Direct URCA Process in Neutron Stars*

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Abstract The onset of the most powerful neutrino emission candidate in the cooling of neutron stars, direct URCA process, requires a high threshold proton fraction. The proton fraction in neutron stars relies on the isospin dependent part of nuclear force, which can be constrained by the measurement of the neutron skin thickness in heavy nuclei such as ^{208}Pb. Adding new isospin dependent correction terms to the effective interactions PK1, NL3, S271 and Z271, the correlation between the proton fraction and neutron skin thickness in ^{208}Pb is studied. For a neutron star with fixed mass, the central proton fraction increases with increasing predicted values of neutron skin thickness in ^{208}Pb.

Key words cooling of neutron stars, relativistic mean field theory, neutron skin, D-URCA process

1 Introduction

The most powerful neutrino emission candidate in the cooling of neutron stars is the nucleon direct URCA (D-URCA) process[1]: $n \to p + e^- + \bar{\nu}_e$, $p + e^- \to n + \nu_e$, which emits neutrinos in the inner cores of neutron stars. The well known triangle inequality for momentum conservation requires a high proton fraction (11.1%—14.8%) for the onset of the direct URCA process[1].

Current X-ray observations[2] of middle-aged neutron stars indicate low surface temperatures, which imply a rapid cooling mechanism such as the D-URCA process. Unfortunately, astronomic observations alone may not be able to establish the occurrence of the D-URCA process. On the theoretical side, the determination of the proton fraction in neutron-rich beta equilibrium matter is problematic mainly due to the poor knowledge of the isospin dependence of nuclear forces. One rather sensitive measure for isospin effects in normal nuclei is the neutron skin thickness in heavy nuclei such as ^{208}Pb. Although the proton radius of ^{208}Pb has been accurately determined by electron scattering experiments, the extraction of the neutron radius from hadron-induced experiments is model-dependent and as such suffers from reaction mechanism uncertainties. What is more disconcerting is the large variation in the predicted values of neutron skin thickness S of ^{208}Pb, with S=0.1—0.2fm for nonrelativistic Skyrme models[3], on one hand, and S=0.2—0.3fm for relativistic mean field (RMF) models[3] on the other hand. This dismal situation has prompted an experiment at Jefferson Laboratory to measure the neutron radius in ^{208}Pb accurately and model independently via parity violating electron scattering to an unprecedented accuracy of 1%($\pm$0.05 fm)[4].

Recently we studied[5] the sensitivity of the neutron skin thickness in ^{208}Pb to the addition of isospin-dependent higher order sigma-rho-nucleon couplings to various RMF models (PK1, NL3, S271, Z271). In this paper we extend the latter investigation to

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study the correlation between neutron skin thickness in ^{208}Pb, S, and proton fraction in neutron rich matter. In particular, we determine the threshold density for the onset of D-URCA process in neutron stars.

2 Formalism

The details of RMF theory and its application in nuclear physics are described in Ref. [6—8]. The new higher order isospin-dependent correction terms are respectively, $L_1 = -\Gamma_1\overline{\psi}g_\rho\gamma^\mu(g_\sigma\sigma/m)\boldsymbol{\tau}\cdot\boldsymbol{\rho}_\mu\psi$, $L_2 = -\Gamma_2\overline{\psi}g_\rho\gamma^\mu(g_\sigma\sigma/m)^2\boldsymbol{\tau}\cdot\boldsymbol{\rho}_\mu\psi$ and we also consider the term introduced in Ref. [9]: $L_{HP} = 4\Lambda_\nu g_\rho^2\boldsymbol{\rho}_\mu\cdot\boldsymbol{\rho}^\mu g_\omega^2\omega_\mu\omega^\mu$. The details can be found in Ref. [5].

3 Results and discussion

Details for the extraction of the coupling constants, Γ_1, Γ_2, and Λ_v, can be found in Ref. [5]. For all the effective interactions PK1, NL3, S271 and Z271, we fix the symmetry energy at $k_f = 1.15\,\mathrm{fm}^{-1}$ ($\rho = 0.10\,\mathrm{fm}^{-3}$) for nuclear matter and the binding energy per nucleon in ^{208}Pb in the range $|E/A - (E/A)_{\mathrm{exp}}| < 0.005\,\mathrm{MeV}$, where $(E/A)_{\mathrm{exp}} = -7.868$ MeV.

The chemical potentials, μ, for neutrons, protons, electrons, and muons in beta equilibrium matter satisfy $\mu_\mathrm{p} = \mu_\mathrm{n} - \mu_\mathrm{e}$, and charge neutrality implies that $\rho_\mathrm{p} = \rho_\mu + \rho_\mathrm{e}$ or equivalently, in terms of Fermi momenta, $(k_\mathrm{F}^\mathrm{p})^3 = (k_\mathrm{F}^\mu)^3 + (k_\mathrm{F}^\mathrm{e})^3$. For a given total baryon density ρ, the proton fraction is $Y_\mathrm{P} = \rho_\mathrm{P}/\rho$. The momentum conservation in the D-URCA process implies that the Fermi momenta of neutrons, protons, and electrons must satisfy the following relation $k_\mathrm{F}^\mathrm{n} \leqslant k_\mathrm{F}^\mathrm{p} + k_\mathrm{F}^\mathrm{e}$ [1]. The D-URCA threshold density ρ_{URCA} is defined as the density at which $k_\mathrm{F}^\mathrm{n} = k_\mathrm{F}^\mathrm{p} + k_\mathrm{F}^\mathrm{e}$ satisfies.

As an example, the values of Λ_v and Γ_1 with $\Gamma_2 = 0$ for PK1[10] are extracted and the proton fraction in beta equilibrium matter is shown in Fig. 1.

In Fig. 2 the direct URCA threshold density ρ_{UCRA} is shown as a function of neutron skin thickness S of ^{208}Pb for PK1, NL3[11], S271 and Z271[7] with the new terms. It is seen that ρ_{URCA} decreases with S. The effective interactions which give large S produce low D-URCA threshold density. Furthermore, ρ_{URCA} changes more rapidly for S271 and Z271 than for NL3 and PK1.

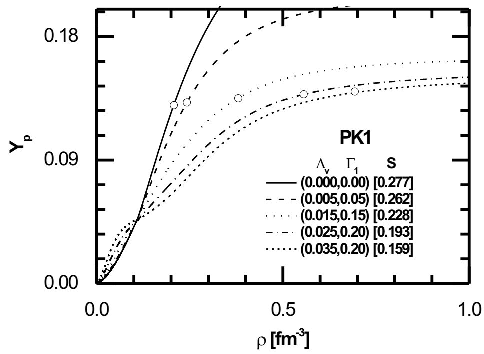

Fig. 1. The proton fraction, Y_P, in beta equilibrium matter is shown as a function of the baryon density, ρ, for different combinations of Λ_v and Γ_1, with $\Gamma_2 = 0$, for the PK1 effective interaction. The corresponding values of the neutron skin thickness, S (in fm), are indicated in square brackets.

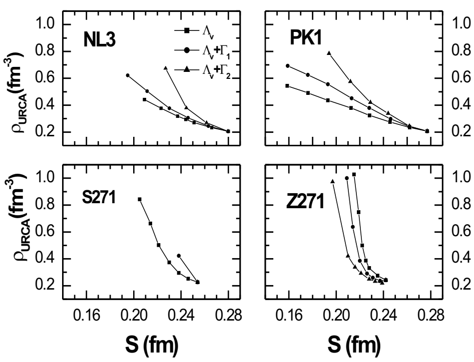

Fig. 2. D-URCA threshold density, ρ_{URCA} (in fm^{-3}), versus the neutron skin thickness, S (in fm), of ^{208}Pb for the PK1, NL3, S271, and Z271 effective interactions for various combinations of Λ_v and Γ_1, with $\Gamma_2 = 0$, or Λ_v and Γ_2, with $\Gamma_1 = 0$.

The structure of spherical neutron star in hydrostatic equilibrium is solely determined by the equations of state of neutron-rich matter in beta equilibrium. Having specified the equation of state, we determine the mass of neutron stars that may cool via the D-URCA process by integrating the Opperheimer-Volkff equations[12].

In Fig. 3, the threshold neutron star, M_{URCA}, whose central density equals to the corresponding D-URCA threshold density in Fig. 2, is displayed as a function of neutron skin thickness S for all effective interactions. The parameter sets with large neutron skin thicknesses produce small threshold neutron star masses with a model dependency as shown in Fig. 2.

If S is less than 0.2fm, as predicted by nonrelativistic models, the D-URCA is forbidden in neutron star with 1.4 $M_{\odot}$ mass. It may happen in neutron star with large mass, as shown in Fig. 3 for PK1 and NL3.

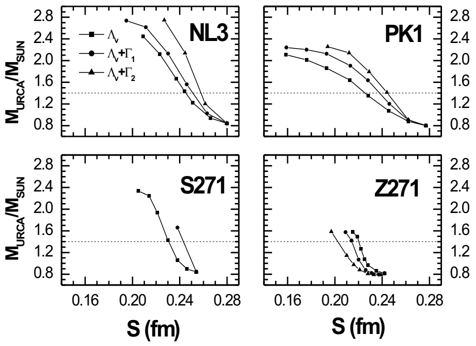

Fig. 3.　D-URCA threshold neutron star mass (in solar mass units) versus the predicted neutron skin thickness, S (in fm), in ^{208}Pb.

4　Summary

Using the effective interactions PK1, NL3, S271 and Z271, and adding new isospin-dependent terms, the feasibility of the D-URCA process was studied by correlating the proton fractions in beta equilibrium matter to the neutron skin S of ^{208}Pb. D-URCA threshold density ρ_{URCA} is found to change more rapidly for S271 and Z271 than for NL3 and PK1. If $S < 0.20$ fm, the proton fractions only allow the direct URCA cooling of neutron stars with large mass. If $S > 0.26$ fm, the direct URCA process is allowed by all models to cool down a $1.4M_{\odot}$ neutron star.

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中子星的直接URCA过程*

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摘要　D-URCA过程是中子星发射中微子冷却中最快的机制. 中子星发生D-URCA过程需要较高的质子分数比, 该比值取决于核力的同位旋依赖性, 而核力的同位旋依赖性与重核(如^{208}Pb)的中子皮厚度相关. 为此, 基于相对论平均场理论, 采用PK1，NL3，S271，Z271有效相互作用, 在拉氏量中引入同位旋相关的高阶修正项, 本文研究了中子星的质子分数比以及D-URCA过程与^{208}Pb的中子皮厚度之间的关系.

关键词　中子星冷却　相对论平均场　中子皮　D-URCA过程

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