On the moment of inertia of PSR J0348+0432

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The moment of inertia of the massive neutron star PSR J0348+0432 is studied in the framework of the relativistic mean field theory by choosing suitable hyperon coupling constants. By this method, we find that the suggested radius of the massive neutron star PSR J0348+0432 is in the range $R = 12.957 \sim 12.246$ km by the observation $M = 1.97 \sim 2.05 \, M_\odot$. We also find that the suggested moment of inertia $I$ of the massive neutron star PSR J0348+0432 is in the range $I = 1.9073 \times 10^{45} \sim 1.5940 \times 10^{45}$ g cm$^2$ by the observation $M = 1.97 \sim 2.05 \, M_\odot$. Massive pulsars hint that the interaction inside them should be very "strong". Though hyperons considered will reduce the maximum mass, but in principle we may have models predicting maximum masses higher than $2 \, M_\odot$ by choosing suitable parameters, in a degree of freedom of hadron. Our calculations have proved the above and perfectly agree with the results both of Aaron W et al and Ptri J et al.

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1. Introduction

In 2013, Antoniadis et al observed the massive neutron star PSR J0348+0432, which is a $2.01 \pm 0.04 \, M_\odot$ pulsar and spins at 39 ms in a 2.46-hour orbit with a $0.172 \pm 0.003 \, M_\odot$ white dwarf. It has highly rotating speed and may be the largest mass neutron star by now. So, how to theoretically describe its mass and its rotational property, e.g. moment of inertia, would be a very important work for astrophysics.

Overgard et al examined three models of astrophysical quark matter in 1991. Assuming the validity of Einstein’s theory of gravitation, they calculated the total mass, radius, and moment of inertia for quark stars. An approximation for the moment of inertia of a neutron star, in terms of only its mass and radius, is presented by Bao G et al in 1994, and insight into it is obtained by examining the behavior of the relativistic structural equations.
In 2000, Kalogera V et al calculate new optimal bounds on the masses, radii, and moments of inertia of slowly rotating neutron stars that show kilohertz quasi-periodic oscillations (QPOs) \cite{4}. Considering the limits derived for the Crab pulsar, moments of inertia for neutron and strange stars were studied by Bejger M et al in 2002 \cite{5}. Lattimer J M et al and Bejger M et al in 2005 \cite{5,6} and Morrison I A et al in 2014 \cite{7} estimated the constraint on the equation of state with the moment of inertia measurements of the neutron star PSR J0737-3039A.

Wen D H et al calculated the frame dragging effect on moment of inertia and radius of gyration of neutron star in 2007 \cite{9}. In 2008, Aaron W et al studied the nuclear constraints on the momenta of inertia of neutron stars \cite{10}. In 2010, Yunes N et al’s results show that the Chern-Simons correction affects only the gravitomagnetic sector of the metric to leading order, thus introducing modifications to the moment-of-inertia but not to the mass-radius relation \cite{11}. Sensitivity of the moment of inertia of neutron stars to the equation of state of neutron-rich matter was examined using accurately calibrated relativistic mean-field models by Fatoyev F J et al in 2010 \cite{12}.

Constraining the mass and moment of inertia of neutron stars from quasi-periodic oscillations in X-ray binaries was examined by Ptri J in 2011 \cite{13}. In 2015, crust thicknesses, moments of inertia and tidal deformabilities was determined by Steiner A W et al with neutron star observations \cite{14}.

Studies have shown that the mass of a neutron star is very sensitive to the nucleon coupling constants and the hyperon coupling constants \cite{15,16} and the ratio of hyperon coupling constant to nucleon coupling constant is determined in the range of $\sim 1/3$ to 1 \cite{16}.

Hartle et al derived the equations of the moment of inertia of a slowly rotating neutron star from the general relativistic theory in 1967 \cite{17} and they calculated the equilibrium structure of rotating white dwarfs and neutron stars in 1968 \cite{18}. In the last few years, although many works have been done on the moment of inertia of neutron stars \cite{19,20,21}, none of them are on the massive neutron star PSR J0348+0432.

In this paper, the relativistic mean field (RMF) theory, which can better describe limited nuclear matter \cite{22,23}, is applied to describe the moment of inertia of the massive neutron star PSR J0348+0432 by choosing the suitable hyperon coupling constants.

2. The RMF theory and the mass of a neutron star

The Lagrangian density of hadron matter reads as follows \cite{24}
\[
\mathcal{L} = \sum_B \overline{\Psi}_B (i\gamma_\mu \partial^\mu - m_B + g_{\sigma B} \sigma - g_{\omega B} \gamma_\mu \omega^\mu \\
- \frac{1}{2} g_{\rho B} \tau \cdot \rho^\mu) \Psi_B + \frac{1}{2} \left( \partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2 \right) \\
- \frac{1}{4} \omega_{\mu \nu} \omega^{\mu \nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - \frac{1}{4} \rho_{\mu \nu} \cdot \rho^{\mu \nu} + \frac{1}{2} m_\rho^2 \rho_\mu \cdot \rho^\mu \\
- \frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4 + \sum_{\lambda=e,\mu} \overline{\Psi}_\lambda (i\gamma_\mu \partial^\mu - m_\lambda) \Psi_\lambda.
\]

Here, \(\Psi_B\) is the Dirac spinor of the baryon \(B\), whose mass is \(m_B\). \(\sigma, \omega\) and \(\rho\) are the field operators of the \(\sigma, \omega\) and \(\rho\) mesons, respectively. \(m_\sigma, m_\omega\) and \(m_\rho\) are the masses of these mesons and \(m_\lambda\) expresses the leptonic mass. \(g_{\sigma B}, g_{\omega B}\) and \(g_{\rho B}\) are, respectively, the coupling constants of the \(\sigma, \omega\) and \(\rho\) mesons with the baryon \(B\). \(\frac{1}{3} g_2 \sigma^3 + \frac{1}{4} g_3 \sigma^4\) expresses the self-interactive energy, in which \(g_2\) and \(g_3\) are the self-interaction parameters of \(\sigma\)-meson. And the last term expresses the Lagrangian of both electron and muon.

The energy density \(\varepsilon\), pressure \(p\), mass \(M\), radius \(R\) and the moment of inertia \(I\) of a neutron star can be seen in Ref. [24].

### 3. Parameters

The GL85 nucleon coupling constant can better describe the properties of neutron stars and so we choose it in this work: the saturation density \(\rho_0 = 0.145 \text{ fm}^{-3}\), binding energy \(B/A = 15.95 \text{ MeV}\), a compression modulus \(K = 285 \text{ MeV}\), charge symmetry coefficient \(a_{\text{sym}} = 36.8 \text{ MeV}\) and the effective mass \(m^*/m = 0.77\) [1].

For the hyperon coupling constant, we define the ratios: \(x_{\sigma h} = \frac{g_{\sigma h}}{g_\sigma} = x_\sigma, \quad x_{\omega h} = \frac{g_{\omega h}}{g_\omega} = x_\omega, \quad x_{\rho h} = \frac{g_{\rho h}}{g_\rho}\). Here, \(h\) denoting hyperons \(\Lambda, \Sigma\) and \(\Xi\).

We choose \(x_{\rho \Lambda} = 0, x_{\rho \Sigma} = 2, x_{\rho \Xi} = 1\) according to SU(6) symmetry at first [25].

For the parameters \(x_{\sigma h}\), we choose \(x_{\sigma h} = 0.4, 0.5, 0.6, 0.7, 0.8, 0.9\) at first (\(h\) denotes hyperons \(\Lambda, \Sigma\) and \(\Xi\), respectively) [16]. For each \(x_{\sigma h}\), the \(x_{\omega h}\) is chosen to fit to the hyperon well depth [24]

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

The experimental data of the well depth are \(U_\Lambda^{(N)} = -30 \text{ MeV}\) [20], \(U_\Sigma^{(N)} = 10 \sim 40 \text{ MeV}\) [27, 28, 29, 30, 31] and \(U_\Xi^{(N)} = -28 \text{ MeV}\) [32]. Therefore, in
this work we choose $U_{\Lambda}^{(N)} = -30$ MeV, $U_{\Sigma}^{(N)} = +40$ MeV and $U_{\Xi}^{(N)} = -28$ MeV.

For $x_{\sigma\Lambda}=0.9$, we get $x_{\omega\Lambda}=1.0729$, which is greater than 1 and is deleted. So we only 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 (see Table 1).

As $x_{\sigma\Sigma}=0.6, 0.7, 0.8, 0.9$, $x_{\omega\Sigma}$ all will be greater than 1 (e.g. $x_{\sigma\Sigma}=0.6$, $x_{\omega\Sigma}=1.1069$). Thus, we can only choose $x_{\sigma\Sigma}=0.4, 0.5$, correspondingly we obtain $x_{\omega\Sigma}=0.3679, 0.5221$. For the positive $U_{\Sigma}^{(N)}$ restricting the production of the hyperon $\Sigma$, so in this work 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 1).

For $x_{\sigma\Xi}$, we first choose $x_{\sigma\Xi}=0.4, 0.5, 0.6, 0.7, 0.8, 0.9$. Through fitting to the hyperon well depth, we obtain $x_{\omega\Xi}=0.3811, 0.5221, 0.6630, 0.8040, 0.9450, 1.0860$, respectively. Obviously, $x_{\sigma\Xi}=0.9$ and $x_{\omega\Xi}=1.0860$ should be deleted. Thus, the parameters that can be chosen are listed in Table 1.

Table 1. 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.

| $x_{\sigma\Lambda}$ | $x_{\omega\Lambda}$ | $x_{\sigma\Sigma}$ | $x_{\omega\Sigma}$ | $x_{\sigma\Xi}$ | $x_{\omega\Xi}$ |
|-------------------|--------------------|-------------------|-------------------|----------------|----------------|
| 0.4               | 0.3679             | 0.4               | 0.8250            | 0.4            | 0.3811         |
| 0.5               | 0.5090             | 0.5               | 0.9660            | 0.5            | 0.5221         |
| 0.6               | 0.6500             |                  | 0.6               | 0.6630         |
| 0.7               | 0.7909             |                  | 0.7               | 0.8040         |
| 0.8               | 0.9319             |                  | 0.8               | 0.9450         |

From the parameters chosen above, we can compose of 25 sets of suitable parameters (named as NO.1-25) (see Table 2).

For every set of parameters we calculate the mass of the neutron star. Only parameters NO.24 ($x_{\sigma\Lambda}=0.8, x_{\omega\Lambda}=0.9319$; $x_{\sigma\Sigma}=0.4, x_{\omega\Sigma}=0.825$; $x_{\sigma\Xi}=0.7, x_{\omega\Xi}=0.804$. $M_{\text{max}}=2.0132 \, M_\odot$) and NO.25 ($x_{\sigma\Lambda}=0.8, x_{\omega\Lambda}=0.9319$; $x_{\sigma\Sigma}=0.4, x_{\omega\Sigma}=0.825$; $x_{\sigma\Xi}=0.8, x_{\omega\Xi}=0.945$. $M_{\text{max}}=2.0572 \, M_\odot$) can give the mass greater than that of the massive neutron star PSR J0348+0432 (see Fig. 1). Next, we use parameters NO.25 to describe the properties of the neutron star PSR J0348+0432.

Considering the SU(6) symmetry [23] and choosing $U_{\Lambda}^{(N)} = -30$ MeV, $U_{\Sigma}^{(N)} = +40$ MeV and $U_{\Xi}^{(N)} = -28$ MeV, the hyperon coupling constants obtained are $x_{\sigma\Lambda}=0.6118, x_{\omega\Lambda}=0.6667$; $x_{\sigma\Sigma}=0.2877, x_{\omega\Sigma}=0.6667$; $x_{\sigma\Xi}=0.6026, x_{\omega\Xi}=0.3333$. In this case, the maximum mass of the neutron star calculated are only $M_{\text{max}}=1.3374 \, M_\odot$, which is far less than that of
Table 2. The 25 sets of hyperon coupling constants used in this work.

| NO. | $x_{\sigma\Lambda}$ | $x_{\omega\Lambda}$ | $x_{\sigma\Sigma}$ | $x_{\omega\Sigma}$ | $x_{\sigma\Xi}$ | $x_{\omega\Xi}$ |
|-----|---------------------|---------------------|---------------------|---------------------|-----------------|-----------------|
| 01  | 0.4                 | 0.3679              | 0.4                 | 0.8250              | 0.4             | 0.3811          |
| 02  | 0.4                 | 0.3679              | 0.4                 | 0.8250              | 0.5             | 0.5221          |
| 03  | 0.4                 | 0.3679              | 0.4                 | 0.8250              | 0.6             | 0.6630          |
| 04  | 0.4                 | 0.3679              | 0.4                 | 0.8250              | 0.7             | 0.8040          |
| 05  | 0.4                 | 0.3679              | 0.4                 | 0.8250              | 0.8             | 0.9450          |
| 06  | 0.5                 | 0.5090              | 0.4                 | 0.8250              | 0.4             | 0.3811          |
| 07  | 0.5                 | 0.5090              | 0.4                 | 0.8250              | 0.5             | 0.5221          |
| 08  | 0.5                 | 0.5090              | 0.4                 | 0.8250              | 0.6             | 0.6630          |
| 09  | 0.5                 | 0.5090              | 0.4                 | 0.8250              | 0.7             | 0.8040          |
| 10  | 0.5                 | 0.5090              | 0.4                 | 0.8250              | 0.8             | 0.9450          |
| 11  | 0.6                 | 0.6500              | 0.4                 | 0.8250              | 0.4             | 0.3811          |
| 12  | 0.6                 | 0.6500              | 0.4                 | 0.8250              | 0.5             | 0.5221          |
| 13  | 0.6                 | 0.6500              | 0.4                 | 0.8250              | 0.6             | 0.6630          |
| 14  | 0.6                 | 0.6500              | 0.4                 | 0.8250              | 0.7             | 0.8040          |
| 15  | 0.6                 | 0.6500              | 0.4                 | 0.8250              | 0.8             | 0.9450          |
| 16  | 0.7                 | 0.7909              | 0.4                 | 0.8250              | 0.4             | 0.3811          |
| 17  | 0.7                 | 0.7909              | 0.4                 | 0.8250              | 0.5             | 0.5221          |
| 18  | 0.7                 | 0.7909              | 0.4                 | 0.8250              | 0.6             | 0.6630          |
| 19  | 0.7                 | 0.7909              | 0.4                 | 0.8250              | 0.7             | 0.8040          |
| 20  | 0.7                 | 0.7909              | 0.4                 | 0.8250              | 0.8             | 0.9450          |
| 21  | 0.8                 | 0.9319              | 0.4                 | 0.8250              | 0.4             | 0.3811          |
| 22  | 0.8                 | 0.9319              | 0.4                 | 0.8250              | 0.5             | 0.5221          |
| 23  | 0.8                 | 0.9319              | 0.4                 | 0.8250              | 0.6             | 0.6630          |
| 24  | 0.8                 | 0.9319              | 0.4                 | 0.8250              | 0.7             | 0.8040          |
| 25  | 0.8                 | 0.9319              | 0.4                 | 0.8250              | 0.8             | 0.9450          |

the massive neutron star PSR J0348+0432. In order to obtain the larger neutron star mass, we have to broke the SU(6) symmetry and choose parameters NO.25 to describe the neutron star PSR J0348+0432.

4. The radius of the massive neutron star PSR J0348+0432

Fig. 2 gives the radius of the neutron star as a function of the mass. We see the radius of the massive neutron star PSR J0348+0432 is $R = 12.957$ km as the mass $M=1.97\, M_\odot$ and is $R = 12.246$ km as the mass $M=2.05\, M_\odot$. That is to say, the suggested radius of the massive neutron star PSR J0348+0432 is in the range $R = 12.957 \sim 12.246$ km by the observation
Fig. 1. The mass $M$ of the neutron stars as a function of the central energy density $\varepsilon_c$.

$M=1.97 \sim 2.05 \, M_\odot$. This result also can be seen in Table 3.

We also see from Fig. 2 that the central energy density of the massive neutron star PSR J0348+0432 is $\varepsilon_c = 1.2601 \times 10^{15} \, \text{g.cm}^{-3}$ corresponding to the mass $M=1.97 \, M_\odot$ and is $\varepsilon_c = 1.7774 \times 10^{15} \, \text{g.cm}^{-3}$ to the mass $M=2.05 \, M_\odot$, namely, the suggested central energy density of the massive neutron star PSR J0348+0432 is in the range $\varepsilon_c = 1.2601 \times 10^{15} \sim 1.7774 \times 10^{15} \, \text{g.cm}^{-3}$ by the observation $M=1.97 \sim 2.05 \, M_\odot$ (see Table 3).

Fig. 2. The radius $R$ of the neutron star as a function of the mass.
Table 3. The mass \( M \), radius \( R \) and the moment of inertia \( I \) of the massive neutron star PSR J0348+0432.

| \( M \) (\( \odot \)) | \( \varepsilon_c \) \( \times 10^{15} \text{ g/cm}^3 \) | \( R \) (km) | \( I \) \( \times 10^{45} \text{ g cm}^2 \) |
|----------------|-------------------|--------|------------------|
| 1.97           | 1.2601            | 12.957 | 1.9073           |
| 2.05           | 1.7774            | 12.246 | 1.5940           |

5. The moment of inertia of the massive neutron star PSR J0348+0432

The moment of inertia \( I \) of the neutron star as a function of the mass is given in Fig. 3 from which we can see that the moment of inertia \( I \) decreases with the increase of the mass \( M \).

We also see the moment of inertia \( I \) of the massive neutron star PSR J0348+0432 is \( I = 1.9073 \times 10^{45} \text{ g cm}^2 \) corresponding to the mass \( M = 1.97 \odot \) and is \( I = 1.5940 \times 10^{45} \text{ g cm}^2 \) to the mass \( M = 2.05 \odot \). The suggested moment of inertia \( I \) of the massive neutron star PSR J0348+0432 is in the range \( I = 1.9073 \times 10^{45} \sim 1.5940 \times 10^{45} \text{ g cm}^2 \) by the observation \( M = 1.97 \sim 2.05 \odot \).

![Fig. 3. The moment of inertia \( I \) of the neutron star as a function of the mass \( M \).](image)

Obviously, other sets of parameters (for example, NO.24) also can be got considering the constraints of the hyperon well depth in the nucleon matter. The coupling constants (NO.25) used in this work is only one of them.
In this paper, the moment of inertia of the massive neutron star PSR J0348+0432 is studied in the framework of the RMF theory by choosing suitable hyperon coupling constants. By fitting to the experimental data of the hyperon well depth one model of the massive neutron star PSR J0348+0432 is found. With it the moment of inertia of the massive neutron star PSR J0348+0432 is studied.

We find the suggested radius of the massive neutron star PSR J0348+0432 is in the range \( R = 12.957 \sim 12.246 \text{ km} \) and the suggested central energy density is in the range \( \varepsilon_c = 1.2601 \times 10^{15} \sim 1.7774 \times 10^{15} \text{ g.cm}^{-3} \) by the observation \( M=1.97\sim2.05 \text{ M}_\odot \). We also find that the suggested moment of inertia \( I \) of the massive neutron star PSR J0348+0432 is in the range \( I=1.9073\times10^{45} \sim 1.5940\times10^{45} \text{ g.cm}^2 \) by the observation \( M=1.97\sim2.05 \text{ M}_\odot \).

In fact, the variation of the saturation density \( \rho_0 \), binding energy \( B/A \), compression modulus \( K \), charge symmetry coefficient \( a_{\text{sym}} \) and the effective mass \( m^*/m \) will cause the fluctuation of the maximum mass in the range \( 1.97 \sim 3.4 \text{ M}_\odot \) and cause the corresponding radius in the range \( 10.3 \sim 15.2 \text{ km} \) with no hyperons included \( [34] \). On the other hand, the nucleon coupling constants \( g_\sigma \), \( g_\omega \) and \( g_\rho \) are connected with the properties of the nuclear matter. So, the variation of the nuclear matter would cause the uncertainty of the \( g_\sigma \), \( g_\omega \) and \( g_\rho \). These would further cause the uncertainty of the mass, radius and the moment of inertia. In this work, all these factors are not considered.

Massive pulsars hint that the interaction inside them should be very ”strong”. Although Hyperons considered will reduce the maximum mass \( [15] \), in principle one may have models predicting maximum masses higher than \( 2 \text{ M}_\odot \) by choosing ”suitable” parameters, in a degree of freedom of either hadron or quark.

The results of Aaron W et al show the moment of inertia is in the range of \( I=1.3\sim1.63\times10^{45} \text{ g.cm}^2 \) for the neutron star mass \( 1.338 \text{ M}_\odot \) \( [4] \) and those of Ptri J et al is in the range of \( I=1\sim3\times10^{45} \text{ g.cm}^2 \) corresponding to the neutron star mass \( 2\sim2.2 \text{ M}_\odot \) \( [13] \). Our calculations perfectly agree with them.

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