Effects of Reactor Antineutrino Anomaly on Measurement of Theta-13

Animesh Chatterjee, Luis Serra Diaz-Cano,
Aaron Osborn
INSS Group Project
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Overview

- Reactor experiments have been vital to the study of neutrino (ν) oscillations.
- Observed antineutrino rates have typically been lower than those expected from ν-spectrum calculations
- Recent improvements to ν-spectrum parameters result in an increase in the *expected* ν rate
- However, this increase in the expected rate makes the ratio $N_{observed}/N_{predicted}$ even lower
- This increased ν-deficit is called the reactor antineutrino anomaly
- This anomaly changes the results of prior experiments and must be considered for current/future research

Calculation of Neutrino Spectra

- Precise calculation of neutrino spectra is very complicated and uses *many* parameters

$$\Phi_{\nu}(E,t) = \frac{P_{th}(t)}{\sum_k \alpha_k(t) \times E_k} \times \sum_k \alpha_k(t) \times S_k(E)$$

- E is the neutrino energy
- $\phi_v(E,t)$ is reactor neutrino flux
- $P_{th}(t)$ is reactor thermal power at time t
- $\alpha_k(t)$ is fraction of all fissions at time t due to isotope k, where k is a major fuel isotope: ^{235}U, ^{238}U, ^{239}Pu, or ^{241}Pu
- E_k is energy per fission of isotope k
- $S_k(E)$ is neutrino spectrum per fission of isotope k

- The $S_k(E)$ term is broken down even further…

Calculation of Neutrino Spectra

- Expansion of $S_k(E)$:

$$S_k(E) = \sum_{fp}^{N_{fp}} \mathrm{A(T)} \times \left(\sum_{b=1}^{N_b} BR_{fp}^{b} \times S_{fp}^{b}(Z, A, E_{0,fp}^{b}, E) \right)$$

- A(T) is decay probability for fission product fp of isotope k
- BR^b_{fp} is the branching ratio of decay possibility b of fission product fp of isotope k
- $S^b_{fp}(Z, A, E^b_{0,fp}, E)$ is the neutrino spectrum per decay for decay possibility b of fission product fp of isotope k
- Z and A are proton and mass number of nucleus of fp, respectively
- $E^b_{0,fp}$ is the end-point energy of decay along branch b

- And this is broken down even further…

Calculation of Neutrino Spectra

- $S^b_{fp}(Z, A, E^b_{0,fp}, E)$ consists of the following:

$$S^b_{fp}(Z,A,E^b_{0,fp},E) = K^b_{fp} \times \mathfrak{F}(Z,A,E) \times pE(E-E^b_{0,fp})^2 \times \\ \times C^b_{fp} \times (1+\delta^b_{fp}(Z_{fp},A_{fp},E))$$

- K^b_{fp} is normalization factor
- $F(Z, A, E)$ is the Fermi function
- $pE(E-E^b_{0,fp})^2$ is a phase-space factor
- C^b_{fp} is the shape function
- the last term contains corrections, δ^b_{fp} consists of:
  - δ_{recoil}
  - $\delta_{\text{weak magnetism}} = E \times A_W = E \times (0.47\% / \text{MeV})$
  - $\delta_{\text{Coulomb}} = E \times A_C = E \times (-10Z\alpha R/9\hbar c)$, $R \simeq (1.5\ \text{fm}) \times A^{1/3}$

- The recent improvement to these calculations then affects the calculation of cross-sections:

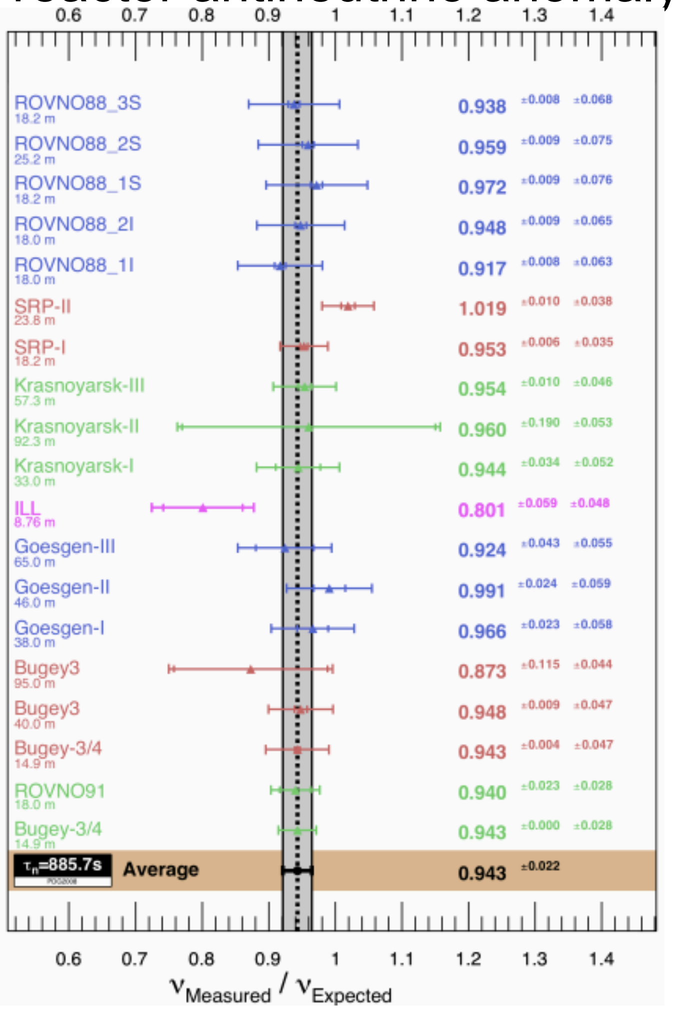
$$\sigma_f^{predicted} = \int_0^\infty S_{tot}(E_\nu)\sigma_{V-A}(E_\nu)dE_\nu = \sum_k f_k \sigma_{f,k}^{predicted}$$

Enhancement of ν-spectra

- Previous ν-spectrum calculations used ~30 effective β-branches
- These calculations have recently been refined greatly, now including ~800 daughter nuclei of fuel isotopes and ~10,000 β-branches!
- Some systematic errors have been fixed as well
  - for low (<4MeV) energies, new $\delta_{\text{weak magnetism}}$ and δ_{Coulomb} terms deviate from the linear correction used in older experiments
  - for high (>4MeV) energies, previous calculations ignored dispersion of Z, using a mean value instead
- Using the newer, larger set of parameters:
  - for ^{235}U, $\sigma_{f,k}^{\text{predicted,new}} = 1.025\sigma_{f,k}^{\text{predicted,old}}$
  - for ^{239}Pu, $\sigma_{f,k}^{\text{predicted,new}} = 1.031\sigma_{f,k}^{\text{predicted,old}}$
  - for ^{241}Pu, $\sigma_{f,k}^{\text{predicted,new}} = 1.037\sigma_{f,k}^{\text{predicted,old}}$
  - for ^{238}U, $\sigma_{f,k}^{\text{predicted,new}} = 1.098\sigma_{f,k}^{\text{predicted,old}}$
- Average increase of 3.5%
- Increased cross-section *increases* the number of neutrinos an experiment expects to observe

Reactor Antineutrino Anomaly

- This increase in N_{exp} leads to a *decrease* in the ratio N_{obs}/N_{exp}
- Previous average was 0.976±0.024, decreased to 0.943±0.013
- This effect is the reactor antineutrino anomaly

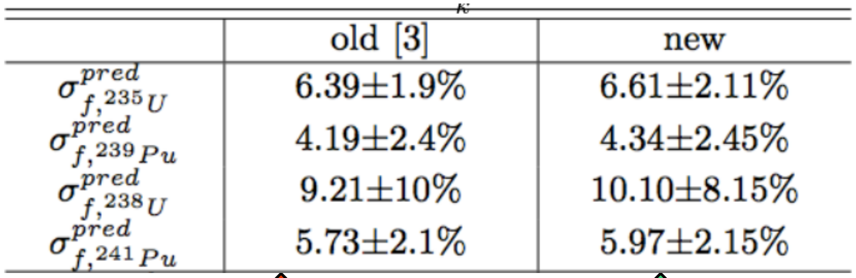


Effect on Upcoming Experiments

- Evidence of this reactor anti-ν anomaly results in having to make a choice of the correct cross-section per fission to use for constraints
- Use of $\sigma_{f,k}^{predicted,new}$, if it is incorrect, will lead to overestimation of θ_{13}, thereby “faking” a discovery
- However, if the 3 + sterile hypothesis is correct, use of the new cross-section is still possible
- If average reactor experiments are correct, it is possible to use the anomalous cross-section, an average from all short-baseline reactor experiments
- Using σ_f^{ano} can absorb either a small physical ν-defecit or a small miscalculation of reactor fluxes, but will lead to a conservative constraint on θ_{13}
- This choice only affects Double Chooz during far-only phase, as a multi-detector configuration absorbs uncertainties in reactor antineutrino fluxes
- In the 3 + sterile case, upcoming experimental sensitivities will be unaffected due to large value of Δm_{new}^2
- Oscillations into $\nu_{sterile}$ are an energy-independent suppression of anti-ν_e rate by a factor $(1/2)\sin^2(2\theta_{new})$, as first approximation

Impact on CHOOZ

Because $\sigma^{old} \sim \sigma^{bugey}$



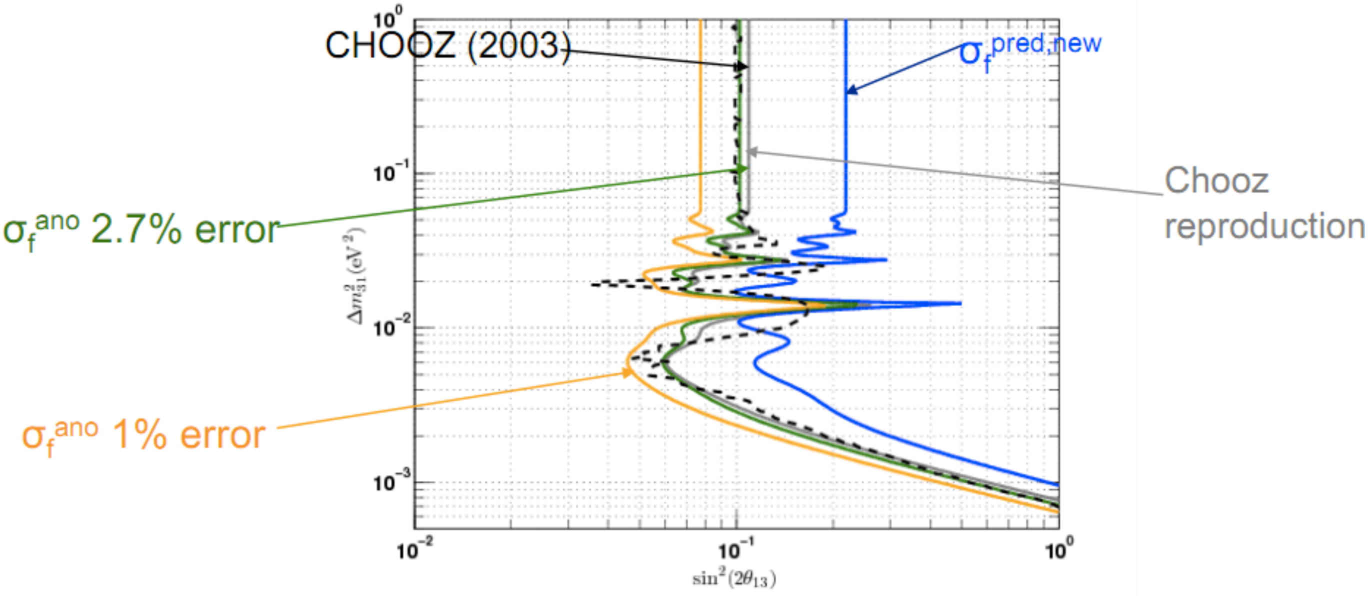
	old [3]	new
$\sigma^{pred}_{f,^{235}U}$	6.39±1.9%	6.61±2.11%
$\sigma^{pred}_{f,^{239}Pu}$	4.19±2.4%	4.34±2.45%
$\sigma^{pred}_{f,^{238}U}$	9.21±10%	10.10±8.15%
$\sigma^{pred}_{f,^{241}Pu}$	5.73±2.1%	5.97±2.15%

Now $\sigma^{new} = 1.05\ \sigma^{old}$, now CHOOZ cannot use Bugey data

Revisited results: $\Delta m^2_{13} = 2.4\ 10^{-3}\ eV^2$

- Old result of CHOOZ — $\sin^2(2\theta_{13}) < 0.14$ (1dof)
- Same analysis, new cross section — $\sin^2(2\theta_{13}) < 0.22$ (1dof)
- Deficit of ν_e due to θ_{13} — $\sin^2(2\theta_{13}) < 0.11$ (1dof)
- 4th family of neutrinos. Sterile — $\sin^2(2\theta_{13}) < 0.10$ (1dof)

Impact on CHOOZ



They couldn't reproduce the results from 2003 -> Different statistics.

The result of θ_{13} with this new σ doesn't change dramatically, but θ_{13} compatible with 0 now

$\Delta m^2_{13}=2.4\ 10^{-3}$ eV^2

Arguments for re-evaluation

- Re-evaluation of cross-section used .

- Increase the systematic error.

- Check effects with near and far detector :

$$\mathrm{near}/\mathrm{far} \equiv (N_{\mathrm{near}}/N^0_{\mathrm{near}})/(N_{\mathrm{far}}/N^0_{\mathrm{far}})$$

so $$\frac{\mathrm{near}}{\mathrm{far}} \sim \frac{\overline{P}_{ee}(\mathrm{near})}{\overline{P}_{ee}(\mathrm{far})}$$

this will give effects of Θ_{13} and Θ_{14} with the different detector.

- Forth-neutrino hypothesis

3+1 neutrino Hypothesis

- This may give some information about new non-standard neutrino, called sterile neutrino.
- The motivation is the explanation of the antineutrino deficit by an oscillation of electron neutrinos into a new neutrinos state with a large $\Delta m^2_{\text{new.}}$ & $\sin^2(2\theta_{\text{new}})$
- *4th neutrino Hypothesis :*

We are adding to the 3 active neutrinos a 4th sterile state and hence faced with four neutrino mass eigenstate. Then electron neutrino(or anti-neutrino) survival probability as

$$P_{ee} = \left| \sum_{i=1,2,3,4} |U_{ei}|^2 \exp\left(i \frac{\Delta m^2_{i1} L}{2E_\nu} \right) \right|^2 ,$$
$$= 1 - \sum_{i<j} 4 |U_{ei}|^2 |U_{ej}|^2 \sin^2 \left(\frac{\Delta m^2_{ij} L}{4E_\nu} \right)$$

arXiv:0809.5076v1[hep-ph]

Cntd..

- where L is the propagation distance(baseline) and E_ν is the neutrino energy.

- For reactor neutrino experiment and in the limit of L< 2 km & E_ν >2MeV
- Oscillation Probability (neglecting solar oscillation)

$$P_{ee} = 1 - \cos^4\theta_{\mathrm{new}} \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} L}{4E_{\bar{\nu}_e}}\right) - \sin^2(2\theta_{\mathrm{new}}) \sin^2\left(\frac{\Delta m^2_{\mathrm{new}} L}{4E_{\bar{\nu}_e}}\right).$$

- So by 1st approximation could be seen as a suppression of the electron anti-neutrino rate by 0.5* $\sin^2(2\theta_{\mathrm{new}})$
- This will give information about new mixing angle and $\Delta m^2_{\mathrm{new.}}$
- Thus 3% shift of the reactor neutrino flux can give some information about sterile neutrino.