The Properties of the Neutron Star PSR B2303+46

Xian-Feng Zhao,[1] Ai-Jun Dong,[1] and Huan-Yu Jia[2]
[1] *College of Mechanical and Electronic Engineering, Chuzhou University, Chuzhou, 239000, China*
[2] *Institute for Modern Physics, Southwest Jiaotong University, Chengdu, 610031, China*
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The properties of the neutron star PSR B2303+46 are investigated within the framework of relativistic mean field theory for the baryon octet system through adjusting the hyperon coupling constants. Models for the neutron star B2303+46 are obtained by choosing suitable hyperon coupling constants $x_{\sigma h}$ and $x_{\omega h}$, with $x_{\rho h}$ being determined by the constituent quark model SU(6) symmetry and the nucleon coupling constants being chosen as the set CZ11. Our results show that the field strengths of the mesons σ, ω, and ρ, the chemical potentials of the neutron and electron, the relative particle number density of the electron, muon, neutron, proton, Λ, Σ, and Ξ, and the pressure and energy density of the neutron star PSR B2303+46 all have an uncertain value region, respectively.

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I. INTRODUCTION

The neutron star PSR B2303+46 [1] was first observed by Dewey *et al.* in 1985 [2]. It is a binary system with eccentric orbit ($e = 0.658$), with the mass being $M = 1.38^{+0.06}_{-0.10}$ $M_\odot$ [3] and the orbital period being 12.34 d [4].

We know that the binary PSR B2303+46 contains a white dwarf as a companion star. For the white dwarf first evolving and not leaving a source of matter for the neutron star to accrete, no recycling takes place in this case [5]. The mechanism behind this reversal is very different from that of a neutron-neutron two binary system, and therefore the properties of the former must be different from that of the latter. Because of such reasons, we are very interested in the properties of the neutron star PSR B2303+46.

For the neutron star matter being studied, we can use the relativistic mean field (RMF) theory, which is a better method for describing the neutron star matter [6, 7]. Theoretically calculated results of the neutron star matter show that the properties of the neutron star are very sensitive to the hyperon-to-nucleon coupling constants with the nucleon-to-nucleon coupling constants being fixed [8–11]. Thus, it will be possible to obtain the mass of the neutron star PSR B2303+46 by only adjusting the hyperon-to-nucleon coupling constants with the nucleon-to-nucleon coupling constants being fixed. Furthermore, its properties can be studied.

In this paper, by choosing the appropriate hyperon coupling parameters the properties of the neutron star PSR B2303+46 are examined within the RMF approach considering the baryon octet. Here, the temperature of the neutron star is assumed to be zero, and the rotation is not considered.

II. THE RMF THEORY OF A NEUTRON STAR

The Lagrangian density of the neutron star matter reads as follows [9]:

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

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

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

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

where, m^* is the effective mass of baryons,

$$m^* = m_B - g_{\sigma B}\sigma. \qquad (4)$$

The mass and the radius of neutron stars can be obtained by the Oppenheimer-Volkoff (O-V) equations as follows:

$$\begin{aligned}
\frac{\mathrm{d}p}{\mathrm{d}r} &= -\frac{(p+\varepsilon)\left(M+4\pi r^3 p\right)}{r\left(r-2M\right)}, \qquad (5) \\
M &= 4\pi\int_0^r \varepsilon r^2\mathrm{d}r. \qquad (6)
\end{aligned}$$

III. PARAMETERS

In our calculations, we choose the parameters CZ11 (see Table I), which is a a new set of nucleon coupling constants [12].

We define the ratios $x_{\sigma h} = \frac{g_{\sigma h}}{g_{\sigma N}}$, $x_{\omega h} = \frac{g_{\omega h}}{g_{\omega N}}$, $x_{\rho h} = \frac{g_{\rho h}}{g_{\rho N}}$, with h denoting hyperons.

The $g_{\rho\Lambda}$, $g_{\rho\Sigma}$, $g_{\rho\Xi}$ are given by SU(6) symmetry as $g_{\rho\Lambda} = 0$, $g_{\rho\Sigma} = 2g_\rho$, $g_{\rho\Xi} = g_\rho$ [13], and therefore in our calculations we choose $x_{\rho\Lambda} = 0$, $x_{\rho\Sigma} = 2$, $x_{\rho\Xi} = 1$. The ratio of the

TABLE I: The nucleon coupling constants for the set CZ11.

$(\frac{g_\sigma}{m_\sigma})^2$ fm^2	$(\frac{g_\omega}{m_\omega})^2$ fm^2	$(\frac{g_\rho}{m_\rho})^2$ fm^2	b $\times 100$	c $\times 100$
10.1937	4.8557	4.2090	0.0105	−0.0100

hyperon coupling constant to the nucleon coupling constant is in the range of $\sim 1/3$ to 1 [14]. So, for x_σ we choose x_σ=0.33, 0.4, 0.5, 0.6, 0.7, 0.8, and 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, and 0.9.

The well depth of the hyperons Λ, Σ, and Ξ in nuclear matter is given as follows [9]:

$$U_h^{(N)} = m_B \left(\frac{m_n^*}{m_n} - 1 \right) x_{\sigma h} + \left(\frac{g_{\omega N}}{m_\omega} \right)^2 \rho_0 x_{\omega h}. \tag{7}$$

The experimental data of the well depth are $U_\Lambda^{(N)} = -30$ MeV [15], $U_\Xi^{(N)} = -28$ MeV ~ -14 MeV [16–19], and $U_\Sigma^{(N)} = 10 \sim 40$ MeV [20–27], respectively. For the hyperon coupling constants chosen by us, we calculate the corresponding well depth of the hyperons and find that only several sets of parameters are consistent with the experimental data (see Table II).

Taking one of each group of the hyperon coupling constants corresponding to $U_\Lambda^{(N)}$, $U_\Sigma^{(N)}$, and $U_\Xi^{(N)}$ in Table II, we can get 48 sets of parameters, corresponding to each of which the mass of the neutron star is calculated. Because the mass of the neutron star PSR B2303+46 is $M = 1.38$ M$_\odot$, only a neutron star whose maximum mass is greater than 1.38 M$_\odot$ can give the mass of the neutron star PSR B2303+46. We see that the hyperon coupling constants named as G1, G2, G3, and G4 cannot give a neutron star mass greater than 1.38 M$_\odot$ (listed in Table III), while those named as A, B, and C can give a neutron star mass greater than 1.38 M$_\odot$, i.e., 1.4721 M$_\odot$, 1.4787 M$_\odot$, and 1.6150 M$_\odot$ (listed in Table IV). As for the parameters G5 listed in Table III, they cannot give a stable neutron star.

IV. THE PROPERTIES OF THE NEUTRON STAR PSR B2303+46

The neutron star mass and radius as a function of central energy density calculated by us is given in Fig. 1. We see that the parameter groups A, B, and C can give a mass that is greater than 1.38 M$_\odot$, while the parameter groups G1, G2, G3, and G4 cannot do that. So, we can use the A, B, and C groups of parameters to describe the properties of the neutron star PSR B2303+46. From Fig. 1, we also see that the radius for the parameter groups A, B, and C are smaller that those for the parameter groups G1, G2, G3, and G4. Corresponding to the mass of the neutron star PSR B2303+46 $M = 1.38$ M$_\odot$, the calculated central energy density by the parameter A, B, and C groups is 0.9883×10^{15} g.cm^{-3}, 0.9949×10^{15} g.cm^{-3}, and 0.9070×10^{15} g.cm^{-3}, respectively.

TABLE II: The suitable hyperon coupling constants chosen by us. The unit of $U_{\Lambda}^{(N)}$, $U_{\Sigma}^{(N)}$, and $U_{\Xi}^{(N)}$ is MeV.

$U_{\Lambda}^{(N)}$	$x_{\sigma\Lambda}$	$x_{\omega\Lambda}$
−31.33	0.50	0.50
−28.53	0.70	0.80
$U_{\Xi}^{(N)}$	$x_{\sigma\Xi}$	$x_{\omega\Xi}$
−20.68	0.33	0.33
−25.07	0.40	0.40
−16.00	0.50	0.60
−22.27	0.60	0.70
$U_{\Sigma}^{(N)}$	$x_{\sigma\Sigma}$	$x_{\omega\Sigma}$
20.71	0.33	0.60
36.05	0.33	0.70
20.93	0.40	0.70
36.26	0.40	0.80
14.66	0.50	0.80
29.99	0.50	0.90

The field strengths of the mesons σ, ω, and ρ as a function of baryon number density are shown in Fig 2. We see that, corresponding to the mass of the neutron star PSR B2303+46, there is a value range of the field strengths of the mesons σ, ω, and ρ. For the field strength of the σ meson, it increases with an increase of the baryon density. The parameter group C gives the largest value of the field strength, while the parameter group A gives the smallest one. As the baryon density $\rho = 1.2$ fm^{-3}, the maximum value of the field strength of the σ mesons for parameter group A is 0.4800 fm^{-1} while that for parameter group C is 0.5197 fm^{-1}. For the field strength of mesons ω, parameter group C gives the largest value of the field strength, while parameter group A gives the smallest one. As the baryon density $\rho = 1.2$ fm^{-3}, the maximum value of the field strength of the ω mesons for the parameter group A is 0.4928 fm^{-1} while that for parameter group C is 0.5674 fm^{-1}. For the field strength of the ρ mesons, parameter group B gives the largest value of the field strength, while parameter group C gives the smallest one. As the baryon density $\rho = 1.2$ fm^{-3}, the maximum value of the field strength of the ρ mesons for parameter group C is -0.0652 fm^{-1}, while that for parameter group B is -0.0462 fm^{-1}.

The chemical potentials of the neutrons and electrons of the neutron star PSR B2303+46 as a function of the baryon number density are given in Fig. 3. We see that the chemical potential of the neutrons increases with an increase of the baryon density.

TABLE III: The calculated mass of the neutron star corresponding to the hyperon coupling constants G1, G2, G3, G4, and G5. The unit of the mass M is $M_{\odot}$.

NO.	$x_{\sigma\Lambda}$	$x_{\omega\Lambda}$	$x_{\sigma\Sigma}$	$x_{\omega\Sigma}$	$x_{\sigma\Xi}$	$x_{\omega\Xi}$	M
	0.50	0.50	0.33	0.60	0.33	0.33	1.3257
	0.50	0.50	0.33	0.70	0.33	0.33	1.3257
G1	0.50	0.50	0.40	0.70	0.33	0.33	1.3257
	0.50	0.50	0.40	0.80	0.33	0.33	1.3257
	0.50	0.50	0.50	0.80	0.33	0.33	1.3257
	0.50	0.50	0.50	0.90	0.33	0.33	1.3257
	0.50	0.50	0.33	0.60	0.40	0.40	1.3247
	0.50	0.50	0.33	0.70	0.40	0.40	1.3247
G2	0.50	0.50	0.40	0.70	0.40	0.40	1.3247
	0.50	0.50	0.40	0.80	0.40	0.40	1.3247
	0.50	0.50	0.50	0.80	0.40	0.40	1.3247
	0.50	0.50	0.50	0.90	0.40	0.40	1.3247
	0.50	0.50	0.33	0.60	0.50	0.60	1.3589
	0.50	0.50	0.33	0.70	0.50	0.60	1.3589
G3	0.50	0.50	0.40	0.70	0.50	0.60	1.3589
	0.50	0.50	0.40	0.80	0.50	0.60	1.3589
	0.50	0.50	0.50	0.80	0.50	0.60	1.3589
	0.50	0.50	0.50	0.90	0.50	0.60	1.3589
	0.50	0.50	0.33	0.60	0.60	0.70	1.3588
	0.50	0.50	0.33	0.70	0.60	0.70	1.3588
G4	0.50	0.50	0.40	0.70	0.60	0.70	1.3588
	0.50	0.50	0.40	0.80	0.60	0.70	1.3588
	0.50	0.50	0.50	0.80	0.60	0.70	1.3588
	0.50	0.50	0.50	0.90	0.60	0.70	1.3588
	0.70	0.80	0.33	0.60	0.60	0.70	—
	0.70	0.80	0.33	0.70	0.60	0.70	—
G5	0.70	0.80	0.40	0.70	0.60	0.70	—
	0.70	0.80	0.40	0.80	0.60	0.70	—
	0.70	0.80	0.50	0.80	0.60	0.70	—
	0.70	0.80	0.50	0.90	0.60	0.70	—

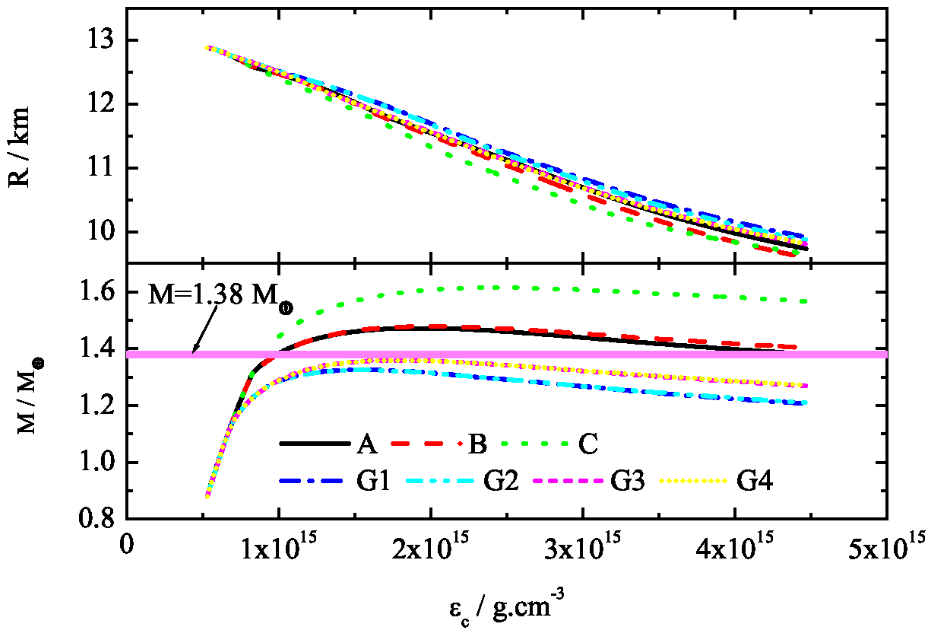

FIG. 1: The calculated neutron star masses that are greater than 1.38 $M_{\odot}$, as a function of the central energy density.

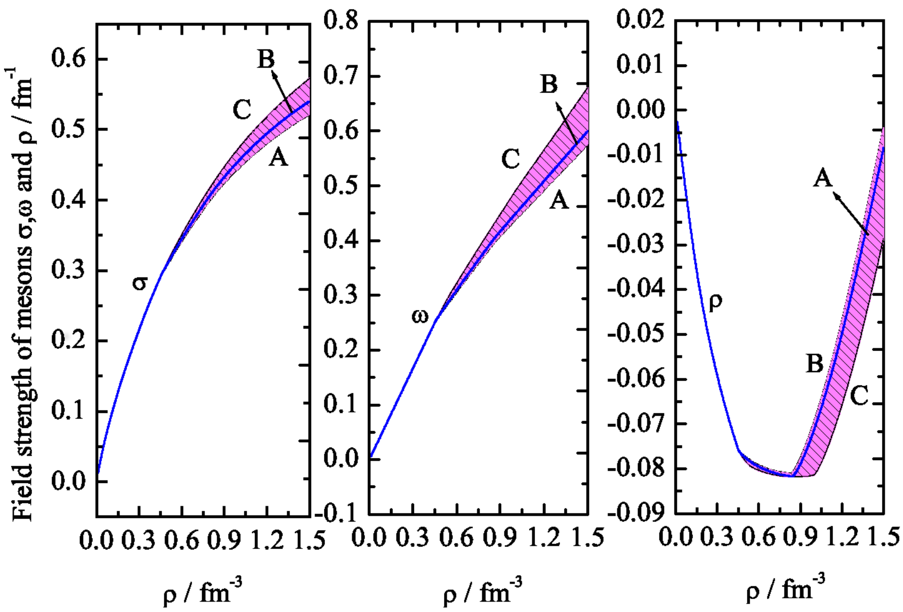

FIG. 2: The field strengths of the mesons σ, ω, and ρ as a function of baryon number density.

TABLE IV: The calculated mass of the neutron star corresponding to the neutron star PSR B2303+46 through the reasonable hyperon coupling constants chosen in this work. The unit of the mass M is $M_{\odot}$.

NO.	$x_{\sigma\Lambda}$	$x_{\omega\Lambda}$	$x_{\sigma\Sigma}$	$x_{\omega\Sigma}$	$x_{\sigma\Xi}$	$x_{\omega\Xi}$	M
	0.70	0.80	0.33	0.60	0.33	0.33	1.4721
	0.70	0.80	0.33	0.70	0.33	0.33	1.4721
A	0.70	0.80	0.40	0.70	0.33	0.33	1.4721
	0.70	0.80	0.40	0.80	0.33	0.33	1.4721
	0.70	0.80	0.50	0.80	0.33	0.33	1.4721
	0.70	0.80	0.50	0.90	0.33	0.33	1.4721
	0.70	0.80	0.33	0.60	0.40	0.40	1.4787
	0.70	0.80	0.33	0.70	0.40	0.40	1.4787
B	0.70	0.80	0.40	0.70	0.40	0.40	1.4787
	0.70	0.80	0.40	0.80	0.40	0.40	1.4787
	0.70	0.80	0.50	0.80	0.40	0.40	1.4787
	0.70	0.80	0.50	0.90	0.40	0.40	1.4787
	0.70	0.80	0.33	0.60	0.50	0.60	1.6150
	0.70	0.80	0.33	0.70	0.50	0.60	1.6150
C	0.70	0.80	0.40	0.70	0.50	0.60	1.6150
	0.70	0.80	0.40	0.80	0.50	0.60	1.6150
	0.70	0.80	0.50	0.80	0.50	0.60	1.6150
	0.70	0.80	0.50	0.90	0.50	0.60	1.6150

As the parameters are chosen as the A, B, and C groups, the value range of the chemical potentials of the neutrons will be different. The parameters A gives the minimum value of the chemical potential for neutrons, while the parameters C gives the maximum one. As the baryon density $\rho = 1.2$ fm^{-3}, the maximum value of the chemical potential of neutrons for parameters A is 6.8336 fm^{-1}, while that for parameters C is 7.4275 fm^{-1}. The uncertainty value range of the maximum chemical potentials of neutrons is in the range of $\sim$ 6.8336 fm^{-1} to 7.4275 fm^{-1}. We also can see that the chemical potentials of the electrons have the value range with the parameters being chosen as the A, B, and C groups. As the baryon density $\rho = 1.2$ fm^{-3}, the maximum value of the chemical potential of electrons for parameter group B is 0.4950 fm^{-1}, while that for parameter C is 0.7303 fm^{-1}. The uncertainty value range of the maximum chemical potentials of the electrons is in the range of $\sim$ 0.4950 fm^{-1} to 0.7303 fm^{-1}.

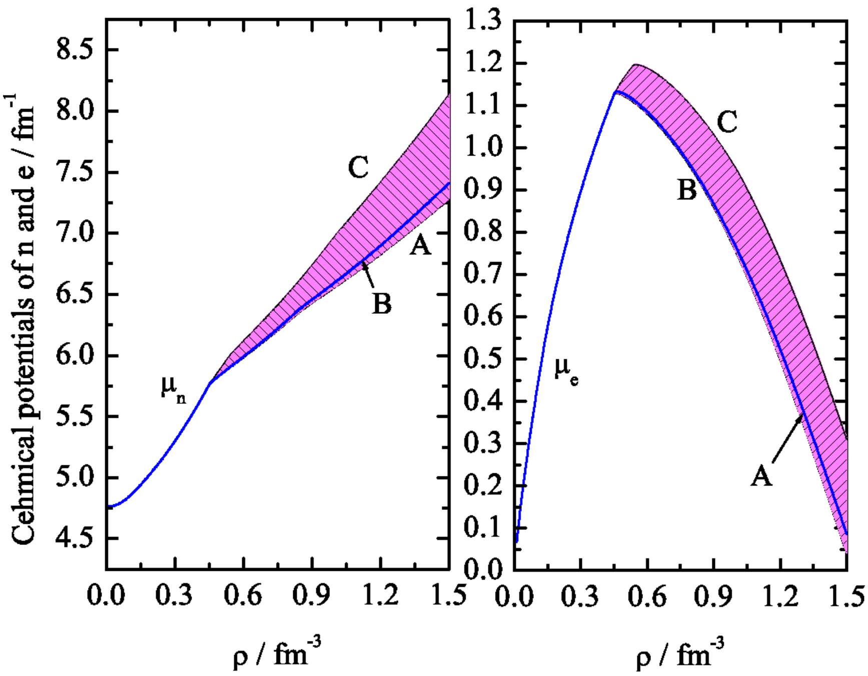

FIG. 3: The chemical potentials of neutrons and electrons as a function of the baryon number density.

Figure 4 shows the value range of the particle number density of the neutrons, protons, electrons, and muons as a function of the baryon number density. We see that as the parameters are chosen as the A, B, and C groups the particle number density of the neutrons, protons, electrons, and muons respectively have a value range. As the baryon density $\rho = 0.8$ fm^{-3}, the uncertainty value range of the calculated particle number density of neutrons is in the range of $\sim$ 0.4402 to 0.4766, that of protons is in the range of $\sim$ 0.2098 to 0.2530, that of electrons is in the range of $\sim$ 0.0376 to 0.0571, and that of muons is in the range of $\sim$ 0.0204 to 0.0369. That is to say that corresponding to the mass of the neutron star PSR B2303+46, the relative particle number density of neutrons, protons, electrons, and muons would have a value range.

Figure 5 gives the value range of the calculated relative particle number density of the hyperons Λ, Ξ^-, and Ξ^0 as a function of the baryon number density. We see that the relative particle number density of the hyperons Λ, Ξ^-, and Ξ^0 all increase with an increase of the baryon number density. As the parameters are chosen as the A, B, and C groups, the particle number density of the hyperons Λ, Ξ^-, and Ξ^0, respectively, have a value range too. As the baryon density $\rho = 1.2$ fm^{-3}, the uncertainty value range of the relative particle number density of Λ is in the range of $\sim$ 0.1365 to 0.2796, that of Ξ^- is in the range of $\sim$ 0.1919 to 0.2287, and that of Ξ^0 is in the range of $\sim$ 0.0440 to 0.1260.

The value range of the relative particle number density of the hyperons Σ^-, Σ^0, and

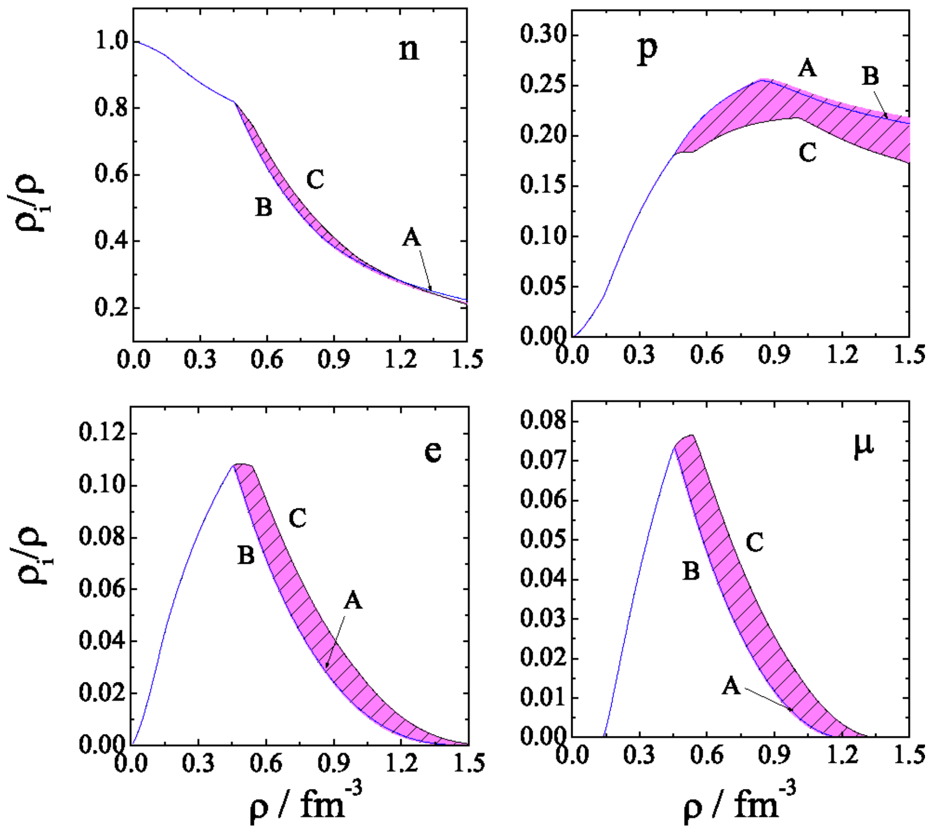

FIG. 4: The value range of the calculated relative particle number density of neutrons, protons, electrons, and muons as a function of the baryon number density.

Σ^+ as a function of the baryon number density is shown in Figure 6. We see that the hyperons Σ^-, Σ^0, and Σ^+ appear only when the baryon density is greater than 1.0 fm^{-3}, and their relative particle number densities all increase with an increase of the baryon number density. In our calculations, the maximum value of the baryon density calculated by us is 1.5 fm^{-3}. We see that the hyperons Σ^-, Σ^0, and Σ^+ do not all appear for the parameters A and B in this condition. As the parameters are chosen as the C group the particle number density of these three hyperons respectively have a value range. As the baryon density $\rho = 1.5$ fm^{-3}, the uncertainty value range of the relative particle number density of Σ^- is in the range of ~ 0 to 0.0162, that of Σ^0 is in the range of ~ 0 to 0.0065, and that of Σ^+ is in the range of ~ 0 to 0.0005. The relative particle number density of the hyperons Σ^-, Σ^0, and Σ^+ are so small that they are less that 2 percent.

The value range of the pressure and the energy density as a function of the baryon number density is given in Figure 7. We see that the pressure and the energy density increase with an increase of the baryon density. As the parameters are chosen as the A, B, and C groups the pressure and the energy density respectively have a value range. As the

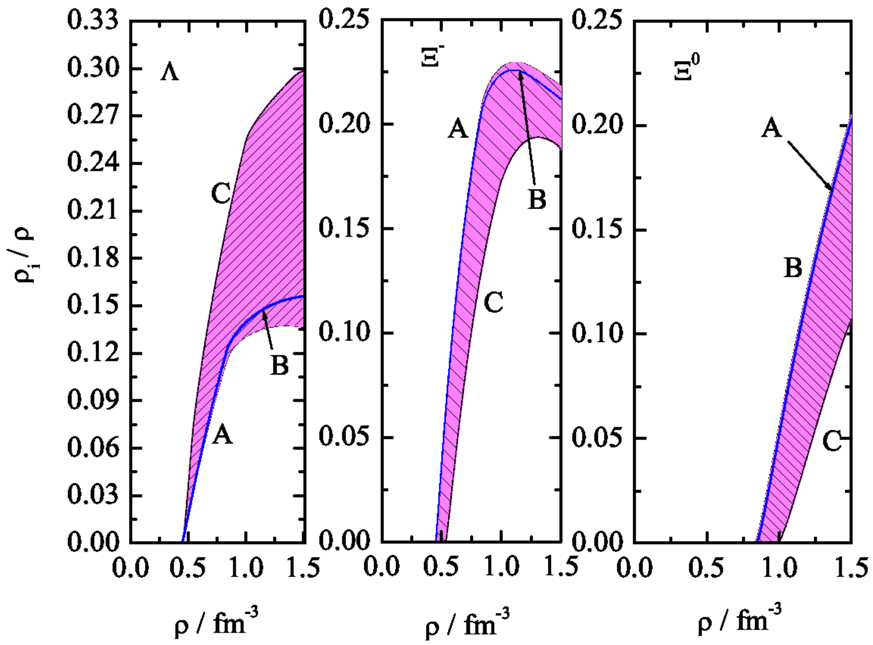

FIG. 5: The value range of the calculated relative particle number density of the hyperons Λ, Ξ^-, and Ξ^0 as a function of the baryon number density.

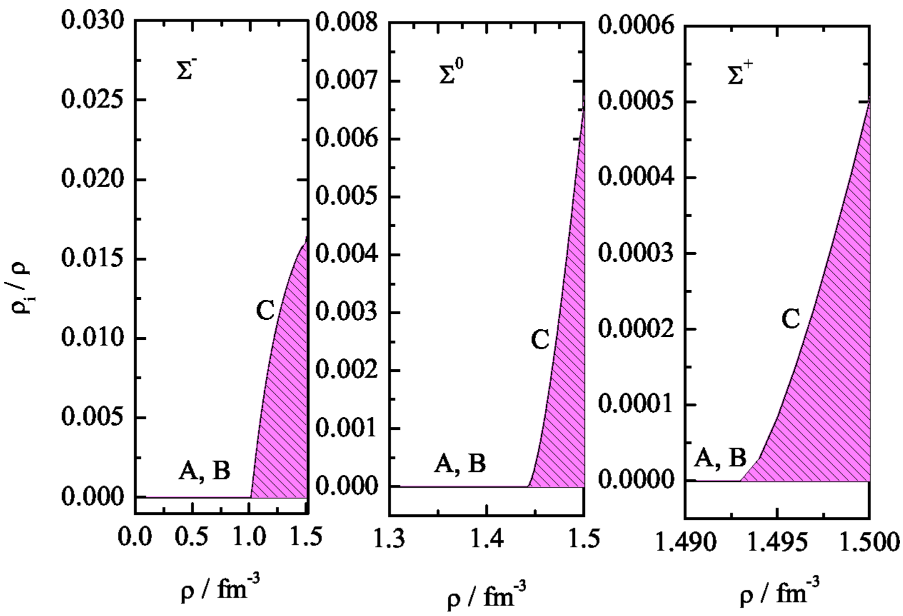

FIG. 6: The value range of the calculated relative particle number density of the hyperons Σ^-, Σ^0, and Σ^+ as a function of the baryon number density.

baryon density $\rho = 1.5$ fm^{-3}, the uncertainty value range of the pressure is in the range of $\sim$ 1.7492 fm^{-4} to 2.5899 fm^{-4}, and that of the energy density is in the range of $\sim$ 9.1170 fm^{-4} to 9.5084 fm^{-4}.

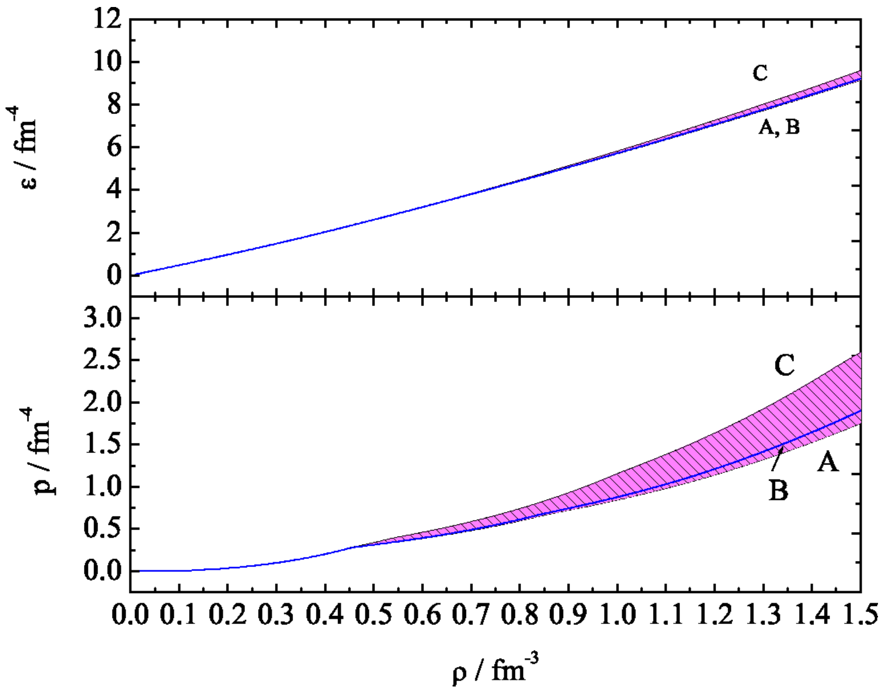

FIG. 7: The value range of the pressure and the energy density as a function of the baryon number density.

From the results above, we cannot precisely define the properties of the neutron star PSR B2303+46 but only a value range can be determined. This is because the experimental data of the hyperon well depth $U_{\Xi}^{(N)}$ and $U_{\Sigma}^{(N)}$ are not precisely defined, but are in the range of ~ -28 MeV to -14 MeV and 10 MeV to 40 MeV, respectively.

V. SUMMARY

In conclusion, in this paper by adjusting the hyperon coupling constants the properties of the neutron star PSR B2303+46 are investigated within the framework of RMF theory for the baryon octet. We can obtain any model for the neutron star B2303+46 by choosing suitable hyperon coupling constants $x_{\sigma h}$ and $x_{\omega h}$, with the $x_{\rho h}$ being determined by the constituent quark model [SU(6) symmetry] and the nucleon coupling constants being chosen as the set CZ11. Our calculations indicate the field strengths of the mesons σ, ω and ρ, the chemical potentials of the neutron and electron, the relative particle number density of the electron, muon, neutron, proton, Λ, Σ, Ξ, the pressure and the energy density of the neutron star PSR B2303+46 all have a respective value range.

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