ROLE OF NUCLEONIC FERMI SURFACE DEPLETION IN NEUTRON STAR COOLING

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ABSTRACT

The Fermi surface depletion of beta-stable nuclear matter is calculated to study its effects on several physical properties that determine the neutron star (NS) thermal evolution. The neutron and proton Z factors measuring the corresponding Fermi surface depletions are calculated within the Brueckner–Hartree–Fock approach, employing the AV18 two-body force supplemented by a microscopic three-body force. Neutrino emissivity, heat capacity, and in particular neutron $^3$PF$_2$ superfluidity, turn out to be reduced, especially at high baryonic density, to such an extent that the cooling rates of young NSs are significantly slowed.

Key words: dense matter – neutrinos – stars: neutron

1. INTRODUCTION

Neutron stars (NSs) with typical masses of $M \sim 1.4 M_\odot$ and radii of $R \sim 10$ km are natural laboratories for investigating exotic phenomena that lie outside the realm of terrestrial laboratories. They have been arousing tremendous interest because they are related to many branches of contemporary physics, as well as astronomy (Haensel et al. 2006). In particular, NSs play the role of connecting nuclear physics with astrophysics, since they realize one of the densest forms of nuclear matter in the observable universe. Concerning NSs, important astrophysical quantities can be measured with increasing accuracy, such as mass, radius, surface temperature, spin period, and spin-down, which provide valuable information and knowledge about these objects. On the theoretical side, much attention has been paid to the equation of state (EOS) of dense matter, including superfluid states, and cooling mechanisms via neutrino emission, to understand the NS thermal evolution (Haensel et al. 2006).

The measurements of the NS surface temperature, such as Cas A (Heinke & Ho 2010; Posselt et al. 2013), allow us to investigate the thermal evolution of NSs more deeply (Page et al. 2011; ShTERNIN et al. 2011; Blaschke et al. 2012, 2013; Newton et al. 2013; Sedrakian 2013; Bonanno et al. 2014). Since the thermal evolution is quite sensitive to the EOS of NS matter, in particular to its composition and superfluid states, one may glean crucial information and knowledge of the NS interior from its study. Thus, the exploration of NS cooling might solve some difficult issues in nuclear physics, for instance, the density dependence of symmetry energy at supranuclear densities. The NS cools down via neutrino emission from the stellar interior in the first $10^5$ years (Yakovlev & Pethick 2004), and several types of neutrino sources in the NS cores have been proposed as cooling mechanisms, such as the direct Urca (DU), modified Urca (MU) processes, and nucleon–nucleon (NN) bremsstrahlung (see the review articles Yakovlev et al. 1999, 2001; Page et al. 2004, 2006).

It has been stressed that NS cooling relies on many factors (Yakovlev et al. 1999), including the neutrino emission mechanisms, heat capacity, thermal conductivity, and reheating mechanisms in dense and superfluid states of matter. The latter has to be described as a quasi-degenerate Fermi system characterized by a large depletion of the Fermi surface due to the strong short-range correlations of NN interaction (Migdal 1967). The Z factor, which measures the deviation from a perfect Fermi gas described by the Fermi–Dirac distribution ($Z = 1$), can take values much less than one. This fact influences the level density of nucleons around the Fermi surface that controls many properties of fermion systems related to particle-hole excitations around the Fermi energy. In our previous work, the Z factor effect on the $^3$PF$_2$ superfluidity of pure neutron matter was studied (Dong et al. 2013) and it was found that the gap was dramatically reduced. In this work, we generalize the previous approach to investigate the neutron $^3$PF$_2$ superfluidity of asymmetric nuclear matter and $\beta$-stable matter. The NS interior is assumed to be made of npe$\mu$ matter without exotic degrees of freedom. In such a context the Z factor effects on various neutrino processes, on heat capacity, and on NS cooling are calculated. The paper is organized as follows. In Section 2, superfluidity, various neutrino processes, and heat capacity affected by the Fermi surface depletion are respectively calculated and analyzed. Based on those results as inputs, the NS cooling is discussed in Section 3. Finally, a summary is given in Section 4.

2. QUASI-DEGENERATE NUCLEAR MATTER IN BETA-STABLE STATE: SUPERFLUIDITY, NEUTRINO EMMISSIVITY, AND HEAT CAPACITY

The deviation of a correlated Fermi system from the ideal degenerate Fermi gas is measured by the quasi-particle strength (Migdal 1967)

$$
Z(k) = \left[1 - \frac{\partial \Sigma(k, \omega)}{\partial \omega}\right]_{\omega=\epsilon(k)}^{-1},
$$

where $\Sigma(k, \omega)$ is the self-energy as a function of momentum $k$ and energy $\omega$. According to the Migdal–Luttinger theorem (Migdal 1957; Luttinger 1960), the Z factor at the Fermi surface equals the discontinuity of the occupation number at the Fermi surface. We calculated the Z factors in the framework of the Brueckner–Hartree–Fock (BHF) approach by employing the AV18 two-body force with a microscopic...
three-body force (Li et al. 2008). The self-energy is truncated to the fourth order of the expansion in powers of $G$-matrix (Jeukenne et al. 1976; Day 1978), namely, $\Sigma = \Sigma_1 + \Sigma_2 + \Sigma_3 + \Sigma_4$. Figure 1 displays, for the sake of illustration, the occupation probability of neutrons and protons in strongly symmetric nuclear matter. The momentum distribution around the Fermi surface significantly departs from the typical profile of a degenerate Fermi system, especially at high densities, which is attributed to the strong short-range correlations. In Figure 2, we show the $Z$ factors at the Fermi surface $Z_F$ calculated for nuclear matter in a $\beta$-stable state, suitable for application to NSs. The fraction of each component is determined by the EOS of nuclear matter from a BHF approximation.

In $\beta$-stable nuclear matter, the effect of the neutron–proton $^3S_1$ coupling tensor channel (namely, $I = 0$ SD channel where $I$ is the total isospin of two nucleons) of the nuclear interaction drives the deviation of neutron and proton $Z$ factors versus total density. At very low density the system is mainly composed of neutrons and the neutron $Z_F$ is that of a degenerate Fermi gas weakly interacting with few protons. On the contrary, the very diluted proton fraction is strongly interacting, via the $I = 0$ force, with large neutron excess, resulting in a strong depletion of the proton momentum distribution at low density. As the total density increases, the proton fraction density also increases for the competition with $I = 1$ force, inducing an increasing $Z_F$ value. Therefore, from the interplay between the two mechanisms the proton $Z_F$ first increases and then decreases as shown in the figure. The calculated $Z$ factor will be used in the following calculations.

2.1. Neutron $^3PF_2$ Superfluidity

The superfluidity gap at the Fermi surface quenches all processes that involve elementary excitations around the Fermi surface, which could lead to a remarkable effect on the NS cooling. The $^3PF_2$ superfluidity in pure neutron matter has been investigated in a previous work with the inclusion of the $Z$ factor (Dong et al. 2013). Here we generalize the investigation to isospin-asymmetric nuclear matter in a $\beta$-stable condition. The $^3PF_2$ pairing gaps are determined by the following coupled equations:

$$\begin{align*}
\langle \Delta_L(k) \rangle = & -\frac{1}{\pi} \int_0^\infty d\epsilon \epsilon \langle Z(k)Z(k') \rangle \times \left( V_{L,L}(k,k') V_{L+2,L+2}(k,k') \right) \\
& \times \frac{\Delta_L(k')}{\Delta_L(k')},
\end{align*}$$

with $E_k = \sqrt{\epsilon(k) - \mu^2 + \Delta_0^2}$ and $\Delta = \sqrt{\Delta_L^2 + \Delta_{L+2}^2}$. $V_{L,L}(k,k')$ is the matrix element of the realistic NN interaction including three-body forces. Here, the angle-average approximation is adopted, and the relation between the gap at $T = 0$ and the critical temperature $T_c$ is given by $k_B T_c = 0.57 \Delta$ ($T = 0$) (Baldo et al. 1992).

The calculated neutron $^3PF_2$ gaps for the $\beta$-stable matter are depicted in Figure 3, with $Z = 1$ (upper panel) and $Z = 1$ (lower panel). Similar to the case of pure neutron matter (Dong et al. 2013), the $Z$ factor effect quenches the peak value by about one order of magnitude, and it is extremely sizable at higher densities. Ding et al. (2015) calculated the influence of short-range correlations on the $^3PF_2$ pairing gap in pure neutron matter at high density with a different method, and also found that the gap is strongly suppressed. The peak value drops to 0.04 MeV and the superfluidity domain shrinks to 0.1–0.4 fm$^{-3}$. Such a weak superfluidity is not expected to explain the observed rapid cooling of NSs in the case of Cas A via the enhanced neutrino emission from the onset of the breaking and formation of neutron $^3PF_2$ Cooper pairs. Therefore, the role of the $^3PF_2$ superfluidity in NS cooling is limited. The $^3PF_2$ pairing gaps do not change very much, even if the fraction of each component is controlled by a soft symmetry energy, such as in the case of APR EOS (Akmal et al. 1998).

To further explore the $^3PF_2$ superfluidity, the neutron gaps as a function of the total nucleonic density $\rho$ for different isospin asymmetries $\beta$ were calculated, and the results are shown in Figure 4. The isospin asymmetry is defined as $\beta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$, where $\rho_n$ and $\rho_p$ are the neutron and proton density, respectively. As $\beta$ increases, the neutron density for a given total nucleonic density increases as well. Accordingly, the peak value of the gap increases and their
corresponding location shifts to lower density, which is primarily attributed to the decrease of the neutron Z factor for increasing β. Due to the departure of the system from the ideal degenerate limit, the neutron $^3PF_2$ gap is dramatically suppressed and the peak value is no more than 0.05 MeV. For the nuclear matter with small isospin asymmetry, the gap may be vanishingly small. Therefore, in finite nuclei, the pairing coming from the $^3PF_2$ channel is completely negligible.

2.2. Neutrino Emission

Since the deformation of the Fermi surface hinders particle-hole excitations around the Fermi level, the neutrino emission is accordingly expected to be depressed. To determine the neutrino emissivity, the key step is to derive the nucleon momentum distribution $n(k)$

$$n(k) = \int \frac{d\omega}{2\pi} S(k, \omega)f(\omega),$$

(3)

at finite temperature $T$ and $Z$ (Kadanoff & Baym 1962).

The spectral function $S(k, \omega)$ is a weighting function with total weight unity. $f(\omega) = 1/\left[1 + \exp\left(-\frac{\omega - \mu}{T}\right)\right]$ is Fermi distribution with temperature $T$ and chemical potential $\mu$. In the limit when $k$ is extremely close to the Fermi momentum, the spectral function $S(k, \omega)$ can be expressed as

$$S(k, \omega) \approx Z(k)\delta(\omega - \omega_F), \, k \approx k_F.$$ (4)

As a consequence, the momentum distribution function $n(k)$ of nucleons close to the Fermi surface is given as

$$n(k) = \frac{Z_F}{1 + \exp\left(\frac{\omega - \mu}{T}\right)} - \frac{k}{k_F},$$ (5)

The most efficient neutrino emission is provided by DU processes in the NS core

$$n \rightarrow p + l + \nu_l, \, p + l \rightarrow n + \nu_l,$$ (6)

which correspond to neutron beta decay and proton electron capture, respectively. The DU process occurs only if the proton fraction is sufficiently high. We derive the neutrino emissivity $Q^{(\text{DU})}$ of the DU process under the beta equilibrium condition with the inclusion of the Z factor. It is given by

$$Q^{(\text{DU})} = 2 \int \frac{\varepsilon dk_n}{(2\pi)^3} \epsilon dW_{l-f} n_n(k)$$

$$\times [n_p(k)|_{T=0} - n_p(k)](1 - f_l),$$ (7)

where $dW_{l-f}$ is the beta decay differential probability, $n_p(k)$ is the distribution function of nucleons including the $Z$ factor, and $f_l$ is the Fermi–Dirac distribution function of leptons. Since the main contribution to this integral stems from the very narrow regions of momentum space close to the Fermi surface of each particle, the distribution function of Equation (5) can be employed here, and thus the above Equation (7) reduces to

$$Q^{(\text{DU})} \approx 2 \int \frac{\varepsilon dk_n}{(2\pi)^3} Z_{F,n} \frac{Z_{F,n}}{1 + \exp\left(-\frac{\omega - \mu_n}{T}\right)}$$

$$\times (1 - f_l)$$

$$= 2Z_{F,n}Z_{F,p} \int \frac{\varepsilon dk_n}{(2\pi)^3} dW_{l-f} f_n(1 - f_n)(1 - f_l),$$ (8)

where $Q_0^{(\text{DU})}$ is the neutrino emissivity of the DU process without introducing the Z factor, which has been thoroughly studied (see, e.g., the review papers, Yakovlev et al. 1999, 2001).

It is usually believed that some of the main neutrino energy loss processes in NSs are the MU processes, which are several orders of magnitude less efficient than the DU processes. The MU processes differ from the direct one by a bystander nucleon required to allow momentum conservation

$$n + N \rightarrow p + N + l + \nu_l, \, p + N + l \rightarrow n + N + l,$$ (9)

where N denotes a neutron or proton. It is labeled by the superscript MN, where N = (n,p) denotes the neutron (proton) branch of the MU processes. Analogous to the procedure for

Figure 3. Neutron $^3PF_2$ gap vs. total baryonic density in $\beta$-stable nuclear matter. The calculations with $Z = 1$ and $Z = 1$ are shown for comparison.

Figure 4. Neutron $^3PF_2$ gap as a function of nucleonic density in asymmetric matter for various isospin asymmetries $\beta$. 

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the DU processes, we derive the neutrino emissivity under the condition of beta equilibrium:

\[
Q^{(\text{Mn})} = Z_{\text{F,n}}^3 Z_{\text{F,p}}^3 Q_0^{(\text{Mn})}, \\
Q^{(\text{Mp})} = Z_{\text{F,n}} Z_{\text{F,p}}^3 Q_0^{(\text{Mp})}.
\] (10)

The NN bremsstrahlung process

\[
N + N \rightarrow N + N + \nu + \tau,
\] (11)
is another neutrino process based on neutral current that produces \(\nu\)\(\tau\) pairs to take away the NS thermal energy, but is much less efficient than the MU processes. The corresponding neutrino emissivities, with the inclusion of the Z factor, are

\[
Q^{(\text{nn})} = Z_{\text{F,n}}^2 Q_0^{(\text{nn})}, \\
Q^{(np)} = Z_{\text{F,n}} Z_{\text{F,p}}^2 Q_0^{(np)}, \\
Q^{(pp)} = Z_{\text{F,n}}^2 Q_0^{(pp)}.
\] (12)

The onset of pairing also opens a new channel of neutrino emission due to the continuous formation and breaking of Cooper pairs

\[
N + N \rightarrow [\text{NN}] + \nu + \tau,
\] (13)
that leads to energy release via \(\nu\)\(\tau\) emission, analogous to the NN bremsstrahlung process. It is very intense at temperatures slightly below the critical temperature \(T_c\) (Page et al. 2006, 2009), and it can be one order of magnitude more efficient than the pairing of unsuppressed \(\nu\nu\) processes (Page et al. 2006). This Cooper pair breaking and formation (PBF) process due to neutron \(^3\)PF\(_2\) pairing may be employed to explain the observed rapid cooling of the NS in Cas A (Page et al. 2011). With the inclusion of the Z factor, the neutrino emissivity \(Q\) is given as

\[
Q^{(\text{PBF,n})} = Z_{\text{F,n}}^2 Q_0^{(\text{PBF,n})}.
\] (14)

Figure 5 displays the calculated \(Q/Q_0\) for the DU, MU, and \(\nu\nu\) bremsstrahlung processes as a function of density \(\rho\). The DU process occurs just when the proton fraction exceeds a critical threshold, and the threshold relies on the density dependence of the symmetry energy at high densities. A stiff symmetry energy, such as that from the Brueckner theory, gives a low threshold. Frankfrett et al. (2008) showed that the modification of the nucleon momentum distribution due to the short-range correlations results in a significant enhancement of the neutrino emissivity of the DU process, and the DU process has a probability of being opened even for low proton fractions. However, our calculations reveal that the neutrino emissivity is reduced by more than \(\approx 50\%\), which is in complete contrast to their conclusion. We stress that the short-range correlations responsible for the Fermi surface depletion should be embodied in the quasi-particle properties because the real system is actually a degenerate system of quasi-particles with the same Fermi momentum as the previous one. Therefore, the kinematic conditions giving rise to the threshold for the DU process does not change. The beta decay of neutrons and its inverse reaction can be cyclically triggered just by thermal excitation, and thus \(k > k_F\) and \(k < k_F\) states do not participate in the DU process because the thermal energy \(\sim k_B T\) is too low to excite those states. Accordingly, the occupation probability of a proton hole for the thermal excitation, namely \([n_p(k)]_{\rho<0} - n_p(k)\), should be employed in Equation (7), instead of \([1 - n_p(k)]\). The neutrino emissivities for the MU processes are reduced by \(>50\%\) for the neutron branch and \(>70\%\) for the proton branch. Because the proton \(Z\) factor is lower than the neutron one, as shown in Figure 2, the \(Q^{\text{MN}}\) of the proton branch is more intensively depressed by the Fermi surface depletion. At high densities such as \(\rho = 0.8\,\text{fm}^{-3}\), the \(Q^{\text{MN}}\) is reduced by one order of magnitude. Similarly, the NN bremsstrahlungs for \(n-n\), \(n-p\), and \(p-p\) are reduced more distinctly at high densities. The computed \(Q/Q_0\) for those processes do not rely on whether or not the superfluidity set on. The \(Q/Q_0\) with a soft symmetry energy from APR (Akmal et al. 1998) does not provide very different results compared with those within BHF for the MU, NN bremsstrahlung, and PBF processes, but the threshold of the DU process is much larger due to the softer symmetry energy.

2.3. Heat Capacity

The specific heat capacity of the stellar interior is the sum of the contributions of each fraction \(i\) (leptons and nucleons; Page et al. 2004)

\[
c_v = \sum_i c_{v,i}, \quad \text{with } c_{v,i} = \left(\frac{m_i^* p_{E,i}}{3 h^3}\right) k_B^2 T.
\] (15)
4. SUMMARY

We have investigated the superfluidity, neutrino emissivity for DU, MU, NN bremsstrahlung, and PBF processes, and heat capacity, taking into account the Fermi surface depletion characterized by the Z factor. The Z factor is calculated in the framework of the BHF approach using the two-body AV18 force plus a microscopic three-body force. The superfluidity, neutrino emissivity, and heat capacity are reduced by the Z factor, especially at high baryonic density. The effect of the Fermi surface depletion is needed to be included in a theoretically rigorous exploration of the NS thermal evolution, such as that for the NS remnant in Cas A whose cooling rate was measured. Finally, based on the above results, we calculated the cooling curve for canonical NSs using the APR EOS, and we found that the Fermi surface depletion visibly affects the NS cooling.

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Figure 6. Cooling curves of a canonical NS. The stellar structure is built with the APR EOS. The calculations without any Z factors, with Z factors only in superfluidity, with Z factors both in superfluidity and neutrino emission, and with Z factors in the three inputs, are shown for comparison. The inset shows the neutron and proton Z factors vs. density in $\beta$-stable matter, the fraction of each component being determined by the APR EOS.

$m_i^*$ and $p_{F,i}$ are effective mass and Fermi momentum of particle $i$. This equation is obtained under the assumption of non-correlated gas described by the Fermi–Dirac distribution. If the effect of the Fermi surface depletion is included, the specific heat of the nucleon $i$ is given by

$$c_{v,i} = Z_{F,i} \left( \frac{m_i^* p_{F,i}}{3\hbar^3} \right) k_B^2 T, \quad i = n, p.$$  \hspace{1cm} (16)

The heat capacity can still be altered by strong superfluidity.

3. NS COOLING

To show the influence of the Z-factor-induced reduction of the above three inputs, namely pairing gaps, neutrino emissivity, and heat capacity, on NS cooling, we calculated the cooling curve for canonical NSs using the publicly available code NSCool.4 We employ the minimal cooling paradigm (Page et al. 2006) without fast neutrino emission, with no charged meson condensate, no hyperons, and no confinement quarks in canonical NSs. Therefore, we select the APR EOS and the above results as inputs, and the cooling curves are displayed in Figure 6.

The Z factor suppressing the neutron $^3PF_2$ superfluidity retards the NS cooling for the first $3 \times 10^3$ years but accelerates the cooling thereafter. The critical temperature $T_c$ for neutron $^3PF_2$ superfluidity is quite low as a result of the inclusion of Z factor. Therefore, the PBF cooling channel opens as soon as the stellar temperature falls below $T_c$, which leads to a relatively fast cooling because it is more efficient than MU processes. The weak neutron $^3PF_2$ superfluidity, dramatically quenched by the Fermi surface depletion, cannot play a significant role in the cooling of young NSs. The Z factor substantially reduces the neutrino emission of MU, NN bremsstrahlung, and PBF processes, and thus it slows down the thermal energy loss. Therefore, it significantly retards the cooling. The heat capacity of the NS is reduced by the Z factor, with the result that the thermal energy becomes lower than in the case of excluding the Z factor effect. As a consequence, the NS cooling turns out to be enhanced, but this effect is not so sharp, as shown in Figure 6. It is well-known that the neutrino emission and heat capacity are sensitive to the superfluidity of the stellar interior. However, due to the weak neutron $^3PF_2$ superfluidity reduced by the Z factor, neutrino emissivity and heat capacity cannot be suppressed.
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