MOMENT as multiple neutrino sources

Ye Yuan

for MOMENT Joint-Study Group
Institute of High Energy Physics, CAS
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• Motivation and opportunity

• MOMENT: muon decay source

• MOMENT plus: pion decay source and decay at rest

• Summary
Measurement of CP

Method
• Compare $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (CP violation)
• Measure $\nu_\mu \rightarrow \nu_e$ (absolute measurement)
• Compare $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu$ (T violation)
International effort on CP measurement

Long baseline accelerator experiments

**Past**
- **K2K**
  - KEK to Kamioka
  - 250 km, 5 kW

**Current**
- **MINOS (+)**
  - FNAL to Soudan
  - 734 km, 400 kW
- **NOvA**
  - FNAL to Ash River
  - 810 km, 700 kW
- **T2K**
  - J-PARC to Kamioka
  - 295 km, 380-750 kW

**Future**
- **LBNF/DUNE**
  - FNAL to Homestake
  - 1300 km, 1.2 MW (→ 2.3 MW)
- **Hyper-K**
  - J-PARC to Kamioka
  - 295 km, 750 kW (→..)

And beyond...
- ESSnuB, neutrino factories
- DAEδALUS

Aim for CP (and other osc. pars)

Kate Scholberg @ WIN2015
Oscillation probability

- $\theta_{13}$ controls the amplitude.
- CP is a low energy effect.
- MH is determined in the high energy part.
How low is the best for CP?

• Below in-elastic threshold: \( \sim 300 \text{ MeV} \rightarrow \text{baseline} = 150 \text{ km} \)

• Such a threshold is similar for CC/NC & \( \nu/\bar{\nu} \)

• Although we lose statistics due to the lower cross section, but we have less systematics by being \( \pi^0 \) free

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J. Formaggio and G. Zeller, Rev. Mod. Phys. 84.3(2012)1307
Very high intensity proton beam is needed!
China-ADS Roadmap

- A proton LINAC for ADS is now under development in China
- If R&D is successful, a CW Linac based ~15 MW proton driver can be used for neutrino beams

Goal in 2014, 5 MeV

Goal in 2015, 10 MeV

Stage 1: Research facility
(~10 MW, ~2023)
key technology R&D

Stage 2: Exp. facility
(~100 MW, ~2030)

Stage 3: Demo facility
(~1000 MW, ~2040)

“Strategic Priority Research Program” of the Chinese Academy of Sciences
Baseline design: muon decay neutrino source

MOMENT: Muon-decay medium-baseline neutrino beam facility

PhysRevSTAB.17.090101
Target and pion/muon capture

- Mercury jet target (similar to NF design, MERIT experiment)
  - Easier to some extent due to CW proton beam (no shock-wave problem)
  - Fluidized tungsten-powder target or granular tungsten-ball target can also be considered
- High field (14T) SC capture solenoid
  - High beam power: heat load, radioactivity, challenge to shielding, cooling, deal with spent protons
Secondary beamline

• Transporting both pions and muons
  • A straight section in SC solenoids for the pions to decay into muons

• A selection section to select $\pi^+/\mu^+$ from $\pi^-/\mu^-$

• A long decay channel of muon designed for production of neutrinos
Neutrino flux

- POT (5000 h): $1.125 \times 10^{24}$ proton/year
- Muon yield: $1.62 \times 10^{-2}$ $\mu$ /proton
- Total neutrino yield: $4.8 \times 10^{-3}$ $\nu$/proton (in pair)
  
  $5.4 \times 10^{21}$ $\nu$/year (in pair)

(NF: $1.1 \times 10^{21}$ $\nu$/year)

- Neutrino flux at detector: dependent on the distance
  
  $4.7 \times 10^{11}$ $\nu$/m$^2$/year (@150 km)
Many challenges have been mentioned in Jingyu Tang’s report this morning.

Plenty works needed to be done and are under studying, some of them about target station and beamline will be showed in this session:

- Studies on pion/muon capture at MOMENT
- Cooling structure at the MOMENT target
- Protons after bombarding the target at MOMENT
- Studies on charge selection at MOMENT
Detector

• $\mu$ decay
  • $\mu^+$:
    $$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$$
  • $\mu^-$:
    $$\mu^- \rightarrow e^- + \nu_e + \nu_\mu$$

• Requirement to the detector
  • **Flavor sensitive**
    • $e/\mu$ identification: water Cherenkov detector; liquid Argon; liquid scintillator (challenge)
  • **Charge sensitive**
    • Neutrino/antineutrion identification: magnetized detector, liquid scintillator or Gd-doped water for IBD
  • **NC/CC sensitive**
    • NC background rejection: negligible at low energies
# Detector performance

<table>
<thead>
<tr>
<th></th>
<th>LS</th>
<th>Water</th>
<th>Gd water</th>
</tr>
</thead>
<tbody>
<tr>
<td>e/μ id</td>
<td>• μ id: micheal electron, eff~70%, e mis-id: 4x10^{-4}</td>
<td>• electron efficiency: 62%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Tracking threshold, e: 250MeV, μ: 100-200MeV (LENA)</td>
<td>• μ mis-id: 0.1% (T2K)</td>
<td></td>
</tr>
<tr>
<td>Antineutrino</td>
<td>IBD for electron-antineutrino, H capture(2.2MeV) eff&gt;63%</td>
<td>nH(2.2MeV) eff<del>20%, B/S</del>2% (SuperK)</td>
<td>nGd(8MeV) eff<del>67% accidental</del>2x10^{-4} (SuperK)</td>
</tr>
<tr>
<td>tagging (IBD)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positronium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NC/CC</td>
<td>N/A</td>
<td>NC mis-id: 1%</td>
<td></td>
</tr>
</tbody>
</table>

**IBD eff in Gd water:** 62%×67%≈40%
Issues in MOMENT

• Intrinsic background of IBD
  • Spallation neutron from CC with $^{12}\text{C}/^{16}\text{O}$: cross section has large uncertainty

• Atmospheric neutrino background
  • Major background for continuous-wave (CW) beam

• $e/\mu$ identification
  • Not fully explored in liquid scintillator detector
e/μ identification in liquid scintillator

- Michel electron from muon decay
- Separation of Cherenkov light and scintillation light
  - Detected Cherenkov light < 1%
  - Cherenkov light is faster
  - Need very good time resolution
Neutrino direction

- Forward scattering of positron
- Strong suppression of atmospheric neutrino background with a good tracking

\[ \overline{\nu}_e + p \rightarrow e^+ + n \]
Magnetized detector for muon decay beam?

... 

Your ideas are welcome!
Multiple sources with MOMENT

- Pion decay neutrino beam based on MOMENT

Proton driver (15MW, 1.5GeV)
CW superconducting linac (~300m)

Pion target
Dump

\( \pi^- \) or \( \pi^+ \) decay section (~50m)

\( \mu^+ \) and \( \mu^- \) selection section (~2m)

\( \pi^+ \) or \( \pi^- \) decay section (~50m)

Bending section (~20m)

Detector

\( \bar{\nu}_\mu / \nu_e \) or \( \nu_\mu / \bar{\nu}_e \)
To detector (~150km)

\( \mu \) decay channel (~600m)
(SC solenoids or quads)
# Neutrino spectrum

<table>
<thead>
<tr>
<th>Type</th>
<th>Mag. field, off-axis angle</th>
<th>Mean Value (MeV)</th>
<th>Yield (0km) (/year)</th>
<th>Yield (150km) (/m^2/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ (pion+)</td>
<td>14 T, 0°</td>
<td>175MeV</td>
<td>2.80E+22</td>
<td>1.71E12</td>
</tr>
<tr>
<td>Anti $\nu_\mu$ (pion-)</td>
<td>14 T, 0°</td>
<td>152MeV</td>
<td>1.24E+22</td>
<td>5.75E11</td>
</tr>
</tbody>
</table>

The graphs show the intensity of neutrino energy (MeV) for both $\nu_\mu$ (pion+) and Anti $\nu_\mu$ (pion-) from $\pi^+$ and $\pi^-$ decay, with different magnetic field strengths and off-axis angles.
Background

<table>
<thead>
<tr>
<th>Type</th>
<th>Mag. field, Off-axis ang.</th>
<th>Mean Value (MeV)</th>
<th>Yield (0km) (/year)</th>
<th>Yield (150km) (/m²/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti $\nu_\mu$ (mu+)</td>
<td>14 T, 0°</td>
<td>134MeV</td>
<td>1.29E+21</td>
<td>1.78E10</td>
</tr>
<tr>
<td>$\nu_\mu$ (mu-)</td>
<td>14 T, 0°</td>
<td>107MeV</td>
<td>5.26E+20</td>
<td>5.82E9</td>
</tr>
</tbody>
</table>
Decay-at-rest neutrino sources

• An absolute measurement of CP phase in the antineutrino mode

• Advantages
  • High efficiency of neutrino production: no focusing, decay pipe, charge separation ...
  • No $\nu_\mu$ CC contamination
  • Lower energy, shorter baseline -> lower matter effect
  • Known spectrum

• A concept by DAEδALUS: PRL 104, 141802 (2010)

• Neutrino flux at MOMENT-DAR
  • POT: $1.1 \times 10^{24}$/year
  • Flux at 20km: $7.6 \times 10^9$/cm$^2$/year
Summary

• MOMENT offers a good opportunity to CP measurement from low energy side

• Studies on target station, beam line and detector are making progress

• Potential for multiple neutrino sources has been considered

Thanks!