Short range correlation and Urca processes in neutron stars

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Content:

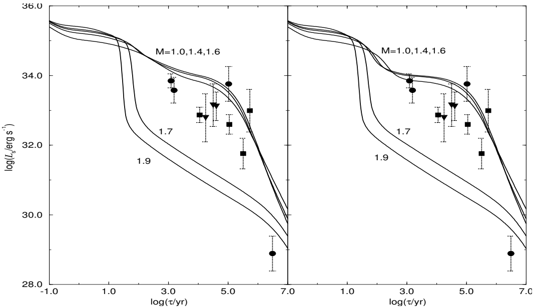
- Motivation
- Emissivities and different schemes of computing the baryon polarization tensor
- Computation of NFL Urca process
- Numerical results
- Conclusion

Based on: A. S., Phys. Rev. Lett. 133, 171401 (2024), arXiv:2406.16183

See also: M. G. Alford, A. Haber, Z. Zhang, Phys. Rev. C 110, L052801, arXiv:2406.13717

Well-known fast vs slow paradigm of cooling of compact stars

$$\left(\int_0^{R_c} nc_v(r,T)dV_p\right)\frac{dT'}{dt} = -\int_0^{R_c} n\epsilon_\nu(r,T)e^{2\Phi}dV_p - 4\pi\sigma R^2 T_S^4 e^{2\Phi_c} \quad (1)$$



- Jump-like transition in cooling once direct Urca or other fast processes are allowed.
- Minimal cooling paradigm (Page et al. 2004, 2009 +) postulates absence of any fast agent and obtains good fits to data
- Similar situation with hyperon Urca processes (but not quarks).

Standart neutrino reactions in NS:

- Urca process

$$n \to p + e + \bar{\nu}, \quad p + e \to n + \nu.$$

- Modified Urca/brems process

$$n + n \to n + p + e + \bar{\nu},$$
$$n + n \to n + p + \nu + \bar{\nu},$$

- Crustal bremsstrahlung

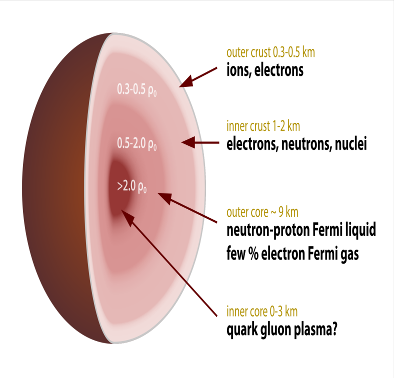
$$e + (A, Z) \to e + (A, Z) + \nu + \bar{\nu},$$

- Cooper pair-breaking-formation

$$[NN] \to [NN] + \nu + \bar{\nu},$$

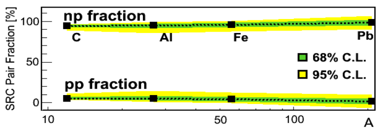
- Surface photo-emission

$$L_\gamma = 4\pi\sigma R^2 T^4$$

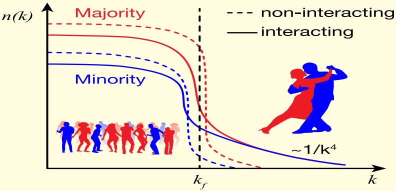


SRC in experiments (break-down of Fermi-liquid picture in nuclei):

- JLab experiments on electron scattering on nuclei ^{12}C, ^{27}Al, ^{56}Fe and ^{208} Pb targets show highly correlated neutron-proton pairs [figures from O. Hen, Science, 346, 614-617 (2014)]



- The momentum-distribution deviates from Fermi function form



- Such SRC are consistent with phase shift analysis $^3S_1$-$^3D_1$ np channel is much stronger than $^1S_0$ for nn and pp pairs.

Boltzmann equation in Kadanoff-Baym formalism [see A. S. et al. Phys. Lett. B463 (1999) 145; Phys. Rev. D62 (2000) 083002, also work by Voskresensky and Senatorov, PLB 1986]

$$\left[\partial_t + \vec{\partial}_q\, \omega_\nu(\boldsymbol{q})\vec{\partial}_X\right] f_{\bar{\nu}}(\boldsymbol{q}) = \int_{-\infty}^{0} \frac{dq_0}{2\pi} \mathrm{Tr}\left[\sigma^<(q) S_{\bar{\nu}}^{>}(q) - \sigma^>(q) S_{\bar{\nu}}^{<}(q)\right]. \qquad (2)$$

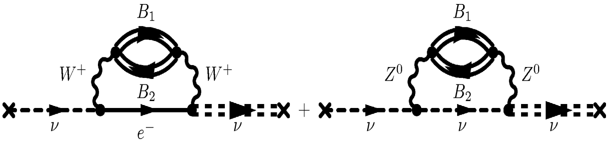
Emissivity is found by integration of of Boltzmann equation over phase space

$$\begin{aligned} \epsilon_{\bar{\nu}} &= \frac{d}{dt}\int \frac{d^3q}{(2\pi)^3} f_{\bar{\nu}}(\boldsymbol{q})\omega_\nu(\boldsymbol{q}) \\ &= -2\left(\frac{\tilde{G}}{\sqrt{2}}\right)^2 \int \frac{d^3q_1}{(2\pi)^3 2\omega_e(\boldsymbol{q}_1)} \int \frac{d^3q_2}{(2\pi)^3 2\omega_\nu(\boldsymbol{q}_2)} \int d^4q\, \delta(\boldsymbol{q}_1 + \boldsymbol{q}_2 - \boldsymbol{q}) \\ &\quad \delta(\omega_e + \omega_\nu - q_0)\, \omega_\nu(\boldsymbol{q}_2) g_B(q_0) \left[1 - f_e(\omega_e)\right] \Lambda^{\mu\zeta}(q_1, q_2) \mathrm{Im}\, \Pi^R_{\mu\zeta}(q), \qquad (3) \end{aligned}$$

where the leptonic trace is given by

$$\Lambda^{\mu\zeta}(q_1, q_2) = \mathrm{Tr}\left[\gamma^\mu (1-\gamma^5)\, \not{q}_1 \gamma^\zeta (1-\gamma^5)\, \not{q}_2\right]$$

The key problem is to compute the polarization loop $\Pi^R_{\mu\zeta}(q)$.



- Charge current (left) diagram for self-energy corresponding to Urca/mod. Urca process.
- Charge neutral (right) diagram for self-energy corresponding to bremsstrahlung.
- The free and full neutrino propagators are shown by the dashed and double dashed lines
- The electrons and baryons - by the solid and double-solid lines
- The wavy lines correspond to the gauge W^+ and Z-boson propagators

Quasiparticle scheme (loop expansion)

1. dUrca process: one-loop, quasiparticle $T = 0$ response functions (Lattimer et al, 1992)
2. Finite-T dUrca: one-loop, quasiparticle $T \neq 0$ response functions (this work, but see Yakovlev et al. Phys. Rep. 354, 1 (2001).
3. Modified Urca: two-loop, quasiparticle $T = 0$ and $T \neq 0$ response function

Finite-width scheme (sceleton expansion)

1. One-loop, finite width proton particles for Urca process (this work)
2. One-loop finite width bremsstrahlung, Raffelt, Sigl, Phys. Rev. D 54, 2784 (1996), Phys. Rev. D 60, 023001 (1999), A. S. et al. Phys. Lett. B463 (1999).

Computation of NFL Urca process

- Emissivity:

$$\epsilon_\nu = -\left(\frac{2G}{\sqrt{2}}\right)^2 \int \frac{d^3k}{(2\pi)^3 2\omega_\nu(\vec{k})} \int \frac{d^3k'}{(2\pi)^3 2\omega_e(\vec{k}')} \int d^4q\, \delta(k+k'-q)$$
$$g(q_0)\bar{f}_e(\omega_e)\mathrm{Im}[\Lambda^{\mu\nu}(k,k')\,\Pi^R_{\mu\nu}(q)] = 2G^2 \int d^4q L_1(q)\, L_2(q), \quad (4)$$

- Loop integrals separate the leptonic and hadronic contributions

$$L_1(q) = \int \frac{d^4p'\, d^4p}{(2\pi)^2} \delta^{(4)}(p-p'+q) A_n(p) A_p(p') f(p') \bar{f}(p), \quad (5)$$

$$L_2(q) = \int \frac{d^3k d^3k'}{(2\pi)^6} \bar{f}(k')\bar{f}(k)\omega_{\bar{\nu}}\delta^4(k+k'-q), \quad (6)$$

where p' and p refer to the four-momenta of the neutrons and protons.

Spectral functions

- The spectral functions of the nucleons with $\tau \in n, p$ are given by

$$A_\tau(p) = \frac{\gamma_\tau}{[\epsilon - \epsilon_\tau(p)]^2 + \gamma_\tau^2/4}, \tag{7}$$

– $\epsilon_\tau(p) = \epsilon_\tau^{\rm kin} + {\rm Re}\,\Sigma_\tau^R(p) - \mu_\tau$, $\epsilon_\tau^{\rm kin}(p)$ is the kinetic energy
– $\Sigma_\tau^R(p)$ is the retarded self-energy and $\gamma_\tau = -2{\rm Im}\Sigma_\tau^R(p)$
– μ_τ is the chemical potential

- In the small γ_τ limit

$$A_\tau(p) = 2\pi z_\tau \delta[\epsilon_\tau - \epsilon_\tau(p)] - \frac{\gamma_\tau}{[\epsilon_\tau - \epsilon_\tau(p)]^2} + O(\gamma_\tau^2) \tag{8}$$

– $\epsilon_\tau(p) = p^2/2m_\tau^* - \mu_\tau$ is the quasiparticle spectrum and m_τ^* is the quasiparticle mass defined as

$$\frac{m_\tau}{m_\tau^*} = 1 + \frac{m_\tau}{p_{F\tau}} \frac{\partial \Sigma_\tau^R(p)}{\partial p}\bigg|_{p=p_{F\tau}}, \tag{9}$$

z_τ is the wave-function renormalization, which we include in the effective mass via $z_\tau m_\tau^* \to m_\tau^*$.

Zero-width limit

- Emissivity in the limit $\gamma_p \to 0$:

$$\epsilon_\nu = G^2 \frac{p_{Fe} m_p^* m_n^*}{4\pi^5} \int_0^\infty d\omega_\nu \omega_\nu^3 \int_{-\infty}^\infty d\omega g(\omega) f_e(\omega_\nu - \omega) L_1(\omega, q = p_{Fe}). \tag{10}$$

- with analytically computed loop

$$L_1(q) = cT \ln \left| \frac{1 + \exp\left(-\frac{\epsilon_{\rm min} - \mu_p}{T}\right)}{1 + \exp\left(-\frac{\epsilon_{\rm min} + \omega - \mu_p}{T}\right)} \right|, \tag{11}$$

where

$$c \equiv m_n^* m_p^* / 2\pi q \quad \epsilon_{\rm min} = (m_n^*/2q^2) \left(\mu_n + \omega - \mu_p + q^2/2m_p^*\right)^2 .$$

Eqs. (11) in Eq. (10) give the general form of dUrca emissivity at finite temperatures

- Low temperatures, the small ω expansion leads to

$$\frac{L_1(q)}{cT\omega} = \{\exp[(\epsilon_{\rm min} - \mu_p)/T] + 1\}^{-1} \simeq \theta(\mu_p - \epsilon_{\rm min}) = \theta(|p_{Fe} + p_{Fp} - p_{Fn}|),$$

which is the results of Lattimer et al. 1992.

Finite-width case

- With the full spectral function for protons given by Eq. (7) we find

$$L_1(q) = c\int d\epsilon[f(\epsilon) - f(\omega+\epsilon)]\left\{\frac{1}{2} - \frac{1}{\pi}\text{atan}\left[\frac{\epsilon_{\text{min}} - \epsilon}{\gamma_p/2}\right]\right\}. \quad (12)$$

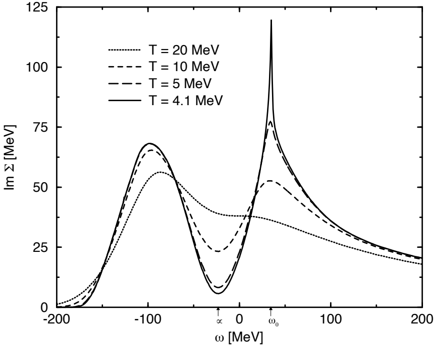
  – We assume $\epsilon_\tau(p) = p^2/2m^*_\tau - \mu_\tau$, where $m^*_\tau/m_\tau = 0.7$ and μ_τ is taken to be equal to the Fermi energy computed from the partial density $n_\tau = k^3_{F\tau}/3\pi^2$

- The width of proton quasiparticles:

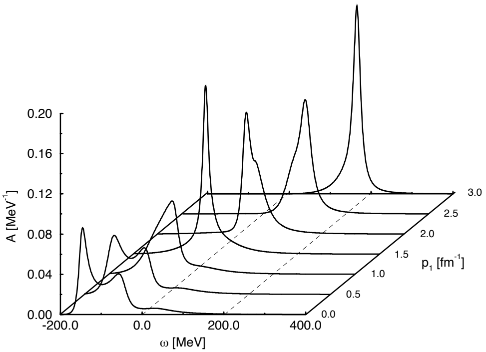
$$\gamma_p = a_p T^2\left[1 + \left(\frac{\epsilon - \mu_p}{\pi T}\right)^2\right], \quad (13)$$

  where $a_p = (\hbar v_{Fp}\mu_p^{-1})\sum_{\tau=n,p}\bar{\sigma}_{p\tau}n_\tau\mu_\tau^{-1}$, where v_{Fp} is the proton Fermi velocity, n_τ are the number densities and $\bar{\sigma}_{np} = 7$ fm^2 and $\bar{\sigma}_{pp} = 4$ fm^2 are the angle averaged cross sections for neutron-proton and proton-proton scattering.

The imaginary part of the nucleon self-energy in nuclear matter as a function of energy for momentum $p = 0$.

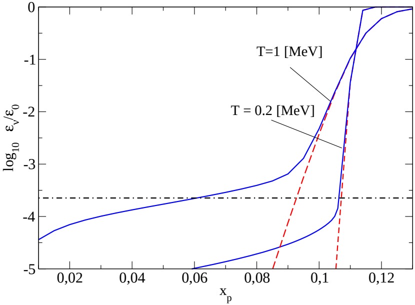


The density is at the saturation density $n_0 = 0.16\,fm^{-3}$ *. The selfenergy is given for several temperatures above the critical temperature for superfluidity (* $T_c = 4.02\text{MeV}$ *). The chemical potential* $\mu = -23.5\text{MeV}(T = 4.1\text{MeV})$ *and the location of the pairing peak at* $\omega_0 = 2\mu - \epsilon_1 = 35.6\text{MeV}$ *are indicated. Credit: Alm, et al, Phys. Rev. C53, 2181-2193 (1996).*



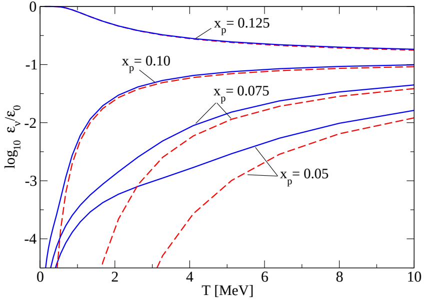
The nucleon spectral function at saturation density and T = 10 MeV in the energy-momentum plane. Credit: Alm, et al, Phys. Rev. C53, 2181-2193 (1996).

NFL Urca emissivity for finite proton width:



The nFL-Urca emissivity in units of ϵ_0 for $T = 1$ MeV and $T = 0.2$ MeV for density $\rho = 1.5\rho_0$ with $\rho_0 = 2.7 \times 10^{14}$ g cm^{-3} as a function of proton fraction x_p. The dashed lines show the dUrca process, i.e., the quasiparticle limit corresponding to $\gamma_p = 0$. For comparison, we show the FL one-pion-ρ exchange based mUrca process $\epsilon_{\rm mUrca}/\epsilon_0$ for $T = 1$ MeV by the dot-dashed horizontal line. The corresponding result for $T = 0.2$ MeV is $\epsilon_{\rm mUrca}/\epsilon_0 = -5$.

NFL Urca emissivity for finite proton width:



The nFL-Urca emissivity in units of ϵ_0 for $x_p = 0.05$, 0.10 and 0.125 and $\rho = 1.5\rho_0$ as a function of temperature. The solid lines show the full result, whereas the dashed lines – the limit $\gamma_p = 0$.

Conclusions:

- The sharp dUrca thershold is replaced by smooth transition in the scheme which is based on NFL Urca expression
- The finite width approach unifies the dUrca and modified Urca processes by replacing the qusiparticle loop expansion, i.e., its a different summation scheme - not a new process!
- The modified Urca process corresponds to second-Born approximation to the neutrino self-energy. The width can include more complicated resummations, such as *G*-matrix.

Perspectives:

- A new way to account for pole structure of intermediate propagator, see P. S. Shternin, M. Baldo, and P. Haensel, In-medium enhancement of the modified Urca neutrino reaction rates, Phys. Lett. B 786, 28 (2018).
- Alternative of including pion softening effects, see A. B. Migdal, E. E. Saperstein, M. A. Troitsky, and D. N. Voskresensky, Pion degrees of freedom in nuclear matter, Phys. Rep. 192, 179 (1990).