Effects of fermionic dark matter on properties of neutron stars

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By assuming that there is only gravitation between dark matter (DM) and normal matter (NM), we study the properties of DM admixed neutron stars (DANSs) using a two-fluid TOV formalism. We have considered fermionic DM candidates with various masses and interactions and studied their effects on the properties of neutron stars. It is found that the mass-radius relationship of DANSs depends sensitively on the mass of DM candidate, the amount of DM, and interactions among DM candidates. The existence of DM in DANSs results in a spread of mass-radius relationships that cannot be interpreted with a unique equilibrium sequence. In some cases, the DM distribution can surpass the NM distribution to form DM halo. Specifically, if the repulsion of DM exists supposedly, it is favorable to form an explicit DM halo. We have found that the contamination of DM in neutron stars can significantly affect the astrophysical extraction of nuclear EOS by virtue of neutron star measurements. It is interesting to find that the difference caused by various density dependencies of nuclear symmetry energy can run to disappear, as long as the repulsion of accumulated DM is sufficient.

PACS numbers: 95.35.+d, 97.60.Jd, 26.60.Kp, 21.60.Jz

I. INTRODUCTION

Nowadays, dark matter (DM) is an inevitable reality in both astrophysics \cite{1} and particles physics \cite{2}, and it seems clear that it is the dominant matter in the universe. Recent advances in cosmological precision tests further consolidate the minimal cosmological standard model, indicating that the universe contains 4.9\% ordinary matter, 26.8\% DM, and 68.3\% dark energy \cite{3}. However, the properties of DM, including its mass and interactions, are still unknown. It is thus of great interest to explore the properties of DM through direct or indirect methods.

There are usually three well-known methods to detect DM particles: using particle accelerators \cite{4}, direct detecting of scattering cross section by terrestrial detectors (CDMS II, CRESST, and CoGeNT), and indirect detecting of products from DM particle annihilation in the galactic halo \cite{5}. The latest experimental results are not conclusive. The data from the DAMA/LIBRA \cite{6}, CoGeNT \cite{7, 8}, and CRESST-II \cite{9} experiments are consistent with detecting DM particles with mass $10 GeV$, which are incompatible with the null results from CDMS-II \cite{10}, SIMPLE \cite{11} and XENON10/100 \cite{12, 13}. It’s suggested that isospin-violating DM would relax the tensions between the results of DAMA, CoGeNT and XENON experiments \cite{14}. But the possible tensions between some experiments such

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as those between DAMA and SIMPLE are unlikely to be affected by isospin-violating interactions.

One indirect method that is gaining attention in recent years is to study the effects of DM on compact stars. On one hand, the high baryonic density in compact stars increases the probability of DM capture within the star and eventually results in gravitational trapping. The DM accumulation inside stars will affect the stellar structure and even contribute to the collapse of a neutron star [15]. On the other hand, at the later periods of their evolution, neutron stars can be rather cold objects due to lack of possible burning or heating mechanisms, and therefore the heating effect by possible DM annihilation is favorable and possibly observable. At the same time, self-annihilation of DM in the inner regions of neutron stars may significantly affect their kinematical properties, including linear and angular momentum [16]. Therefore, it is of great significance to study the potential effects of DM on the properties of neutron stars.

The neutron star properties are intimately connected to the nuclear equation of state (EOS) of asymmetric matter, while the latter consists roughly of the EOS of symmetric matter and the density dependence of the nuclear symmetry energy. In the past, great progress has been achieved to constrain the EOS of symmetric nuclear matter using terrestrial nuclear experiments for more than three decades, see, e.g. [17, 18], for a review. It is known that the EOS around normal density can be well constrained by nuclear giant monopole resonances [17], while at supra-normal densities it can be constrained by the collective flow data from high energy heavy-ion reactions [18]. Stringent constraints on the nuclear EOS are dispensable to portray neutron stars. For instance, the maximum mass of neutron stars is mainly determined by the high-density EOS of symmetric nuclear matter. Recently, several neutron stars with large masses around $2M_\odot$ have been observed [19–21]. In particular, the $2M_\odot$ pulsar J1614-2230 was measured rather accurately through the Shapiro delay [22]. These observations can provide astrophysical constraints on the high-density nuclear EOS. On the other hand, the density dependence of the symmetry energy that affects mostly the radius of NSs is still not well determined especially at high densities. In the past, the constraints on the symmetry energy have been extracted either from the terrestrial laboratories using the isospin diffusion data [23] or from the astrophysical observations on properties of neutron stars [24]. Neutron stars are natural laboratories for the exploration of baryonic matter under extreme conditions, complementary to those created in terrestrial experiments. Jointly using the radius and mass observations, it is hopeful to constrain the nuclear EOS of asymmetric matter at densities of interest [24, 25]. One should however note that such constraints can not provide detailed information about the neutron star compositions or interplay between them. As far as the DM is concerned, it is rather interesting to explore many relevant issues of DM, such as its accretion on neutron stars, interplay between normal matter (NM) and DM, interactions among DM, its effect on properties of neutron stars, and
The dark-matter admixed neutron stars (DANSs) have been studied recently in several articles [26–31]. Li et. al. [26] considered DM as Fermi-gas-like matter, and by taking the total pressure (energy density) as the simple sum of those of the DM and NM, mixed equally the DM and NM. Sandin and Ciarcelluti [27, 28] considered the mirror DM and assumed that neutron stars with a DM core are inherently two-fluid systems where the NM and DM couple essentially only through gravity. By varying the relative size of the DM core, they may reproduce all astrophysical mass measurements based on one nuclear matter EOS. Leung et al. [29] used the general relativistic two-fluid formalism to study the various structures of DANS. Following the approach used by Sandin and Ciarcelluti [27, 28], we consider in this work a broad variety of DM with various masses and interactions in neutron stars and examine the effects of DM on static properties of neutron stars. The paper is organized as follows.

In Sec. II, we present briefly the formalism of DM based on the Lagrangian of the relativistic mean-field models as well as the formalism of two-fluid model for neutron stars. In Sec. III, numerical results and discussions are presented. At last, a summary is given in Sec. IV.

II. FORMALISM

In the RMF approach, the nucleon-nucleon interaction is usually described via the exchange of three mesons: the isoscalar meson $\sigma$, which provides the medium-range attraction between the nucleons, the isoscalar-vector meson $\omega$, which offers the short-range repulsion, and the isovector-vector meson $b_0$, which accounts for the isospin dependence of the nuclear force. The relativistic Lagrangian can be written as:

$$\mathcal{L} = \overline{\psi} \left[ i \gamma_\mu \partial^\mu - M + g_\sigma \sigma - g_\omega \gamma_\mu \omega^\mu - g_\rho \gamma_\mu \tau_3 b_0^\mu \right] \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{2} m_\rho^2 b_{0\mu} b_{0\nu}$$

$$+ \frac{1}{2} (\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) + U_{\text{eff}}(\sigma, \omega^\mu, b_{0\mu}).$$

(1)

where $\psi, \sigma, \omega, b_0$ are the fields of the nucleon, isoscalar, isoscalar-vector, and neutral isovector-vector mesons, with their masses $M, m_\sigma, m_\omega$, and $m_\rho$, respectively. $g_i (i = \sigma, \omega, \rho)$ are the corresponding meson-nucleon couplings. $F_{\mu\nu}$ and $B_{\mu\nu}$ are the strength tensors of $\omega$ and $\rho$ mesons respectively,

$$F_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu, \quad B_{\mu\nu} = \partial_\mu b_{0\nu} - \partial_\nu b_{0\mu}. \quad (2)$$

The self-interacting terms of $\sigma, \omega$ mesons and the isoscalar-isovector coupling are given generally as

$$U_{\text{eff}}(\sigma, \omega^\mu, b_{0\mu}) = - \frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4 + \frac{1}{4} c_3 (\omega_\mu \omega^\mu)^2 + 4 \Lambda V g_p^2 g_\sigma^2 \omega_\mu \omega^\mu b_{0\mu} b_{0\nu}. \quad (3)$$

With these nonlinear meson self-interaction terms, the models are usually invoked as the nonlinear models. In the relativistic mean-field (RMF) approximation, the energy density $\varepsilon$ and pressure $p$ are
metric nuclear matter at β DM current through $g$ scalar density of DMs through $g$ need to be additionally considered, which are written as: BR scaling.

equilibrium. For asymmetric nuclear matter at β equilibrium, the chemical equilibrium and charge neutrality conditions need to be additionally considered, which are written as:

\[ \mu_n = \mu_p + \mu_e, \]

\[ \rho_e = \rho_p, \]

\[ \rho = \rho_n + \rho_p. \]

where $\mu_n, \mu_p, \mu_e$ are the chemical potential of neutron, proton and electron, respectively, and $\rho_e$ is the number density of electrons. In neutron stars, the EOS is obtained by adding the contribution of the free electron gas to Eqs.(4) and (5).

We regard DM candidates as fermions, and assume that a neutral scalar meson couples to the scalar density of DMs through $g_s \bar{\psi}_D \psi_D \phi$ and that a neutral vector meson couples to the conserved DM current through $g_v \bar{\psi}_D \gamma_\mu \psi_D V^\mu$. This modelling of the interactions is rather universal according
to the covariance, and it’s an extension of those used in Ref. [34]. Similar to the potential for baryons [35], the meson exchange gives rise to an effective DM-DM potential:

\[ V_{\text{eff}}(r) = \frac{g_s^2}{4\pi} \frac{e^{-m_s r}}{r} - \frac{g_s^2}{4\pi} \frac{e^{-m_s r}}{r}. \]  

(11)

With appropriate coupling constants and masses, the above potential is attractive at large separations and repulsive at short distances.

The Lagrangian density for the present DM model can be written as:

\[ \mathcal{L}_D = \bar{\psi}_D[\gamma_\mu(i\partial^\mu - g_\mu V^\mu) - (M_D - g_\phi \phi)]\psi_D + \frac{1}{2}(\partial_\mu \phi \partial^\mu \phi - m_\phi^2 \phi^2) - \frac{1}{4}g_{\mu\nu}D^{\mu\nu} + \frac{1}{2}m_D^2 V_\mu V^\mu \]  

(12)

where \( D_{\mu\nu} \) is the strength tensor of vector meson

\[ D_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu. \]

The relativistic quantum field theory generated by this Lorentz-invariant \( \mathcal{L}_D \) is renormalizable, for it is similar to the massive QED with a conserved current and an additional scalar interaction.

The energy density and pressure of DM are given as:

\[ \varepsilon_D = \frac{2}{(2\pi)^3} \int^{k_{FD}} \text{d}k \sqrt{k^2 + (M_D^2)^2} + \frac{g_\nu^2}{2m_\nu^2} \rho_D^2 + \frac{m_\phi^2}{2g_s^2}(M_D - M_D^*)^2, \]

(13)

\[ \rho_D = \frac{1}{3} \frac{2}{(2\pi)^3} \int^{k_{FD}} \text{d}k \sqrt{k^2 + (M_D^2)^2} + \frac{g_\nu^2}{2m_\nu^2} \rho_D^2 - \frac{m_\phi^2}{2g_s^2}(M_D - M_D^*)^2, \]

(14)

where \( \rho_D \) is the number density of DM, \( M_D \) is the mass of the DM candidate, \( M_D^* \) is the effective mass of DM determined by \( M_D = M_D - g_\phi \phi_0 \) with \( \phi_0 \) being the RMF scalar field.

To study a two-fluid compact star, we adopt the formulation given in [28]. For a static and spherically symmetric space-time \( d\tau^2 = e^{2\nu(r)}dt^2 - e^{2\lambda(r)}dr^2 - r^2(d\theta^2 + \sin^2\theta d\phi^2) \). The structure equations for a two-fluid compact star are given by [28] (units are chosen such that \( G = c = 1 \))

\[ \frac{d\nu}{dr} = \frac{M(r) + 4\pi r^3 \rho(r)}{r[r - 2M(r)]}, \]

\[ \frac{dp_N}{dr} = -[p_N(r) + \rho_N(r)]\frac{d\nu}{dr}, \]

\[ \frac{dp_D}{dr} = -[p_D(r) + \rho_D(r)]\frac{d\nu}{dr}, \]

(15)

where \( r \) is the radial coordinate from the center of the star, \( p_N(r) [p_D(r)] \) and \( \rho_N(r) [\rho_D(r)] \) are the pressure and energy density of NM [DM] at position \( r \). \( p(r) = p_N(r) + p_D(r) \) is the sum pressure at the position \( r \). While \( M(r) = \int r d\tau 4\pi r^2 (\rho_N(\vec{r}) + \rho_D(\vec{r})) \) is the sum mass contained in the sphere of the radius \( r \).

The radius \( R \) and mass \( M(R) \) of a neutron star are obtained from the condition \( p(R) = p_N(R) = p_D(R) = 0 \). Because the neutron star matter, consisting of neutrons, protons, and electrons (upe)
at $\beta$ equilibrium in this work, undergoes a phase transition from the homogeneous matter to the inhomogeneous matter at the low density region, the RMF EOS obtained from the homogeneous matter does not apply to the low density region. For a thorough description of neutron stars, we thus adopt the empirical low-density EOS in the literature [36, 37].

### III. NUMERICAL RESULTS AND DISCUSSIONS

In the universe, DM has been proposed to explain the mass discrepancies according to the observed galactic rotation velocities. The latest data indicate that DM occupies about 26.8% of the total, while the ordinary visible matter only has the proportion of 4.9% and the leftover is the Dark energy. For DM as the majority of matter, people have gained no information of its mass and interaction strength. Except for the gravitational effect, the astrophysical objects consisting of DM are regarded to be too faint to be detectable. Though DM that interacts very weakly with NM is difficult to be captured by normal massive stars, the accretion of DM can succeed if the DM that already resides in stars can have necessary self-interaction. Since the majority of matter is DM in our universe, one can imagine the existence of a large number of the massive objects consisting of DM in our Universe. Similar accretion of NM can take place in those DM stars. With these in mind, we thus assume the DM fraction in neutron stars as arbitrary quantity in the present exploration, regardless of accretion details. Similar to the spirit of Ref. [34], in this work we consider DM candidates with various masses and interaction strengths in compact stars, while the emphasis is put on the effect of various admixture of DM on neutron star properties.

For NM, we adopt the nuclear EOS obtained from the density-dependent RMF models SLC and SLCd [32, 33]. The unique difference between the models SLC and SLCd is that the latter has a softer symmetry energy than the former. In this way, we may investigate the symmetry energy effect on neutron stars involving the DM. For comparisons, we also perform calculations with the improved nonlinear RMF model IU-FSU [38]. Parameters and saturation properties of these parameter sets are listed in Table I.

|         | $g_\sigma$ | $g_\omega$ | $g_\rho$ | $m_\sigma$ | $m_\omega$ | $m_\rho$ | $g_2$ | $g_3$ | $c_3$ | $\Lambda_v$ | $\rho_0$ | $\kappa$ | $E_{sym}$ |
|---------|------------|------------|----------|-------------|-------------|----------|-------|-------|-------|-------------|---------|---------|----------|
| SLC     | 10.141     | 10.326     | 3.802    | 590.000     | 783.000     | 770      | -     | -     | -     | 0.16        | 230     | 31.6    |
| SLCd    | 10.141     | 10.326     | 5.776    | 590.000     | 783.000     | 770      | -     | -     | -     | 0.16        | 230     | 31.6    |
| IU-FSU  | 9.971      | 13.032     | 6.795    | 508.194     | 782.501     | 763      | 8.493 | 0.488 | 144.219| 0.046       | 0.155   | 231.2   | 31.3     |

Shown in Fig. 1 are for various models the Mass-radius relations with the inclusion of different
kinds of free DM particles that differ in masses. At present, the central energy density of DM and NM is assumed to be the same. We have no preference to use this unitary ratio at the center of neutron stars. Different from the work that mixes NM and DM equally, we actually take this ratio as flexible parameter. Later on, we will go back to this point to see the effect by changing this ratio. It is clearly seen that if the mass of DM is much heavier, e.g. $\geq 2\text{GeV}$, it has little impact on the Mass-radius relations of DANSs. If the mass of DM is small (e.g. $500\text{MeV}$), it can influence the mass-radius relations of DANS significantly. In this case, the minimum mass we get is found to be too heavy ($M \geq 1.32M_\odot$ for SLC and $M \geq 1.38M_\odot$ for IU-FSU) to explain the small neutron star mass observed [39–41]. By now, we don’t know the mass of DM candidates. There are many DM candidates, ranging from lightest axions($M \sim \mu\text{eV} - 10\text{meV}$) to heaviest WIMPs ($M \sim 10\text{GeV} - \text{TeV}$) [2]. Our research implies that one can perhaps distinguish them through their impact on neutron stars. Recently, an analysis about the XENON10 data claimed that direct detection experiments can be sensitive to DM candidates with masses well below the GeV scale [12].

Our calculation indicates that if neutron stars contain DM, the observation of neutron stars is also sensitive to DM with its mass below GeV scale. Of course, the identification of DM with the neutron star involves the details of the celestial DM distribution and accretion.

In Fig. 2, we show the mass-radius relations of DANSs for different models. Here, the mass of free DM candidate is set to be 1 GeV. We see that the existence of DM would lower the maximum stable mass of neutron stars allowed by the corresponding EOS. The reduction of the maximum mass due to the inclusion of DM is different. This reduction is in deed not apparent in RMF models SLC and SLCd that feature a stiff EOS at high densities [32]. More apparent phenomenon in Fig. 2 is
the shift of the neutron star radius caused by the inclusion of DM. Let’s see the neutron star and DANS that have the same mass, for instance, 1.4$M_\odot$, denoted by the straight line in Fig. 2). We observe that very significant reduction of the radius comes up with the inclusion of DM in neutron stars. The apparently smaller radius of DANS indicates that DANS is more compact, compared with neutron stars. It is of special interest to point out that the 1GeV DM candidate is possibly relevant to the mirror particle of visible nucleonic matter [28]. In Fig. 2, we also include the constraints of mass-radius for $r_{ph} >> R$ obtained by Steiner et al.[24]. We see that the inclusion of DM can lead to a more vertical shape, which is favorable for models SLC and SLCd to be consistent with observational constraints. Based on the general understanding of neutron star properties, the slope of the nuclear symmetry energy at normal density was extracted to be in the range 36-55 MeV at the 95% confidence level [42]. Were DM to be present in neutron stars, the astrophysical extraction of the symmetry energy should face up significant modification due to the distinct effects induced by DM.

![Mass-radius relations of neutron stars and DANSs for different models.](image)

**FIG. 2:** Mass-radius relations of neutron stars and DANSs for different models. In the legend, the RMF models without the suffix DM represent results of normal neutron stars, while the ones with the suffix DM stands for results of DANSs. The hatched areas give the probability distributions with 1σ (blue) and 2σ (violet) confidence limits for $r_{ph} >> R$ summarized in Ref. [24].

Given the appreciable DM effect on the neutron star radius, it is interesting to compare and look over various matter distributions in neutron stars and DANS. For this aim, we choose the neutron star and DANS that have the same mass and radius. The neutron star marked by M, as shown in Fig. 1, is the exact one that meets the criterion. The intersection point M corresponds for the neutron star and DANS to the mass (1.33$M_\odot$) and R (12.76km), while the mass of DM candidate is here 0.5 GeV. The number density profiles with the SLC are displayed in Fig. 3: the upper panel for the normal neutron star and the lower panel for the DANS. Significant difference in the density
FIG. 3: Density profiles in the neutron star and DANS that have the same mass $1.33M_{\odot}$ and radius (12.76 km). For the DANS, the DM mass is 0.5 GeV. The mass and radius setup corresponds to the point marked by M in Fig. 1. The upper panel is for the normal neutron star, and the lower panel is for the DANS.

Profiles in the neutron star and DANS is observed. In the DANS, we see that a smaller NM core ($R \sim 9$ km) is surrounded by a DM halo. Since the two stars have the same mass, it seems impossible to distinguish them only by their gravitational effects on other neighboring stellar objects. However, their visible radii are different. Thus, it is possible to distinguish them by measuring the gravitational redshift of spectral lines. In fact, the radius of the neutron star is 12.76 km, while the visible radius (namely the radius of the NM core) of the DANS is 9 km. According to the gravitational redshift formula: $z = \frac{1}{\sqrt{1-2GM/rc^2}} - 1$, the redshift of the neutron star is obtained to be 0.202, and it is 0.331 for the DANS.

FIG. 4: Constituent masses in DANS with the DM mass being 0.5 GeV. DANS_NM (DANS_DM) is for the mass-radius relationship of NM (DM) in DANS, and DANS_SM corresponds to the total one. Besides, curves for normal neutron star and pure DM star (DS) are depicted.
In order to further study the behavior shown in Fig. 1, we depict the mass-radius relationships of DM and NM in Fig. 4. Here, the mass of DM candidate is again chosen to be 0.5 GeV, and the central DM energy density to the NM one is fixed to be equal. It’s obvious that with the increase of the radius, the mass proportion of NM in DANSs decreases, while the mass proportion of DM in DANSs increases. The reason for this phenomenon lies in the fact that in the current two-fluid model DM particles interact with ordinary particles only through the gravity. Both DM and NM produce their own maximum masses and corresponding radii. For neutron stars without DM, the maximum mass is $2.02M_\odot$ ($1.94M_\odot$) and the corresponding radius is 9.24km (11.21km) with the SLC (IU-FSU). With the inclusion of DM, the original maximum mass with the SLC (IU-FSU) is reduced to $1.82M_\odot$ ($1.44M_\odot$), and corresponding radius is decreased to 8.98km (10.3km). At the same time, for pure DM star, the maximum mass is determined by $M_{\text{max}} = 0.627M_\odot (\frac{1 GeV}{M_D})^2$ and corresponding radius is $R_D = 8.115km(\frac{1 GeV}{M_D})^2$ [34]. By substituting $M_D = 0.5 GeV$, we get the maximum mass $2.5 M_\odot$ and corresponding radius 32.46km. When the DM admixture starts to take place, the maximum mass and corresponding radius will be changed, as shown in Fig. 4. At the cross point (marked by D), the mass proportion of DM and NM in the DANS is equal. As the star radius continues to increase, the mass proportion of DM will be larger than that of NM, eventually leading to DM-dominant stars.

![Fig. 5: Mass-radius relations for various DM proportions. The Ratio parameter represents the central energy density ratio of the DM to the NM. The zero ratio means DM-free normal neutron star.](image)

Shown in Fig. 5 are the mass-radius relations of DANSs for various proportions of DM. Here, the mass of the DM candidate is taken to be $M_D = 1GeV$. We see that with increasing the DM ratio, the maximum mass and corresponding radius of DANS decrease. At the same time, the minimum mass of DANS increases. Similar to results shown in previous figures, the reduction of maximum
mass in SLC is much less appreciable than that in IU-FSU. It is seen that the structure of DANSs is dependent on the amount of DM, and this results in a spread of mass-radius relationships that cannot be interpreted with a unique equilibrium sequence.

Generally speaking, the amount of DM in DANSs is expected to vary and depends on the whole history of the star, especially on the environments from which it originates and in which it lives. In fact, the capture of DM is difficult both because of their low reaction cross section (typically about $10^{-44} \text{cm}^2$ [43]) and the low average density of matter in the universe. But NM galaxy and galaxy clusters could act as a whole to capture DM, and make the density of DM in some section to be high enough to produce observable signals. Actually, most evidences of DM come from these observations [44–46]. Recently, a research claimed that neutron stars in binary systems might increase the probability to accumulate the DM [47]. Besides, neutron star could capture enough DM to be observed due to its high density [48]. Though the DM is usually assumed to be collisionless, the assumption of self-interacting DM can not be simply ruled out [49]. Even though the majority of DM is regarded to be cold and collisionless, Fan et. al. proposed most recently that a subdominant fraction of DM could have much stronger interactions [50]. In the following, we consider DM that features interactions.

Now, we examine the equation of state with various interaction strengths in DM. From Eqs.(13) and (14), we know that the repulsion (attraction) potential is just determined by the ratio parameter $C_{DV} = g_v/m_v$ ($C_{DS} = g_s/m_s$) in the RMF approximation. So, these ratio parameters can represent the interaction strength. In order to make the potential in Eq.(11) attractive at large separations and repulsive at short distances, $m_v$ must be greater than $m_s$, and $g_v$ must be greater than $g_s$. 

![Pressure and energy density relationship of DM](image)

**FIG. 6:** Pressure and energy density relationship of DM. The interactions with various strengths are considered. The units of $c_{DV}$ and $c_{DS}$ are $\text{GeV}^{-1}$. For comparisons, the results of NM with the SLC and IU-FSU are also displayed.
However, there are no limits on the size of \( C_{DV} \) and \( C_{DS} \). Note that \( C_{DS} \) is not allowed to too big. Otherwise, the pressure may be negative and then not be a monotonous function of energy density, invalidating the use of the TOV equation. The strengths we use here are a little arbitrary, but this does not hamper us to draw a rough conclusion concerning the DM interaction. Shown in Fig. 6 is the pressure-energy density relationship of DM. Here, the free DM particle mass is taken as 1GeV, and we choose \( C_{DV} = 10\text{GeV}^{-1} \) and/or \( C_{DV} = 4\text{GeV}^{-1} \) in the calculation. It is seen in Fig. 6 that the repulsion with a large \( C_{DV} \) stiffens clearly the EOS of DM, while attraction interaction softens moderately the EOS of DM because of a much smaller \( C_{DS} \). For comparisons, we also depict the NM results with the SLC and IU-FSU.

![Fig. 7: Mass-radius relationship with various DM EOSs. The attractive and/or repulsive strengths are labelled in the legend.](image)

With various DM EOSs, we display the mass-radius relation in Fig. 7. In principle, the repulsion provides resistance to the gravitational attraction. The more the repulsion, the heavier the star. In one-fluid model, this is simply right. However, in the two-fluid model, the mass-radius relation is not so simple. Because of the gravity provided by the other fluid, the maximum mass of each fluidic constituent reduces, while the repulsion added by the DM just increases the maximum mass of the DM constituent. This can be clearly observed by comparing the results of solid and red-dashed curves in Fig. 7. In the case of pure attraction for DM, we see that the mass-radius relation is just modified moderately. The reason lies in the fact the attraction diminishes the DM proportion in the star. It’s obvious that the stiffer the EOS of DM shown in Fig. 6, the more effect it could have on the mass-radius relation of DANSs. Here, our results are obtained with the specific mass of DM candidate, but are qualitatively valid for other kinds of DM that could exist in the neutron star.

While the interactions of DM lead to various mass-radius relations, it is interesting to investigate
FIG. 8: Number density profiles in DANSs. In the legend, $R$ ($A$) represents the pure repulsion (attraction) with interaction strength $C_{DV} = 10 GeV^{-1}$, $C_{DS} = 0$ ($C_{DV} = 0$, $C_{DS} = 4 GeV^{-1}$), while $No$ represents no interaction in DM. These cases are corresponding to those in Figs.6 and 7.

constituent density profiles in DANSs. Shown in Fig.8 are various particle number density profiles of the DANSs. Here, the central energy density is fixed to be $600 MeV/fm^3$. In this case, the mass of the DANS ranges from $1.13 M_{\odot}$ to $1.38 M_{\odot}$ and from $1.34 M_{\odot}$ to $1.60 M_{\odot}$ for the SLC and IU-FSU, respectively. We can observe that the attraction of DM shrinks the DM density distribution, leading to the increase of the number density gradient of DM in the DANS together with the decrease of the number density gradient of NM. The repulsion supports an spatial extension, opposite to the shrinkage provided by the attraction. The DM extension out of NM actually produces a clear DM halo. We see here that the DM halo has a much denser number density compared to that shown in Fig.3. Our calculation also indicates that it’s more likely to form the DM halo with a lower central energy density. The halo structure is somehow dependent on nuclear EOS, as shown in Fig. 8. This is because various EOSs provide different NM distribution that screens DM. Though DM halo is invisible, the visible size of DANSs is now certainly affected by the interaction of DM. We can address that the visible radius of DANSs is not only affected by the DM proportion, but also affected by the interaction of DM. This would affect the extraction of EOS from astrophysical observations.

Since the DANS mass varies with the interaction of DM at given central energy density, we here consider a specific case that the mass from constituent NM is fixed to be $1.30 M_{\odot}$. By varying the interaction of DM, we then observe how much DM can be contained in the DANS according to the mechanical equilibrium between the gravity and matter pressure. The results are tabulated in the Table II. Here, the interaction strength of DM is identical to that used to obtain results in Fig. 8, and the central energy density of NM and DM is set to be equal. From Table II, we see that the DM amount in the neutron star, allowed by the mechanical equilibrium, causes the increase of the $\epsilon_c$ of
TABLE II: The allowance of the amount of the DM accumulation in normal neutron star with fixed mass of $1.30 M_\odot$ due to the equilibrium between the gravity and matter pressure. $\epsilon_c$ is the central energy density which is equal for DM and NM, and $R_{DM}$ ($R_{NM}$) and $M_{DM}/M_\odot$ ($M_{NM}/M_\odot$) are the respective radius and mass in DANSs. The energy density and radius are in units of MeV/fm$^{-3}$ and km, respectively. The interaction type in the first column stands for the various interaction strengths of DM that are the same as the corresponding cases in Fig. 8.

| Model   | $\epsilon_c$ | $R_{DM}$ | $M_{DM}/M_\odot$ | $R_{NM}$ | $M_{NM}/M_\odot$ | $M_{SM}/M_\odot$ |
|---------|--------------|----------|------------------|----------|------------------|------------------|
| NO DM   | SLC 508      | -        | 12.85            | 1.30     | 1.30             | 1.30             |
| SLCd    | 621          | -        | 11.75            | 1.30     | 1.30             | 1.30             |
| Attraction | SLC 620 4.56 | 0.03     | 12.40            | 1.30     | 1.33             | 1.33             |
| SLCd    | 725          | 4.24     | 11.39            | 1.30     | 1.33             | 1.33             |
| No interaction | SLC 820 5.36 | 0.10     | 11.46            | 1.30     | 1.40             | 1.40             |
| SLCd    | 900          | 5.12     | 10.67            | 1.30     | 1.40             | 1.40             |
| Repulsion | SLC 1800 6.26 | 0.34     | 8.53             | 1.30     | 1.64             | 1.64             |
| SLCd    | 1776         | 6.25     | 8.31             | 1.30     | 1.63             | 1.63             |

The stiffer the EOS of DM, the greater the $\epsilon_c$. At the same time, as the amount of DM in the DANS increases to provide more gravitation, NM in DANS is more compressed and become more compact.

![Number density profiles in the DANS with different DM interactions for models SLC and SLCd.](image)

FIG. 9: Number density profiles in the DANS with different DM interactions for models SLC and SLCd.

In Fig. 9, we plot various number density profiles corresponding to various interactions, same as those in Table II. In the present case, we see that DM resides in the central region of DANS and no DM halo forms. We see in Fig. 9 that DM in DANS can influence the distribution of NM. In the case
without DM, we know that the different matter distribution with the SLC and SLCd is attributed to their different nuclear symmetry energy. It is interesting to see that DM in the DANS results in the decrease of the difference in the NM density profiles. Moreover, the extent of the decrease can be strengthened by stiffening the DM EOS. If there is only appropriate repulsion between DM, the difference between SLC and SLCd runs almost to disappear. Because the unique difference between SLC and SLCd is their prediction on the density dependence of nuclear symmetry energy, the astrophysical extraction of the constraint on the symmetry energy seems to be impossible as long as the neutron star is contaminated by DM featuring sufficiently strong repulsion.

IV. SUMMARY

In this work, we have considered fermionic DM candidates with various masses and interactions and studied their effects on the properties of neutron stars. With the inclusion of DM, we assume that there is only gravitation between DM and NM and use the two-fluid TOV formalism to study the properties of DANS. It is found that the mass-radius relationship of DANSs depends sensitively on the mass of DM candidate, the amount of DM, and interactions among DM candidates. The existence of DM in DANSs results in a spread of mass-radius relationships that cannot be interpreted with a unique equilibrium sequence. The mass region of DM candidates where DM affects significantly the DANS properties is found to be below a few GeV. The inclusion of DM decreases the original neutron star maximum mass, while the decrement depends rather sensitively on high-density behavior of nuclear EOS. With the low DM candidate mass, e.g., $M_D = 500\text{MeV}$, the minimum mass of DANSs can be appreciably increased. In this case, the DM distribution can surpass the NM distribution to form DM halo. Moreover, if the repulsion of DM is supposed to exist, it is favorable to form an explicit DM halo. It can be observed that the contamination of DM in neutron stars would significantly affect the astrophysical extraction of nuclear EOS by virtue of neutron star measurements. More strikingly, as long as the repulsion of accumulated DM is sufficient, the difference caused by various density dependencies of nuclear symmetry energy can run to disappear.

Acknowledgement

The work was supported in part by the SRTP Grant of the Educational Ministry No. 1210286047, and the National Natural Science Foundation of China under Grant Nos. 10975033 and 11275048.

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