ASYMMETRY OF THE NEUTRINO MEAN FREE PATH IN HOT NEUTRON MATTER UNDER STRONG MAGNETIC FIELDS

Isaac Vidaña, INFN Catania

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The talk in few words

- ✧ Study of the neutrino mean free path in hot neutron matter under the presence of strong magnetic fields.

- ✧ Polarized neutron matter described within the non-relativistic BHF approach using the Av18 NN + UIX NNN & the HF one with the LNS Skyrme force. Explicit expressions of the σ/V for the scattering of a neutrino from spin up and spin down neutrons are derived from Fermi Golden rule.

- ✧ Strong dependence of the mean free path on the angle of the incoming neutrino.

In collaboration with: Julio Torres Patiño & Eduardo Bauer (La Plata, Argentina)

For details see:

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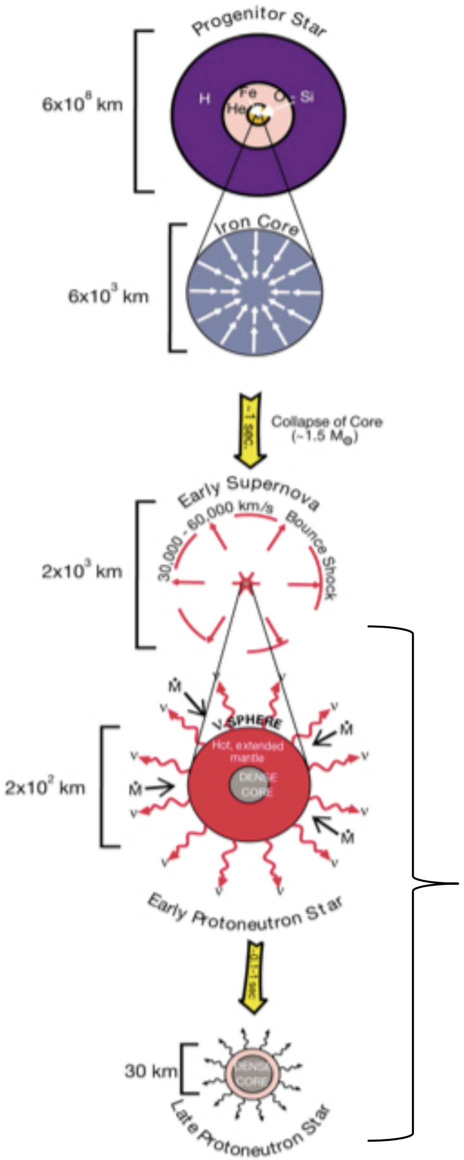
Neutrinos, SN & NS

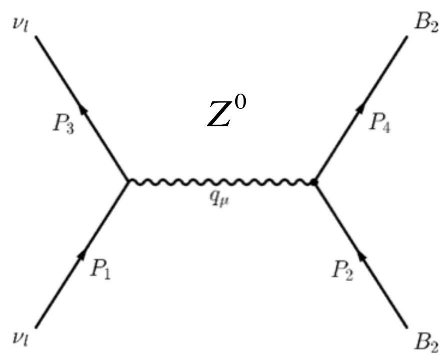


Neutrinos play a crucial role in the physics of supernova, in the early evolution of neutron stars & binary merger of compact objects

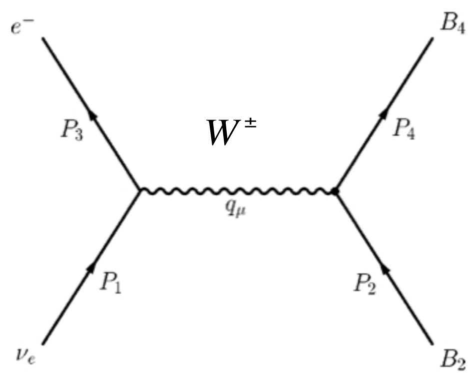
- ✧ Large number of neutrinos produced by e-capture during the collapse of the pre-supernova core. Most of the initial gravitational binding energy is stored in neutrinos
- ✧ λ_ν decreases as the radius of the neutron star shrinks from ~ 100 km to ~ 10 km becoming smaller than the NS radius ⟶ *neutrino trapping* ⟶ strong influence on the overall properties of hot & lepton-rich newborn neutron star, substantially different from the cold & deleptonized one.
- ✧ Cooling of newly born NS driven first by neutrino emission from the interior
- ✧ Neutrino cross sections & emissivities fundamental inputs for SN simulations and cooling calculations can be affected by the presence of magnetic fields (e.g., asymmetric emission)

Neutrino Interactions with Matter

During their propagation in matter neutrinos can be:



Scattered via weak coupling with **baryon neutral currents**



Absorbed via weak coupling with **baryon charged currents**

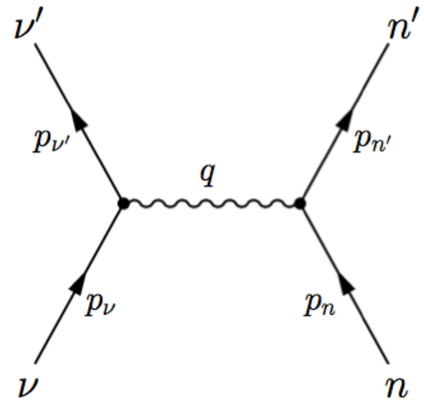
$$L_{NC} = \frac{G_F}{\sqrt{2}} l_\mu^\nu j_Z^\mu$$

$$l_\mu^\nu = \frac{1}{2}\bar{\psi}_\nu \gamma_\mu (1-\gamma_5)\psi_\nu, \quad j_Z^\mu = \bar{\psi}_4 \gamma^\mu (c_v - c_A\gamma_5)\psi_2$$

$$L_{CC} = \frac{G_F \cos\theta_c}{\sqrt{2}} l_\mu j_W^\mu$$

$$l_\mu = \bar{\psi}_l \gamma_\mu (1-\gamma_5)\psi_\nu, \quad j_W^\mu = \bar{\psi}_4 \gamma^\mu (g_v - g_A\gamma_5)\psi_2$$

Scattering Cross Section: Non-polarized Case



Here we consider only the ν-MFP in pure neutron matter ⟶ only scattering processes contribute

Using the Fermi Golden rule:

$$\frac{\sigma(p_\nu)}{V} = \int \frac{d\vec{p}_{\nu'}}{(2\pi)^3} \int \frac{d\vec{p}_n}{(2\pi)^3} \int \frac{d\vec{p}_{n'}}{(2\pi)^3} (2\pi)^4 \delta^{(4)}\left(p_\nu + p_n - p_{\nu'} - p_n\right) f_n(\vec{p}_n, T)(1 - f_{n'}(\vec{p}_{n'}, T)) \frac{\left\langle \left| M_{\nu'n',\nu n} \right|^2 \right\rangle}{16 E_\nu E_{\nu'} E_n E_{n'}}$$

where the square of the transition matrix is

$$\left| M_{\nu'n',\nu n} \right|^2 = \frac{1}{2} G_F l^{\mu\alpha} H_{\mu\alpha}$$

with

$$l^{\mu\alpha} = \left(\bar{\psi}_\nu \gamma^\mu (1 - \gamma_5) \psi_{\nu'}\right)\left(\bar{\psi}_{\nu'} \gamma^\alpha (1 - \gamma_5) \psi_\nu\right)$$

$$H_{\mu\alpha} = \left(\bar{\psi}_n (C_V + C_A \gamma_5) \gamma_\mu \psi_{n'}\right)\left(\bar{\psi}_{n'} \gamma_\alpha (C_V - C_A \gamma_5) \psi_n\right)$$

Scattering Cross Section: Spin polarized Case

In the presence of a magnetic field matter is polarized. In this case is convenient to write the hadronic tensor as sum of two terms by using the identity operator $I=\Lambda_{+}+\Lambda_{-}$

$$H_{\mu\alpha} = H^{-}_{\mu\alpha} + H^{+}_{\mu\alpha}$$

with

$$H^{\pm}_{\mu\alpha} = \left(\bar{\psi}_n \Lambda_{\pm} (C_V + C_A\gamma_5)\gamma_\mu \psi_{n'}\right)\left(\bar{\psi}_{n'}\gamma_\alpha (C_V - C_A\gamma_5)\Lambda_{\pm}\psi_n\right)$$

$$\Lambda_{\pm} = \frac{1}{2}(1+\gamma_5 \not{\omega}_{\pm})$$

$$\omega_{\pm} = (0,0,0,\pm 1)$$

Consequently we have:

$$\left|M^{\pm}_{\nu' n', \nu n}\right|^2 = \frac{1}{2} G_F l^{\mu\alpha} H^{\pm}_{\mu\alpha}$$

$$\frac{\sigma^{\pm}(p_\nu)}{V} = \int \frac{d\vec{p}_{\nu'}}{(2\pi)^3} \int \frac{d\vec{p}_n}{(2\pi)^3} \int \frac{d\vec{p}_{n'}}{(2\pi)^3} (2\pi)^4 \delta^{(4)}\left(p_\nu + p_n - p_{\nu'} - p_n\right) f_n(\vec{p}_n, T)(1 - f_{n'}(\vec{p}_{n'}, T)) \frac{\left\langle \left|M^{\pm}_{\nu' n', \nu n}\right|^2 \right\rangle}{16 E_\nu E_{\nu'} E_n E_{n'}}$$

Total cross section:

$$\frac{\sigma(p_\nu)}{V} = \left(\frac{1+A}{2}\right)\frac{\sigma^{+}(p_\nu)}{V} + \left(\frac{1-A}{2}\right)\frac{\sigma^{-}(p_\nu)}{V}, \quad A = \frac{\rho_+ - \rho_-}{\rho_+ + \rho_-}$$

Scattering Cross Section: Spin polarized case (non-relativistic limit)

Neutron matter is described here within non-relativistic (BHF & Skyrme) approaches. For consistency, neutrino scattering cross sections are evaluated in the non-relativistic limit

$$\left\langle \left| M^{\pm}_{\nu' n', \nu n} \right|^2 \right\rangle = 16 G_F^2 m^2 E_\nu E_{\nu'} \Big((C_V^2 + C_A^2) + (C_V^2 - C_A^2)\cos\theta_{\nu\nu'} \pm 2C_A \big((C_V + C_A)\cos\theta_\nu + (C_V - C_A)\cos\theta_{\nu'} \big) \Big)$$

we obtain

$$\frac{\sigma^{\pm}(p_\nu)}{V} = G_F^2 \int \frac{d\vec{p}_{\nu'}}{(2\pi)^3} \Big((C_V^2 + C_A^2) + (C_V^2 - C_A^2)\cos\theta_{\nu\nu'} \pm 2C_A \big((C_V + C_A)\cos\theta_\nu + (C_V - C_A)\cos\theta_{\nu'} \big) \Big) S^0_{\pm}(q_0, \vec{q}, T)$$

with

$$S^0_{\pm}(q_0, \vec{q}, T) = \frac{1}{(2\pi)^2} \int d\vec{p}_n f_n^{\pm}(\vec{p}_n, T)(1 - f_{n'}^{\pm}(\vec{p}_n + \vec{q}, T))\, \delta\Big(q_0 + E_n^{\pm}(\vec{p}_n, T) - E_{n'}^{\pm}(\vec{p}_n + \vec{q}, T) \Big)$$

the structure function describing the response of neutron matter to the excitations induced by neutrinos

A few remarks

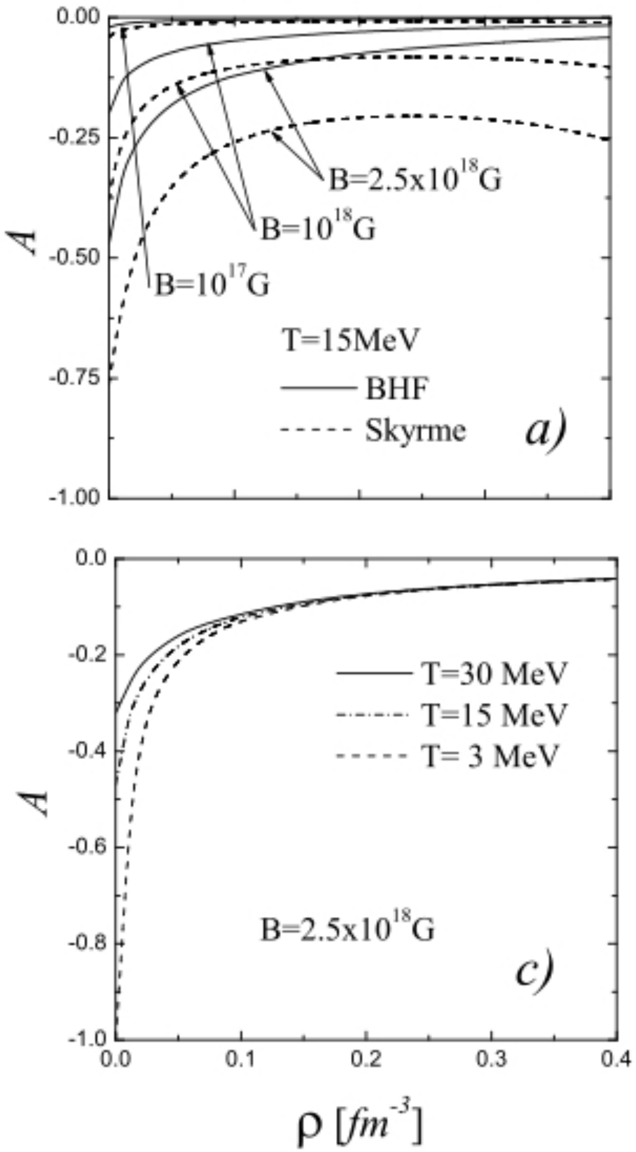
Note that in absence of the magnetic field A=0 and we will have $S^0_- = S^0_+ = S^0$ & $\sigma^- = \sigma^+$ so:

$$\frac{\sigma(p_\nu)}{V} = G_F^2 \int \frac{d\vec{p}_{\nu'}}{(2\pi)^3} \left(C_V^2 (1+\cos\theta_{\nu\nu'}) + C_A^2 \left(3-\cos\theta_{\nu\nu'}\right)\right) S^0(q_0,\vec{q},T)$$

we recover the expression frequently found in the literature. Comparing it with that for the polarized case we see:

- The new terms due to spin polarization are those propotional to $\cos\theta_\nu$ and $\cos\theta_{\nu'}$
- Since the integral is done over $\mathbf{p}_{\nu'}$ the contribution from the term proportional $\cos\theta_{\nu'}$ is almost negligible but not zero because $S^0_{+/-}$ depends implicitly on $\cos\theta_{\nu'}$
- If the momentum of the incoming neutrino is perpendicular to the magnetic field then $\cos\theta_\nu = 0$ and one expects no appreciable difference with respect to the non-polarized case.

Spin Asymmetry



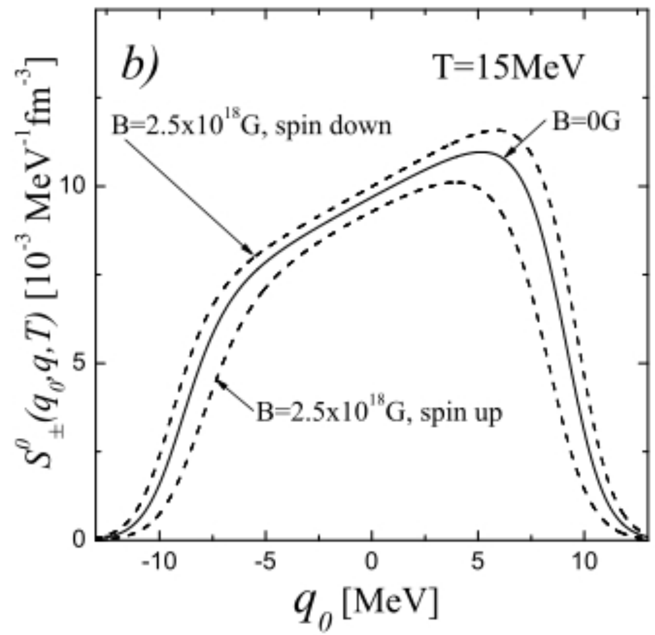
Polarization state of the system $\Rightarrow \dfrac{\partial(\varepsilon - TS - \vec{M}\cdot\vec{B})}{\partial A} = 0$

- If B=0 the system is non-polarized (A = 0)
- For low densities & temperatures the system is expected to be totally polarized (A = -1) up to a given density & partially polarized above it with predominance of spin-down states
- BHF: A grows monotonously with density and would reach the non-polarized state asymptotically at high densities.
- Skyrme: reaches a maximum and decreases (ferromagnetic instability)
- As one intuitively expects the increase of B (T) makes the system more (less) polarized

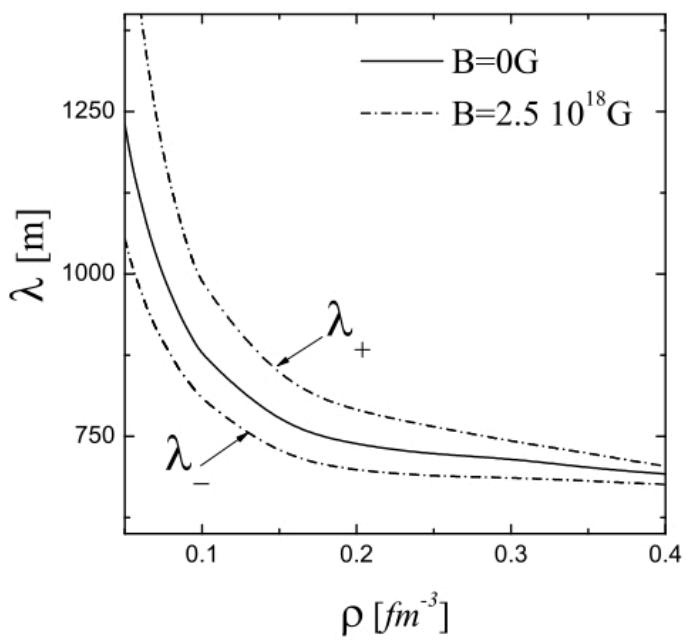
Structure Function

B induces a splitting between S_+ and S_- with $S_+ < S_-$ due to the dependence of the neutron s.p. energy on the spin polarization induced by B.

Phase space of spin up neutrons is smaller than that of spin down

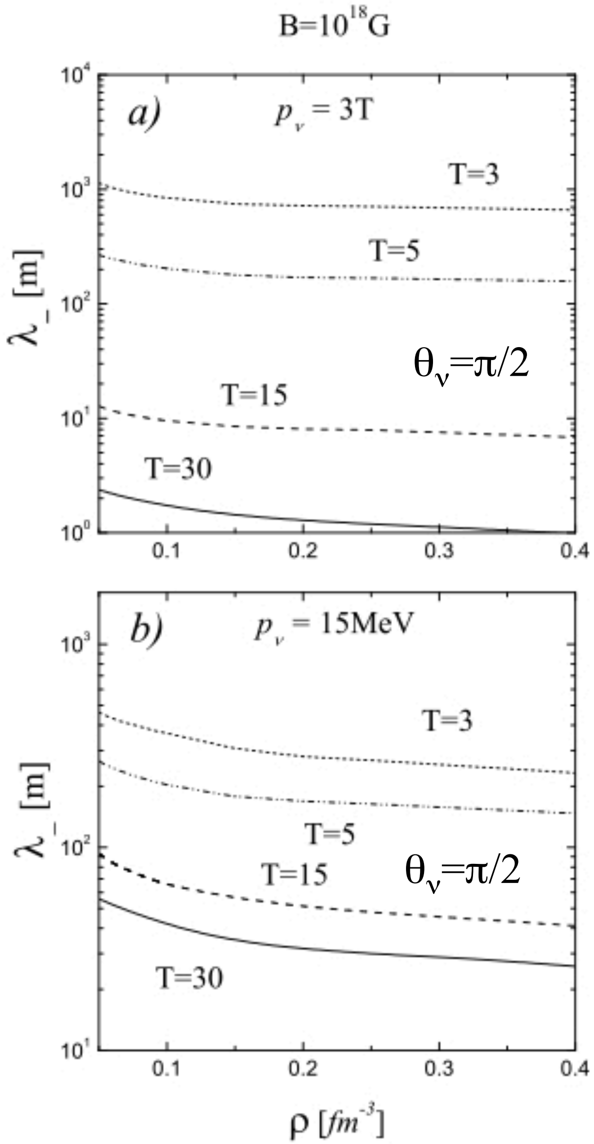


T=3MeV



An increase of B → decrease (increase) of σ_+ (σ_-) and therefore to an increase (decrease) of λ_+ (λ_-)

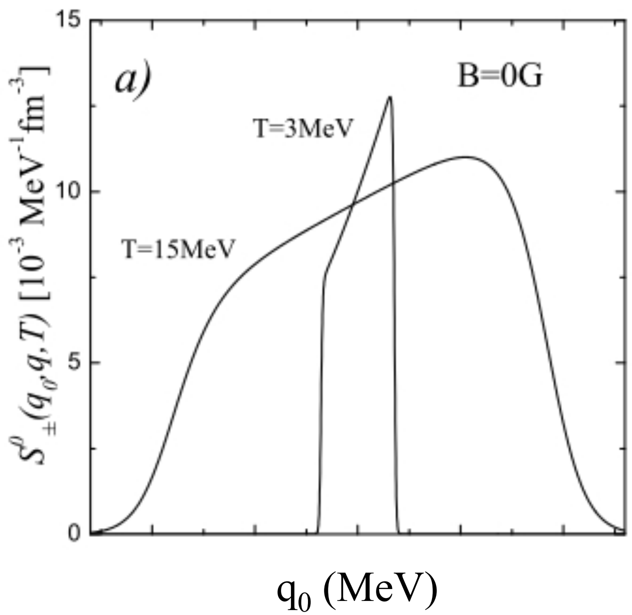
Temperature dependence of the ν mean free path



For fixed T, the larger p_ν the smaller λ because the response of the system to the excitations induced by neutrinos is larger for larger values of p_ν.

λ decreases dramatically when incresing T due to the temperature dependence of the structure function.

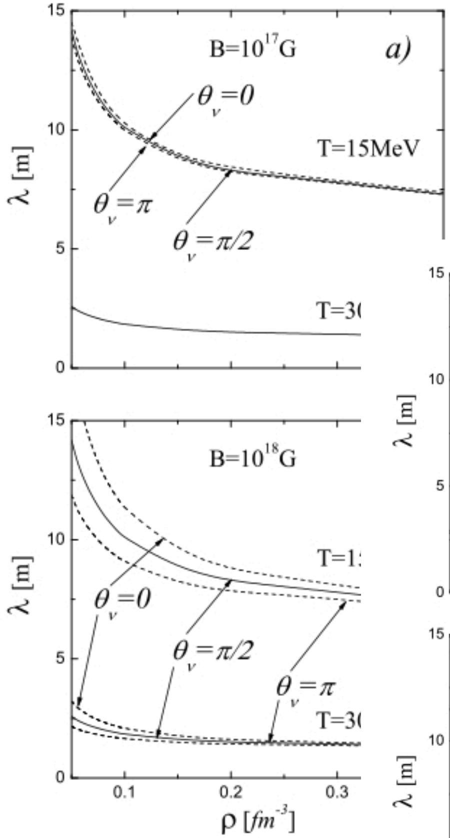
An increase of T leads to a much broader structure function (due to increase of the phase space) and consequently to a larger (smaller) cross section (ν mean free path)



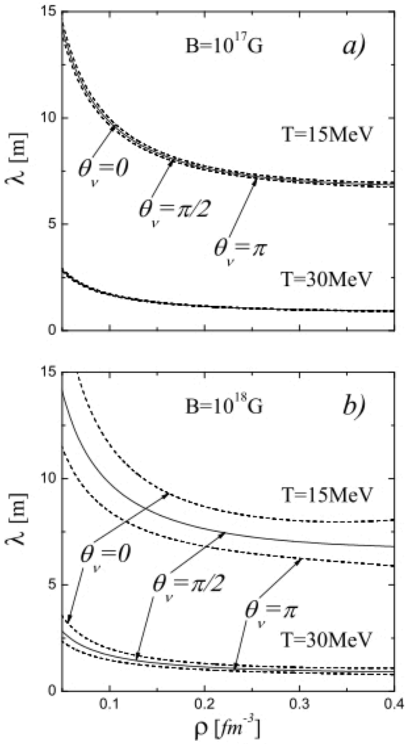
Dependence of the ν mean free path on the angle θ_ν

$$\lambda(p_\nu) = \frac{2\lambda_-(p_\nu)\lambda_+(p_\nu)}{(1-A)\lambda_-(p_\nu) + (1+A)\lambda_+(p_\nu)}$$

BHF



Skyrme



- Polarized matter is more transparent to neutrinos when they move parallel to the magnetic field (θ_ν=0) & more opaque when they move anti-parallel to it (θ_ν=π)

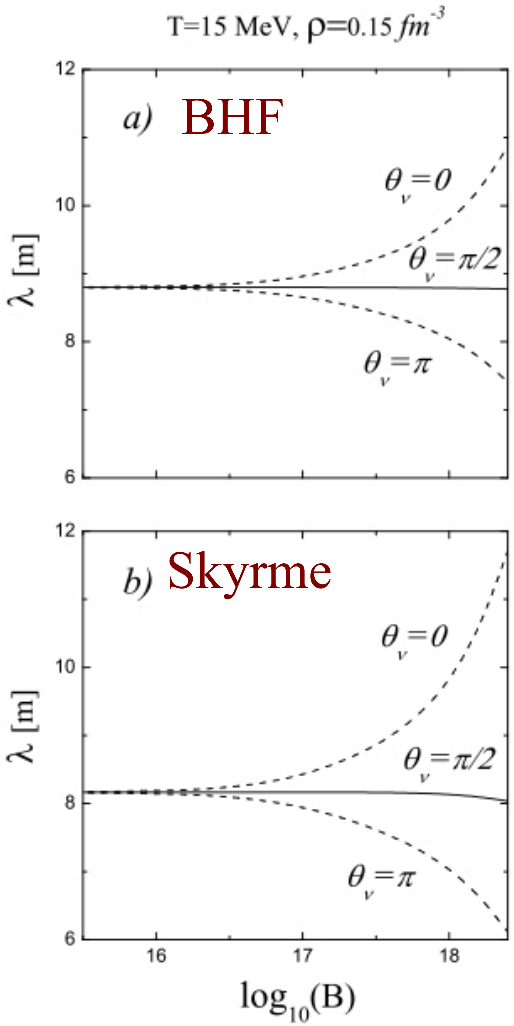
- We define a "mean free path asymmetry"

$$\chi_\lambda = \frac{\lambda(\theta_\nu = 0) - \lambda(\theta_\lambda = \pi)}{\lambda(\theta_\nu = \pi/2)}$$

ρ [fm^{-3}]	$\chi_\lambda(B=10^{16}G)$		$\chi_\lambda(B=10^{17}G)$		$\chi_\lambda(B=10^{18}G)$	
	BHF	Skyrme	BHF	Skyrme	BHF	Skyrme
0.050	0.0032	0.0036	0.0322	0.0357	0.2705	0.3647
0.150	0.0021	0.0023	0.0232	0.0257	0.1516	0.2657
0.400	0.0019	0.0027	0.0151	0.0311	0.0519	0.3212

- ✓ larger for higher fields
- ✓ relevant for low & medium densities
- ✓ as density increases nuclear interaction overcomes the coupling of neutrons with B

Magnetic field dependence of the ν mean free path



- If B=0 λ does not depend on the direction of the incoming neutrino

- The presence of B establishes a preferred direction & λ depends on the angle between the momentum of the incoming neutrino $\mathbf{p}_\nu$ and **B**

- However if $\theta_\nu=\pi/2$ λ is expected to be quite insensitive to B (see figure). The term proportional to cos θ_ν vanishes & remains only an small implicit dependence through the structure function

- The only remaining dependence on B is that of the structure function which is mostly appreciable in the low/medium density region where the spin asymmetry A is larger in absolute value

The Message (again) of this Talk

- ✧ Study of the neutrino mean free path in hot neutron matter under the presence of strong magnetic fields.

- ✧ Polarized neutron matter described within the non-relativistic BHF approach using the Av18 NN + UIX NNN & the HF one with the LNS Skyrme force. Explicit expressions of the σ/V for the scattering of a neutrino from spin up and spin down neutrons are derived from Fermi Golden rule.

- ✧ Strong dependence of the mean free path on the angle of the incoming neutrino.

- You for your time & attention
- My collaborators: Julio Torres Patiño & Eduardo Bauer