First measurements of the ^{239}Pu fission fraction and long term reactor power monitoring using antineutrino spectrum

Nataliya Skrobova (Kurchatov Institute, LPI RAS)
on behalf of the DANSS collaboration

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Motivation

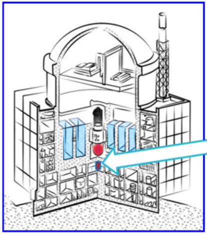
Fundamental

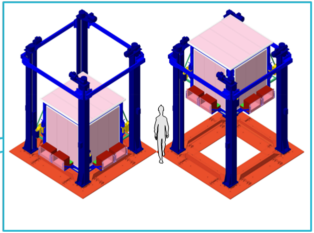
- Reactor Antineutrino Anomaly (Phys.Rev. D 83 073006): deficit in $\tilde{\nu_e}$ fluxes
- $\sigma_{235}/\sigma_{239}$ measured by DB (Phys. Rev. Lett. 120, 022503) is smaller than Huber+Mueller (Phys.Rev. C 84 024617, Phys.Rev. C 83 054615) predictions
- Resent KI measurements of cumulative β spectra(Phys. Rev. D 104, L071301) don't agree with ILL measurements and hence with HM model

Applied

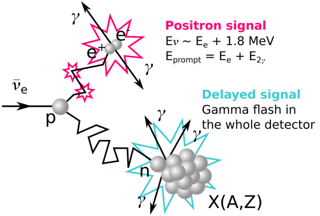
- Remote reactor power measurements with neutrinos are important for cross-checks of the conventional methods of the power measurements and could be useful for non-proliferation control
- Independent measurements of fission fractions could be useful for reactor operation. Remote ^{239}Pu fission fraction determination using antineutrinos could be useful for nuclear non-proliferation control

Introduction



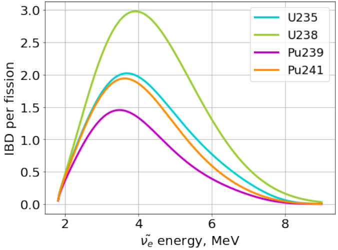


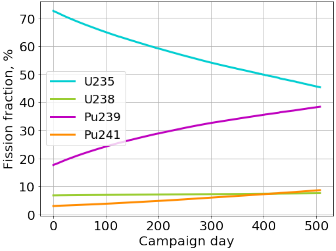
$\bar{\nu}_e$ registration: $\bar{\nu}_e + p \rightarrow e^+ + n$



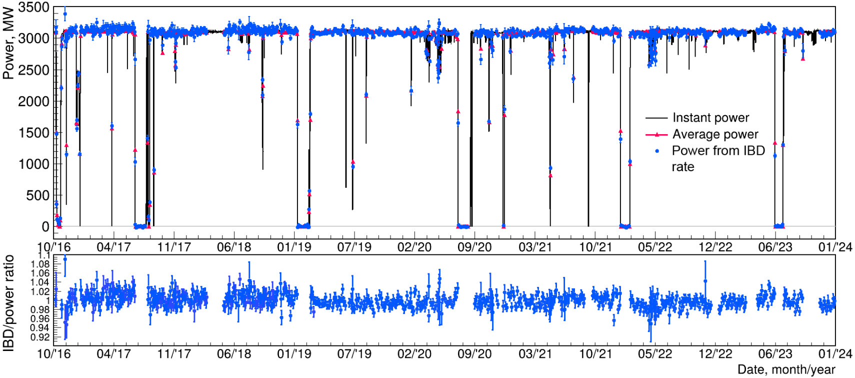
Kalinin Nuclear Power Plant:

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

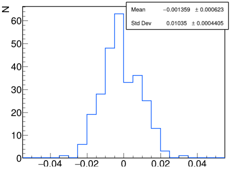




Power monitoring



- DANSS points after all corrections (all backgrounds including adjacent reactor fluxes (0.6%), fuel composition using H-M model, etc.) and normalization to the reactor power using the first month of observation in 2016 agree with reactor power measured with conventional methods
- Reactor power is measured by the DANSS with neutrino flux with 1% accuracy in a week measurement during 7 years
- Statistical error of measurement is 0.67% ⇒ additional systematic error of about 0.79% (includes uncertainties in the conventional method of the reactor power determination)



Measurements of σ_5/σ_9

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

N – IBD counts per fission,
σ_i – IBD yield,
f_i – fission fractions,
i corresponds to ^{238}U, ^{241}Pu, ^{235}U, and ^{239}Pu
α – proportionality coefficient

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

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

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

Measurements of σ_5/σ_9

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

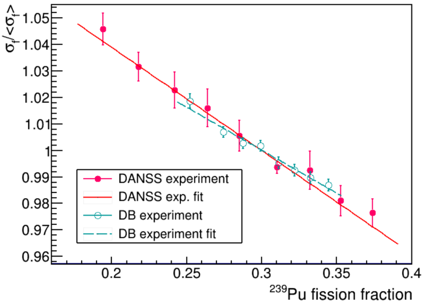
(σ_8/σ_9 and σ_1/σ_9 are taken from HM)

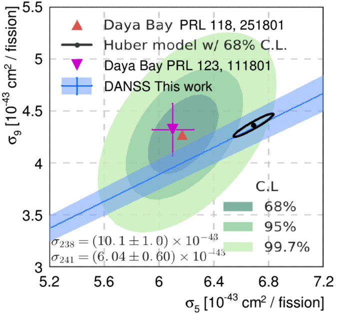
DANSS result $\sigma_5/\sigma_9 = 1.54 \pm 0.06$ is a bit larger than Day Bay (1.412 ± 0.089) and agrees with HM (1.53 ± 0.05) .

Use of DB-Slope in our formula gives: $\sigma_5/\sigma_9 = 1.459 \pm 0.052$.

$\Rightarrow$ difference between DANSS and DB is due to slope

Maybe it's premature to say that RAA is solved by new σ_5/σ_9?

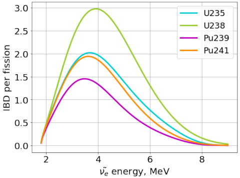


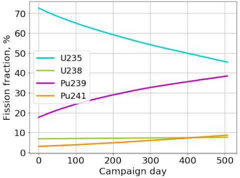


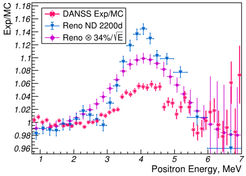
Fission fraction reconstruction

Inverse problem: reconstruct fission fractions by fitting positron spectra

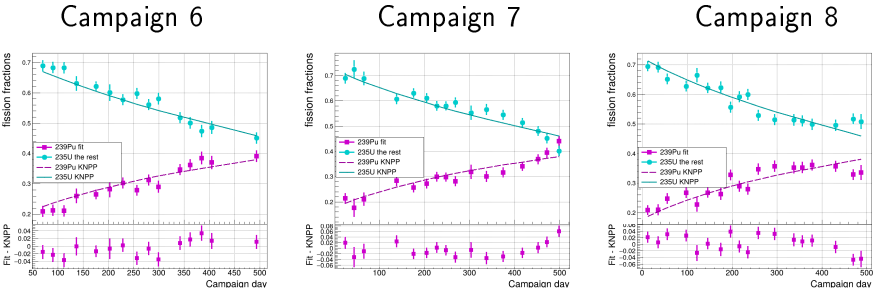
- We fit observed positron spectra using the sum of 4 isotops (HM model)
- Each measurement corresponds to $\sim$ 6-10 days of data taking
- ^{238}U and ^{241}Pu fission fractions dependences on time are parametrized for campaign 5 and then used in analysis for campaigns 6–8
- Mean normalization for the whole campaign is used
- Correction for dead time, efficiency, neighbor reactors power (individually)
- Reactor 4 power and fission points distribution profile are not taken into account
- Fit range: 1 – 3 MeV and 5.5 – 7 MeV (excluding "bump")



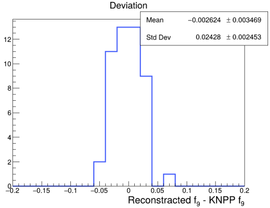




Fission fraction reconstruction: preliminary!



- Results for the top detector position
- Statistical errors only!
- Fit is consistent with the KNPP data ($\sigma = 2.4\%$, mean is consistent with 0)
- Excellent agreement between two completely different measurements provide confidence in both of them



Summary

- DANSS measures reactor power using antineutrinos with 1% error in a week measurement (including 0.8% systematic uncertainty attributed both to DANSS measurements and conventional method) during 7 years
- The relative IBD σ dependence on the ^{239}Pu fission fraction is consistent with the HM model and it is slightly steeper than the Daya Bay results.
- The estimated ratio of $\sigma_5/\sigma_9 = 1.54 \pm 0.06$ is consistent with the HM model (1.53 ± 0.05) and it is slightly larger than the KI (1.45 ± 0.03) and Daya Bay (1.412 ± 0.089) results.
- Reconstructed fission fractions using antineutrino spectrum agree within about 3% accuracy with the fission fractions provided by KNPP which are based on the neutron flux simulations inside the reactor and have completely different sources of systematic. This excellent agreement provide confidence in both methods.

Thank you!

See talk by I. Alekseev this evening about DANSS recent results and perspectives

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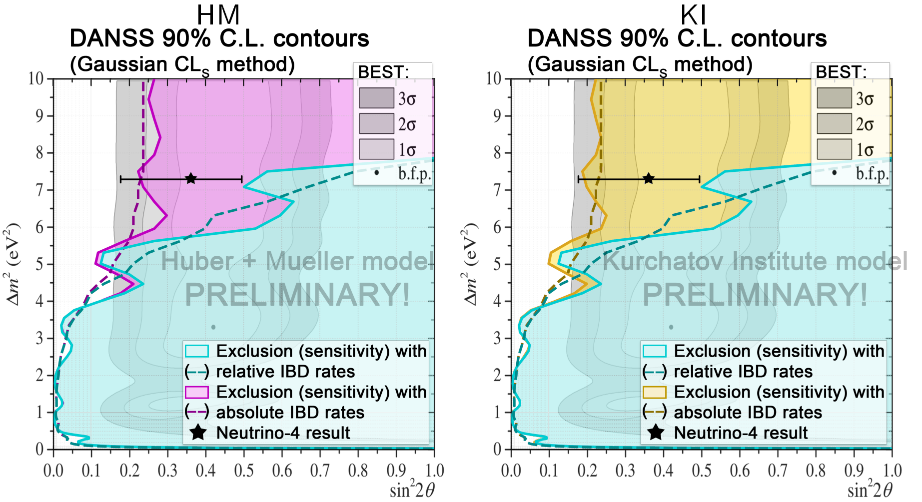
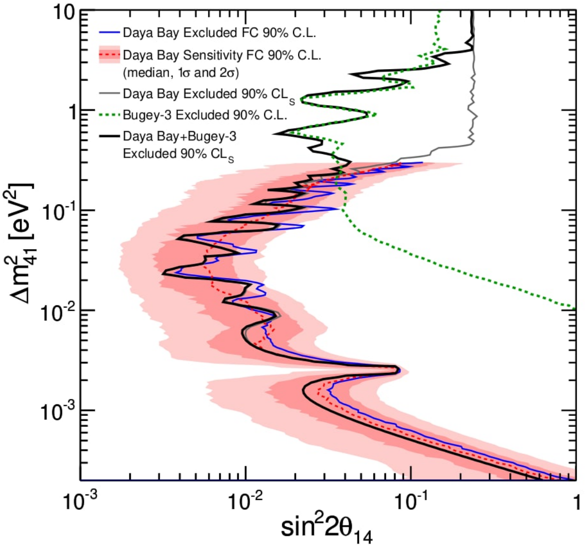
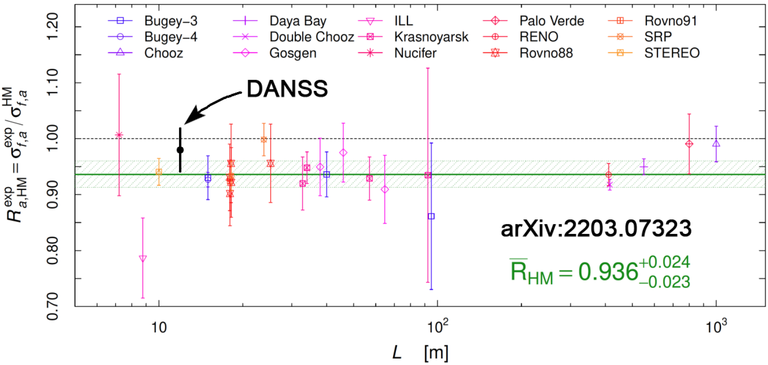
Exclusions


HM
DANSS 90% C.L. contours
(Gaussian CLs method)
BEST:
3σ
2σ
1σ
b.f.p.
Huber + Mueller model
PRELIMINARY!
Exclusion (sensitivity) with
relative IBD rates
Exclusion (sensitivity) with
absolute IBD rates
Neutrino-4 result
Δm² (eV²)
sin²2θ
KI
DANSS 90% C.L. contours
(Gaussian CLs method)
BEST:
3σ
2σ
1σ
b.f.p.
Kurchatov Institute model
PRELIMINARY!
Exclusion (sensitivity) with
relative IBD rates
Exclusion (sensitivity) with
absolute IBD rates
Neutrino-4 result
Δm² (eV²)
sin²2θ

Sterile neutrinos




Bugey–3
Bugey–4
Chooz
Daya Bay
Double Chooz
Gosgen
ILL
Krasnoyarsk
Nucifer
Palo Verde
RENO
Rovno88
Rovno91
SRP
STEREO
DANSS
arXiv:2203.07323
$\overline{R}_{HM} = 0.936^{+0.024}_{-0.023}$
$R^{exp}_{a,HM} = \sigma^{exp}_{f,a} / \sigma^{HM}_{f,a}$
L [m]
0.70
0.80
0.90
1.00
1.10
1.20
10
10^2
10^3

Cross-sections

Table 1. Cross section for the reaction $\bar{\nu}_e + p \to n + e^+$ in the $\bar{\nu}_e$ spectra of fissile isotopes, σ_f^i ($i = 5, 9, 8$, and 1 stand for, respectively, ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu), and in the reactor-antineutrino spectrum, σ_Σ, as well as the cross-section ratio σ_f^5/σ_f^9 obtained from experimental data and from the calculated and conversion spectra of $\bar{\nu}_e$ (the cross sections are given in 10^{-43} cm^2 fiss^{-1} units)

	$\sigma_\Sigma^{(1)}$	σ_f^5	σ_f^9	σ_f^8	σ_f^1	σ_f^5/σ_f^9
1. Experiment:						$1.44^{(2)}$
Daya Bay [24]	5.94 ± 0.09	6.10 ± 0.15	4.32 ± 0.25	–	–	1.412
RENO [23]	–	6.15 ± 0.19	4.18 ± 0.26	–	–	1.471
2. Calculation:						$1.44^{(2)}$
[10]	6.00	6.28	4.42	10.1	6.23	1.421
[28]	6.16	6.49	4.49	10.2	6.4	1.445
[15]$^{(3)}$	6.09	6.50	4.50	9.07	6.48	1.444
3. Conversion:						$1.52^{(2)}$
Huber–Mueller	6.22	6.69	4.40	10.1	6.10	1.520
Mueller	6.16	6.61	4.34	10.1	6.04	1.523
ILL–Vogel	5.93	6.44	4.22	9.07	5.81	1.526
4. Conversion with correction:						$1.44^{(2)}$
Huber–Mueller	6.02	6.33	4.40	10.1	6.10	1.439
Mueller	5.96	6.26	4.34	10.1	6.04	1.442
ILL–Vogel	5.73	6.09	4.22	9.07	5.81	1.443

(1) For the ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu fuel composition in the following fractions of fission events (Daya Bay): $\alpha5 = 0.564$, $\alpha9 = 0.304$, $\alpha8 = 0.076$, and $\alpha1 = 0.056$.
(2) Average value.
(3) The data on the cross section for the reaction in (1) were normalized to the free-neutron lifetime of 880.2 s.

KI spectra

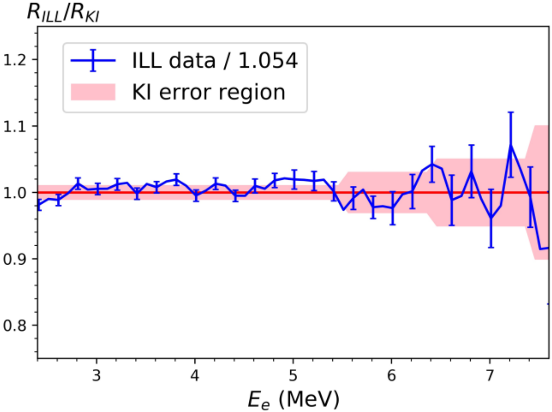
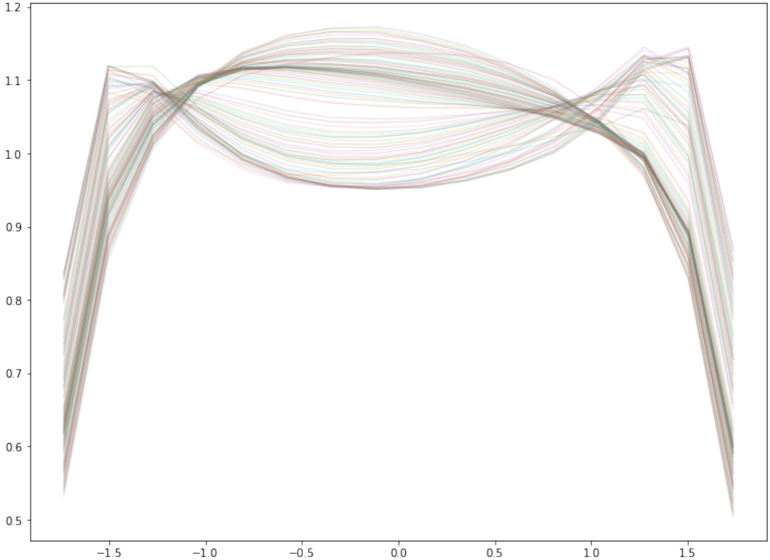


FIG. 2. Ratios R between cumulative β spectra from ^{235}U and ^{239}Pu, normalized to the KI data. Plotted ILL quantities were divided by 1.054, as explained in the text. The colored region shows KI uncertainties.

Fission points distribution



Absolute IBD counting rates

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

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

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),
$P(L, E_\nu)$ is the survival probability due to neutrino oscillations