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In-medium enhancement of the modified Urca neutrino reaction rates

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ABSTRACT

We calculate modified Urca neutrino emission rates in the dense nuclear matter in neutron star cores. We find that these rates are strongly enhanced in the beta-stable matter in regions of the core close to the direct Urca process threshold. This enhancement can be tracked to the use of the in-medium nucleon spectrum in the virtual nucleon propagator. We describe the in-medium nucleon scattering in the non-relativistic Bruckner–Hartree–Fock framework taking into account two-body as well as the effective three-body forces, although the proposed enhancement does not rely on a particular way of the nucleon interaction treatment. Finally we suggest a simple approximate expression for the emissivity of the neutron branch of the modified Urca process that can be used in the neutron stars cooling simulations with any nucleon equation of state of dense matter.

1. Introduction

Neutron stars (NSs) are the densest stars in the Universe. Their cores contain cold superdense matter with densities reaching several times the nuclear saturation density $n_0 = 0.16\ \mathrm{fm}^{-3}$. NSs occupy the unique location in the QCD phase diagram, currently unreachable by the modern ground-based experimental studies, and as such the composition and equation of state (EOS) in NS interiors is largely unknown [1]. On the other hand, NSs have extremely large diversity of astrophysical manifestations spanning the whole electromagnetic [2], and, recently, gravitational wave spectrum [3,4]. It is believed that confronting the observational data with the results of theoretical modeling of various processes in NSs one can constrain uncertain properties of their interiors and, as a consequence, increase the knowledge about the fundamental interactions in dense matter. That is why NS studies attract constant attention.

One of a few insights into the uncertain physics of the NS interiors comes from the study of the thermal evolution of these objects, either isolated or in binary systems, see, e.g. [5,2]. One of the main cooling regulators, alongside with the surface electromagnetic emission, is the neutrino emission from the NS bulk. For sufficiently hot NSs the latter is in fact the main ingredient of the NS cooling theory [5].

There is a big diversity of neutrino generation processes inside NSs, with the liquid stellar core being the source of the strongest ones [6]. Operation of these processes and their rates inevitably depend on the NS EOS and composition. For instance, the most powerful mechanism of the neutrino emission in nucleon cores of NSs, the so-called direct Urca process, consists of a pair of charged weak current reactions $\mathrm{n} \to \mathrm{p} + \ell + \bar{\nu}_\ell$, $\mathrm{p} + \ell \to \mathrm{n} + \nu_\ell$, where ℓ is a lepton, electron or muon, and ν_ℓ is the corresponding neutrino. Strong degeneracy of the NS matter puts a fundamental restriction on the direct Urca process requiring that $p_{\mathrm{Fn}} < p_{\mathrm{Fp}} + p_{\mathrm{F}\ell}$, where $p_{\mathrm{F}i}$ is the Fermi momentum of the i species. This suggests that the proton fraction should be sufficiently high for the direct Urca process to operate. Therefore, the direct Urca process can proceed in sufficiently heavy NSs with central density larger than some threshold density n_{dU}. Different EOSs predict different n_{dU}. In lighter NSs and for some EOSs in all NSs up to maximally massive ones, direct Urca processes are forbidden and other reactions come into a play. In this case, the basic neutrino emission mechanisms in the (non-superfluid) NSs involve nucleon collisions. The strongest process of this type is the modified Urca process which also proceeds via the charged weak current and is given by a pair of reactions:

$$\mathrm{n} + \mathrm{N} \to \mathrm{p} + \mathrm{N} + \ell + \bar{\nu}_\ell, \quad \mathrm{p} + \mathrm{N} + \ell \to \mathrm{n} + \mathrm{N} + \nu_\ell. \tag{1}$$

Here N is the additional nucleon which relaxes the momenta restrictions. The companion nucleon bremsstrahlung processes which

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involve neutral weak currents are order of magnitude less powerful [6].

The standard benchmark for the treatment of modified Urca reactions in NS physics is the work by Friman and Maxwell [7]. It is based on the free one-pion exchange (OPE) model and the central part (nuclear correlations) is described by a certain set of Landau parameters. Several studies expand results of Ref. [7], basically focusing on the improvement of the in-medium effects treatment, see, e.g., Ref. [8]. In particular, Ref. [9] estimated the effect of the replacement of the free one-pion exchange interaction with the in-medium T-matrix and found some reduction of the emissivity. Recent study [10] employed independent pair approximation extending Ref. [11]. They calculated pair correlation function in the variational approach accounting for two-body as well as three-body forces. The final result turned out to be not so far from those of Ref. [7].

In a series of papers staring from Ref. [12] the scenario named ‘medium modified Urca’ was developed, see Refs. [13,14] for review. The basis of this scenario is the pion-exchange model of the interaction with a strong softening of the in-medium pion (medium-modified one-pion exchange, or MOPE). This leads to the strong enhancement of the modified Urca rates. Moreover, it was argued that the strongest subprocess involving charged weak current is the conversion of the virtual charged pion to virtual neutral pion with the emission of the lepton pair. However these results are strongly dependent on a particular choice of the model parameters. In some cases a strong softening of the pion mode is the precursor of the real pion condensation at higher density [13].

In this letter we show that all previous studies missed an important piece of a picture. Specifically, we argue that the account of the nucleon potential energy in the medium amplifies considerably the modified Urca rates. The proposed amplification is universal, resulting only from the requirement of the beta-equilibrium, and the importance of this amplification increases when the density gradually approaches $n_{\rm dU}$.

The paper is organized as follows. In Sec. 2 we briefly present the standard formalism for the calculations of the modified Urca rates. The in-medium nucleon propagator is discussed in Sec. 2.1; this section contains the main result of our work. In Sec. 2.2 we outline the adopted model for in-medium scattering. We describe the nucleon interaction by means of the G-matrix of the Brueckner–Hartree–Fock theory constructed on top of the realistic nucleon potential with inclusion of the effective three-body forces. We discuss our results and illustrate their effect on the model cooling calculations in Sec. 3 and conclude in Sec. 4.

For concreteness, we focus on the neutron branch of the modified Urca process, where $N = n$ in Eq. (1), although the obtained results are qualitatively applicable to the proton branch ($N = p$) as well. Effects of superfluidity and magnetic fields are not considered. Unless otherwise is indicated, we use the natural unit system with $k_B = \hbar = c = 1$.

2. Formalism

In the conditions appropriate for the NS cores below the direct Urca threshold, it is enough to describe nucleons in the non-relativistic quasi-particle approximation. The modified Urca emission rate can then be found from the Fermi golden rule for each of the reactions (1). The detailed derivation is given, for instance, in the review [6]. Under the conditions of beta-equilibrium, the rates of forward and reverse reactions are equal, so one can consider one reaction of the pair [we focus on the first reaction in (1)] and double the result. The neutrino emissivity is then

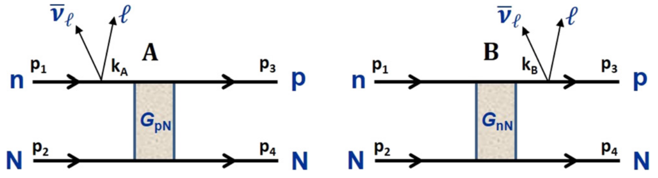

Fig. 1. Direct external leg Feynmann diagrams A (left) and B (right) contributing to the modified Urca process.

$$Q_{\rm MU}^{(\ell)} = 2\int\prod_{j=1}^{4}\frac{d\mathbf{p}_j}{(2\pi)^3}\int\frac{d\mathbf{p}_\ell}{(2\pi)^3}\int\frac{d\mathbf{p}_\nu}{(2\pi)^3}\,\varepsilon_\nu(2\pi)^4 \times\delta(E_f-E_i)\delta(\mathbf{P}_f-\mathbf{P}_i)\mathcal{F}s\mathcal{M}_{fi}, \qquad (2)$$

where j enumerate nucleons, $\mathcal{F} = f_1 f_2(1-f_3)(1-f_4)(1-f_\ell)$ is the Pauli blocking factor with $f_i = [1+\exp((\varepsilon_i-\mu_i)/T)]^{-1}$ being the Fermi–Dirac function, ε_i, $\mathbf{p}_i$, and μ_i are the quasiparticle energy, momentum, and chemical potential, respectively, T is the temperature, $\mathcal{M}_{fi} \equiv \sum_{\rm spins}|M_{fi}|^2$ is the squared matrix element of the process, summed over the spin states, $s = 2^{-1}$ is the symmetry factor that accounts for the double-counting of the same collision events, $(E_f, \mathbf{P}_f)$ and $(E_i, \mathbf{P}_i)$ are the total energy and momentum of the final and initial particles, respectively.

Since neutron star matter is strongly degenerate, all fermions except neutrinos in Eq. (2) are placed at the respective Fermi surfaces. The neutrino momentum is small (of the order of T), therefore it can be neglected in the momentum conservation and in the matrix element. These facts allow to decompose energy and angular integrations in Eq. (2) which greatly simplifies the calculations. As a result, the phase space averaging of the matrix element contains only four non-trivial angular integrations, see, e.g., [6,8,15].

In the non-relativistic $V-A$ approximation, the weak interaction Lagrangian is

$$\mathcal{L} = \frac{G_F\cos\theta_C}{\sqrt{2}}\,l^\mu\Psi_p^\dagger\left(g_V\delta_{\mu,0} - g_A\delta_{\mu,i}\sigma_i\right)\Psi_n, \qquad (3)$$

where $G_F = 1.17\times10^{-5}$ GeV^{-2} is the Fermi coupling constant, $\cos\theta_C = 0.975$ is the cosine of the Cabibbo angle, Ψ_p and Ψ_n are the proton and neutron spinors, respectively, σ_i, $i = 1\ldots3$, are the Pauli matrices, $g_V = 1$ and $g_A \approx 1.26$ are nucleon weak vector and axial vector coupling constants, respectively. Lepton charged current is $l_\mu = \bar{l}\gamma_\mu(1-\gamma_5)\nu$, where l and ν are lepton and antineutrino Dirac spinors, γ_μ and γ_5 are Dirac matrices. Here we neglect additional contributions from the weak magnetism or induced pseudoscalar interactions [16].

The basic direct diagrams which contribute to the modified Urca processes are given in Fig. 1 where the hatched blocks represent the nucleon interaction. The amplitude corresponding to diagrams in Fig. 1 is (neglecting neutrino momentum)

$$M_{fi}^{\rm dir} = l^\nu\Big(\hat\Gamma_\nu\mathcal{G}_p(\varepsilon_1-\varepsilon_\ell, \mathbf{p}_1-\mathbf{p}_\ell)G_{pn} + G_{nn}\mathcal{G}_n(\varepsilon_3+\varepsilon_\ell, \mathbf{p_3}+\mathbf{p}_\ell)\hat\Gamma_\nu\Big), \qquad (4)$$

where $\hat\Gamma_\nu$ is the weak vertex, which follows from (3), $\mathcal{G}_{n(p)}$ is the neutron (proton) propagator, and G_{pn} and G_{nn} are the scattering matrices corresponding to the proton-neutron interaction for the diagram A and neutron-neutron interaction for the diagram B, respectively. The exchange diagrams correspond to the interchange of initial states $\{1 \leftrightarrow 2\}$. In addition to the external-leg emission diagrams shown in Fig. 1, there are other diagrams that can contribute to the modified Urca process, see, e.g., Refs. [9,17,8]. These diagrams correspond to intermediate state processes and generally

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