Updated results on reactor antineutrino oscillation amplitude and frequency for 2900 days at RENO

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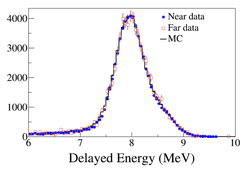
Introduction

Measurement of θ_{13} and $|\Delta m_{ee}^2|$

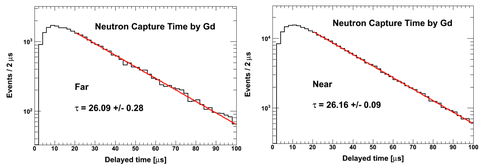
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$\simeq 1 - \sin^2 2\theta_{13}\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

where, $\Delta_{ij} \equiv 1.267\Delta m_{ij}^2 L/E$

n-Gd IBD



Neutron capture on Gd

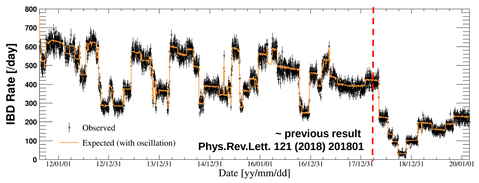


Neutron capture time by Gd

2900days of data & Reduction of Backgrounds
→ Precise measurement of θ_{13} and Δm_{ee}^2

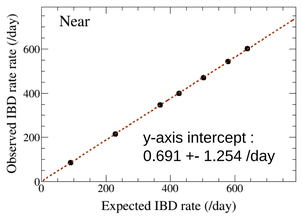
Updated Data Set

■ Since Feb. 2018, an additional ~700 day data has been analyzed with improved methods to obtain an updated result.

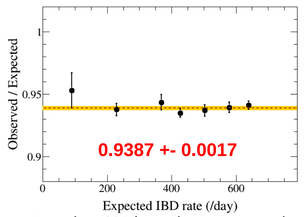


■ A period of rather minimal thermal power by the reactors
→relatively low fluxes of reactor antineutrinos

■ Observed data is well checked with expectation



Good background subtraction



Data is ~6% less than expectation

IBD & Backgrounds

■ Data taking since Aug. 2011 (Far, Near detectors with DAQ efficiency ~95%)

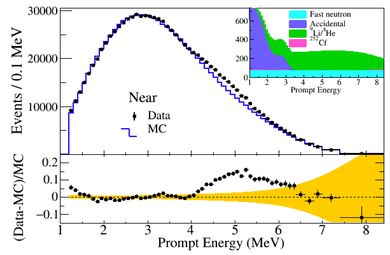
■ Observed IBD and Backgrounds

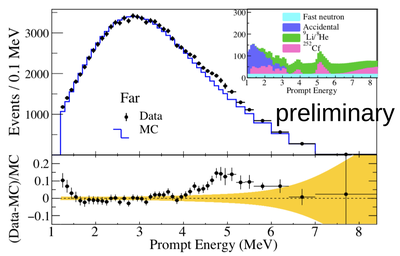
*() is event rate [/day]

Detector	IBD candidates	Total Backgrounds	Bkg. subtracted IBD
FAR (2908.01 days)	120383 +- 346.963 (41.40 +- 0.1193)	5737.36 +- 232.891 (1.973 +- 0.0801)	114645.6 +- 417.877 (39.42 +- 0.1437)
NEAR (2508.87 days)	989736 +- 994.855 (394.5 +- 0.40)	22370.9 +- 524.619 (8.917 +- 0.21)	967365 +- 1124.71 (385.6 +- 0.45)

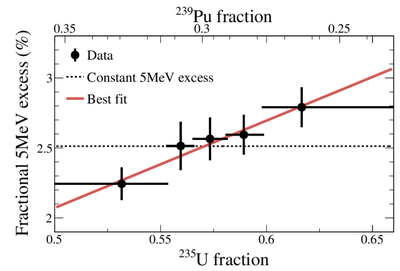
Far background ratio in IBD candidates : 4.77 +- 0.19 %
Near background ratio in IBD candidates : 2.26 +- 0.05 %

IBD Observed & Expected Spectra





■ 5MeV excess (Near : 2.50 +- 0.06% , Far : 2.26 +- 0.18%)



■ Also, Fractional 5MeV excesses is correlated to $\bar{F}_{235}$ (no correalation is disfavored at 3.21 σ)

Result from Rate+Spectral analysis

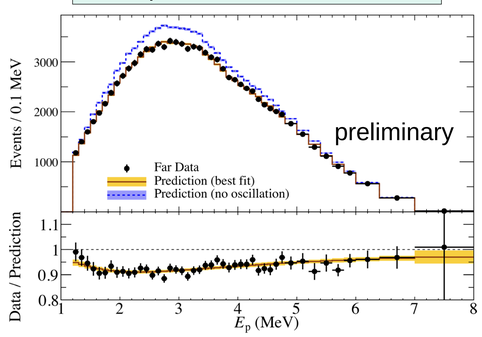
Oscillation parameters are determined using far/near ratio of IBD prompt energy spectrum

Observed Far/Near — Expected Far/Near

$$\chi^2 = \sum_{p=before,After}\left\{\sum_{i=1\sim N_b}\frac{\left(\frac{N_{obs}^{F,i}}{N_{obs}^{N,i}} - \frac{N_{Exp}^{F,i}}{N_{Exp}^{N,i}}\right)^2}{(U_i)^2}\right\} + Pull\_Terms$$

$$U_i = \frac{N_{obs}^{F,i}}{N_{obs}^{N,i}}\cdot\sqrt{\frac{N_{obs}^{F,i}+N_{bkg}^{F,i}}{(N_{obs}^{F,i})^2} + \frac{N_{obs}^{N,i}+N_{bkg}^{N,i}}{(N_{obs}^{N,i})^2}}$$

Far to prediction from near data

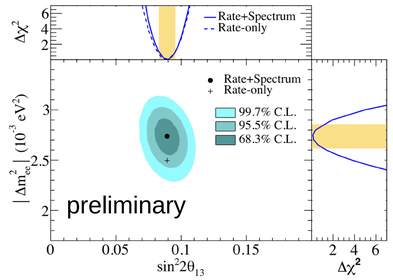


Sources of systematic uncertainties	Input uncertainties
Isotope fraction	0.7 %
Thermal power	0.5 %
Detection efficiency	0.22 %
Backgrounds (near) (far)	3.26 % 5.61 %
Energy Scale	0.15 %

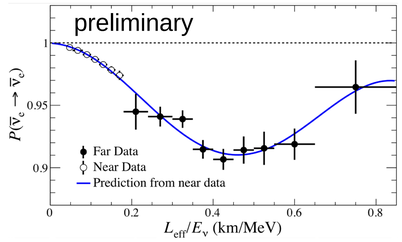
$$\sin^2 2\theta_{13} = 0.0892 \pm 0.0044(stat.) \pm 0.0045(sys.)$$ (± 7 %)

$$|\Delta m_{ee}^2| = 2.74 \pm 0.10(stat.) \pm 0.06(sys.)(\times 10^{-3} eV^2)$$ (± 4 %)

Contour Plot for spectral analysis



Observed L/E dependent oscillation



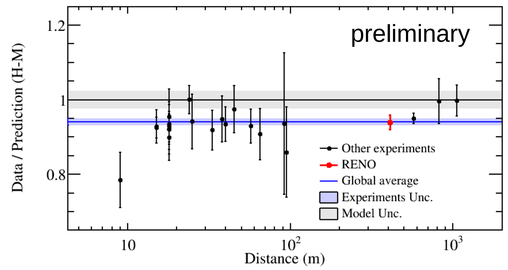
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13}\sin^2\left(\Delta m_{ee}^2 \frac{L}{4E_\nu}\right)$$

Absolute Flux Ratio

■ A flux ratio R (data/predicton) is introduced to scale the expected IBD rate to measured one using both near and far, serially.

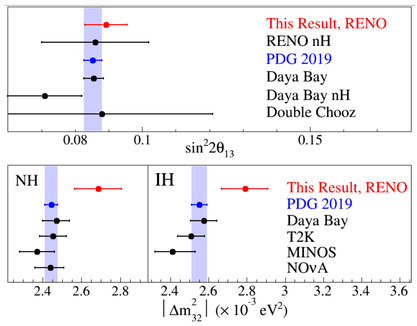
$$\chi^2 = \sum_{p=before,after}\sum_{d=near,far}\frac{[O_p^d - RT_p^d + b_p^d + \beta_p^d S_{LiHe}^d]^2}{O_p^d + Bkg_p^d} + \sum_p\sum_d\left(\frac{b_p^d}{\sigma_{bkg,p}^d}\right)^2 + \sum_d\left(\frac{S_{LiHe}^d}{\sigma_{LiHe}^d}\right)^2 + \left(\frac{f_{uncor}}{\sigma_{f,uncor}}\right)^2 + \sum_d\left(\frac{\xi_{uncor}^d}{\sigma_{\xi,uncor}^d}\right)^2 + \left(\frac{\xi_{cor}}{\sigma_{\xi,cor}}\right)^2$$

(*T_p^d is expected)



R (data/prediction) = 0.940
± 0.001 (stat.)
± 0.020 (sys.)

Comparison with other experiments



$$|\Delta m_{ee}^2| = cos^2(\theta_{12})\Delta m_{31}^2 + sin^2(\theta_{12})\Delta m_{32}^2$$
$$= |\Delta m_{32}^2| \pm (1 - sin^2(\theta_{12}))\Delta m_{21}^2$$
$$\simeq |\Delta m_{32}^2| \pm 5.21 \times 10^{-5} eV^2$$

(+ : normal, - : inverted)

$$|\Delta m_{32}^2| = 2.69 \pm 0.12(\times 10^{-3} eV^2)$$ **(NH)**

$$|\Delta m_{32}^2| = 2.79 \pm 0.12(\times 10^{-3} eV^2)$$ **(IH)**

■ $sin^2(\theta_{13})$ and Δm_{32}^2 agrees well with other experiments.