for it.

DOI:10.5506/APhysPolB.43.1783
PACS numbers: 26.60.Kp 21.65.Mn

## 1. Introduction

Recently, Demorest *et al.* [1] observed the neutron star PSR J1614-2230, which has the mass of $1.97\,M_{\odot}$ and may be the heaviest neutron star observed up to now. How to describe it theoretically will be an interesting work.

Glendenning [2] first applied the relativistic mean field (RMF) theory to the study of the neutron star matter in 1985.

Generally, the mass considering hyperons would be smaller than that only considering nucleons. Considering the octet, Glendenning [3] obtained the mass of neutron star being in the range of $1.5 \sim 1.8\,M_{\odot}$. Schulze *et al.* [4] performed Brueckner–Hartree–Fock calculations of hypernuclear matter employing the recent Nijmegen ESC08 hyperon–nucleon potentials and they found the very low maximum masses below $1.4\,M_{\odot}$. By the same method considering the three-body forces on the maximum mass of neutron stars, Vidaña *et al.* [5] showed that hyperonic three-body forces can reconcile the maximum mass of hyperonic stars with the limit of $1.4 \sim 1.5\ M_{\odot}$.

On the other hand, the masses of neutron stars, which only include nucleons, calculated by Hotokezaka *et al.* [6] in 2011 are $2.213\,M_{\odot}$ and $2.049\,M_{\odot}$ corresponding to different Equation of State (EoS). Glendenning [3] in his early work, considering only nucleons in the neutron star, also obtained the mass being $2.36\,M_{\odot}$.

So, if only the nucleons are included in the neutron star, we may likely obtain $1.97\,M_{\odot}$ of the neutron-star mass.

In this paper, assuming the neutron star only consists of neutrons, protons and electrons, we apply the RMF theory to describe the mass of neutron star PSR J1614-2230 by only adjusting the nucleon coupling constants.

## 2. The energy density and the pressure of neutron star matter

The Lagrangian density of hadron matter reads as follows [7]

$$\begin{aligned}\mathcal{L} = & \sum_N \overline{\Psi}_N \left(i\gamma_\mu \partial^\mu - m_N + g_{\sigma N}\sigma - g_{\omega N}\gamma_\mu \omega^\mu\right. \\ & \left. - g_{\rho\ N}\gamma_\mu \tau\,\rho^\mu\right)\Psi_N + \tfrac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) \\ & - \tfrac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \tfrac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \tfrac{1}{4}\rho_{\mu\nu}\,\rho^{\mu\nu} + \tfrac{1}{2}m_\rho^2\rho_\mu\,\rho^\mu \\ & - \tfrac{1}{3}g_2\sigma^3 - \tfrac{1}{4}g_3\sigma^4 + \overline{\Psi}_e\left(i\gamma_\mu\partial^\mu - m_e\right)\Psi_e\,, \end{aligned} \tag{1}$$

where $N$ denotes nucleons. Then, we solve the field equations in the usual RMF approximation.

The energy density and the pressure of neutron star matter are then given by

$$\begin{aligned}\varepsilon = & \tfrac{1}{2}m_\sigma^2\sigma^2 + \tfrac{1}{3}g_2\sigma^3 + \tfrac{1}{4}g_3\sigma^4 + \tfrac{1}{2}m_\omega^2\omega_0^2 + \tfrac{1}{2}m_\rho^2\rho_{03}^2 \\ & + \sum_N \frac{2J_N+1}{2\pi^2}\int_0^{\kappa_N}\kappa^2 d\kappa\sqrt{\kappa^2+m^{*2}} + \frac{1}{3\pi^2}\int_0^{\kappa_e}\kappa^2 d\kappa\sqrt{\kappa^2+m_e^{*2}}\,, \end{aligned} \tag{2}$$

$$\begin{aligned}p = & -\tfrac{1}{2}m_\sigma^2\sigma^2 - \tfrac{1}{3}g_2\sigma^3 - \tfrac{1}{4}g_3\sigma^4 + \tfrac{1}{2}m_\omega^2\omega_0^2 + \tfrac{1}{2}m_\rho^2\rho_{03}^2 \\ & + \frac{1}{3}\sum_N \frac{2J_N+1}{2\pi^2}\int_0^{\kappa_N}\frac{\kappa^4}{\sqrt{\kappa^2+m^{*2}}}d\kappa + \frac{1}{3\pi^2}\int_0^{\kappa_e}\frac{\kappa^4}{\sqrt{\kappa^2+m_e^{*2}}}d\kappa\,. \end{aligned} \tag{3}$$

In our calculations, we choose 9 sets of nucleon coupling constants such as CZ11 [8], DD-MEI [9], GL85 [2], GL97 [7], NL1 [10], NL2 [10], NLSH [11], TM1 [12] and TM2 [12]. The nucleon saturation properties and the nucleon coupling constants are listed in Table I and Table II, respectively.

TABLE I

The nucleon saturation properties.

| Parameter | $m$ [MeV] | $m_\sigma$ [MeV] | $m_\omega$ [MeV] | $m_\rho$ [MeV] | $\rho_0$ [fm$^{-3}$] | $B/A$ [MeV] | $K$ [MeV] | $a_{\mathrm{sym}}$ [MeV] | $m^*/m$ |
|---|---|---|---|---|---|---|---|---|---|
| CZ11 | 939 | 500.00 | 782.00 | 770 | 0.160 | −16.300 | 211.00 | 31.60 | 0.770 |
| DD-MEI | 938 | 550.00 | 783.00 | 763 | 0.152 | −16.230 | 244.00 | 33.06 | 0.578 |
| GL85 | 939 | 500.00 | 782.00 | 770 | 0.145 | −15.950 | 285.00 | 36.80 | 0.770 |
| GL97 | 939 | 500.00 | 782.00 | 770 | 0.153 | −16.300 | 240.00 | 32.50 | 0.780 |
| NL1 | 938 | 492.25 | 795.36 | 763 | 0.132 | −16.200 | 344.00 | 35.80 | 0.571 |
| NL2 | 938 | 504.89 | 780.00 | 763 | 0.132 | −16.200 | 344.00 | 35.80 | 0.571 |
| NLSH | 939 | 526.06 | 783.00 | 763 | 0.146 | −16.346 | 355.36 | 36.10 | 0.600 |
| TM1 | 938 | 511.20 | 783.00 | 770 | 0.145 | −16.300 | 281.00 | 36.90 | 0.634 |
| TM2 | 938 | 526.44 | 783.00 | 770 | 0.132 | −16.200 | 344.00 | 35.80 | 0.571 |

TABLE II

The nucleon coupling parameter sets.

| | $g_\sigma$ | $g_\omega$ | $g_\rho$ | $g_2$ | $g_3$ |
|---|---|---|---|---|---|
| CZ11 | 8.0899 | 8.7325 | 8.0055 | 26.4563 | −42.9951 |
| DD-MEI | 10.4434 | 12.8939 | 3.8053 | 0.0000 | 0.0000 |
| GL85 | 7.9955 | 9.1698 | 9.7163 | 10.0698 | 29.2620 |
| GL97 | 7.9835 | 8.7000 | 8.5411 | 20.9660 | −9.3850 |
| NL1 | 10.1380 | 13.2850 | 4.9760 | 12.1720 | −36.2650 |
| NL2 | 9.1110 | 11.4930 | 5.5070 | −2.3040 | 13.7840 |
| NLSH | 10.4440 | 12.9450 | 4.3830 | −6.9090 | −15.8300 |
| TM1 | 10.0290 | 12.6140 | 4.6322 | −7.2320 | 0.6183 |
| TM2 | 11.4690 | 14.6380 | 4.6783 | −4.4440 | 4.6070 |

For the outer crust with $4.73 \times 10^{-15}\,\mathrm{fm}^{-3} < \rho < 8.907 \times 10^{-3}\,\mathrm{fm}^{-3}$, we use the EoS of BPS, for the region of $\rho > 8.907 \times 10^{-3}\,\mathrm{fm}^{-3}$, we use the EoS for neutron star matter corresponding to nuclear properties identified in Table I and Table II.

The pressures as a function of energy density are shown in Fig. 1. It can be seen that, for all the nine cases the pressure increase with the energy density increase.

From Fig. 1, it also can be seen that, for the NLSH set the EoS is the hardest while for the CZ11 set the EoS is the softest. The larger compression $K$ corresponds to the larger mass of the neutron star. The compression $K$ for NLSH set is 355.36 MeV, being the largest one, while that for CZ11 set is 211 MeV, being the smallest one. So the EoS for NLSH set is the hardest one and the CZ11 set the softest one.

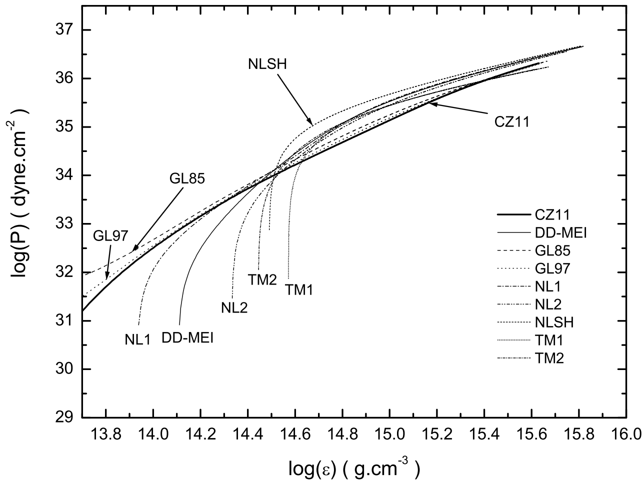


Fig. 1. The pressure as a function of energy density.

## 3. The mass of the neutron star

The mass of a neutron star is an important physical quantity, which is connected to the EoS either being hard or soft. We use the Oppenheimer–Volkoff equation (O–V equation) to obtain the mass and the radius of a neutron star

$$\frac{dp}{dr} = -\frac{(p+r)\left(M+4\pi r^3 p\right)}{r(r-2M)}\,, \tag{4}$$

$$M = 4\pi \int_0^r \varepsilon r^2 dr\,. \tag{5}$$

Figure 2 shows the masses of the neutron stars. Here, the central energy density is in units of the density of ordinary nuclear matter $\varepsilon_0 = 2.5 \times 10^{14}\,\mathrm{g/cm^3}$.

From Fig. 2 it can be seen that for each set of nucleon coupling constant, there exists a maximum value. Whether the EoS is harder or softer will determine the mass of neutron star larger or smaller [7]. From Fig. 1 we know that the EoS for NLSH set is the hardest and the CZ11 set the softest. So NLSH set will give the largest mass of neutron star and CZ11 set will give the smallest one.

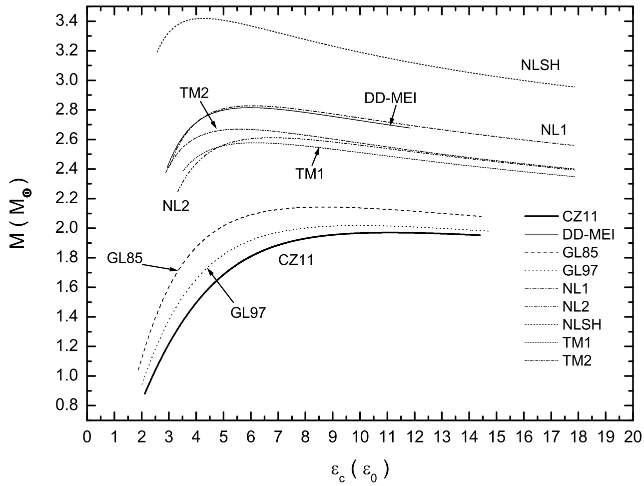


Fig. 2. The mass of the neutron star as a function of central energy density.

For the cases of CZ11, DD-MEI, GL85, GL97, NL1, NL2, NLSH, TM1 and TM2, each maximum value of neutron star mass is sketched in Fig. 3 and listed in Table III. In Fig. 3, the solid symbols express the maximum mass of the neutron star calculated in this work and the open symbols express that in our prior works considering baryon octet [8]. It can be seen that, including the hyperons in neutron star, the neutron-star mass would greatly decrease.

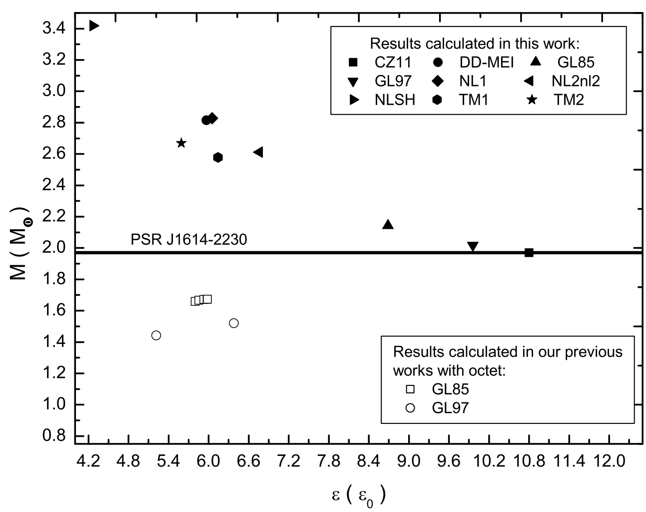


Fig. 3. The maximum mass of the neutron star as a function of central energy density.

In this work, for the cases of DD-MEI, GL85, GL97, NL1, NL2, NLSH, TM1 and TM2, the masses calculated are all greater than $2.0\,M_\odot$, especially for NLSH set the mass being $3.4189\,M_\odot$. But for CZ11 set the neutron star mass is $1.9702\,M_\odot$, which is just the same as the mass of neutron star PSR J1614-2230. If we assume that the neutron star only consists of neutrons, protons and electrons, then the results calculated with CZ11 may provide a possible model for neutron star PSR J1614-2230.

TABLE III

The maximum mass, the corresponding radius and the surface gravitational redshift of neutron stars.

| | $\varepsilon_c$ $\varepsilon_0$ | $P_c$ $\times 10^{35}$ dyne/cm$^2$ | $M$ $[M_\odot]$ | $R$ [km] |
|---|---|---|---|---|
| CZ11 | 10.8000 | 10.7180 | 1.9702 | 10.3220 |
| DD-MEI | 5.9652 | 6.6963 | 2.8152 | 13.2720 |
| GL85 | 8.6876 | 7.3920 | 2.1432 | 11.6160 |
| GL97 | 9.9572 | 8.7072 | 2.0177 | 10.8770 |
| NL1 | 6.0520 | 7.0978 | 2.8278 | 13.2530 |
| NL2 | 6.7612 | 7.2559 | 2.6117 | 12.4480 |
| NLSH | 4.2644 | 5.2324 | 3.4189 | 15.2230 |
| TM1 | 6.1436 | 5.1060 | 2.5777 | 12.6760 |
| TM2 | 5.5920 | 4.4895 | 2.6695 | 13.4300 |

## 4. Summary

In conclusion, in this paper we examine the effect of nucleon coupling constants on the neutron star properties, especially on the mass in the framework of RMF theory. Here, we assume that the neutron star only consists of neutrons, protons and electrons. It is found that, for all the nine nucleon coupling constants chosen by us, the EoS given by NLSH set is the hardest and that given by CZ11 set is the softest. Consequently, the neutron star mass calculated with NLSH set is the largest while that calculated with CZ11 set is the smallest.

If we assume that the neutron star only consists of neutrons, protons and electrons, we may obtain a possible model for neutron star PSR J1614-2230 because for CZ11 set the neutron star mass is $1.9702\,M_\odot$, which is just the same as the mass of neutron star PSR J1614-2230.

The NLSH set gives the hardest EoS and the largest mass of neutron star. So, as the hyperons are considered within neutron star on purpose of getting the mass of neutron star $1.97\,M_\odot$, we will choose the nucleon coupling constant NLSH set at first and then examine which hyperon coupling constant is suitable. This is our next, other work.

This work was supported by the Anhui Provincial Natural Science Foundation under grant 1208085MA09, the Natural Science Research Program Foundation of Institutions of Higher Education of Anhui Province under grant KJ2012Z297 and the Fundamental Research Funds for the Central Universities under grant SWJTU12ZT11.

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