Measurements of the absolute reactor antineutrino energy spectrum dependence on the fuel composition

Nataliya Skrobova (LPI, ITEP)
for the DANSS collaboration

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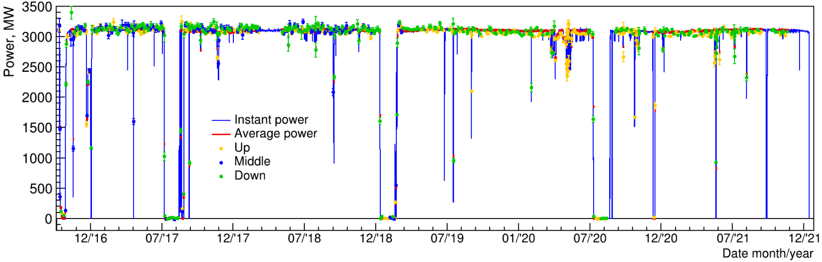
Motivation

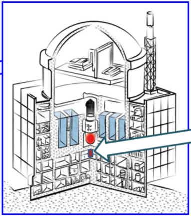
- Reactor Antineutrino Anomaly (Phys.Rev. D 83 073006): deficit in $\tilde{\nu}_e$ fluxes
- $\sigma_{235}/\sigma_{239}$ measured by DB (Phys. Rev. Lett. 120, 022503) is smaller than Huber+Mueller (Phys.Rev. C 84 024617, Phys.Rev. C 83 054615) predictions
- Resent KI measurements (Phys. Rev. D 104, L071301) don't agree with ILL measurements and hence with HM model
- Sterile neutrino searches for large Δm^2_{41} values

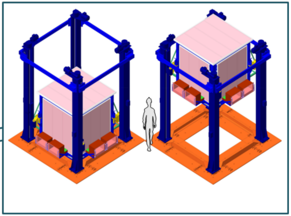
Stable performance of the DANSS detector allows us to perform analysis with absolute counting rates. Absolute counting rates address RAA directly.



Reactor power measurements with $\tilde{\nu}_e$. Normalization from a short period at the beginning of data taking.

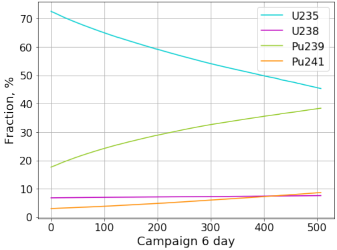
Introduction

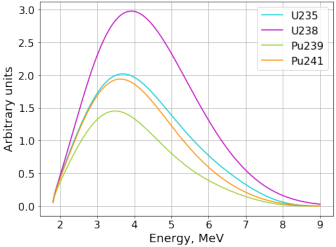




KNPP:

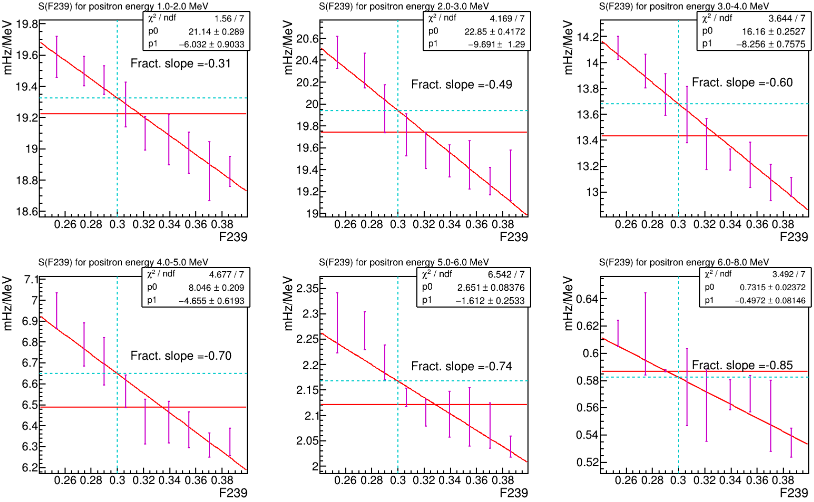
- High $\tilde{\nu}_e$ flux ($5 \cdot 10^{13} \tilde{\nu}_e$ cm^{-2} s^{-1})
- Large core: h = 3.7 m, d = 3.2 m
- Fuel: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu (other components $< 0.3\%$)



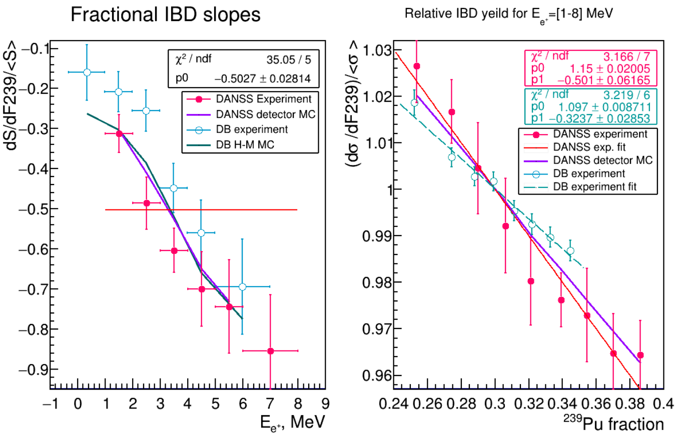


Relative slopes

- Positron spectrum is split into several energy intervals
- The whole dataset is split into several intervals depending on ^{239}Pu fission fraction
- Slope at F239=0.3 (as Daya Bay) is used for normalization



Spectrum dependence on fuel composition



IBD rate dependence on 239Pu fission fraction $(d\sigma/dF239)/\sigma(F239{=}0.3)$ for various E_{e^+} agrees with H-M model and a bit more steep than at Daya Bay.

Measurements of σ_5/σ_9

$$N = \alpha \cdot (\sigma_8 f_8 + \sigma_1 f_1 + \sigma_5 f_5 + \sigma_9 f_9)$$

$$\frac{dN}{df_9} = \alpha \cdot \left(\sigma_8 \frac{df_8}{df_9} + \sigma_1 \frac{df_1}{df_9} + \sigma_5 \frac{df_5}{df_9} + \sigma_9 \right)$$

$$SI = \left(\frac{dN}{df_9} \right) / N = \frac{\frac{\sigma_8}{\sigma_9}\frac{df_8}{df_9} + \frac{\sigma_1}{\sigma_9}\frac{df_1}{df_9} + \frac{\sigma_5}{\sigma_9}\frac{df_5}{df_9} + 1}{\frac{\sigma_8}{\sigma_9} f_8 + \frac{\sigma_1}{\sigma_9} f_1 + \frac{\sigma_5}{\sigma_9} f_5 + f_9}$$

$$\frac{\sigma_5}{\sigma_9} = -\frac{\frac{\sigma_8}{\sigma_9}(SI \cdot f_8 - \frac{df_8}{df_9}) + \frac{\sigma_1}{\sigma_9}(SI \cdot f_1 - \frac{df_1}{df_9}) + (SI \cdot f_9 - 1)}{SI \cdot f_5 - \frac{df_5}{df_9}}$$

DANSS: $\sigma_5/\sigma_9 = 1.64 \pm 0.09$
(σ_8/σ_9 and σ_1/σ_9 are taken from HM)
HM: $\sigma_5/\sigma_9 = 1.53 \pm 0.05$, DB: $\sigma_5/\sigma_9 = 1.445 \pm 0.097$
σ_8/σ_9 and σ_1/σ_9 from HM, DB-Slope, our formula: $\sigma_5/\sigma_9 = 1.448 \pm 0.057$
$\Rightarrow$ difference between DANSS and DB is due to slope

Absolute DANSS counting rates

$$\frac{dN(t)}{dt} = N_p \cdot \int_{E_{th}}^{E_{max}} \varepsilon \frac{1}{4\pi L^2} \sigma(E_\nu) \frac{d^2\phi(E_\nu, t)}{dEdt} \cdot P(L, E_\nu) dE$$

$$\frac{d^2\phi(E, t)}{dEdt} = \frac{W_{th}}{< E_{fis} >} \sum f_i \cdot s_i(E)$$

$$< E_{fis} >= \sum E_i \cdot f_i$$

N_p – the number of target protons,
ε – detector efficiency,
L – the distance between the centers of the detector and the reactor core (distribution of fission points, reactor and detector sizes are taken into account)
$\sigma(E_\nu)$ – the IBD reaction cross section,
W_{th} – reactor thermal power (data from KNPP),
E_{fis} – energy released per fission (Phys. Rev. C 88, 014605),
f_i – fission fraction
s_i – $\tilde{\nu_e}$ energy spectrum per fission (Huber + Mueller and Kurchatov Institute models are considered),
P(E, L) is the survival probability due to neutrino oscillations

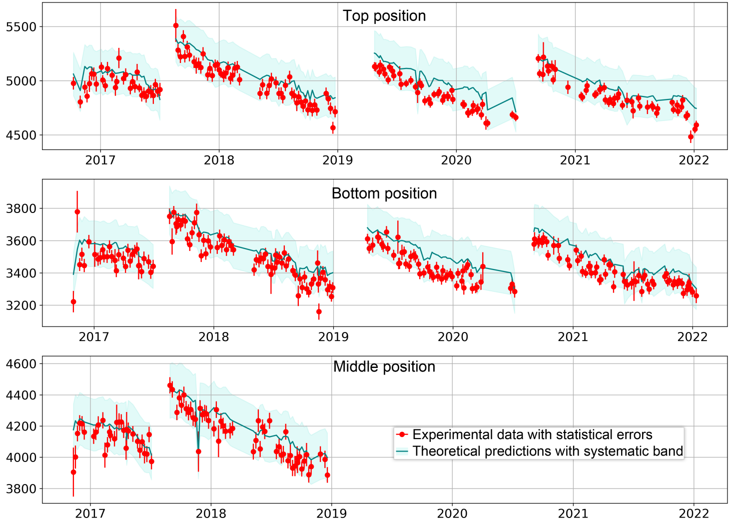
Systematic uncertainties

Source	Uncertainty
Number of protons	2%
Selection criteria	2%
Geometry (distance + fission points distribution)	1%
Fission fractions (from KNPP)	2%
Average energy per fission (Phys. Rev. C 88, 014605)	0.3%
Reactor power (from KNPP)	1.5%
Backgrounds	0.5%
Total	4%
Flux predictions	2-5%
Total with fluxes	5-7%

We hope to reduce experimental uncertainties in future.
However, flux prediction uncertainty dominates.

Comparison of the predicted and observed DANSS rates

Huber+Mueller predictions. Model uncertainties are not included!

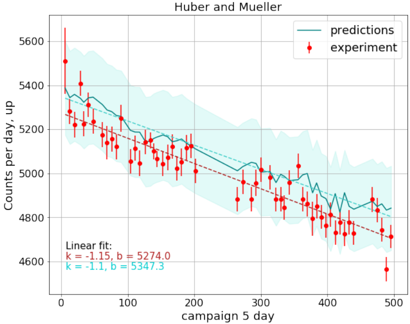


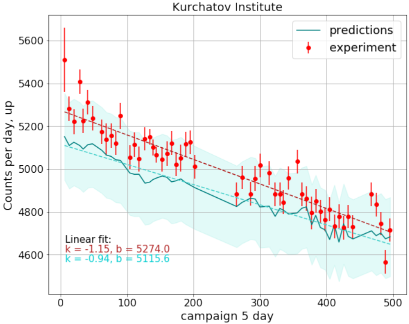
DANSS results are bellow HM predictions but within experimental uncertainties.

(average ratio: 0.98 ± 0.04)

Comparison with HM and KI models (campaign 5)

We estimate KI model predictions by reducing σ_5 and σ_8 by 5.4% in comparison with HM model



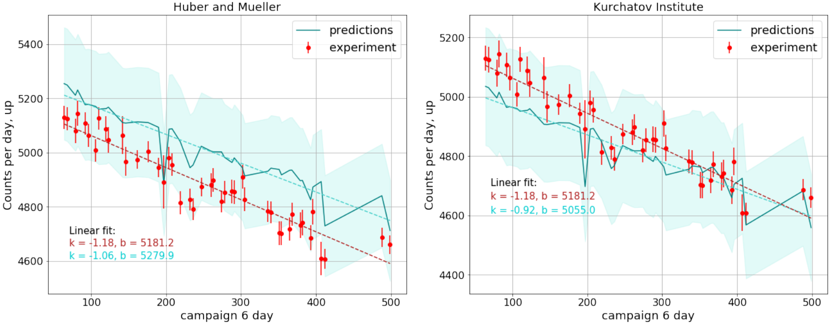


Model uncertainties are not included!

- Absolute counting rates are smaller than predictions in HM model but consistent within errors.
- Absolute counting rates are larger than predictions from KI model but consistent within errors.
- Uncertainties in flux predictions are large.

Comparison with HM and KI models (campaign 6)

We estimate KI model predictions by reducing σ_5 and σ_8 by 5.4% in comparison with HM model



Model uncertainties are not included!

- Absolute counting rates are smaller than predictions in HM model but consistent within errors.
- Absolute counting rates are larger than predictions from KI model but consistent within errors.
- Uncertainties in flux predictions are large.

Oscillation analysis: test statistics

Test statistics is defined as follows:

$$\chi^2 = \min_{\eta,k} \sum_{i=1}^{N_{bins}} \begin{pmatrix} Z_{1i} & Z_{2i} \end{pmatrix} \cdot W^{-1} \cdot \begin{pmatrix} Z_{1i} \\ Z_{2i} \end{pmatrix} + \sum_{i=1}^{N_{bins}} \frac{Z_{1i}^2}{\sigma_{1i}^2} + \sum_{j=1,2} \frac{(k_j - k_j^0)^2}{\sigma_{kj}^2} + \sum_{l} \frac{(\eta_l - \eta_l^0)^2}{\sigma_{\eta l}^2}$$

phase I
Top, Middle, Bottom

phase II
Top, Bottom

penalty
terms

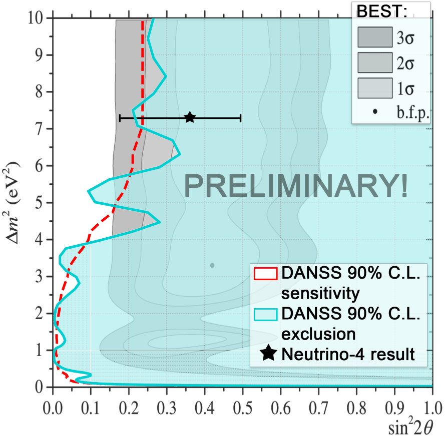
$$+((N_{top} + N_{mid} + N_{bottom})^{\mathrm{obs}} - (N_{top} + k_2 \cdot \sqrt{k_1} \cdot N_{mid} + k_1 \cdot N_{bottom})^{\mathrm{pre}})^2 / \sigma_{abs}^2$$

term for absolute rates

i – energy bin (36 total) in range 1.5–6 MeV;
$Z_j = R_j^{\mathrm{obs}} - k_j \times R_j^{\mathrm{pre}}(\Delta m^2,\ \sin^2 2\theta,\ \eta)$ for each energy bin,
$R_1 = Bottom/Top, R_2 = Middle/\sqrt{Bottom \cdot Top}$, where
$Top,\ Middle,\ Bottom$ – absolute count rates per day for each detector position,
k – relative efficiency (nominal values $k_1^0 = k_2^0 = 1$),
$\eta(\eta^0)$ – other nuisance parameters (and their nominal values),
W – covariance matrix to take into account correlations in spectra ratios at different positions (Z_1 and Z_2),
N – total absolute rates,
σ_{abs} – systematic uncertainty (7% in absolute rates).

Oscillation analysis: preliminary results

DANSS 90% C.L. exclusion and sensitivity areas calculated with Raster Scan method and HM model using information about absolute counting rates



All systematic uncertainties discussed earlier are included

flux uncertainty is 5%, total: 7%

Raster Scan method:

$\Delta\chi^2 = \chi^2_{\Delta m^2,\,\theta} - \chi^2_{min(\Delta m^2)}$

90% C.L: $\Delta\chi^2 > 2.71$

Large Δm^2_{41} limit: $N \sim 1 - \frac{1}{2}\sin^2 2\theta_{ee}$

Sensitivity border (90% C.L.):

$\sin^2 2\theta_{ee} \approx 2 \cdot \sigma \cdot \sqrt{2.71} \approx 0.24$

Exclusions for large Δm^2_{41} are consistent with previous results (Daya Bay, Bugey-3, ...)

Our preliminary results exclude the dominant fraction of BEST expectations as well as best fit point of Neutrino-4 experiment. In KI model exclusions are more strict.

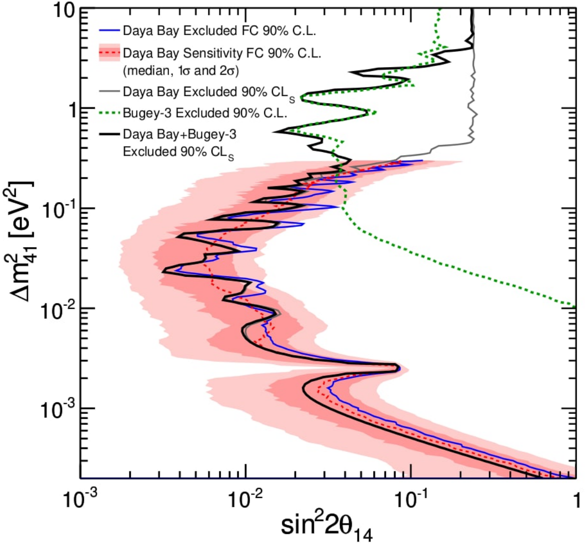
However, these results are model-dependent.

Summary

- Absolute counting rates are smaller than predictions in HM model but consistent within errors.
- Absolute counting rates are larger than predictions from KI model but consistent within errors.
- Relative IBD σ dependence on 239Pu fraction is slightly stepper than in HM model and considerably steeper than at DB and in KI models.
- Estimated ratio of σ_5/σ_9 is consistent with HM model and larger than KI and DB results.
- Oscillation analysis with absolute counting rates (HM model) excludes practically all sterile parameter space preferred by BEST and the best fit point of Neutrino-4 experiment.
  However, this result is model-dependent.

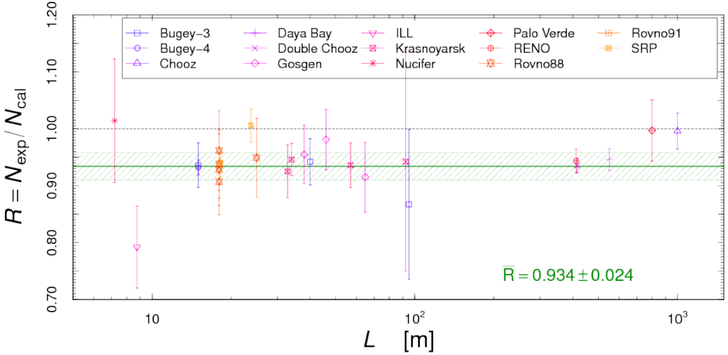
Thank you!

Sterile neutrinos



Comparison of the predicted and observed DANSS rates

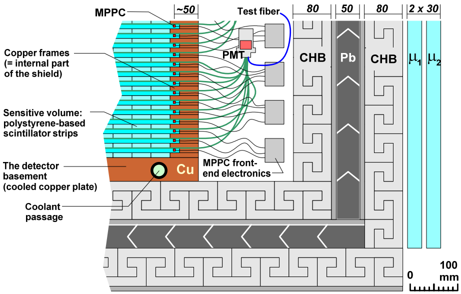
DANSS rates to Huber+Mueller: 0.98 ± 0.04

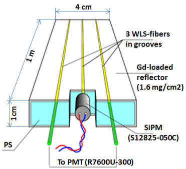


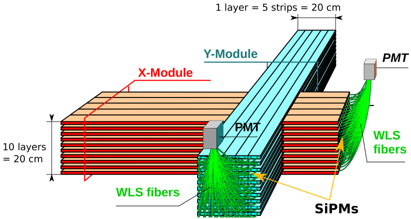
(arXiv:1906.01739v2)

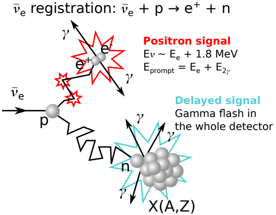
DANSS design [JINST 11 (2016) no.11, P11011]

- Multilayer passive shielding: electrolytic copper frame 5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
- 2-layer active μ-veto on 5 sides
- 2500 scintillator strips with Gd containing coating for neutron capture
- Light collection with 3 WLS fibers
- Central fiber read out with individual SiPM
- Side fibers from 50 strips make a bunch of 100 on a PMT cathode = Module









Due to high granularity we can measure positron kinetic energy (without γ)

Test statistics

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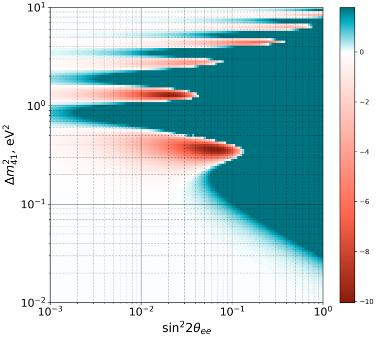
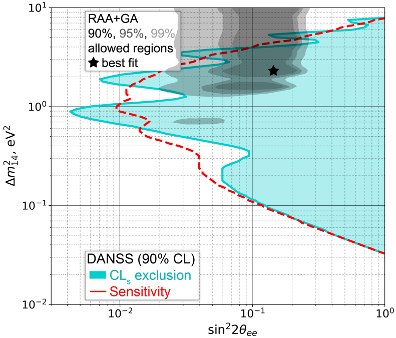


$\Delta\chi^2 = \chi^2_{4\nu} - \chi^2_{3\nu}$ distribution (6 mln events)

Preliminary results

DANSS 90% C.L. exclusion and sensitivity areas calculated with Gaussian CL_s method (Nucl.Inst.Meth. A 827 63). It is more conservative than Feldman-Cousins approach.



Systematic uncertainties (1σ values):

- relative detector efficiencies at different distances (0.2%)
- distance to the fuel burning profile center (5 cm)
- cosmic background (25%)
- fast neutron background (30%)
- additional smearing in energy resolution (25%)
- energy scale (2%)
- energy shift (25 keV)

A large and the most interesting fraction of available parameter space for sterile neutrino was excluded. Obtained exclusions don't depend on theoretical predictions for $\tilde{\nu_e}$ spectrum and absolute detector efficiency!