Effects of δ mesons on baryonic direct Urca processes in neutron star matter*

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Abstract: This study investigates the relativistic neutrino emissivity of the nucleonic and hyperonic direct Urca processes in the degenerate baryon matter of neutron stars, within the framework of relativistic mean field theory. In particular, we study the influence of the isovector scalar interaction on the nucleonic and hyperonic direct Urca processes by exchanging δ mesons. The results indicate that δ mesons lead to obvious enhancement of the total neutrino emissivity, which must result in a more rapid cooling rate of neutron star matter.

Key words: neutron star, direct Urca processes, δ meson, neutrino emissivity

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1 Introduction

Compact stellar object studies allow us to build a better and more comprehensive understanding of the properties of nuclear matter under extreme conditions. Neutron stars (NS) are an ideal model for studies of dense matter physics. They are the remnants of supernovae explosions with an internal temperature as high as 10^{11}–10^{12} K, cooling within minutes to 10^{10} K by emitting neutrinos [1–5]. Then the long-term cooling process is mainly through neutrino emission in the NS interior over about 10^6 years. The primary mechanisms in the cooling stage can be divided into two categories: (1) enhanced neutrino processes, which include the nucleonic direct Urca (NDURCA) processes and hyperonic direct Urca (YDURCA) processes, and (2) standard neutrino processes, such as modified Urca processes and Bremsstrahlung processes. NS cooling properties tend to be dominated by whichever reaction has the highest neutrino emissivity. It is well known that NDURCA processes produce the most powerful neutrino emissivity, followed by YDURCA processes in the NS core, which are more efficient than standard processes [6–8]. In these works, the formulae of neutrino emissivity for NDURCA and YDURCA processes are still non-relativistic. In fact, the threshold densities for NDURCA and YDURCA processes are larger than the nuclear saturation density. Above the threshold densities, the baryonic motion is relativistic in the NS core. Thus the relativistic formulae should be used to calculate the neutrino emissivity for NDURCA and YDURCA processes. Meanwhile the equation of state (EOS) must be relativistic, which can be consistent with the relativistic approach. The relativistic mean field theory (RMFT) is an effective model for studying the properties of NSs [9–15]. The standard RMFT includes isoscalar-scalar meson σ, isoscalar-vector meson ω and isovector-vector meson ρ. The isovector scalar channel is usually not included because it is not expected to be essential to nuclei. However, the isovector scalar interaction could have an important role for asymmetric nuclear matter. It can be introduced through a coupling to the δ ($a_0(980)$) meson which has been studied by many authors [16–24]. These studies have shown that δ mesons have definite contributions to isospin-asymmetric nuclear matter, especially at high densities. NSs keep away from isospin-symmetric nuclear matter due to charge neutrality. Therefore, in this work we extend the analysis of the contribution of the δ field in dense asymmetric matter to NS matter. When an NS includes δ mesons, the δ field not only changes the abundance of neutrons, protons and hyperons, but also changes the bulk properties of the NS, which must affect the neutrino emissivity of the NDURCA and YDURCA processes.

In this work, we use the RMFT including σ, ω, ρ and δ mesons with additional cubic and quartic nonlinearities of σ meson to describe baryonic interactions. The σ and ω mesons supply medium-range attractive and

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short-range repulsive interactions between baryons, respectively. The δ and ρ mesons provide the corresponding attractive and repulsive potentials in the isovector channel, respectively. We adopt the simplest NS model, assuming an NS core consists of n, p, Λ, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0, e and μ. This work mainly focuses on the effects of the δ meson on the total neutrino emissivity for NDURCA and YDURCA processes in the NS core.

2 Models

The effective Lagrangian function for the RMFT can be written as follows:

$$\begin{aligned}\mathcal{L} = &\sum_{\mathrm{B}}\overline{\Psi}_{\mathrm{B}}[\mathrm{i}\gamma_\mu\partial^\mu-(m_{\mathrm{B}}-g_{\delta\mathrm{B}}\boldsymbol{\tau}\cdot\boldsymbol{\delta}-g_{\sigma\mathrm{B}}\sigma)-g_{\omega\mathrm{B}}\gamma_\mu\omega^\mu\\ &-g_{\rho\mathrm{B}}\boldsymbol{\tau}\cdot\boldsymbol{\rho}^\mu]\Psi_{\mathrm{B}}+\frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma-m_\sigma^2\sigma^2)-U(\sigma)\\ &+\frac{1}{2}m_\omega^2\omega_\mu\omega^\mu+\frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu+\frac{1}{2}(\partial_\mu\boldsymbol{\delta}\partial^\mu\boldsymbol{\delta}-m_\delta^2\boldsymbol{\delta}^2)\\ &+\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-\frac{1}{4}\boldsymbol{G}_{\mu\nu}\boldsymbol{G}^{\mu\nu}+\sum_{\mathrm{l}}\overline{\Psi}_{\mathrm{l}}[\mathrm{i}\gamma_\mu\partial^\mu-m_{\mathrm{B}}]\Psi_{\mathrm{l}},\end{aligned} \quad (1)$$

where the potential function $U(\sigma)=\frac{1}{3}a\sigma^3+\frac{1}{4}b\sigma^4$, $F_{\mu\nu}=\partial_\mu\omega_\nu-\partial_\nu\omega_\mu$ and $\boldsymbol{G}_{\mu\nu}=\partial_\mu\boldsymbol{\rho}_\nu-\partial_\nu\boldsymbol{\rho}_\mu$.

In the RMFT, the meson fields can be considered as classical fields, where the field operators are replaced by their expectation values. Meson field equations are obtained as follows:

$$m_\sigma^2\sigma+a\sigma^2+b\sigma^3=\sum_{\mathrm{B}}\frac{g_{\sigma\mathrm{B}}}{\pi^2}\int_0^{p_{\mathrm{B}}}\frac{m_{\mathrm{B}}^*k^2}{\sqrt{k^2+m_{\mathrm{B}}^{*2}}}\mathrm{d}k, \quad (2)$$

$$m_\omega^2\omega_0=\sum_{\mathrm{B}}g_{\omega\mathrm{B}}\rho_{\mathrm{B}}, \quad (3)$$

$$m_\rho^2\rho_0=\sum_{\mathrm{B}}g_{\rho\mathrm{B}}I_{3\mathrm{B}}\rho_{\mathrm{B}}, \quad (4)$$

$$m_\delta^2\sigma_0=\sum_{\mathrm{B}}\frac{g_{\delta\mathrm{B}}}{\pi^2}\int_0^{p_{\mathrm{B}}}\frac{m_{\mathrm{B}}^*k^2}{\sqrt{k^2+m_{\mathrm{B}}^{*2}}}\mathrm{d}k, \quad (5)$$

where p_{B} is the baryonic Fermi momentum, $I_{3\mathrm{B}}$ is the baryonic isospin projection, the baryonic density ρ_{B} is expressed by:

$$\rho_{\mathrm{B}}=\frac{p_{\mathrm{B}}^3}{3\pi^2}. \quad (6)$$

The baryonic effective mass m_{B}^* is written:

$$m_{\mathrm{B}}^*=m_{\mathrm{B}}-g_{\sigma\mathrm{B}}\sigma_0-I_{3\mathrm{B}}g_{\sigma\mathrm{B}}\delta_0. \quad (7)$$

Under β equilibrium conditions, the chemical potentials of baryons and leptons satisfy the following relationship:

$$\mu_{\mathrm{B}}=\mu_{\mathrm{n}}-q_{\mathrm{B}}\mu_{\mathrm{e}},\mu_\mu=\mu_{\mathrm{e}}. \quad (8)$$

Under the zero temperature approximation, they are expressed as follows:

$$\mu_{\mathrm{B}}=\sqrt{p_{\mathrm{B}}^2+m_{\mathrm{B}}^{*2}}+g_{\omega\mathrm{B}}\omega_0+g_{\rho\mathrm{B}}\rho_0I_{3\mathrm{B}}, \quad (9)$$

$$\mu_{\mathrm{l}}=\sqrt{p_{\mathrm{l}}^2+m_{\mathrm{l}}^{*2}}. \quad (10)$$

In NS, the conditions of electrical neutrality and baryon number conservation must be satisfied, expressed as follows:

$$\sum_{\mathrm{B}}q_{\mathrm{B}}\rho_{\mathrm{B}}-\rho_{\mathrm{e}}-\rho_\mu=0, \quad (11)$$

$$\sum_{\mathrm{B}}\rho_{\mathrm{B}}=\rho, \quad (12)$$

where ρ is total baryonic density.

The possible neutrino emission processes consist of two successive reactions, beta decay and capture, expressed as follows:

$$\mathrm{B}_1\to\mathrm{B}_2+\mathrm{l}+\overline{\nu}_{\mathrm{l}},\mathrm{B}_2+\mathrm{l}\to\mathrm{B}_1+\nu_{\mathrm{l}}, \quad (13)$$

where B_1 and B_2 are baryons, and l is a lepton. This paper focuses on electron processes. The relativistic neutrino emissivity can be given by the Fermi golden rule. The relativistic expression of the energy loss Q_{R} per unit volume and time is expressed as [25]:

$$\begin{aligned}Q_{\mathrm{R}} = &\frac{457\pi}{10080}G_{\mathrm{F}}^2C^2T^6\Theta(p_{\mathrm{e}}+p_{\mathrm{B}_2}-p_{\mathrm{B}_1})\\ &\times\{f_1g_1[(\varepsilon_{\mathrm{F}_1}+\varepsilon_{\mathrm{F}_2})p_{\mathrm{e}}^2-(\varepsilon_{\mathrm{F}_1}-\varepsilon_{\mathrm{F}_2})(p_{\mathrm{B}_1}^2-p_{\mathrm{B}_2}^2)]\\ &+2g_1^2\mu_{\mathrm{e}}m_{\mathrm{B}_1}^*m_{\mathrm{B}_2}^*+(f_1^2+g_1^2)[\mu_{\mathrm{e}}(2\varepsilon_{\mathrm{F}_1}\varepsilon_{\mathrm{F}_2}-m_{\mathrm{B}_1}^*m_{\mathrm{B}_2}^*)\\ &+\varepsilon_{\mathrm{F}_1}P_{\mathrm{e}}^2-\frac{1}{2}(p_{\mathrm{B}_1}^2-p_{\mathrm{B}_2}^2+p_{\mathrm{e}}^2)(\varepsilon_{\mathrm{F}_1}+\varepsilon_{\mathrm{F}_2})],\end{aligned} \quad (14)$$

where $G_{\mathrm{F}}=1.436\times10^{-49}$ erg·cm^3 is the weak-coupling constant, f_1 and g_1 are the vector and axial-vector constants, and C is the Cabibbo factor. μ_{e} is the chemical potential of an electron, p_{B_1}, p_{B_2} and p_{e} are the Fermi-momenta of baryons B_1, B_1 and electrons, respectively. $\varepsilon_{\mathrm{F}_1}$ and $\varepsilon_{\mathrm{F}_2}$ are the kinetic energy of baryons B_1 and B_1. When $x\geqslant0$, $\Theta(x)=1$, and when $x<0$, $\Theta(x)=0$. The parameters C, f_1, and g_1 for NDURCA and YDURCA in NS matter are listed in Table 1 [26, 27].

Table 1. The constants of NDURCA and YDURCA processes. $\sin\theta_{\mathrm{c}}$=0.231±0.003, F=0.477± 0.012, D=0.756±0.011.

process	transition	C	f_1	g_1
1	$\mathrm{n}\to\mathrm{pe}\bar{\nu}_{\mathrm{e}}$	$\cos\theta_{\mathrm{C}}$	1	$F+D$
2	$\Lambda\to\mathrm{pe}\bar{\nu}_{\mathrm{e}}$	$\sin\theta_{\mathrm{C}}$	$-\sqrt{3/2}$	$-\sqrt{3/2}(F+D/3)$
3	$\Sigma^-\to\mathrm{ne}\bar{\nu}_{\mathrm{e}}$	$\sin\theta_{\mathrm{C}}$	-1	$-(F-D)$
4	$\Sigma^-\to\Lambda\mathrm{e}\bar{\nu}_{\mathrm{e}}$	$\cos\theta_{\mathrm{C}}$	0	$\sqrt{3/2}D$
5	$\Sigma^-\to\Sigma^0\mathrm{e}\bar{\nu}_{\mathrm{e}}$	$\cos\theta_{\mathrm{C}}$	$\sqrt{2}$	$\sqrt{2}F$
6	$\Xi^-\to\Lambda\mathrm{e}\bar{\nu}_{\mathrm{e}}$	$\sin\theta_{\mathrm{C}}$	$\sqrt{3/2}$	$\sqrt{3/2}(F-D/3)$
7	$\Xi^-\to\Sigma^0\mathrm{e}\bar{\nu}_{\mathrm{e}}$	$\sin\theta_{\mathrm{C}}$	$\sqrt{1/2}$	$(F+D)/\sqrt{2}$
8	$\Xi^-\to\Sigma^+\mathrm{e}\bar{\nu}_{\mathrm{e}}$	$\sin\theta_{\mathrm{C}}$	1	$F+D$
9	$\Xi^-\to\Xi^0\mathrm{e}\bar{\nu}_{\mathrm{e}}$	$\cos\theta_{\mathrm{C}}$	1	$F-D$

Solving the coupling equations self-consistently at total baryonic density ρ, one can obtain a list of physical quantities, such as the particle fraction, effective mass, nucleon Fermi momentum. Then the total relativistic neutrino emissivity for NDURCA and YDURCA processes can be obtained.

3 Discussion

A primary contribution for NSs including δ mesons is changing the EOS, which must lead to a change of the bulk properties of NSs [17–19]. We substitute the EOS into the Tolman–Oppenheimer–Volkoff (TOV) equations [28, 29], and the mass-radius relations for NSs can also be obtained. The most important physical quantities for the neutrino emissivity of NDURCA and YDURCA processes are the particle fraction, Fermi momentum and effective mass of nucleon and hyperon. This paper focuses on the effect of the inclusion of δ mesons on NDURCA and YDURCA processes in NSs. Next, we will give the numeric results of the relativistic neutrino emissivity for NDURCA and YDURCA processes with and without δ mesons. The properties of NSs are obtained with the parameter sets presented in Table 2. The hyperon couplings are represented as the ratios to the nucleon coupling $g_{\sigma\mathrm{H}} = 0.7g_{\sigma\mathrm{N}}$, $g_{\omega\mathrm{H}} = 0.7g_{\omega\mathrm{N}}$, $g_{\rho\mathrm{H}} = 0.7g_{\rho\mathrm{N}}$, and $g_{\delta\mathrm{H}}=0.7g_{\delta\mathrm{N}}$.

The mass-radius relations of NSs with and without δ mesons are compared in Fig. 1. The maximum masses $M_{\max}$, the corresponding radii R and center densities ρ_{c} with and without δ mesons are displayed in Table 3. From Fig. 1 and Table 3, one can find that the inclusion of δ mesons leads to a larger radius for an NS with the same mass.

Table 2. Parameter set. f_{i} is the four boson coupling constants, $f_{\mathrm{i}}=(g_{\mathrm{i}}/m_{\mathrm{i}})^2(\mathrm{fm}^2)$, i=σ, ω, ρ, δ, and $A=a/g_\sigma^3(\mathrm{fm}^{-1})$, $B=b/g_\sigma^4$.

parameter	f_σ	f_ω	f_ρ	f_δ	A	B
without δ	10.33	5.42	0.95	0.00	0.033	−0.0048
with δ	10.33	5.42	3.15	2.50	0.033	−0.0048

Table 3. Maximum masses $M_{\max}$, and corresponding radii R and center densities ρ_{c} with and without δ mesons.

parameter	$M_{\max}/M_{\mathrm{s}}$	R	ρ_{c}
without δ	1.72	10.40	1.23
with δ	1.70	10.58	1.20

The particle fraction Y_{i} as a function of the total baryonic density ρ, with or without δ mesons is shown in Fig. 2. As seen in Fig. 2, whether or not the δ meson is included, the Σ, Λ and Ξ appear one by one. This is because a hyperonic type is populated only if its chemical potential exceeds its lowest energy state in NS matter, e.g. $\mu_{\mathrm{n}}-q_{\mathrm{B}}\mu_{\mathrm{e}}\geqslant m^*_{\mathrm{B}}+g_{\omega\mathrm{B}}\omega_0+g_{\rho\mathrm{B}}\rho_0 I_{3\mathrm{B}}$. So when the thresholds are reached, additional hyperonic species are populated. As shown in Fig. 2, the inclusion of δ mesons changes the baryonic threshold conditions, the threshold densities of p, Λ, Σ^0, Σ^- and Ξ^0 with δ mesons are shifted to lower densities. The fractions Y_{p}, Y_Λ, Y_{Σ^0}, Y_{Σ^-} and Y_{Ξ^0} with δ mesons are larger than the corresponding values without δ mesons. Then according to Eq. (6), when the δ field is included, p_{p}, p_Λ, p_{Σ^0}, p_{Σ^-} and p_{Ξ^0} are larger than the corresponding values without the δ field. From Fig. 2, we can also see that the inclusion of δ mesons makes the fractions Y_{n}, Y_{Σ^+} and Y_{Ξ^-} decrease due to the charge neutrality and β-equilibrium conditions. The changes of baryonic fractions must change the neutrino emissivity of NDURCA and YDURCA processes.

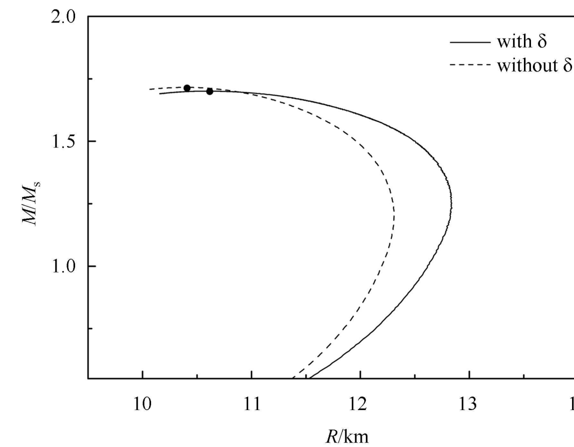

Fig. 1. The mass-radius relations for NS with and without δ mesons. The dots stand for the NS maximum masses for the two cases.

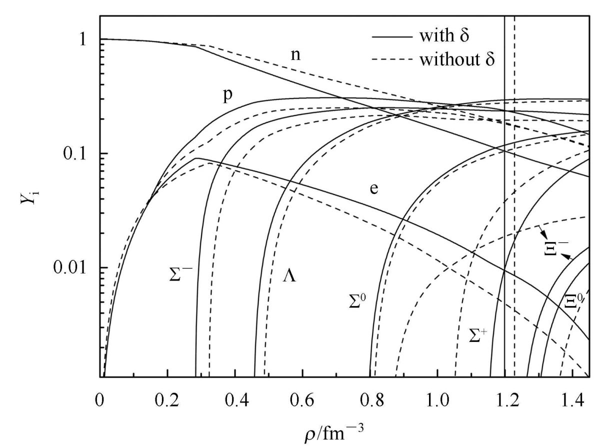

Fig. 2. The particle fractions of baryons and leptons as a function of the total baryonic density ρ with and without δ mesons. The two vertical lines represent the maximum center densities of the maximum masses NS with and without δ mesons.

Figure 3 represents the hyperonic effective masses of hyperons as a function of the total baryonic density ρ with and without δ mesons. According to Eq. (7), the δ field strength is directly related to the baryonic effective mass. From Fig. 3, one can find the effective mass splitting for hyperons with similar species but different isospins. The relativistic neutrino emissivity of NDURCA and YDURCA processes as a function of the total baryonic density ρ with and without δ mesons are plotted in Fig. 4. One can find in Fig. 4 the different direct Urca reactions 1–9 in Table 1 appear with increasing of the total baryonic density ρ. When the reaction 4 (or 5) happens in NS matter with (or without) δ mesons, the relativistic neutrino emissivity Q_{R} reaches a maximum value. However, reactions 6–9 (or 8 and 9) with (or without) δ mesons would never have happened within stable NSs, because they occur at higher densities which are larger than the center densities of the maximum masses NSs. As shown in Fig. 4, whether or not the δ meson is included in NS matter, reactions 2 and 3 occur as long as Λ and Σ^- hyperon appear. Namely, the triangle condition $p_{\mathrm{B}_2}+p_{\mathrm{E}}>p_{\mathrm{B}_1}$ in Eq. (14) is satisfied automatically for reactions 2 and 3 if Λ, Ξ^- hyperons appear in NS core. The occurrence of reactions 2 and 3 does not need Y_Λ, Y_{Σ}^- reach a certain quantity; they are much more likely to happen than the other direct Urca reactions.

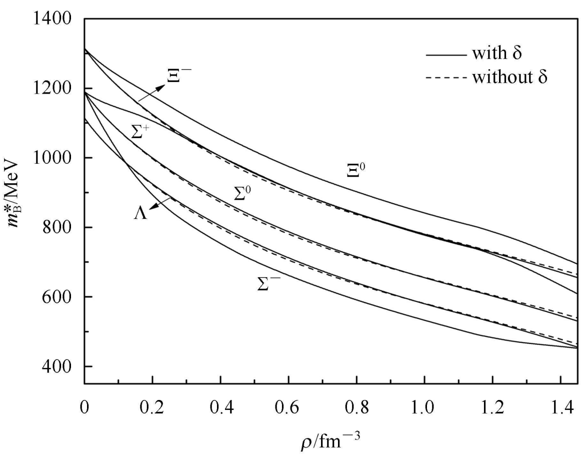

Fig. 3. The hyperonic effective masses as a function of the total baryonic density ρ with and without δ mesons.

Reactions 4 and 5 (or 4–7) with (or without) δ mesons occur later. Reactions 6 and 7 only occur in NSs without inclusion of δ mesons. As shown in Fig. 4, when δ mesons are included, the relativistic neutrino emissivity Q_{R} is obviously larger than the corresponding values without δ mesons. It may be concluded that the inclusion of δ mesons would accelerate nonsuperfluid NS cooling in most mass ranges of NDURCA and YDURCA processes.

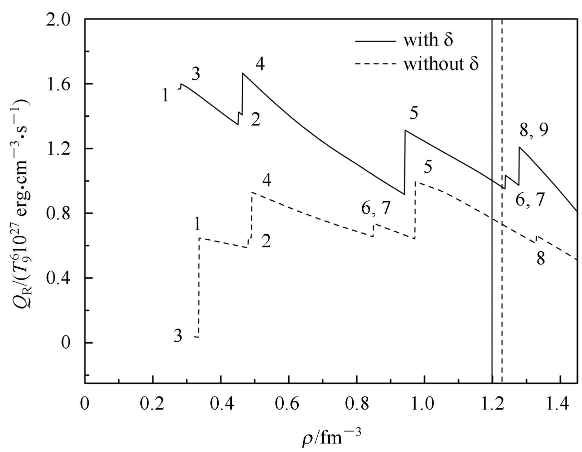

Fig. 4. The relativistic neutrino emissivity Q_{R} as a function of the total baryonic density ρ with and without δ mesons in NS matter. The two vertical lines represent the center densities of the maximum masses NS with and without δ mesons.

4 Conclusions

We have shown the influence of δ mesons on the relativistic neutrino emissivity for NDURCA and YDURCA processes by adopting the RMFT in NS matter. Results show that the inclusion of δ mesons makes the baryonic threshold densities change in NS matter, which leads to the threshold densities of reactions 1–5 changing. Furthermore, the inclusion of δ mesons makes processes 6–9 with δ mesons impossible to occur within stable NS matter. The fractions of p, Λ, Σ^0, Σ^- increase, which leads to an obvious enhancement of the relativistic neutrino emissivity in NS matter. Thus the δ mesons would speed up the nonsuperfluid NS cooling rate in most mass ranges of NDURCA and YDURCA processes which occur.

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