Measuring the Neutrino Mass Hierarchy

Report by the LBNL Neutrino Mass Hierarchy Task Force


arXiv:1307.5487 and SNOW13-00069

Nuclear Science Division
Physics Division
Motivation: Role of the National Lab

• Critically address issues facing the community at large
• Provide leadership, guidance, and technical expertise
  □ Long history of achievement in neutrino experiments in both Physics and Nuclear Science Divisions
• While we have involvement in some projects described below, we have attempted to survey the field independently and pedagogically
  □ Rely (mostly) on existing literature and presentations
Neutrino Mass Hierarchy

- Open questions in Neutrino Physics:
  - The very nature of the neutrino: Majorana vs Dirac
  - Absolute mass scale
    - Sensitivity to GUT mass scales
  - Neutrinos as a probe
  - Structure of neutrino mixing
  - Neutrino mass hierarchy

![Neutrino mass hierarchy diagram]

\[ \Delta m_{21}^2 > 0 \]

\[ \Delta m_{32}^2 < 0 \]
Measurements Sensitive to MH

1. Solar neutrinos
2. Supernova neutrinos
3. Direct mass measurements
4. Neutrinoless double beta decay
5. Long-baseline experiments
6. Reactor neutrinos
7. Atmospheric neutrinos
8. Cosmology
Measurements Sensitive to MH

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Very limited scope for definitive measurement
Measurements Sensitive to MH

Some potential...

(1) Solar neutrinos
(2) Supernova neutrinos
(3) Direct mass measurements
(4) Neutrinoless double beta decay

(5) Long-baseline experiments
(6) Reactor neutrinos
(7) Atmospheric neutrinos
(8) Cosmology

Very limited scope for definitive measurement
Mass hierarchy defines the scope for future $0\nu\beta\beta$ experiments.

Current and future cosmological measurements of $\Sigma m$ in combination with $M_H$ determine the absolute mass scale of each $\nu$ scale.
Supernova

- Robust MSW signal but very complicated dynamics
- Possible signal for a specific S/N model
- Model uncertainties too large to guarantee a definitive measurement
- Hierarchy measurement is a very useful input for S/N models!
Complementary baselines: T2K measures CP asymmetries, NOvA can then subtract them off from matter effects
Good chance (~40%) to have an indication of the hierarchy before LBNE/HyperK turn on
LBNE

- >3σ stat significance for determination of MH in (in combination with NOvA + T2K) independently of δ_{CP}
  - Major part of US program
- However:
  - Timescale & cost, may not be the first measurement of MH
  - Limited scope (MH, δ_{CP})
  - Poorly understood nuclear effects
HyperK and LBNO

- **HyperK**: focus on CP and proton decay
  - Large WC detector, short baseline: sensitivity to MH primarily from atmospheric $\nu$ vs
  - Very complementary to LBNE
  - Concerns: costs
- **LBNO-LAGUNA**
  - Excellent sensitivity to MH due to long baseline CERN→Finland
  - Concern: costs, likelihood
Reactor Neutrinos (JUNO)

- Statistical sensitivity to MH
- Major project in China (already funded)
- Very challenging measurement
  - Requires major improvements in detector technology (multiple factors of 2)
  - Energy resolution and scale are of paramount importance
  - Improves with percent-level precision on $\Delta m^2_{23}$

Figure mov

$\Delta \chi^2 (\Delta m^2_{ee})$

| $|\Delta m^2_{ee}| \times 10^{-3}$ eV$^2$ |
|------------------|------------------|
| 2.34             | 2.36             |
| 2.38             | 2.40             |
| 2.42             | 2.44             |
| 2.46             | 2.48             |
| 2.50             | 25               |
|                  | 20               |
|                  | 15               |
|                  | 10               |
|                  | 5                |
|                  | 0                |

Normal true MH

- True MH ($\delta m = m_1$)
- False MH ($\delta m = m_3$)
- True MH ($\delta m = 1.5\%$)
- False MH ($\delta m = 1.5\%$)

arXiv:1303.6733
Atmospheric Neutrinos (PINGU)

- Excellent statistical sensitivity to MH
  - Modest cost, timescale
- Issues
  - Energy resolution and scale
    - Impact on sensitivity
    - Practical calibration techniques
  - Rapid recent progress; disagreement with an independent evaluation of sensitivity needs to be resolved

![Graph showing PINGU Geometry - 26m String Spacing](image)

 Estimated significance for determining the neutrino mass hierarchy with

![Graph showing Preliminary](image)

IceCube/DeepCore volume

- 1.5 year procurement/cheron detectors
- 10+ different simulated geometries already
- Different methods to estimate the e
- Effect of this background
- 0.2
- 0.5
- 1.5
- 4.5
- 5

- 0
- 50
- 100
- 150
- 200

- 125m
- 75m
- 26m

- arXiv:1306.5846
Cosmological Constraints

- Cosmological fits are sensitive to the sum of neutrino masses
  - Direct determination of MH is possible iff MH is normal (sum of masses is small)
    - Complementarity to terrestrial measurements
    - 10-15 meV precision on $\Sigma m$ on timescale of 2030
    - Also will measure the number of (relativistic) neutrinos $N_{\text{eff}}$

CF5 report:
Also K. Abazajian’s CF plenary talk on Thu
Current projections of sensitivity and schedule. Complementarity of techniques can improve sensitivity of a combined measurement (c.f. arXiv:1306.3988)
JUNO

- Very challenging measurement; requires detector technology improvements beyond current state of the art
- Energy resolution critical
- No complete independent verification of sensitivity so far
Much recent progress from collaboration
Sensitivity very sensitive to the choice of experimental parameters (efficiency, energy and angular resolution, systematics) and oscillation parameters (in particular, $\Delta m^2_{23}$)
Needs to be resolved