Influence of the weakly interacting light U boson on the properties of massive protoneutron stars *

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Abstract: Considering the octet baryons in relativistic mean field theory and selecting entropy per baryon S=1, we calculate and discuss the influence of U bosons on the equation of state, mass-radius, moment of inertia and gravitational redshift of massive protoneutron stars (PNSs). The effective coupling constant g_{U} of U bosons and nucleons is selected from 0 to 70 GeV^{-2}. The results indicate that U bosons will stiffen the equation of state (EOS). The influence of U bosons on the pressure is more obvious at low density than high density, while the influence of U bosons on the energy density is more obvious at high density than low density. The U bosons play a significant role in increasing the maximum mass and radius of PNS. When the value of g_{U} changes from 0 to 70 GeV^{-2}, the maximum mass of a massive PNS increases from $2.11M_{\odot}$ to $2.58M_{\odot}$, and the radius of a PNS corresponding to PSR J0348+0432 increases from 13.71 km to 24.35 km. The U bosons will increase the moment of inertia and decrease the gravitational redshift of a PNS. For the PNS of the massive PSR J0348+0432, the radius and moment of inertia vary directly with g_{U}, and the gravitational redshift varies approximately inversely with g_{U}.

Keywords: massive protoneutron star, relativistic mean field theory, U bosons, equation of state

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1 Introduction

Massive neutron stars have been observed, such as PSR J1614-2230, which is measured to have a mass of $1.97 \pm 0.04\ M_{\odot}$ using the Shapiro delay method [1], and PSR J0348+0432, which has a mass of $2.01 \pm 0.04\ M_{\odot}$, measured by a combination of radio timing and precise spectroscopy of the white dwarf companion by Antoniadis et al [2]. Many studies on these massive neutron stars support the stiff equation of state (EOS) of neutron star matter [3–8]. For example, Tsuyoshi Miyatsu et al used the chiral quark-meson coupling model within the relativistic Hartree-Fock approximation to reconstruct the EOS for neutron star matter at zero temperature, including nuclei in the crust and hyperons in the core, and obtained a resultant maximum mass of $1.95M_{\odot}$, which is consistent with PSR J1614-2230 [9]. Xian-Feng Zhao and Huan-Yu Jia attempted to find a possible model in relativistic mean field theory (RMFT) to describe the neutron star of PSR J1614-2230 through adjusting different hyperon coupling parameters [10].

Cold neutron stars are one kind of evolutionary outcome of a protoneutron star (PNS) which is formed in the core of a massive star. The properties of the PNS corresponding to these massive neutron stars are of practical importance. Ilona Bednarek and Ryszard Manka considered the complete form of the equation of state of strangeness-rich PNSs to study the influence of the strength of hyperon-hyperon interactions on the properties of the PNS for neutron stars whose mass is below $2M_{\odot}$ [11]. The existence of hyperons will soften the EOS and subsequently decrease the mass of the neutron star. How hot neutron star matter with many hyperons supports these massive protoneutron stars is a significant problem, and there is little work which discusses it.

The possible existence of a neutral weakly coupling light spin-1 gauge U boson [12], which comes from supersymmetric extensions of the Standard Model with an extra U(1) symmetry, has recently attracted much attention due to its multifaceted influences in particle physics, nuclear physics, astrophysics, and cosmology [13]. Such a neutral weakly coupled U boson can be used as the interaction propagator of MeV dark matter and can be used to explain the bright 511 keV γ rays observed from the galactic bulge [14, 15]. It can also play a role in deviating from the inverse square law of gravity due to the Yukawa-type coupling [16–18]. Studying the properties of the U boson is thus important for understanding the relevant new physics beyond the Standard Model. Dong-Rui Zhang et al investigated the effects of the U

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boson on the nuclear matter EOS and neutron star structure, and showed that the vector U boson can significantly stiffen the nuclear matter EOS and, consequently, drastically enhance the maximum mass of neutron stars [13]. However, their discussion only focused on zero temperature. There has been little previous work about whether and how a weakly interacting light U boson stiffens the EOS of hot neutron stars and influences the properties of massive PNSs. The focus of our work, therefore, is to investigate the influence of the U boson on PNSs.

The paper is organized as follows. In Section 2, we give the complete form of relativistic mean field theory (RMFT) at finite entropy including U bosons. In Section 3, nucleon and hyperon coupling constants as well as the value of the coupling constant of the U boson are given. In Section 4, some calculation results of the U boson effect on massive PNSs are given. In Section 5, a summary is presented.

2 Relativistic mean field theory of hot dense matter and PNS properties

Relativistic mean field theory (RMFT) is an effective field theory of hadron interaction [19]. The degrees of freedom relevant to this theory are baryons interacting through the exchange of σ, ω, ρ mesons, of which the scalar meson σ provides the medium-range attraction, the vector meson ω provides short-range repulsion, and the vector-isospin vector meson ρ describes the difference between neutrons and protons.

We study the properties of hot neutron stars in the RMFT, so the partition function of the system is the starting point. From the partition function we can get various thermodynamic quantities at equilibrium.

For a grand canonical ensemble, the partition function can be written as:

$$Z=\mathrm{Tr}\{\exp[-(\hat{H}-\mu\hat{N})/T]\}, \tag{1}$$

where $\hat{H}$ and $\hat{N}$ are the Hamiltonian operator and the particle operator respectively, μ is the chemical potential, and T is the temperature. From the partition function we can get the particle population density, the energy density and pressure:

$$n=\frac{T}{V}\frac{\partial \ln Z}{\partial \mu}, \tag{2}$$

$$\varepsilon=\frac{T^2}{V}\frac{\partial \ln Z}{\partial T}+\mu n, \tag{3}$$

$$P=\frac{T}{V}\ln Z, \tag{4}$$

where V is the volume. Considering the baryons B and leptons l as fermions, we can get:

$$\ln Z_{B,l}=\sum_{B,l}\frac{2J_{B,l}+1}{2\pi^2}\int_0^\infty \ln[1+\mathrm{e}^{-(\varepsilon_{B,l}(k)-\mu_{B,l})/T}]k^2\mathrm{d}k + \frac{V}{T}\langle\mathcal{L}\rangle, \tag{5}$$

where $\varepsilon_{B,l}(k)=\sqrt{k^2+m_{B,l}^2}$ is the single particle energy of different momenta k corresponding to different baryons and leptons, $J_{B,l}$ is the spin quantum number and $\mu_{B,l}$ is the chemical potential of baryon and lepton. $\mathcal{L}$ is the Lagrangian density.

The total partition function $Z_{\text{total}}=Z_BZ_l$, where Z_B and Z_l are the partition function of baryons and the standard noninteracting partition function of leptons respectively. The additional condition of charge neutrality equilibrium is listed as following:

$$\textstyle\sum_{B,l} \quad \frac{2J_{B,l}+1}{2\pi^2}q_{B,l}\int_0^\infty k^2 n_{B,l}(k)\mathrm{d}k=0,$$

where $n_B(k)$ and $n_l(k)$ are the Fermi distribution functions of baryons and leptons respectively. They are given by

$$n_i(k)=\frac{1}{1+\exp[(\varepsilon_i(k)-\mu_i)/T]}(i=B,l). \tag{6}$$

When neutrinos are not trapped, the set of equilibrium chemical potential relations required by the general condition are

$$\mu_i=b_i\mu_n-q_i\mu_{\mathrm{e}}, \tag{7}$$

where b_i is the baryon number of particle i and q_i is its charge.

The properties of a neutron star at finite temperature can be described by the entropy per baryon. The total entropy per baryon is calculated using $S=(S_B+S_l)/(Tn_B)$, where $S_{B,l}=P_{B,l}+\varepsilon_{B,l}-\sum_{B,l}\mu_i n_i$ and the sum are extended over all the baryon and lepton species [20].

The Lagrangian density of neutron star matter is given by [21]:

$$\mathcal{L}=\sum_B \overline{\Psi}_B(\mathrm{i}\gamma_\mu\partial^\mu-m_B+g_{\sigma B}\sigma-g_{\omega B}\gamma_\mu\omega^\mu-\frac{1}{2}g_{\rho B}\gamma_\mu\tau\cdot\rho^\mu)\Psi_B+\frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma-m_\sigma^2\sigma^2\right)$$
$$-\frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu}+\frac{1}{2}m_\omega^2\omega_\mu\omega^\mu-\frac{1}{4}\rho_{\mu\nu}\cdot\rho^{\mu\nu}+\frac{1}{2}m_\rho^2\rho_\mu\cdot\rho^\mu-U(\sigma)+\sum_{l=e,\mu}\overline{\Psi}_l\left(\mathrm{i}\gamma_\mu\partial^\mu-m_l\right)\Psi_l, \quad (8)$$

where the sum on B runs over the octet baryons $(\mathrm{n},\mathrm{p},\Lambda,\Sigma^-,\Sigma^0,\Sigma^+,\Xi^-,\Xi^0)$, and Ψ_B is the baryon field operator. The term $U(\sigma)$ stands for the scalar σ self-interaction:

$$U(\sigma)=\frac{1}{3}g_2\sigma^3+\frac{1}{4}g_3\sigma^4. \quad (9)$$

The last term of Eq. (8) represents the free lepton Lagrangian. In addition, we add in a Lagrangian $\mathcal{L}_\mathrm{u}$ for the influence of the U bosons. According to the conventional view, the Yukawa-type correction [22] to Newtonian gravity resides at the matter part rather than the geometric part. Thus, following the form of the vector meson, $\mathcal{L}_\mathrm{u}$ is written as [18, 23]:

$$\mathcal{L}_\mathrm{u}=-\overline{\Psi}_B g_\mathrm{u}\gamma_\mu u^\mu\Psi_B-\frac{1}{4}U_{\mu\nu}U^{\mu\nu}+\frac{1}{2}m_\mathrm{u}^2u_\mu u^\mu, \quad (10)$$

where u is the field of the U boson, g_u is the coupling constant of U bosons and baryons, $U_{\mu\nu}$ is the strength tensor of the U boson, and m_u is the mass of the U boson.

The relativistic mean field theory gives the formula of energy density and pressure of a neutron star of finite temperature as follows:

$$\varepsilon_0=\frac{1}{3}g_2\sigma^3+\frac{1}{4}g_3\sigma^4+\frac{1}{2}m_\sigma^2\sigma^2+\frac{1}{2}m_\omega^2\omega_0^2+\frac{1}{2}m_\rho^2\rho_{03}^2$$
$$+\sum_B\frac{2J_B+1}{2\pi^2}\int_0^\infty\sqrt{k^2+(m^*)^2}(\exp[(\varepsilon_B(k)-\mu_B)/T]+1)^{-1}k^2\mathrm{d}k$$
$$+\sum_l\frac{2J_l+1}{2\pi^2}\int_0^\infty\sqrt{k^2+m_l^2}(\exp[(\varepsilon_l(k)-\mu_l)/T]+1)^{-1}k^2\mathrm{d}k, \quad (11)$$

$$P_0=-\frac{1}{3}g_2\sigma^3-\frac{1}{4}g_3\sigma^4-\frac{1}{2}m_\sigma^2\sigma^2+\frac{1}{2}m_\omega^2\omega_0^2+\frac{1}{2}m_\rho^2\rho_{03}^2$$
$$+\frac{1}{3}\sum_B\frac{2J_B+1}{2\pi^2}\int_0^\infty\frac{k^2}{\sqrt{k^2+(m^*)^2}}\left(\exp[(\varepsilon_B(k)-\mu_B)/T]+1\right)^{-1}k^2\mathrm{d}k$$
$$+\frac{1}{3}\sum_l\frac{2J_l+1}{2\pi^2}\int_0^\infty\frac{k^2}{\sqrt{k^2+m_l^2}}(\exp[(\varepsilon_l(k)-\mu_l)/T]+1)^{-1}k^2\mathrm{d}k, \quad (12)$$

where, $m^*=m_B-g_{\sigma B}\sigma$ is the effective mass of the baryon. In addition, we consider the weakly interacting light vector U boson at finite temperature RMFT, and the energy density and pressure can be expressed by the direct and exchange contribution. For the finite-range Yukawa interaction, the exchange term contribution can be neglected and the direct term contribution to the energy density and pressure can be expressed in a simple form [23, 24]:

$$\varepsilon_{\mathrm{U}B}=P_{\mathrm{U}B}=\frac{1}{2}\frac{g_\mathrm{u}^2}{m_\mathrm{u}^2}n_B^2, \quad (13)$$

where n_B is the total number density of baryons. For simplification, we define the effective coupling constants of the U boson and baryon as $g_\mathrm{U}=\frac{g_\mathrm{u}^2}{m_\mathrm{u}^2}$, where the U-boson-nucleon coupling constant g_U and the mass m_u are largely uncertain [23, 25]. According to the KLOE experiment, the mass region is restricted from 520 MeV to 980 MeV [26]. From the above forms, the total energy density may be expressed as $\varepsilon=\varepsilon_0+\varepsilon_{\mathrm{U}B}$ (ε_0 denotes the energy density without modified gravitational correction), and the pressure $P=P_0+P_{\mathrm{U}B}$.

Once the equation of state is specified, the mass and radius of the neutron star can be obtained by solving the well-known hydrostatic equilibrium equations of Tolman-Oppenheimer-Volkoff (OV) [27].

$$\frac{\mathrm{d}p}{\mathrm{d}r}=-\frac{(p+\varepsilon)(M+4\pi r^3p)}{r(r-2M)}, \quad (14)$$

$$M=4\pi\int_0^r\varepsilon r^2\mathrm{d}r. \quad (15)$$

In a uniformly slow-rotating and axially symmetric neutron star, the moment of inertia is given by the following expression [28]:

$$I \equiv \frac{J}{\Omega} = \frac{8\pi}{3}\int_0^R r^4 \mathrm{e}^{-\nu(r)} \frac{\bar{\omega}(r)}{\Omega} \frac{(\varepsilon(r)+P(r))}{\sqrt{1-2GM(r)/r}}\mathrm{d}r, \quad (16)$$

where J is the angular momentum, Ω is the angular velocity of the star, $\nu(r)$ and $\bar{\omega}(r)$ are radially dependent metric functions, and $R, M(r), \varepsilon(r)$ and $P(r)$ are the radius, mass, energy density and pressure of the star respectively. The specific form of $\nu(r)$ is determined by the following expression:

$$\nu(r) = -G\int_r^R \frac{(M(r)+4\pi x^3 P(x))}{x^2(1-2GM(x)/x)}\mathrm{d}x + \frac{1}{2}\ln\left(1-\frac{2GM}{R}\right). \quad (17)$$

In particular, the dimensionless relative frequency $\tilde{\omega}(r) \equiv \bar{\omega}(r)/\Omega$ satisfies the following second-order differential equation:

$$\frac{\mathrm{d}}{\mathrm{d}r}\left(r^4 j(r)\frac{\mathrm{d}\tilde{\omega}(r)}{\mathrm{d}r}\right) + 4r^3\frac{\mathrm{d}j(r)}{\mathrm{d}r}\tilde{\omega}(r) = 0, \quad (18)$$

where

$$j(r) = \mathrm{e}^{-\nu(r)-\lambda(r)} = \begin{cases} \mathrm{e}^{-\nu(r)}\sqrt{1-2GM(r)/r} & r \leqslant R, \\ 1 & r > R. \end{cases} \quad (19)$$

Note that $\tilde{\omega}(r)$ is subject to the following two boundary conditions:

$$\tilde{\omega}'(0) = 0,$$

$$\tilde{\omega}(R) + \frac{R}{3}\tilde{\omega}'(R) = 1. \quad (20)$$

With the EOS and the OV equation, Eqs. (16–20) can be solved.

General relativity gives the gravitational redshift of the star obeying the relation [29]:

$$z = \left(1-\frac{2GM}{c^2R}\right)^{-1/2} - 1, \quad (21)$$

where M, R are the mass and radius of the neutron star respectively.

3 Coupling constants

In order to calculate the EOS of PNS matter and its properties, we need three kinds of coupling constant. The first kind is the nucleon coupling constants, which can be determined from the saturation properties of nuclear matter, such as nuclear saturation density, binding energy per baryon number, effective mass of the nucleon, nuclear compression modulus and asymmetry energy coefficient. These nuclear matter properties are consistent with constraints from theoretical calculations of neutron matter, experimental findings and astrophysics observation of neutron stars [30, 31]. Recently, several different models [31–33] have been successfully used to describe massive neutron stars. For this study, we choose the nucleon coupling constants to be the parameter set GL85 listed in Table 1, which has been used to successfully describe the interaction between nucleons and cold massive neutron stars [21, 34].

Table 1. GL85 nucleon coupling constants.

m/MeV	m_σ/MeV	m_ω/MeV	m_ρ/MeV	g_σ	g_ω	g_ρ
939	500	782	770	7.9955	9.1698	9.7163
g_2/fm^{-1}	g_3	ρ_0/fm^{-3}	(B/A)/MeV	K/MeV	a_{sym}/MeV	m^*/m
10.07	29.262	0.145	15.95	285	36.8	0.77

The second kind is the hyperon coupling constants. For the coupling constants related to hyperons, we define the ratios:

$$x_{\sigma H} = \frac{g_{\sigma H}}{g_{\sigma N}}, \quad (22)$$

$$x_{\omega H} = \frac{g_{\omega H}}{g_{\omega N}}, \quad (23)$$

$$x_{\rho H} = \frac{g_{\rho H}}{g_{\rho N}}, \quad (24)$$

where N denotes the nucleons (neutron and proton) and H denotes hyperons (Λ, Σ and Ξ). Hyperon coupling constants cannot be decided by the saturation properties of nuclear matter, but can be extrapolated through the hypernuclear experimental data. The hypernuclear potential depth in nuclear matter U_H^N, which is known in accordance with available hypernuclear data, serves to strictly correlate the values of $x_{\sigma H}$ and $x_{\omega H}$ [35]:

$$U_H^N = x_{\omega H}V - x_{\sigma H}S, \quad (25)$$

where $S = m - m^*$, $V = (g_\omega/m_\omega)^2\rho_0$ are the values of the scalar and vector field strengths for symmetric nuclear matter at saturation respectively. With U_H^N, if we give the value of $x_{\omega H}$, we can get the value of $x_{\sigma H}$. The experimental data of hypernuclear potential depth of U_Λ^N, U_Σ^N and U_Ξ^N are [36–41]:

$$U_{\Lambda}^{N}=-30\,\mathrm{MeV},$$
$$U_{\Sigma}^{N}=+30\,\mathrm{MeV},$$
$$U_{\Xi}^{N}=-15\,\mathrm{MeV}.$$

In studying the properties of a neutron star with the RMFT, considerable uncertainty exists in the value of $x_{\omega H}$ [42]. In order to calculate the mass of a massive neutron star, such as 2 $M_{\odot}$, we choose $x_{\omega\Lambda}=x_{\omega\Sigma}=x_{\omega\Xi}=1$. This means that we do not consider the difference between hyperon and nucleon coupling with ω.

Then the coupling constants $x_{\sigma\Lambda}, x_{\sigma\Sigma}$ and $x_{\sigma\Xi}$ can be calculated by Eq. (25):

$$x_{\sigma\Lambda}=0.85,\, x_{\sigma\Sigma}=0.57,\, x_{\sigma\Xi}=0.78.$$

The hyperon coupling constants $x_{\rho\Lambda}, x_{\rho\Sigma}$ and $x_{\sigma\Xi}$ are determined by using SU(6) symmetry [43]:

$$x_{\rho\Lambda}=0,\, x_{\rho\Sigma}=2,\, x_{\sigma\Xi}=1.$$

Using these coupling constants, we calculate the maximum mass of a zero temperature neutron star, and the resultant maximum mass is as high as 2.10 $M_{\odot}$. The corresponding radius is 11.8 km, which is consistent with observation results [1, 2] and other works [44, 45], so the above coupling constants are suitable for describing massive cold neutron stars. Sequentially, these coupling constants can be extrapolated to study PNSs.

The third kind of coupling constant required is that of the U boson coupling with nucleons. Reference [18] gives the effective coupling constant g_{U} to be 0–150 GeV^{-2}. Many works [17, 23, 24] have investigated the influence of U bosons on cold neutron stars and got some interesting results which are consistent with the massive pulsars. In this work, studying PNSs, we choose the value range of g_{U} from 0 to 70 GeV^{-2}.

4 Calculation and results

We focus on the influence of the strength of effective coupling constants g_{U} on the EOS, mass-radius, moment of inertia and gravitational redshift of a massive PNS. Virtually, there are different stages during PNS evolution. The entropy in the central regions is moderately high and the value of the entropy per baryon is about 1 or 2 (in units of Boltzmann's constant), which corresponds to temperatures in the range $T=20-50$ MeV. The first stage corresponds to an entropy per baryon S=1. The second stage is called the deleptonization era and corresponds to maximum heat and entropy per baryon S=2 [20]. However, the effects of U bosons on the PNS are similar for entropy per baryon S=1 or 2. We only give the results for the entropy per baryon S=1, corresponding to the first stage of the PNS.

4.1 PNS equation of state

The equation of state of PNS matter is shown in Fig. 1 and Fig. 2. In Fig. 1, we give the influence of different g_{U} on the energy and pressure as a function of baryon number density. The pressure and energy density all increase with baryon number density for different g_U under $S=1$, while higher g_{U} will give higher pressure and higher energy density. Figure 2 shows that the inclusion of the U boson will stiffen the EOS. This is physically obvious since the vector form of the U boson provides an excess repulsion in addition to the vector mesons ω.

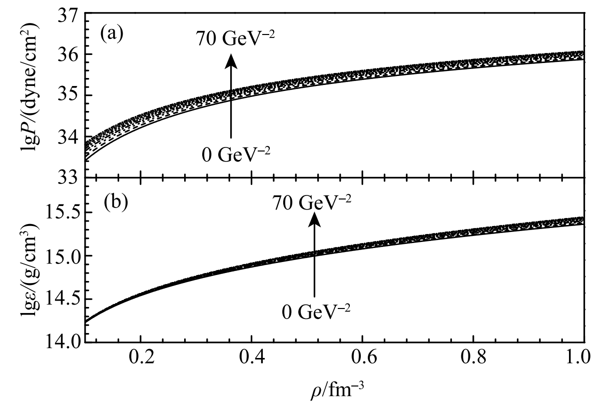

Fig. 1. Pressure (panel (a)) and energy density (panel (b)) as a function of baryon number density for different g_{U}.

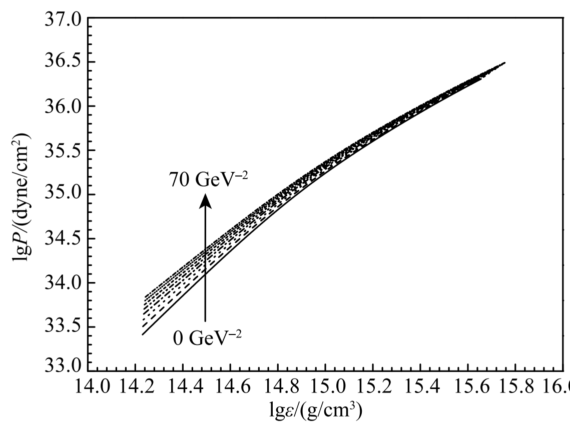

Fig. 2. The EOS of a PNS ($S=1$) for different g_{U}.

The influence of the U boson on the EOS can be read from Fig. 1. In panel (a), at $\rho=0.145$ fm^{-3} (saturation density), the value of g_{U} changes from 0 to 70 GeV^{-2}, and the value of lg$P$ increases from 33.84 dyne/cm^2 to 34.20 dyne/cm^2, an increase of 0.36 dyne/cm^2 (1.06%). At $\rho=0.5$ fm^{-3} (around central density), 0 to 70 GeV^{-2} of g_{U} gives 35.29 dyne/cm^2 to 35.43 dyne/cm^2 of lg$P$, an increase of 0.14 dyne/cm^2 (0.39%). The effect of g_{U} on the pressure is more obvious at low density than high density. In comparison, in panel (b), at $\rho=0.145$ fm^{-3}, as the value of g_{U} changes from 0 to 70 GeV^{-2}, the value of lgϵ increases from 14.40 g/cm^{-3} to 14.41 g/cm^{-3}, an increase of 0.01 g/cm^{-3} (0.06%). At $\rho = 0.5$ fm^{-3}, 0 to 70 GeV^{-2} of $g_{\rm U}$ gives 14.98 g/cm^{-3} to 15.03 g/cm^{-3} of lgε, an increment of 0.05 g/cm^{-3} (0.33%). The effect of $g_{\rm U}$ on the energy density is more obvious at high density than low density.

4.2 Mass-radius of PNS

Substituting the above equation of state into the OV equation, we can solve the PNS masses and radii.

The resultant PNS masses are shown in Fig. 3. In Fig. 3, the PNS mass as a function of the central density is given for different effective coupling constants $g_{\rm U}$. The maximum PNS masses can be read from Fig. 3. It is found that the maximum PNS mass increases significantly with the effective coupling constant. When the value of $g_{\rm U}$ changes from 0 to 70 GeV^{-2}, the maximum PNS mass increases from $2.11M_\odot$ to $2.58M_\odot$. In these calculations we consider the octet baryons; with each addition of hyperon species, the equation of state is softened because the Fermi pressure of neutrons and protons near the top of their Fermi seas is relieved by allowing them to hyperonize to unoccupied low-momentum states [21], consequently leading to decreased mass. However, including the U boson stiffens the EOS and increases the mass of the neutron star because it provides extra repulsion in addition to the vector meson ω. So this equilibrium result strongly supports the existence of massive PNSs whose mass is larger than $2M_\odot$.

The PNS mass corresponding to PSR J0348+0432 is marked in Fig. 3. It is shown that the central density of the PNS of PSR J0348+0432 will change with the effective coupling constant. The larger $g_{\rm U}$ is, the lower the central density is. When $g_{\rm U}$=0, the central density of PNS of PSR J0348+0432 is 0.62 fm^{-3}, while when $g_{\rm U}$=70 GeV^{-2}, the central density becomes 0.21 fm^{-3}.

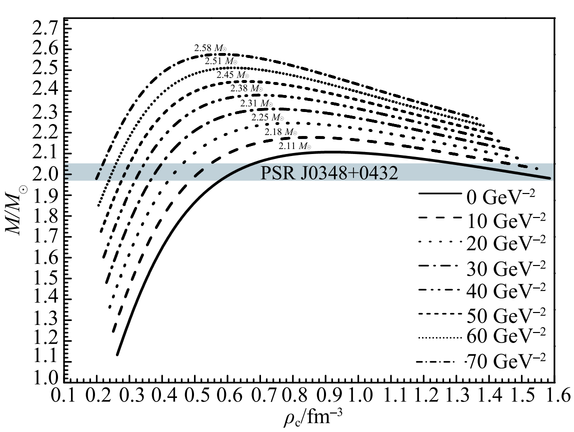

Fig. 3. The masses of massive PNS for different $g_{\rm U}$. The shaded area corresponds to the mass of PSR J0348+0432.

The mass-radius relation is shown in Fig. 4. In Fig. 4 the PNS mass as a function of the radius is given with the inclusion of the U boson with different effective coupling constants. The U bosons significantly increase the radius of the PNS. Here we give the radius of the PNS corresponding to PSR J0348+0432. When the value of g_U changes from 0 to 70 GeV^{-2}, the radius increases from 13.71 km to 24.35 km and it is easily seen that if g_U increases to larger than $g_{\rm U}$=70 GeV^{-2}, the radius will become bigger than 25 km. V. Dexheimer et al have pointed out that the PNS radius should not exceed 30 km [46]. This is the reason why we choose $g_{\rm U}$ in the range 0–70 GeV^{-2}.

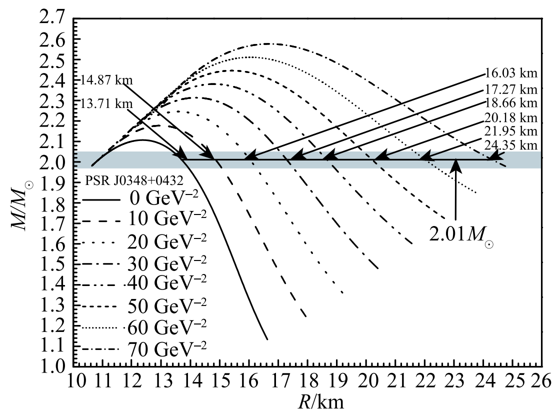

Fig. 4. The mass-radius relation of massive PNS for different $g_{\rm U}$. The shaded area corresponds to PSR J0348+0432.

4.3 Moment of inertia and gravitational redshift of PNS

The moment of inertia and gravitational redshift are shown in Fig. 5 and Fig. 6. It can be seen that the moment of inertia increases with $g_{\rm U}$, but the gravitational redshift decreases as $g_{\rm U}$ increases. This is due to the bigger $g_{\rm U}$ giving a larger radius, as known from Fig. 4.

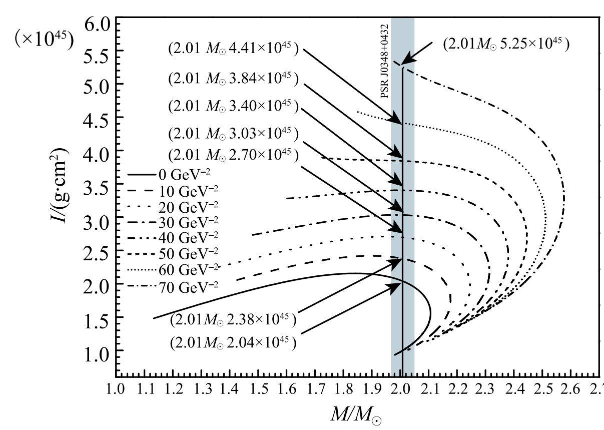

Fig. 5. The relation between moment of inertia and mass for different $g_{\rm U}$. The shaded area corresponds to PSR J0348+0432.

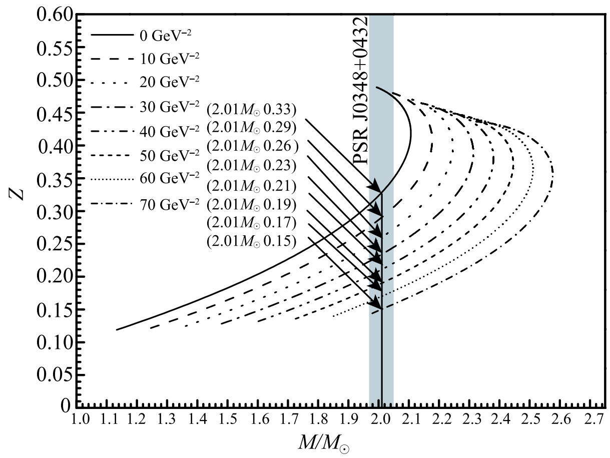

Fig. 6. The relation between gravitational redshift and mass for different g_{U}. The shaded area corresponds to PSR J0348+0432.

Finally, the change of radius, moment of inertia and gravitational redshift with g_{U} for a massive PNS of PSR J0348+0432, with mass of $2.01M_{\odot}$, is shown in Fig. 7. The radius and moment of inertia vary directly with g_{U}, while the gravitational redshift varies approximately inversely with g_{U}.

5 Summary

Based on relativistic mean field theory, considering the octet baryons and selecting entropy per baryon $S=1$, we have calculated and discussed the influence of U bosons which are weakly coupled to nucleons on massive PNS matter. The effective coupling constant g_{U} of U bosons and nucleons was selected from 0 to 70 GeV^{-2}. It is found that the strength of effective coupling constant g_{U} has an obvious influence on the EOS of PNS matter, mass, radius, moment of inertia and gravitational redshift of a massive PNS. The results indicate that U bosons will stiffen the EOS. The influence of U bosons on the pressure are more obvious at low density than high density, while the influence of U bosons on energy density are more obvious at high density than low density. The g_{U} plays a significant role in increasing the maximum mass and radius of a PNS. When the value of g_{U} changes from 0 to 70 GeV^{-2}, the maximum mass of a massive PNS increases from $2.11M_{\odot}$ to $2.58M_{\odot}$, and the radius of a PNS corresponding to PSR J0348+0432 increases from 13.71 km to 24.35 km. The g_{U} will increase the moment of inertia and decrease the gravitational redshift. For the PNS of the massive PSR J0348+0432, the radius and moment of inertia vary directly with g_{U} , and the gravitational redshift varies approximately inversely with g_{U}.

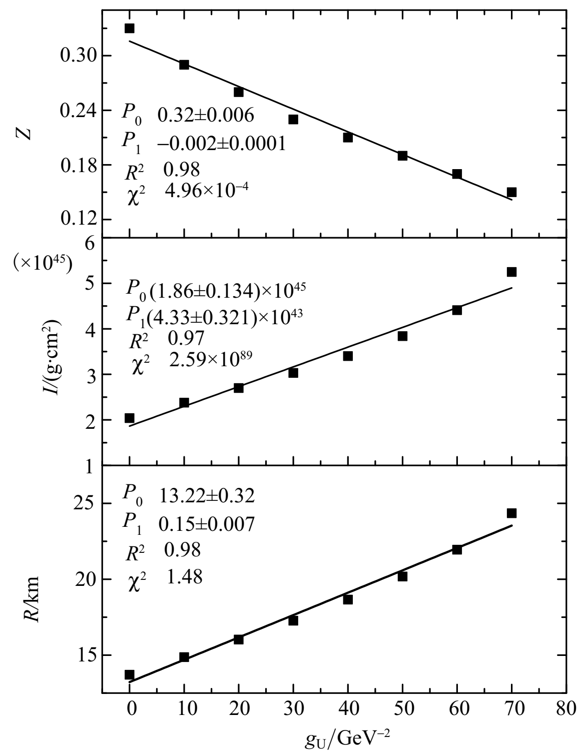

Fig. 7. The properties of massive PNS of PSR J0348+0432 vs different g_{U}. P_0 and P_1 are the y-intercept and slope of the linear fitting respectively, R^2 is the coefficient of determination, and χ^2 is the sum of squared residuals.

The influence of U bosons on PNSs may be dependent on the interaction model of the nuclear matter. This should be investigated in our future work.

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