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Mass of the neutron star PSR J1614-2230

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We attempted to determine the possible models for the neutron star PSR J1614-2230 in the framework of the relativistic mean field theory considering the baryon octet. It was found that the maximum mass of the neutron star will increase as the x_ω increases, with the $x_{\rho\Lambda}$, $x_{\rho\Sigma}$, $x_{\rho\Xi}$, and the x_σ being fixed. By successively adopting the approximate methods, we can obtain four of the possible models: (i) $x_\sigma = 0.33$ and $x_\omega = 0.6964$, (ii) $x_\sigma = 0.4$ and $x_\omega = 0.7435$, (iii) $x_\sigma = 0.5$ and $x_\omega = 0.8106$, and (iv) $x_\sigma = 0.6$ and $x_\omega = 0.8772$. Here, the hyperon coupling constants x_ρ are $x_{\rho\Lambda} = 0$, $x_{\rho\Sigma} = 2$, $x_{\rho\Xi} = 1$, and the nucleon coupling constants are chosen as GL97. Further, the possible value range of x_σ and x_ω, which corresponds to the mass of the neutron star PSR J1614-2230, is also determined through the four values of hyperon coupling constants determined in this paper. Our results may prove that the hadronic theory model can describe the mass of the neutron star PSR J1614-2230.

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I. INTRODUCTION

The neutron star PSR J1614-2230, whose mass is 1.97 $M_\odot$ and may be the heaviest up to now, was observed in 2010 [1]. Obviously, it will be meaningful to describe its mass theoretically.

Based on equation-of-state–independent analytic solutions of Einstein's equations, Demorest *et al.* calculated the mass of the neutron star and found that the calculations, which are based on the hadronic level, can not obtain the mass of the neutron star PSR J1614-2230 because of its small mass [1]. But we think that this may be questionable.

Surely, considering the octet, the mass of the neutron star calculated by Glendenning is in the range of $1.5 \sim 1.8\ M_\odot$ in the framework of relativistic mean field (RMF) theory. But if only nucleons were included its mass would be 2.36 $M_\odot$ [2]. It is obvious that considering the hyperons within the neutron star would reduce the mass.

In the interior of a neutron star, the hyperons would be produced with an increase of the baryon number density. So it is reasonable to think that neutron stars contain hyperons.

Calculations show that the neutron star mass is very sensitive to the hyperon coupling constants [3–6]. One of the parameter selection methods is to choose the coupling constants of meson ω by the constituent quark model [SU(6) symmetry] and to choose the coupling constants of meson σ by fitting the Λ, Σ, and Ξ well depth in nuclear matter. Because the energy density of neutron star matter is several times larger than the saturation nucleon density, the prior methods are to a great extent extrapolative.

From the above results it can be seen that, considering nucleons within neutron stars, the mass of a neutron star that is greater than 1.97 $M_\odot$ may be obtained if the suitable equations of state (EOS) and the coupling constants are chosen.

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In this paper, we apply the RMF theory to describe the mass of the neutron star PSR J1614-2230 by adjusting the hyperon coupling constants.

II. RELATIVISTIC MEAN FIELD THEORY AND MASS OF A NEUTRON STAR

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

$$\begin{aligned}\mathcal{L} = {} & \sum_B \overline{\Psi}_B\Big(i\gamma_\mu\partial^\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu\omega^\mu \\ & - \frac{1}{2}g_{\rho B}\gamma_\mu\tau\rho^\mu\Big)\Psi_B + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) \\ & - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\rho_{\mu\nu}\rho^{\mu\nu} + \frac{1}{2}m_\rho^2\rho_\mu\rho^\mu \\ & - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 + \sum_{\lambda=e,\mu}\overline{\Psi}_\lambda(i\gamma_\mu\partial^\mu - m_\lambda)\Psi_\lambda. \qquad (1)\end{aligned}$$

The energy density and pressure of a neutron star are given by

$$\begin{aligned}\varepsilon = {} & \frac{1}{2}m_\sigma^2\sigma^2 + \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\rho^2\rho_{03}^2 \\ & + \sum_B \frac{2J_B+1}{2\pi^2}\int_0^{\kappa_B}\kappa^2 d\kappa\sqrt{\kappa^2 + m^{*2}} \\ & + \frac{1}{3}\sum_{\lambda=e,\mu}\frac{1}{\pi^2}\int_0^{\kappa_\lambda}\kappa^2 d\kappa\sqrt{\kappa^2 + m_\lambda^{*2}}, \qquad (2)\end{aligned}$$

$$\begin{aligned}p = {} & -\frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 + \frac{1}{2}m_\omega^2\omega_0^2 + \frac{1}{2}m_\rho^2\rho_{03}^2 \\ & + \frac{1}{3}\sum_B \frac{2J_B+1}{2\pi^2}\int_0^{\kappa_B}\frac{\kappa^4}{\sqrt{\kappa^2 + m^{*2}}}d\kappa \\ & + \frac{1}{3}\sum_{\lambda=e,\mu}\frac{1}{\pi^2}\int_0^{\kappa_\lambda}\frac{\kappa^4}{\sqrt{\kappa^2 + m_\lambda^{*2}}}d\kappa, \qquad (3)\end{aligned}$$

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TABLE I. The coupling constants of the nucleons GL97 and GL85 sets.

	m	m_σ	m_ω	m_ρ	g_σ	g_ω	g_ρ	g_2
GL97	939	500	782	770	7.9835	8.7	8.5411	20.966
GL85	939	500	782	770	7.9955	9.1698	9.7163	10.07
	g_3	C_3	ρ_0	B/A	K	a_{sym}	m^*/m	
GL97	−9.835	0	0.153	16.3	240	32.5	0.78	
GL85	29.262	0	0.145	15.95	285	36.8	0.77	

where m^* is the effective mass of baryons

$$m^* = m_B - g_{\sigma B}\sigma. \tag{4}$$

We use the Oppenheimer-Volkoff (O-V) equation to obtain the mass and the radius of neutron stars

$$\frac{dp}{dr} = -\frac{(p+\varepsilon)\left(M+4\pi r^3 p\right)}{r\,(r-2M)}, \tag{5}$$

$$M = 4\pi\int_0^r \varepsilon r^2 dr. \tag{6}$$

The above equations of state will be used to solve the mass and radius of a neutron star.

III. APPROXIMATE LIMITATION OF HYPERON COUPLING CONSTANTS

Up to now, several sets of nucleon coupling constants having been used [7–11]. In this work, we choose the GL97 set [7] listed in Table I.

We define the ratios:

$$x_{\sigma h} = \frac{g_{\sigma h}}{g_\sigma} = x_\sigma, \tag{7}$$

$$x_{\omega h} = \frac{g_{\omega h}}{g_\omega} = x_\omega, \tag{8}$$

$$x_{\rho h} = \frac{g_{\rho h}}{g_\rho}, \tag{9}$$

with h denoting hyperons Λ, Σ, and Ξ.

The $g_{\rho\Lambda}, g_{\rho\Sigma}, g_{\rho\Xi}$ are given by SU(6) symmetry as follows: $g_{\rho\Lambda} = 0$, $g_{\rho\Sigma} = 2g_\rho$, $g_{\rho\Xi} = g_\rho$ [12]. So in our calculations, we choose $x_{\rho\Lambda} = 0$, $x_{\rho\Sigma} = 2$, $x_{\rho\Xi} = 1$. Reference [13] shows that the ratio of hyperon coupling constant to nucleon coupling constant is in the range of ∼1/3 to 1 [13]. Therefore, for x_σ we choose $x_\sigma = 0.33, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9$. For each x_σ, the x_ω are respectively chosen as 0.33, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9.

At first, we want to determine the extreme values of the x_σ and x_ω, through which the maximum neutron star mass calculated is 1.97 $M_\odot$. Then, once this is done the value range of x_σ and x_ω can be determined.

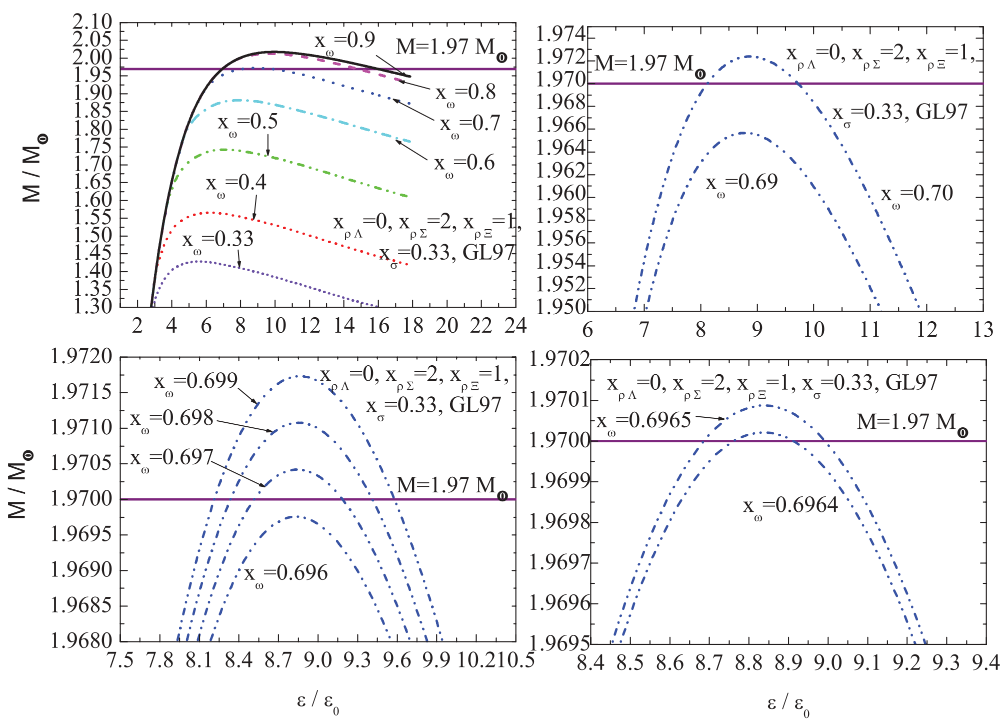

FIG. 1. (Color online) A possible model, corresponding to which the $x_{\rho\Lambda} = 0$, $x_{\rho\Sigma} = 2$, $x_{\rho\Xi} = 1$, $x_\sigma = 0.33$, and $x_\omega = 0.6964$, for the neutron star PSR J1614-2230.

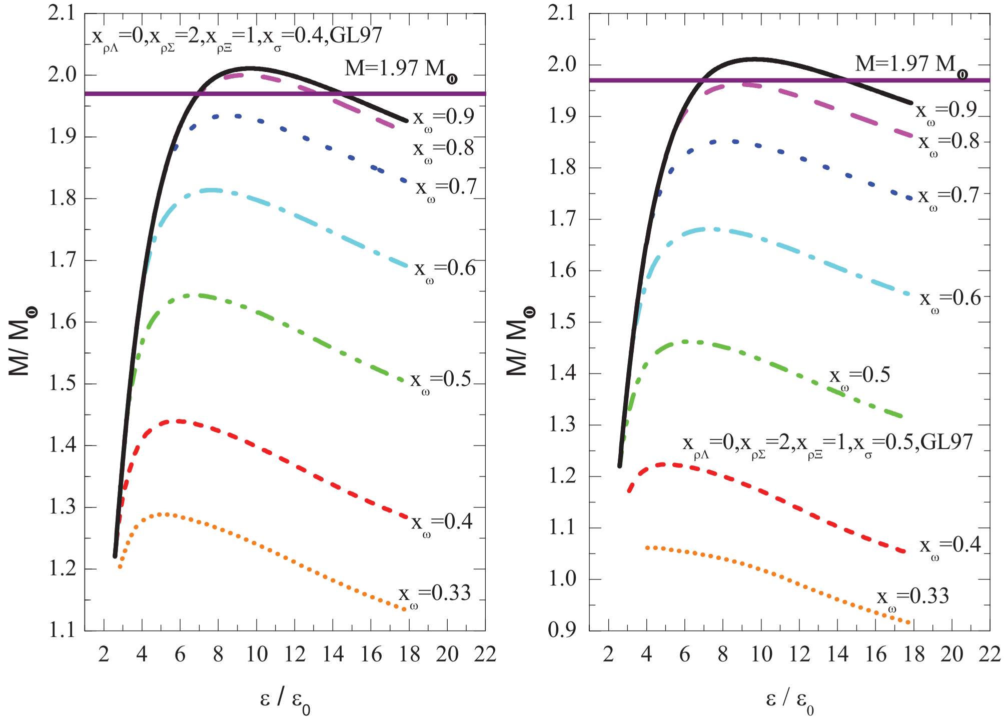

FIG. 2. (Color online) The mass as a function of central energy density with $x_\sigma = 0.4, 0.5$.

In the results calculated, if the mass of the neutron star is greater than 1.97 $M_\odot$, then we would change the coupling constants so as to obtain the mass of 1.97 $M_\odot$. If the mass of the neutron star is less than 1.97 $M_\odot$, the coupling constants would be abandoned.

In order to determine which x_σ and x_ω can obtain the mass 1.97 $M_\odot$ as the nucleon coupling constant being chosen as GL97 and the x_ρ being chosen as $x_{\rho\Lambda} = 0$, $x_{\rho\Sigma} = 2$, $x_{\rho\Xi} = 1$, for each x_σ we in turn choose the $x_\omega = 0.33, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9$ to calculate the mass of neutron star. The results are plotted in Figs. 1–3.

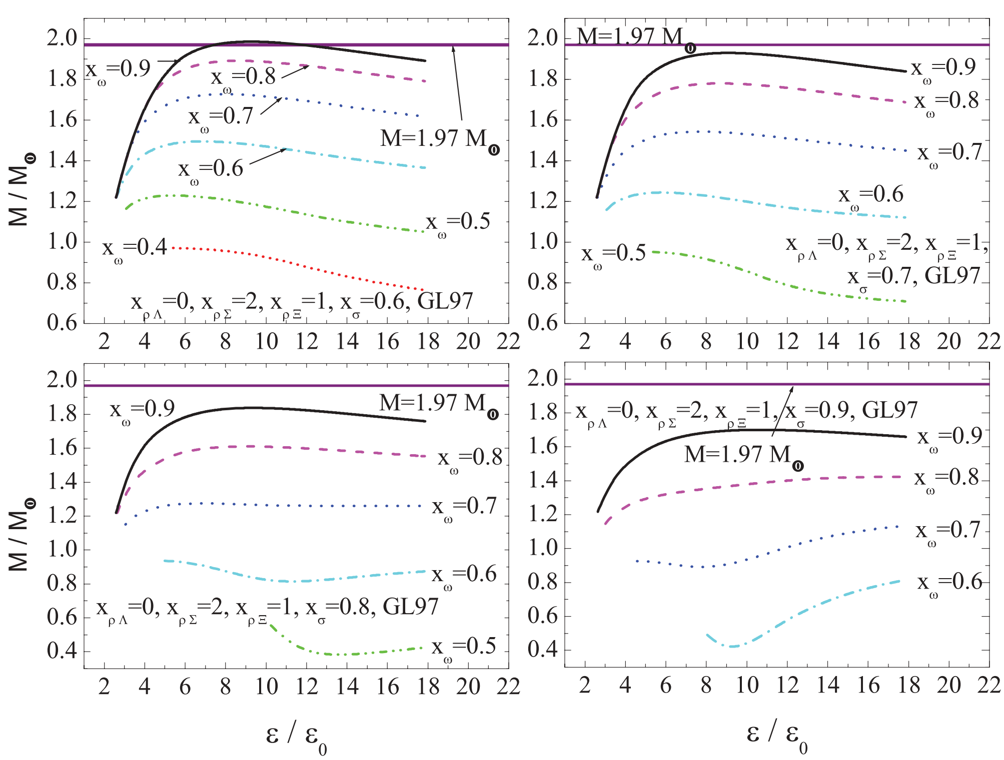

FIG. 3. (Color online) The mass as a function of central energy density with $x_\sigma = 0.6, 0.7, 0.8, 0.9$.

TABLE II. The maximum mass of the neutron star calculated as $x_{\rho\Lambda} = 0$, $x_{\rho\Sigma} = 2$, $x_{\rho\Xi} = 1$, and $x_\sigma = 0.33$.

x_ω	M $M_\odot$	x_ω	M $M_\odot$	x_ω	M $M_\odot$	x_ω	M $M_\odot$
0.33	1.4284	**0.69**	**1.9657**	**0.696**	**1.9698**	**0.6964**	**1.9700**
0.4	1.5659	**0.70**	**1.9724**	**0.697**	**1.9704**	0.6965	1.9701
0.5	1.7428			0.698	1.9711		
0.6	**1.8820**			0.699	1.9717		
0.7	**1.9724**						
0.8	2.0125						
0.9	2.0177						

Figure 1 shows the mass as a function of central energy density with $x_\sigma = 0.33$. Here, the central energy density is in units of the density of ordinary nuclear matter $\varepsilon_0 = 2.5 \times 10^{14}$ g/cm^3. From Fig. 1 it can be seen that, when $x_\sigma = 0.33$, there are three cases in which the masses are all greater than 1.97 $M_\odot$.

If the x_σ is chosen as 0.4, there are two cases in which the masses are greater than 1.97 $M_\odot$, as can be seen in Fig. 2.

When the hyperon coupling constants are chosen as $x_\sigma =$ 0.5 or 0.6, there is only one case in which the masses are all greater than 1.97 $M_\odot$. We can see these circumstances in Figs. 2 and 3.

But for the cases of $x_\sigma = 0.7, 0.8, 0.9$, the maximum masses of the neutron stars calculated are all less than 1.97 $M_\odot$. A rough drawing for these cases is shown in Fig. 3.

From the results above we can see that only as the hyperon coupling constants x_σ are chosen as 0.33, 0.4, 0.5, or 0.6 do we obtain the maximum mass of the neutron star. But for the cases of $x_\sigma = 0.7$, 0.8, or 0.9, the value of the mass 1.97 $M_\odot$ can not be obtained. Therefore, $x_\sigma = 0.33$, 0.4, 0.5, or 0.6 provide the only valid models for the mass of the neutron star PSR J1614-2230.

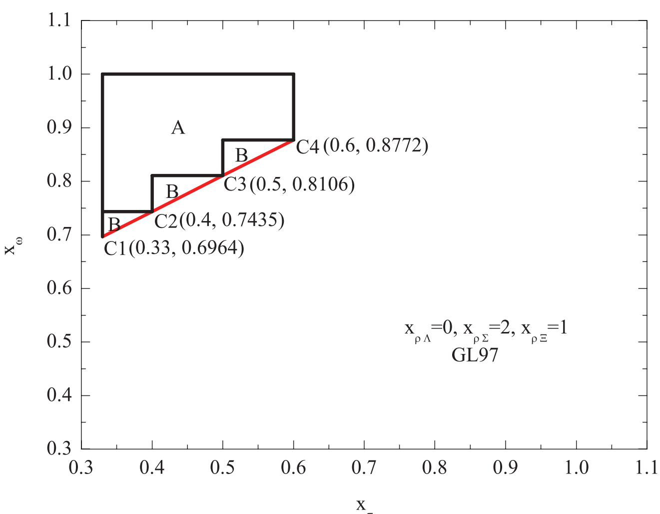

FIG. 4. (Color online) The possible value range of x_σ and x_ω, which corresponds to the mass of the neutron star PSR J1614-2230.

IV. FOUR OF THE POSSIBLE MODELS FOR NEUTRON STAR PSR J1614-2230

In order to determine the value range of x_σ and x_ω, which corresponds to the mass of the neutron star PSR J1614-2230, we should precisely define the extreme value of the hyperon coupling constants. The specific methods are as follows.

As an example, we in detail describe the steps to identify the hyperon coupling constants x_ω as the $x_{\rho\Lambda} = 0$, $x_{\rho\Sigma} = 2$, $x_{\rho\Xi} = 1$, and the $x_\sigma = 0.33$. This case is shown in Fig. 1 and Table II.

From Fig. 1 it can be seen that the masses corresponding to $x_\omega = 0.7$, 0.8, 0.9 are all greater than 1.97 $M_\odot$. The mass of neutron star is 1.8820 $M_\odot$ as $x_\omega = 0.6$ and is 1.9724 $M_\odot$ as $x_\omega = 0.7$. The value 1.9724 $M_\odot$ is closer to 1.97 $M_\odot$ than 1.8820 $M_\odot$, so we can choose the x_ω that is closer to 0.7 (i.e., we choose $x_\omega = 0.69$). The maximum value of the neutron star mass is 1.9657 $M_\odot$, which is smaller than that of 1.9724 $M_\odot$, corresponding to $x_\omega = 0.70$. Next, the x_ω is set to 0.696 and 0.697 respectively and the mass obtained is 1.9698 and 1.9704 $M_\odot$. Then we conclude that x_ω should be in the range of 0.696 and 0.697 and is very likely to be in the middle of that range. So we choose $x_\omega = 0.6964$, 0.6965 and we get the value of the maximum mass as 1.9700 $M_\odot$ and 1.9701 $M_\odot$, respectively. Thus we have obtained one possible model for the neutron star PSR J1614-2230, which corresponds to $x_{\rho\Lambda} = 0$, $x_{\rho\Sigma} = 2$, $x_{\rho\Xi} = 1$, $x_\sigma = 0.33$, and $x_\omega = 0.6964$. All these steps are also shown in Table II.

Similar steps can be applied to the cases of $x_\omega = 0.4$, 0.5, 0.6. The x_σ and x_ω for the other three possible models, corresponding to $x_{\rho\Lambda} = 0$, $x_{\rho\Sigma} = 2$, $x_{\rho\Xi} = 1$, are: (i) $x_\sigma = 0.4$ and $x_\omega = 0.7435$, (ii) $x_\sigma = 0.5$ and $x_\omega = 0.8106$, and (iii) $x_\sigma = 0.6$ and $x_\omega = 0.8772$.

Thus, we get four possible models for the mass of the neutron star PSR J1614-2230. From Figs. 1–3 and Table II it can be seen that the maximum mass of the neutron star decreases with increasing x_σ and increases with increasing x_ω. So the possible value range of x_σ and x_ω, which corresponds to the mass of the neutron star PSR J1614-2230, can be determined through the four values of hyperon coupling constants obtained above.

Figure 4 gives the possible value range of x_σ and x_ω, which corresponds to the mass of the neutron star PSR J1614-2230. Here, $x_{\rho\Lambda} = 0$, $x_{\rho\Sigma} = 2$, $x_{\rho\Xi} = 1$. The four points C1(0.33, 0.6964), C2(0.4, 0.7435), C3(0.5, 0.8106), and C4(0.6, 0.8772)

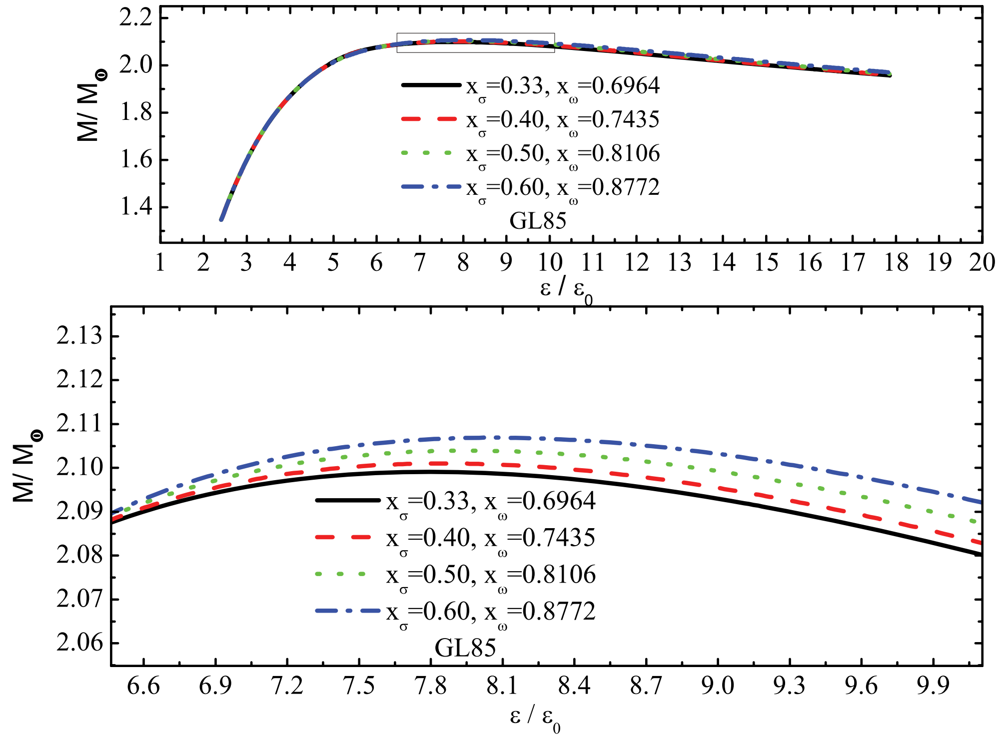

FIG. 5. (Color online) The mass of neutron star calculated with the nucleon coupling constant GL85 and the hyperon coupling constants suggested in this paper.

correspond to the four sets of extreme values of hyperon coupling constants. The values of x_σ and x_ω in area A in Fig. 4 can give the mass of the neutron star PSR J1614-2230, but those in area B are not necessarily the case. In our calculations, we only consider that the baryon-baryon interaction is mediated by the exchange of scalar σ, vector ω, and isovector ρ mesons, which can be named as model $\sigma\omega\rho$.

The same calculation on the mass of the neutron star PSR J1614-2230 was also done by Weissenborn *et al.* [14]. The nucleon coupling constants used in their calculations are the same as those in our calculations. The hyperon coupling constants $g_{\omega h}, g_{\rho h}$ used in their calculations are chosen by S(6) symmetry but the $g_{\sigma h}$ are chosen by adjusting to the potential depths $U_h^{(N)}$ felt by a hyperon h in a bath of nucleons at saturation. By S(6) symmetry, the hyperon coupling constants are $x_{\omega\Lambda} = x_{\omega\Sigma} = 2/3, x_{\omega\Xi} = 1/3$. Their results show the variation of $U_h^{(N)}$ in model $\sigma\omega\rho$, gives too low a mass and cannot account for the mass of the neutron star PSR J1614-2230. According to our results (Fig. 4), the values of the hyperon coupling constants are outside the range of area A and the constants can not give a mass greater than 1.97 $M_\odot$. Our calculations are consistent with theirs. Their results also display that the above values of the hyperon coupling constants would give the mass of the neutron star PSR J1614-2230 as the ϕ meson is included in the model. That is to say the value range of x_σ and x_ω, defined by us, giving the mass of the neutron star PSR J1614-2230 will change if the model $\sigma\omega\rho\phi$ is considered.

With a model based on a microscopic Brueckner-Hartree-Fock approach of hyperonic matter supplemented with additional simple phenomenological density-dependent contact terms, the effect of hyperonic three-body forces on the maximum mass of neutron stars is estimated by Vidaña *et al.* [15]. Assuming that the strength of these forces is either smaller or as large as the pure nucleonic ones, their results show that maximum masses of hyperonic stars lie in a narrow range from 1.27–1.60 $M_\odot$, which is still compatible with the

TABLE III. The maximum mass and the corresponding central energy density calculated in this work. $x_{\rho\Lambda} = 0, x_{\rho\Sigma} = 2, x_{\rho\Xi} = 1$.

x_σ	x_ω	GL97			GL85		
		$\varepsilon_c / \varepsilon_0$	M ($M_\odot$)	R (km)	$\varepsilon_c / \varepsilon_0$	M ($M_\odot$)	R (km)
0.33	0.6964	8.8382	1.9700	11.4150	7.7928	2.0991	12.138
0.4	0.7435	8.8913	1.9700	11.3820	7.8514	2.1010	12.095
0.5	0.8106	8.9892	1.9700	11.3280	7.9540	2.1039	12.030
0.6	0.8772	9.1009	1.9700	11.2680	8.0623	2.1069	11.962

canonical value of ∼1.4–1.5 $M_\odot$, but it is incompatible with the mass of the neutron star PSR J1614-2230.

Can the values suggested in this paper be applied to other neutron stars as well? With the nucleon coupling constant GL85 (see Table I) and the hyperon coupling constants suggested in this paper, the mass of other neutron stars can also be calculated. The results are shown in Fig. 5 and Table III. It can be seen that the four values of the hyperon coupling constants obtained above correspond to different mass and central energy densities of neutron stars as with the nucleon coupling constants being chosen as GL85. The four possible models and the value range of the hyperon coupling constants obtained in this paper are suitable for only GL97. As the nucleon coupling constants being chosen change, the value range of the hyperon coupling constants corresponding to the mass of the neutron star PSR J1614-2230 will also change.

V. SUMMARY

In this paper, considering the baryon octet, the possible models for the neutron star PSR J1614-2230 were determined in the framework of the relativistic mean field theory. It was found that, for each set of hyperon coupling constants, there exists a maximum mass of the neutron star. The maximum mass will increase with the x_ω increasing, as the $x_{\rho\Lambda}$, $x_{\rho\Sigma}$, $x_{\rho\Xi}$, and the x_σ are fixed. By adopting successively approximate methods, we can obtain four of the possible models, in which the hyperon coupling constants x_ρ all are $x_{\rho\Lambda} = 0, x_{\rho\Sigma} = 2, x_{\rho\Xi} = 1$. The four possible models for the neutron star PSR J1614-2230 obtained in this paper are: (i) $x_\sigma = 0.33$ and $x_\omega = 0.6964$, (ii) $x_\sigma = 0.4$ and $x_\omega = 0.7435$, (iii) $x_\sigma = 0.5$ and $x_\omega = 0.8106$, and (iv) $x_\sigma = 0.6$ and $x_\omega = 0.8772$. Then the possible value range of x_σ and x_ω, which corresponds to the mass of the neutron star PSR J1614-2230, is determined through the four values of hyperon coupling constants. Our results suggest that the hadronic theory model can describe the mass of the neutron star PSR J1614-2230.

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