CPC(HEP & NP), 2011, **35**(9): 812–816 **Chinese Physics C** Vol. 35, No. 9, Sep., 2011

Effects of the δ meson on the direct Urca processes in neutron stars*

YU Zi(喻孜)[1;1)] DING Wen-Bo(丁文波)[2]

[1] College of Science, Nanjing Forestry University, Nanjing 210037, China
[2] Physics Department of Bohai University, Jinzhou 121000, China

Abstract: In the framework of the relativistic mean field theory, the effects of the δ meson on the direct Urca (DURCA) processes are investigated. In a neutron star, the DURCA processes involving nucleons, Λ and Ξ^- can take place while the process involving the Ξ^0 can not. With the inclusion of the δ meson, the threshold densities for the DURCA processes become lower. With the δ included, the threshold neutron star mass for the DURCA process among nucleons and electrons becomes smaller while the threshold masses for the processes involving hyperons become larger. When the δ meson is included, the total neutrino emissivity remarkably increases in the density range of 0.32–0.41 fm^{-3}. The total neutrino luminosity increases with the neutron star mass first and then decreases. The neutrino luminosity gets larger with the inclusion of the δ meson. The cooling of the EXO0748-676 is sensitive to the isovector scalar interaction.

Key words: isovector-scalar interaction, neutron star, direct Urca process

PACS: 26.60.+c, 21.65.+f, 21.30.Fe **DOI:** 10.1088/1674-1137/35/9/004

1 Introduction

A neutron star is born at an interior temperature greater than 10^{11} K immediately after the supernova explosion, however, the temperature drops to 10^9 K after several minutes. Neutrino emission dominates the cooling of the star over the first 10^4-10^5 years until the temperature falls to $<10^6$ K and the photon emission overtakes neutrino emission. With the development of observations and theoretical knowledge, much greater attention is being paid to the cooling of neutron stars [1–7]. So far, the cooling models have been divided into two categories: slow cooling [1, 8] and enhanced cooling [3, 4, 9]. The latter mainly includes the direct Urca (DURCA) process. The cooling via the DURCA process is more rapid than that via the other processes. The previous researches show that the neutrino emissivity from the DURCA porcess depends sensitively on the composition of the Neutron star core.

The relativistic mean field theory (RMFT) is now widely used to describe the neutron star core. The RMFT includes σ-ω-ρ mesons. The isovector scalar channel is never contained since it is not expected to play an important role for the nuclei. The isovector scalar channel can be introduced through a coupling to δ ($a_0(980)$) meson and actually the δ-meson exchange is an essential ingredient of all nucleon-nucleon realistic potentials. The role of the δ meson was studied some years ago [10, 11]. Previous investigations indicated that this isovector scalar meson had definite contributions to isospin-asymmetric matter, leading to a harder equation of state (EOS) at densities larger than $\sim 1.5\rho_0$. Therefore, in dense matter such as neutron star matter, the effects of the δ meson should be important and the isovector scalar channel should be turned on. At present, neutron stars with the inclusion of the δ meson have been investigated [12–17]. These investigations show that the composition of the neutron star is changed when the δ meson is included. Consequently, the DURCA process in the neutron star should also be changed. An interesting issue is that of what the effects of the δ meson are on the DURCA process. Moreover, the hyperons may

Received 8 November 2010

* Supported by National Natural Science Foundation of China (10675024, 11075063) and Natural Science Fundamental Research Project of Jiangsu Colleges and Universities (10KJB140002)

1) E-mail: ziyu1981@gmail.com

appear in neutron stars since their presence can soften the EOS. In fact, some authors [5, 18] have studied the DURCA process involving hyperons. The hyperon species they considered are Λ,Σ and Ξ. However, recent research [19–21] seems to show that the Σ hyperon could not exist in neutron stars. The exclusion of the Σ hyperon changes the composition of the neutron star and consequently should change the DURCA processes. We may ask how the neutrino emissivity via the DURCA processes changes after the Σ hyperon is excluded. This article aims to answer the above questions in the framework of the RMFT with the δ meson included.

2 The theory model

In the RMFT, the Lagrangian density of neutron star including the δ meson is,

$$L = L_{\rm B} + L_{\rm M} + L_{\rm l}, \tag{1}$$

with,

$$L_{\rm B} = \sum_{\rm B} \overline{\psi}_{\rm B}[{\rm i}\gamma_\mu \partial^\mu - (M_{\rm B} - g_{\delta{\rm B}}\vec{\tau}\cdot\vec{\delta} - g_{\sigma{\rm B}}\sigma) - g_{\omega{\rm B}}\gamma_\mu\omega^\mu - g_{\rho{\rm B}}\gamma_\mu\vec{\tau}\cdot\vec{\rho^\mu}]\psi_{\rm B}, \tag{2}$$

$$L_{\rm M} = \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) - U(\sigma) + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{2}m_\rho^2\vec{\rho_\mu}\cdot\vec{\rho^\mu} + \frac{1}{2}(\partial_\mu\vec{\delta}\cdot\partial^\mu\vec{\delta} - m_\delta^2\vec{\delta}^2) - \frac{1}{4}F^{\mu v}F_{\mu v} - \frac{1}{4}G^{\mu v}G_{\mu v}, \tag{3}$$

and $L_{\rm l}$ standing for the contribution from leptons.

$$F_{\mu v} = \partial_\mu\omega_v - \partial_v\omega_\mu, \quad G_{\mu v} = \partial_\mu\vec{\rho}_v - \partial_v\vec{\rho_\mu},$$

and

$$U(\sigma) = \frac{1}{3}a\sigma^3 + \frac{1}{4}b\sigma^4$$

[15]. The baryon species are denoted by B. In neutron star matter, the chemical equilibrium among baryons and leptons implies the relation,

$$\mu_{\rm B} = \mu_{\rm n} - q_{\rm B}\mu_{\rm e}.$$

Electrical neutrality requires

$$q_{\rm B}\rho_{\rm B} + q_{\rm e}\rho_{\rm e} + q_\mu\rho_\mu = 0, \tag{4}$$

where $q_{\rm B}$ stands for the electric charge of baryon B. In the mean field approximation, the field equations for mesons are,

$$\sum_{\rm B} g_{\sigma{\rm B}}\rho_{\rm SB} = m_\sigma^2\sigma + a\sigma^2 + b\sigma^3, \tag{5}$$

$$\sum_{\rm B} g_{\omega{\rm B}}\rho_{\rm B} = m_\omega^2\omega_0, \tag{6}$$

$$\sum_{\rm B} g_{\rho{\rm B}}\rho_{\rm B}I_{3{\rm B}} = m_\rho^2\rho_0, \tag{7}$$

$$\sum_{\rm B} g_{\delta{\rm B}}\rho_{\rm SB}I_{3{\rm B}} = m_\delta^2\delta_0, \tag{8}$$

where $\rho_{\rm SB}$ and $\rho_{\rm B}$ are the scalar and vector densities of baryon B, respectively. They are,

$$\rho_{\rm SB} = \frac{1}{\pi^2}\int_0^\infty {\rm d}kk^2\frac{M_{\rm B}^*}{\sqrt{k^2+M_{\rm B}^{*2}}}, \tag{9}$$

$$\rho_{\rm B} = \frac{1}{\pi^2}\int_0^\infty {\rm d}kk^2. \tag{10}$$

Here, $M_{\rm B}^*$ denotes the effective mass of baryon B,

$$M_{\rm B}^* = M_{\rm B} - g_{\sigma{\rm B}}\sigma_0 - I_{3{\rm B}}g_{\delta{\rm B}}\delta_0. \tag{11}$$

where $I_{3{\rm B}}$ denotes the isospin of the baryon B.

Solving the above equations consistently, the DURCA processes can be calculated. The four reactions among baryons and electrons are as follows:

$${\rm n} \longrightarrow {\rm p} + {\rm e} + \overline{\nu_{\rm e}} \quad ({\rm A}),$$

$$\Lambda \longrightarrow {\rm p} + {\rm e} + \overline{\nu_{\rm e}} \quad ({\rm B}),$$

$$\Xi^- \longrightarrow \Lambda + {\rm e} + \overline{\nu_{\rm e}} \quad ({\rm C}),$$

$$\Xi^- \longrightarrow \Xi^0 + {\rm e} + \overline{\nu_{\rm e}} \quad ({\rm D}).$$

There are also reactions among baryons and muons. They have the similar forms and hence are not listed.

Table 1. The weak constants. $\theta_{\rm c}$=0.231±0.003, F=0.477±0.012, D=0.756±0.011 [5].

process	C	f_1	g_1
A	$\cos\theta_{\rm c}$	1	$F+D$
B	$\sin\theta_{\rm c}$	$-\sqrt{3/2}$	$-\sqrt{3/2}(F+D/3)$
C	$\sin\theta_{\rm c}$	$\sqrt{3/2}$	$\sqrt{3/2}(F-D/3)$
D	$\cos\theta_{\rm c}$	1	$F-D$

In the following, the above processes are referred to as A, B, C and D processes, respectively. The emissivity due to the neutrino emission can be derived from the Fermi Golden Rule. The specific expression of the energy loss Q per unit volume has the form of [3],

$$Q = \frac{457\pi G_{\rm F}^2C^2(f_1^2+3g_1^2)}{10080\hbar^{10}c^5}T^6m_{\rm B1}^*m_{\rm B2}^*\mu_{\rm l}\Theta, \tag{12}$$

$G_{\rm F} = 1.436\times10^{-49}$ erg cm^3 is the weak-coupling constant. Θ is the step function corresponding to the triangle condition. C, f_1, g_1 are decided by the weak constants. Their values are listed in Table 1. $\mu_{\rm l}$ is the chemical potential of the lepton.

3 Results

The effect of the δ meson leads to a larger symmetry energy [10]. With a larger symmetry energy, the proton abundance in neutron star matter increases. The increment of the proton abundance corresponds to the increment of the proton Fermi momentum. Consequently, the triangle conditions for nucleons and electrons are satisfied at a lower density. As shown in Fig. 1, the threshold density for the process A is 0.27 fm^{-3} (0.34 fm^{-3}) when the δ meson is included (excluded). The effect of the δ meson leads to a lower threshold density for the process A. The neutron star mass corresponding to the threshold density is marked as circles in Fig. 1. With the δ meson, only when the neutron star mass is larger than 1.03 $M_\odot$, can the process A take place in the star, while without the δ meson, the threshold mass is 1.10 $M_\odot$. The inclusion of the δ meson decreases the threshold mass for the process A. The δ meson makes the nucleon effective mass split (see Eq. (11)). The splitting of the effective mass results in the increment of the neutrino emissivity (see Eq. (12)). Therefore, with the inclusion of the δ meson, the neutrino emissivity of the process A increases (see Fig. 1). As the density increases, two curves in Fig. 1 are closer and closer. This means the effect of the δ meson on the neutrino emissivity of the process A is suppressed at high densities.

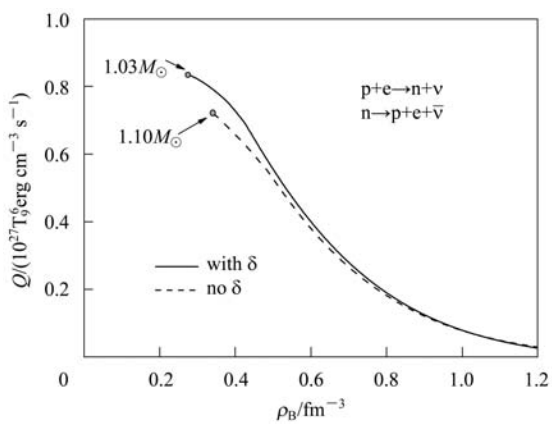

Fig. 1. The neutrino emissivity of the process A. The threshold neutron star masses for the process A are marked as circles in the figure.

The introduction of the isovector-scalar interaction changes the threshold conditions for hyperons [17]. Consequently, the threshold densities for the direct Urca processes involving hyperons are shifted to lower densities. As shown in Fig. 2, with (without) the δ meson included, the process B begins to happen at ρ_B=0.38(0.42) fm^{-3} while the process C begins to happen at ρ_B=0.43(0.49) fm^{-3}. For the process B, the threshold mass is 1.44 $M_\odot$ (1.38 $M_\odot$) with (without) the δ meson included. For the process C, the threshold mass is 1.55 $M_\odot$ (1.52 $M_\odot$) with (without) the δ meson. The inclusion of the δ meson results in a larger threshold mass for the direct Urca processes involving hyperons. This is different from the cases of the process A. One can also see from Fig. 2 that the inclusion of the δ meson results in larger neutrino emissivity of the process B. The neutrino emissivity of the process C is not sensitive to the inclusion of the δ meson. As the density increases, the δ meson effect on the neutrino emissivity of the process B decreases. The threshold density for the process D is too high, even higher than the maximum central density of the neutron star. Therefore, in the neutron star, the process D can not happen.

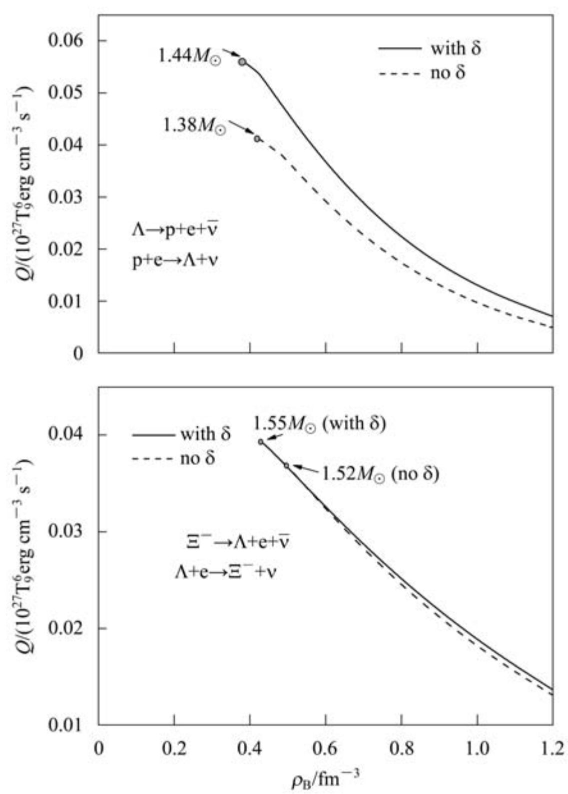

Fig. 2. The neutrino emissivity of the process B (upper panel) and C (lower panel). The threshold neutron star masses for the process B and C are marked as circles in the figure.

Besides the processes among baryons and electrons, the processes among baryons and muons can also take place in the neutron star. The processes involving muons have different thresholds from those involving electrons. However, they lead to the same neutrino emissivity according to Eq. (12). So, the figures about muons are not presented in this article. Fig. 3 shows the total neutrino emissivity. It includes the contributions of the process A, B and C as well as the similar processes involving muons. As the density increases, the total neutrino emissivity reaches peaks. with (without) the δ meson, at ρ_B=0.32(0.41) fm^{-3}, the total neutrino emissivity goes up remarkably. The reason is that the process among nucleons and muons begins to happen at ρ_B=0.32(0.41) fm^{-3} when the δ meson is included (excluded). For the same reason, the other peaks in Fig. 3 correspond to the densities where new processes (B, C and the similar processes involving muons) happen. One can see that the increment of the total neutrino emissivity caused by the inclusion of the δ meson is remarkable at densities ρ_B=0.32–0.41 fm^{-3}. In this region, the increment is nearly 150%. However, when the density exceeds 0.5 fm^{-3}, the effect of the δ meson is suppressed with further increase of the density.

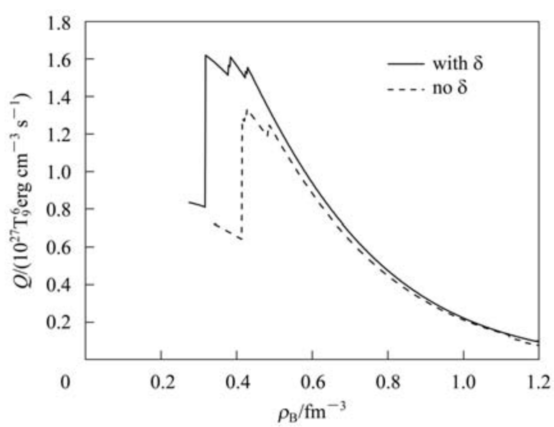

Fig. 3. The total neutrino emissivity. It includes the contributions of the process A, B and C as well as the similar processes involving muons.

Figure 4 shows the total neutrino luminosity as a function of the neutron star mass. As the mass increases, the total neutrino luminosity increases first then decreases. There is the maximum mass with which the neutron star cools fastest. The maximum value is 1.74 (1.76) $M_\odot$ when the δ meson is included (excluded). There is a special mass region where two different star masses can correspond to the same neutrino luminosity. When the δ meson is included (excluded), one can read that the special mass region is 1.66–1.76 (1.70–1.78) $M_\odot$, which corresponds to the region bounded by the line AB (CD) in Fig. 4. It can also be seen that with the inclusion of the δ meson, the total neutrino luminosity becomes much larger.

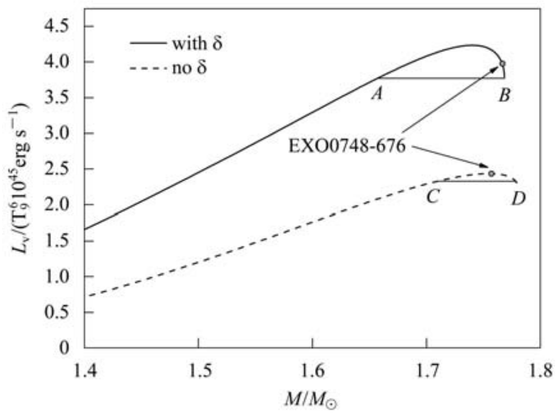

Fig. 4. The total neutrino luminosity. In the region bounded by the line AB (CD), two different masses can correspond to the same neutrino luminosity. The luminosity of the EXO0748-676 is marked as circles in the figure.

The X-ray Binary EXO0748-676 [22] was observed by the XMM-Newton observatory [23] during its commissioning and calibration phases for almost half a million seconds, spread over six satellite orbits between February 21 and April 21, 2000. A redshift z=0.35 is obtained for the EXO0748-676, which corresponds to the ratio of M/R=0.15. With the δ meson included (excluded), the EXO0748-676 has a mass 1.77 (1.76) $M_\odot$ with a radius of 11.8 (11.7) km. The δ meson effect on the mass of the EXO0748-676 is very small. However, its effect on the total neutrino luminosity is very large. With the δ meson included (excluded), the neutrino luminosity is 4.0^{45} (2.4^{45}) T_9^6erg·s^{-1}. The effect of the δ meson increases the luminosity of the EXO0748-676 almost by 67%. This implies that the observation on the cooling of the EXO0748-676 should be helpful for studying the isovector-scalar interaction between baryons.

4 Conclusions

In the framework of the RMFT, this article studies the effect of the δ meson on the DURCA process in neutron stars. In neutron stars, the process A, B and C can take place while the process D can not happen. The inclusion of the δ meson leads to lower threshold densities for the direct Urca processes. The total neutrino emissivity becomes larger when the δ meson is included. The threshold mass for the process A is shifted to smaller mass with the inclusion of the δ meson while the threshold masses for the process B and C are shifted to larger masses. The total neutrino luminosity increases with the star mass first and then decreases. In the special mass region, two different masses can have the same luminosity. With (without) the inclusion of the δ meson, stars with the mass of 1.74 (1.76) $M_\odot$ cools fastest. For the EXO0748-676, turning on the isovector-scalar channel increases the total neutrino luminosity remarkably.

It is interesting to compare this work with the previous papers. In Ref. [5], the triples of the Σ hyperons are considered. Here, the Σ hyperons are excluded. The exclusion of the Σ hyperons changes the threshold condition for the Ξ hyperon and consequently makes the process C become present in the neutron star. The contributions to the neutrino emissivity from the Σ hyperon is larger than that from the Ξ hyperon. Hence, the exclusion of the Σ slowers the cooling of the neutron star. In Ref. [10], the effects of the δ meson on nuclear matter become obvious only when the density is high enough [10]. However, the δ meson effect on the neutrino emissivity of the neutron star is obvious only in the mediate density region. When the density becomes higher still, the effects of the δ meson become very small. This behavior is similar to the case in Ref. [17], where the δ meson effects on the composition of protoneutron star matter are also negligible at high densities. Therefore, the effects of the δ meson on β-equilibrated neutron star matter are some different from those on nuclear matter. The previous papers [12–17] also show that the δ meson effects on the star mass and radius are very small. So the observations on the star mass can not be used to define the isovector-scalar interaction between baryons. In this article, one can see that the δ meson has remarkable influences on the cooling of the star. For the EXO0748-676, the increment of the total neutrino luminosity caused by the δ meson reaches almost 67%. Therefore, the observation of the cooling of the EXO0748-676 should be helpful for studying the isovector-scalar interactions between baryons.

References

1 Page D, Lattimer J M, Prakash M et al. ApJS, 2004, **155**: 623

2 Heinke C O, Jonker P G, Wijnands R et al. ApJ, 2007, **660**: 1424

3 Lattimer J M, Pethick C J, Prakash M et al. Phys. Rev. Lett., 1991, **66**: 2701

4 Kubis S, Kutschera M. Nucl. Phys. A, 2003, **720**:189

5 Prakash M, Prakash M, Lattimer J M et al. ApJ, 1992, **390**: L77

6 Kubis S. Phys. Rev. C, 2006, **73**:015805

7 DING W B, LIU G Z, ZHU M F et al. A&A, 2009, **506**: L13–L16

8 Yakovlev D G, Kaminker A D, Gnedin O Y et al. Phys. Rep., 2001, **354**: 1

9 Leinson L B. Nucl. Phys. A, 2002, **707**: 543

10 LIU B, Greco V, Baran V et al. Phys. Rev. C, 2002, **65**: 045201

11 Kubis S, Kutschera M. Phys. Lett. B, 1997, **399**: 191

12 GUO H, CHEN Y J, LIU B et al. Phys. Rev. C, 2003, **68**: 035803

13 Menezes D P, Providência C. Phys. Rev. C, 2004, **70**: 058801

14 WEI F X, MAO G J, KO C M et al. J. Phys. G, 2006, **32**: 47

15 LIU B, GUO H, Toro M D et al. Eur. Phys. J. A, 2005, **25**: 293

16 LIU B, Toro M D, Greco V et al. Phys. Rev. C, 2007, **75**: 048801

17 YU Z, LIU G Z, ZHU M F et al. Chin. Phys. Lett., 2009, **26**: 022601

18 Haensel P, Gnedie O Y. Astron. Astrophysics, 1994, **290**: 458–462

19 Batty C J, Friedman E, Gal A et al. Phys. Lett. B, 1994, **335**: 273

20 Balberg S, Gal A, Schaffner J. Prog. Theor. Phys. Suppl, 1994, **117**: 325

21 Stoks V G J, Lee T S H. Phys. Rev. C, 1999, **60**: 024006

22 Parmar A N, White N E, Giommi P et al. APJ, 1986, **308**: 199

23 Jansen F, Lumb D, Altieri B et al. Astr. Astrophys, 2001, **365**: L1