Examination of the influence of the $f_0(975)$ and $\phi(1020)$ mesons on the surface gravitational redshift of the neutron star PSR J0348+0432

Xian-Feng Zhao*

School of Sciences, Southwest Petroleum University, Chengdu 610500, China
and School of Electronic and Electrical Engineering, Chuzhou University, Chuzhou 239000, China
(Received 2 February 2015; revised manuscript received 30 August 2015; published 9 November 2015)

The effect of the mesons $f_0(975)$ and $\phi(1020)$ on the surface gravitational redshift of the neutron star PSR J0348+0432 is examined in the framework of the relativistic mean field theory by choosing the suitable hyperon coupling constants. We find that compared with that without considering the mesons $f_0(975)$ and $\phi(1020)$, the value range of the radius R of the neutron star PSR J0348+0432 would be changed from a narrow range 12.964 km $\sim$ 12.364 km to a wider range 12.941 km $\sim$ 11.907 km corresponding to the observation mass $M = 1.97$ $M_\odot \sim 2.05$ $M_\odot$. We also find that the value range of the surface gravitational redshift z of the neutron star PSR J0348+0432 changes from 0.3469 $\sim$ 0.3997 to 0.3480 $\sim$ 0.4263 corresponding to the observation mass $M = 1.97$ $M_\odot \sim 2.05$ $M_\odot$ with the mesons $f_0(975)$ and $\phi(1020)$ being considered. This means that the radius R and the surface gravitational redshift z both will be constrained in a wider scope with the mesons $f_0(975)$ and $\phi(1020)$ being considered. We also can see that the difference of the radius and the surface gravitational redshift is not so large whether the mesons $f_0(975)$ and $\phi(1020)$ are considered or not. This indicates that the mesons $f_0(975)$ and $\phi(1020)$ do not play a major role in the massive neutron star PSR J0348+0432.

DOI: 10.1103/PhysRevC.92.055802 PACS number(s): 26.60.−c, 21.30.Fe, 21.65.−f, 24.10.Jv

I. INTRODUCTION

In 2010, Demorest *et al.* first observed the massive neutron star PSR J1614-2230 [1], which was soon theoretically studied by many researchers with various methods [2–12]. Recently, a more massive neutron star PSR J0348+0432 with the mass of 2.01 ± 0.04 $M_\odot$ was observed by Antoniadis *et al.* in 2013 [13]. The neutron star mass would restrict its properties, such as energy density, pressure, baryon number density, and chemical potential, which depend on the neutron star maximum mass [14].

Neutron stars, especially massive neutron stars, are high-density objects. Within them hyperons should be produced. The interactions between nucleon-nucleon or nucleon-hyperon can be represented by mesons σ,ω, and ρ [16]. But the interactions between the nucleons and hyperons can be represented by mesons $f_0(975)$ and $\phi(1020)$ [15].

In the calculations of the neutron star matter with the relativistic mean field (RMF) theory, the nucleon coupling constants and the hyperon coupling constants should be determined. The theoretical results showed that the nucleon coupling constant GL85 is a better parameter to describe the properties of the neutron star matter [16]. For the hyperon coupling constants, there are many selection methods. For example, we can select the hyperon coupling constants of mesons ρ,ω by SU(6) symmetry and those of mesons σ by fitting the Λ, Σ, and Ξ well depth in nuclear matter [17]. These selection methods may connect the latest progress in nuclear physics experiments with observations of neutron stars.

The surface gravitational redshift is closely linked to the neutron star mass and so it is also an important physical quantity [18]. But the experimental data and theoretical study of the surface gravitational redshift of the neutron star PSR J0348+0432 are very few. So theoretical study on it is necessary.

In this paper, on the hadronic basis, we examine the effect of $f_0(975)$s and $\phi(1020)$s on the surface gravitational redshift of the massive neutron star PSR J0348+0432 in the framework of the RMF theory considering the baryon octet.

II. THE RMF THEORY OF A NEUTRON STAR

The Lagrangian density of hadron matter containing mesons $f_0(975)$ and $\phi(1020)$ reads as follows [18]:

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

The last term represents the contribution of the mesons $f_0(975)$ and $\phi(1020)$ and reads

$$\begin{aligned}\mathcal{L}^{YY} = {} & \sum_B g_{f_0 B}\overline{\Psi}_B\Psi_B f_0 - \sum_B g_{\phi B}\overline{\Psi}_B\gamma_\mu\Psi_B\phi^\mu \\ & + \frac{1}{2}\big(\partial_\mu f_0\partial^\mu f_0 - m_{f_0}^2 f_0^2\big) - \frac{1}{4}S_{\mu\nu}S^{\mu\nu} + \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu. \end{aligned} \quad (2)$$

Here, $S_{\mu\nu} = \partial_\mu\phi_\nu - \partial_\nu\phi_\mu$.

*zhaopioneer.student@sina.com

Then the RMF approach is used. From the condition of β equilibrium in neutron star matter, the chemical equilibrium is

$$\mu_i = b_i \mu_n - q_i \mu_e, \tag{3}$$

where b_i is the baryon number of a species i.

III. THE PARAMETERS

The nucleon coupling constant GL85 set is chosen in this work [16]: the saturation density $\rho_0 = 0.145\ \text{fm}^{-3}$, binding energy $B/A = 15.95$ MeV, the compression modulus $K = 285$ MeV, charge symmetry coefficient $a_{\text{sym}} = 36.8$ MeV, and the effective mass $m^*/m = 0.77$.

We define the ratios of hyperon coupling constant to nucleon coupling constant: $x_{\sigma h} = \frac{g_{\sigma h}}{g_\sigma} = x_\sigma$, $x_{\omega h} = \frac{g_{\omega h}}{g_\omega} = x_\omega$, $x_{\rho h} = \frac{g_{\rho h}}{g_\rho}$, with h denoting hyperons Λ, Σ, and Ξ.

We select $x_{\rho\Lambda} = 0, x_{\rho\Sigma} = 2, x_{\rho\Xi} = 1$ according to SU(6) symmetry [19]. The experimental data of the hyperon well depth are $U_\Lambda^{(N)} = -30$ MeV [20], $U_\Sigma^{(N)} = 10 \sim 40$ MeV [21–24], and $U_\Xi^{(N)} = -28$ MeV [25], respectively. We then choose $U_\Lambda^{(N)} = -30$ MeV, $U_\Sigma^{(N)} = +40$ MeV, and $U_\Xi^{(N)} = -28$ MeV in this work.

The calculations show that the ratio of hyperon coupling constant to nucleon coupling constant is in the range of $\sim 1/3$ to 1 [26]. So we choose $x_{\sigma\Lambda} = 0.4, 0.5, 0.6, 0.7, 0.8, 0.9$ at first and considering the restriction of the hyperon well depth [18]

$$U_h^{(N)} = m_n \left(\frac{m_n^*}{m_n} - 1\right) x_{\sigma h} + \left(\frac{g_\omega}{m_\omega}\right)^2 \rho_0 x_{\omega h}, \tag{4}$$

the hyperon coupling constants $x_{\omega\Lambda}$ will be obtained. As $x_{\sigma\Lambda} = 0.9$, $x_{\omega\Lambda}$ will be 1.0729 considering the restriction of the hyperon well depth. Therefore, we choose $x_{\sigma\Lambda} = 0.4, 0.5, 0.6, 0.7, 0.8$ and correspondingly we obtain $x_{\omega\Lambda} = 0.3679, 0.5090, 0.6500, 0.7909, 0.9319$, respectively.

As $x_{\sigma\Sigma} = 0.6, 0.7, 0.8, 0.9$, $x_{\omega\Sigma}$ all will be greater than 1 (e.g., $x_{\sigma\Sigma} = 0.6$, $x_{\omega\Sigma} = 1.1069$). So we choose $x_{\sigma\Sigma} = 0.4, 0.5$; correspondingly we obtain $x_{\omega\Sigma} = 0.8250, 0.9660$. For the positive $U_\Sigma^{(N)}$ restricting the production of the hyperon Σ [27], we only choose $x_{\sigma\Sigma} = 0.4$, $x_{\omega\Sigma} = 0.8250$ while $x_{\sigma\Sigma} = 0.5$, $x_{\omega\Sigma} = 0.9660$ can be deleted (see Table I).

For $x_{\omega\Xi}$, we first choose $x_{\omega\Xi} = 0.4, 0.5, 0.6, 0.7, 0.8, 0.9$ and the $x_{\sigma\Xi}$ is obtained through fitting to the hyperon well depth. Thus, the parameters chosen are listed in Table I.

From the parameters chosen above, we can compose 30 sets of suitable parameters (named Nos. 1–30), for which we calculate the mass of the neutron star (see Fig. 1) through the Oppenheimer-Volkoff (O-V) equation [18]

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

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

Considering the effect of the mesons $f_0(975)$ and $\phi(1020)$, the parameters can be chosen as follows.

TABLE I. The hyperon coupling constants fitted to the experimental data of the well depth, which are $U_\Lambda^N = -30$ MeV, $U_\Sigma^N = +40$ MeV, and $U_\Xi^N = -28$ MeV.

No.	$x_{\sigma\Lambda}$	$x_{\omega\Lambda}$	$x_{\sigma\Sigma}$	$x_{\omega\Sigma}$	$x_{\sigma\Xi}$	$x_{\omega\Xi}$
(1–30)	0.4	0.3679	0.4	0.8250	0.4134	0.4
	0.5	0.5090	0.5	0.9660	0.4843	0.5
	0.6	0.6500			0.5553	0.6
	0.7	0.7909			0.6262	0.7
	0.8	0.9319			0.6971	0.8
					0.7681	0.9
31	0.8	0.9319	0.4	0.8250	0.7752	0.91
32	0.8	0.9319	0.4	0.8250	0.7893	0.93
33	0.8	0.9319	0.4	0.8250	0.8035	0.95
34	0.8	0.9319	0.4	0.8250	0.8177	0.97
35	0.8	0.9319	0.4	0.8250	0.8319	0.99
36	0.8	0.9319	0.4	0.8250	0.8326	0.991
37	0.8	0.9319	0.4	0.8250	0.8340	0.993
38	0.8	0.9319	0.4	0.8250	0.8355	0.995
39	0.8	0.9319	0.4	0.8250	0.8369	0.997
40	0.8	0.9319	0.4	0.8250	0.8383	0.999

The coupling constant of the mesons $\phi(1020)$ is obtained by the quark model relationships

$$g_{\phi\Xi} = 2g_{\phi\Lambda} = -2\sqrt{2}g_\omega/3. \tag{7}$$

For the mesons $f_0(975)$, we use the mass of the obtained $f_0(975)$ meson, but treat its couplings purely phenomenologically so as to satisfy the equation of potential depths

$$U_\Lambda^{(\Xi)} \simeq = U_\Xi^{(\Xi)} \simeq 2U_\Lambda^{(\Lambda)} \simeq 40\ \text{MeV}. \tag{8}$$

Thus we yield $g_{f_0\Lambda}/g_\sigma = g_{f_0\Sigma}/g_\sigma = 0.69$, $g_{f_0\Xi}/g_\sigma = 1.25$.

For parameters No. 1 to No. 30, considering the effect of the mesons $f_0(975)$ and $\phi(1020)$ the mass obtained is also shown in Fig. 1. From Fig. 1 we see that the masses including the mesons $f_0(975)$ and $\phi(1020)$ are less than those not considering those two mesons. Whether considering the

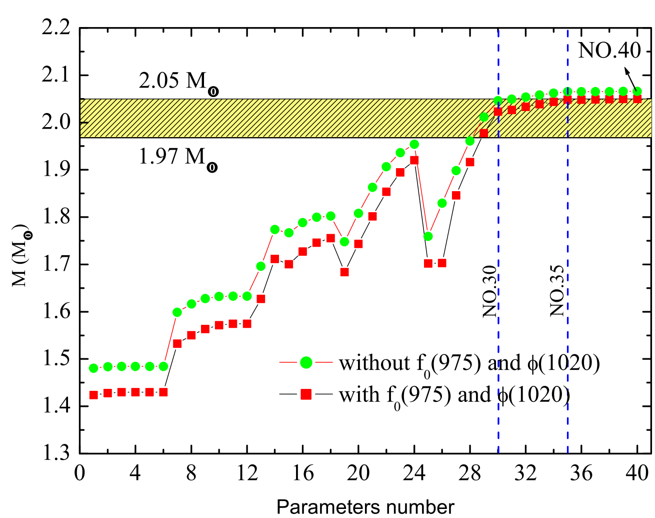

FIG. 1. (Color online) The mass of the neutron star as a function of the parameters number.

effect of the mesons $f_0(975)$ and $\phi(1020)$ or not, parameters No. 30 ($x_{\sigma\Lambda} = 0.8$, $x_{\omega\Lambda} = 0.9319$; $x_{\sigma\Sigma} = 0.4$, $x_{\omega\Sigma} = 0.8250$; $x_{\sigma\Xi} = 0.7681$, $x_{\omega\Xi} = 0.9$) give the largest mass of the neutron star, which is less than 2.05 $M_\odot$.

In order to obtain larger mass of the neutron star, we choose $x_{\omega\Xi} = 0.91, 0.93, 0.95, 0.97, 0.99$ and we obtain $x_{\sigma\Xi} = 0.7752, 0.7893, 0.8035, 0.8177, 0.8319$ by fitting to the well depth $U_\Xi^{(N)} = -28$ MeV. Thus we get parameters No. 31 to No. 35. We find that the largest mass obtained (by No. 35) is also less than 2.05 $M_\odot$ considering the effect of the mesons $f_0(975)$ and $\phi(1020)$. So, by further choosing $x_{\omega\Xi} = 0.991$, 0.993, 0.995, 0.997, 0.999, we obtain the corresponding five $x_{\sigma\Xi}$s considering the constraints of the well depth $U_\Xi^{(N)} = -28$ MeV and we therefore get five sets of parameters named as No. 36 to No. 40. We find that the largest mass obtained by No. 40 is $M = 2.05$ $M_\odot$ considering the mesons $f_0(975)$ and $\phi(1020)$.

In the next step, we use parameters No. 40 ($x_{\sigma\Lambda} = 0.8$, $x_{\omega\Lambda} = 0.9319$; $x_{\sigma\Sigma} = 0.4$, $x_{\omega\Sigma} = 0.8250$; $x_{\sigma\Xi} = 0.8383$, $x_{\omega\Xi} = 0.999$) to study the effect of $f_0(975)$s and $\phi(1020)$s on the surface gravitational redshift of the massive neutron star PSR J0348+0432.

IV. THE GRAVITATIONAL REDSHIFT OF THE MASSIVE NEUTRON STAR PSR J0348+0432 WITHOUT $f_0(975)$ AND $\phi(1020)$ MESONS

For the neutron star PSR J0348+0432, its mass is in the range ~1.97 $M_\odot \leqslant M \leqslant 2.05$ $M_\odot$.

In the first case, we assume that the neutron star PSR J0348+0432 does not contain the mesons $f_0(975)$ and $\phi(1020)$, and parameters No. 40 are used.

The radius of PSR J0348+0432 calculated by us is $R = 12.964$ km corresponding to $M = 1.97$ $M_\odot$ and is $R = 12.364$ km as $M = 2.05$ $M_\odot$. In this case, the radius (R) range of the neutron star PSR J0348+0432 should be suggested as 12.964 km ~ 12.364 km by the observation $M = 1.97$ $M_\odot$ ~ 2.05 $M_\odot$ (see Fig. 2).

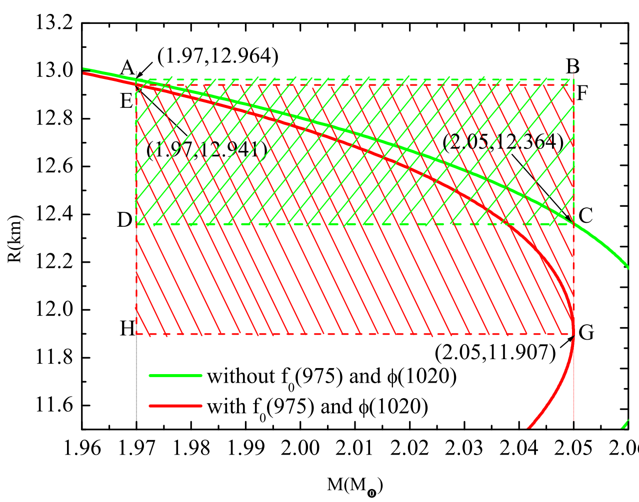

FIG. 2. (Color online) The radius of the neutron star as a function of the mass. Case 1 does not include the mesons $f_0(975)$ and $\phi(1020)$ while case 2 includes them.

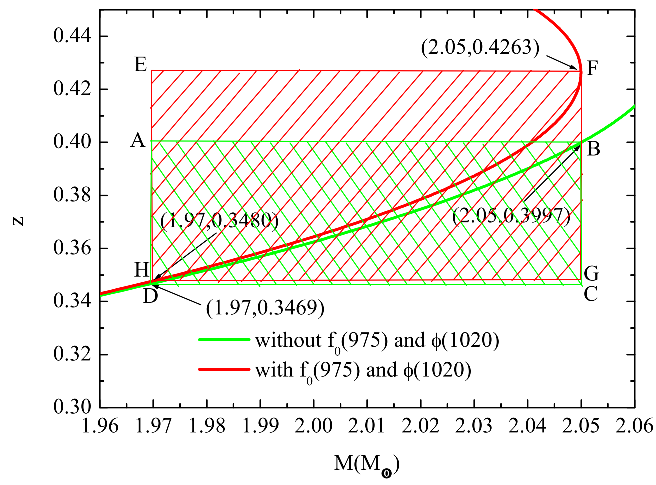

FIG. 3. (Color online) The radius of the neutron star as a function of the mass. Case 1 does not include the mesons $f_0(975)$ and $\phi(1020)$ while case 2 includes them.

The surface gravitational redshift of a neutron star is given by [18]

$$z = \left(1 - \frac{2M}{R}\right)^{-1/2} - 1. \tag{9}$$

According to the M and R previously obtained, the surface gravitational redshift of the neutron star PSR J0348+0432 calculated is $z = 0.3469$ corresponding to $M = 1.97$ $M_\odot$ and $R = 12.964$ km (Fig. 3) and is $z = 0.3997$ as $M = 2.05$ $M_\odot$ and $R = 12.364$ km. Thus, the surface gravitational redshift of the neutron star PSR J0348+0432 should be suggested in the range 0.3469 ~ 0.3997 without the mesons $f_0(975)$ and $\phi(1020)$ being considered.

V. THE GRAVITATIONAL REDSHIFT OF THE MASSIVE NEUTRON STAR PSR J0348+0432 CONSIDERING THE $f_0(975)$ AND $\phi(1020)$ MESONS

Next, we assume that the neutron star PSR J0348+0432 contains the mesons $f_0(975)$ and $\phi(1020)$ and parameters No. 40 are also used.

Corresponding to $M = 1.97$ $M_\odot$, the calculated radius of PSR J0348+0432 is $R = 12.941$ km and is $R = 11.907$ km for $M = 2.05$ $M_\odot$. Here, the radius (R) range of the neutron star PSR J0348+0432 should be suggested as 12.941 km ~ 11.907 km by the observation $M = 1.97$ $M_\odot$ ~ 2.05 $M_\odot$.

We further obtain the surface gravitational redshift of the neutron star PSR J0348+0432 according to the previously obtained mass M and radius R. The surface gravitational redshift of the neutron star PSR J0348+0432 we calculate is $z = 0.3480$ corresponding to $M = 1.97$ $M_\odot$ and $R = 12.941$ km (Fig. 3) and is $z = 0.4263$ as $M = 2.05$ $M_\odot$ and $R = 11.907$ km. The suggested surface gravitational redshift of the neutron star PSR J0348+0432 should be in the range 0.3480 ~ 0.4263 with the mesons $f_0(975)$ and $\phi(1020)$ being considered.

TABLE II. The radius R and the surface gravitational redshift z calculated in this work. Case 1 considers $f_0(975)$ and $\phi(1020)$ mesons while case 2 does not consider them. The unit of the cental energy density ϵ_c is $\times 10^{15}$ g cm^3.

case	ϵ_c	M ($M_\odot$)	R (km)	z	ϵ_c	M ($M_\odot$)	R (km)	z
1	1.2470	1.97	12.964	0.3469	1.6721	2.05	12.364	0.3997
2	1.2754	1.97	12.941	0.3480	2.0660	2.05	11.907	0.4263

VI. DISCUSSION ON THE GRAVITATIONAL REDSHIFT OF THE MASSIVE NEUTRON STAR PSR J0348+0432 WITH AND WITHOUT THE f_0(975) AND ϕ(1020) MESONS

From the results obtained above, we see the radius (R) range of the neutron star PSR J0348+0432 is 12.964 km $\sim$ 12.364 km without the $f_0(975)$ and $\phi(1020)$ mesons and is 12.941 km $\sim$ 11.907 km with those two mesons being considered by the observation $M = 1.97\ M_\odot \sim 2.05\ M_\odot$. That is to say, considering $f_0(975)$ and $\phi(1020)$ mesons the radius range of the neutron star PSR J0348+0432 changes from $R = 12.964$ km $\sim$ 12.364 km to $R = 12.941$ km $\sim$ 11.907 km.

We also can see that the surface gravitational redshift of the neutron star PSR J0348+0432 is in the range $z = 0.3469 \sim 0.3997$ without the $f_0(975)$ and $\phi(1020)$ mesons and is $z = 0.3480 \sim 0.4263$ with those two mesons being considered by the observation $M = 1.97\ M_\odot \sim 2.05\ M_\odot$. Namely, considering $f_0(975)$ and $\phi(1020)$ mesons the surface gravitational redshift of the neutron star PSR J0348+0432 changes from $z = 0.3469 \sim 0.3997$ to $z = 0.3480 \sim 0.4263$.

The results above also can be seen in Table II.

VII. SUMMARY

In this paper, we fit out the mass of the neutron star PSR J0348+0432 not containing or containing the mesons $f_0(975)$ and $\phi(1020)$ by adjusting the hyperon coupling constant in the framework of the RMF theory. Then we study the effect of the mesons $f_0(975)$ and $\phi(1020)$ on the radius and the surface gravitational redshift of the neutron star. We find that compared with that without considering the mesons $f_0(975)$ and $\phi(1020)$, the value range of the radius (R) will be changed from a narrow range 12.964 km $\sim$ 11.364 km to a wider range 12.941 km $\sim$ 11.907 km corresponding to the observation mass $M = 1.97\ M_\odot \sim 2.05\ M_\odot$.

For the surface gravitational redshift z of the neutron star PSR J0348+0432, considering the effect of the mesons $f_0(975)$ and $\phi(1020)$ on the neutron star matter, it is suggested that the value range changes from 0.3469 $\sim$ 0.3997 to 0.3480 $\sim$ 0.4263 and the central energy density ϵ_c changes from 1.2470×10^{15} g cm^{-3} $\sim$ 1.6721×10^{15} g cm^{-3} to 1.2754×10^{15} g cm^{-3} $\sim$ 2.0660×10^{15} g cm^{-3} corresponding to the observation mass $M = 1.97\ M_\odot \sim 2.05\ M_\odot$.

This means that the radius R, the surface gravitational redshift z, and the central energy density ϵ_c all will be constrained in a wider scope with the mesons $f_0(975)$ and $\phi(1020)$ being considered.

From the above we also see that whether considering the mesons $f_0(975)$ and $\phi(1020)$ in the massive neutron star PSR J0348+0432 or not, the difference of the radius and the surface gravitational redshift is not so large. This indicates that the mesons $f_0(975)$ and $\phi(1020)$ do not play a major role in the massive neutron star PSR J0348+0432. In other words, the interactions between the nucleons and the hyperons are very weak.

ACKNOWLEDGMENTS

We are thankful to the anonymous referee for many useful comments and suggestions and Researcher Shan-Gui Zhou for fruitful discussions. This work was supported by the Natural Science Foundation of China (Grant No. 11447003) and the Anhui University Provincial Natural Science Research Project, China (Grant No. KJ2014A182).

[1] P. B. Demorest, T. Pennucci, S. M. Ransom *et al.*, Nature (London) **467**, 1081 (2010).
[2] É. Massot, J. Margueron, and G. Chanfray, Europhys. Lett. **97**, 39002 (2012).
[3] K. Masuda, T. Hatsuda, and T. Takatsuka, Astrophys. J. **764**, 12 (2013).
[4] R. Mallick, Phys. Rev. C **87**, 025804 (2013).
[5] D. L. Whittenbury, J. D. Carroll, A. W. Thomas, K. Tsushima, and J. R. Stone, arXiv:1204.2614.
[6] J. I. Kapusta and K. A. Olive, Phys. Rev. Lett. **64**, 13 (1990); J. Ellis, J. I. Kapusta, and K. A. Olive, Nucl. Phys. B **348**, 345 (1991).
[7] W. Z. Jiang, B. A. Li, and L. W. Chen, Astrophys. J. **756**, 56 (2012).
[8] S. Weissenborn, D. Chatterjee, and J. Schaffner-Bielich, Phys. Rev. C **85**, 065802 (2012).
[9] N. Chamel, A. F. Fantina, J. M. Pearson, and S. Goriely, Astron. Astrophys. **553**, A22 (2013).
[10] T. Katayama, T. Miyatsu, and K. Saito, Astrophys. J. Suppl. **203**, 22 (2012).
[11] S. Weissenborn, D. Chatterjee, and J. Schaffner-Bielich, Nucl. Phys. A **881**, 62 (2012).
[12] I. Bednarek, P. Haensel, J. L. Zdunik, M. Bejger, and R. Mańka, Astron. Astrophys. **543**, A157 (2012).
[13] J. Antoniadis, P. C. C. Freire, N. Wex, T. M. Tauris, R. S. Lynch, M. H. van Kerkwijk, M. Kramer, C. Bassa, V. S. Dhillon, T. Driebe, J. W. T. Hessels, V. M. Kaspi, V. I. Kondratiev, N. Langer, T. R. Marsh, M. A. McLaughlin, T. T. Pennucci, S. M. Ransom, I. H. Stairs, J. van Leeuwen, J. P. W. Verbiest, and D. G. Whelan, Science **340**, 448 (2013).
[14] J. M. Lattimer and M. Prakash, arXiv:1012.3208.
[15] J. Schaffner, C. B. Dover, and A. Gal, Ann. Phys. **235**, 35 (1994).
[16] N. K. Glendenning, Astrophys. J. **293**, 470 (1985).
[17] X. F. Zhao and H. Y. Jia, Phys. Rev. C **85**, 065806 (2012).

[18] N. K. Glendenning, *Compact Stars: Nuclear Physics, Particle Physics, and General Relativity* (Springer-Verlag, New York, 1997).
[19] J. Schaffner and I. N. Mishustin, Phys. Rev. C **53**, 1416 (1996).
[20] C. J. Batty, E. Friedman, and A. Gal, Phys. Rep. **287**, 385 (1997).
[21] M. Kohno, Y. Fujiwara, Y. Watanabe, K. Ogata, and M. Kawai, Phys. Rev. C **74**, 064613 (2006).
[22] T. Harada and Y. Hirabayashi, Nucl. Phys. A **759**, 143 (2005).
[23] T. Harada and Y. Hirabayashi, Nucl. Phys. A **767**, 206 (2006).
[24] E. Friedman and A. Gal, Phys. Rep. **452**, 89 (2007).
[25] J. Schaffner-Bielich and A. Gal, Phys. Rev. C **62**, 034311 (2000).
[26] N. K. Glendenning and S. A. Moszkowski, Phys. Rev. Lett. **67**, 2414 (1991).
[27] X. F. Zhao, Astrophys. Space Sci. **332**, 139 (2011).