Study of Reactor Antineutrino Spectral Characteristics and Fuel Evolution of a VVER-1000 Reactor with the iDREAM Detector

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on behalf of the iDREAM collaboration

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Motivation and objective

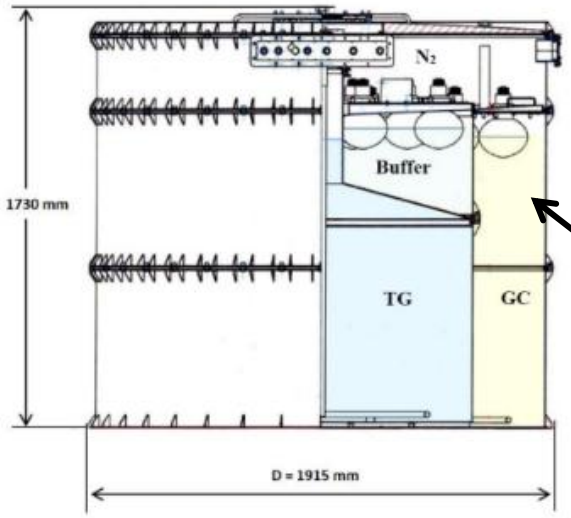
Motivation:

- **Fundamental questions**
  - Measure how the antineutrino spectrum shape changes during the reactor campaign.
  - Study the model–data spectral discrepancy in the 5 MeV region.
  - Test whether the excess depends on the $^{235}U/^{239}Pu$ fuel evolution.
- **Applied direction**
  - Previous reactor antineutrino experiments have demonstrated that reactor thermal power can be monitored using the measured antineutrino rate.
  - Next step: move from power monitoring to fuel-composition monitoring.
  - Estimate fission fractions and plutonium buildup from rate and spectral evolution.

Goal:

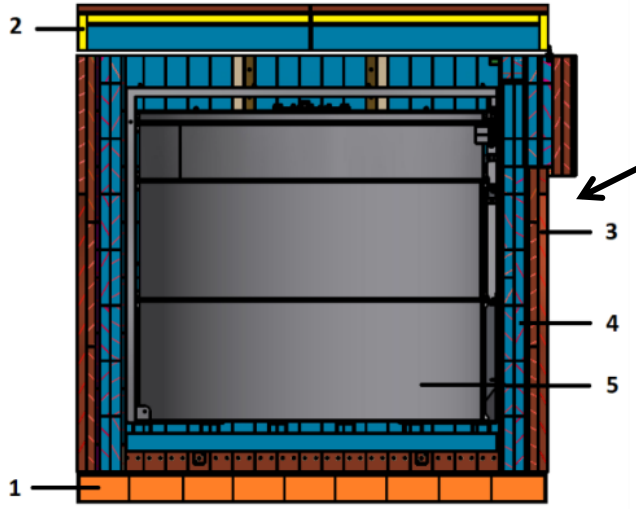
- Analyze the iDREAM prompt-energy spectrum and count-rate evolution to connect spectral-shape effects with fuel-composition changes.

iDREAM basics

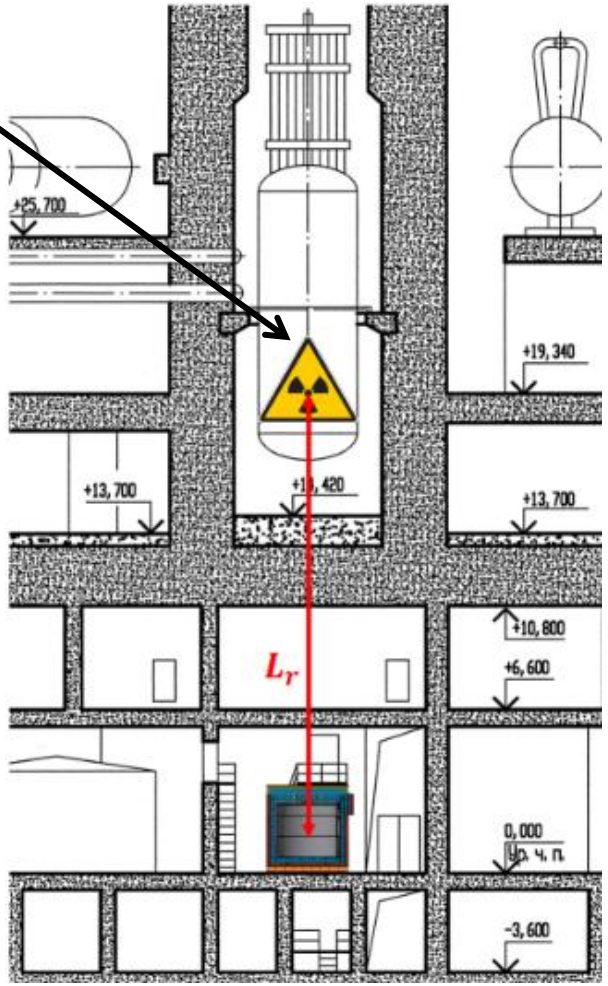


3 GWt VVER -1000
Active zone (KNPP 3-rd energy unit, Russia)
$L_r = 19.5 \pm 0.1\ m$

- Buffer – pure LAB, 0.5 m^3
- γ-catcher (GC) – LOS w/o Gd, 1.8 m^3
- Target (TG) – Gd-LOS (1 g/l) , 1.1 m^3
- 16 R5912 PMT in TG, 12 in GC
- Two μ –plates above detector



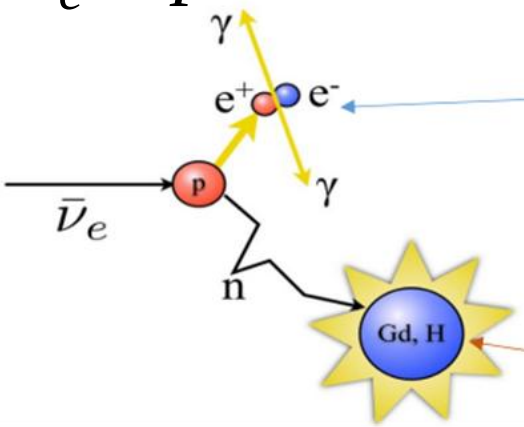
1 (orange) – cast iron (14 см)
2 (yellow) – lead (5 см)
3 (brown) – pure polyethylene (10 см)
4 (blue) – borated polyethylene (16 см)
5 – detector body



Detection & Selection

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

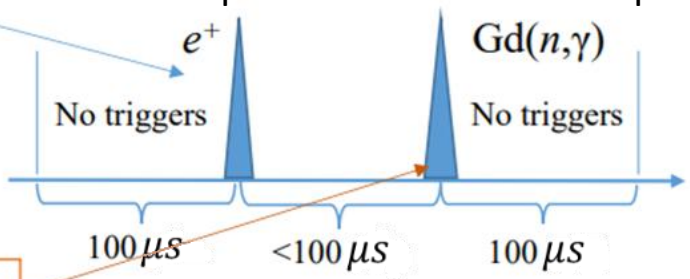
Delayed coincidence technique:



Prompt event- positron

Delayed event - neutron

Mean neutron capture time: τ= 32.9±1.3 μs



- E_{prompt} ∈ [2; 8] MeV
- $E_{delayed}$ ∈ [5;10] MeV
- ΔT < 100 μs
- Multiplicity cut: absence of any trigger within 100 μs before prompt and after the delayed event

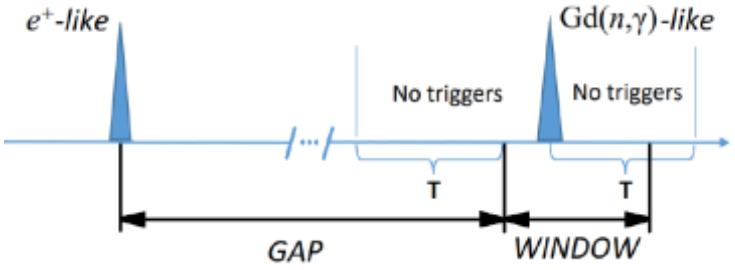
$\bar{\nu}_e + p \rightarrow e^+ + n$ – the inverse beta-decay reaction (IBD)

E_{th} = 1,8 MeV – energy threshold

$E_{prompt} = E_\nu - 0{,}78$ MeV

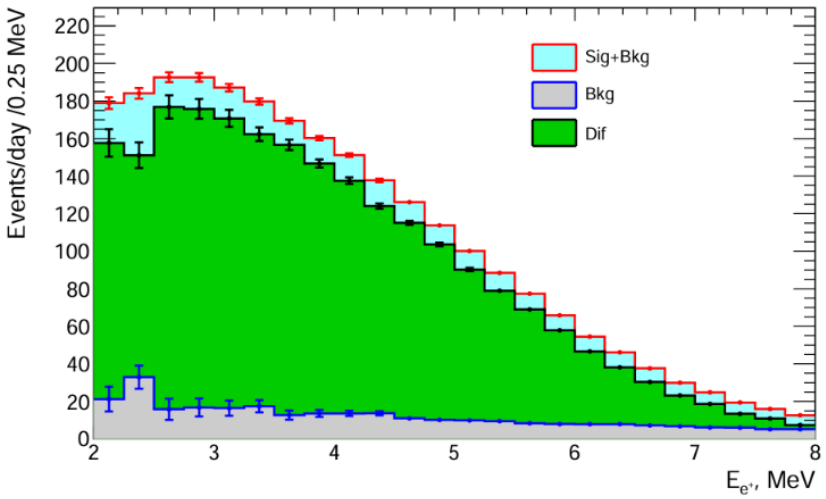
Accidentals approximation("off-time window" method)

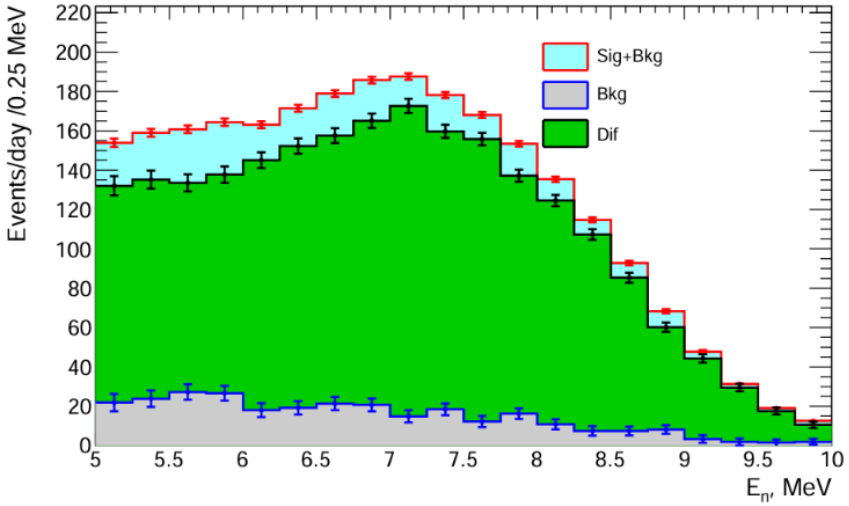
- GAP = 500 μs;
- WINDOW = 100 μs;
- 100 consecutive windows

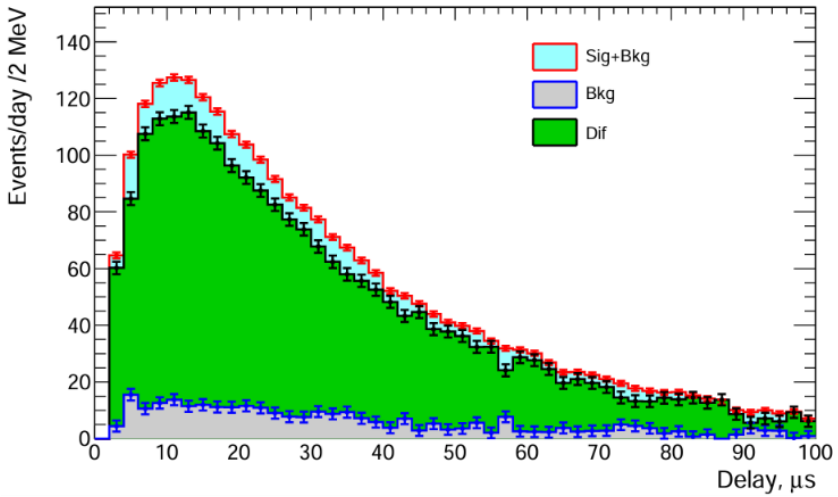


Selection performance

Signal/correlated background ≈ 10. Random coincidences are determined with an off-time window.







- A clear IBD signal remains after subtraction of accidental coincidences and the reactor-off correlated background.
- The delay distribution is consistent with neutron-capture timing.
- The selected sample is suitable for spectral and rate analyses.

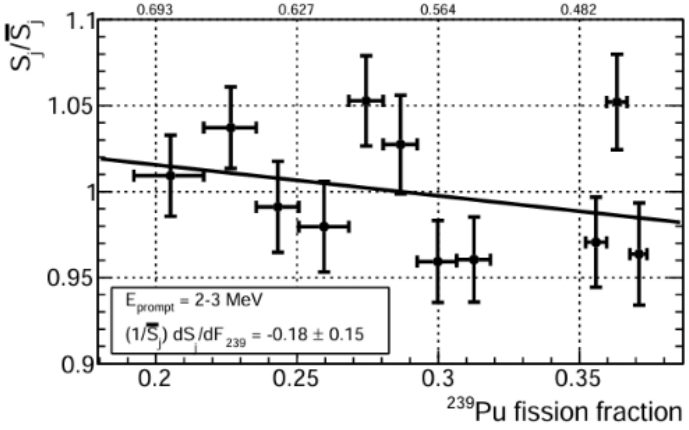
Antineutrino Spectrum Evolution

Spectral shape · Fuel dependence · 5 MeV excess

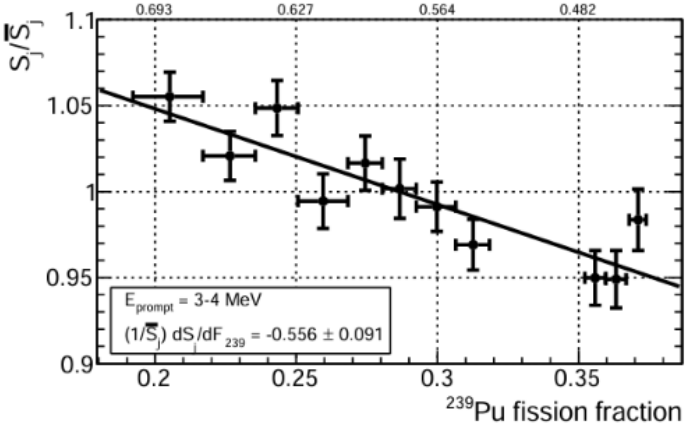
Energy dependence of the rate evolution

$$S_j = \frac{4\pi L^2}{N_p \varepsilon} \frac{N_j^{\mathrm{IBD}}}{T_j} \frac{\sum_k \alpha_{k,\mathrm{j}} E_k}{P_{\mathrm{th},j}}$$ - IBD yield per fission for time period j

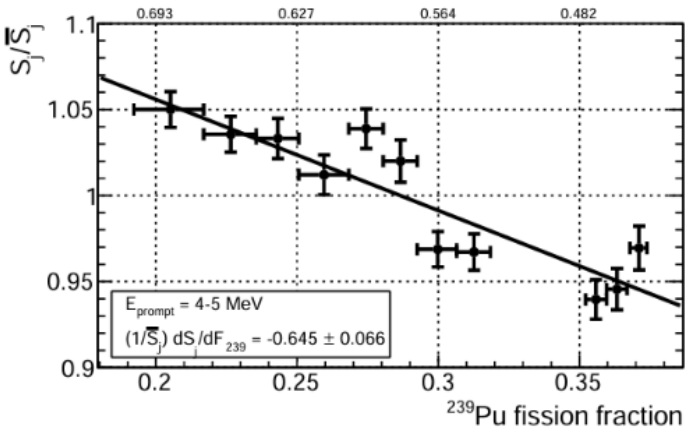
2-3 MeV



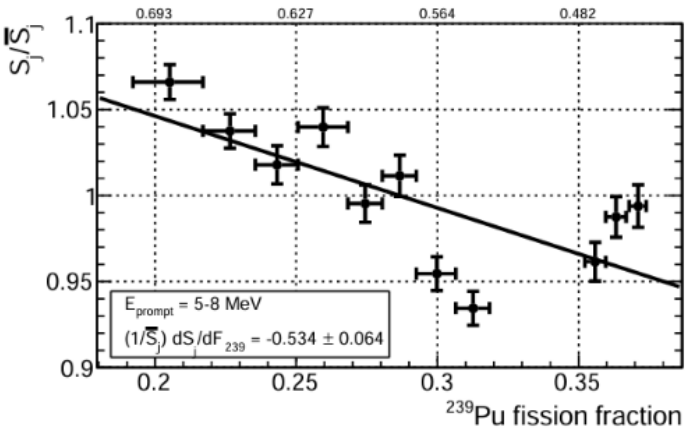
3-4 MeV



4-5 MeV



5-8 MeV

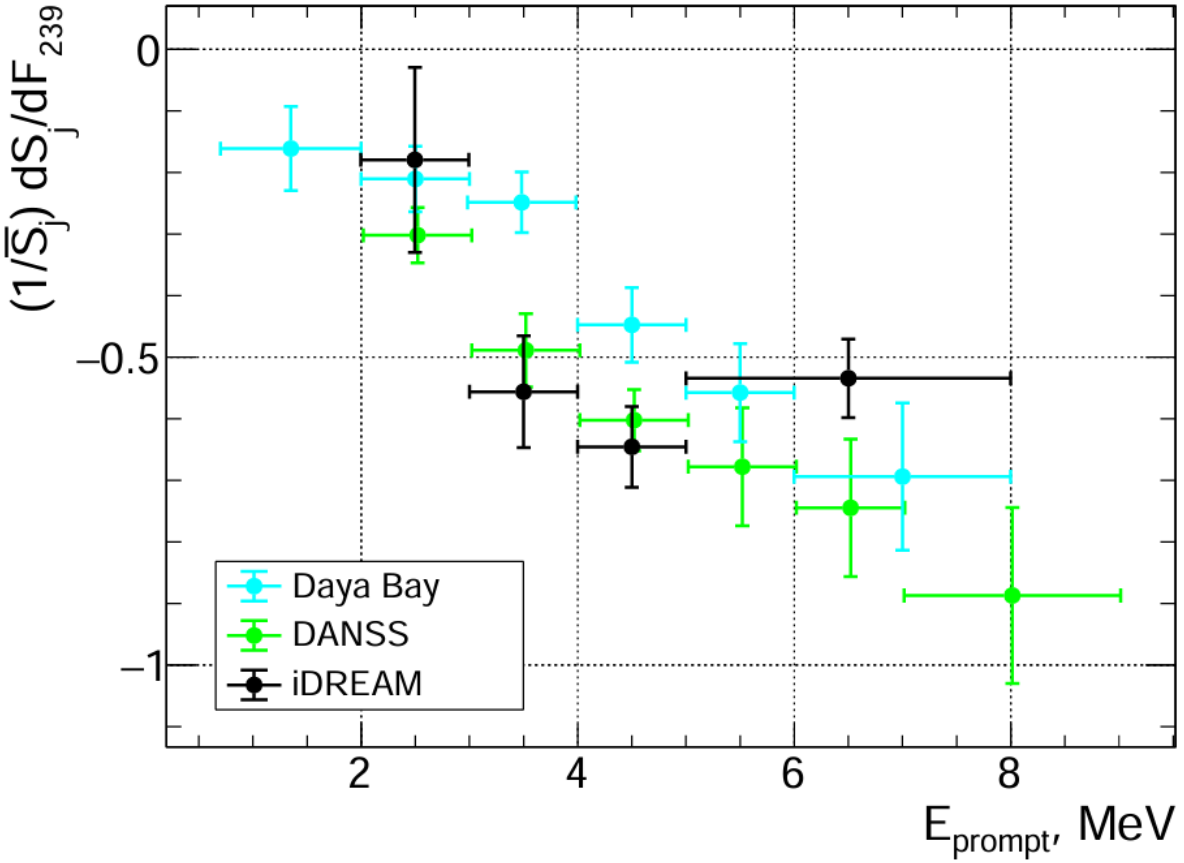


Energy intervals show different rate slopes versus the ^{239}Pu fission fraction.

The prompt-energy spectrum therefore evolves during the fuel cycle.

Energy dependence of the rate evolution

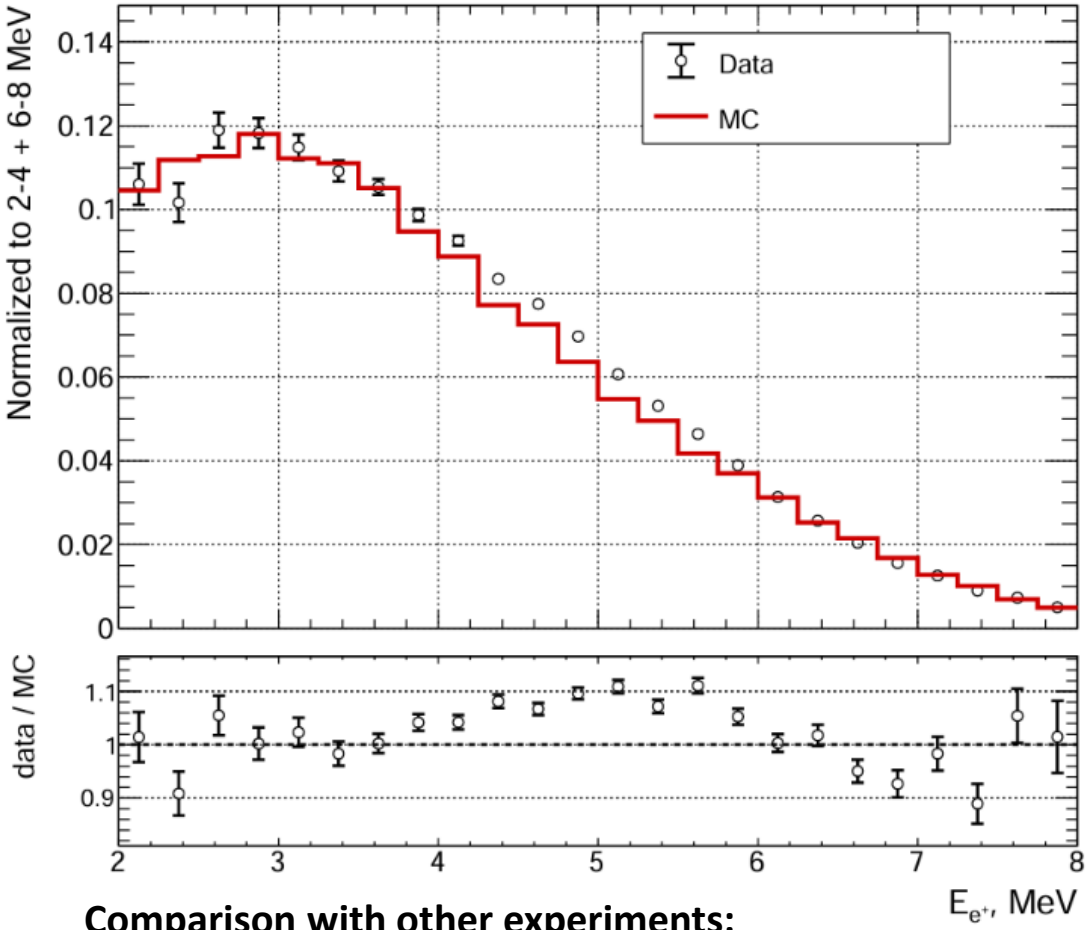
The iDREAM slopes agree with DANSS[1] and Daya Bay[2] within uncertainties; the closer match to DANSS may reflect reactor and fuel-evolution differences.



[1] *New results from the DANSS experiment*, PoS(ICHEP2022) 616 (2022)

[2] *Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay*, Phys. Rev. Lett. 118, 251801 (2017).

Spectral-shape deviation near 5 MeV



The data and MC spectra were normalized to the same number of events outside the bump region.

An excess is observed in the 4–6 MeV range, with the maximum deviation near 5 MeV.

The integrated relative excess in this region is:

$$\Delta_{4-6} = 100\left[\frac{N_{4-6}^{Data} / N_{side}^{Data}}{N_{4-6}^{MC} / N_{side}^{MC}} - 1\right]\% = 7.6 \pm 1.2\%$$

Comparison with other experiments:

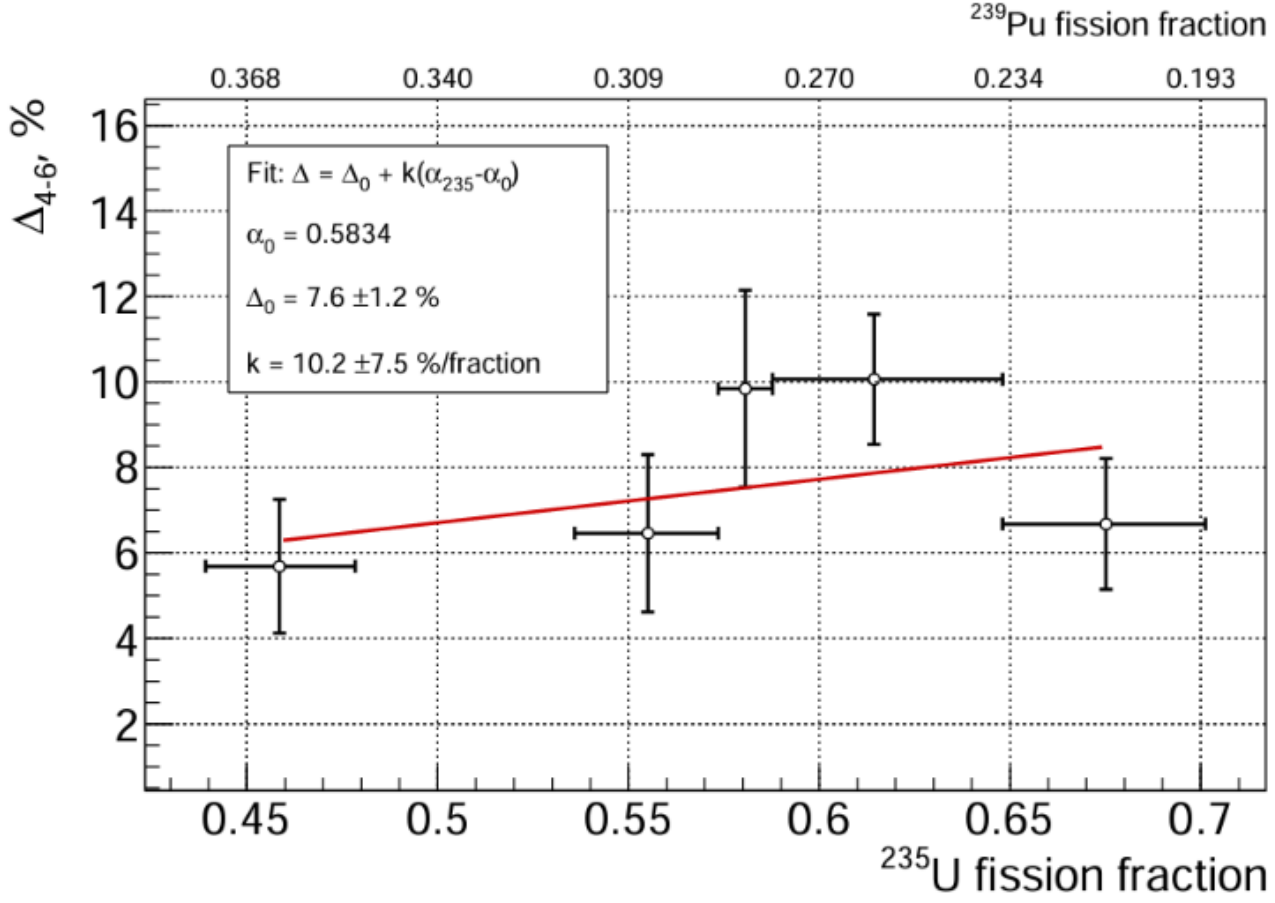
Daya Bay: ~10% excess (4–6 MeV) Daya Bay, *PRL 116, 061801* (2016).

Double Chooz: (9 ± 2)% excess (4.25–6 MeV) Novella P., Adv. High Energy Phys. 2015, 364392 (2015).

A direct quantitative comparison requires accounting for differences in normalization, energy ranges, and detector response.

Time evolution of the 5 MeV bump

The 5 MeV excess is observed throughout the fuel cycle but no statistically significant dependence on the ^{235}U fission fraction is found at current precision.

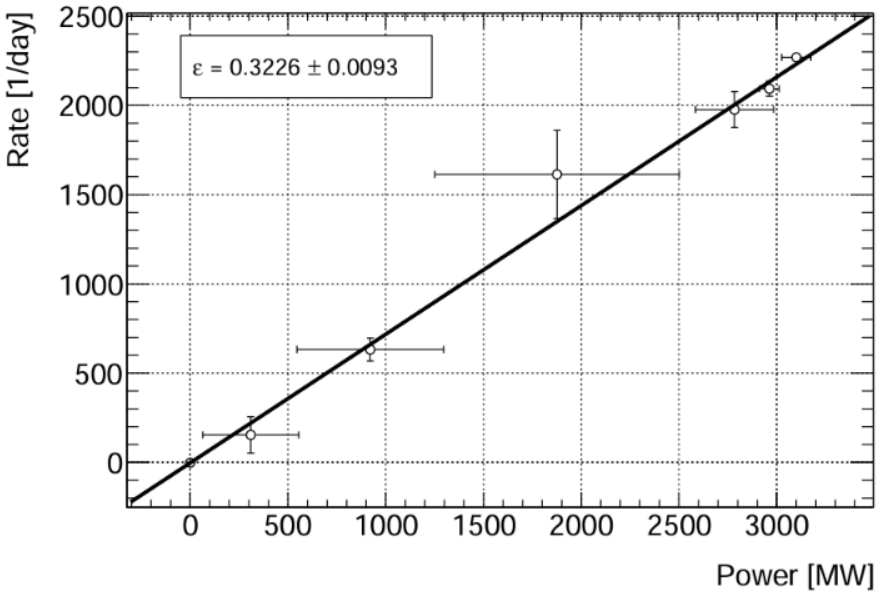


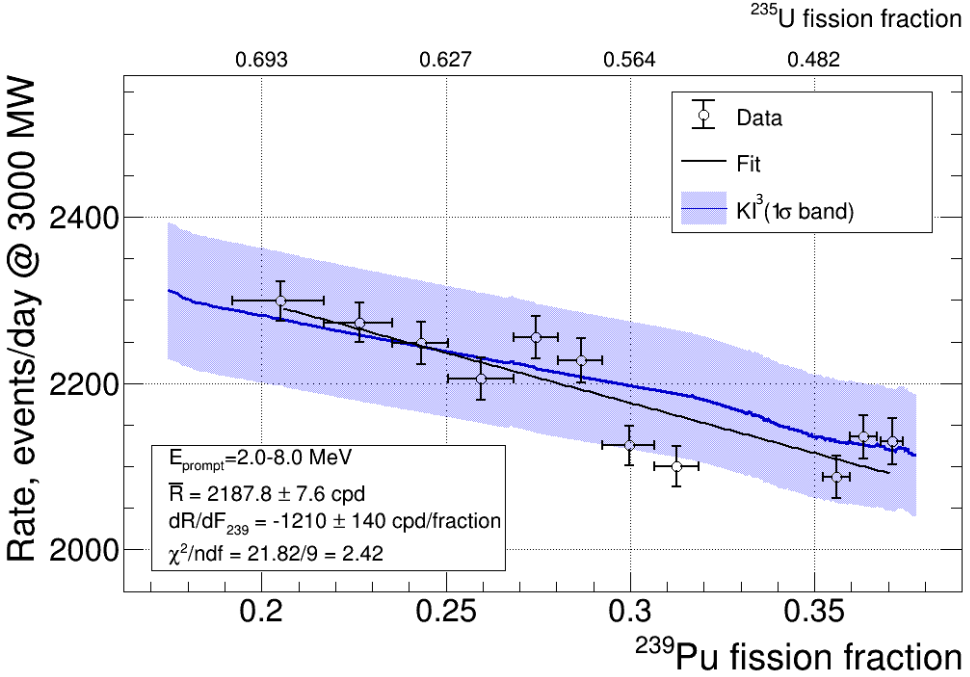
Toward advanced reactor monitoring

Rate evolution · fission fractions · plutonium buildup

Detection Efficiency

$$R_{\mathrm{IBD}} = \frac{N_p \varepsilon P_{\mathrm{th}} \sum_k \alpha_k \sigma_k^{\mathrm{IBD}}}{4\pi L^2 \sum_k \alpha_k E_k} \rightarrow \varepsilon = \frac{4\pi L^2 \sum_k \alpha_k E_k}{N_p \sum_k \alpha_k \sigma_k^{\mathrm{IBD}}} \frac{R_{\mathrm{IBD}}}{P_{\mathrm{th}}}$$





Detection efficiency: MC 32.6%; from the rate–power fit, (32.2 ± 0.9)%.

The results agree within uncertainties; rate evolution is used to reconstruct fuel composition.

[3] V. Kopeikin, M. Skorokhvatov, O. Titov, Phys. Rev. D 104, L071301 (2021)

Fission fraction estimation

$$R = \frac{N_p \varepsilon}{4\pi L^2} \frac{P_{th} \sum_k \alpha_k \sigma_k}{\sum_k \alpha_k E_k}$$

$$\alpha_{235}^{\mathrm{IBD}} = 1 - \alpha_{238} - \alpha_{241} - \alpha_{239}^{\mathrm{IBD}}$$

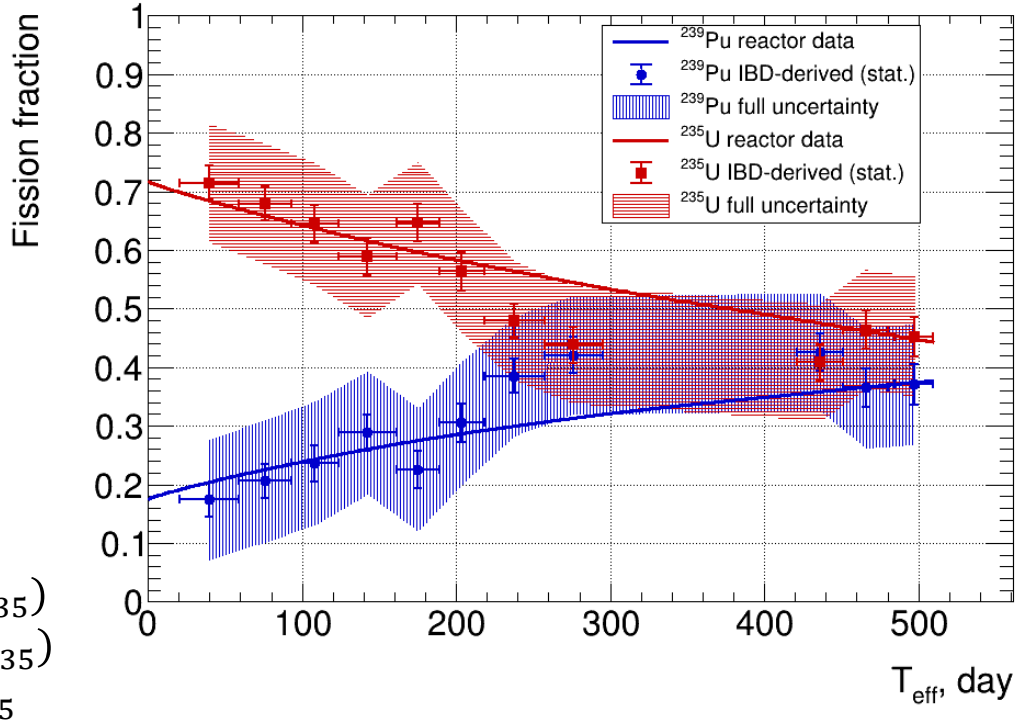
$$\boxed{\alpha_{239}^{\mathrm{IBD}} = \frac{KA - RB}{R\Delta E_{9-5} - K\Delta\sigma_{9-5}}}$$

$$K = \frac{N_p \varepsilon}{4\pi L^2} P_{\mathrm{th}}$$

$$A = \sigma_{235} + \alpha_{238}(\sigma_{238} - \sigma_{235}) + \alpha_{241}(\sigma_{241} - \sigma_{235})$$

$$B = E_{235} + \alpha_{238}(E_{238} - E_{235}) + \alpha_{241}(E_{241} - E_{235})$$

$$\Delta\sigma_{9-5} = \sigma_{239} - \sigma_{235}, \qquad \Delta E_{9-5} = E_{239} - E_{235}$$

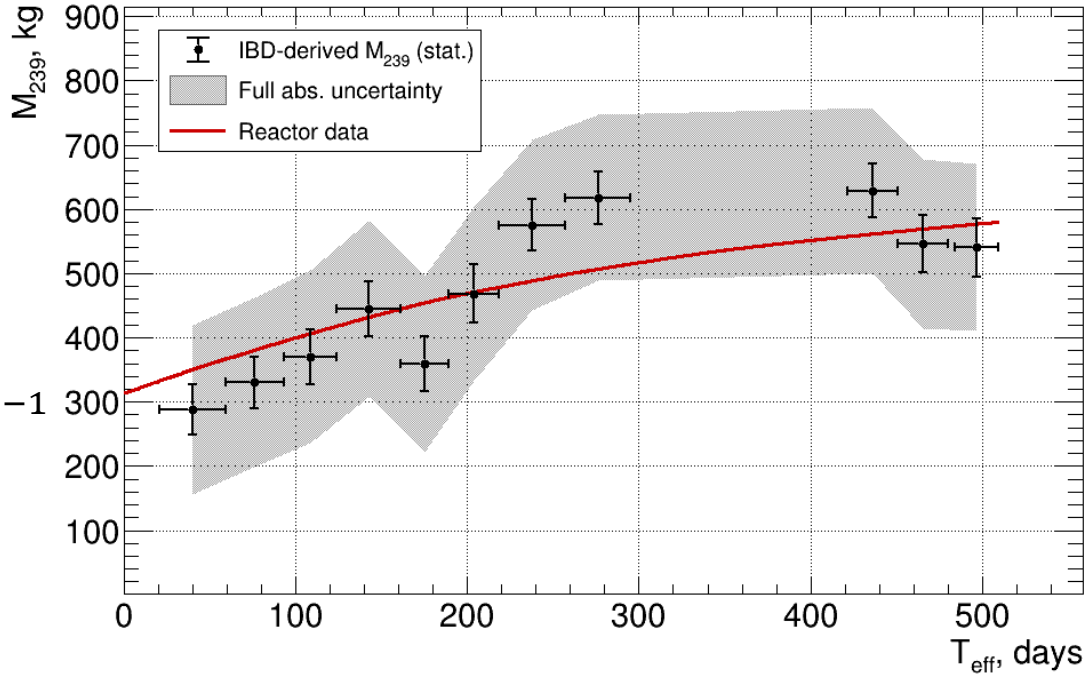


With independently known ^{238}U and ^{241}Pu fission fractions, the measured IBD rate yields the ^{239}Pu fraction.
The reconstructed ^{235}U/ ^{239}Pu evolution agrees with reactor data within uncertainties.

Evolution of the ^{239}Pu inventory

$$M_{239,i} = \frac{m_{239}}{N_A} \frac{\alpha_{239,i}^{\mathrm{IBD}} P_i}{\overline{E}_{f,i} \langle \Phi \sigma_{f,239} \rangle}$$

$$\langle \Phi \sigma_{f,239} \rangle \approx 750\ barns \cdot 3.6{\cdot}10^{13} cm^{-2} s^{-1} \approx 2.7{\cdot}10^{-8} s^{-1}$$



The reconstructed ^{239}Pu fraction is used to estimate plutonium buildup,[4] with an effective fission rate based on typical VVER-1000 parameters.
The buildup agrees with reactor calculations within uncertainties and with published PWR/VVER estimates.[5,6]

[4] E. Christensen, P. Huber, P. Jaffke, Sci. Glob. Secur. 23, 20–47 (2015).
[5] Suk et al., *Nucl. Eng. Des.* **377** (2021), 111133.
[6] Faghihi et al., *Math. Probl. Eng.* (2009), 249162.

Conclusions

- The iDREAM data were analyzed over the reactor campaign in two directions: spectral-shape studies and advanced monitoring.
- The prompt-energy spectrum shows a 5 MeV excess: Δ_{4-6}= 7.6±1.2%.
- No statistically significant dependence of the excess on the ^{235}U fission fraction is observed within current precision.
- The energy dependence of the rate evolution indicates a change of the spectrum shape over the campaign and is consistent with other reactor experiments.
- The measured rate evolution was used to estimate $^{235}U/^{239}Pu$ fission fractions and ^{239}Pu buildup.