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PERSPECTIVES IN HADRONIC PHYSICS
Particle-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies

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Effect of the Neutrino Electromagnetic Form Factors on Neutrino Interaction in Dense Matter

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INDONESIA

These are preliminary lecture notes, intended only for distribution to participants
Effect of the Neutrino Electromagnetic Form Factors on Neutrino Interaction in Dense Matter

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Particles-Nucleus and Nucleus-Nucleus Scattering at Relativistic Energies
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OUTLINE

- The Aim of Research
- Formalism (Model of matter, Neutrino interaction with matter)
- Results and Discussion
- Conclusion
In Standard Model neutrino have zero charge radius \((R)\), zero magnetic moment \((\mu_\nu)\) and massless.

However, there are experimental evidences found that \(\mu_\nu < 10^{-10} \mu_B\) at the 90% confidence level \([Z. \, Daraktchieva \, et \, al \, (MUNU \, Collaboration) \, PLB \, 564, \, 190 \, (2003)]\).

LAMF experiment also found that neutrino have \(R^2 = (22.5 \pm 67.5) \times 10^{-12} \, \text{MeV}^{-2}\) \([P. \, Vilain \, et \, al, \, PLB \, 345, \, 115 \, (1995)]\).

According to this results
1. We observe the effect of neutrino and anti-neutrino electromagnetic form factors on neutrino mean free path (\( \lambda \)).

2. We also observe effect the weak magnetism of nucleons on neutrino mean free path.
RELATIVISTIC NUCLEAR MODEL

The Effective Lagrangian of E-RMF Model

\[ L^{\text{nuc}} = L_N + L_M, \]

where the nucleon part, up to order \( \nu = 3 \), has the form

\[ L_N = \bar{\psi} [i \gamma^\mu (\partial_\mu + i \nu_\mu + ig_\rho b_\mu + ig_\omega V_\mu) \]

\[ + g_A \gamma^\mu \gamma^5 \bar{a}_\mu - M + g_\sigma \sigma] \psi \right] - \frac{f_\rho g_\rho}{4M} \bar{\psi} \bar{b}_{\mu \nu} \sigma^{\mu \nu} \psi, \]

with

\[ \psi = \begin{pmatrix} p \\ n \end{pmatrix}, \quad \bar{\nu}_\mu = -\frac{i}{2} (\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger) = \bar{\nu}_\mu^t, \]
RELATIVISTIC NUCLEAR MODEL

\[ \tilde{a}_\mu = -\frac{i}{2} (\tilde{\xi}^\dagger \Xi \tilde{\xi} - \tilde{\xi} \Xi \tilde{\xi}^\dagger) = \tilde{a}_\mu^\dagger, \]

\[ \tilde{\xi} = \exp(i\tilde{\pi}(x)/f_\pi), \quad \tilde{\pi}(x) = \frac{1}{2} \tilde{\tau} \cdot \tilde{\pi}(x), \]

\[ \tilde{\pi}(x) = \frac{1}{2} \tilde{\tau} \cdot \tilde{\pi}(x), \]

\[ \tilde{\beta}_{\mu\nu} = D_\mu \tilde{b}_\nu - D_\nu \tilde{b}_\mu + ig_\rho [\tilde{b}_\mu, \tilde{b}_\nu], \quad D_\mu = \partial_\mu + i\tilde{\nu}_\mu, \]

\[ V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu, \]

\[ \sigma^{\mu\nu} = \frac{1}{2} [\gamma^\mu, \gamma^\nu]. \]

RELATIVISTIC NUCLEAR MODEL

\[
\mathcal{L}_M = \frac{1}{4} f_\pi^2 \text{Tr}(\partial_\mu \tilde{U} \partial^\mu \tilde{U}^\dagger) + \frac{1}{4} f_\pi^2 \text{Tr}(\tilde{U} \tilde{U}^\dagger - 2) \\
+ \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - \frac{1}{2} \text{Tr}(\tilde{b}_{\mu \nu} \tilde{b}^{\mu \nu}) - \frac{1}{4} \gamma_\nu \gamma_\nu \\
- g_\rho \pi^2 \left( \frac{2 f_\pi^2}{m_\rho^2} \text{Tr}(\tilde{b}_{\mu \nu} \tilde{b}^{\mu \nu}) + \frac{1}{2} \left( 1 + \eta_1 \frac{g_\sigma \sigma}{M} \right) \\
+ \frac{\eta_2 g_\omega^2 \sigma^2}{2 M^2} \right) m_\omega^2 \gamma_\mu \gamma^\mu + \frac{1}{4} \frac{\xi_0 g_\omega^2 (\gamma_\mu \gamma^\mu)^2}{M^2} \\
+ \left( 1 + \eta_1 \frac{g_\sigma \sigma}{M} \right) m_\rho^2 \text{Tr}(\tilde{b}_\mu \tilde{b}^\mu) \\
- m_\sigma^2 \sigma^2 \left( 1 + \frac{\kappa_3 g_\sigma \sigma}{3M} + \frac{\kappa_4 g_\sigma^2 \sigma^2}{4M^2} \right),
\]

where

\[
\tilde{U} = e^{i^{\gamma^5}}, \quad \tilde{b}_{\mu \nu} = \partial_\mu \tilde{\nu}_\nu - \partial_\nu \tilde{\nu}_\mu + i[\tilde{\nu}_\mu, \tilde{\nu}_\nu] = -i[\tilde{a}_\mu, \tilde{a}_\nu].
\]

### PARAMETER SET

<table>
<thead>
<tr>
<th>Parameter</th>
<th>G2</th>
<th>NL-3</th>
<th>G2*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_\pi/M$</td>
<td>0.554</td>
<td>0.541</td>
<td>0.554</td>
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<tr>
<td>$\varepsilon_s/(4\pi)$</td>
<td>0.835</td>
<td>0.813</td>
<td>0.835</td>
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<tr>
<td>$\varepsilon_V/(4\pi)$</td>
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<td>1.024</td>
<td>1.016</td>
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<tr>
<td>$\varepsilon_s/(4\pi)$</td>
<td><strong>0.755</strong></td>
<td><strong>0.712</strong></td>
<td><strong>0.938</strong></td>
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<td>$\kappa_3$</td>
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<td>1.465</td>
<td>3.247</td>
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<td>$\kappa_4$</td>
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<td>-5.668</td>
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<tr>
<td>$\zeta_0$</td>
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<td>2.642</td>
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<tr>
<td>$\eta_1$</td>
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<td>0</td>
<td>0.650</td>
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<tr>
<td>$\eta_2$</td>
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<td>0</td>
<td>0.110</td>
</tr>
<tr>
<td>$\eta_p$</td>
<td>0.390</td>
<td>0</td>
<td>4.490</td>
</tr>
</tbody>
</table>

**Why we choose this parameter sets?**

A. Sulaksono, C. K. Williams, P.T.P. Hutauruk and T. Mart

*Phys Rev C73, 025803(2006)*
PARAMETER SET

Because $G_2^*$ parameter set predicts a soft EOS at high density and has coincides with the direct URCA process threshold.

Shaded region data experiment from P. Danielewicz
The Lagrangian density of neutrino matter interactions for each constituent

\[
\mathcal{L}_{\text{int}}^j = \frac{G_F}{\sqrt{2}} (i \Gamma^\mu_{W(j)} \bar{\psi}_j J^W_{\mu j} \psi_j) + \frac{4\pi \alpha}{q^2} (i \Gamma^\mu_{\text{EM}}) \bar{\psi}_j J^\text{EM}_{\mu j} \psi_j,
\]

\[
\Gamma^\mu_{W(j)} = \gamma^\mu (1 - \gamma^5),
\]

\[
J^W_{\mu j} = F_1^{Wj} \gamma^\mu - G_A^j \gamma^\mu \gamma^5 + iF_2^{Wj} \frac{\sigma_{\mu\nu} q^\nu}{2M},
\]

\[
\Gamma^\mu_{\text{EM}} = f_{\nu\lambda} \gamma^\mu + g_{\nu\lambda} \gamma^\mu \gamma^5 - (f_{\nu\lambda} + ig_{\nu\lambda}) \frac{p^\mu}{2m_e},
\]

\[
J^\text{EM}_{\mu j} = F_1^{\text{EM}j} \gamma^\mu + iF_2^{\text{EM}j} \frac{\sigma_{\mu\nu} q^\nu}{2M}.
\]
**FORM FACTORS OF NUCLEON**

<table>
<thead>
<tr>
<th>Target</th>
<th>$F_1^W$</th>
<th>$G_A$</th>
<th>$F_2^W$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>$-0.5$</td>
<td>$-g_A/2$</td>
<td>$-1/2(\mu_p - \mu_n) - 2\sin^2\theta_W\mu_n$</td>
</tr>
<tr>
<td>$p$</td>
<td>$0.5 - 2\sin^2\theta_W$</td>
<td>$g_A/2$</td>
<td>$-1/2(\mu_p - \mu_n) - 2\sin^2\theta_W\mu_n$</td>
</tr>
<tr>
<td>$e$</td>
<td>$0.5 + 2\sin^2\theta_W$</td>
<td>$1/2$</td>
<td>$0$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$-0.5 + 2\sin^2\theta_W$</td>
<td>$-1/2$</td>
<td>$0$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Target</th>
<th>$F_1^{EM}$</th>
<th>$F_2^{EM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>$0$</td>
<td>$\mu_n$</td>
</tr>
<tr>
<td>$p$</td>
<td>$1$</td>
<td>$\mu_p$</td>
</tr>
<tr>
<td>$e$</td>
<td>$1$</td>
<td>$0$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$1$</td>
<td>$0$</td>
</tr>
</tbody>
</table>

For neutrinos, while for anti-neutrinos the sign are changed, $g_A$ becomes $-g_A$.

- $\mu_p = 1.793$
- $\mu_n = -1.913$
- $g_A = 1.260$
- $\sin^2\Theta_W = 0.231$

FORM FACTORS OF NEUTRINO

\[ \Gamma^\mu_W = \gamma^\mu (1 - \gamma^5), \]

while the electromagnetic properties of Dirac neutrinos are described in terms of four form factors \( f_{1\nu}, g_{1\nu}, f_{2\nu}, \) and \( g_{2\nu} \), which stand for the Dirac, anapole, magnetic, and electric form factors, respectively. The electromagnetic vertex \( \Gamma^\mu_{BM} \) contains electromagnetic form factors [29,30]. Explicitly, it reads

\[ \Gamma^\mu_{BM} = f_{m\nu} \gamma^\mu + g_{1\nu} \gamma^\mu \gamma^5 - (f_{2\nu} + ig_{2\nu} \gamma^5) \frac{p^\mu}{2m_e}, \]

where \( f_{m\nu} = f_{1\nu} + (m_\nu/m_e)f_{2\nu}, \) \( p^\mu = k^\mu + k^{\mu'}, \) and \( m_\nu \) and \( m_e \) are the neutrino and electron masses, respectively. In the static limit, the reduced Dirac form factor \( f_{1\nu} \) and the neutrino anapole form factor \( g_{1\nu} \) are related to the vector and axial vector charge radii \( (R^2_V) \) and \( (R^2_A) \) through [29]

\[ f_{1\nu}(q^2) = \frac{1}{6}(R^2_V)q^2 \quad \text{and} \quad g_{1\nu}(q^2) = \frac{1}{6}(R^2_A)q^2, \]

where the neutrino charge radius is defined by \( R^2 = (R^2_V) + (R^2_A). \) In the limit of \( q^2 \to 0, f_{2\nu} \) and \( g_{2\nu}, \) respectively, define the neutrino magnetic moment and the Charge Parity (CP) violating electric dipole moment [29,31], i.e.,

\[ \mu^m_{\nu} = f_{2\nu}(0)\mu_B \quad \text{and} \quad \mu^e_{\nu} = g_{2\nu}(0)\mu_B, \]
FORMALISM

- Neutrino and Anti-Neutrino Differential Cross Section

\[
\left( \frac{1}{V} \frac{d^3\sigma}{d^2\Omega dE'} \right) = - \frac{1}{16\pi^2} \frac{E'_v}{E_v} \left[ \left( \frac{G_F}{\sqrt{2}} \right)^2 \left( L^{\mu\nu}_{\nu'} \prod_{\mu\nu}^{(W)} \right) 
+ \left( \frac{4\pi\alpha}{q^2} \right)^2 \left( L^{\mu\nu}_{\nu'} \prod_{\mu\nu}^{(SM)} \right) 
+ \frac{8G_F\pi\alpha}{q^2\sqrt{2}} \left( L^{\mu\nu}_{\nu'} \prod_{\mu\nu}^{(INT)} \right) \right] .
\]

A. Sulaksono, C. K. Williams, P. T. P. Hutauruk and T. Mart, PRC 73, 025803 (2006)

- Neutrino and Anti-Neutrino Mean Free Path
LEPTON TENSOR OF NEUTRINO

\[ L_{\nu}^{\mu \nu}(W) = 8 \left[ 2k^\mu k^\nu - (k^\mu q^\nu + k^\nu q^\mu) + g^{\mu \nu}(k \cdot q) - i \epsilon^{\alpha \mu \beta \nu} k_\alpha k'_\beta \right], \]

\[ L_{\nu}^{\mu \nu}(EM) = \left( f_{m \nu}^2 + g_{1 \nu}^2 \right) \left[ 2k^\mu k^\nu - (k^\mu q^\nu + k^\nu q^\mu) + g^{\mu \nu}(k \cdot q) \right] - 8i f_{m \nu} g_{1 \nu} \epsilon^{\alpha \mu \beta \nu} (k_\alpha k'_\beta) \]

\[ = f_{2 \nu}^2 + \frac{g_{2 \nu}^2}{m_{\nu}^2} (k \cdot q) [4k^\mu k^\nu - 2(k^\mu q^\nu + q^\mu k^\nu) + q^\mu q^\nu], \]

\[ f_{m \nu} = f_{1 \nu} + (m_{\nu}/m_{\nu}) f_{2 \nu}, \]

\[ L_{\nu}^{\mu \nu}(INT) = 4(f_{m \nu} + g_{1 \nu}) \left[ 2k^\mu k^\nu - (k^\mu q^\nu + k^\nu q^\mu) + g^{\mu \nu}(k \cdot q) - i \epsilon^{\alpha \mu \beta \nu} k_\alpha k'_\beta \right], \]

\( f_{1 \nu}, \ g_{1 \nu}, \ f_{2 \nu}, \ g_{2 \nu} \) are Dirac, anapole, magnetic, electric form factors respectively.
\[
\Pi^{\text{Im}(W)ij}_{\mu\nu} = (F_1^W j^2 + G_A^2 j^2) \Pi^{Vj}_{\mu\nu} \\
+ \left( G_A^2 j^2 + \frac{q^2}{2mM} F_1^W j F_2^W j \right) \Pi^{A j}_{\mu\nu} g_{\mu\nu} \\
- 2 \left( F_1^W j G_A^j + \frac{m}{M} F_2^W j G_A^j \right) \Pi^{Vj - Aj}_{\mu\nu} + \frac{F_2^W j^2}{M^2} \\
\times \left[ \left( m^2 + \frac{q^2}{4} \right) (q^2 g_{\mu\nu} - q_{\mu} q_{\nu}) - \frac{q^2}{8} \Pi^{Vj}_{\mu\nu} \right],
\]

\[
\Pi^{\text{Im}(BM)j}_{\mu\nu} = F_1^{BM} j^2 \Pi^{Vj}_{\mu\nu} + \frac{q^2}{2mM} F_1^{BM} j F_2^{BM} j \Pi^{Aj}_{\mu\nu} g_{\mu\nu} \\
+ \frac{F_2^{BM} j^2}{M^2} \left[ \left( m^2 + \frac{q^2}{4} \right) \\
\times (q^2 g_{\mu\nu} - q_{\mu} q_{\nu}) - \frac{q^2}{8} \Pi^{Vj}_{\mu\nu} \right],
\]

\[
\Pi^{\text{Im}(BM)j}_{\mu\nu} = \left( F_1^W j F_1^{BM} j + \frac{q^2}{4M^2} F_2^W j F_2^{BM} j \right) \Pi^{Vj}_{\mu\nu} \\
+ \frac{F_2^{BM} j^2}{4M^2} \left( 1 + \frac{q^2}{4m^2} \right) \\
- \left( F_1^W j F_2^{BM} j + F_2^W j F_1^{BM} j \right) \frac{4mM}{F_2^{BM} j F_1^{BM} j} \\
\times (q^2 g_{\mu\nu} - q_{\mu} q_{\nu}) \Pi^{A j}_{\mu\nu} \\
+ \left( \frac{m}{M} F_2^{BM} j G_A^j - F_1^{BM} j G_A^j \right) \Pi^{Vj - Aj}_{\mu\nu},
\]
CONTRACTION RESULTS

\[
(L^\mu_\nu \Pi^{\mu\nu})^{(W)} = -8q^2 \sum_{j=n,p,\bar{e},\mu^-} \left[ A^j_W (\Pi^j_L + \Pi^j_T) + B^j_{1W} \Pi^j_T + B^j_{2W} \Pi^j_A + C^j_W \Pi^j_{VA} \right],
\]

\[
(L^\mu_\nu \Pi^{\mu\nu})^{(BM)} = q^2 \sum_{j=n,p,\bar{e},\mu^-} \left[ A^j_{BM} (\Pi^j_L + \Pi^j_T) + B^j_{1BM} \Pi^j_T + B^j_{2BM} \Pi^j_A \right],
\]

\[
(L^\mu_\nu \Pi^{\mu\nu})^{(INT)} = -4q^2 \sum_{j=n,p,\bar{e},\mu^-} \left[ A^j_{INT} (\Pi^j_L + \Pi^j_T) + B^j_{1INT} \Pi^j_T + B^j_{2INT} \Pi^j_A + C^j_{INT} \Pi^j_{VA} \right].
\]
CONTRACTION RESULTS

\[
\Pi_L = \frac{q^2}{2\pi |\vec{q}|^3} \left[ \frac{1}{4}(E_F - E^*) + \frac{q_0}{2}(E_F^2 - E^{*2}) + \frac{1}{3}(E_F^3 - E^{*3}) \right],
\]

\[
\Pi_{VA} = \frac{i q^2}{8\pi |\vec{q}|^3} \left[ (E_F^2 - E^{*2}) + q_0(E_F - E^*) \right].
\]

\[
\Pi_A = \frac{i}{2\pi |\vec{q}|} M^{*2}(E_F - E^*). \]
CONTRACTION RESULTS

\[ A^j_w = \left( \frac{2E(E - q_0) + \frac{1}{2} q^2}{|q|^2} \right) \left[ F_1^{wj} + G_A^{j2} - \frac{F_2^{wj} q^2}{4M^2} \right], \]

\[ B^j_{1w} = \left[ F_1^{wj} + G_A^{j2} - \frac{F_2^{wj} q^2}{4M^2} \right], \]

\[ B^j_{2w} = -G_A^{j2} + \frac{q^2}{2mM} F_1^{wj} F_2^{wj} - \frac{F_2^{wj} q^2}{4M^2} \left( 1 + \frac{q^2}{4m^2} \right), \]

\[ C^j_w = -2(2E - q_0) \left[ F_1^{wj} G_A^j + \frac{m}{M} F_2^{wj} G_A^j \right], \]

\[ A^j_{BM} = \left[ \left( \frac{2E(E - q_0) + \frac{1}{2} q^2}{|q|^2} \right) (bq^2 - a) + \frac{1}{2} bq^2 \right] \times \left[ F_1^{BMj2} - \frac{F_2^{BMj2} q^2}{4M^2} \right], \]

\[ B^j_{1BM} = -\frac{1}{2} (bq^2 + a) \left[ F_1^{BMj2} - \frac{F_2^{BMj2} q^2}{4M^2} \right], \]

\[ B^j_{2BM} = \frac{1}{2} (bq^2 + a) \left[ \frac{q^2}{2mM} F_1^{BMj} F_2^{BMj} \right. \right.

\[ \left. - \frac{F_2^{BMj2} q^2}{4M^2} \left( 1 + \frac{q^2}{4m^2} \right) \right], \]
CONTRACTION RESULTS

\[ A_j^{BM} = \left[ \left( \frac{2E(E - q_0) + \frac{1}{2}q^2}{|\vec{q}|^2} \right) (bq^2 - a) + \frac{1}{2} bq^2 \right] \times \left[ F_1^{BMj^2} - \frac{F_2^{BMj^2} q^2}{4M^2} \right], \]

\[ B_1^{BM} = -\frac{1}{2} (bq^2 + a) \left[ F_1^{BMj^2} - \frac{F_2^{BMj^2} q^2}{4M^2} \right], \]

\[ B_2^{BM} = \frac{1}{2} (bq^2 + a) \left[ \frac{q^2}{2mM} F_1^{BMj^2} F_2^{BMj} - \frac{F_2^{BMj^2} q^2}{4M^2} \left( 1 + \frac{q^2}{4m^2} \right) \right], \]
RESULTS AND DISCUSSION

- $\nu_e$ and $\bar{\nu}_e$ Mean Free Path Results

$\bar{\nu}_e$ mean free path is bigger than $\nu_e$, due to the effects of weak magnetism of nucleon.
RESULTS AND DISCUSSION

- $\nu_e$ and $\bar{\nu}_e$ Mean Free Path Results

If the $E_\nu$ increase, neutrino and anti-neutrino decrease. The effect moment magnetic and charge radius is too small.
RESULTS AND DISCUSSION

- $\nu_\tau$ and $\bar{\nu}_\tau$ Mean Free Path Results
RESULTS AND DISCUSSION

- $\nu_\tau$ and $\bar{\nu}_\tau$ Mean Free Path Results

![Graph 1](image1)

- $E_\nu = 150$ MeV
- $R = 0, \mu_\nu = 0$

![Graph 2](image2)

- $E_\nu = 150$ MeV
- $R = 3 \times 10^{-6}$ MeV$^{-1}$
- $\mu_\nu = 3 \times 10^{-7} \mu_B$
RESULTS AND DISCUSSION

- $\nu_\mu$ and $\bar{\nu}_\mu$ Mean free Path Results
RESULTS AND DISCUSSION

- $\nu_\mu$ and $\bar{\nu}_\mu$ Mean free Path Results

![Graph 1](image1.png)

- $E_\nu = 150$ MeV
- $R = 0$, $\mu_\nu = 0$

![Graph 2](image2.png)

- $E_\nu = 150$ MeV
- $R = 5 \times 10^{-6}$ MeV$^{-1}$
- $\mu_\nu = 5 \times 10^{-10}$ $\mu_B$
CONCLUSION

- The effect of electromagnetic form factor depend on the moment magnetic and charge radius of neutrino

\[ \nu_\tau, \bar{\nu}_\tau < \nu_\mu, \bar{\nu}_\mu < \nu_\tau, \bar{\nu}_\tau, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau, \nu_\mu, \bar{\nu}_\mu \]

- The effect of weak magnetism make a differentiable for neutrino and anti neutrino mean free path.

[Similar results of C.J. Horowitz. et.al.PRC68,025803 (2003)]

- Neutrino and antineutrino mean free path decrease if energy neutrino increase.

- In general, the neutrino and anti neutrino have influence on neutrino and antineutrino mean free path but too small.
THE END

THANK YOU FOR YOUR ATTENTION