Short-range correlation effects on the neutron star cooling

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Abstract

Short-range correlations (SRC) have been known to be an important aspect of nuclear theory for some time. Recent works have re-ignited interest on this topic, particularly due to the fact that it has recently been demonstrated that SRC may be responsible for breaking pairing gaps in nuclear matter. In this work we revisit the concept of SRC for beta equilibrated matter in neutron stars. We construct two equivalent models, with and without SRC and proceed to investigate the thermal evolution of stars described by such models. We show that SRC play a major role in the thermal evolution of neutron stars. It will be shown that while the SRC largely leaves the macroscopic properties of the star unaltered, it significantly alters the proton fraction, thus leading to an early onset of the direct Urca (DU) process, which in turns leads to stars exhibiting much faster cooling.

Keywords: Short-range correlations, neutron star cooling, relativistic mean-field model

1. Introduction

Claims that the pairing interaction plays an important role in astrophysics are very common. In fact, superfluidity has been investigated both in infinite nuclear matter and finite nuclei \cite{1} and it is a key ingredient in the neutron star cooling process \cite{2–10}. On the other hand, short-range correlations (SRC) have also become a hot topic recently \cite{11, 12} and one of the reasons for the new enthusiasm on an old topic is the fact that SRC can be responsible for breaking the pairs around the Fermi surface and hence, reduce the pairing gap mechanism \cite{13, 14}.

One of the experiments used to probe the existence of the short-range correlations took place in the Thomas Jefferson National Accelerator Facility (JLab), and it was concluded that the high energy incident beams of protons, or electrons, in the $^{12}$C nucleus, give rise to ejected nucleon pairs \cite{15} submitted to the short-range correlations (SRC) \cite{11, 12, 16–27}. It was found that about 20\% of the nucleons in the $^{12}$C nucleus form such correlated structures. Among them, 90\% are composed by the np pair with the remaining mn and pp pairs divided into 5\% for each one of them. The dominance of the correlated np pair is also observed in experiments involving $^{27}$Al, $^{56}$Fe and $^{208}$Pb nuclei \cite{28}.

Effects of short range correlations on infinite nuclear matter equations of state (EOS) are known to not be negligible for a long time \cite{29}. The very same kind of EOS, obtained from relativistic models, are often used to describe neutron star matter and as input to the analyses of the star cooling process.

In the present work, we explicitly include SRC in a relativistic mean field model and later analyze the effects on the thermal evolution of neutron stars. For this purpose we proceed to calculate the macroscopic properties of stars in two equivalent models, with and without SRC. The family of stars constructed is then used in thermal evolution calculations. As we will see SRC play a major role in the thermal history of neutron stars. As of the writing of this letter, and to the best of our knowledge this is the first study of this nature.

2. Short-range correlations in a relativistic mean-field model

From the theoretical point of view, a direct effect of the SRC in the nuclear dynamics is the change in its momentum distribution function, $n(k)$. For our study, we closely follow the structure for $n(k)$ proposed in Ref. \cite{30}, namely, $n_{np}(k_F,y) = \Delta_{np}$ for $0 < k < k_{Fnp}$, and $n_{np}(k_F,y) = C_{np}(k_{Fnp}/k)^4$ for $k_{Fnp} < k < \phi_{np}/k_{Fnp}$. The proton fraction is given by $y = \rho_p/\rho$, with $\rho_p$ being the proton density and $\rho = 2k_F^4/(3\pi^2)$ the total one. The $\Delta_{np}$ constants, namely, the depletion of the Fermi sphere at zero momentum \cite{31–33}, are written in terms of $C_{np}$ and $\phi_{np}$ as $\Delta_{np} = 1 - 3C_{np}(1 - 1/\phi_{np})$, where $C_p = C_0[1 - C_1(1 - 2y)]$, $C_n = C_0[1 + C_1(1 - 2y)]$, $\phi_p = \phi_0[1 - \phi_1(1 - 2y)]$ and $\phi_n = \phi_0[1 + \phi_1(1 - 2y)]$. Analysis of $(e,e')$ reactions and medium-energy photonuclear absorptions allowed to determine the value of $C_0 = 0.161$ \cite{34}. Constraints from nuclear many-body theories and the equations of state of cold atoms under unitary condition were used to find $C_n$ in pure neutron matter equal to 0.12, consequently resulting in $C_1 = -0.25$ \cite{34}. Furthermore, $\phi_0 = 2.38$ was found from systematic investigation of $(e,e')$ reactions and data from two-nucleon knockout reactions, as also described in Ref. \cite{34}. As in pure neutron matter $\phi_n$ was found to be 1.04, it was also possible to determine $\phi_1 = -0.56$ \cite{34}.

The structure given by $n_{np}$ is used in the equations of state obtained from the following Lagrangian density \cite{30, 35–38},

$$
\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - M_m)\psi + g_{\sigma\rho}(\bar{\psi}\gamma^\sigma\psi - g_{\omega\rho}\bar{\psi}\gamma^\omega\psi)
$$
The chemical potentials for protons and neutrons are obtained from the general definition \( \mu_{n,p} = \partial E / \partial n_{n,p} \), giving rise to \( \mu_{n,p} = \mu_{\text{kin}}(nuc) + \Delta \mu_{n,p} \), with the sign (+) for protons (neutrons). Here, \( \mu_{\text{kin}}(nuc) = (k_F^2 n + M^2)^{1/2} \) and

\[
P_{\text{kin}}^n = 3C_{\text{kin}} \left[ \mu_{\text{kin}}^n - \frac{(k_F^2 n + M^2)^{1/2}}{\phi_{n,p}} \right] + 4C_{\text{nuc}} k_F n
\]

\[
\phi_{n,p} = \frac{\phi_{n,p} F_{n,p} + (\phi_{n,p}^2 k_{n,p}^2 + M^2)^{1/2}}{k_{n,p}(k_F^2 n + M^2)^{1/2}}.
\]

Since the thermodynamics of the system is completely defined, it is possible to determine the coupling constants of the model, namely, \( g_{\sigma}, g_{\omega}, g_{\rho}, A, B, C \) and \( \alpha' \). In order to proceed with this calculation, we use the following bulk parameters: \( \rho_0 = 0.15 \text{ fm}^{-3} \) (saturation density), \( B_0 = -16.0 \text{ MeV} \) (binding energy), \( M_0^2 / M_{\text{nuc}} = 0.60 \) (ratio of the effective mass to the nucleon rest mass), \( K_0 = 230 \text{ MeV} \) (incompressibility), \( J = 31.6 \text{ MeV} \) (symmetry energy) and \( L_0 = 58.9 \text{ MeV} \), where \( B_0 = E(\rho_0) - M_0 = M(\rho_0) \), \( K_0 = 9(\partial E / \partial \rho)_{\rho_0} \), \( J = S(\rho) \) and \( L_0 = 3(\partial S / \partial \rho)_{\rho_0} \), with \( S(\rho) = (1 / 3 \rho)^3 [E(\rho) / 3 - 1] \) and \( E(\rho) = (\rho / \rho_0) \). In Table 1, we show the values of the coupling constants of the model with and without the implementation of the SRC.

| Coupling constant | Value (with SRC) | Value (without SRC) |
|-------------------|------------------|---------------------|
| \( g_\sigma \)     | 10.5550          | 10.4301             |
| \( g_\omega \)     | 12.3443          | 13.5478             |
| \( g_\rho \)       | 15.4069          | 11.1935             |
| \( A/M_{\text{nuc}} \) | 2.96396          | 1.77118             |
| \( B \)             | -29.8233         | 3.92522             |
| \( \alpha' \)      | 0.00800924       | 0.0631432           |

In order to study the neutron star cooling it is necessary to impose charge neutrality and \( \beta \)-equilibrium to the system since we take into account the weak process and its inverse reaction, namely, \( n \rightarrow p + e^- + \bar{\nu}_e \) and \( p + e^- \rightarrow n + \nu_e \), respectively. Here we consider stellar matter composed by protons, neutrons, electrons and muons, with the last particles emerging at densities for which the electron chemical potential (\( \mu_e \)) exceeds the muon mass (\( m_{\mu} = 105.7 \text{ MeV} \)). In our approach, neutrinos are assumed to escape due to their small cross-sections. This leads to the following conditions upon chemical potentials and densities: \( \mu_n - \mu_p = \mu_e = \mu_\nu \) and \( \rho_n = \rho_p = \rho_\nu \), where \( \rho_\nu = (\mu_\nu^2 - m_{\nu}^2)^{1/2} / (3 \pi^2) \) and \( \mu_\nu = (3 \pi^2 \rho_\nu)^{1/2} \). The total energy density and pressure of \( \beta \)-equilibrated stellar matter is then given by \( E = \epsilon + \epsilon_e + \epsilon_\nu \) and \( P = \rho + p_\nu + p_e \), respectively. This specific EOS is show in Fig. 1a. Some neutron star properties, such as its mass-radius profile, can be found by solving the Tolman-Oppenheimer-Volkoff (TOV) equations [39, 40]. Such a diagram is displayed in Fig. 1b.

The bulk parameters and their values used here to calibrate the coupling constants are the same studied in Ref. [30]. However, the output values of our couplings are different from those...
of Ref. [30] because we choose to fix $C = 0.005$ instead of $C = 0.01$. In Ref. [30], the choice of the latter number implies a maximum neutron star mass of $M_{\text{max}} = 1.87M_\odot$ and $M_{\text{max}} = 1.74M_\odot$, respectively, with and without the inclusion of SRC. These numbers do not satisfy the limits related to the PSR J1614-2230 [41] and PSR J0348+0432 [42] pulsars, namely, $(1.97 \pm 0.04)M_\odot$ and $(2.01 \pm 0.04)M_\odot$, respectively, neither the more recent prediction of $2.14^{+0.16}_{-0.18}M_\odot$ $(2.14^{+0.09}_{-0.10})M_\odot$ at 95.4% (68.3%) credible level from the MSP J0740+6620 pulsar [43]. For this reason we choose to redefine the $C$ parameter in order to make the model compatible with these predictions. Since it is known that the decreasing of this parameter leads to a maximum neutron star mass increasing [44], we use here $C = 0.005$. This modification implies in a model presenting $M_{\text{max}} = 2.04M_\odot$ and $M_{\text{max}} = 1.96M_\odot$ with and without SRC effects included, respectively. Notice that the effect of the SRC is to increase even further the maximum mass, as pointed out in Ref. [30]. The change in the $C$ parameter does not modify this feature.

3. Neutron star cooling formalism

We now investigate how the SRC influence the thermal evolution of neutron stars. We recall that the thermal evolution of a compact star is given by the general relativistic equations for thermal energy balance and transport, that can be written as [45–47]

$$\frac{\partial (le^{2\theta})}{\partial m} = -\frac{1}{E \sqrt{1 - 2m/r}} \left(e_{\epsilon} e^{2\theta} + e_{\epsilon} \frac{\partial (Te^{\theta})}{\partial \theta}ight), \quad (8)$$

$$\frac{\partial (Te^{\theta})}{\partial m} = -\frac{(le^{2\theta})}{16 \pi^2 r^2 k E \sqrt{1 - 2m/r}}. \quad (9)$$

In order to solve Eqs. (8)-(9) one needs to combine information from the micro and macroscopic realms. The microscopic model provides information about the density/Fermi momentum/effective mass of all particles within the star which in turn can be used to calculate the specific heat, thermal conductivity and neutrino luminosity. The macroscopic information, obtained from solving the TOV equations furnish us with mass, radius and curvature information, as well as the spatial distribution of the aforementioned microscopic properties. One also needs boundary conditions, which is given by the vanishing luminosity at the star center (which is evident as at $r = 0$ there is no heat flow) and by the thermal properties of the star atmosphere [48–50]. In this work we consider the simplest atmosphere possible, without strong magnetic field and without accreted matter due to fallback.

With all micro and macroscopic data, as well as the proper boundary conditions we perform numerical calculations to obtain detailed solution to Eqs. (8)-(9) for neutron stars covering a wide range of masses in both the RMF and SRC models. We note that all possible neutrino emissivities processes are accounted for, most prominent of which is the direct Urca (DU) process, modified Urca process (MU) and Bremsstrahlung (BR) process (all of which takes place in the star core). For a detailed review of such processes we refer the reader to [6, 51].

Particular attention must be given to the DU process - as it is significantly more powerful than other neutrino emission processes. The DU process consists of the neutron beta decay ($n \rightarrow p + e^- + \bar{\nu}$) and proton electron capture ($p + e^- \rightarrow n + \nu$). It has a very large luminosity ($\sim 10^{37}(T_9)^6$ erg/cm$^3$s), although it can only take place if the triangle inequality $k_{\bar{\nu}e} \leq k_{fp} + k_{fe}$ is satisfied. This generally mean that it will only occur for high enough proton fractions (usually $\sim 11 - 15\%$ [50, 52]). This is particularly important for the work presented in this paper, as the SRC will substantially modify the proton Fermi momentum, which subsequently modify the proton fraction within the star. Thus, as we will discuss below, the inclusion of the SRC can lead to substantially different cooling properties, even though the overall macroscopic properties of the star (mass, radius) and bulk properties of the model are not too different.

4. Results

We now show the thermal evolution of stars described by the microscopic models discussed in the previous sections. We show the cooling of stars with different masses, representative of the families shown in Fig. 1. The thermal evolutions of such stars are plotted in Figs. 2 - 3.

The results depicted in Figs. 2 - 3 clearly show a significant difference in the qualitative cooling behavior of such stars, which is somewhat surprising given that both models have similar bulk properties, namely, $\rho_0 = 0.15$ fm$^{-3}$, $B_0 = -16.0$ MeV, $M_0/M_{\text{max}} = 0.60$, $K_0 = 230$ MeV, $J = 31.6$ MeV and $L_0 = 58.9$ MeV. This indicates that the mere presence of short-range-correlations is enough to cause a significant deviation in the cooling nature of the star (especially for more massive stars). We can see that in the absence of short range correlations (RMF model) stars with masses up to $\sim 1.6M_\odot$ exhibit slow cooling. Stars above this mass start to allow for the DU process, leading to a fast cooling behavior. The inclusion of short-range-correlations (SRC model) drastically change this, and all stars in the model allow the DU process.
The behavior exhibited by stars with SRC indicates that the threshold above which the DU is allowed is drastically reduced by the presence of SRC. This indicates that Fermi momentum of the particles that take place in the DU process should be drastically different between the RMF and SRC models. This is confirmed by Figs. 4-5 where we show the neutron and proton Fermi momentum as a function of density for the two models studied.

While Fig. 4 shows us that (at the same density) the neutron Fermi momentum is slightly smaller for the model with SRC, there is an equivalent increase in the proton Fermi momentum. Such interchange leaves the baryon density unchanged but significantly increases the proton fraction for the SRC model, thus leading to an early onset of the DU process. This is confirmed by Fig. 6 where we see the proton fraction as a function of density - which shows a significantly higher proton fraction for the SRC model.

5. Summary and concluding remarks

In this work we investigated the influence of SRC on the cooling of neutron stars. For that purpose, we based our study on a relativistic mean field model with SRC phenomenology firstly implemented in Ref. [30]. Basically, the modification in the RMF model comes from the momentum distribution function, $n(k)$, that now takes into account a high momentum tail in
which $n(k)$ depends on $k$ as $n(k) \sim k^{-4}$ for values greater than the Fermi momentum. The change in $n(k)$ results in the split of the momentum integrals present in the energy density, pressure and scalar density of the model into two parts, as one can see in Eqs. (2) to (4). As in Ref. [30], we also fixed the bulk parameters of the model in the same values, as already mentioned. However, we fixed the coupling constant $C$ to the value of 0.005 instead of $C = 0.01$ previously used in Ref. [30] because this new value ensures the model presents $M_{\text{max}} = 2.04M_\odot$ and $M_{\text{max}} = 1.96M_\odot$ with and without SRC effects, respectively (see Fig. 1), in agreement with the limits of recently detected pulsars.

This study has demonstrated that short range correlations play an important role in the thermal evolution of neutron stars. Our investigation has shown that for two equivalent models, the one with the inclusion of SRC exhibits a drastically different cooling behavior. We have tracked the origin of such difference back to the proton and neutron Fermi momenta and have shown that for the SRC model there is an increase in the proton Fermi momentum, accompanied by a reduction of the neutron one. This leads to approximately the same baryon density but with a significantly larger proton fraction for the SRC model - which in turn leads to an early onset of the DU process. This is reflected in the thermal evolution of SRC stars, which undergo a much faster cooling than their non-SRC counterparts. We conclude that SRC potentially influence the thermal evolution of neutron stars, although they do not alter considerably the macroscopic properties of such objects. As we have shown in this study, the EoS and consequently the Mass-Radius diagrams of both the RMF and SRC are largely similar, and yet there is a significant difference in the thermal evolution of the family of stars these EOS describe. Further observation of neutron star cooling may potentially shed some light on the intensity of SRC in neutron star matter, or equivalently further understanding of SRC may aid us in improving our comprehension of the cooling of neutron stars.

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References

[1] D. J. Dean, M. Hjorth-Jensen, Pairing in nuclear systems: from neutron stars to finite nuclei, Rev. Mod. Phys. 75 (2003) 607–656. doi:10.1103/RevModPhys.75.607. URL https://link.aps.org/doi/10.1103/RevModPhys.75.607.

[2] P. S. Sherrin, D. G. Yakovlev, C. O. Heinke, W. C. G. Hs, D. J. Patnaude, Cooling neutron star in the Cassiopeia A supernova remnant: evidence for superfluidity in the core, Monthly Notices of the Royal Astronomical Society: Letters 412 (1) (2011) L108–L112. doi:10.1111/j.1745-3933.2011.01015.x. URL http://onlinelibrary.wiley.com/doi/10.1111/j.1745-3933.2011.01015.x/full http://doi.wiley.com/10.1111/j.1745-3933.2011.01015.x http://nrn.atl.muni.cz/cgi/doi/10.1111/j.1745-3933.2011.01015.x.

[3] D. G. Yakovlev, W. C. G. Ho, P. S. Sherrin, C. O. Heinke, A. Y. Potekhin, Cooling rates of neutron stars and the young neutron star in the Cassiopeia A supernova remnant, Monthly Notices of the Royal Astronomical Society 411 (3) (2011) 2017–1988. doi:10.1111/j.1365-2966.2010.17827.x. URL http://doi.wiley.com/10.1111/j.1365-2966.2010.17827.x.

[4] D. Page, M. Prakash, J. M. Lattimer, A. W. Steiner, Rapid Cooling of the Neutron Star in Cassiopeia A Triggered by Neutron Superfluidity in Dense Matter, Physical Review Letters 106 (8) (2011) 081101. doi:10.1103/PhysRevLett.106.081101. URL http://link.aps.org/doi/10.1103/PhysRevLett.106.081101.

[5] D. Page, J. M. Lattimer, M. Prakash, A. W. Steiner, Minimal Cooling of Neutron Stars: A New Paradigm, The Astrophysical Journal Supplement Series 155 (2) (2004) 623–650. doi:10.1086/424844. URL http://link.aps.org/doi/10.1103/PhysRevD.85.041301.

[6] D. Yakovlev, C. Pethick, NEUTRON STAR COOLING, Annual Review of Astronomy and Astrophysics 42 (1) (2004) 169–210. arXiv:0402143. doi:10.1146/annurev.astro.42.053103.123614. URL http://arjournals.annualreviews.org/doi/abs/10.1146/annurev.astro.42.053102.134013.

[7] R. Negreiros, S. Schramm, F. Weber, Impact of Rotation-Driven Particle Repopulation on the Thermal Evolution of Pulsars (2011) 1–5 arXiv:1103.3870v3.

[8] R. Negreiros, S. Schramm, F. Weber, Thermal evolution of neutron stars in two dimensions, Physical Review D 85 (10) (2012) 104019. doi:10.1103/PhysRevD.85.104019. URL http://link.aps.org/doi/10.1103/PhysRevD.85.104019.

[9] S. Beloin, S. Han, A. W. Steiner, D. Page, Constraining superfluidity in dense matter from the cooling of isolated neutron stars, Physical Review C 97 (1) (2018) 015804. doi:10.1103/PhysRevC.97.015804. URL http://arxiv.org/abs/1612.04289 http://dx.doi.org/10.1103/PhysRevC.97.015804.

[10] R. Negreiros, S. Schramm, F. Weber, Fully self-consistent thermal evolution studies of rotating neutron stars, Astronomy & Astrophysics 603 (2017) A44. doi:10.1051/0004-6361/201730435. URL http://www.aanda.org/abstract.php?article_id=201730435.

[11] M. Duer, O. Hen, E. Psasetzky, et al., Probing high-momentum protons and neutrons in neutron-rich nuclei, Nature (2018). doi:10.1038/s41586-018-0400-z. URL https://www.nature.com/articles/s41586-018-0400-z.

[12] O. Hen, G. A. Miller, E. Psasetzky, L. B. Weinstein, Nucleon-nucleon correlations, short-lived excitations, and the quarks within, Reviews of Modern Physics (2017). arXiv:1711.03982 arXiv:1612.04289.

[13] D. Ding, A. Rios, H. Dussan, et al., Pairing in high-density neutron matter including short- and long-range correlations, Phys. Rev. C 94 (2016) 025802. doi:10.1103/PhysRevC.94.025802. URL https://link.aps.org/doi/10.1103/PhysRevC.94.025802.

[14] A. Rios, A. Polls, W. H. Dickhoff, Pairing and Short-Range Correlations in Nuclear Systems, Journal of Low Temperature Physics (2017). doi:10.1007/s10909-017-1818-7.

[15] R. Subedi, R. Shineor, P. Monaghan, et al., Probing cold dense nuclear matter, Science (2008). doi:10.1126/science.1156675. URL https://science.sciencemag.org/content/318/5851/1691.

[16] K. S. Egiyan, N. B. Dashyan, M. M. Sargsian, et al., Measurement of two- and three-nucleon short-range correlation probabilities in nuclei, Phys. Rev. Lett. 96 (2006) 082501. doi:10.1103/PhysRevLett.96.082501.
M. Duer, O. Hen, E. Piasetzky, et al., Measurement of nuclear trans-
Z. Li, Z. Ren, B. Hong, H. Lu, D. Bai, Neutron stars within a relativistic
L. L. Frankfurt, M. I. Strikman, D. B. Day, M. Sargsyan, Evidence for
B.-J. Cai, B.-A. Li, Symmetry energy of cold nucleonic matter within a
P. K. Panda, D. P. Menezes, C. Providência, J. da Providência, Aspects of
A. Tang, J. W. Watson, J. Aclander, et al.,
C. Ciofi degli Atti, In-medium short-range dynamics of nucleons: Recent
tories and the emc e
054620
https://link.aps.org/doi/10.1103/PhysRevLett.119.054620
https://link.aps.org/doi/10.1103/PhysRevC.60.015801
https://link.aps.org/doi/10.1103/PhysRevC.85.055203
https://link.aps.org/doi/10.1103/PhysRevLett.108.092502
https://link.aps.org/doi/10.1103/PhysRevLett.108.092502
https://link.aps.org/doi/10.1103/PhysRevC.21.1546
10.1103/PhysRevC.99.045202.
doi:10.1103/PhysRevC.99.045202.
https://link.aps.org/doi/10.1103/PhysRevC.99.045202.
R. C. Tolman, Static solutions of einstein’s field equations for spheres of
J. Antoniadis, P. C. Freire, N. Wex, et al., A massive pulsar in a compact
P. B. Demorest, T. Pennucci, S. M. Ransom, S. M. Roberts, J. W. Hes-
sels, A two-solar-mass neutron star measured using Shapiro delay, Nature
J. M. Lattimer, S. A. Van, Neutron star envelopes, The Astrophysical Journal 272 (1983) 286.
E. H. Gudmundsson, C. J. Pethick, R. I. Epstein, Structure of neutron star
E. Gudmundsson, Neutron star envelopes, The Astrophysical Journal 259 (1982) L19.
D. Page, U. Geppert, F. Weber, The cooling of compact stars, Nuclear Physics A 605 (4) (1996) 531–565.
doi:10.1016/0375-9474(96)00164-9
http://linkinghub.elsevier.com/retrieve/pii/S0375947405011164
H. Müller, B. D. Serot, Relativistic mean-field theory and the high-density nuclear equation of state, Nuclear Physics A (1996). arXiv:9603037.
doi:10.1016/0375-9474(96)00187-X
arXiv:1904.06759
Shapiro delay measurements of an extremely massive millisecond pulsar, Nature Astronomy (2020). arXiv:1904.06759.
doi:10.1038/s41598-019-0980-2.
H. T. Cromartie, E. Fonseca, S. M. Ransom, et al., Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar, Nature Astronomy (2020). arXiv:1904.06759.
doi:10.1038/s41598-019-0980-2.
F. Weber, Pulsars as astrophysical laboratories for nuclear and particle physics, Institute of Physics, Bristol, U.K., 1999.
C. Schaaf, F. Weber, M. K. Weigel, N. K. Glendenning, Thermal evolution of compact stars, Nuclear Physics A 605 (4) (1996) 531–565.
doi:10.1016/0375-9474(96)00164-9.
URL
https://link.aps.org/doi/10.1103/PhysRevC.95.045202
https://link.aps.org/doi/10.1103/PhysRevC.99.045202.
https://link.aps.org/doi/10.1103/PhysRevC.99.045202.
D. Page, U. Geppert, F. Weber, The cooling of compact stars, Nuclear Physics A 777 (2006) 497–530.
doi:10.1016/j.nuclphysa.2005.09.019.
F. Weber, Pulsars as astrophysical laboratories for nuclear and particle physics, Institute of Physics, Bristol, U.K., 1999.
C. Schaaf, F. Weber, M. K. Weigel, N. K. Glendenning, Thermal evolution of compact stars, Nuclear Physics A 605 (4) (1996) 531–565.
doi:10.1016/0375-9474(96)00164-9.
URL
https://link.aps.org/doi/10.1103/PhysRevC.90.055203
https://link.aps.org/doi/10.1103/PhysRevC.90.055203
[52] J. M. Lattimer, C. Pethick, M. Prakash, P. Haensel, Direct URCA Process in Neutron Stars, Physical Review Letters 66 (21) (1991) 2701–2704.