The Reactor Antineutrino Anomaly and Light Sterile Neutrinos

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Reactor Antineutrino Anomaly

Mueller (^{238}U)-Huber (^{235}U, Pu) IBD rate calculation for reactor antineutrino experiments showed a **rate excess of ~6% in the model** compared to short baseline measures

$$N_{IBD}(E_{\bar{\nu}_e}, t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle (t)} \times \langle \sigma_f \rangle (E_{\bar{\nu}_e}, t)$$

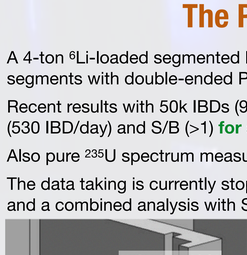
Mueller et al., Phys. Rev. C **83.5** (2011): 054615
Huber P., Phys. Rev. C **84.2** (2011): 024617
Mention et al., Phys. Rev. D **83.7** (2011): 073006

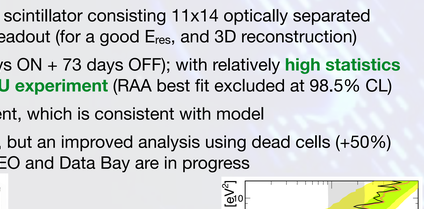
Adding a new neutrino (0.1-1 eV mass) consisting almost exclusively of an extra **sterile flavour** can account for the observed deficit

Sterile neutrinos in fact do not interact weakly but can mix with standard neutrinos, generating the disappearance via neutrino oscillation

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

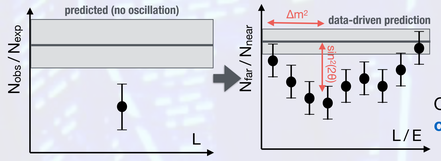
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L \lesssim 10m) \simeq 1 - \sin^2(\theta_{ee}) \sim^2 (1.27 \Delta m^2_{14} L/E)$$

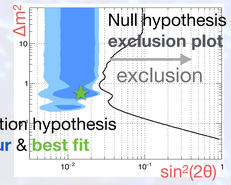




Search for the Light Sterile Neutrino

Difficulty in predicting neutrino rate limits the sensitivity of past rate-only measurements, so we need to disentangle the oscillating signature from the absolute rate by getting close to the reactor and measuring the antineutrino spectral shape





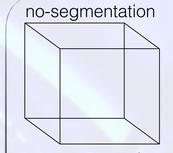
The main challenge of the searches at very short baseline is the background from cosmics (surface level) and neutrons (from the reactor itself)

To deal with background, several strategies are employed:

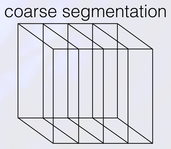
- Use the IBD topology (E_{prompt}, $E_{delayed}$, Δt, $\Delta \vec{x}$) to remove the sea of single-events
- Pack your detector in shielding layers (PE, B, Fe, H_20) and put active vetoes
- Use pulse shape discrimination (PSD)
- Estimate accidental coincidences and cosmogenic background from reactor OFF data and subtract statistically (the higher the statistics the smaller the error)

Different Reactors and Technologies

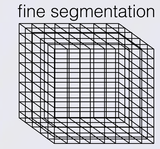
Detector segmentation



compare $\bar{\nu}$ spectrum with prediction

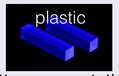


compare $\bar{\nu}$ spectra in different segments



compare $\bar{\nu}$ spectra in sections + background rejection w/ topology

Scintillator



better segmentation & less edge-effects

allows larger volumes

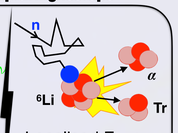
Reactor

Short baseline & compact core, no fuel evolution
$\mathcal{O}10^2$ MW_{th}, limited space, background from facility

$\mathcal{O}$$GW_{th}$, some overburden possible
Lower sensitivity at low energy, fuel burnup

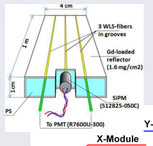
Neutron-capturing isotope

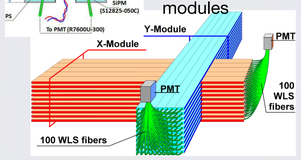
well-established, high E_{dep} and $\sigma_{capture}$



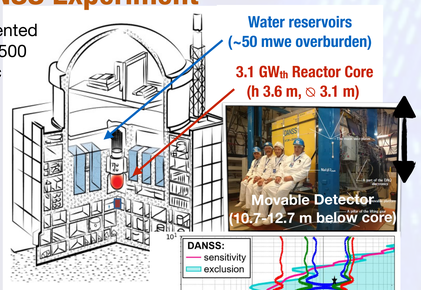
Localised E_{dep}: quenched but can select via PSD

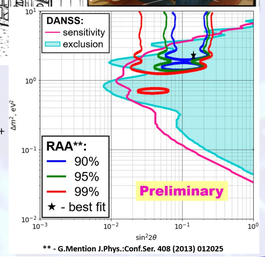
The DANSS Experiment





~m³ highly-segmented ν spectrometer: 2500 Gd-coated plastic scintillator strips arranged in 50 modules





3.5 ×10⁶ IBDs (~5000/day) collected from April 2016, **excellent S/B (~60)**

Oscillation hypotheses tested by comparing up/down e⁺ spectra → **large portion of RAA excluded** @ 95% CL

Ongoing improvement of MC modelling and evaluation of systematics, preparation of phase-II with more SiPM and better scintillator

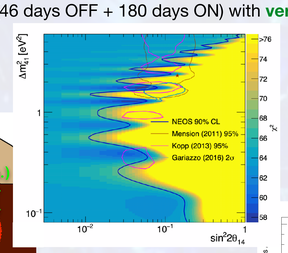
** - G.Mention J.Phys.:Conf.Ser. 408 (2013) 012025

The NEOS Experiment

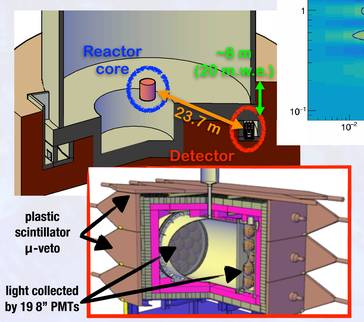
Homogeneous 1008 L Gd-loaded (0.48%) liquid scintillator

Oscillation analysis on phase-I (46 days OFF + 180 days ON) with **very high statistics** (~2000 ν/day) and good S/B

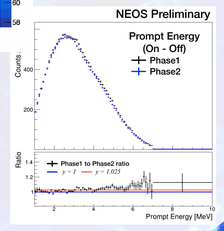
Good sensitivity especially in the low Δm^2 region



New phase-II with spectrum recently released and expected X2 increase in the sensitivity in the exclusion plot



The systematics are driven by the comparison with the Daya Bay energy spectrum



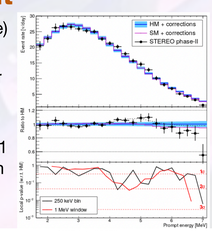
The STEREO Experiment

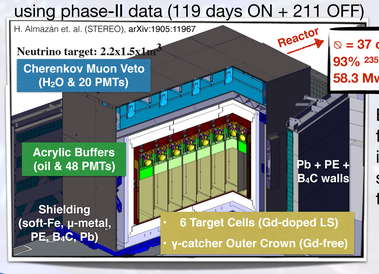
6 cells filled with Gd-loaded liquid scintillator (9-11 m from core)

Compact core & short baseline provide **little damping of oscillation**; but the little overburden and the noise from reactor facility (core, neighbours) are challenging

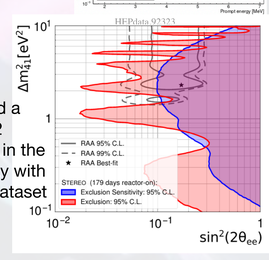
Cell-to-cell relative oscillation analysis with phase-I and -II combined data (65k IBDs, 179 days ON + 235 OFF) with S/B ~1 resulted in the exclusion of the best fit and portion of the region

Absolute ^{235}U rate and spectral shape was recently released using phase-II data (119 days ON + 211 OFF)





Expected a factor X2 increase in the sensitivity with the full dataset



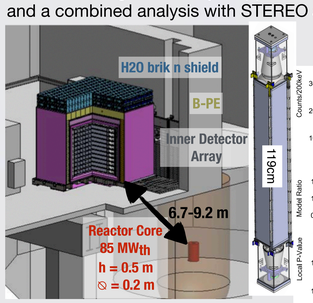
The PROSPECT Experiment

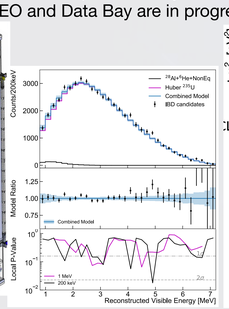
A 4-ton ^{6}Li-loaded segmented liquid scintillator consisting 11x14 optically separated segments with double-ended PMT readout (for a good E_{res}, and 3D reconstruction)

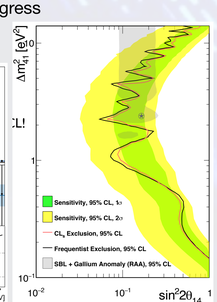
Recent results with 50k IBDs (96 days ON + 73 days OFF); with relatively **high statistics** (530 IBD/day) and S/B (>1) **for a HEU experiment** (RAA best fit excluded at 98.5% CL)

Also pure ^{235}U spectrum measurement, which is consistent with model

The data taking is currently stopped, but an improved analysis using dead cells (+50%) and a combined analysis with STEREO and Data Bay are in progress





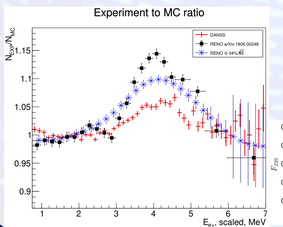


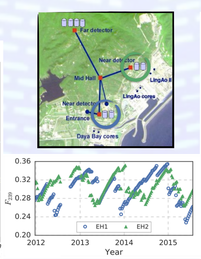
Spectral Distortion & Reactor Flux Decomposition

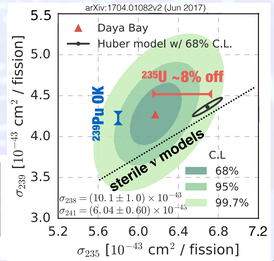
An anomalous **spectral distortion** observed at E_ν ~ 6 MeV in θ_{13}-aimed neutrino experiments (2014) raised questions on a possible underestimation of model uncertainties

The effect could be due to **unknown branches** (isotope related); nevertheless, both LEU (NEOS, DANSS) and HEU (STEREO, PROSPECT) experiments **confirm the excess**, although with different magnitude

Furthermore, Data Bay and RENO analysis on the separate ^{235}U and ^{239}Pu contribution to neutrino flux shows that the **rate deficit comes mainly from ^{235}U** disfavouring the sterile neutrino hypothesis







Limits of Current Neutrino Spectrum Models

Converted spectra method (used for ^{235}U, Pu):

- Have large uncertainty for the weak magnetism term — P. Huber PRC84.024617(2011); D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015)
- The selection of average effective Z distributions used in the fit of the ILL spectra can have a large impact on the uncertainties (up to 5%)
- The treatment of forbidden decays could change both normalisation and spectral shape, thus the measurement of the shape factors for the most important forbidden decays is crucial — A . Hayes et al. Phys. Rev. Lett. 112, 202501 (2014); D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015); X.B. Wang, J. L. Friar and A. C. Hayes Phys. Rev. C 95 (2017) 064313 and Phys. Rev. C 94 (2016) 034314; L. Hayen et al. Phys. Rev. C 031301(R)(2019) and PRC.100.054323

Summation method (used for ^{238}U)

- Suffers from incomplete or biased nuclear decay schemes
- Pandemonium effect can be solved by total absorption γ-ray spectroscopy measurements (data-model discrepancy reduced to < 2%) — J.C.Hardy et al., Phys. Lett. B. 71, 307 (1977); M. Fallot et al. PRL 109.202504 (2012), SM-2012

The combination of the rapidly-advancing analysis of data from reactor short-baseline experiments, and the improvement of models, could allow us to solve the reactor antineutrino anomaly