Search for Heavy Neutrinos with the T2K near detector

PHENICS Fest

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2 Where? (Experiment)

3 How? (Analysis)
Why? (Theory)
Neutrinos

Neutrinos come in three flavours: $\nu_e$, $\nu_\mu$, $\nu_\tau$

They are left-handed (right-handed neutrinos have never been observed)

Neutrinos are massless

Neutrino oscillations

Neutrinos change flavours between production and detection.

Two-flavours oscillations:

$$\text{Prob}(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$$

$\Delta m^2 \neq 0 \Rightarrow$ Neutrinos are massive
Why neutrinos are massless in the Standard Model?

$\mathcal{L} = m \bar{\Psi}_L \Psi_R + m \bar{\Psi}_R \Psi_L$ (Dirac mass term)
Why? (Theory)

Right-handed partner for the neutrino

- Introduction of right-handed neutrinos

When you write the whole theory, you end up with:

- 3 light neutrinos \((m \sim 0.1 \text{ eV}) \Rightarrow \text{the ones we know}\)
- 3 heavy neutrinos \((m_N = \text{keV, MeV, GeV, ... ?})\) that interact through weak interaction with a penalty factor \(U_\alpha = \text{mixing between light and heavy neutrinos} \Rightarrow \text{new particles!}\)
Why is it interesting?

We can choose heavy neutrino mass and mixing $U_\alpha$ to solve other issues.

**Example:** $\nu$MSM by Asaka and Shaposhnikov (2005), 3 new states:

- $N_1$ with $M_1 \sim \mathcal{O}(\text{keV})$ ⇒ candidate for warm dark matter
- $N_{2,3}$ with $M_{2,3} \sim \mathcal{O}(\text{GeV})$ ⇒ explains matter-antimatter asymmetry

We can look for new physics with current experiments by putting limits in $m_N - U_\alpha^2$ plane ($U_\alpha^2 \lesssim 10^{-8}$ from past exp.)
How can we see heavy neutrinos?

- It behaves like a neutrino
- The kinematic is different, because of different mass
- We add an additional factor $U^2_{\alpha}$ each time we put an heavy neutrino instead of a standard neutrino $\nu_{\alpha}$ ($\alpha = e, \mu, \tau$)

\[ K^+ \rightarrow e^+\nu_e \quad \Rightarrow \quad K^+ \rightarrow e^+ N \quad \text{if} \quad m_N < m_K - m_e \quad \text{with mixing} \quad U^2_{e}\]
\[ \pi^+ \rightarrow \mu^+\nu_\mu \quad \Rightarrow \quad N \rightarrow \pi^-\mu^+ \quad \text{if} \quad m_N > m_\pi - m_\mu \quad \text{with mixing} \quad U^2_{\mu}\]
\[ Z \rightarrow \nu N, \quad N \rightarrow \mu^+e^-\nu, \quad N \rightarrow 3\nu, \quad N \rightarrow \gamma\nu... \]
Where? (Experiment)
The T2K experiment

Neutrino oscillation experiment in Japan, running since 2010

- At J-PARC, 30 GeV proton beam is sent on a graphite target
- It produces kaons/pions that decays to neutrinos
- They propagate up to far detector (295 km) and are detected through their interaction with nucleus
The T2K experiment

At J-PARC, 30 GeV proton beam is sent on a graphite target
- It produces kaons that decays to heavy neutrinos ($\# \propto U^2_\alpha$)
- They decay within a few kilometers and can be detected through their decay in the near detector
- Number of decays is proportional to $U^2_\alpha U^2_\beta$
- Heavy neutrino mass should be: $m_\pi < m_N < m_K$
The near detector ND280

- **Initial goal:** detect standard neutrino interaction on nuclei
- **Target:** carbon scintillators + water modules
- **Tracking:** using Argon gas Time Projection Chambers

Heavy neutrino search

- **Signal:** $N \rightarrow \mu \pi$ or $N \rightarrow e \pi \Rightarrow$ \# of events $\propto$ volume
- **Background:** $\nu_\mu A \rightarrow \mu^- A' + X \Rightarrow$ \# of events $\propto$ mass

$S/B \propto 1/$density $\Rightarrow$ light materials are an excellent lab for the search!
Particles ionize the gas

Energy loss $\rightarrow$ Identification

Curvature $\propto$ momentum

9 cubic meters of gas
How? (Analysis)
Analysis strategy

- simulation of heavy neutrino signal for different possible $m_N$
- selection of the signal based on the simulation
- background study
- study of systematic uncertainties for
  - signal (detector effects, flux...)
  - background (theory, flux...)
- sensitivity analysis
Selection

- Two opposite charge tracks
- Good quality tracks
- Reconstructed vertex in TPC
- No other activity before
- Particle identification
- Correct kinematics

Bkg: 3697 events
Selection

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- Good quality tracks
- Reconstructed vertex in TPC
- No other activity before
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How? (Analysis)

Selection

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Selection

- Two opposite charge tracks
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- Reconstructed vertex in TPC
- No other activity before
- Particle identification
- Correct kinematics

Bkg: 17 events

lepton+pion identification

How? (Analysis)
Selection

- Two opposite charge tracks
- Good quality tracks
- Reconstructed vertex in TPC

- No other activity before
- Particle identification
- Correct kinematics
Conclusions

- Selection is more efficient for higher masses
- Lower efficiency when asking for an electron

⇒ to be taken into account in the analysis
Remaining background

Less than 1 event expected for all 6 years of T2K data

Example: Coherent pion production on Argon

- exactly like signal
- not precisely known

Muon and pion share all the energy

Nucleus remains unchanged ($|t|$ small)
### Source of systematics

#### Signal
- statistical error on efficiency
- detector response: momentum/position resolution, PID discrepancy between data and MC...
- flux: beam intensity, kaon production...

#### Background
- statistical error on background
- knowledge of background
- flux
# Source of systematics

## Signal
- Statistical error on efficiency \( \Rightarrow \delta \varepsilon = \sqrt{\frac{\varepsilon(1-\varepsilon)}{N}} \)
- Detector response: momentum/position resolution, PID discrepancy between data and MC... \( \Rightarrow \) variance of toy experiments
- Flux: beam intensity, kaon production... \( \Rightarrow \) throwing flux randomly

## Background
- Statistical error on background \( \Rightarrow \delta B = \sqrt{B} \)
- Knowledge of background \( \Rightarrow \) checked using control samples
- Flux \( \Rightarrow \) 10% normalization uncertainty
Sensitivity

Conversion of all information (efficiency, background, uncertainties) to a limit on mixings $U_\alpha$, using a Bayesian posterior probability

$$p(s\mid n) \propto \int_0^\infty db \int_0^\infty d\eta \frac{(s\eta + b)^n}{n!} e^{-s\eta - b} \pi_S(\eta)\pi_B(b)$$

We define an upper limit $s_{up}$ at 90% by:

$$\int_0^{s_{up}} p(s\mid n) ds = 0.90$$
Sensitivity

How? (Analysis)

[Graph showing sensitivity with various lines and markers, labeled with experiment names such as ATLAS, E949, BEBC, CHARM II, DELPHI, FMMF, CMS, ATLAS, Kaon decay, L3, NuTeV, PS191, BELLE, LHCb. The graph is labeled with $U_{\mu I}$ on the y-axis and $M_I$ [GeV] on the x-axis. The T2K region is highlighted with an orange band.]

150 200 250 300 350 400 450 500

$\mu U_{\mu e U} 10^{-10} 9^{-10} 8^{-10} 7^{-10} 6^{-10}$

T2K region

$\pi \mu e(\rightarrow eN \rightarrow K)$ T2K
$\pi (e\mu \rightarrow N \mu \rightarrow K)$ PS191

HNL mass [MeV]

10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1}
Standard model \[+\] \(3\ \nu_R\] \(\neq 0\) \(m\nu\)

Matter-antimatter asymmetry

Dark matter

- T2K can look for heavy neutrinos with \(140 < m < 500\) MeV
- Simulation + complete study have been done.
- Background is reduced to less than 1 event in current data.
- Limits on mixing between active and heavy neutrinos \(U_\alpha\) can be put.
Backups
Introduction of $\nu_R$ singlet

Simple case with one $\nu_L$ and one $\nu_R$:

$$\text{mass term} = \frac{1}{2}(\overline{\nu_L} \overline{\nu_R^c}) \begin{pmatrix} 0 & A \\ A & B \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

- **Dirac term**
- **Majorana term**

- left-handed neutrino
- right-handed neutrino

- weak int.
- + gravitation

- gravitation only

- Dirac term: as for charged fermions
- Majorana term: additional term allowed as neutrinos are neutral
Right-handed partner for the neutrino

**Introduction of \( \nu_R \) singlet**

**Simple case with one \( \nu_L \) and one \( \nu_R \):**

\[
\text{mass term} = \frac{1}{2}(\bar{\nu}_L \nu_R^c) \begin{pmatrix} 0 & A \\ A & B \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}
\]

- **Dirac term**
- **Majorana term**

If \( \theta \equiv A/B \ll 1 \) (seesaw condition), the matrix has two mass eigenstates:

- one mainly left (active) with mass \( m \simeq \theta^2 B \)
- one mainly right (sterile) + a fraction \( \theta \) of left (active) with mass \( M \simeq B \)

\( \sim 0.1 \text{ eV} \)

keV?  
GeV?  
\( 10^{16} \) GeV?
Matter-antimatter asymmetry with neutrinos at GeV-scale

<table>
<thead>
<tr>
<th>Baryogenesis via leptogenesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Singlet neutrinos are produced through their Yukawa coupling, equally split in +1 and -1 helicities, then $L_I = 0$ (conserves CP)</td>
</tr>
<tr>
<td>- Singlet neutrinos oscillate conserving $L_{\text{tot}} = L_{\text{active}} + \sum_{i=1}^{3} L_I = 0$, but $\Delta L_I \neq 0$ (violates CP)</td>
</tr>
<tr>
<td>- Singlet neutrinos communicate their asymmetries to active neutrinos $L_{\text{active}} \neq 0$ through active-sterile mixing</td>
</tr>
<tr>
<td>- $L_{\text{active}} \neq 0$ is converted to $B \neq 0$ by sphaleron process (that conserves only $B - L$ and not $B, L$ individually)</td>
</tr>
</tbody>
</table>

Requires two degenerate heavy neutrinos at GeV-scale, or three free heavy neutrinos
Dark matter candidate

Astro-H SXS
Perseus, 1 Msec
$kT = 6.5 \text{ keV}, 0.6 \text{ solar}$
$z=0.0178$
$v(\text{baryons}) = 300 \text{ km/s}$
$v(\text{line}) = 1300 \text{ km/s}$
Exclusions from other experiments

\[ \Sigma_{\nu} \sin^2(2\theta_{\nu}) \]

- |\(\mu_\nu| = 0\)
- |\(\mu_\nu| = 1.24 \times 10^{-4}\)
- |\(\mu_\nu| = 7 \times 10^{-4}\)

Excluded by X-ray observations

\[ U^2 \]

- PS191
- \(\text{NuTeV}\)
- \(\text{CHARM}\)
- \(\text{BBN}\)
- \(\text{Seesaw}\)

Excluded by phase space analysis
Cut variables

- Distance between tracks starting positions in XY [mm]
- Variables:
  - HNL sim
  - TPC1
  - TPC2
  - TPC3
  - FGD1
  - FGD2
  - DsECAL
  - BrECAL
  - P0DECAL
  - P0D
  - SMRD
  - Other
  - No truth

- Number of events (arbitrary units)

- Masses:
  - $m = 270$ MeV
  - $m = 350$ MeV
  - $m = 450$ MeV
As compared to standard neutrinos, heavy neutrinos need more time to reach ND280:

$$\Delta t = \frac{d}{c} \left( \frac{\sqrt{p^2 + m^2}}{p} - 1 \right)$$
Background for electron channel

$\nu A \rightarrow X + \pi^0, \pi^0 \rightarrow \gamma \gamma, \gamma \rightarrow e^+ e^-$, one misidentification
How to use the results?

What we have

- Expected number of events if $U = 1$ ($N_{\text{exp}} = N_{\text{sim}} \times \epsilon$) with its error
- Expected number of background $N_b$ with its error $\delta N_b$
- Measurement of a number of events $n_{\text{obs}}$

What we want to know

- have we observed new physics?
- signal $\in [s_{\text{down}}, s_{\text{up}}]$ at a given confidence level (e.g. 90%)
- a confidence interval for $U^2_e$, $U_e U_\mu$ and $U^2_\mu$:

\[
(U_\alpha U_\beta) \in \left[ \sqrt{\frac{s_{\text{down}}}{N_{\text{up}}(U = 1)}}, \sqrt{\frac{s_{\text{max}}}{N_{\text{exp}}(U = 1)}} \right]
\]
Bayesian computation of an upper limit

- If background $b$ and signal acceptance $\eta$ are known, $s$ follows:
  \[ \mathcal{L}(s, \eta, b|n) = \frac{(s\eta + b)^n}{n!} e^{-s\eta - b} \]  
  (Likelihood)

- $b$ and $\eta$ have a given distribution with standard deviation $\neq 0$, e.g.
  \[ \pi_B(b) = \frac{1}{\sqrt{2\pi\sigma_B}} e^{-\frac{(b - B)^2}{2\sigma_B^2}} \]  
  (Prior)

- Then, $s$ follows
  \[ p(s|n) \propto \int_0^\infty db \int_0^\infty d\eta \mathcal{L}(s, \eta, b|n)\pi_S(\eta)\pi_B(b) \]  
  (Posterior)

From the posterior probability, we define an upper limit $s_{up}$ at 90% by

\[ \int_0^{s_{up}} p(s|n) ds = 0.90 \]