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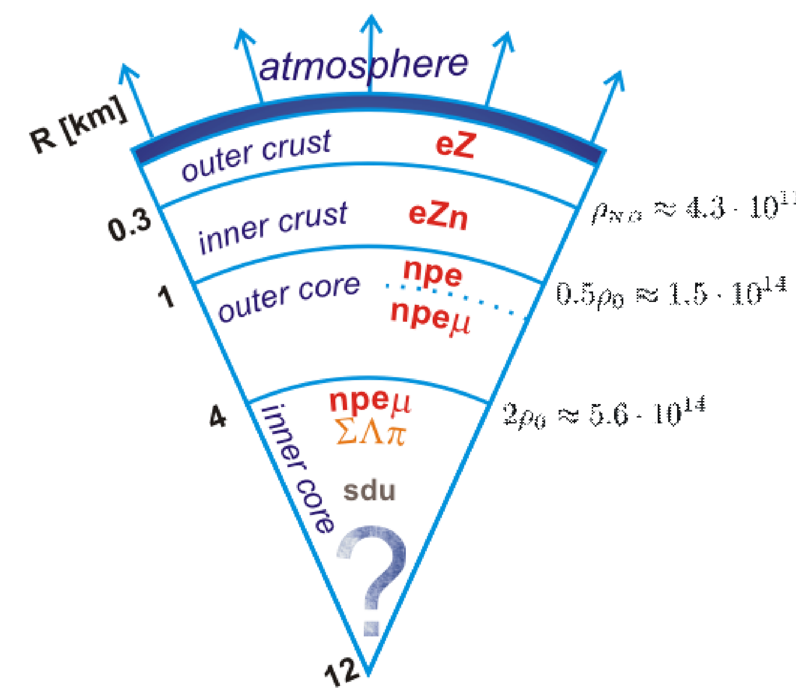
Transport coefficients of superdense matter in nucleon cores of neutron stars in BHF approach. Comparison of different nucleon potentials

Transport coefficients of the superdense matter in neutron star cores are important ingredients for modelling of various evolutionary processes. Thermal conductivity of neutron star cores is necessary for studies of young neutron stars (NS) cooling. Shear viscosity regulates the damping of the stellar oscillations and stability of rotating neutron stars. Here we study thermal conductivity and shear viscosity of non-superfluid npeμ neutron star cores. The focus is made on the nucleon sector. Collision frequencies are calculated in the Brueckner-Hartree-Fock framework as was done in Shternin et al., 2013, PRC 88, 065803 for a one model of the nuclear potential. In the present work we compare different nuclear potentials, namely Argonne v18 and CD-Bonn. The effects of the different way to include the three-body forces are also investigated



Formalism

Transport coefficients are mediated by the electromagnetic and strong nuclear forces

$$\kappa = \kappa_{e\mu}[ee, e\mu, ep] + \kappa_n[nn, np]$$

Effective relaxation times solve the system of transport equations. In the neutron star cores all particles are degenerate and the simplest variational solution is sufficient. This results in the linear equation system

$$\kappa = \sum_c \frac{\pi^2 k_B^2 T n_c \tau_c^{\kappa}}{3 m_c^*}; \quad \eta = \sum_c \frac{n_c p_{Fc}^2 \tau_c^{\eta}}{5 m_c^*}$$

$$\sum_{i=n,p} \nu_{ci}\tau_i = 1$$

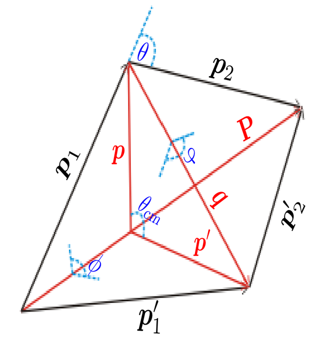
Effective collision frequencies are expressed through the transport cross-sections which are the angular averages of the transition probabilities over the corresponding phase-space.

$$\nu_{ci}^{(\kappa)} = \frac{64 m_c^* m_i^{*2}(k_B T)^2}{5 m_N^2 \hbar^3} S_{\kappa ci}, \quad \nu_{ci}^{(\eta)} = \frac{16 m_c^* m_i^{*2}(k_B T)^2}{3 m_N^2 \hbar^3} S_{\eta ci}.$$

$$\begin{aligned}
S_{\kappa cc} &= \frac{m_N^2}{128\pi^2\hbar^4 p_c^2}\int_0^{2p_c} dP \int_0^{q_m(P)} dq \frac{(4p_c^2 - P^2)}{\sqrt{q_m^2 - q^2}}\mathcal{Q}_{cc},\\
S_{\kappa ci} &= \frac{m_N^2}{128\pi^2\hbar^4 p_c^2}\int_{|p_c-p_i|}^{p_c+p_i} dP \int_0^{q_m(P)} dq \frac{(4p_c^2 + q^2)}{\sqrt{q_m^2 - q^2}}\mathcal{Q}_{ci}, \quad c\neq i,\\
S_{\eta cc} &= \frac{3m_N^2}{128\pi^2\hbar^4 p_c^6}\int_0^{2p_c} dP \int_0^{q_m(P)} dq \frac{q^2(4p_c^2 - P^2 - q^2)}{\sqrt{q_m^2 - q^2}}\mathcal{Q}_{cc},\\
S_{\eta ci} &= \frac{3m_N^2}{128\pi^2\hbar^4 p_c^6}\int_{|p_c-p_i|}^{p_c+p_i} dP \int_0^{q_m(P)} dq \frac{q^2(4p_c^2 - q^2)}{\sqrt{q_m^2 - q^2}}\mathcal{Q}_{ci}, \quad c\neq i,
\end{aligned}$$

$$\sum_{\text{spins}} w_{ci}(12|1'2') = 4\frac{(2\pi)^4}{\hbar}\delta(\epsilon_1+\epsilon_2-\epsilon_1'-\epsilon_2')\delta(\boldsymbol{P}-\boldsymbol{P}')\mathcal{Q}_{ci},$$

All particles on the Fermi surfaces



Angular averaging

$$\frac{1}{\tau_i} = \frac{1}{\tau_i}\left[\langle w(12|1'2')\beta(\theta,\phi)\rangle\right]$$

Brueckner-Hartree-Fock approach

The scattering equation in the medium is solved self-consistently with the single-particle energy, at the two-hole-line level (with account for the Pauli principle in the medium)

Bethe-Brueckner-Salpeter equation

$$\langle p_1p_2|G^{\alpha\beta}(\omega)|p_3p_4\rangle = \langle p_1p_2|V^{\alpha\beta}|p_3p_4\rangle + \sum_{k_1,k_2}\langle p_1p_2|V^{\alpha\beta}|k_1k_2\rangle\frac{Q^{\alpha\beta}(k_1,k_2)}{\omega-\epsilon_\alpha(k_1)-\epsilon_\beta(k_2)}\langle k_1k_2|G^{\alpha\beta}|p_3p_4\rangle$$

$Q^{\alpha\beta}(k_1,k_2)$ – Pauli operator

Self-consistent potential

$$U_\alpha(p_1) = \sum_{\beta;\, p_2<p_{F\beta}}\langle p_1p_2|G^{\alpha\beta}(\epsilon_1(p_1)+\epsilon_2(p_2))|p_1p_2\rangle_A$$

Single-particle potential

$$\epsilon_\alpha(p) = \frac{p^2}{2m_\alpha} + U_\alpha(p)$$

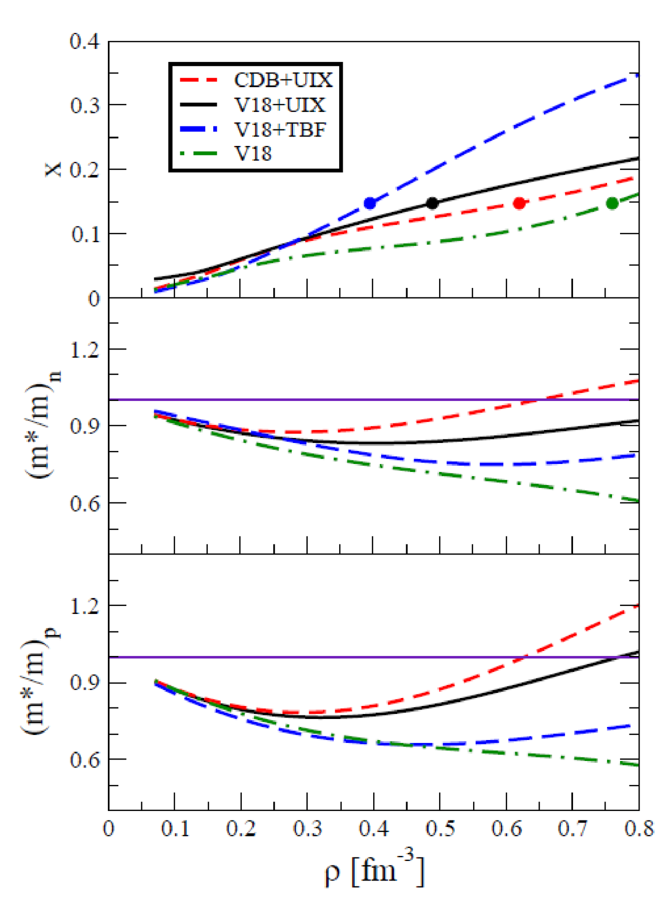
The soluition of the BBS equation gives the scattering matrix (G-matix) and effective masses

We consider two potentials: Av18 (*Wiringa et al., 1995, PRC 51,38*) and CD-Bonn (*Machleidt, 2001, PRC 51, 024001*. Three-nucleon forces are required for the correct saturation point of the nuclear matter in non-relativistic theory.
In the BHF approach three-body forces are included in effective way by averaging over the third nucleon in the self-consistent iterative procedure.

We use the same three-nucleon forces as in *Baldo et al. 2014, PRC 89, 048801*. Namely we use phenomenological model URBANA IX *(e.g., Pudliner et al., 1997, PRC 56, 1720)* where the model parameters depend on the two-nucleon potential (Av18 or CD-Bonn) and are fitted to the saturated point position.

We also consider microscopic three-body forces (TBF) based on the meson-exchange model. The exchange constants are taken to be the same as for the two-nuleon potential. In our case we use TBF developed for the Av18 potential (*Li et al. 2008, PRC 77, 034316; 2008, PRC 78, 028801*). Similar interaction for the CD-Bonn potential is not constructed.

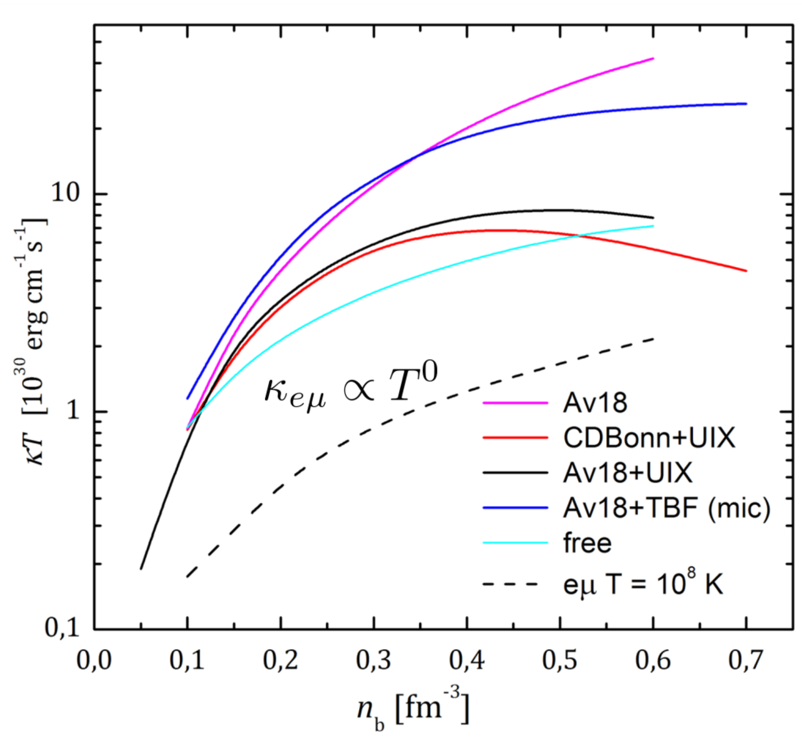
Effective masses $m^* = p\left(\frac{d\epsilon}{dp}\right)^{-1}$

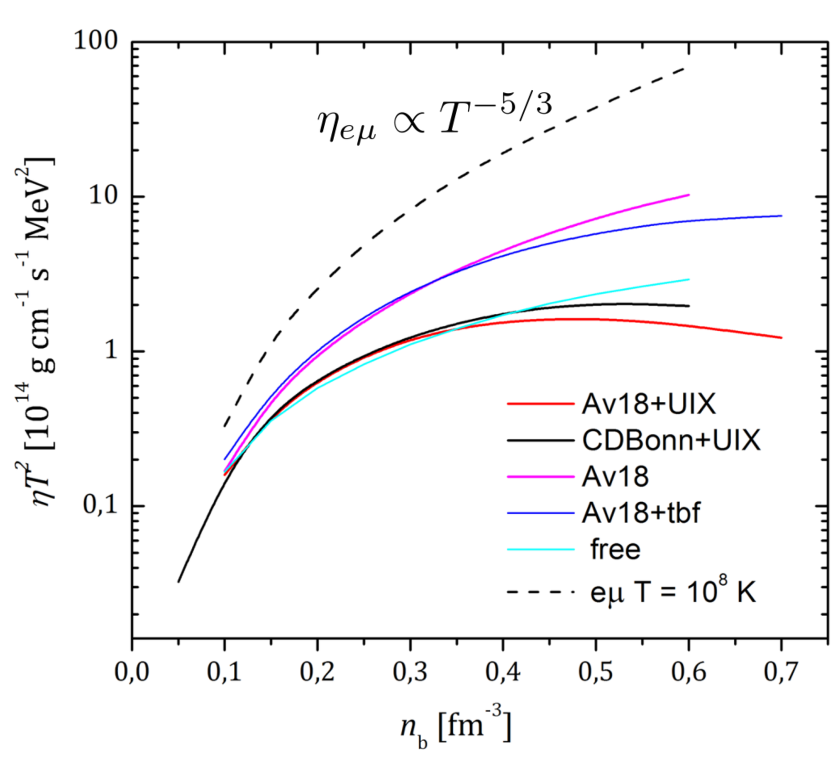


Baldo et al. 2014, PRC 89, 048801

Results

The results of calculations are compared with the model calculations preformed without many-body effects included (free) and with the electron-muon contribution (basing on Shternin&Yakovlev 2007,2008). In all cases, considered in this study we find $\kappa_n \gg \kappa_{e\mu}, \quad \eta_n \ll \eta_{e\mu}$





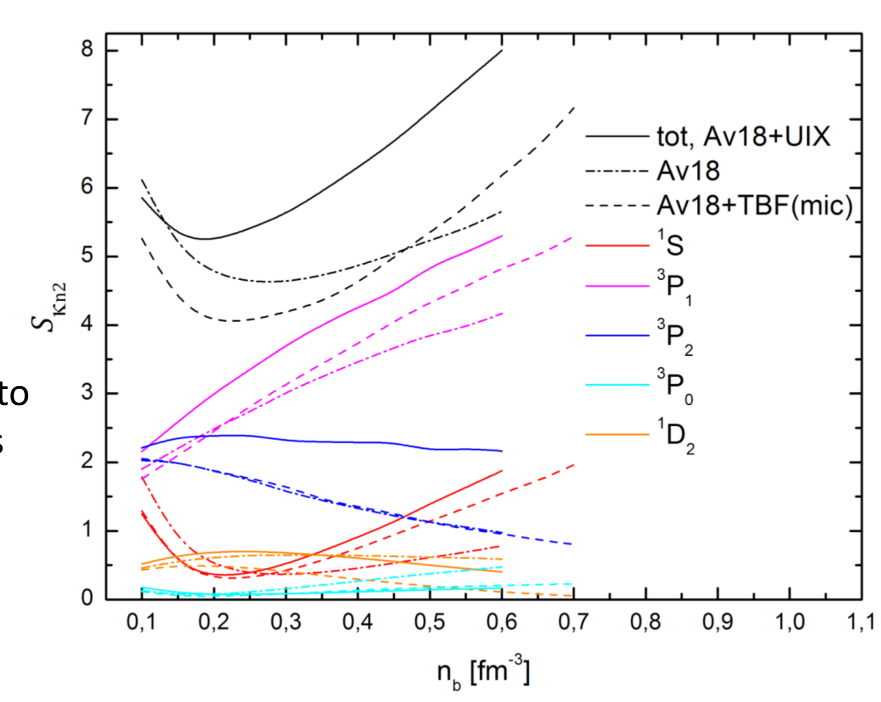
«Anatomy» of the transport cross-sections

Bethe-Brueckner-Salpeter equation in partial waves representation (solved up to J=12)

$$G_{\ell\ell'}^{JS}(P,p,p';w) = V_{\ell\ell'}^{JS}(p,p') + \sum_{\bar\ell}\int dk\, k^2 V_{\ell\bar\ell}^{JS}(p,k)\frac{\overline{Q}(P,k)}{\omega-\overline{E}(P,k)}G_{\bar\ell\ell'}^{JS}(P,k,p';\omega)$$

$$\mathcal{Q} = \frac{1}{4}\sum_L \frac{1}{4\pi^2}\mathcal{P}_L(\hat{p}\hat{p}')\sum i^{\ell'-\ell+\bar\ell-\bar\ell'}\Pi_{\ell\ell'\bar\ell\bar\ell'}\Pi_{J\bar J}^2 C_{\ell'0\bar\ell'0}^{L'0}C_{\ell 0\bar\ell 0}^{L0}\begin{Bmatrix}\bar\ell & S & \bar J\\ J & L & \ell\end{Bmatrix}\begin{Bmatrix}\bar\ell' & S & \bar J\\ J & L & \ell'\end{Bmatrix}G_{\ell\ell'}^{JS}\left(G_{\bar\ell\bar\ell'}^{\bar J S}\right)^*$$

When the squared matrix element is calculated, all partial waves couple. The contribution for the main partial waves is shown for the $S_{\kappa n2}$ cross-section and Av18 potential. We show only the conributions from the diagonal components of the G-matrix. It is problematic to select the only one partial wave which modification due to the inclusion of three-nucleon forces gives the main contribution.



Conclusions

- Neutron thermal conductivity and shear viscosity strongly depend on the employed model of the three-nucleon interaction. The difference between the Av18 (CD-Bonn) + UIX and Av18+TBF can be an order of magnitude large. Nevertheless, the electrons and muons give the dominate contribution to the shear viscosity.
- Both effective mass and matrix element modifications give comparable contribution to the resulting values of the transport coefficients.
- The main contribution to the transport cross-sections, which is responsible for the difference between the considered models comes from ^{1}S and ^{3}P partial waves

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