Monoenergetic Neutrino Beam for Long Baseline Experiments

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1. Introduction

**Neutrino Observation** Indicate Neutrino Masses and Lepton Mixings

- Solar Neutrino / Reactor (Kamland)
- Atmospheric Neutrino / K2K /MINOS

\[ \delta m^2_{21}, \theta_{12} \]
\[ \delta m^2_{31}, \theta_{23} \]

Two Mixing Angles and Two Mass Square differences

\[ \theta_{13} \]
Small ; upper bound from Reactor (Chooz)

\[ \delta \]
CP Phase ; Unknown (no constraint)
In future Experiments
Precision Measurement for $\theta_{ij}, \delta m^2_{ij}$
Particular interest Determination of $\theta_{13}, \delta$

Needs for well-controlled neutrino beam(s)

Current Ideas

Superbeam, Neutrino Factory, Beta Beam

**Superbeam**

\[
\pi^+ \rightarrow \mu^+ + \nu_\mu
\]

\[
e^+ + \nu_e (\sim 0.1\%) : \nu_\mu \rightarrow \nu_e \text{ Fake events}
\]

Basically same as K2K

T2K, MINOS, NO $\nu$ A
Neutrino Factory

\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]

\[ \nu_e \rightarrow \nu_\mu \] Will be used

Charge ID

\[ \nu_\mu^- > \mu^- \text{ VS } \bar{\nu}_\mu^- > \mu^+ \]

Wrong Sign Muon

High energy neutrinos \( \rightarrow \) Deep inelastic scattering

\( \rightarrow \) energy is reconstructed statistically

If charge ID is perfect, NO “Fake Event”
Neutrinos from beta decays

\[ ^{18}\text{Ne} \rightarrow ^{18}\text{F} + e^+ + \nu_e \]
\[ ^{6}\text{He} \rightarrow ^{6}\text{Li} + e^- + \bar{\nu}_e \]

“Q-value” \( \sim 3.5\text{MeV} \)

Low energy \( \leftrightarrow \) Quasi Elastic events

\( \rightarrow \) clean

Technically most difficult
Measurement of Oscillation Parameters

Fixing values of parameters and neutrino energy
→ Oscillation Probability

By measuring the probability with one energy, we draw a supersurface of the parameter space.

With different oscillation mode, we obtain different surface

By overlapping supersurfaces for different energies and/or oscillation modes, we obtain “correct” values for parameters, in principle

In a real situation, difficulties due to

○ Supersurface is not a “surface” but a volume, with a width due to uncertainties.
○ Similar shape for supersurface for similar energy

How to get “thin” surface
Note on Measurement:

We measure only charged leptons created by neutrinos

→ induces energy uncertainty

☆ Low energy neutrino :: quasi elastic scattering

SuperBeam  BetaBeam

Elastic scattering

Reconstruction of neutrino energy by the neutrino and the charged lepton

However, there are uncertainties in measurement on the direction and the energy of charged leptons

Furthermore, intrinsic uncertainty due to Fermi motion/energy
New Idea to determine Neutrino Energy at a Detector?

High energy neutrino :: inelastic scattering
(SuperBeam) Neutrino Factory

No “direct” measurement on neutrino energy
Statistically “reconstruct” the distribution of neutrino energy

More uncertainty on “neutrino energy

New Idea to determine Neutrino Energy at a Detector?

Precise Energy Determination for Neutrino
2. Basic Idea for capture beam

Electron Capture

$$(Z, A) + e^- \rightarrow (Z - 1, A) + \nu_e$$

$$M(Z, A) + \Delta E = M(Z - 1) + Q$$

$M$: Atom mass  $\Delta E$: Binding energy  $(Q \ll M)$

$Q$: Neutrino Energy at Rest: Definite

Boosting Mother Nuclei  $(Z, A)$ by $\gamma m$

Control Neutrino Energy and Get Monoenergetic Neutrino Beam
Experimental Setup

Concept

Neutral

Ionized

$(Z, A)$

$\nu e$

$e^-$ Injection

Remove

Or Partially ionized!? Bernabeu et al
Condition on \( \mathcal{Q} \) (and \( \gamma m \))

Neutrino Energy in Lab \( 0 < E_\nu < 2\gamma m Q \) 

Highest Energy
(Which Energy Range ?)

Assuming a beam pointing to a detector:
At first glance

\[
\frac{\delta m^2 L}{4E_\nu} \bigg|_{E_\nu=2\gamma m Q} = P \quad (\text{say, } = \frac{\pi}{2})
\]

determines \( \gamma m = \frac{\delta m^2 L}{8P} \frac{1}{Q} \)
Neutrinos “fly” $L' \equiv L/\gamma_m$ Baseline in rest frame

Inverse of “Quality Factor” (Zucchelli)

Larger $\gamma_m$ Preferable to get higher intensity beam

Lower $Q$ better
However, Lower $Q$ $\rightarrow$ Longer lifetime $\tau$
for mother nucleus

Constraint from “our (experiment)” lifetime $T$

$T$ : At most several years

$\gamma m < T \Rightarrow \frac{\delta m^2 L}{8PT} < \frac{Q}{\tau}$

Upper bound for $\gamma m$ “Lower bound” for $Q$

Find a nuclei with lower $Q$
and shorter $\tau$
Theoretical Aspects

Case (i) : Purely monoenergetic neutrino

No positron emission

Consider $^{110}_{50}\text{Sn}$

$\tau_{\text{Sn}}$ 4.11 hour

$^{110}_{50}\text{Sn} + e^- \rightarrow ^{110}_{49}\text{In}^* + \nu_e$

$Q = (638 - 343) - 28 = 267\text{keV}$

Mass difference  Excited Energy  Binding Energy

Neutrino Energy in rest frame
Acceleration of $^{110}_{50}$Sn

$$\gamma_{Sn} = \frac{\delta m^2 L}{8P} \frac{1}{Q_{Sn}}$$

$$= 378 \left( \frac{\delta m^2}{2.5 \times 10^{-3} \text{eV}^2} \right) \left( \frac{L}{100 \text{km}} \right) \left( \frac{\pi/2}{P} \right) \left( \frac{267 \text{keV}}{Q_{Sn}} \right)$$

Baseline in the rest frame

$$L'_{Sn} = 264 \left( \frac{2.5 \times 10^{-3} \text{eV}^2}{\delta m^2} \right) \left( \frac{P}{\pi/2} \right)$$

\(L\) independent

\(Q\) dependent
For $P = \frac{\pi}{3}$

\[ \gamma_{\text{Sn}} = 567 \left( \frac{L}{100\text{km}} \right) \]

\[ \gamma_{\text{Sn}} \tau_{\text{Sn}} = 96 \left( \frac{L}{100\text{km}} \right) \text{ days} \]

\[ L'_{\text{Sn}} = 176 \text{ m} \]

Lifetime in lab

Baseline length in the rest frame

"All/2" $\nu_e$ hit a detector with diameter $D=176\text{m}!$
Neutrino Energy as a function of $R$

$$E_\nu(R) = \frac{2\gamma m Q}{1 + R^2 / L'^2}.$$  

For a detector size $D$

$$\frac{2\gamma m Q}{1 + D^2 / L'^2} < E_\nu < 2\gamma m Q,$$

For example $D = L'$

$$\gamma m Q \leq E_\nu \leq 2\gamma m Q$$

Very wide range of neutrino energy
Energy resolution

For the position resolution \( \delta R(\delta R^2 = 2 R \delta R) \sim 30 \text{ cm for SK} \)

Energy uncertainty is related with \( \delta R \)

\[
\left| \frac{\delta E_{\nu}}{E_{\nu}} \right| = \frac{\delta R^2/L'^2}{(1 + R^2/L'^2)} < 10^{-4}.
\]

Much better than others

Detection Position = Neutrino Energy !!
Energy Distribution

In a solid angle $d\Omega = 2\pi \sin \theta d\theta$ in rest frame the number of neutrinos distribute uniformly.

The solid angle is related with detector position

$$2\pi \sin \theta d\theta = \frac{4\pi}{\left(1 + \frac{R^2}{L'^2}\right)^2 \frac{dR^2}{L'^2}} = \frac{2\pi}{\gamma m Q} dE_\nu.$$ 

neutrino beam uniformly distributed in its energy

Optimum $\gamma m$, baseline? How large detector?

Show Later
## Candidate Nucleus

Up to $A=114$

<table>
<thead>
<tr>
<th>Mother, $E^K$</th>
<th>Daughter, $E^K$</th>
<th>$\Delta$</th>
<th>$\tau$</th>
<th>$\gamma_m$</th>
<th>$\tau \gamma_m$</th>
<th>Detector Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{110}_{50}$Sn, 29</td>
<td>$^{110}_{49}$In* $^{[343]}$, 28</td>
<td>295</td>
<td>4.11 h</td>
<td>567</td>
<td>97 d</td>
<td>176 m</td>
</tr>
<tr>
<td>$^{111}_{49}$In, 28</td>
<td>$^{111}_{48}$Cd* $^{[417]}$, 27</td>
<td>449</td>
<td>2.80 d</td>
<td>359</td>
<td>1005 d</td>
<td>278 m</td>
</tr>
</tbody>
</table>

Table 1: Nucleus candidates for case (i). $\gamma_m$ is determined by $P = \pi/3$ for a detector at $L = 100$km and $\delta m^2 = 2.5 \times 10^{-3}$eV$^2$. The energy unit is keV. N$^*[E]$ means the excited state of the nucleus N with energy E[keV]. “Detector Size” indicates the radius within which a half of the emitted neutrinos are included at the detector distance.
Case (ii) : Monoenergetic and Continuous energy neutrino

If \( Q > 2m_e \)

Both Electron capture and Positron Emission occur

Still Lower Q Nucleus

<table>
<thead>
<tr>
<th>Mother, ( E^K )</th>
<th>Daughter, ( E^K )</th>
<th>( \Delta )</th>
<th>( \tau )</th>
<th>( \gamma_m )</th>
<th>( \tau \gamma_m )</th>
<th>EC</th>
<th>( \text{e}^+ \text{emission} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( _{18}^{18}\text{F}, 0.7 )</td>
<td>( _{18}^{18}\text{O}, 0.5 )</td>
<td>1656</td>
<td>110 m</td>
<td>61</td>
<td>4.65 d</td>
<td>3.4</td>
<td>96.6</td>
</tr>
<tr>
<td>( _{48}^{48}\text{Cr}, 6 )</td>
<td>( _{48}^{48}\text{V}^*, [420], 5 )</td>
<td>1239</td>
<td>21.56 h</td>
<td>82</td>
<td>74 d</td>
<td>98.0</td>
<td>2.0</td>
</tr>
<tr>
<td>( _{111}^{111}\text{Sn}, 29 )</td>
<td>( _{49}^{111}\text{In}, 28 )</td>
<td>2445</td>
<td>35.3 m</td>
<td>42</td>
<td>24.7 h</td>
<td>40.5</td>
<td>59.5</td>
</tr>
<tr>
<td>( _{113}^{113}\text{Sn}^*[77], 29 )</td>
<td>( _{49}^{113}\text{In}, 28 )</td>
<td>1113</td>
<td>21.4 m</td>
<td>93</td>
<td>33.2 h</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 1: Candidate Nuclei for case (ii). \( \gamma_m \) is determined by \( P = \pi/2 \) instead \( \pi/3 \).

Energy distribution in rest frame

\[ \#(\nu_e) \]

\[ E_{\nu_e} \]
$Q$ is high $\rightarrow \gamma_m$ is small

At a detector, neutrinos from EC are monoenergetic

$$E_{\nu_e} = 2\gamma_m Q$$

EC dominates in decay of $^{48}_{24}\text{Cr}$, $^{113}_{50}\text{Sn}^*[77]$

also $^{140}_{66}\text{Dy}$ Bernabeu et al

By varying $\gamma_m$

we can survey oscillation with definite energy resolution

Optimum combination of $\gamma_m$'s ~?
EC and $e^+$ Emission almost half and half $^{111}\text{Sn}_{50}$

Can we make use of both line spectrum and continuum spectrum?

Appropriate $\gamma_m$?

First maximum?

Second maximum?

$\#(\nu_e)$

$E_{\nu_e}$
3. Sensitivity for high \( \gamma \) scenario

Set Up \(^{110}_{50}\text{Sn} + e^- \rightarrow ^{110}_{49}\text{In}^* + \nu_e\)

\( \epsilon = 0.55 \)
Background rejection \(10^{-4}\)
Systematical Uncertainty
Signal 2.5%
Background 5%

Fiducial 500kt
Setup II
\[ L = 250\text{km} \quad \gamma_m = 2000 \]

Setup III
\[ L = 600\text{km} \quad \gamma_m = 900/2000 \]

Input for “known” params
\[ \frac{2\gamma_m Q}{1 + \gamma_m^2 R_{\text{max}}^2/L^2} < E_\nu < 2\gamma_m Q, \]
\[
\Delta m_{31}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \quad \sin^2 2\theta_{23} = 1
\]
\[
\Delta m_{21}^2 = 8.2 \times 10^{-5} \text{ eV}^2 \quad \sin^2 2\theta_{12} = 0.83
\]
Sensitivity to $\sin^2 2\theta_{13}$

Test against the hypothesis $\sin^2 2\theta_{13} = 0$

CP Phase free, other params within current errors

Better to observe the second maximum

As strongly emphasized in Arafune&Sato, Arafune&Koike&Sato
Comparison with NuFact

$10^{21}$ decay / yr with 50kt MID

$10^{18}$ decay / yr for monobeam with 500kt Water Cherenkov
Importance of the second maximum

Set up II  Set up I  NuFact

Set up I = Setup III – second max ($\gamma = 900$)

Degenerate solutions are removed by the information from second max

Gray lines: total rate only
Colored lines: energy information used
Sensitivity to $\delta_{CP}$

Note: Naively there is no dependence on $\sin^2 2\theta_{13}$ in vacuum. Freund et al

See Setup III
4. Sensitivity for low $\gamma$ scenario

Now Calculating
Summary and Discussion

Summary

Electron Capture:

- Definite Neutrino Energy at rest frame \( Q \)
- Control Neutrino Energy at lab by boosting mother nuclei \( \gamma m \)

For very low \( Q \) Very large \( \gamma m \)

If large enough, almost all neutrinos hit a detector

Very efficient use of neutrinos

Very good “quality factor”
Furthermore we can survey very wide range of neutrino energy simultaneously and energy is extremely “measured” by the detector position.

\[ E_\nu(R) = \frac{2\gamma m Q}{1 + R^2/L'^2}. \]

Neutrino energy as a function of detector position

Simultaneous experiment with definite energy

Position is determined very precisely

Can we remove backgrounds more efficiently !?
Compare with NuFact

0.1% neutrinos are used

$10^{18} \, ^{110}_{50}\text{Sn}$ will give better sensitivity than NuFact

Can we reduce "life time" for electron capture?

Maybe .... Nomura, J.S. Shimomura hep-ph/0605031
For not low $Q > 2m_e$

Both Electron capture and Positron Emission occur

EC dominates in decay of $^{48}_{24}$Cr $^{113}_{50}$Sn*[77]

Monoenergetic Neutrino at a detector due to lower $\gamma m$

$2\gamma m Q$

By varying $\gamma m$

we can survey oscillation with definite energy resolution

EC and $e^+$ Emission almost half and half $^{111}_{50}$Sn

Efficient $\gamma m$?

Making use of both continuous and line spectrum?
Problems

CP/T conjugate channels?

How to create anti-neutrino beam?

How to create muon-neutrino beam?

Otherwise

Rely on parameter fitting? As in the last half of my talk

Or Controll pions??