

Magnetization of neutron star matterJianmin Dong,¹ Wei Zuo,^{1,*} and Jianzhong Gu²¹*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*²*China Institute of Atomic Energy, P.O. Box 275(10), Beijing 102413, China*

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The magnetization of neutron star matter in magnetic fields is studied by employing the FSUGold interaction. It is found that the magnetic susceptibilities of the charged particles (proton, electron, and muon) can be larger than that of the neutron. The effects of the anomalous magnetic moments of each component on the magnetic susceptibility are examined in detail. It is found that the proton and electron anomalous magnetic moments affect their respective magnetic susceptibility evidently in strong magnetic fields. In addition, they are the protons instead of the electrons that contribute most significantly to the magnetization of the neutron star matter in a relative weak magnetic field, and the induced magnetic field due to the magnetization can appear to be very large. Finally, the effect of the density-dependent symmetry energy on the magnetization is discussed.

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I. INTRODUCTION

Neutron stars in the Universe tend to contain matter of supranuclear density in their interiors, with typical mass $M \sim 1.4M_{\odot}$ and radii $R \sim 10$ km. As one class of compact objects, neutron stars have been arousing tremendous interest among scientists because of many novel features. One of the features of neutron stars is their strong magnetic field that could be the largest one observed in nature. The typical magnitudes of surface magnetic fields are as large as 10^{11} – 10^{13} G [1]. It is currently assumed that the soft gamma repeaters and anomalous x-ray pulsars, candidates for magnetars, have strong surface magnetic fields up to 10^{14} – 10^{15} G [2]. The magnetic field in the interior could be as large as 10^{18} G according to the scalar virial theorem [3]. It is interesting that strong magnetic fields were also created in heavy-ion collisions [4,5], which may help us to understand the response of dense matter under the presence of strong magnetic fields.

Over the past decades, many works have been dedicated to the effects of the magnetic field on neutron star properties, such as the equations of state [6], neutron star structure [7], transport properties, and the cooling or heating of magnetized stars [8]. An unclear but interesting problem is the origin of such a strong magnetic field. A simple analysis showed that a weak magnetic field in a progenitor star could be amplified during the gravitational collapse due to magnetic flux conservation. However, it cannot explain the very strong surface magnetic field in magnetars [9]. Another explanation called the magnetohydrodynamic dynamo mechanism based on the rapidly rotating plasma of a protoneutron star [10], which is generally accepted as the standard explanation for the origin of the magnetar's large magnetic fields, is unable to explain all the features of the supernova remnants surrounding these objects [11,12].

An interesting mechanism being suggested for the origin is the possible existence of a phase transition to a ferromagnetic state, namely, spontaneous magnetization. Such an argument has been investigated widely within various theoretical approaches (without the background magnetic field) [13], but the results are still divergent. Some authors even showed a possibility that a strong magnetic field is produced by color ferromagnetic quark matter in neutron stars [14]. Astronomical observations found that the soft gamma repeater 1806-20 emitted a giant flare on 27 December 2004 with the total flare energy by 2×10^{46} erg, and the energy release probably occurred during a catastrophic reconfiguration of the neutron star's magnetic field, since the emitted energy significantly exceeds the rotational energy loss in the same period [15]. These phenomena are perhaps related to the magnetization of the neutron star matter. In addition, the anisotropic pressure is related to the magnetization for the magnetized matter [16]. Therefore, magnetization is an important physical quantity for neutron stars.

Some calculations have been performed for the magnetization of nuclear matter or pure neutron matter in magnetic fields [16–18]. Seldom calculations were carried out for the β -stable matter. In Ref. [19], the magnetization of the β -stable matter was studied, and it is shown that the magnetization never appears to become very large. However, this conclusion could be revised according to our calculations, as shown later. Because of the small mass and hence the small magneton, the magnetization of electrons may be important compared with that of the neutron. Therefore, in the present study, the magnetization of the β -stable neutron star matter, which consists of protons, neutrons, electrons, and muons, will be investigated. Not only the anomalous magnetic moments (AMM) of nucleons but also the one of leptons are included here. The main purposes of this study are as follows. First, the contribution of each component as well as the effect of the AMM will be

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analyzed in detail. Second, we further explore whether the strong magnetic fields of the neutron stars originate from the highly degenerate relativistic electron gas. Finally, the symmetry energy effects on the magnetization will be presented.

This work is organized as follows. In Sec. II, a brief introduction of the relativistic mean field approach is presented. The magnetization of each component of the neutron star matter, along with the effects of the AMM and the symmetry energy, are analyzed in detail in Sec. III. Finally, a summary is given in Sec. IV.

II. RELATIVISTIC MEAN FIELD WITH THE NEW INTERACTION—FSUGOLD

Nowadays, the relativistic mean field (RMF) theory as a density-functional approach has become a very useful tool in nuclear physics [20]. In the RMF theory of nuclear matter made of nucleons (p, n) and leptons (e, μ) in a uniform magnetic field B , the total interacting Lagrangian density is given by

$$\begin{aligned} \mathcal{L} = & \bar{\psi}_b \left(i\gamma^\mu \partial_\mu - M - g_\sigma \sigma - \frac{g_\rho}{2} \gamma^\mu \boldsymbol{\tau} \cdot \boldsymbol{\rho}_\mu + g_\omega \gamma^\mu \omega_\mu \right. \\ & \left. - q_b \gamma^\mu \frac{1 + \tau_3}{2} A_\mu - \frac{1}{4} \kappa_b \sigma_{\mu\nu} F^{\mu\nu} \right) \psi_b - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - \left(\frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{3} g_2 \sigma^3 + \frac{1}{4} g_3 \sigma^4 \right) \\ & - \frac{1}{4} \Omega_{\mu\nu} \Omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + \frac{\zeta}{4!} g_\omega^4 (\omega_\mu \omega^\mu)^2 \\ & - \frac{1}{4} \mathbf{R}_{\mu\nu} \cdot \mathbf{R}^{\mu\nu} + \frac{1}{2} m_\rho^2 \boldsymbol{\rho}_\mu \cdot \boldsymbol{\rho}^\mu + \Lambda_\nu g_\rho^2 \boldsymbol{\rho}_\mu \cdot \boldsymbol{\rho}^\mu g_\omega^2 \omega_\mu \omega^\mu \\ & + \bar{\psi}_l \left(i\gamma^\mu \partial_\mu - m_l - q_l \gamma^\mu A_\mu - \frac{1}{4} \kappa_l \sigma_{\mu\nu} F^{\mu\nu} \right) \psi_l \quad (1) \end{aligned}$$

with $A^\mu = (0, 0, Bx, 0)$ and $\sigma^{\mu\nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu]$. $\kappa_p = 1.7928 \mu_N$, $\kappa_n = -1.9130 \mu_N$, $\kappa_e = 1.15965 \times 10^{-3} \mu_B$, and $\kappa_\mu = 1.16592 \times 10^{-3} \mu_B$ are the AMM for protons, neutrons, electrons, and muons, respectively [21], where μ_N (μ_B) denotes the nuclear (Bohr) magneton of nucleons (leptons). M , m_σ , m_ω , and m_ρ are the nucleon-, the σ -, the ω -, and the ρ -meson masses, respectively. The nucleon field ψ_b interacts with the σ , ω , ρ meson fields σ , ω_μ , ρ_μ and with the photon field A_μ . The field tensors for the vector meson are given as $\Omega_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu$ and by similar expression for the ρ meson and the photon. The self-coupling terms with coupling constants g_2 and g_3 for the σ meson, which turned out to be crucial [22], are introduced. Compared with the previous RMF models, the RMF interactions employed in this work are FSUGold where two additional parameters ζ and Λ_ν have been introduced: ω meson self-interactions as described by ζ , which soften the equation of state at high density, and the nonlinear mixed isoscalar-isovector coupling described by Λ_ν that modifies the density dependence

of the symmetry energy. The FSUGold interaction gives a good description of ground state properties as well as excitations of finite nuclei [23]. In our previous work, this new interaction was used to study the properties of dense matter and symmetry energy in strong magnetic fields [24].

The energy spectra of the proton, neutron, electron, and muon are given by

$$E_{\nu,s}^p = \sqrt{k_z^2 + \left(\sqrt{M^{*2} + 2Be\nu} - s\kappa_p B \right)^2} + g_\omega \omega_0 + g_\rho \rho_{30}, \quad (2)$$

$$E_s^n = \sqrt{k_z^2 + \left(\sqrt{M^{*2} + k_x^2 + k_y^2} - s\kappa_n B \right)^2} + g_\omega \omega_0 - g_\rho \rho_{30}, \quad (3)$$

$$E_{\nu,s}^e = \sqrt{k_z^2 + \left(\sqrt{m_e^2 + 2Be\nu} - s\kappa_e B \right)^2}, \quad (4)$$

$$E_{\nu,s}^\mu = \sqrt{k_z^2 + \left(\sqrt{m_\mu^2 + 2Be\nu} - s\kappa_\mu B \right)^2}, \quad (5)$$

where $\nu = 0, 1, 2, 3 \dots$ denotes the Landau levels for charged particles and $s = 1$ (-1) is spin-up (spin-down). The chemical potentials μ are obtained by replacing the k_z by $k_{f,\nu,s}$, where k_z is the momentum along the z axis and $k_{f,\nu,s}$ is the Fermi momentum.

III. MAGNETIZATION OF NEUTRON STAR MATTER

The thermodynamical potential for the charged particle is given by

$$\Omega = -\frac{eB}{2\pi^2} \sum_{\nu,s} \int_0^\infty dk_z \frac{1}{\beta} \ln [1 + e^{-\beta(E_{\nu,s} - \mu)}], \quad (6)$$

where the contribution of antiparticles is not taken into account. The magnetization $M = -\left(\frac{\partial \Omega}{\partial B}\right)_{T,V,\mu}$ takes the form

$$\begin{aligned} M = & \frac{e}{2\pi^2} \sum_{\nu,s} \int_0^\infty dk_z \frac{1}{\beta} \ln [1 + e^{-\beta(E_{\nu,s} - \mu)}] \\ & - \frac{eB}{2\pi^2} \sum_{\nu,s} \int_0^\infty dk_z \frac{e^{-\beta(E_{\nu,s} - \mu)}}{1 + e^{-\beta(E_{\nu,s} - \mu)}} \frac{\partial E_{\nu,s}}{\partial B}. \quad (7) \end{aligned}$$

In the zero-temperature limit the proton magnetization is

$$\begin{aligned} M_p = & -\frac{\varepsilon_p}{B} + \frac{\rho_p E_f^p}{B} - \frac{eB}{2\pi^2} \sum_{\nu,s} \left(\sqrt{M^{*2} + 2e\nu B} - s\kappa_p B \right) \\ & \times \left(\frac{e\nu}{\sqrt{M^{*2} + 2e\nu B}} - s\kappa_p \right) \ln \left| \frac{E_f^p + k_{f,\nu,s}^p}{\sqrt{M^{*2} + 2Be\nu} - s\kappa_p B} \right|, \quad (8) \end{aligned}$$

where ρ_p is the proton density and the energy density of the proton is

$$\varepsilon_p = \frac{eB}{4\pi^2} \sum_{\nu,s} \left[k_{f,\nu,s}^p E_f^p + (\sqrt{M^{*2} + 2\nu eB} - s\kappa_p B)^2 \right. \\ \left. \times \ln \left| \frac{k_{f,\nu,s}^p + E_f^p}{\sqrt{M^{*2} + 2\nu eB} - s\kappa_p B} \right| \right]. \quad (9)$$

Here the feeble change of the σ field is neglected. A similar expression can be obtained for the electron and muon. For simplicity, we calculate the neutron magnetization with $M_n = (\rho_{n\uparrow} - \rho_{n\downarrow})\kappa_n$. The magnetic susceptibility is given as $\chi = M/B$. We would like to stress that, due to their Landau diamagnetism, there is not such a simple relation between the magnetization and spin polarization for the charged particles.

The magnetic susceptibilities of the proton, electron, muon, and neutron versus the density ρ for the β -stable neutron star matter under different magnetic fields are presented in Fig. 1. For the charged particles, the magnetic susceptibilities show the oscillations, in particular in the case of a relatively weak magnetic field. Besides, as shown in the top three panels of Fig. 1, they are positive in most cases and sometimes fall into their negative ranges in the case of rather weak magnetic fields. The ‘‘oscillation period’’ of the magnetic susceptibility depends on the density of the Landau energy states. This density of state reduces with the increase of the magnetic field strength and, hence, the oscillation period. It is found that the magnetic susceptibilities of the charged particles tend to be larger than that

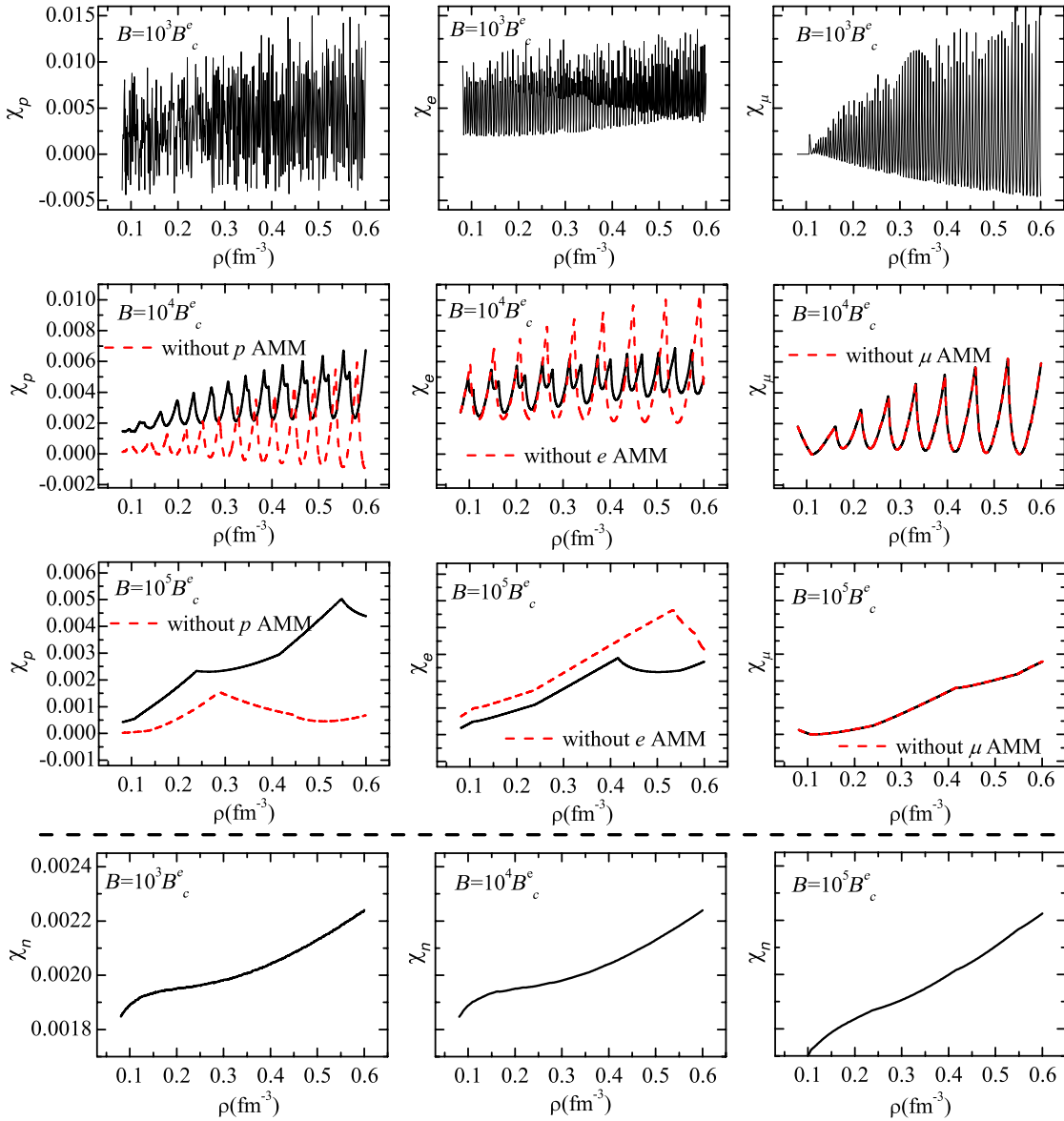


FIG. 1 (color online). Magnetic susceptibilities of n , p , e , and μ for the β -stable matter as a function of nuclear matter density for different values of the magnetic field B . The subgraphs above the dashed line are magnetic susceptibilities for charged particles. The neutron magnetic susceptibilities are displayed in the last row. The magnetic field is in units of the electron critical field $B_c^e = 4.414 \times 10^{13}$ G.

of the neutron, indicating that the neutron star matter cannot be treated simply as pure neutron matter when one studies its magnetization. Neutrons carry no charge, so that they have no Landau levels to fill. Hence, the direct coupling of neutrons to the magnetic field is just due to the neutron AMM. For the protons, electrons, and muons, however, their charge strongly couples with the magnetic field forming the Landau levels, and this coupling is much stronger than the direct coupling between the AMM and magnetic field. Roughly speaking, the more Landau levels, the stronger the magnetization. In an extreme case that the particles occupy the Landau ground state (only one Landau level), the magnetization vanishes due to the Landau diamagnetism being counterbalanced by the Pauli paramagnetism if one ignores the AMM. Our calculations indicate that the magnetization of the electrons is only a few percent, which is not much larger than those of other components. Accordingly, in contradiction with the investigation of Ref. [25], the primal magnetic field of the neutron stars cannot be greatly boosted up by the magnetization of the highly degenerate relativistic electron gas. The fundamental reason is that the Pauli paramagnetism is canceled out to a large degree by the diamagnetism for the electron.

To show the effects of the AMM of each component on the magnetic susceptibility χ , we present the calculated χ_p , χ_e , and χ_μ without the inclusion of their AMM in the middle six panels of Fig. 1 marked by dashed curves for comparison. The effect of the muon AMM can be neglected completely because of its quite small value (about 1/207 of the electron AMM). The proton and electron AMM affect their respective magnetic susceptibility evidently. With the

inclusion of the AMM, the doubly degeneracy with opposite spin projections is destroyed, and hence the peaks and shapes of the curves are modified. On the whole, the proton AMM leads to an enhancement of χ_p , while the electron AMM causes the χ_e reduce slightly, which has connection with the spin polarization—positive polarizability for protons but negative for electrons. Compared with the proton AMM, the effect of the electron AMM is weaker, because the electron AMM is about a thousandth of its normal magnetic moment, while the proton AMM shares the same order of magnitude as its normal magnetic moment.

The magnetic susceptibility versus the magnetic field strength are presented in Fig. 2 taking the β -s matter at $\rho = 0.16 \text{ fm}^{-3}$ as an example. The detailed structure of the magnetization exhibits strong de Haas-van Alphen oscillations. The amplitudes of the oscillations become increasing small as the magnetic field strength increases, and the magnetic susceptibilities of the charged particles tend toward zero when the magnetic field is very strong. The reason lies in the reduction of the Landau levels as the magnetic field strength increases. Though the neutron has no Landau levels to occupy, its magnetic susceptibility also fluctuates with the magnetic field owing to the fact that the magnetic field affects the neutron density at a given nucleon density. One conspicuous phenomenon is that the absolute value of the proton magnetization M_p tends to be much larger than the M_e , M_μ , and M_n in a relative weak magnetic field—that is, the proton is much stronger magnetized compared with other components. One can easily realize this from the relevant discussions about Fig. 1. When the magnetic field is weak, the induced magnetic field due to the magnetization can be much stronger than the original field

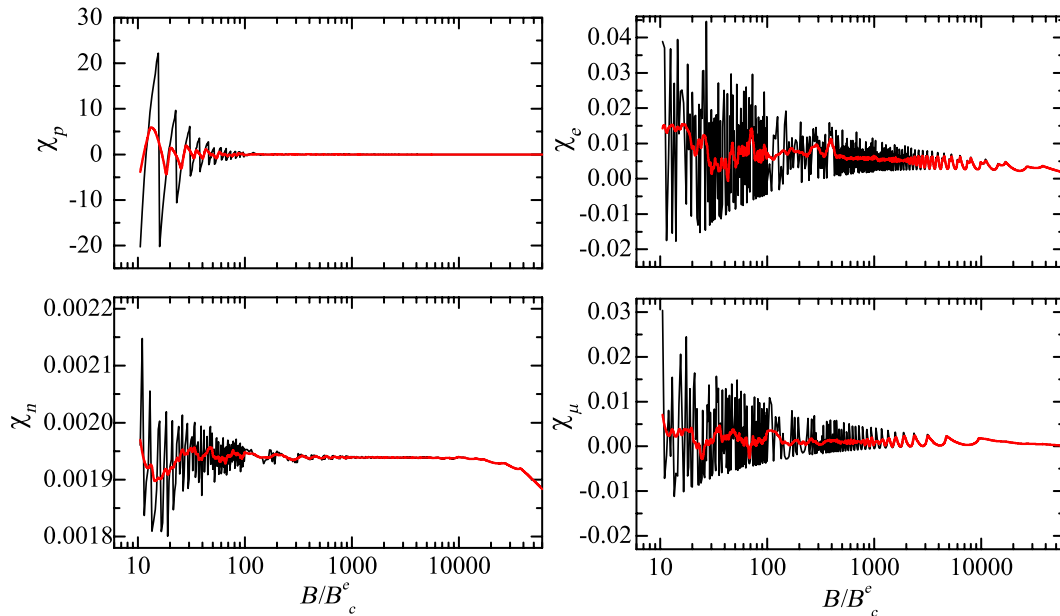


FIG. 2 (color online). Magnetic susceptibilities of n , p , e , and μ for the β -stable matter as a function of the magnetic field strength B . The bold red curves correspond to the average over a long period. The density we selected is $\rho = 0.16 \text{ fm}^{-3}$ as an example.

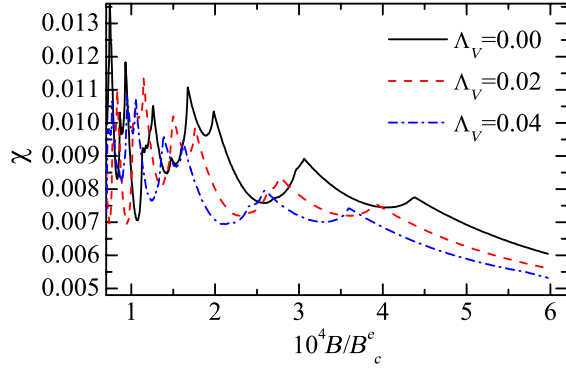


FIG. 3 (color online). Magnetic susceptibilities of the neutron star matter versus the magnetic field strength B . The density we selected is $\rho = 0.16 \text{ fm}^{-3}$ as an example. The calculations are performed with the modified FSUGold interactions [33] providing stiff ($\Lambda_v = 0.00$) to soft ($\Lambda_v = 0.04$) symmetry energy.

but fluctuated wildly. The irregularity oscillations can be averaged to smooth out the wild oscillations to a large extent, being analogous to the averaged viscosities in the presence of strong magnetic fields discussed in Ref. [26]. The strong magnetization perhaps has something to do with the origin of the magnetic field in neutron stars: The original seed field is gradually amplified by the magnetization. Of course, it needs further investigation.

The density-dependent symmetry energy plays a crucial role in understanding a variety of issues in nuclear physics as well as astrophysics [27–35]. Figure 3 displays the total magnetic susceptibility χ as a function of the magnetic field strength with the modified FSUGold interactions which yield stiff to soft symmetry energy, where Λ_v is varied while g_ρ is adjusted so that for each Λ_v the asymmetry energy remains fixed at a given density, and this prescription ensures that the binding energy as well as the proton density of a heavy nucleus, such as ^{208}Pb , are within the measured values [33]. The interaction with a stiff symmetry energy tends to yield a large χ at a strong magnetic field $B > 10^4 B_c^e$, and the “peaks” shift forward compared with that yields a soft symmetry energy. These stem from the fact that a stiffer symmetry energy gives a lower neutron fraction. As a consequence, the effects of the symmetry energy on the magnetization are distinct at strong magnetic fields.

IV. SUMMARY

The magnetization of neutron star matter in magnetic fields has been studied within the FSUGold interaction.

The present analysis is based on the zero-temperature limit for simplicity, since the Fermi temperature is much larger than the real temperature in normal neutron stars. The main conclusions are summarized as follows. (i) The magnetic susceptibilities of the neutron are not dominant, indicating that the neutron star matter cannot be treated as pure neutron matter for simplicity when one studies its magnetization. (ii) Being inconsistent with the conclusion in Ref. [25], the small electron magnetic susceptibility indicates that the observed superstrong magnetic field of neutron stars does not originate from the induced Pauli paramagnetism of the highly degenerate relativistic electron gas in the neutron star interiors. (iii) The proton and electron AMM affect their respective magnetic susceptibility evidently, whereas the muon AMM can be neglected completely. The role of the AMM of the neutron, proton, and electron suggested that they cannot be discarded arbitrarily. (iv) The proton is found to be much stronger magnetized compared with other components when the magnetic field is relatively weak ($B < 10^2 B_c^e$). The magnetization of the matter can appear to be very large, which differs from the conclusion in Ref. [19]. The calculation in Ref. [19] was correct, but it did not include the case of the very low magnetic fields, so that it concluded the magnetic susceptibility is only a few percent. The magnetization perhaps is related to the origin of the strong magnetic field in neutron stars, but it needs to be explored further. (v) The magnetization of neutron star matter is affected distinctly by the density-dependent symmetry energy.

At low temperature and weak fields, pairing correlations may dominate the magnetic susceptibility. Pairing in the 1S_0 and 3PF_2 channels may have a large impact on the magnetic response of the system, which needs to be further investigated.

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