# CAN THE MASSIVE NEUTRON STAR PSR J0348+0432 BE A HYPERON STAR?

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Whether the massive neutron star PSR J0348+0432 can change into a hyperon star is studied in the framework of the relative mean-field theory by choosing the suitable hyperon coupling constants. We find that notwithstanding the mesons $\sigma^*$ and $\phi$ are considered or not, the neutron star PSR J0348+0432 can all change into a hyperon star and the hyperon star transition density are the same for the two cases. We also find that the canonical mass neutron star can also change into a hyperon star in a minor hyperon star transition density as the mesons $\sigma^*$ and $\phi$ are not considered. Our results confirm some of recent conclusions.

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## 1. Introduction

When the neutron chemical potential exceeds a certain mass of hyperon, the neutron will be converted to the hyperon. These situations can occur frequently within the neutron stars. In the neutron star, the chemical potentials of the neutrons will increase with the increase of the baryon number density. Once they exceed the mass of a hyperon, the hyperon would be produced. In the inner region of the neutron star, the baryon number density is so high that the chemical potentials of the neutrons would be greater than the masses of multiple hyperons, such as $\Lambda$, $\Sigma$ and $\Xi$ *etc.* As soon as the hyperons are produced, we can think the neutron star has changed into a hyperon star [1].

The critical baryon number density, at which the hyperons are produced, is known as the transition density of a hyperon star.

In 2010, a massive neutron star PSR J1614-2230 with the mass of $1.97^{+0.04}_{-0.04}\ M_\odot$ was observed by Demorest *et al.* [2]. Recently, its mass was determined to be $1.928^{+0.017}_{-0.017}$ (68.3% credibility) [3].

Up to now, the massive neutron stars have been widely studied in various models, such as the massive hadronic neutron stars [4–10], the quark–hadron hybrid stars [11–13], the hadronic stars within other approximations such as Brueckner–Hartree–Fock [14–16].

The recently observed massive neutron star PSR J0348+0432 with the mass of $2.01 \pm 0.04\ M_{\odot}$ [17] has aroused great interest. For us, the most interesting is the conversion from neutrons to hyperons inside the neutron star, and furthermore, if the massive neutron star PSR J0348+0432 can change into a hyperon star. Solving this problem can give us information on the structure inside the massive neutron star.

In the calculations of the neutron star with the relativistic mean-field (RMF) approximation [18, 19], there are two kinds of parameters that should be determined.

The first one is the nucleon coupling constant. The results show that the GL85 set can better describe the properties of the neutron stars [1, 4, 20].

The another one is the hyperon coupling constant. For this kind of parameters, the hyperon coupling constants to the vector mesons can be fixed by the quark constituent SU(6) symmetry, whereas the coupling to the scalar mesons $\sigma$ by fitting to the $\Lambda, \Sigma$ and $\Xi$ depth of the potential well of the saturation point of nuclear matter.

The above model considers only the interactions between the nucleon–nucleon ($NN$) and the hyperon–nucleon ($YN$) which are described by the mesons $\sigma$, $\omega$ and $\rho$. We name it the $\sigma\omega\rho$ model.

To finely describe the interaction between the hyperon–hyperon ($YY$), the mesons $f_0(975)$ (denoted as $\sigma^*$) and $\phi(1020)$ (denoted as $\phi$), which only interact between hyperons, should be considered [21]. This is named the $\sigma\omega\sigma^*\phi\rho$ model.

In this paper, we study whether the massive neutron star PSR J0348+0432 can change into a hyperon star in the framework of the RMF theory with the above two models.

## 2. The RMF theory and the mass of the massive neutron star PSR J0348+0432

We start from the Lagrangian density of hadron matter containing mesons $\sigma^*$ and $\phi$ [21, 22]

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

$$+\sum_{\lambda=e,\mu}\overline{\Psi}_\lambda\left(i\gamma_\mu\partial^\mu-m_\lambda\right)\Psi_\lambda$$
$$+\mathcal{L}^{YY}\,. \tag{1}$$

The last term representing the contribution of the mesons $\sigma^*$ and $\phi$ reads

$$\begin{aligned}\mathcal{L}^{YY} &= \sum_B g_{\sigma^* B}\overline{\Psi}_B\Psi_B\sigma^* - \sum_B g_{\phi B}\overline{\Psi}_B\gamma_\mu\Psi_B\phi^\mu \\ &\quad +\tfrac{1}{2}\left(\partial_\mu\sigma^*\partial^\mu\sigma^*-m_{\sigma^*}\sigma^{*2}\right)-\tfrac{1}{4}S_{\mu\nu}S^{\mu\nu}+\tfrac{1}{2}m_\phi^2\phi_\mu\phi^\mu\,. \end{aligned}\tag{2}$$

Here, $S_{\mu\nu}=\partial_\mu\phi_\nu-\partial_\nu\phi_\mu$. Then the RMF approximation is used [22].

The condition of $\beta$ equilibrium in neutron star matter demands the chemical equilibrium

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

where $b_i$ is the baryon number of a species $i$.

In this work, we choose the nucleon coupling constant GL85 set [1]: the saturation density $\rho_0=0.145$ fm$^{-3}$, binding energy $B/A=15.95$ MeV, a compression modulus $K=285$ MeV, charge symmetry coefficient $a_{\rm sym}=36.8$ MeV and the effective mass $m^*/m=0.77$.

For the hyperon coupling constant, we define the ratios: $x_{\sigma h}=\frac{g_{\sigma h}}{g_{\sigma n}}$, $x_{\omega h}=\frac{g_{\omega h}}{g_{\omega n}}$ and $x_{\rho h}=\frac{g_{\rho h}}{g_{\rho n}}$. Here, $h$ denotes hyperons $\Lambda,\Sigma$ and $\Xi$ and $n$ nucleons.

We choose $x_{\rho\Lambda}=0, x_{\rho\Sigma}=2, x_{\rho\Xi}=1$ by quark constituent SU(6) symmetry [23, 24]. The ratio of hyperon coupling constant to nucleon coupling constant is determined in the range of $\sim 1/3$ to 1 [20]. So we choose $x_{\sigma\Lambda}=0.4$, 0.5, 0.6, 0.7, 0.8, 0.9,1.0. For each $x_{\sigma\Lambda}$, the $x_{\omega\Lambda}$ should fit to the hyperon well depth [22]

$$U_h^{(N)}=m_n\left(\frac{m_n^*}{m_n}-1\right)x_{\sigma h}+\left(\frac{g_{\omega n}}{m_\omega}\right)^2\rho_0x_{\omega h}\,. \tag{4}$$

Similarly, we also choose $x_{\sigma\Sigma},x_{\sigma\Xi}=0.4$, 0.5, 0.6, 0.7, 0.8, 0.9,1.0 and for each $x_{\sigma\Sigma},x_{\sigma\Xi}$, we choose $x_{\omega\Sigma},x_{\omega\Xi}$ to fit to the hyperon well depth.

The experiments show $U_\Lambda^{(N)}=-30$ MeV [25], $U_\Sigma^{(N)}=10\sim40$ MeV [26–29] and $U_\Xi^{(N)}=-28$ MeV [30]. Then we can choose $U_\Lambda^{(N)}=-30$ MeV, $U_\Sigma^{(N)}=+40$ MeV and $U_\Xi^{(N)}=-28$ MeV.

The parameters that fit to the experimental data of the hyperon well depth are listed in Table I.

TABLE I

The hyperon coupling constants fitting 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, respectively. As the positive $U_{\Sigma}^{(N)}$ will restrict the production of the hyperon $\Sigma$, we can choose only $x_{\sigma\Sigma} = 0.4$ and $x_{\omega\Sigma} = 0.825$, while $x_{\sigma\Sigma} = 0.5$ and $x_{\omega\Sigma}$=0.9660 can be deleted.

| $x_{\sigma\Lambda}$ | $x_{\omega\Lambda}$ | $U_{\Lambda}^{(N)}$ | $x_{\sigma\Sigma}$ | $x_{\omega\Sigma}$ | $U_{\Sigma}^{(N)}$ | $x_{\sigma\Xi}$ | $x_{\omega\Xi}$ | $U_{\Xi}^{(N)}$ |
|---|---|---|---|---|---|---|---|---|
| 0.4 | 0.3679 | −30.0300 | 0.4 | 0.8250 | 40.0005 | 0.4 | 0.3811 | −28.0041 |
| 0.5 | 0.5090 | −30.0100 | $\underline{0.5}$ | $\underline{0.9660}$ | 40.0044 | 0.5 | 0.5221 | −28.0002 |
| 0.6 | 0.6500 | −30.0032 | | | | 0.6 | 0.6630 | −28.0116 |
| 0.7 | 0.7909 | −30.0146 | | | | 0.7 | 0.8040 | −28.0076 |
| 0.8 | 0.9319 | −30.0106 | | | | 0.8 | 0.9450 | −28.0037 |

From the parameters listed in Table I, we can make up 25 sets of suitable parameters (named as NO.01, NO.02, ..., NO.25, respectively), for each set we calculate the mass of the neutron star by the Oppenheimer–Volkoff (OV) equation [22]

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

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

Figure 1 shows the neutron star mass as a function of the radius without considering the contribution of the mesons $\sigma^*$ and $\phi$. We see only the parameters NO.24 ($x_{\sigma\Lambda} = 0.8, x_{\omega\Lambda} = 0.9319$; $x_{\sigma\Sigma} = 0.4, x_{\omega\Sigma} = 0.825$; $x_{\sigma\Xi} = 0.7, x_{\omega\Xi} = 0.804$, the maximum mass calculated is $M_{\max} = 2.0132\ M_{\odot}$) and NO.25 ($x_{\sigma\Lambda} = 0.8, x_{\omega\Lambda} = 0.9319$; $x_{\sigma\Sigma} = 0.4, x_{\omega\Sigma} = 0.825$; $x_{\sigma\Xi} = 0.8, x_{\omega\Xi} = 0.945$, the maximum mass calculated is $M_{\max} = 2.0572\ M_{\odot}$) can give the mass greater than that of the massive neutron star PSR J0348+0432 (2.01 $M_{\odot}$). Since the mass corresponding to NO.24 is closer to the mass 2.01 $M_{\odot}$, we have fine tuning parameters from $x_{\sigma\Xi} = 0.7$ to 0.69, 0.695, 0.6946, respectively, and the $x_{\omega\Xi}$ obtained by fitting to the hyperon well depth. Thus, we get one set of parameters ($x_{\sigma\Lambda} = 0.8, x_{\omega\Lambda} = 0.9319$; $x_{\sigma\Sigma} = 0.4, x_{\omega\Sigma} = 0.825$; $x_{\sigma\Xi} = 0.6946, x_{\omega\Xi} = 0.7964$) corresponding to the mass of the massive neutron star PSR J0348+0432 (2.01 $M_{\odot}$). In the next step, we use this set of parameters to study whether the massive neutron star PSR J0348+0432 can change into a hyperon star.

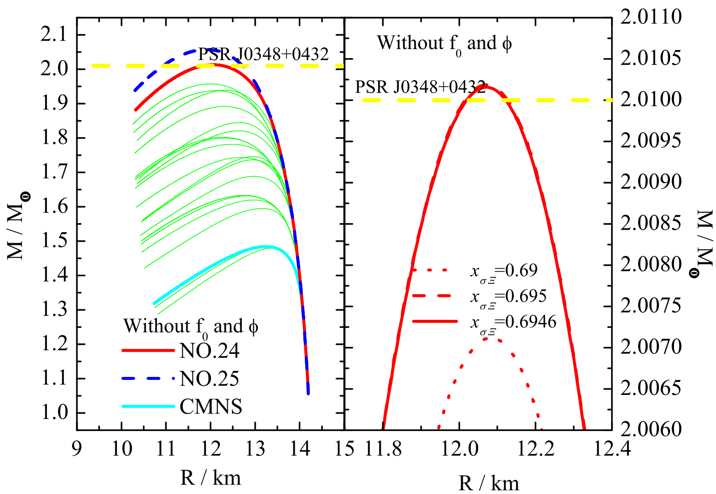


Fig. 1. The mass as a function of the radius of the neutron star. Here, the mesons $\sigma^*$ and $\phi$ are not considered.

## 3. The massive neutron star PSR J0348+0432 can be a hyperon star without considering the mesons $\sigma^*$ and $\phi$

The hyperon star transition density $\rho_{\rm t}$ of a neutron star is defined as the baryon number density at which the hyperons are produced.

The chemical potentials of the nucleons as a function of the baryon number density is given in Fig. 2. The baryon number density is in units of the density of ordinary nuclear matter $\rho_0 = 0.145\ \mathrm{fm}^{-3}$.

We see the chemical potentials of the nucleons increase with the increase of the baryon number density. As the chemical potentials of the nucleons exceed the mass of the $\Lambda$, *i.e.* 1116 MeV, the $\Lambda$s are produced. Afterwards, as the nucleons's chemical potentials exceed the mass of the $\Xi$, *i.e.* 1313 MeV, the $\Xi$s are produced. As the positive $U_{\Sigma}^{(N)}$ restricts the production of the hyperon $\Sigma$, even the nucleons's chemical potentials exceed the mass of the $\Sigma$, *i.e.* 1193 MeV, and the $\Sigma$ would not appear. We can also see that the central baryon number density is $\rho_{\rm c} = 6.3142\ \rho_0$ and within the neutron star, the hyperons $\Lambda$ and $\Xi$ all will be produced.

So, within the neutron star PSR J0348+0432, with the increase of the baryon number density more and more nucleons will decay to hyperons $\Lambda$ and $\Xi$. At the center of the neutron star, the relative number density of the hyperons will arrive at its maximum value and that of the neutrons will arrive at its minimum value.

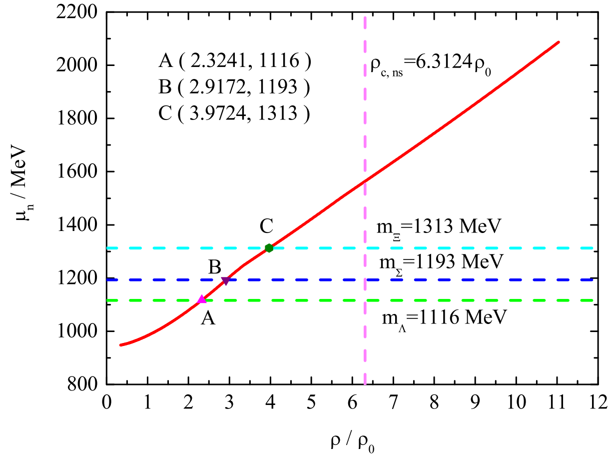


Fig. 2. The chemical potentials of the nucleons as a function of the baryon number density. The mesons $\sigma^*$ and $\phi$ are not considered.

Figure 3 displays the relative particle number density of $n$, $p$, $\Lambda$, $\Xi^-$ and $\Xi^0$ as a function of the baryon number density. We see that the firstly generated hyperon is $\Lambda$, which will be produced as $\rho \geq 3.041\ \rho_0$ (at which the relative number density of $\Lambda$ is $\rho_\Lambda/\rho = 0.001358\%$). So the massive neutron star PSR J0348+0432 can be a hyperon star in this case. The hyperon star transition density of the neutron star is $\rho_{\mathrm{t,s}} = 3.041\ \rho_0$ as the mesons $\sigma^*$ and $\phi$ are not considered.

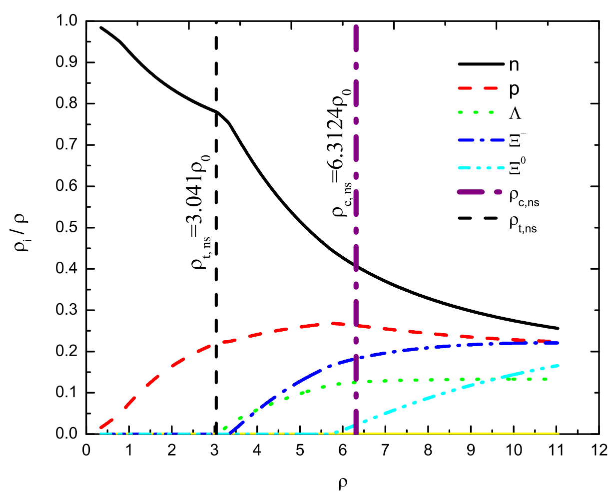


Fig. 3. The relative number density as a function of the baryon number density. Here, the mesons $\sigma^*$ and $\phi$ are not considered.

## 4. The massive neutron star PSR J0348+0432 also can be a hyperon star with the mesons $\sigma^*$ and $\phi$ being considered

Adopting the similar steps as above, we can obtain a model of the massive neutron star PSR J0348+0432 with the mesons $\sigma^*$ and $\phi$ being considered: $x_{\sigma\Lambda} = 0.8, x_{\omega\Lambda} = 0.9319$; $x_{\sigma\Sigma} = 0.4, x_{\omega\Sigma} = 0.825$; $x_{\sigma\Xi} = 0.7447, x_{\omega\Xi} = 0.8671$. This case can be seen in Fig. 4.

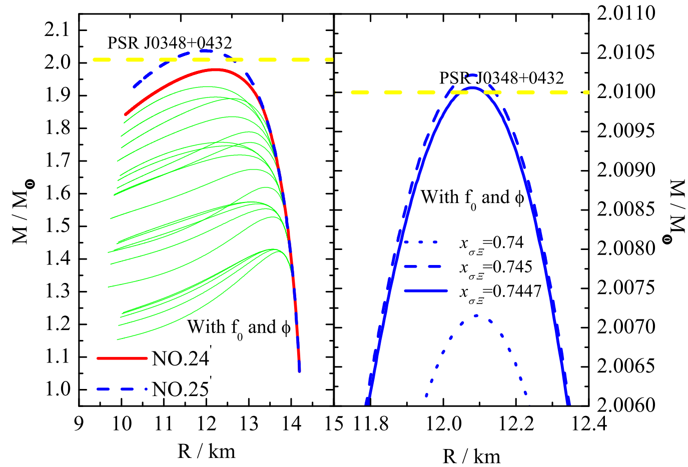


Fig. 4. The mass as a function of the radius of the neutron star. In this case, the mesons $\sigma^*$ and $\phi$ are considered.

Figure 5 gives the chemical potentials of the nucleons as a function of the baryon number density. The dashed raising/blue curve includes the mesons $\sigma^*$ and $\phi$, and the solid raising/red curve does not consider them. We see that the chemical potentials of the nucleons without considering the mesons $\sigma^*$ and $\phi$ are almost the same as that with considering them since the baryon number density is less than the central one $\rho < \rho_{\mathrm{c,ns}} \approx \rho_{\mathrm{c,s}}$. Thus, the hyperons $\Lambda$s and $\Xi$s would be also produced with the increase of the baryon number density. From the above reasoning, one can conclude that the hyperon $\Sigma$ also cannot appear.

The relative particle number density as a function of the baryon number density with and without considering the mesons $\sigma^*$ and $\phi$ are shown in Fig. 6. We see, considering the contribution of the mesons $\sigma^*$ and $\phi$, the hyperon $\Lambda$ is produced as $\rho = 3.041\ \rho_0$, at which the relative number density of $\Lambda$ is $\rho_\Lambda/\rho = 0.001374\%$. That is to say, with the $\sigma^*$ and $\phi$ mesons present, the massive neutron star PSR J0348+0432 can also be a hyperon star. The hyperon star transition density of the neutron star is also $\rho_{\mathrm{t,ns}} = 3.041\ \rho_0$ if the mesons $\sigma^*$ and $\phi$ are considered.

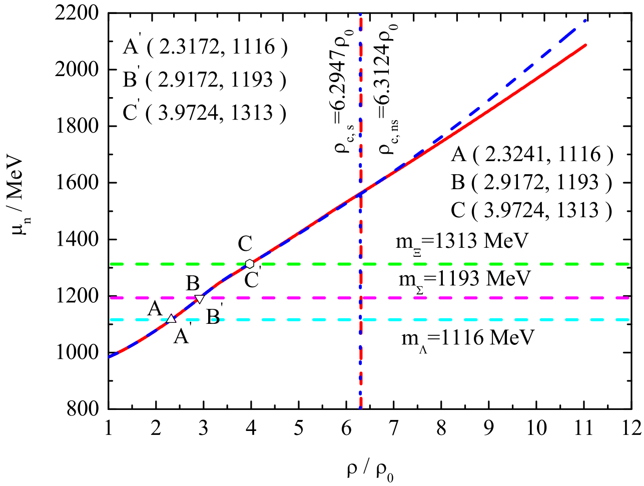


Fig. 5. (Color online) The chemical potentials of the nucleons as a function of the baryon number density. The dashed raising/blue curve includes the mesons $\sigma^*$ and $\phi$ and the solid raising/red curve does not consider them.

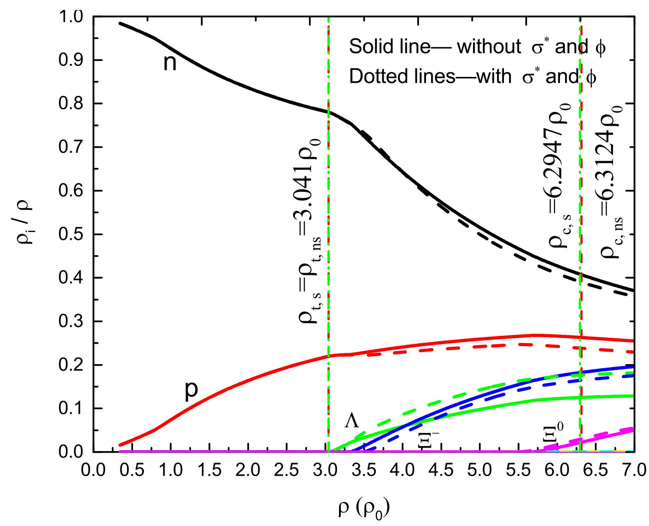


Fig. 6. (Color online) The relative number density as a function of the baryon number density. Here, the dashed lines include the mesons $\sigma^*$ and $\phi$, while the solid lines do not include them.

## 5. The canonical mass neutron star also can be a hyperon star with the mesons $\sigma^*$ and $\phi$ not being considered

In our calculations, without considering the mesons $\sigma^*$ and $\phi$, the parameters $x_{\sigma\Lambda} = 0.4, x_{\omega\Lambda} = 0.3679$; $x_{\sigma\Sigma} = 0.4, x_{\omega\Sigma} = 0.825$; $x_{\sigma\Xi} = 0.8, x_{\omega\Xi} = 0.9450$ give a model of a canonical mass neutron star (denoted as CMNS, of the mass obtained by us is $M = 1.4843\ M_\odot$, see Fig. 1). Figure 7 shows the hyperon star transition density of the CMNS with the mesons $\sigma^*$ and $\phi$ not being considered. We can see that the central baryon density of the CMNS is $\rho_c = 4.8\ \rho_0$. As the baryon number density is $\rho = 2.1586\ \rho_0$, the $\Lambda$s begin to be produced (though its relative number density is very small: only $\rho_\Lambda/\rho = 0.00793\%$). This means the CMNS can be a hyperon star and the hyperon star transition density of the CMNS is $\rho_t = 2.1586\ \rho_0$.

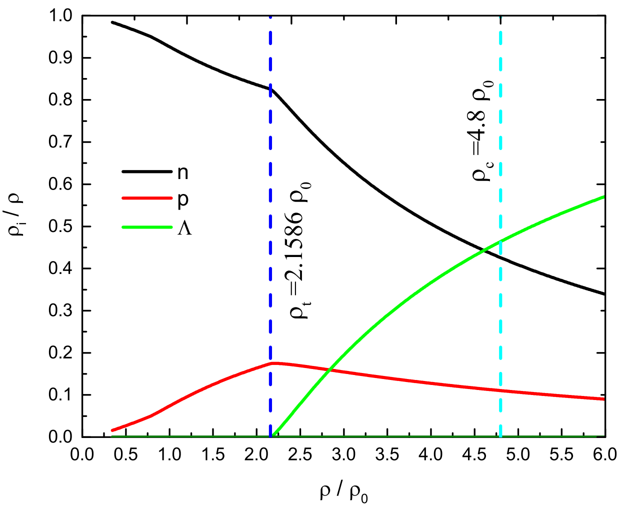


Fig. 7. The hyperon star transition density of the canonical mass neutron star with the mesons $\sigma^*$ and $\phi$ not being considered.

## 6. Summary

In this paper, it is studied in the framework of the RMF theory by choosing the suitable hyperon coupling constants whether the massive neutron star PSR J0348+0432 can be a hyperon star. It is found that the hyperons ($\Lambda$s) will first be produced at the baryon number density $\rho = 3.041\ \rho_0$ as the mesons $\sigma^*$ and $\phi$ are not considered. So the massive neutron star PSR J0348+0432 can be a hyperon star.When the mesons $\sigma^*$ and $\phi$ are considered, the first kind of hyperons ($\Lambda$s) can also be produced at the baryon number density $\rho = 3.041\ \rho_0$. Therefore, if the mesons $\sigma^*$ and $\phi$ are considered, the massive neutron star PSR J0348+0432 can also be a hyperon star. For the two cases, the hyperon star transition density of the neutron star is the same. For the CMNS, as the baryon number density is $\rho = 2.1586\ \rho_0$, the first kind of hyperons ($\Lambda$s) are produced with the mesons $\sigma^*$ and $\phi$ not being considered. Then the hyperon star transition density of the CMNS is $\rho_{\mathrm{t}} = 2.1548\ \rho_0$, which is smaller than that of the massive neutron star PSR J0348+0432.

In order to reconcile the existence of massive neutron stars as the massive neutron star PSR J0348+0432 with the softening of hyperon equations of state due to the increasing number of degrees of freedom, we choose the larger coupling constants $x_{\omega h}$, which can provide a larger repulsion force. On this subject, a lot of works have been done over the last years. Our results confirm the conclusions obtained by Bednarek *et al.* [5], Kolomeitsev *et al.* [31], Dexheimer *et al.* [32] and Weissenborn *et al.* [33].

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