Impact of the neutrino magnetic moment on Supernova r-process Nucleosynthesis

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Introduction

R-process nucleosynthesis, alpha effect

- *Type IIb SN = possible site for* **heavy elements nucleosynthesis** *through* **r-process** *(rapid neutron capture)*
- *But "***alpha-effect***": almost all the protons and an equal amount of neutrons combine into alpha particles which have a large binding energy* $\Rightarrow$ **Reduces the number of free neutrons taking place in the r-process***.*

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Supernova neutrinos

- *SNII : 99% of the energy is released by* **neutrinos** *(of all flavors)*
- $\Rightarrow$ *The neutrino-induced reaction* $\nu_e + n \rightarrow p + e^-$ *can modify the neutron-to-proton ratio.*
- $\Rightarrow$ **Non-standard neutrino properties** *can influence the nucleosynthesis.*

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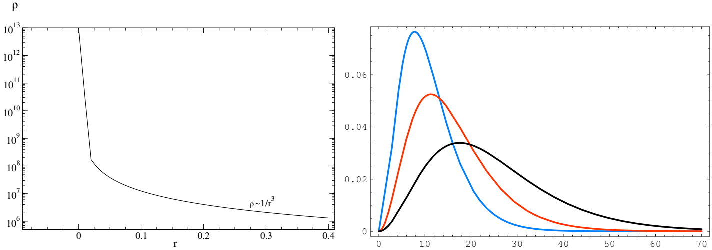
Can the neutrino magnetic moment help r-process nucleosynthesis ?

Density & ν fluxes



(LEFT) Nucl. density (g.cm^3), as a function of r=distance from the NS surface (RIGHT) ν's energy distributions as a function of E_ν.

Nucleon (electron) density

- *Falls off steeply close to the NS surface*
- *For regions sufficiently far,* $\sim 1/r^3$

Neutrinos fluxes at the neutrino sphere

- *Fermi-Dirac distributions*
- **Hierarchical** *neutrinos energies* $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$

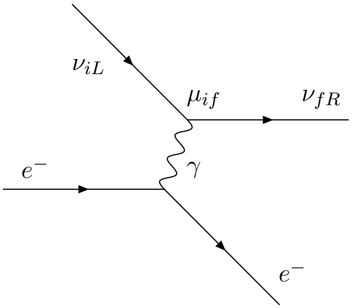
We ignore the possibility of large magnetic fields near the SN-core ($\Rightarrow$ no spin-flavor

Magnetic moment interaction in the SN plasma

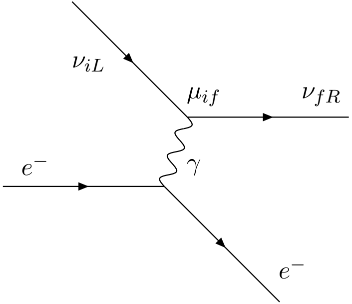
Neutrino magnetic moment

$$\mathcal{L} \supset \frac{1}{2} \mu_{if} \overline{\psi}^{f}_{\nu} \sigma^{\mu\nu} \psi^{i}_{\nu} F_{\mu\nu} \qquad (1)$$

This interaction with the electromagnetic field **flip the chirality** *of the neutrino.*
Of order $10^{-19}\mu_B$ *in the SM+*ν_R.



Magnetic moment interaction in the SN plasma



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Differential cross-section

$$\frac{d\sigma}{dt} = \left(\sum_f \mu_{if}{}^2 \right) \frac{\pi\alpha^2}{m_e^2} \frac{s+t-m_e^2}{(t-m_\gamma{}^2)(s-m_e^2)}. \qquad (2)$$

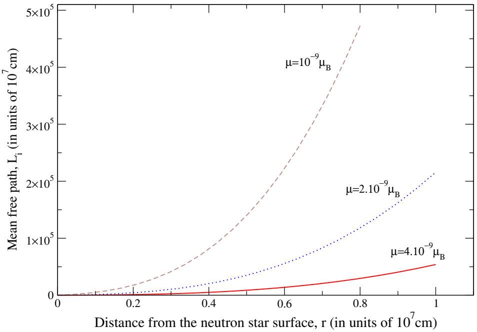
SN plasma (relativistic & degenerate near the NS) ⇒ **Effective photon mass** *[Braaten, Segel 93]:*

$$m_\gamma = m_\gamma(N_e(r), T) \qquad (3)$$

Cross-section and Neutrino Mean Free Path

Cross-section

$$\sigma = \left(\sum_f \mu_{if}{}^2\right)\frac{\pi\alpha^2}{m_e^2}\left[\left(1+\frac{m_\gamma^2}{2m_eE_\nu}\right)\times\log\left(\frac{2m_eE_\nu+m_\gamma^2}{m_\gamma^2}\right)-1\right]. \quad (4)$$



Neutrino mean free path

$$L_i = \frac{1}{\sigma(r, E_\nu, \sum \mu_{if}^2)N_e(r)}. \quad (5)$$

Fig.1 : $L_i =$ *very large* $\gg R_{SN}$

Magnetic moment interactions significant only for $r \ll 1$

Dirac Neutrinos

RESULTS IN THE CASE OF DIRAC-TYPE NEUTRINOS

- $\nu_{\alpha L} \longrightarrow$ *sterile states : net loss of flux,* $\mid \psi_\nu \mid^2 \sim e^{-r/L_i}$
- *Both* ν_e & $\bar{\nu}_e$ *fluxes are reduced.*

Evolution equation

Standard matter effects ($\hat{H}_{\rm MSW}$) + magnetic moment interactions :

$$i\frac{\partial}{\partial r}\left[\begin{array}{c}\Psi_{\nu_e}(E_\nu,r)\\ \Psi_{\nu_\mu}(E_\nu,r)\\ \Psi_{\nu_\tau}(E_\nu,r)\end{array}\right]=\left(\hat{H}_{\rm MSW}+\left[\begin{array}{ccc}-\frac{i}{2L_e} & 0 & 0\\ 0 & -\frac{i}{2L_\mu} & 0\\ 0 & 0 & -\frac{i}{2L_\tau}\end{array}\right]\right)\left[\begin{array}{c}\Psi_{\nu_e}(E_\nu,r)\\ \Psi_{\nu_\mu}(E_\nu,r)\\ \Psi_{\nu_\tau}(E_\nu,r)\end{array}\right]. \qquad (6)$$

(same form for anti-neutrinos)

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(same form for anti-neutrinos)

Electron fraction

$$Y_e=\frac{N_{prot}}{N_{prot}+N_{neut}}=\frac{1}{1+\frac{\lambda(\bar{\nu}_e p\to en)}{\lambda(\nu_e n\to ep)}} \quad (7)$$

- $Y_e < 1/2$: *neutron-rich medium*
- $Y_e \geq 1/2$: *proton-rich medium, no heavy elements nucleosynthesis possible.*

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Reaction rates :

$$\lambda(r) \propto \int \sigma_{weak}(E_\nu) \overbrace{\underbrace{f_D(E_\nu, T_\nu)}_{E_\nu \text{ Distributions}} \underbrace{|\psi(r,E_\nu)|^2}_{\text{Probabilities}}}^{\sim \text{Fluxes}} \mathrm{d}E_\nu \quad (8)$$

Effect on Y_e

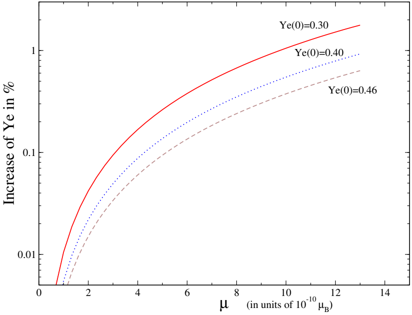

Figure :

- $(Y_e(r) - Y_e(r=0))/Y_e(r=0)$
- *Evaluated at $r = 4$ km from the NS surface where magnetic moment interactions become* **ineffective** *(cf L_i).*
- $\mu = (\sum_f \mu_{ef}^2)^{1/2}$

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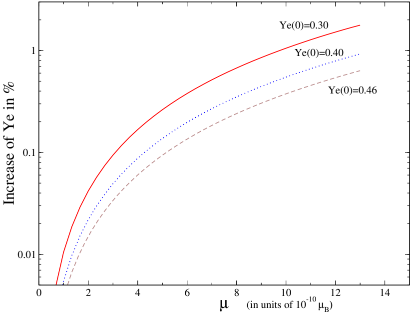

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Comments

- *Strong dependence on μ (cf L_i)*
- $\mu = \mathcal{O}(10^{-9})\ \mu_B \Rightarrow$ *Increase of Y_e of 1%,* $\mu = \mu_{exp}^{MAX} = 0.74 \times 10^{-10}\ \mu_B \Rightarrow$ *less than 0.01%*
- *Smaller effect for a $Y_e(r=0)$ closer to the critical value 0.5.*

Majorana Neutrinos

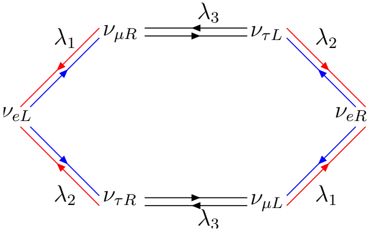
Results in the case of Majorana-type neutrinos

- ν_R's are *not sterile* anymore
- $\nu_{\alpha L} \longrightarrow \nu_{\beta R}$ = *conversion between Neutrinos & Antineutrinos*
- *transition magnetic moment only :*

$$\mu = \begin{pmatrix} 0 & \mu_{e\mu} & \mu_{e\tau} \\ -\mu_{e\mu} & 0 & \mu_{\mu\tau} \\ -\mu_{e\tau} & -\mu_{\mu\tau} & 0 \end{pmatrix} \tag{9}$$

Evolution equation

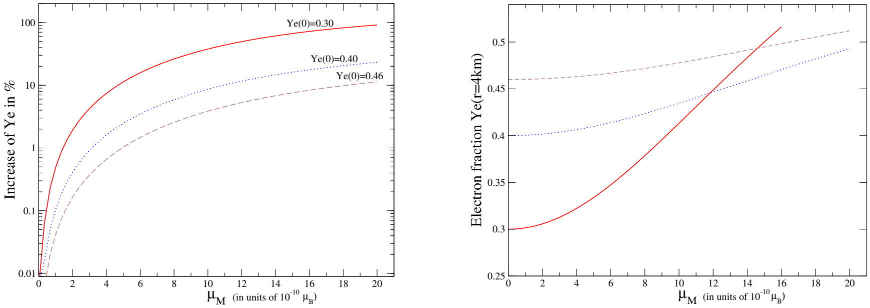
- *For each species, there are four conversions : two contribute positively (gain), two negatively (loss).*
- $\hat{H}_{\rm MSW}$ *very small effect for* $r \ll 1$
- *Evolution equation directly for neutrino number fractions* $\mathcal{N}_\nu$ *(probabilities)*



$$\frac{\partial}{\partial r}\begin{bmatrix} \mathcal{N}_{\nu_{eL}} \\ \mathcal{N}_{\nu_{\mu L}} \\ \mathcal{N}_{\nu_{\tau L}} \\ \mathcal{N}_{\nu_{eR}} \\ \mathcal{N}_{\nu_{\mu R}} \\ \mathcal{N}_{\nu_{\tau R}} \end{bmatrix} = \begin{bmatrix} -\lambda_1-\lambda_2 & 0 & 0 & 0 & \lambda_1 & \lambda_2 \\ 0 & -\lambda_1-\lambda_3 & 0 & \lambda_1 & 0 & \lambda_3 \\ 0 & 0 & -\lambda_2-\lambda_3 & \lambda_2 & \lambda_3 & 0 \\ 0 & \lambda_1 & \lambda_2 & -\lambda_1-\lambda_2 & 0 & 0 \\ \lambda_1 & 0 & \lambda_3 & 0 & -\lambda_1-\lambda_3 & 0 \\ \lambda_2 & \lambda_3 & 0 & 0 & 0 & -\lambda_2-\lambda_3 \end{bmatrix}\begin{bmatrix} \mathcal{N}_{\nu_{eL}} \\ \mathcal{N}_{\nu_{\mu L}} \\ \mathcal{N}_{\nu_{\tau L}} \\ \mathcal{N}_{\nu_{eR}} \\ \mathcal{N}_{\nu_{\mu R}} \\ \mathcal{N}_{\nu_{\tau R}} \end{bmatrix}$$

with $\lambda_1 = 1/L_{e\mu}$, $\lambda_2 = 1/L_{e\tau}$, $\lambda_3 = 1/L_{\mu\tau}$ (L_{if} = mean free path with μ_{if})

Effect on Y_e



(LEFT) $(Y_e(r = 4km) - Y_e(r = 0))/Y_e(r = 0)$ as a function of $\mu_M = \mu_{e\mu} = \mu_{e\tau}$, (RIGHT) $Y_e(r = 4km)$

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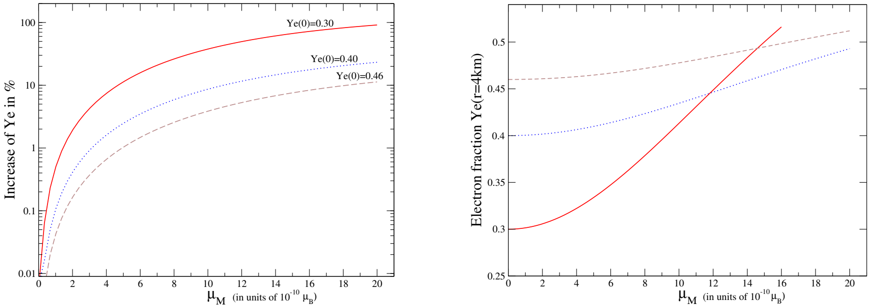

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Comments

- *For $\mu_{e\mu}$, $\mu_{e\tau} = \mathcal{O}(1.5 - 2 \times 10^{-9} \mu_B)$, Y_e meets the critical value of 0.5 for all $Y_e(0)$.*
- *Strong dependence on μ & smaller effect for a $Y_e(r=0)$ closer to 0.5. (idem Dirac)*
- *Larger effects than in the Dirac case*

Summary and conclusions

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- *We included the neutrino magnetic moment*
- *We studied its impact on the electron fraction Y_e which is a key quantity for nucleosynthesis*
- *We studied both Dirac & Majorana cases*

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- *Neutrino magnetic moment* $\mathcal{O}(1.5 - 2 \times 10^{-9} \mu_B)$ **kills nucleosynthesis** (MAJORANA)
- $< 1\%$ *effects on nucleosynthesis with actual experimental upper-limits on* μ*'s*

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Perspectives

However, $\nu - \nu$ *interactions (not included) could play a* **significant role** *near the neutron star* **and since** 10^{-9} *is not so far from experimental limits, the question of magnetic moment should be* **reconsidered** *once* $\nu - \nu$*'s interactions can be calculated exactly.*