Recent Results of the Daya Bay Experiment

On Behalf of the Daya Bay Experiment Collaboration

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IPNP, Charles University in Prague

Protvino, 26.6.2014

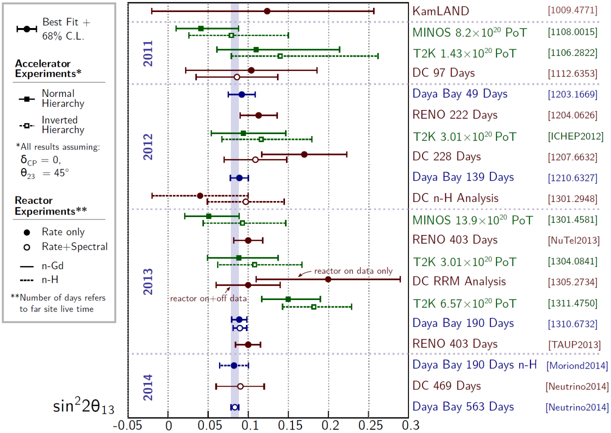
Outline

- Daya Bay Experiment
- Update on $\sin^2\theta_{13}$ and Δm^2_{ee} measurement using neutron capture on gadolinium
- Independent measurement of $\sin^2\theta_{13}$ using neutron capture on hydrogen
- Search for light sterile neutrino mixing
- Absolute $\bar{\nu}_e$ reactor flux

Most precise measurement of θ_{13}

Key points of Daya Bay success

- Fruitful collaboration
- Large statistics due to large reactor power in total 17.6 GW_{th} and total target volume of 160 t
- Low background experiment - overburden
- Suppressing the uncertainty by relative Near/Far measurement (proposed by L. Mikaelyan)
- The detector related uncertainties well under control by using functionally identical detectors. The advantage is comparison of at least two ADs in one experimental hall



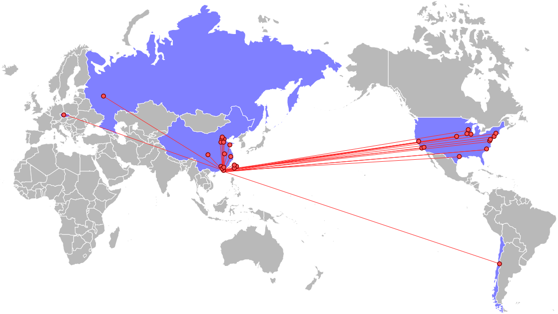
The Daya Bay Collaboration

Asia (21)

Beijing Normal Univ., CGNPG, CIAE, Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United

North America (17)

Brookhaven Natl Lab, CalTech, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Rensselaer Polytechnic, Siena College, UC Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale



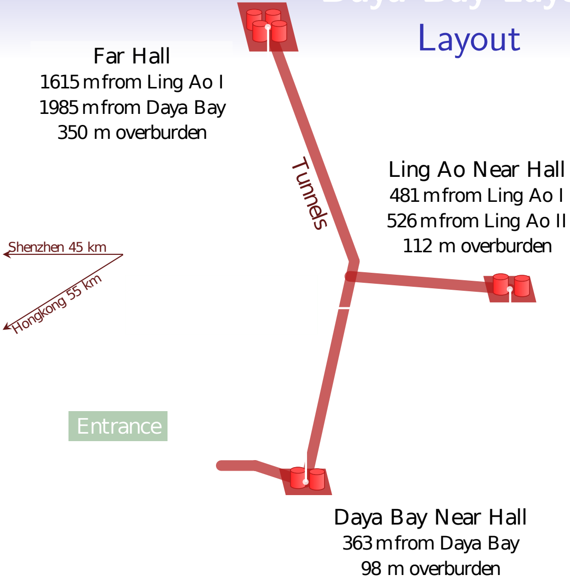
Europe (2)

Charles University, JINR Dubna

South America(1)

Catholic University of Chile

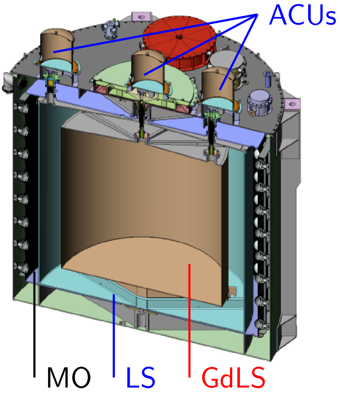
Layout

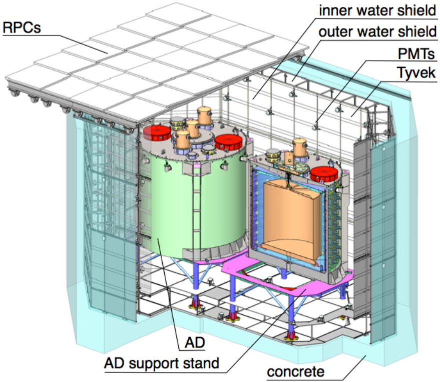

Far Hall
1615 m from Ling Ao I
1985 m from Daya Bay
350 m overburden
Tunnels
Ling Ao Near Hall
481 m from Ling Ao I
526 m from Ling Ao II
112 m overburden
Shenzhen 45 km
Hongkong 55 km
Entrance
Daya Bay Near Hall
363 m from Daya Bay
98 m overburden

Anti-neutrino detector and muon veto system

Anti-neutrino detector

- 3 zones: mineral oil, liquid scintillator, gadolinium doped LS separated by transparent acrylic vessels
- 192 8” PMTs
- 3 ACUs with radioactive sources for weekly energy calibration

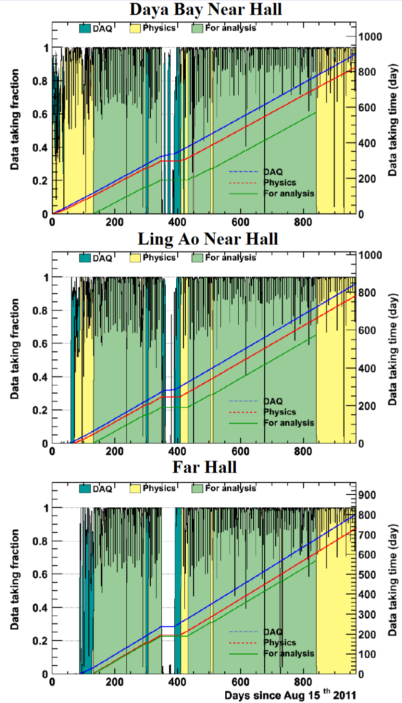




Muon Tagging System

- ADs submerged in the water pool: passive shielding and active muon detector
- Two independent water Čerenkov detectors - IWS, OWS
- Resistive plate chambers array

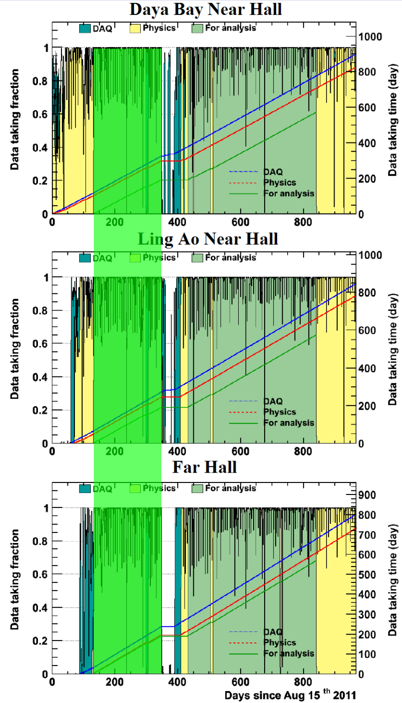
Data periods



Data periods

6 AD Period

- Dec 24, 2011-Jul 28, 2012
- Our previous result PRL 112, (2014), 061801
- Independent measurement of $\sin^2 2\theta_{13}$ using neutron capture on hydrogen
- Absolute $\bar{\nu}_e$ reactor flux
- Light sterile neutrino search



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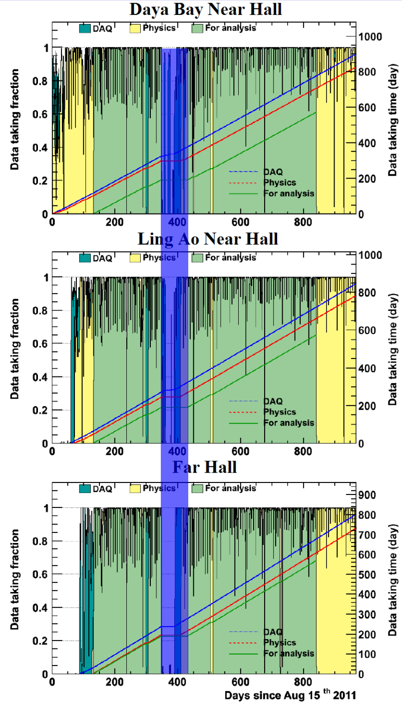
Summer 2012 Intermezzo

- Jul 29, 2012-Oct 18, 2012
- Special calibration campaign
- Installation of last two ADs



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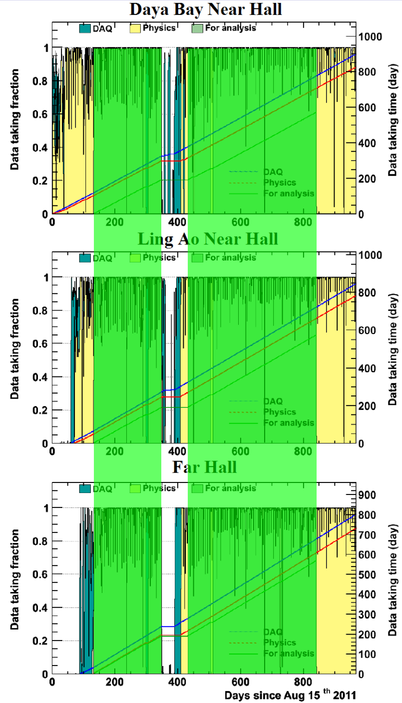
6+8 AD Periods

- Additional period Oct 19, 2012-Nov 27, 2013 with 8 ADs
- In total over 1 million $\bar{\nu}_e$ detected using neutron capture on gadolinium
- New oscillation analysis results on $\sin^2 2\theta_{13}$ and Δm^2_{ee}



Inverse beta decay candidate selection

IBD selection

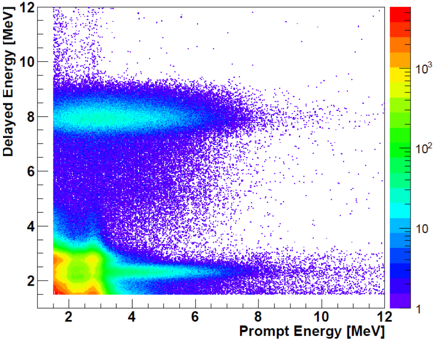
- Remove flashing PMT events
- Prompt Energy Cut: 0.7 MeV $< E_p <$ 12 MeV
- Delayed Energy Cut: 6 MeV $< E_p <$ 12 MeV
- Coincidence Time Cut: 1 μs $< \Delta t <$ 200 μs
- Multiplicity Cut: prompt and delayed signals isolated
- Muon Veto:
  -Water pool muon ($N_{Pmt} > 12$): 0.6 ms
  -AD muon (E $>$ 20 MeV): 1 ms
  -AD shower muon (E $>$ 2.5 GeV): 1 s

Detection method

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

$$30\ \mu s \rightsquigarrow n + Gd \rightarrow Gd^* \rightarrow Gd + \gamma s\ (8\ \text{MeV})$$

$$200\ \mu s \rightsquigarrow n + H \rightarrow D + \gamma\ (2.22\ \text{MeV})$$



Detector related uncertainties

	Efficiency	Relative efficiency uncertainty Correlated	Relative efficiency uncertainty Uncorrelated
Target mass	-	0.47%	0.03%
Flasher Cut	99.98%	0.01%	0.01%
Prompt Energy Cut	99.81%	0.1%	0.01%
Delayed Energy Cut	92.70%	0.97%	0.12%
Time Cut	98.70%	0.12%	0.01%
Gd Capture Ratio	84.2%	0.95%	0.1%
Spill-in	104.9%	1.5%	0.02%
In total	80.6%	2.1%	0.2%

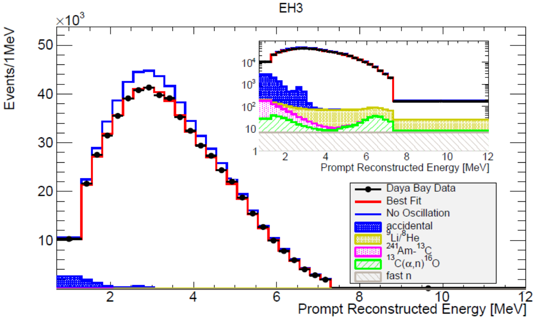
Relevant for absolute flux measurement

Relevant for relative rate and shape measurement

Backgrounds

Uncorrelated background

Accidentals - Largest contribution (2.3% in the Far Hall) but negligible uncertainty



Correlated background

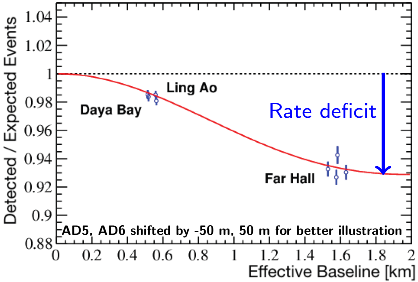
Background	Prompt	Delayed	Far Hall	Uncertainty
		Cosmogenic		
$^9Li/^8He$	β^-	nGd	0.4%	50%
Fast neutrons	inelastic scattering on H	nGd	0.1%	30%
		Radioactivity		
AmC source	inelastic scattering on Fe	nFe	0.2%	50%
$^{13}C(\alpha, n)^{16}O$	inelastic scattering,deexcitation	nGd	0.1%	50%

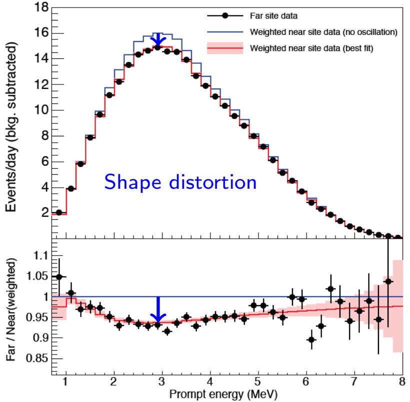
6AD+8AD rate plus shape analysis

Oscillation probability formula

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E} - \sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{ee}L}{4E}$$

$$\sin^2\frac{\Delta m^2_{ee}L}{4E} \equiv \cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}$$





Oscillation pattern

We observe rate deficit and spectral distortion in the Far Hall consistent with three-flavor neutrino oscillations

Oscillation results from 6AD+8AD periods

Best fit

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\ \text{eV}^2$$

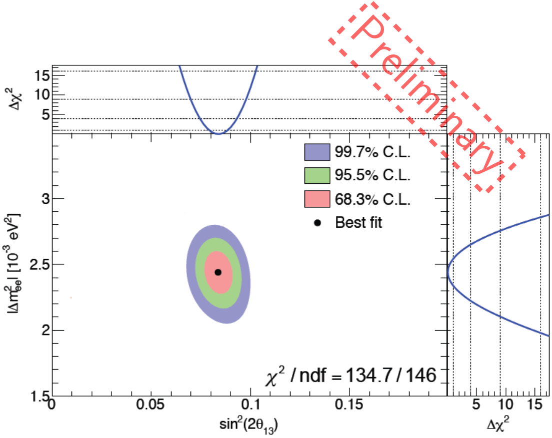
$$\chi^2/NDF = 134.7/146$$

$\sin^2 2\theta_{13}$ measurement

- Most precise measurement up to date
- Precision 6%→3% by the end of 2017

$|\Delta m^2_{ee}|$ measurement

- Comparable precision with long-baseline accelerator experiments
- Consistent result



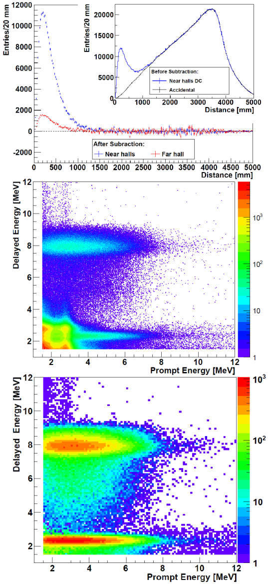
nH capture analysis for 6AD period

Key things about nH capture measurement

- Higher statistic: 16% of captures in GdLS, 96% in LS (20 t of additional target volume compared to nGd)
- However, more accidental background due to lower delayed energy and longer capture time
- Independent measurement of θ_{13} with largely different systematics from nGd

Specifics of nH capture data selection

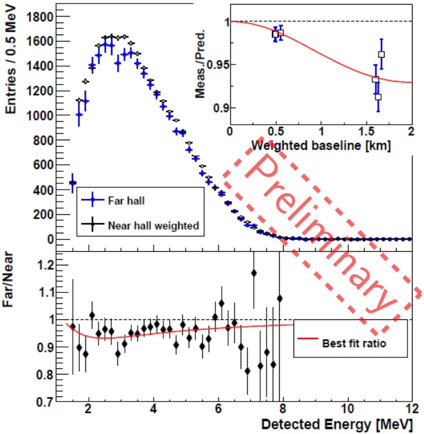
- Raising Prompt Energy Cut: $1.5(0.7nGd)$ MeV $< E_p <$ 12 MeV
- Delayed Energy Cut: $\pm 3\sigma$ around nH capture peak
- Longer Coincidence Time: $1\ \mu s < \Delta t < 400(200nGd)\ \mu s$
- Introduction of Distance Cut between prompt and delayed: $\Delta R < 0.5$ m



nH Rate Analysis Results

Results of 6AD period

- Significant rate deficit observed at the far hall
- Oscillation result: $\sin^2 2\theta_{13} = 0.083 \pm 0.018$, $\chi^2/NDF = 4.5/4$
- $\theta_{13} = 0$ excluded with significance of 4.6σ
- Result consistent with nGd capture analysis



Spectral analysis in progress

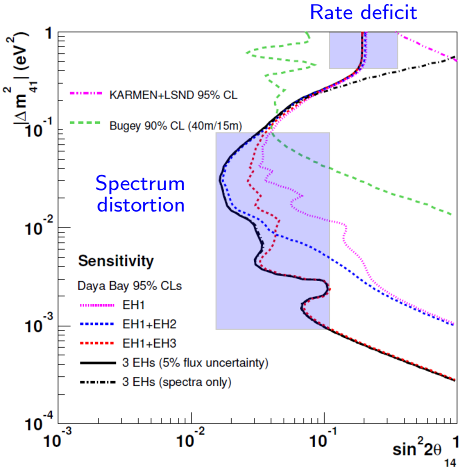
Light sterile neutrino search

3+1 oscillation probability

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{ee}L}{4E} - \sin^2 2\theta_{14}\sin^2\frac{\Delta m^2_{41}L}{4E}$$

Sterile neutrino search in Daya Bay

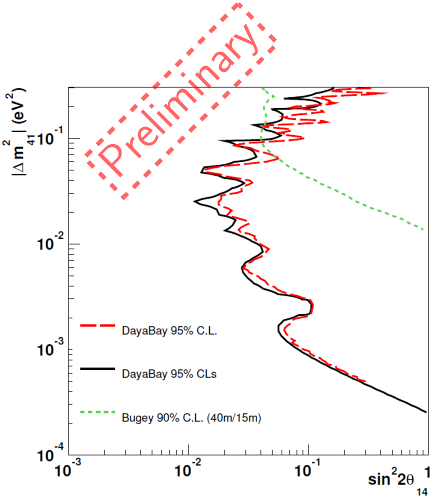
- Daya Bay design provides measurement on various baselines
- Sterile neutrino presence would appear as an additional spectral distortion and rate difference
- For $\Delta m^2_{41} > 0.5$ eV^2 the oscillation pattern is smeared and the prediction is only the absolute rate deficit
- For $\Delta m^2_{41} < 0.1$ eV^2 the shape distortion is highly sensitive to presence of additional light sterile neutrino



Sterile neutrino search results

Results for 6AD period

- Two methods of exclusion contour calculation were used giving consistent results
- Set most stringent limit in region $10^{-3}\ \text{eV}^2 < \Delta m^2_{41} < 10^{-1}\ \text{eV}^2$
- The data are consistent with three-flavor neutrino oscillation
- No evidence for sterile neutrino observed



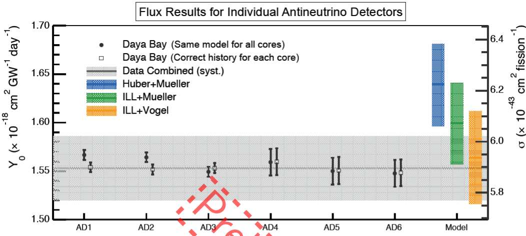
Absolute $\bar{\nu}_e$ Reactor Flux Measurement

Comparison with models

- Result of 6AD data
- Results consistent within ADs
- Discrepancy between current models

Flux uncertainties

Detector related	2.1%
Reactor related	0.8%
θ_{13}	0.2%
Statistics	0.2%
Total	**2.3%**

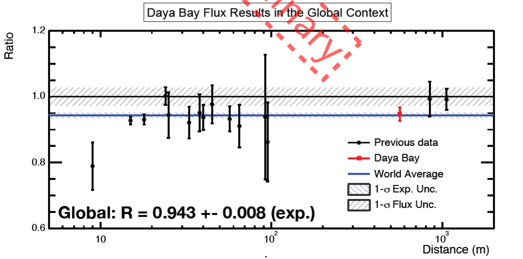


Comparison with worldwide measurements

- Results from previous experiments corrected by oscillation hypothesis
- Based on near detectors
- Daya Bay result consistent with world average
- Daya Bay result supports the existence of 'reactor anomaly'

Results

Y_0 (cm^{2}GW^{-1}day^{-1})	1.553×10^{-18}
σ_f (cm^{2}fission^{-1})	5.934×10^{-43}
^{235}U:^{238}U:^{239}Pu:^{241}Pu	0.586:0.076:0.288:0.050
Data/Prediction (Huber+Mueller)	0.947 ± 0.022



Summary

- Based on 563 days of data the Daya Bay Experiment measured

$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\ \mathrm{eV}^2$$

- Precise measurement together with large value of θ_{13} allows future experiments to investigate the CP-violation in a lepton sector and the neutrino mass hierarchy
- Independent measurement of θ_{13} using neutron capture on hydrogen results in

$$\sin^2 2\theta_{13} = 0.083 \pm 0.018$$

- In the region $10^{-3}\ \mathrm{eV}^2 < \Delta m^2_{41} < 10^{-1}\ \mathrm{eV}^2$ we set the most stringent limit in the search for sterile neutrinos
- Our measurement of absolute reactor anti-neutrino flux is consistent with previous experiments and match to the so called 'reactor anomaly'