Status of the STEREO reactor neutrino experiment

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on behalf of the STEREO collaboration

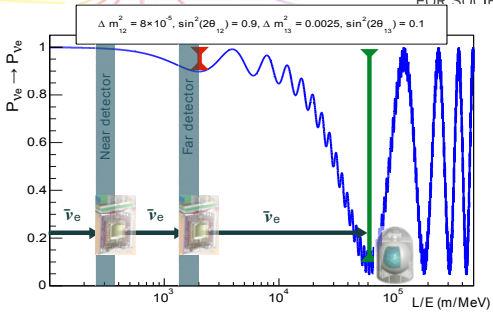
Rencontres du Vietnam - Neutrinos

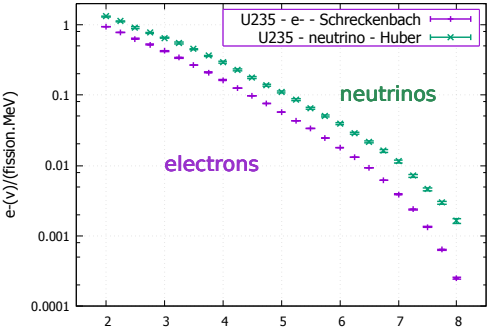
Quy Nhon 21/07/2017

Antineutrinos from nuclear Reactors

- β-decays of neutron rich fission products $\Rightarrow$ pure $\bar{\nu}_e$ flux
- $\sim 10^{17} \bar{\nu}_e / \mathrm{MW_{therm}} / \mathrm{s}$

- long baseline ($\mathcal{O}(100\,\mathrm{km})$): KamLAND: Δm^2_{12}
- short baseline ($\mathcal{O}(100\,\mathrm{m})$-$\mathcal{O}(1\,\mathrm{km})$): Daya Bay, Double Chooz, RENO: Δm^2_{13}
- very short baseline: sterile neutrinos?





- most precise spectra predictions to date: conversion of cumulative fission product β-spectra
- all predictions rely on same data!

$$\underbrace{^{235}\mathrm{U}, ^{239}\mathrm{Pu}, ^{241}\mathrm{Pu},}_{\substack{\beta\text{'s measured by} \\ \text{Schreckenbach } et\ al. \\ \text{at ILL in 1980's}}} \quad \underbrace{^{238}\mathrm{U}}_{\substack{\beta \text{ spectra} \\ \text{by Haag } et\ al. \\ \text{at FRM II, 2014}}} \quad > \quad 99\% \text{ of } \bar{\nu}$$

- or Daya Bay spectrum (PRL116, 061801)

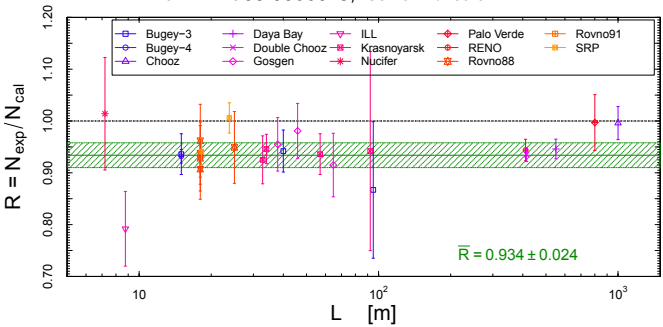
Reactor Antineutrino Anomaly - RAA

RAA:

- reevaluation of expected $\bar{\nu}_e$ spectrum in 2011: (Phys Rev C83, 054615; Phys Rev C84, 024617)

→ 6% deficit in experimental rates w.r.t. new predictions (2.8 σ)

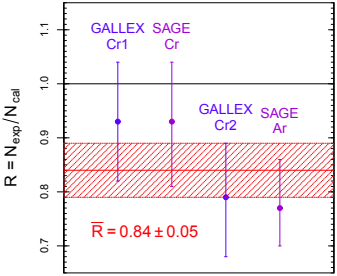
arXiv:1703.00860v3, Gariazzo *et al.*



Supported by **Ga-Anomaly**:

- ν_e deficit (2.9 σ) in calibrations of SAGE and GALLEX with intense isotopic sources
- $\langle L \rangle_{\text{GALLEX}} = 1.9\,\text{m}$, $\langle L \rangle_{\text{SAGE}} = 0.6\,\text{m}$

arXiv:1507.08204v2, Gariazzo *et al.*



Other anomalies

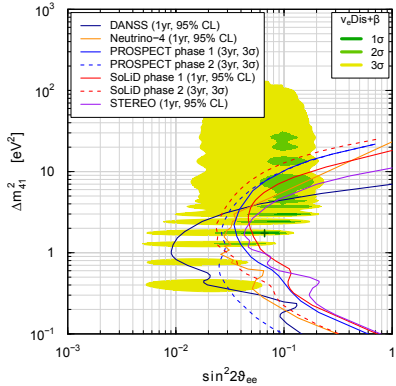
- LSND, MiniBooNe

Investigating the RAA

New Oscillation?

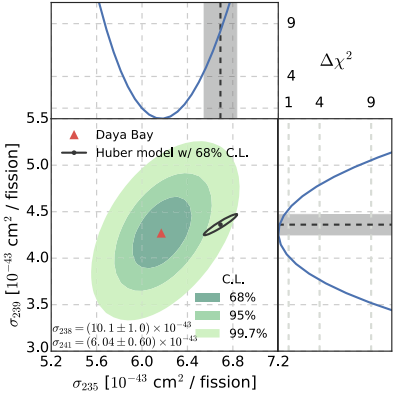
- $P_{ee} \simeq 1 - \sin^2(\theta_{14}) \sin^2\left(1.27 \cdot \frac{\Delta m^2_{14}[eV] L[m]}{E_{\bar{\nu}}[MeV]}\right)$
- STEREO (and others) will explore the RAA at very short baselines ($\sim 10\,\mathrm{m}$)

arXiv:1703.00860v3, Gariazzo *et al.*



Wrong predictions of reactor spectra?

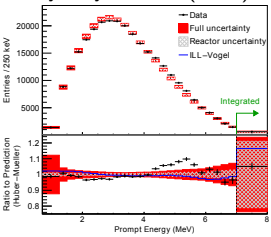
Phys.Rev.Lett. 118, 251801, DayaBay Collab.



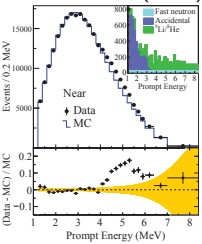
5 MeV Excess

- excess of $\sim 10\%$ at $E_{\bar{\nu}} = 5\,\text{MeV}$ in experimental neutrino rates

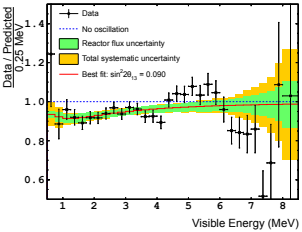
PRL 116, 061801,
DayaBay Collab. (2016)



PRL 116, 211801,
RENO Collab. (2016)



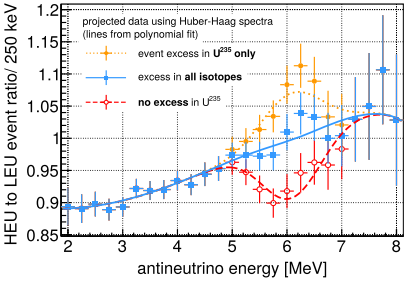
JHEP 10, 086,
Double Chooz Collab. (2014)



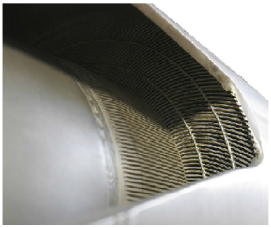
- first restrictions - PRL 118, 042502 (NEOS & Daya Bay spectra ratios): Pu isotopes disfavoured as beeing solely responsible

- potential of STEREO: **pure ^{235}U spectrum** ($> 93\%$ enrichment)
  - ^{235}U contribution to excess
  - test σ_{235} determined by DayaBay

Phys. Lett. B 765, 159, Buck *et al.*

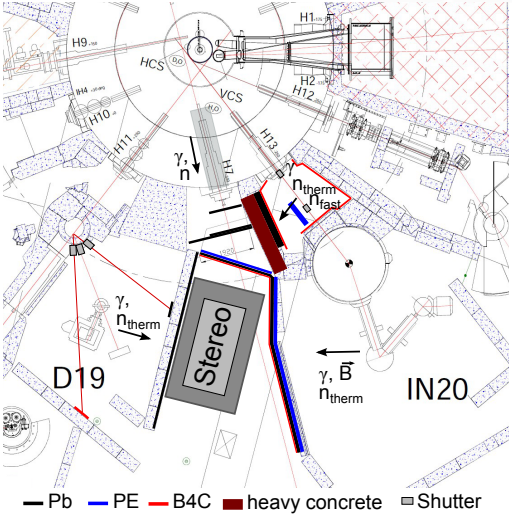


STEREO @ ILL

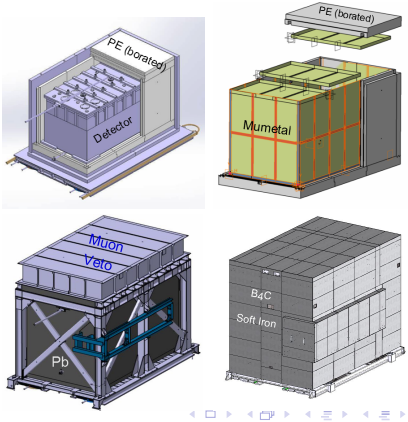


- nominal power: 58.3 MW_{therm}
- operated in cycles of ∼50 d
- compact fuel element: $h \approx 80$ cm, $d \approx 40$ cm
- HEU fuel: 93% ^{235}U
- baseline 8.9-11.1 m
- under a water channel (∼ 15 m.w.e. overburden)
- high γ/n background from neighbour instruments (/reactor)

STEREO Site



- shielding walls around the site
- dedicated shielding of H7 beamtube (tube now removed)
- strong passive shielding included in the detector setup



- 2 neighbouring neutron scattering experiments
- high thermal neutron and (n, γ) background

STEREO Inner Detector

Target:

- Gd-loaded liquid scintillator (LS)
- $2.2 \times 0.9 \times 0.9\,\mathrm{m}^3$, 6 cells
- PSD for fast neutrons
- reconstruction of interaction vertex/event topology
- energy measurement

Outer Crown:

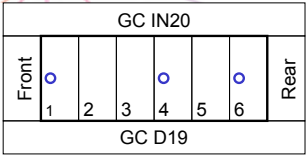
- "Gamma Catcher" (GC)
- background veto
- LS w/o Gd

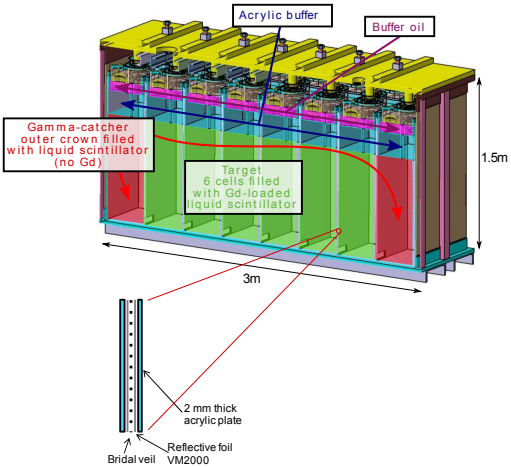
Separation Walls:

- specular reflective
- acrylic sandwiches + airgap + VM2000

Acrylic Buffers:

- mineral oil for optical coupling
- housing 48 PMTs (8")

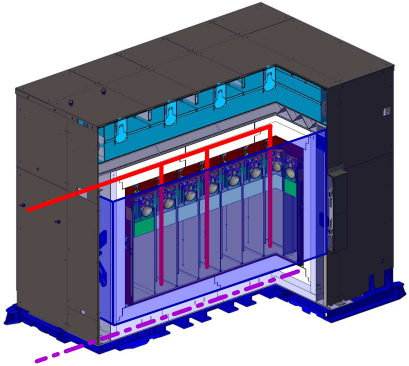




Calibration Systems

Radioactive source deployment

- tubes in three cells
- rail underneath the detector
- 'pantograph' for source calibrations outside (2D)

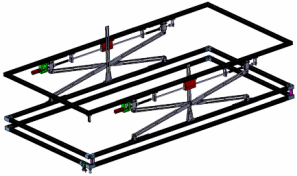


LED system

- light injectors for bottom, mid and top of each cell

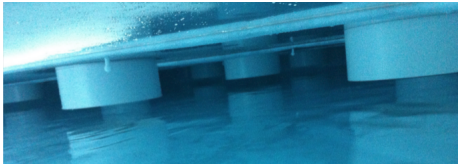
→ single PE calibration or gain-stability calibration

- UV light injection to monitor WLS performance



Muon Veto

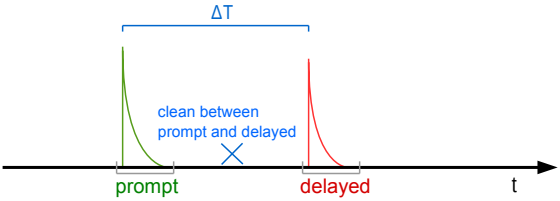
- covering full setup on top
- water Cherenkov detector, equipped with 20 PMTs
- intrinsic efficiency $> 99\%$ (tested with vertical muons)
- veto after muon trigger applied off-line

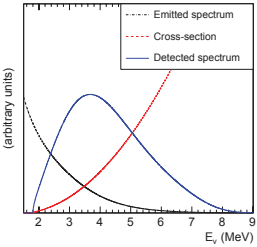


Neutrino Signals

Signal: Inverse beta decay (IBD)

- $\bar{\nu}_e + p \longrightarrow n + e^+ \qquad (E_{\bar{\nu}} > 1.8\,\text{MeV},\ E_{e^+} \sim E_{\bar{\nu}} - 780\,\text{keV})$
- prompt: e^+ - excitation and annihilation: $2\,\text{MeV} < E_{\text{dep}}^{\text{det}} < 8\,\text{MeV}$
- delayed: n - moderation & capture (Gd), $\tau \approx 17\,\mu\text{s}$: $5\,\text{MeV} < E_{\text{dep}}^{\text{det}} < 10\,\text{MeV}$
- coincidence time window: $70\,\mu\text{s}$



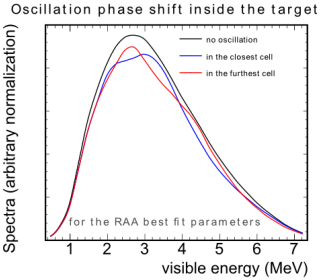


Background:

- random coincidences of single events
- correlated events (e.g. fast neutron scattering & capture)

STEREO Oscillation Analysis

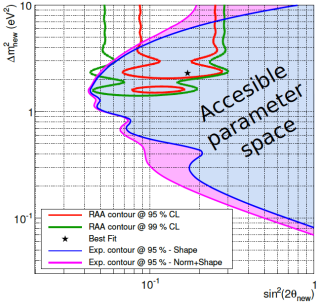
- shape analysis along 6 identical cells ($\sim \sin^2(L/E_\nu)$)
  $\rightarrow$ independent of absolute normalisation
- rate/ rate+shape analysis



Data taking:

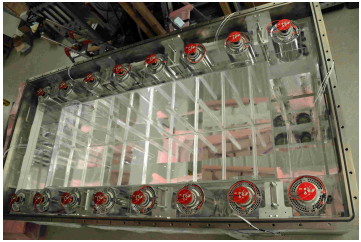
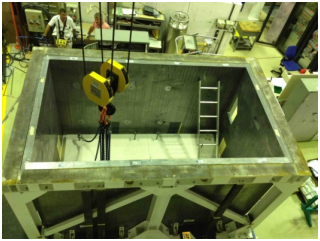
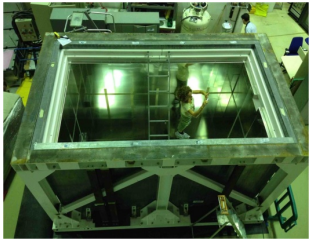
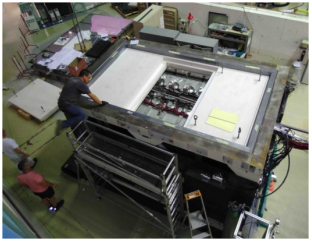
- Nov. 2016 - March 2017:
  - $\sim$ 70 days reactor ON
    (+2 weeks commissioning)
  - $\sim$ 28 days reactor OFF
- March - October 2017
  - reactor shutdown for maintenance
  - used for STEREO maintenance

projected sensitivity (300 d):



STEREO Mounting and Installation



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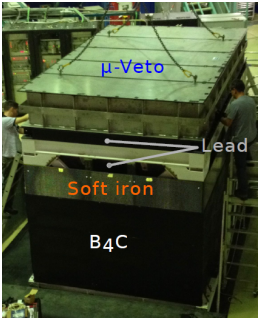
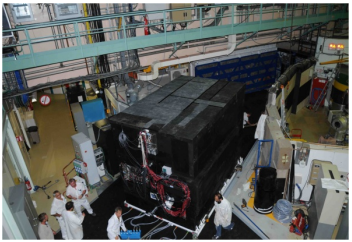




Sept. 2016: STEREO moves in (93 t on aircushions)

final installations

9./10. Nov. 2016: filling

Commissioning

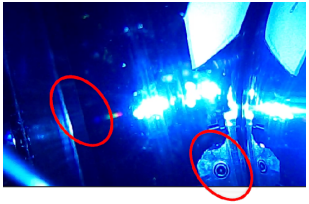
- first light on Nov. 10, 2016
- $< 1\%$ DAQ deadtime up to few kHz
- trigger threshold at $\sim 250\,\mathrm{keV}$

Two problems encountered during comissioning

- buffer oil leakage in one target cell (cell4) and one gamma-catcher cell (front)

$\Rightarrow$ no effect on scintillator

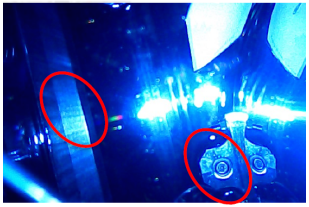
$\Rightarrow$ light collection reduced by $\sim 50\%$ in affected cells



- LS entered the separation walls

$\Rightarrow$ degradation of reflectivity

$\Rightarrow$ larger optical crosstalk in between cells



$\rightarrow$ repaired in current reactor shutdown

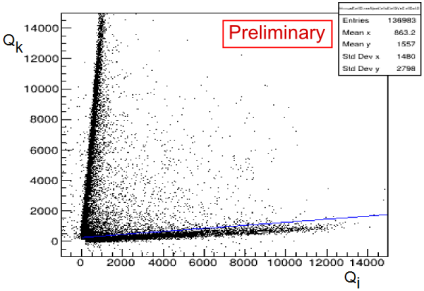
'Light Leaks'

- evolution in time (slow filling of the walls)
- affect light collection of individual cells
- no big effect on global light collection

- calculation from source calibrations (height dependence)
- calculation from physics runs (non-invasive, hourly, cell average):

  fit Q_k in lower band of Q_i vs Q_k distribution

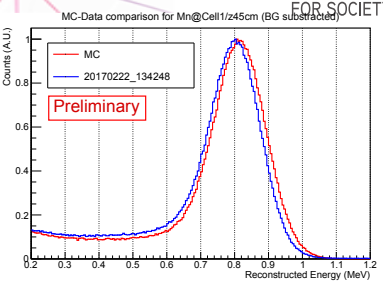
- modelled in MC by partially filling separation walls with scintillator



Energy Reconstruction

- accounting for light produced in the cell and light leaking from other cells

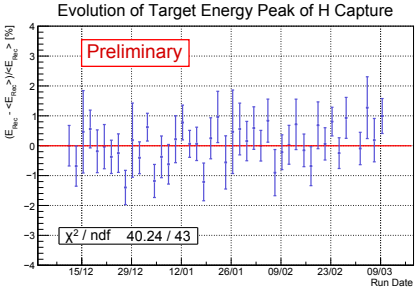
  $Q_i = \sum_j E_j^{\text{dep}} \times C_j \times LL_{ji} = \sum_j E_j^{\text{dep}} \times \mathbf{M}_{ji}$

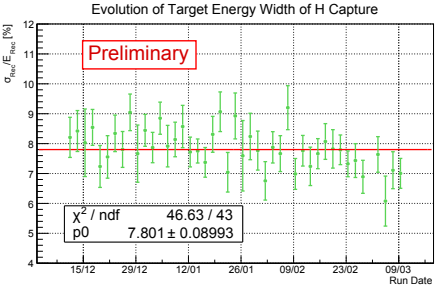


Validation:

- stability of hydrogen neutron capture peak:

  $\mathrm{H}(n,\gamma)\mathrm{D},\ E_\gamma = 2223\,\mathrm{keV}$



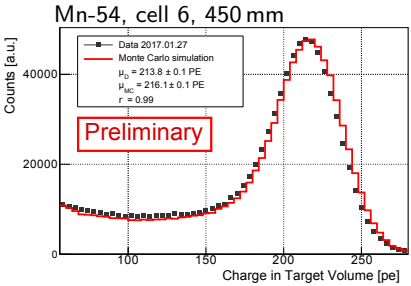


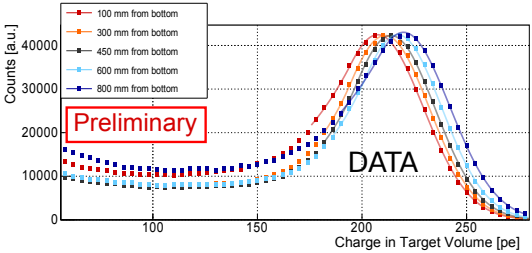
Data - MC Comparison

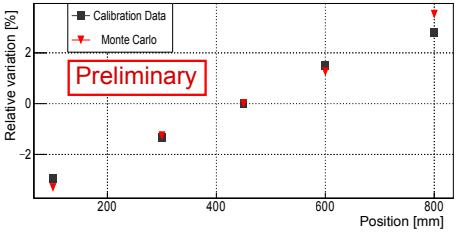
- calibration with Mn-54 (E_γ=834 keV)
- already good agreement in data & MC
- Finetuning of MC parameters pending

- z-dependence of peak position

→ in good agreement in Data & MC for reconstructed energy



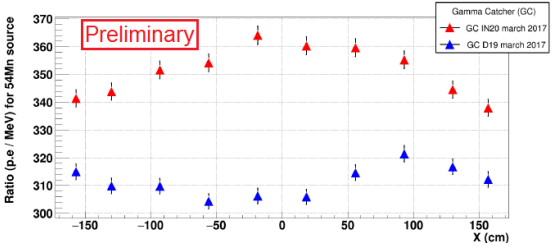




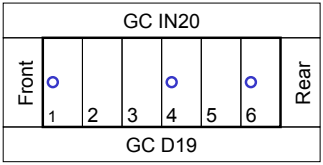
Calibration of the Gamma Catcher

- calibration with pantograph
- source at different positions along gamma catcher
- determination of spatial inhomogeneities in response

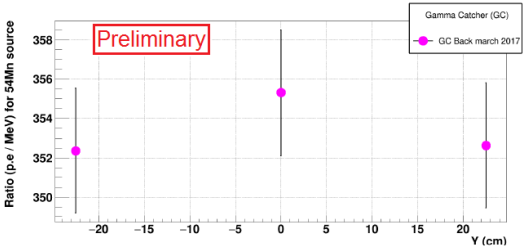
Long Gamma Catcher cell:



- short cell has $\sim$ same geometry as target cells

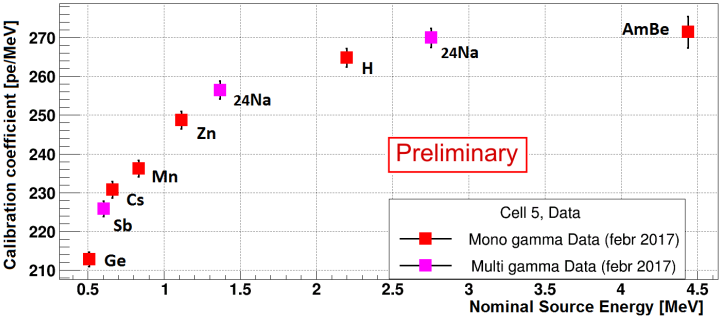


Short Gamma Catcher cell:



Scintillator Non-linearity Analysis

- Birks: $\frac{dS}{dx} = \frac{A\,dE/dx}{1+k_B\,dE/dx}$
- scintillator energy response determined with γ-sources
- Calibration Coefficient $:= \frac{\text{Charge [pe]}|_{\text{Data}}}{\text{Energy deposit [MeV]}|_{\text{MC}}}$



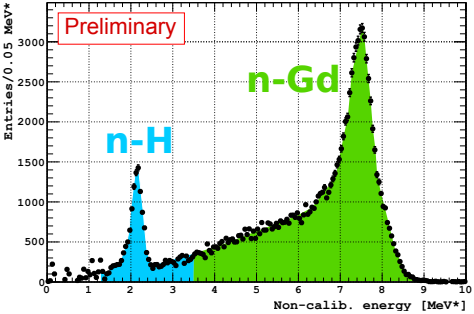
Isotope	Ge-68	Cs-137	Mn-54	Zn-65	Am-Be
E_γ [keV]	2x511	662	834	1115	4439

Isotope	Co-60	Sb-124	Na-24
E_γ [keV]	1173 & 1332	603 & 1691	1369 & 2754

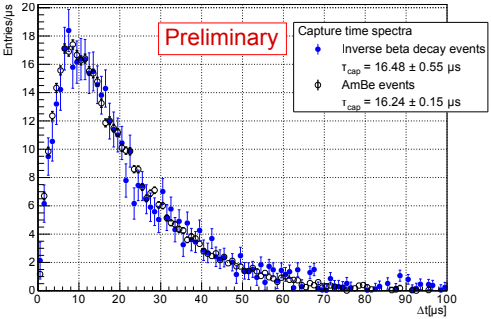
Gd Neutron Capture Fraction

- monitoring of time stability
- relative cell intercalibration
- measured with neutron source (Am-Be)
  - 4,4 MeV γ as prompt
  - fast $n \rightarrow$ need moderation time
    $\Rightarrow$ max. capture probability at $\sim 8\,\mu s$
- Gd-capture fraction $\approx 86\%$

Am-Be, cell6, center



Neutron capture time: Am-Be & IBD

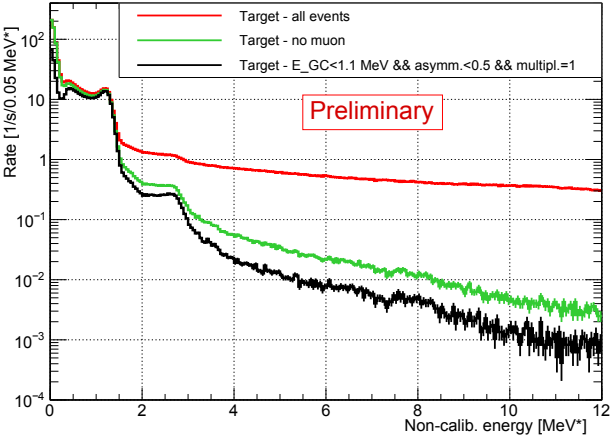


Single Event Rates

- Possible sources: any (μ, γ, n)

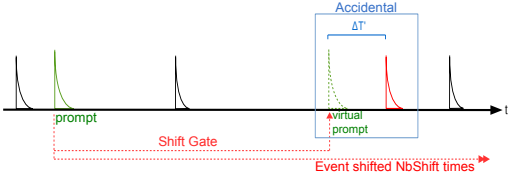
$\Rightarrow$ controlled by passive shielding

- with current shielding:
  - low threshold ($\approx$ 250 keV)
  - kHz trigger rate
- main features in residual spectrum:
  - Ar-41: 1.3 MeV
  - H(n,γ): 2.2 MeV
  - Co-60: 2.5 MeV
  - Tl-208: 2.6 MeV
  - Gd(n,γ): $\sim$8 MeV

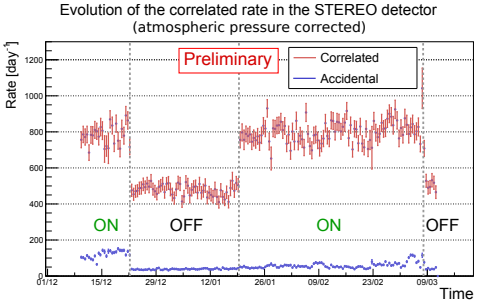


Accidental Coincidences

- purely statistical (by definition), approximately: $R_{\mathrm{acc}} \simeq R_{\mathrm{prompt}} R_{\mathrm{delayed}} T_{\mathrm{coinc}}$
- determined in 'off-time' windows and subtracted statistically
- uncertainty reduced by using multiple windows



- accidental background not dominant



Correlated Background

- Possible sources:
  - fast neutrons from reactor
  - muons/muon induced events (e.m. shower, fast neutrons, multiple neutrons,...)

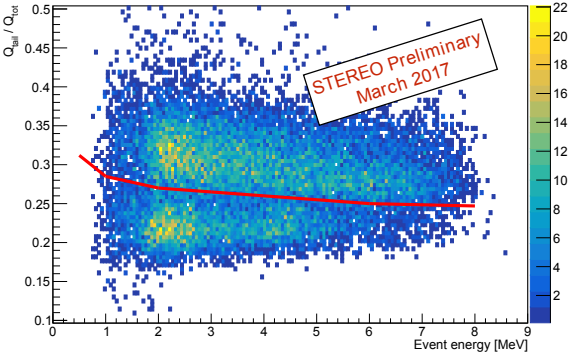
- certain classes of events can be identified by
  - → Trigger of muon veto
  - → **P**ulse **S**hape **D**iscrimination
    - IBD-prompt events have electron-like signature
    - high PSD events = background (e.g. nuclear recoil from neutron scattering)
  - → inhomogeneity of PMT response (e.g. stopping muons)
  - → event topology (e.g. e.m. shower)

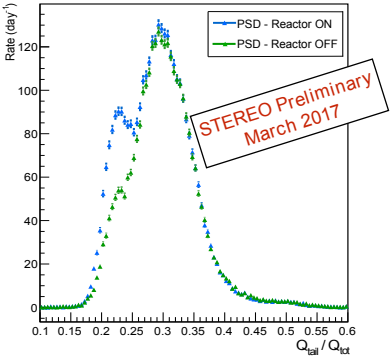
- remaining cosmic background can be corrected for by subtraction of reactor on - reactor off data

Pulse Shape Discrimination

- fast ($\sim \mathcal{O}(1)$ ns) and slow ($\sim \mathcal{O}(10)$ ns) scintillation component
- high dE/dx particles populate higher fraction of slow component $\rightarrow Q_{\mathrm{tail}}/Q_{\mathrm{tot}}$

- energy dependent, conservative PSD cut applied, to avoid cutting ν events

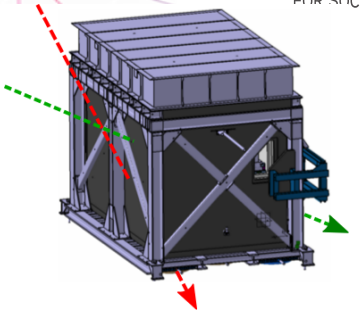




- Reactor on-off comparison:
  - $\Rightarrow$ no significant contribution of fast neutrons from reactor observed so far
  - $\Rightarrow$ dominating background: cosmics (as expected)

Stopped Muon Asymmetry

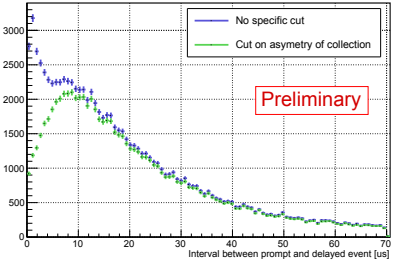
- muons can pass next to the muon veto and
  - hit the detector:
    → high energy deposit ($\sim 2\,\mathrm{MeV/cm}$)
    → stopping muons
  - don't hit the detector:
    → secondaries not vetoed



- stopping muons and Michel e- coincidence ($\tau = 2.2\,\mu\mathrm{s}$) can mimic IBD events

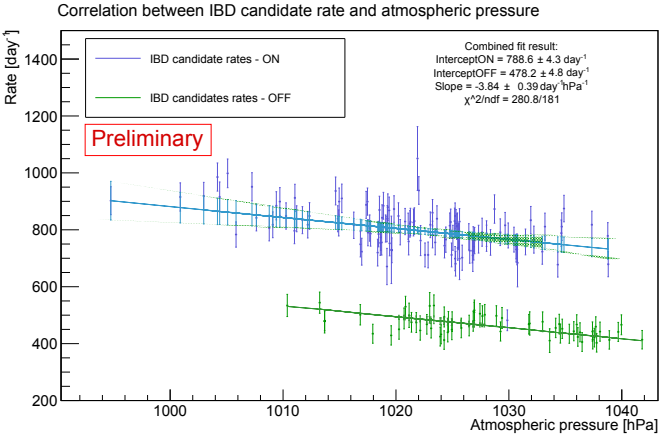
→ requires muon to stop within a few cm ($2\,\mathrm{MeV} < E_{\mathrm{prompt}} < 8\,\mathrm{MeV}$)

- strongly localised energy deposit (close to PMTs) can be identified using event asymmetry in a cell: $Q_{\mathrm{PMT}}^{\mathrm{max}}/Q_{\mathrm{cell}}$



Subtraction of Cosmic Background

- residual cosmic background has to be subtracted using reactor off data
- fluctuations in muon flux to be taken into account, e.g. due to atmospheric pressure
- correlation between atmospheric pressure and rate of coincident events extracted from combined fit of reactor on and off data
- renormalisation of rates to reference pressure



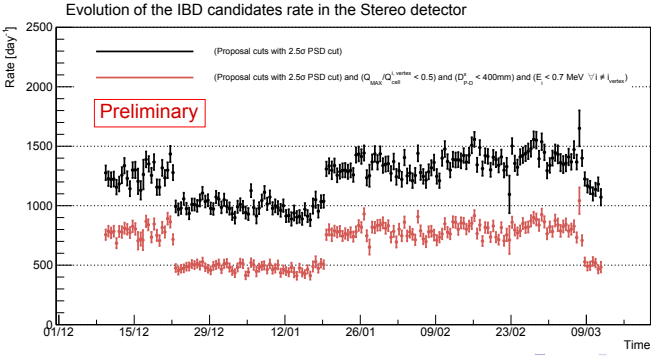
Measured Neutrinos

Proposal Cuts:

- $1.5\,\text{MeV} < E_{\text{Det}}^{\text{prompt}} < 8\,\text{MeV}$ && $E_{\text{GC}}^{\text{prompt}} < 1.1\,\text{MeV}$
- $5\,\text{MeV} < E_{\text{Det}}^{\text{delayed}} < 10\,\text{MeV}$ && $E_{\text{target}}^{\text{delayed}} > 1\,\text{MeV}$
- PSD @ $2.5\,\sigma$
- $\Delta T \leq 70\mu\text{s}$
- Muon veto $100\,\mu$s after muon

+ pressure correction
+ Additional cuts under investigation (e.g. signal asymmetry, topology, multiplicity, ...)

measured neutrino rate with these cuts: $\sim 300/\text{day}$



Next Steps

- cut optimisation studies
- finalisation of energy reconstruction for spectral analysis
- studies of systematics
- reinstallation of STEREO and restart of data taking (Sep./Oct. 2017)
- reactor on data: $+$ 60 days (2017) $+ \sim$ 150 days (2018)

Thank you for your attention!