# 1st Ph.D. annual report
# Department of Physical and Chemical Sciences

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## Activities:

- **Schools, Workshops, Conferences:**
    - **A Ph.D. Seminar** at the University of L'Aquila, Italy, **2026**;
    - **Summer School of Particle Physics** in ICTP, Trieste, Italy, **2025**;
    - **ERASMUS+ exchange program for** 4 **months** at the University of L'Aquila, Italy, **2025-2026**;
    - **Cosmological frontiers in fundamental physics** in Paris, France, **2025**;
    - **Faculty Conference** at Ivane Javakhishvili Tbilisi State University, Tbilisi, Georgia, **2025**;
    - *7th* **International Conference on Innovative Academic Studies** ICIAS Konya, Turkey, **2025**;
    - 2**-month exchange visitor program** at the University of Texas in Dallas, USA, **2024**.
- **Courses attended this semester:**
    - **Dark Matter and Neutrino Physics**;
    - **Cosmic Rays and Multimessenger Astrophysics**;
    - **Gauge Theories**;
    - **Physics Beyond the Standard Model.**
- **Published Papers:**
    - *Dark Energy from Entanglements with Mirror Universe,* **2025**.

# My Ph.D. work

In this thesiswork we are investigating Neutron Oscillations as one possible explanation for Baryogenesis, which is inevitable for creating the Baryon asymmetry we can observe today in the universe. For this, I have studied the papers [4, 2, 1, 3] and derived probability formulas received there. In these papers, Neutron-Antineutron Oscillations and Neutron-Mirror Neutron Oscillations for a single Mirror Sector are considered. In my work, we considered several Mirror Sectors and calculated and plotted probabilities for different numbers of neutron families.

To better explain our work, firstly I will briefly review the papers and the motivation why we should search for Neutron Oscillations at all.

## 1 Introduction

One puzzle of the Standard ModeBaryon Asymmetry of the Universe - the fact that the universe is full of matter but no significant antimatter is observed. We can formulate the baryon number as follows:

$$\left.\frac{n_B-\bar{n}_B}{n_B+\bar{n}_B}\right|_{now}=1, \quad \left.\frac{n_B-\bar{n}_B}{n_B+\bar{n}_B}\right|_{T=1\ GeV}\approx\frac{n_q-\bar{n}_q}{n_\gamma}\approx\left.\frac{n_B-\bar{n}_B}{n_\gamma}\right|_{now}\approx 10^{-10} \tag{1}$$

$$\frac{n_q-\bar{n}_q}{n_\gamma}=\text{const}, \qquad \begin{cases} n_q-\bar{n}_q\propto\frac{1}{R^3} \\ n_\gamma\propto\frac{1}{R^3}\end{cases} \tag{2}$$

From where we can see, that due to some reasons baryon asymmetry has grown from a very tiny amount to almost 100%, as shown in **Figure 1**.

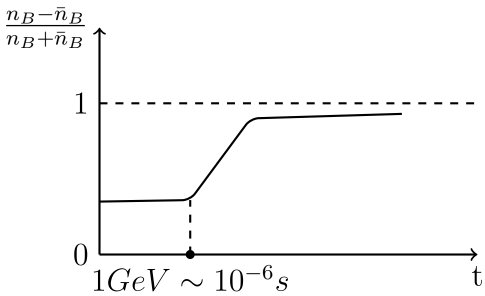


**Figure 1:** Baryon asymmetry change from $T=1\ GeV$ up to today.

For baryogenesis to happen, Sakharov conditions must be satisfied:

- CP violation – which is satisfied in SM via kaon reactions:

$$\begin{aligned} &K^0 \to \pi^- e^+ \nu_e, \\ &\bar{K}^0 \to \pi^+ e^- \bar{\nu}_e \\ &\Gamma_e \neq \Gamma_{\bar{e}} \end{aligned} \tag{3}$$

- Departure from thermal equilibrium – which is also satisfied as the Universe is expanding and:

$$\left.\frac{\Gamma}{H}\right|_{now} < 1 \tag{4}$$

- Baryon number violation, which is not observed in the Standard Model (SM)!

For this reason, baryogenesis cannot be explained in the Standard Model, and solution sould be searched in the beyond the SM (BSM) theories.

Idea, which is suggested by paper [3], is to consider neutron-antineutron oscillations as one possible way of explaining baryogenesis, as the transition

$$n \to \bar{n} \tag{5}$$

violates baryon number by 2 units. But this transition is constrained by nuclear bounds with following constraints on mass mixing and transition probability:

$$\begin{aligned} &\delta m_{n\bar{n}} \lesssim 10^{-24} eV; \\ &P_{n\bar{n}} \lesssim 10^{-15} \end{aligned} \tag{6}$$

To find a solution to this, authors in the paper consider a nondirect transition from neutron to anti-neutron, but via the Mirror Neutron Sector, which is the "twin" universe of the ordinary sector. In this case transition looks like the following:

$$\underset{\text{Neutron}}{\underset{\downarrow}{n}} \to \underset{\substack{\text{Mirror}\\\text{Neutron}}}{\underset{\downarrow}{n'}} \to \underset{\substack{\text{Anti-}\\\text{Neutron}}}{\underset{\downarrow}{\bar{n}}} \tag{7}$$

This case is better than considering direct transition because:

- It is less constrained by experimental bounds;

- It can depend on the magnetic field, and one could look for differences between the transition probabilities as changing the magnetic field.

The Mirror Uuniverse is described as a similar group to the ordinary SM, and the overall framework can be shown as:

$$\underset{\substack{\text{Ordinary}\\ \text{Sector}}}{\underset{\downarrow}{G_{SM}}} \times \underset{\substack{\text{Mirror}\\ \text{Sector}}}{\underset{\downarrow}{G'_{SM}}} \tag{8}$$

$$\mathcal{L}_{\text{tot}} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\text{mix}}, \tag{9}$$

where $\mathcal{L}_{\text{mix}}$ is the mixing between the ordinary and mirror sectors. These two sectors cannot interact via SM forces, but only via gravity or some feeble forces.

The particle content of both unuverses are the following:

- Ordinary sector:
  - $\left(B = \frac{1}{3}\right)$:
    - $q_L = (u_L, d_L)$, which are $SU(2)$ doublets;
    - $u_R, d_R$, which are $SU(2)$ singlets
  - anti-quarks $\left(B = -\frac{1}{3}\right)$:
    - $q_R^c = (u_R^c, d_R^c)$
    - $q_L^c, d_L^c$
- Mirror sector:
  - mirror-quarks $\left(B' = \frac{1}{3}\right)$:
    - $q'_R = (u'_R, d'_R)$, which are $SU(2)$ doublets;
    - $u'_L, d'_L$, which are $SU(2)$ singlets
  - mirror-anti-quarks $\left(B' = -\frac{1}{3}\right)$:
    - $q_L'^c = (u_L'^c, d_L'^c)$;
    - $q_R'^c, d_R'^c$
- Messengers between the ordinary and mirror sectors (BSM particles):
  - $N$ – gauge singlet;
  - $S$ – $SU(3)$ color triplet (scalar);
  - $D$ – Vector-like down- type quark

Considering both sectors, allowed mixings between neutron and antineutron are:

- Direct Majorana Mixing, for which baryon number change is $\triangle B = 2$:
$$n \leftrightarrow \bar{n}; \tag{10}$$

- Baryon-number conserving mirror mixing, where baryon number change in both sectors is $\triangle(B - B') = 0$:
$$n \leftrightarrow n'; \tag{11}$$

- Baryon-number violating mirror mixing, with $\triangle(B - B') = 2$:
$$n \leftrightarrow \bar{n}' \tag{12}$$

The advantage of considering the mirror sector is that probabilities are not constrained by the nuclear bounds, because mirror-neutron does not interact via SM forces, and this transition would not cause decay of the nucleus, which is not observed. So, stability bounds do not eliminate $n \to n'$; the transition probabilities obtained via this mechanism can be as large as:
$$P_{nn'} \lesssim 10^{-15} eV. \tag{13}$$

The mixing terms in the Lagrangian look like the following:
Mixing in separate sectors − neutron with antineutron and mirror neutron with mirror anti-neutron − $\triangle B = 2$:
$$\frac{\epsilon_{n\bar{n}}}{2}\left(\bar{n_c} n + \bar{n'_c} n'_c\right) + \text{h.c.}, \tag{14}$$
where $n_c$ is a complex conjugate of nutron $n$.
Mixing between ordinary and mirror sectors − $\triangle B = 1$:
$$\begin{aligned} &\frac{\varepsilon_{nn'}}{2}\left(\bar{n}' n + \bar{n}'_c n_c\right) + \text{h.c.} \\ &\frac{\varepsilon_{n\bar{n}'}}{2}\left(\bar{n'_c} n + \bar{n}_c n'\right) + \text{h.c.} \end{aligned} \tag{15}$$

Baryon number-violating operators can consist of 6 quarks. These operators are expressed correspondingly for each mixing and are denoted by $O$, $O_{B+B'}$, and $O_{B-B'}$:

$$\begin{aligned} &\frac{O_2}{\Lambda_2^5} = \frac{1}{\Lambda^5}\left[\overline{(u^c d^c d^c)_L}(udd)_R + \overline{(u'^c d'^c d'^c)_R}(u'd'd')_L\right] + \text{h.c.} \\ &\frac{O_B + B')}{\Lambda^5} = \frac{1}{\Lambda^5}\left[\overline{(u'd'd')_L}(udd)_R\right] + \text{h.c.} \quad (B + B')\text{-conserving} \\ &\frac{O_{B-B'}}{\Lambda^6} = \frac{v}{\Lambda^6}\left[(\overline{u'^c d'^c d'^c})_L (udd)_R + \overline{(u^c d^c d^c)}_R (u'd'd')_L\right] + \text{h.c.} \quad (B - B')\text{-conserving} \end{aligned} \tag{16}$$

where, $\Lambda_2$ and $\Lambda$ are some physical scales BSM.

Considering these operators in Lagrangians:

$$\begin{aligned} \mathcal{L}_{\text{Yuk}} &= u_{R,L}^T C d_{R,L} S + S^\dagger N_R^T C d_R + \text{h.c.} \\ \mathcal{L}'_{\text{Yuk}} &= u'^T_{L,R} C d'_{L,R} S' + S'^\dagger N_L C d'_L + \text{h.c.} \end{aligned} \tag{17}$$

$$\begin{aligned} \mathcal{L}_{\text{Yuk}} &= S N_R^T C D_R^c + \phi D_R^T C q_R^c \text{h.c.} \\ \mathcal{L}'_{\text{Yuk}} &= S' N_L^T C D'^c_L + \phi' D'^T_L C q'^c_L \text{h.c.} \end{aligned}, \tag{18}$$

where $N$, $S$, and $D$ are messengers between the ordinary and mirror sectors defined earlier, the following mixing can be obtained:

$$\begin{aligned} \varepsilon_{nn'} &\sim \frac{\Lambda_{\text{QCD}}^6}{\Lambda^5} \\ \epsilon_{n\bar{n}} &\sim \frac{\Lambda_{\text{QCD}}^6}{\Lambda_2^5} \sim \frac{\mu \Lambda_{\text{QCD}}^6}{M_N^2 M S^4} \sim \frac{\mu}{M} \varepsilon_{nn'} \\ \varepsilon_{n\bar{n}'} &\sim \frac{v \Lambda_{B-B'}}{\Lambda^6} \sim \frac{v}{M_D} \varepsilon_{nn'} \end{aligned} \tag{19}$$

In paper [2], the interaction between ordinary and 1 mirror sector is considered. Intraction Hamiltonian is given:

$$H_I = \begin{pmatrix} \mu \boldsymbol{B} \cdot \boldsymbol{\sigma} & \epsilon \\ \epsilon & \mu \boldsymbol{B'} \cdot \boldsymbol{\sigma} \end{pmatrix}, \tag{20}$$

where $\boldsymbol{B}$ and $\boldsymbol{B'}$ are ordinary and mirror magnetic fields. For such a system, transition probabilities for $n \to n'$ and spin flip were calculated:

$$P_{n\to n'} = \sin^2 2\theta(\cos^2(\phi - \phi') \sin(\Omega^- t) + \sin^2(\phi - \phi') \sin^2(\Omega^+ t))\} \leftarrow \begin{aligned} \Omega^+ &= |\omega' + \omega| \\ \Omega^- &= |\omega' - \omega| \end{aligned} \tag{21}$$

$$P_{flip_n} = \cos^4\theta \sin^2(2\tilde{\omega} t) \sin^2 2\phi + \frac{1}{2} \cdot \sin^2 2\theta \sin(\tilde{\omega} t) \sin(\tilde{\omega}' t) \sin 2\phi \sin 2\phi' + \sin^4\theta \sin^2(\tilde{\omega} t) \sin^2 2\phi \tag{22}$$

And some conclusions were made:

- When the mirror magnetic field is $\boldsymbol{B'} = 0$, then $n \to n'$ transition probability is larger when the ordinary magnetic field is 0, $\boldsymbol{B} = 0$;
- But when the mirror magnetic fiel $\boldsymbol{B'} \neq 0$, the transition probability can be maximazed when magnetic fields in two sectors become resonant, $B = B'$.

# 2 Thesiswork

In my thesiswork, we considered more than 1 mirror sectors and looked at what effect it would have for neutron oscillations.

## 2.1 3 Family Neutron-Mirror Neutron oscillations

I will start from considering 3 Family neutron-mirror neutron oscillations.
In this case, we have 2 mirror sectors with denotions:

| | Ordinary Sector | Mirror Sector 1 | Mirror Sector 2 |
|---|---|---|---|
| Neutron | $n$ | $n_1$ | $n_2$ |
| Anti-neutron | $\bar{n}$ | $\bar{n}_1$ | $\bar{n}_2$ |

The overall state can be exprssed as:

$$\begin{pmatrix} n \\ \bar{n} \\ n_1 \\ \bar{n}_1 \\ n_2 \\ \bar{n}_2 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \tag{23}$$

Intraction Hamiltonian in Flavour basis is written as:

$$H^{\mathrm{Fl}} = \left(\begin{array}{cc|cc|cc} m & 0 & 0 & \varepsilon & 0 & \varepsilon \\ 0 & m & \varepsilon & 0 & \varepsilon & 0 \\ \hline 0 & \varepsilon & m & 0 & 0 & \varepsilon \\ \varepsilon & 0 & 0 & m & \varepsilon & 0 \\ \hline 0 & \varepsilon & 0 & \varepsilon & m & 0 \\ \varepsilon & 0 & \varepsilon & 0 & 0 & m \end{array}\right), \tag{24}$$

where $\varepsilon$ is the mixing term. As the flavour eigenstates and mass (energy) eigenstates are not the same, flavour states undergo time evoluton. As a result, we might be able to observe the nonzero probabilities of neutron mixing with different states (anti-neutron, mirror neutrons, mirror antineutrons). For this, we should diagonalize $H^{\mathrm{Fl}}$ and find the Probability matrix. Diagonalization in the case of 3 families is done in 3 rotation steps, which are the following:

1. Rotate everything by 45° with matrix:

$$U_{n\bar{n}} = \left(\begin{array}{cc|cc|cc} \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & 0 & 0 & 0 & 0 \\ \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & 0 & 0 & 0 & 0 \\ \hline 0 & 0 & \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} & 0 & 0 \\ 0 & 0 & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & \frac{\sqrt{2}}{2} & -\frac{\sqrt{2}}{2} \\ 0 & 0 & 0 & 0 & \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} \end{array}\right), \tag{25}$$

which gives result:

$$H_1 = U_{n\bar{n}}^T H^{\mathrm{Fl}} U_{n\bar{n}} = \left(\begin{array}{cc|cc|cc} m & 0 & \varepsilon & 0 & \varepsilon & 0 \\ 0 & m & 0 & -\varepsilon & 0 & -\varepsilon \\ \hline \varepsilon & 0 & m & 0 & \varepsilon & 0 \\ 0 & -\varepsilon & 0 & m & 0 & -\varepsilon \\ \hline \varepsilon & 0 & \varepsilon & 0 & m & 0 \\ 0 & -\varepsilon & 0 & -\varepsilon & 0 & m \end{array}\right) \tag{26}$$

2. Now if we mix states 1 with 3 and 2 with 4, with matrix:

$$U_{1324} = \left(\begin{array}{cc|cc|cc} \frac{\sqrt{2}}{2} & 0 & \frac{\sqrt{2}}{2} & 0 & 0 & 0 \\ 0 & \frac{\sqrt{2}}{2} & 0 & -\frac{\sqrt{2}}{2} & 0 & 0 \\ \hline -\frac{\sqrt{2}}{2} & 0 & \frac{\sqrt{2}}{2} & 0 & 0 & 0 \\ 0 & \frac{\sqrt{2}}{2} & 0 & \frac{\sqrt{2}}{2} & 0 & 0 \\ \hline 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{array}\right), \tag{27}$$

We get:

$$H_2 = U_{1324}^T H_1 U_{1324} = \left(\begin{array}{cc|cc|cc} m-\varepsilon & 0 & 0 & 0 & 0 & 0 \\ 0 & m+\varepsilon & 0 & 0 & 0 & \sqrt{2}\varepsilon \\ \hline 0 & 0 & m-\varepsilon & 0 & \sqrt{2} & 0 \\ 0 & 0 & 0 & m+\varepsilon & 0 & 0 \\ \hline 0 & 0 & \sqrt{2}\varepsilon & 0 & m & 0 \\ 0 & -\sqrt{2}\varepsilon & 0 & 0 & 0 & m \end{array}\right) \tag{28}$$

3. Now we mix states 3 with 5 and 2 with 6, with matrix:

$$U_{3526} = \left(\begin{array}{cc|ccc|c} 1 & 0 & 0 & 0 & 0 & 0 \\ \hline 0 & \frac{\sqrt{3}}{3} & 0 & 0 & 0 & \frac{\sqrt{6}}{3} \\ 0 & 0 & \frac{\sqrt{3}}{3} & 0 & \frac{\sqrt{6}}{3} & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & -\frac{\sqrt{6}}{3} & 0 & \frac{\sqrt{3}}{3} & 0 \\ \hline 0 & -\frac{\sqrt{6}}{3} & 0 & 0 & 0 & \frac{\sqrt{3}}{3} \end{array}\right) \tag{29}$$

Finaly, after third rotation we get $H^{Fl}$ diagonalized with some degenerate states:

$$H_D = U^T_{3526} H_2 U_{3526} = \begin{pmatrix} m-\varepsilon & 0 & 0 & 0 & 0 & 0 \\ 0 & m+\varepsilon & 0 & 0 & 0 & 0 \\ 0 & 0 & m-\varepsilon & 0 & 0 & 0 \\ 0 & 0 & 0 & m+\varepsilon & 0 & \\ 0 & 0 & 0 & 0 & m-2\varepsilon & 0 \\ 0 & 0 & 0 & 0 & 0 & m+2\varepsilon \end{pmatrix} \tag{30}$$

As we see in the case of 3 families, we have 4 independent mass states. The unitary matrix, which diagonahlizes $H^{Fl}$ is:

$$S = U_{n\bar{n}} \times U_{1324} \times U_{3526} \tag{31}$$

Now we can use the equation

$$S_{diag} = e^{-iSH_D S^\dagger t} = Se^{-iH_D t} S^\dagger \tag{32}$$

to get the transition probabilities.

Here I would mention, that for the calculation of probabilities and plots which will be presentet later in this report, we used programming language Python.

For simplicity, I will present here probabilities of neutron transition to: anti-neutron, mirror neutron 1, mirror anti-neutron 1, mirror neutron 2, mirror antineutron 2.

Probabilities:

$$P_{600} = 1 - \frac{4}{9}\sin^2\left(\frac{t\varepsilon}{2}\right) - \frac{4}{9}\sin^2(t\varepsilon) - \frac{4}{9}\sin^2\left(\frac{3t\varepsilon}{2}\right) - \frac{1}{9}\sin^2(2t\varepsilon) \tag{33}$$

$$P_{601} = \frac{4}{9}\sin^2\left(\frac{t\varepsilon}{2}\right) - \frac{4}{9}\sin^4(t\varepsilon) + \frac{8}{9}\sin^2(t\varepsilon) - \frac{4}{9}\sin^2\left(\frac{3t\varepsilon}{2}\right) \tag{34}$$

$$P_{602} = \frac{4}{9}\sin^2\left(\frac{t\varepsilon}{2}\right)\sin^2\left(\frac{3t\varepsilon}{2}\right) \tag{35}$$

$$P_{603} = -\frac{2}{9}\sin^2\left(\frac{t\varepsilon}{2}\right) - \frac{4}{9}\sin^4(t\varepsilon) + \frac{5}{9}\sin^2(t\varepsilon) + \frac{2}{9}\sin^2\left(\frac{3t\varepsilon}{2}\right) \tag{36}$$

$$P_{604} = \frac{4}{9}\sin^2\left(\frac{t\varepsilon}{2}\right)\sin^2\left(\frac{3t\varepsilon}{2}\right) \tag{37}$$

$$P_{605} = -\frac{2}{9}\sin^2\left(\frac{t\varepsilon}{2}\right) - \frac{4}{9}\sin^4(t\varepsilon) + \frac{5}{9}\sin^2(t\varepsilon) + \frac{2}{9}\sin^2\left(\frac{3t\varepsilon}{2}\right) \tag{38}$$

Other mixing probabilities, like mirror neutron 1 to mirror neutron 2, can be calculated similarly.

Then we tried to plot these probabilities for the different parameters. Here I will present the plot for:

- $\varepsilon = 2$:

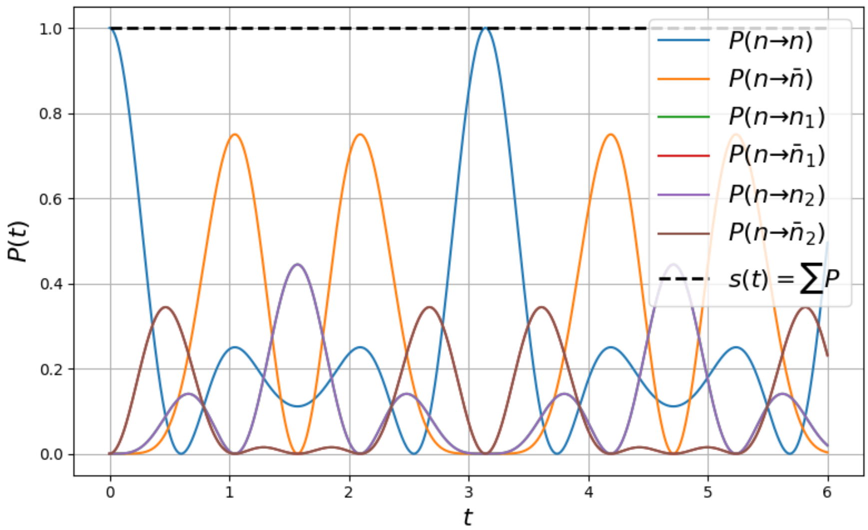


**Figure 2:** 1 Ordinary and 2 Mirror sectors neutron osc. probabilities.

Here the interesting result is that spin preecession probability ($n \to n'$, orange line) is quite significant considering 3 families.

## 2.2 2 Family Neutron-Mirror Neutron oscillations

Here we investigate a 2 family case with the following interaction Hamiltonian:

$$H_2 = \begin{pmatrix} m & 0 & \eta & \varepsilon \\ 0 & m & \varepsilon & \eta \\ \eta & \varepsilon & m & 0 \\ \varepsilon & \eta & 0 & m \end{pmatrix}, \tag{39}$$

where we have different mixing for neutron with mirror neutron and mirror antineutron. We plotted this case for parameters:

- $\varepsilon = 2$;
- $\eta = 0$,

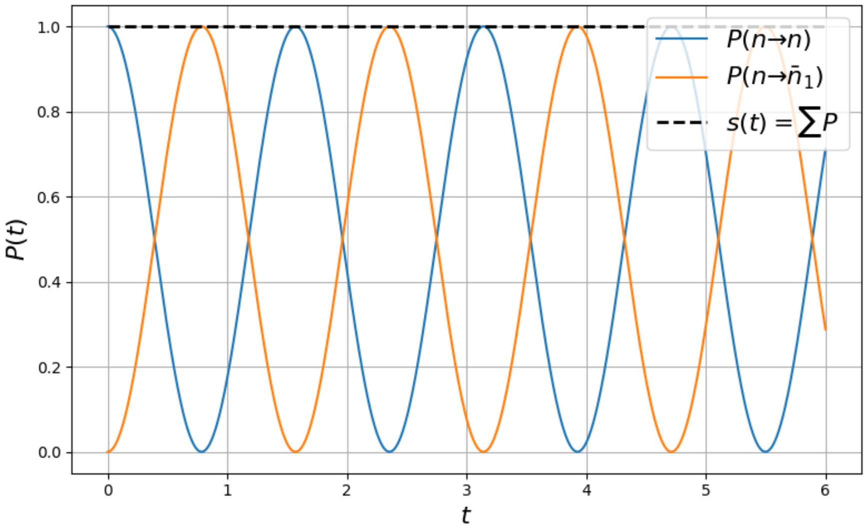


**Figure 3:** 1 Ordinary and 1 Mirror sectors neutron osc. probabilities with no precession.

Here, as we see, precession probability is 0. Now we check how it changes when we make parameter $\eta \neq 0$.
For parameters:

- $\varepsilon = 2$;
- $\eta = 1/2$,

Here we can observe that all transition probabilities are nonzero, and an interesting case is that at some point we get full conversion from neutron to mirror neutron (green line in Fig.4).

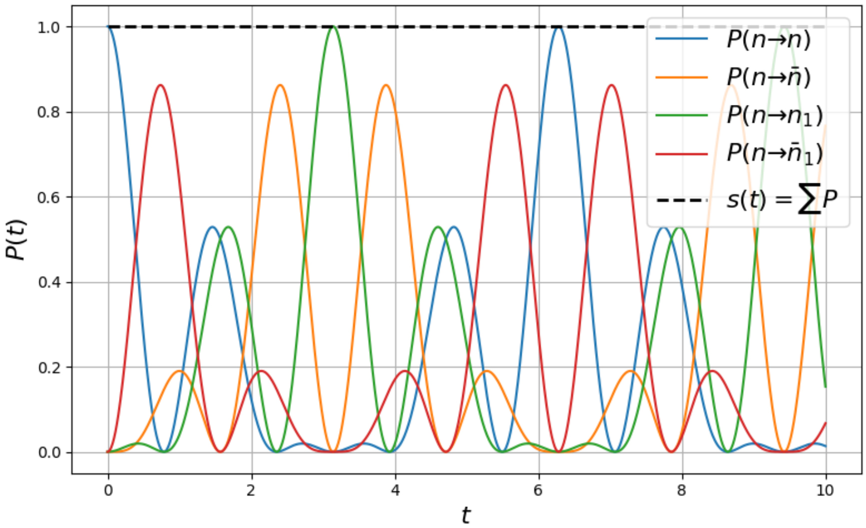


**Figure 4:** 1 Ordinary and 2 Mirror sectors neutron osc. probabilities with nonzero precession.

## 2.3 4 Family Neutron-Mirror Neutron oscillations

For 1 ordinary and 3 mirror sectors we can write the interaction Hamiltonian as:

$$H_4 = \begin{pmatrix} m & 0 & 0 & \varepsilon & 0 & \varepsilon & 0 & \varepsilon \\ 0 & m & \varepsilon & 0 & \varepsilon & 0 & \varepsilon & 0 \\ 0 & \varepsilon & m & 0 & 0 & \varepsilon & 0 & \varepsilon \\ \varepsilon & 0 & 0 & m & \varepsilon & 0 & \varepsilon & 0 \\ 0 & \varepsilon & 0 & \varepsilon & m & 0 & 0 & \varepsilon \\ \varepsilon & 0 & \varepsilon & 0 & 0 & m & \varepsilon & 0 \\ 0 & \varepsilon & 0 & \varepsilon & 0 & \varepsilon & m & 0 \\ \varepsilon & 0 & \varepsilon & 0 & \varepsilon & 0 & 0 & m \end{pmatrix} \tag{40}$$

The neutron oscillation probabilities for parameters: $\varepsilon = 2$, will look like:

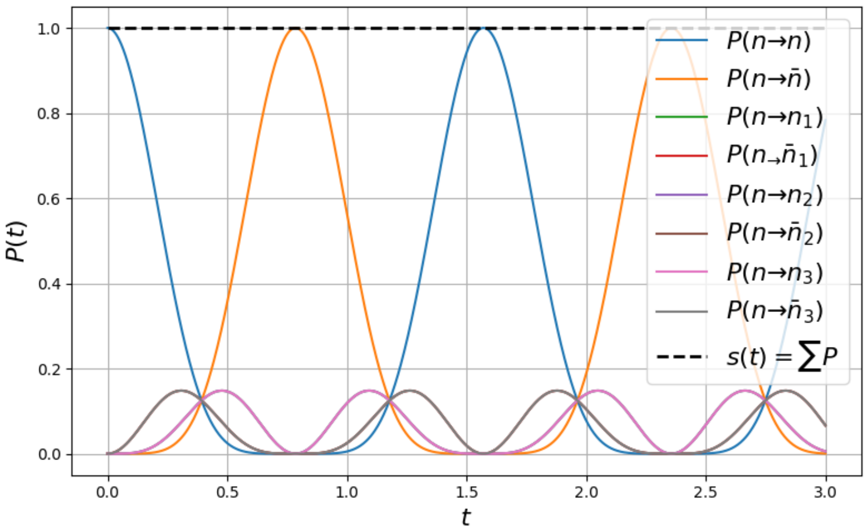


**Figure 5:** 1 Ordinary and 3 Mirror sectors neutron osc. probabilities with the same mixing with different mirror sectors.

The interesting thing here is that after some time, we see a full precession ($n \to n'$, orange line).

In case we have different mixing of ordinary matter with different mirror sectors, as this interaction Hamiltonian prompts:

$$H_4 = \begin{pmatrix} m & 0 & 0 & \varepsilon & 0 & \eta & 0 & \eta \\ 0 & m & \varepsilon & 0 & \eta & 0 & \eta & 0 \\ 0 & \varepsilon & m & 0 & 0 & \eta & 0 & \eta \\ \varepsilon & 0 & 0 & m & \eta & 0 & \eta & 0 \\ 0 & \eta & 0 & \eta & m & 0 & 0 & \varepsilon \\ \eta & 0 & \eta & 0 & 0 & m & \varepsilon & 0 \\ 0 & \eta & 0 & \eta & 0 & \varepsilon & m & 0 \\ \eta & 0 & \eta & 0 & \varepsilon & 0 & 0 & m \end{pmatrix} \tag{41}$$

And we try parameters:

- $\varepsilon = 2$;
- $\eta = 1$,

We get:

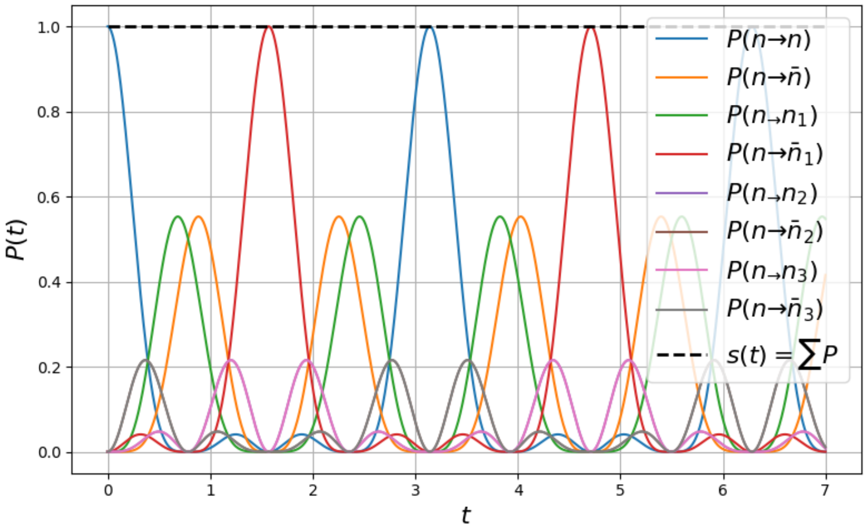


**Figure 6:** 1 Ordinary and 3 Mirror sectors neutron osc. probabilities with different mixing with different mirror sectors.

## 2.4 5 and 6 Family Neutron-Mirror Neutron oscillations

After this we tried to plot transition probabilities for 5 and 6 Family having the same mixing for each mirror sector, with parameters:

- $\varepsilon = 2$:

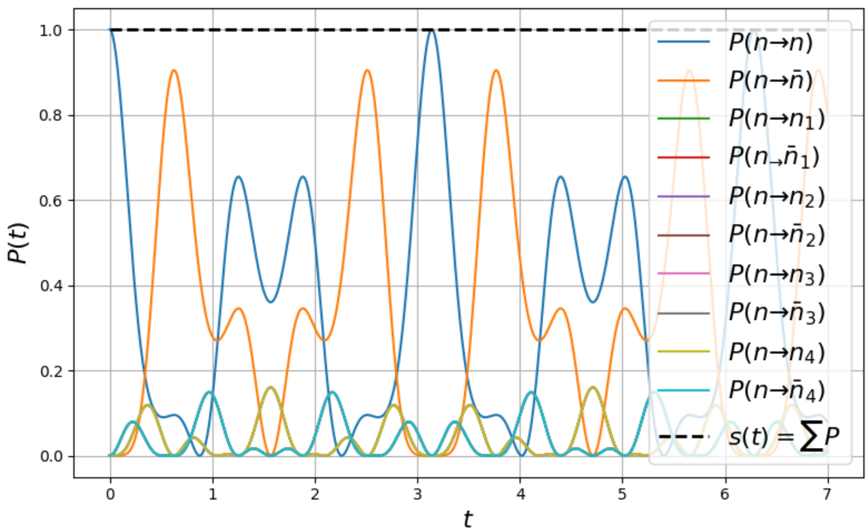


**Figure 7:** 1 Ordinary and 4 Mirror sectors neutron osc. probabilities.

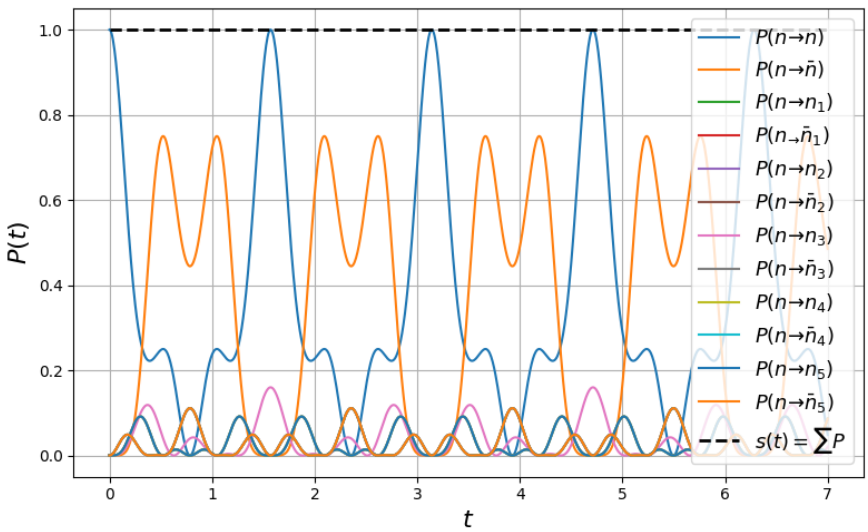


**Figure 8:** 1 Ordinary and 5 Mirror sectors neutron osc. probabilities.

## 2.5 Numerical calculations

After this, we tried to construct a function in python, which would calculate probabilities when the Hamiltonian and the diagonalizing matrix are given. General version for interaction

Hamiltonian is the following:

$$H_{num} = \begin{pmatrix} a\cos\alpha & a\sin\alpha & \eta & \varepsilon \\ a\sin\alpha & -a\cos\alpha & \varepsilon & \eta \\ \eta & \varepsilon & c - b\cos\beta & b\sin\beta \\ \varepsilon & \eta & b\sin\beta & c + b\cos\beta \end{pmatrix} \tag{42}$$

We calculated and plotted probabilities for this interaction Hamiltonian for a different set of parameters, which can be related to the ordinary and mirror magnetic fields.

Here we produce 2 set of parameters:

1. Parameters:

   - $a = 50$;
   - $b = 50$;
   - $\varepsilon = 1$;
   - $\eta = 0$;
   - $\alpha = 0.7$;
   - $\beta = 0.5$;
   - $c = 0$.

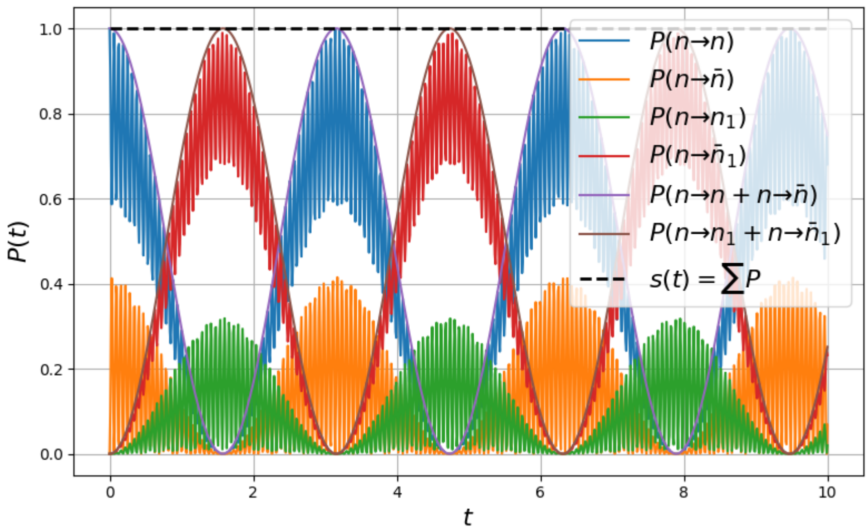


**Figure 9:** 1 Ordinary and 1 Mirror sectors neutron osc. probabilities with different mixings.

2. Parameters:

- $a = 50$;
- $b = 50$;
- $\varepsilon = 1$;
- $\eta = 0.306$;
- $\alpha = 0.905$;
- $\beta = 0.45$;
- $c = 0.45$

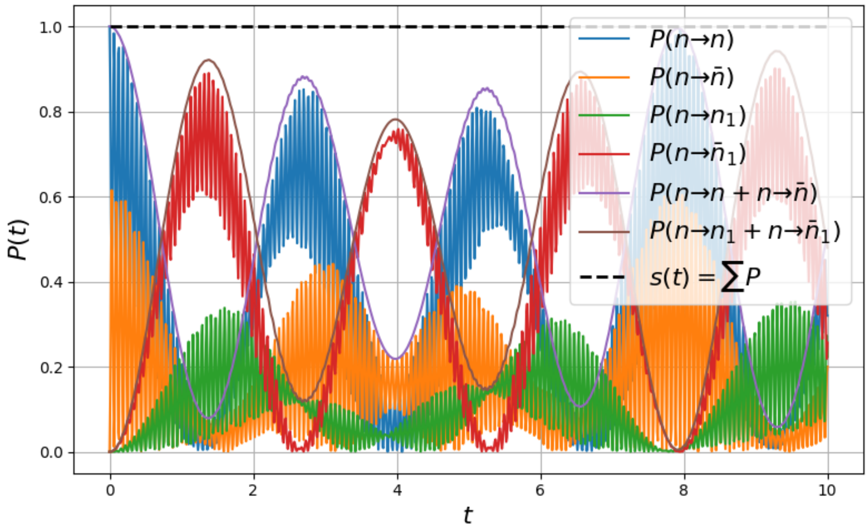


**Figure 10:** 1 Ordinary and 1 Mirror sectors neutron osc. probabilities with different mixings and different parameters.

## 2.6 Conclusions

Then we write some conclusions:

- Spin precession is affected more if it has a nonzero component from the beginning;

- If we split the masses with parameter $\eta$ the oscillations become nonperiodic;

- The larger is $\alpha$, the larger is the probability of spin precession;

- The larger is $\beta$, the larger is the probability of oscillations in the mirror sector.

But the results need to be investigated and analyzed farther.

# References

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