Latest nH analysis in the Double Chooz Experiment

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On behalf of Double Chooz collaboration
Neutrino Mixing

- PNMS matrix can be broken down into three 3*3 matrices:

\[ U = \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\delta_{CP}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta_{CP}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \]

Current Measurements:

\[ \Delta m^2_{21} \sim 8 \times 10^{-5} \text{ eV}^2 \quad \Delta m^2_{31} \sim \Delta m^2_{32} \sim 0.0025 \text{ eV}^2 \]

- Each mixing angle related to a mass splitting between the two mass states
Neutrino oscillation Experiments

Solar: BOREXINO, SNO…

Atmospheric: Super-K…

Accelerator: MINOS, NOvA, T2K…

Reactor: Daya Bay, Double Chooz, RENO, KamLAND…

Cosmic: IceCube…

SNO ($\nu_e \rightarrow \nu_\mu, \tau$)  Super-K($\nu_\mu \rightarrow \nu_\tau$)

NOvA

Double Chooz ($\overline{\nu}_e \rightarrow \overline{\nu}_e$)  IceCube
Double Chooz Experiment

Spokesperson:
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Project Manager:
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Web Site:
www.doublechooz.org/
Neutron created in IBD interaction may be captured by gadolinium (nGd analysis), or by hydrogen (nH analysis). This talk is dedicated to nH analysis.

\[ P_{ee}(E_{\bar{\nu}_e}, L, \Delta m_{31}^2, \theta_{13}) = 1 - \sin^2(2\theta_{13}) \sin^2 \left( 1.27 \frac{\Delta m_{31}^2 [10^{-3} \text{ eV}^2] L [\text{km}]}{E_{\bar{\nu}_e} [\text{MeV}]} \right) \]

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Double Chooz Detector

Outer Veto (OV)
Plastic scintillator strips

Inner Veto (IV)
90 m$^3$ of scintillator in a steel Vessel (10 mm) equipped with 78 PMTs (8 inches)

Buffer
110 m$^3$ of mineral oil in a steel Vessel. (3mm) equipped with 390 low-background PMTs (10 in.)

Gamma Catcher (GC)
22.3 m$^3$ scintillator in an acrylic Vessel (12 mm)

Target
10.3 m$^3$ scintillator doped with 1 g/l of Gd in acrylic vessel (8 mm)
Key improvements in new DC H analysis

- Energy reconstruction
  - improved PE, stability and uniformity calibrations for data and MC
  - take account the light nonlinearity (LNL) and charge nonlinearity (QNL) for MC

- Background reduction
  - Use functional value (FV) to reduce stopping muons and light noise
  - Use ANN (neural network) to reject accidental background
  - Use MPS (Pulse shape) to reject FN contamination

- Detection systematics
  - Consider carefully the proton number uncertainty and spill in/out effect
  - Use volume factorization method to calculate detection efficiency

- Final Fit
  - RRM fit performed, which is model independent
  - New features added to Rate+Shape fit
Energy reconstruction

\[ E_{\text{vis}} = N_{pe} \times f_u(\rho, z) \times f_{PE/\text{MeV}} \times f_s^{\text{data}}(E_{\text{vis}}^0, t) \times f_{\text{MC}}^{\text{MC}} \]

- Use spallation neutron capture in H for spatial uniformity calibration
- Use Cf252 H capture for PE/MeV calibration
- Done for data and MC separately
Energy reconstruction

\[ E_{\text{vis}} = N_{pe} \times f_u(\rho, z) \times f_{\text{PE/Mev}} \times f_{s}^{\text{data}}(E_{\text{vis}}^0, t) \times f_{\text{nl}}^{\text{MC}} \]

- Use natural radioactive sources to do the time stability calibration
- Last terms applied to MC in Final Fit. It comes from the light nonlinearity and charge nonlinearity

**Time stability calibration**

\[ \frac{\sigma}{E_{\text{vis}}} = \sqrt{\frac{\sigma^2}{E_{\text{vis}}} + b^2 + \frac{c^2}{E_{\text{vis}}}^2} \]

**nGd resolution**

- DC-II (Gd-n) Preliminary

8/4/2015  DPF 2015
Backgrounds

Tree kinds of backgrounds considered in the oscillation analysis:

Accidental Background
- rejected by ANN and inner veto to reject compton gamma from outside

Fast Neutron
- rejected by IV, OV tagging and MPS

Stopping muons
- rejected by IV, OV tagging and FV

Li-9/He-8
- rejected by the time and space correlation to the progenitor muon
Backgrounds

- With dT, dE and dR information, we can employ the neural network to get an ANN value.
- The output value can be used to identify the Accidental background.
- Put a cut around 0 and make the signal/background ratio to be ~12.
Backgrounds

- Low energy proton recoil will not be tagged as fast neutron (FN).
- MPS deals with those FN backgrounds.

- Pulse time distribution comes from the summation of all PMT times.
- Good pulse has a distribution shown at the left plot.
- The low energy proton recoil caused by FN may result in a delayed time window.
Detection systematics

- Three factors taken into account:
  - Hydrogen fraction: the fraction of neutrons captured by H
    - Two methods used: IBD and Cf252, they agree very well.
  - Spill in/out: Use discrepancy between different simulation tools to set systematics
  - Proton number uncertainty

IBD delayed energy in GC

Cf252 delayed energy in GC
RRM fit

\[ R^{obs} = B + \left(1 - \sin^2 2\theta_{13} \left\langle \sin^2 \frac{1.27 \Delta m^2 L}{E_\nu} \right\rangle \right) R^{exp, no osc} \]

Observed rate (day$^{-1}$)

- **Data**
- No osc ($\chi^2$/dof=62/7)
- Best fit ($\chi^2$/dof=8.1/6)
- 90% CL

Livetime: 462.72 days

1σ error defined as $\Delta \chi^2=1.0$

Expected rate (day$^{-1}$)

Background rate: 7.29±0.49 day$^{-1}$

$\sin^2(2\theta_{13}) = 0.098^{+0.038}_{-0.039}$ (stat+sys)

DC-III (nH) Preliminary

\[
\sin^2 2\theta_{13} = 0.098^{+0.038}_{-0.039}
\]
Rate+Shape fit

- Apply different detection efficiency correction to different volumes
- Apply new FN model
- 5MeV distortion still there

\[
\sin^2 2\theta_{13} = 0.124^{+0.030}_{-0.039}
\]
- nGd and nH analyses give similar feature.
- Might come from mismodelling of the reactor flux. Need to be updated.
Future sensitivity
Conclusion

-Latest nH RRM analysis best fit gives $\sin^2 2\theta_{13} = 0.098 + 0.038 - 0.039$
and nH R+S analysis gives $\sin^2 2\theta_{13} = 0.124 + 0.030 - 0.039$.

-Near detector has started the data taking. We are preparing for the
Near+Far analysis. Precision of $\sin^2 2\theta_{13}$ will be improved significantly.

-Beyond $\theta_{13}$, Double Chooz is able to do some other kinds of researches,
like sterile neutrino search, reactor flux anomaly, etc. Results will be
reported in the future.