Neutrino Factory and Beta-beams

1. Motivation
2. Operation Principles
3. Neutrino factory the accelerator
4. Neutrino factory the detectors
5. Beta beam the accelerator
6. Beta beam the detectors
7. Overall comparison
8. Conclusions

Today: overview with lots of questions open
Tomorrow: more details on the accelerator
(mostly NUFACT) and R&D
The neutrino mixing matrix: 3 angles and a phase $\delta$

$\theta_{23}$ (atmospheric) = 45°, $\theta_{12}$ (solar) = 32°, $\theta_{13}$ (Chooz) < 13°

$\Delta m^2_{23} = 2 \times 10^{-3}$ eV$^2$

$\Delta m^2_{12} = 8 \times 10^{-5}$ eV$^2$

Unknown or poorly known even after approved program:

$\theta_{13}$, phase $\delta$, sign of $\Delta m^2_{13}$

$\begin{pmatrix}
\sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin \theta_{13} e^{i\delta} \\
\sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\
\sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2}
\end{pmatrix}$

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Motivations

Neutrinos can tell us much more than just ‘we have mass!’

-- is CP violated in neutrino oscillations?
-- is the mixing angle $\theta_{13}$ small, very small, zero?
-- is the mass hierarchy ‘natural’ or ‘bizarre’?
-- is the mixing angle $\theta_{12}$ really very close to $\pi/4$?
-- is the mixing matrix unitary?
-- are there special relations between mixing angles and masses in neutrinos (as perhaps in quarks?)
-- can we measure the mixing parameters with the same precision as for quarks in order to test our theoretical ideas?
Motivations (II)

Conventional neutrino beams (from pion decay) have intrinsic limitations:

1. Exact shape and intensity of flux is not well known Limited by knowledge of hadron production compounded by delicacies of neutrino beam line

2. Neutrino cross sections are poorly known and difficult to measure

3. Near detectors measure flux times cross-sections for the main component of the beam

4. Optimization capability is limited

⇒ Experiments are limited at the ~5% level
K2K beam

T2K off axis Beam
But anti-$\nu$ are also present!
THE CHALLENGE:

If physics of flavour due to symmetry GUT and/or family then

The quark- and lepton-mixing parameters must be related

For the theory of flavour to be developed measurements must be sufficiently precise to remove the model-builders freedom

Challenge to neutrino experimenters:

Measure neutrino-mixing parameters with a precision similar to the precision with which the quark-mixing parameters are known
Consequences of 3-family oscillations:

I. There will be $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\tau \leftrightarrow \nu_e$ oscillation at $L_{\text{atm}}$

$$P (\nu_\mu \leftrightarrow \nu_e)_{\max} \approx \frac{1}{2} \sin^2 2\theta_{13} + \ldots \text{ (small)}$$

II. There will be CP or T violation

CP: $P (\overline{\nu}_\mu \leftrightarrow \overline{\nu}_e) \neq P (\nu_\mu \leftrightarrow \nu_e)$

T: $P (\nu_\mu \leftrightarrow \nu_e) \neq P (\nu_e \leftrightarrow \nu_\mu)$

III. We do not know if the neutrino $\nu_1$ which contains more $\nu_e$ is the lightest one (natural?) or not.

Oscillation maximum $\ 1.27 \ \Delta m^2 \ \ L / E = \pi/2$

Atmospheric $\Delta m^2 = 2.5 \times 10^{-3} \ \text{eV}^2 \ \ L = 500 \text{ km @ 1 GeV}$

Solar $\Delta m^2 = 7 \times 10^{-5} \ \text{eV}^2 \ \ L = 18000 \text{ km @ 1 GeV}$

Oscillations of 250 MeV neutrinos:

$$P (\nu_\mu \leftrightarrow \nu_e)$$

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Three family oscillations look at $\nu_\mu \rightarrow \nu_e$ oscillation

$L = \frac{\pi}{2.54} \frac{E}{\delta m^2}$

$\ell = \frac{\pi}{2.54} \frac{E}{\Delta m^2}$

Figure 3: Sketch of $P(\nu_\mu \rightarrow \nu_e)$ as function of the baseline computed for monochromatic neutrinos of 1 GeV in the solar baseline regime for $\delta_{CP} = 0$ (left) and in the atmospheric baseline regime for $\delta_{CP} = -\pi/2$ (right), where the different terms of eq. 4 are displayed. The following oscillation parameters were used in both cases: $\sin^2 2\theta_{13} = 0.01$, $\sin^2 2\theta_{12} = 0.8$, $\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV$^2$, $\Delta m_{12}^2 = 7 \times 10^{-5}$ eV$^2$. 

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**CP violation**

\[
P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) = \frac{A_{\text{CP}} \alpha \sin \delta \sin (\Delta m^2_{12} L/4E) \sin \theta_{12}}{\sin \theta_{13} + \text{solar term}}
\]

... need large values of \(\sin \theta_{12}, \Delta m^2_{12}\) (LMA) but *not* large \(\sin^2 \theta_{13}\)

... need APPEARANCE ... \(P(\nu_e \rightarrow \nu_e)\) is time reversal symmetric (reactor vs do not work)

... can be large (30%) for suppressed channel (one small angle vs two large)

... asymmetry is opposite for \(\nu_e \rightarrow \nu_\mu\) and \(\nu_e \rightarrow \nu_\tau\)

**An interference phenomenon:**

\[
P(\nu_e \rightarrow \nu_\mu) = |A|^2 + |S|^2 + 2 A S \sin \delta
\]

\[
P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu) = |A|^2 + |S|^2 - 2 A S \sin \delta
\]
asymmetry is a few % and requires excellent flux normalization (neutrino fact., beta beam or off axis beam with not-too-near near detector)

NOTES:
1. sensitivity is more or less independent of $\theta_{13}$ down to max. asymmetry point
2. This is at first maximum! Sensitivity at low values of $\theta_{13}$ is better for short baselines, sensitivity at large values of $\theta_{13}$ is better for longer baselines (2d max or 3d max.)
3. sign of asymmetry changes with max. number.
A  Experiments to find $\theta_{13}$:

search for $\nu_\mu \rightarrow \nu_e$

-- in conventional $\nu_\mu$ beam (MINOS, OPERA)
limitations: NC $\pi^0$ background, intrinsic $\nu_e$ component in beam

-- in reactor experiments

-- Off-axis beam (JPARC-SK, NOvA, T2KK) or

-- Low Energy WBB Superbeam (BNL/FNAL $\rightarrow$ INO, SPL $\rightarrow$ Fréjus)

B  Precision experiments to find CP violation

-- or to search further if $\theta_{13}$ is too small

-- beta-beam

$^6\text{He}^{++} \rightarrow ^6\text{Li}^{+++} \bar{\nu}_e e^-$ and $^{18}\text{Ne}^{10+} \rightarrow ^{18}\text{F}^{9+} \bar{\nu}_e e^+$

-- Neutrino factory with muon decay storage ring

$\nu^+ \rightarrow e^+ \bar{\nu}_e \bar{\nu}_\mu$ and $\nu^- \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu$

fraction thereof will exist.

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CERN: $\beta$-beam baseline scenario

neutrinos of $E_{\text{max}} \approx 600$ MeV

Nuclear Physics

SPL

ISOL target & Ion source
ECR
Cyclotrons, linac or FFAG
Rapid cycling synchrotron

target!

Decay ring
$B = 5$ T
$L_{\text{ss}} = 2500$ m

Stacking!

Same detectors as Superbeam!

$^6\text{He}^{++} \rightarrow ^6\text{Li}^{+++} \bar{\nu}_e e^-$

$^{18}\text{Ne}^{10+} \rightarrow ^{18}\text{F}^9+ \bar{\nu}_e e^+$
3.5 GeV SPL
+ γ = 100 β–beam

End point is $E = 2\gamma Q$

$Q =$ end point in center of mass, 3.5 MeV for $^6$He

Cross section for $\nu N \rightarrow \mu X$

Averaged yearly CC rates in a 10 years run for CP

-- low proton energy:
no Kaons $\rightarrow \nu_e$ background is low

-- region below pion threshold
(low bkg from pions)

but:
low event rate and uncertainties on cross-sections
High gamma beta-beam increases sensitivity considerably

Beta-beam at FNAL?

\[ \gamma_{\text{max}} = \gamma_{\text{max proton}} / 3 \]

for \(^6\text{He}\)

OR one has to buy a new TeV accelerator.

(Hernandez, Gomez-Cadenas)
Combination of beta beam with low energy super beam

Combines CP and T violation tests

$$\nu_e \rightarrow \nu_\mu \quad (\beta^+) \quad (T) \quad \nu_\mu \rightarrow \nu_e \quad (\pi^+)$$

(CP)

$$\bar{\nu}_e \rightarrow \bar{\nu}_\mu \quad (\beta^-) \quad (T) \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e \quad (\pi^-)$$
## EC: A monochromatic neutrino beam

Electron Capture: $N + e^- \rightarrow N' + \nu_e$

<table>
<thead>
<tr>
<th>Decay</th>
<th>$T_{1/2}$</th>
<th>BR$_{\nu}$</th>
<th>EC/$\nu$</th>
<th>B(GT)</th>
<th>$E_{GR}$</th>
<th>$\Gamma_{GR}$</th>
<th>$Q_{EC}$</th>
<th>$E_{\nu}$</th>
<th>$\Delta E_{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{148}$Dy$^+ \rightarrow ^{148}$Tb$^*$</td>
<td>3.1 m</td>
<td>1</td>
<td>0.96</td>
<td>0.96</td>
<td>0.46</td>
<td>620</td>
<td>2682</td>
<td>2062</td>
<td></td>
</tr>
<tr>
<td>$^{150}$Dy$^+ \rightarrow ^{150}$Tb$^*$</td>
<td>7.2 m</td>
<td>0.64</td>
<td>1</td>
<td>1</td>
<td>0.32</td>
<td>397</td>
<td>1794</td>
<td>1397</td>
<td></td>
</tr>
<tr>
<td>$^{152}$Tm$^2^- \rightarrow ^{152}$E$_T^*$</td>
<td>8.0 s</td>
<td>1</td>
<td>0.45</td>
<td>0.50</td>
<td>0.48</td>
<td>4300</td>
<td>520</td>
<td>8700</td>
<td>4400</td>
</tr>
<tr>
<td>$^{150}$Ho$^2^- \rightarrow ^{150}$Dy$^*$</td>
<td>72 s</td>
<td>1</td>
<td>0.77</td>
<td>0.56</td>
<td>0.25</td>
<td>4400</td>
<td>400</td>
<td>7400</td>
<td>3000</td>
</tr>
</tbody>
</table>

![Graph](image.png)

Distance = 130 km, $\theta_{13} = 5$ deg

130 km
1. Production of pions by high power proton accelerator (4 MW)
   Proton energy 5-15 GeV

2. Pt→ PL transfer and pion decay to muons

3. Muon phase rotation and bunching

4. Muon cooling

5. Muon acceleration in large acceptance device

6. Muon storage at 20-50 GeV in decay ring

7. Neutrinos of $E_\nu \leq E_\mu$
Intense K physics
Intense Low-E muons
Neutrino Factory
Higgs(es) Factory(ies)
Energy Frontier \(\rightarrow 5\) TeV

circa 1997-1999
US, Europe, Japan
Neutrino fluxes $\mu^+ \rightarrow e^+ \nu_e \nu_\mu$

$\nu_\mu/\nu_e$ ratio reversed by switching $\mu^+/\mu^-$
$\nu_e \nu_\mu$ spectra are different
No high energy tail.

**Very well known flux ($\pm 10^{-3}$)**

-- $E & \sigma_E$ calibration from muon spin precession
-- angular divergence: small effect if $\theta < 0.2/\gamma$,
-- **absolute flux measured** from muon current
or by $\nu_\mu e^- \rightarrow \mu^- \nu_e$ in near expt.

-- in **triangle or racetrack ring**, 
muon polarization precesses and averages out
(preferred, $\rightarrow$ calib of energy, energy spread)

Similar comments apply to beta beam, except spin 0
$\rightarrow$ Energy and energy spread have to be obtained
from the properties of the storage ring
(Trajectories, RF volts and frequency, etc…)

$\mu$ polarization controls $\nu_e$ flux:
$\mu^+ \rightarrow X \rightarrow \nu_e$ in forward direction
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INO ~7000 km (Magic distance)
**Superbeam & beta-beam: Non-MAGNETIC**

**Nu-Fact: MAGNETIC**

### DETECTORS

<table>
<thead>
<tr>
<th>Beam Type</th>
<th>15Ne</th>
<th>Superbeam $\pi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e \to \nu_\mu$</td>
<td>$T$ violation</td>
<td>$\nu_\mu \to \nu_\theta$</td>
</tr>
<tr>
<td>CP violation</td>
<td>CPT</td>
<td>CP violation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beam Type</th>
<th>$^6$He</th>
<th>Superbeam $\pi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}<em>e \to \bar{\nu}</em>\mu$</td>
<td>$T$ violation</td>
<td>$\bar{\nu}<em>\mu \to \bar{\nu}</em>\theta$</td>
</tr>
</tbody>
</table>

### Neutrino Oscillations

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Muon +</th>
<th>Muon -</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+ \to e^+ \nu_\theta \bar{\nu}_\mu$</td>
<td>$\bar{\nu}<em>\mu \to \bar{\nu}</em>\mu$</td>
<td>$\nu_\mu \to \nu_\mu$</td>
<td>CC</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu \to \bar{\nu}</em>\theta$</td>
<td>$\nu_\mu \to \nu_\theta$</td>
<td>CC</td>
<td>Appearance (‘platinum’ channel)</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu \to \bar{\nu}</em>\tau$</td>
<td>$\nu_\mu \to \nu_\tau$</td>
<td>CC</td>
<td>Appearance (atmospheric oscillation)</td>
</tr>
<tr>
<td>$\nu_\theta \to \nu_\theta$</td>
<td>$\bar{\nu}<em>\theta \to \bar{\nu}</em>\theta$</td>
<td>CC</td>
<td>Disappearance</td>
</tr>
<tr>
<td>$\nu_\theta \to \nu_\mu$</td>
<td>$\bar{\nu}<em>\theta \to \bar{\nu}</em>\mu$</td>
<td>CC</td>
<td>Appearance: ‘golden’ channel</td>
</tr>
<tr>
<td>$\nu_\theta \to \nu_\tau$</td>
<td>$\bar{\nu}<em>\theta \to \bar{\nu}</em>\tau$</td>
<td>CC</td>
<td>Appearance: ‘silver’ channel</td>
</tr>
<tr>
<td>$\nu \to \nu_\theta$</td>
<td>$\bar{\nu} \to \bar{\nu}_\theta$</td>
<td>NC</td>
<td>Global disappearance, sterile neutrinos</td>
</tr>
</tbody>
</table>
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**Mid-energy region:**
- **QE**
- **π**
- **n**
- Super beam (**Numi off, T2KK, CNGS+)**
- High Energy beta-beam (**CERN highQ or SPS+)**
- Water Cherenkov (**Mton**)  
- **TASD (NOvA), Larg TPC**

**Low energy region:**
- **QE** dominates
- Low energy super beam (**T2K, T2HK, T2KK, Frejus**)
- Low energy beta-beam (**CERN baseline scenario**)
- **WATER CHERENKOV (Mton)**

**High-energy region:**
- **DIS**
- Neutrino Factory
- Magnetized Iron
- Emulsion
- Large magnet around: emulsion, TASD, Larg
Magnetized Iron calorimeter
(baseline detector, Cervera, Nelson)
B = 1.7 T  Φ = 15 m, L = 25 m
t(iron) = 4 cm, t(sc) = 1 cm
Fiducial mass = 100 kT
Charge discrimination down to 1 GeV
very similar to MINOS/NOvA/ND280
ex. detector: sci. fi. detector with multipixel APD readout

Event rates for $10^{21}$ muon decays for 50 GeV beam

<table>
<thead>
<tr>
<th>Baseline</th>
<th>$\nu_\mu$ CC</th>
<th>$\nu_e$ CC</th>
<th>$\nu_\mu$ signal ($\sin^2 \theta_{13} = 0.01$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>732 Km</td>
<td>$10^9$</td>
<td>$2 \times 10^9$</td>
<td>$3.4 \times 10^5$ (J-PARC I $\rightarrow$ SK = 40)</td>
</tr>
<tr>
<td>3500 Km</td>
<td>$4 \times 10^7$</td>
<td>$7.5 \times 10^7$</td>
<td>$3 \times 10^5$</td>
</tr>
</tbody>
</table>
Golden: signal and backgrounds

Stored $\mu^+$

50% $\bar{\nu}_\mu$ $\nu_\mu$

50% $\nu_e$ $\bar{\nu}_e$

detector $\mu^+\bar{\nu}_\mu$

$\pi^+\pi^-$

$e^-\nu_e$

wrong sign muon

Backgrounds

Hadron decay

CC $\nu_e\bar{\nu}_\mu$

not detected

$\mu^+e^-D^-\mu^-$

$\pi^+\pi^-$

Charge misidentification

$\bar{\nu}_\mu$

$\mu^+$

$\pi^+\pi^-$

no other lepton detected !!!

in the final state
The MEMPHYS Project

Beta-beam detectors are similar to super-beam detectors

Excavation engineering pre-study has been done for 5 shafts

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A revealing comparison:

A detailed comparison of the capability of observing CP violation was performed by P. Huber (+M. Mezzetto and AB) on the following grounds:

-- **GLOBES** was used.

-- **T2HK** from LOI: 1000kt, 4MW beam power, 6 years anti-neutrinos, 2 years neutrinos. Systematic errors on background and signal: 5%.

-- The beta-beam $5.8\times10^{18}$ He dk/year $2.2\times10^{18}$ Ne dk/year (5+5yrs)
The **Superbeam** from 3.5 GeV SPL and 4 MW. Same 500kton detector
Systematic errors on signal efficiency (or cross-sections) and bkgds are 2% or 5%.

-- **NUFACT** $3.1\times10^{20}\mu^+$ and $3.1\times10^{20}\mu^+$ per year for 10 years
100 kton iron-scintillator at 3000km and 30 kton at 7000km (e.g. INO) (old type!)
The matter density errors of the two baselines (uncorrelated): 2 to 5%
The systematics are 0.1% on the signal and 20% on the background, uncorrelated.

All correlations, ambiguities, etc... taken into account.
What do we learn?

1. Both (BB+SB+MD) and NUFAC'T outperform e.g. T2HK on most cases.
2. Combination of BB+SB is really powerful.
3. For sin²θ₁₃ below 0.01 NUFAC'T outperforms anyone.
4. For large values of θ₁₃ systematic errors dominate:
   Matter effects for NUFAC'T,
   Cross-section errors for low energy beta-beams and superbeams.
   This is because CP asymmetry is small!
Figure 95: The $\sin^2 2\theta_{13}$ sensitivity limit relative to the optimum value of $5.9 \cdot 10^{-5}$ at $L_1 = L_2 \simeq 7500$ km. It is plotted at the $3\sigma$ confidence level as function of the baselines $L_1$ and $L_2$ heading from the 50 GeV Neutrino Factory towards two 25 Kton detectors. The sensitivity limit includes full correlations and degeneracies. The true parameters for this figure are $\Delta m_{31}^2 = 3 \cdot 10^{-3}$ eV$^2$, $\theta_{23} = \pi/4$, $\Delta m_{21}^2 = 7 \cdot 10^{-5}$ eV$^2$ and $\sin^2 \theta_{12} = 0.28$. Figure taken from [41].
at 3000 km, 1st max is at 6 GeV
2d max is at 2 GeV
...but no events down there...
At 7000 km 1st max is at 14 GeV
No real need to go over 20 GeV muon energy
Initial comparison

**Beta-beam**

1. Low energy, even with 1 TeV proton accelerator, $E < 2-3$ GeV
   no taus, no matter resonance

2. Pure $\nu_e$ or anti-$\nu_e$
   Well known flux
   Non-magnetic detectors
   Combination of superbeam required (?)
   for $\nu_\mu$ cross section measts

3. Accelerator issues:
   Ion production (need $10^{19}$ - $10^{21}$/year)
   High intensity, activation of accelerator
   Storage and duty factor

4. Performance: low E BB is inferior.
   High E BB is very competitive for CP at large $\theta_{13}$
   Not for universality test, matter effect

**Neutrino-factory**

1. High energy $E \geq 15$ GeV
   taus, matter resonance

2. $\nu_e$ and anti-$\nu_\mu$ simultaneously
   Well known flux
   Magnetic detectors
   Low energy threshold difficult
   **Golden channel** $\nu_e \sim \nu_\mu \rightarrow \mu^- X + CC$
   Electron charge difficult

3. Accelerator issues:
   4 MW Target station
   Cooling (RF in magnetic field)
   Acceleration, beam monitoring

4. Performance: High E nufact
   Will outperform at small $\theta_{13}$
   for CP, universality test, matter effect, precision.

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5. Technological readiness:
More recent!
Beta-beam not competitive without new concepts (see later) that need to be developed.
Activation in accelerator needs solution

6. Detector
Baseline is Water Cherenkov “just needs money” R&D on phototubes!
Liquid Argon, TASD not demonstrated for very large masses

5. Technological readiness:
Design and ideas are now mature. Unknowns regard RF Volts in magnetic field and power on target.
Cooling, target and accelerator demos are underway

6. Detector
Baseline is Magnetized iron + emulsion target for taus “just needs money” + R&D on photosensors
Liquid Argon, TASD not demonstrated for very large masses in magnetic volume!
7. COST
1G€ for Mton detector + similar for accelerator with sharp dependence on ion energy.

Both projects cost about 2 G€ ~ “ILC/4”. This is 5-10X more than NOvA or T2K

7. COST
ISS cost = 1.4 G$ accelerator + 300M$ for far detector
All costs “unloaded”