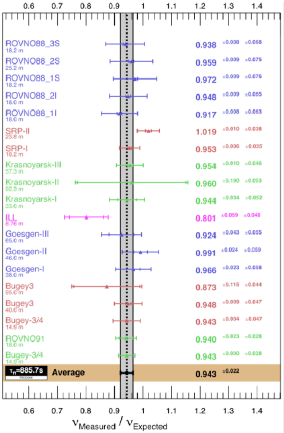

The Reactor Antineutrino Anomaly

Sebastian Lindemann

PhD Student Seminar on Sterile Neutrinos,
November 2012

Outline

1 Fission reactors
  - A clean antineutrino-source
  - Fuel composition

2 Reference antineutrino spectra
  - Ab initio calculation
  - Conversion of beta spectra
  - New antineutrino spectra

3 Short baseline experiments
  - An IBD detector example: Double Chooz
  - Reevaluation using updated cross-sections per fission
  - What comes next?

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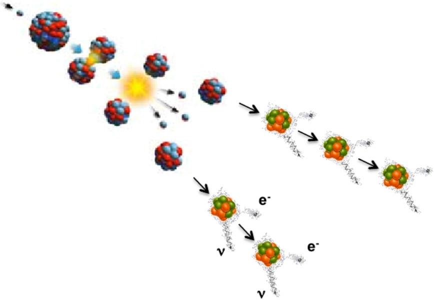
Fission reactors

- Most common nuclear fuels: ^{235}U, ^{239}Pu
- Fission threshold 7-8 MeV (6 MeV through binding of neutron, 1-2 MeV through neutron pairing)
- About 200 MeV per fission → GW thermal power
- Binary fission products centered at 95 ± 15 and 135 ± 15
- 1-3 neutrons produced per fission → chain reaction
- About 9 MeV to antineutrinos

Fission reactors – a clean $\bar{\nu}_e$-source

Fission of U or Pu isotopes

- followed by $\sim 6\,\beta^-$ decays of fission products
- pure $\bar{\nu}_e$ flux at MeV scale
- about 200 MeV / fission
  $\rightarrow 2 \cdot 10^{20}\ \bar{\nu}_e$ / $\mathrm{GW_{th}}$



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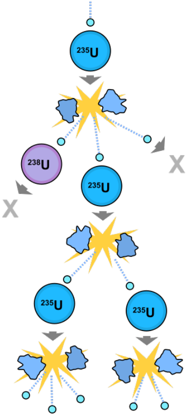
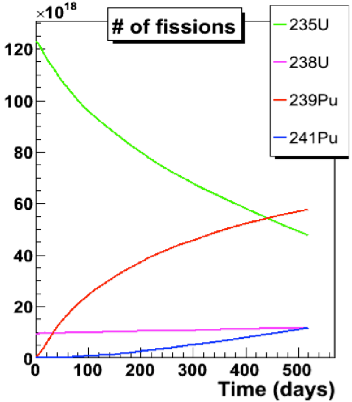
Time development of fuel composition

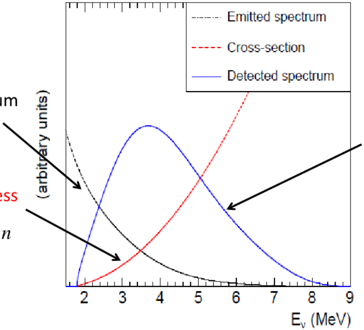




Breeding of ^{239}Pu

$$^{238}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow ^{239}_{92}\mathrm{U} \xrightarrow[23.5\,\mathrm{min}]{\beta^-} ^{238}_{93}\mathrm{Np} \xrightarrow[2.3\,\mathrm{days}]{\beta^-} ^{239}_{94}\mathrm{Pu} \xrightarrow[2.4\cdot 10^4\,\mathrm{years}]{\alpha}$$

Energy spectrum



Exponential
decrease of
emitted spectrum

β inverse
detection process

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

Detected Spectrum

Relevant E range
[1.8 – 8] MeV

IBD – inverse beta decay

- $\bar{\nu}_e + p \rightarrow e^+ + n$
- $E_{\text{prompt}} = E_{\bar{\nu}_e} - (M_n - M_p) + m_e$

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Ab initio calculations

Total β spectrum

$$S_{\mathrm{tot}}(E) = \sum_{k={}^{235}\mathrm{U},{}^{238}\mathrm{U},{}^{239}\mathrm{Pu},{}^{241}\mathrm{Pu}} \alpha_k \times S_k(E)$$

$$S_k(E) = \sum_{fp=1}^{N_{fp}} \mathcal{A}_{fp}(t) \times S_{fp}(E)$$

$$S_{fp}(E) = \sum_{b=1}^{N_b} BR^b_{fp} \times S^b_{fp}(Z_{fp}, A_{fp}, E^b_{0fp}, E)$$

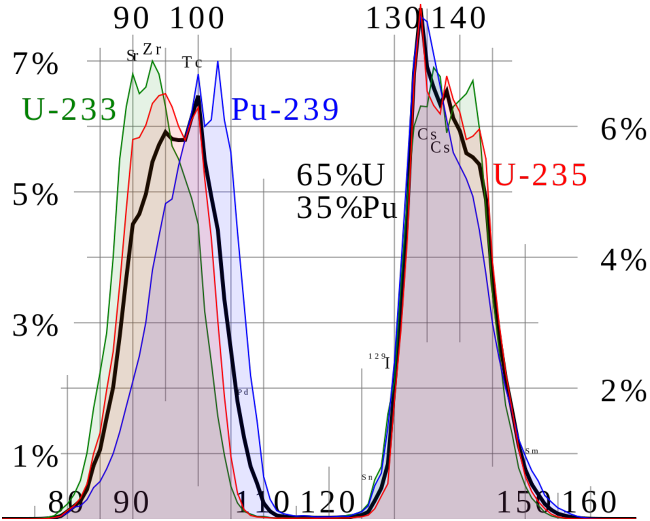
$$S^{b,\mathrm{F}}_{fp} = \underbrace{K^b_{fp}}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E^b_{0fp})^2}_{\text{Phase space}} \times \underbrace{C^b_{fp}(E)}_{\text{Shape factor}}$$

$$S^b_{fp} = S^{b,\mathrm{F}}_{fp} \times \underbrace{L_0(Z_{fp}, E) \times C(Z_{fp}, E)}_{\text{finit size}} \times \underbrace{Sc(Z_{fp}, E)}_{\text{screening}} \times \underbrace{G_\beta(Z_{fp}, E)}_{\text{QED}} \times \underbrace{(1 + \delta_{\mathrm{WM}} E)}_{\text{weak magn.}}$$

Corresponding $\bar{\nu}_e$ spectrum: Replace electron energy E by antineutrino energy

$$E_\nu = E^b_{0fp} - E$$

Binary fission products



Ab initio calculations

Complete simulation of core evolution

Fuel loading, geometry, n-capture and fission physics
→ fission product inventory

Description of all β-decays

- Nuclear databases
- Fermi-theory + corrections
- Nuclear models

β and ν total spectra from some 10^4 branches have to be summed up.

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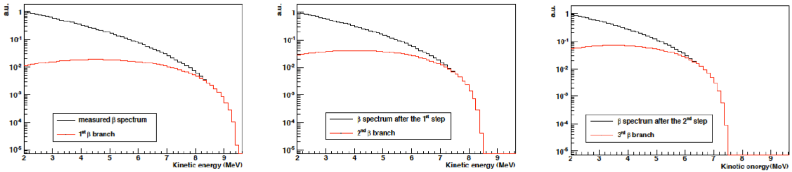
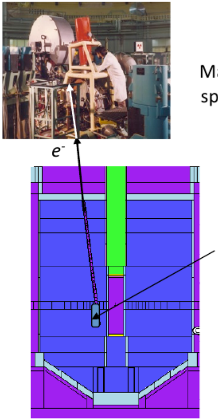
Conversion of β^- spectra to $\bar{\nu}_e$ spectra

- Start from total β^- spectrum
- Break down total spectrum in single β^- branches
  → fit spectrum with 30 virtual branches (Schreckenbach approach)



- Convert each virtual β^- branch to a $\bar{\nu}_e$ branch
- Sum up individual $\bar{\nu}_e$ branches

ILL β^- reference spectra

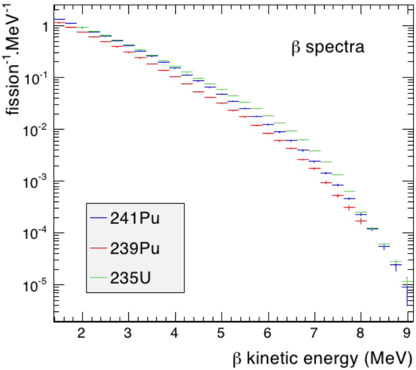


Magnetic BILL spectrometer

Target foil (^{235}U, ^{239}Pu, ^{241}Pu) in thermal n flux

ILL research reactor (Grenoble, France)

Emitted β spectra per fission



A. A. Hahn, K. Schreckenbach et al., *Phys. Let. B218,365 (1989)+ refs therein*

Conversion of total β^- spectra

Total β spectra of fissile isotopes measured at ILL in the 80's

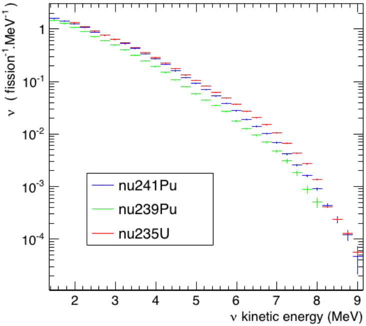
→ accurate reference electron spectra

Conversion to antineutrinos

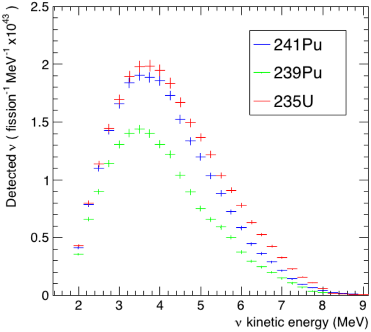
- Use of virtual β-branches
- Fermi-theory + corrections
- Control of approximations

Reference ν spectra per isotope to be combined with prediction of fission rates.

Old ILL antineutrino reference spectra



Emitted



Interacting via IBD

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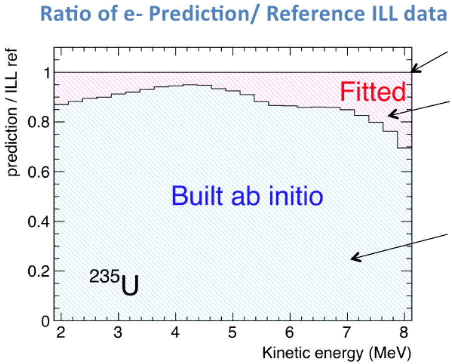
Reevaluation of total $\bar{\nu}_e$ spectra

Comparison to ILL β^- data

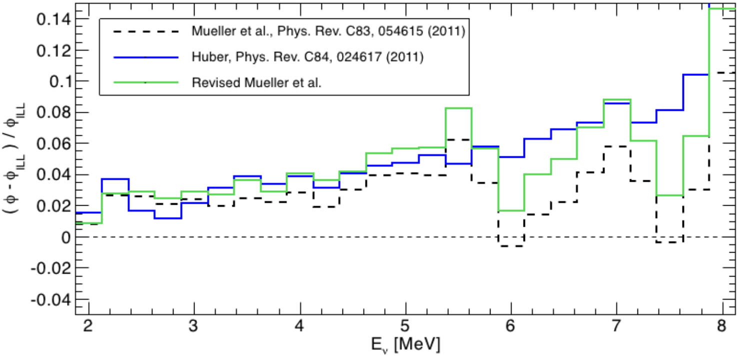


- ILL electron data anchor point
- Fit of residual: five effective branches are fitted to the remaining 10%
  → Suppresses error of full ab initio approach
- “true” distribution of all known β-branches describes >90% of ILL e⁻ data → reduces sensitivity to virtual branches approximations

T. A. Mueller et al., Phys. Rev. C83,054615 (2011)

Reevaluation of total $\bar{\nu}_e$ spectra

Comparison to old spectra



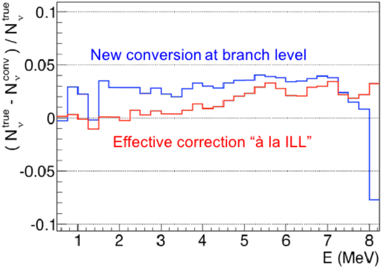
T.A. Mueller, D. Lhuillier

Reevaluation of total $\bar{\nu}_e$ spectra

Where does the difference come from?

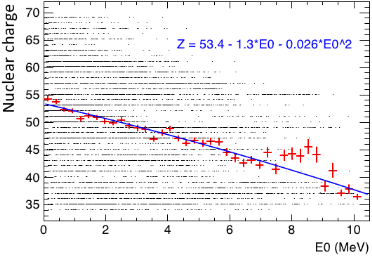
E <4 MeV

Effective linear correction of Coulomb and weak magnetism terms replaced by correction at β-branch level:

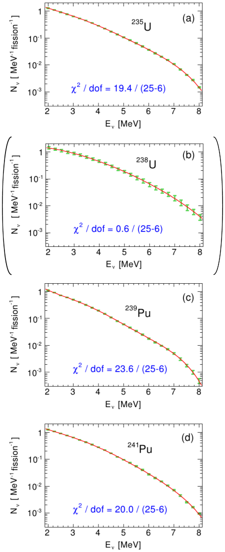


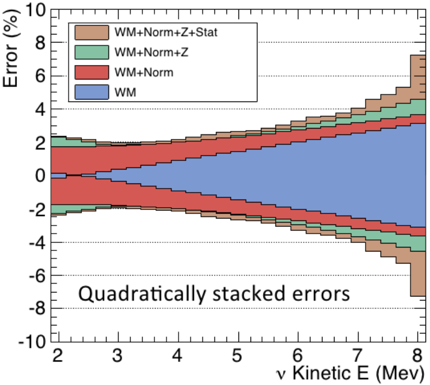
E >4 MeV

Mean fit of nuclear charge doesn’t reflect accurately enough the true distribution of nuclear charges:



Error budget of new conversion approach



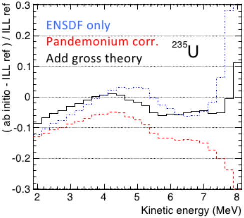


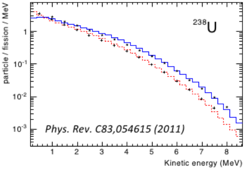
Treatment of weak magnetism neglects nuclear structure:

- Dominant shape uncertainty, 100% error assumed.
- Uncertainty underestimated?

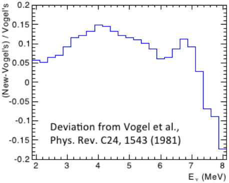
Ab initio approach for antineutrino spectrum of ^{238}U

- Build as complete as possible nuclear database coupled to MCNP Utility for Reactor Evolution (*)
  → full core inventory
- ^{235}U spectrum matches the ILL data at ~10% level
- **^{238}U prediction** 10% higher than previous estimate



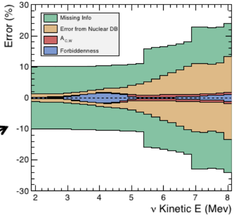


Phys. Rev. C83,054615 (2011)



Deviation from Vogel et al.,
Phys. Rev. C24, 1543 (1981)

- Total error in the 10-20% range. Dominated by systematics of nuclear databases.



(*) http://www.nea.fr/tools/abstract/detail/nea-1845.

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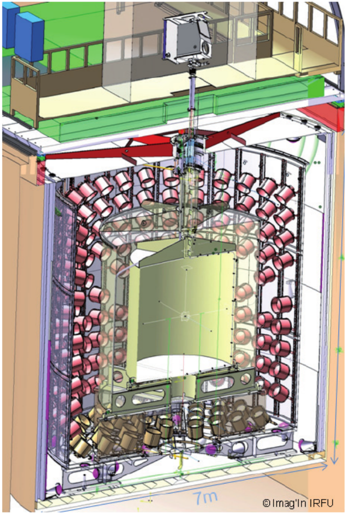
Working principle of IBD detectors for reactor antineutrinos

The Double Chooz detector



Location

- $\bar{\nu}_\mathrm{e}$ source: two 4.25 $\mathrm{GW_{th}}$ reactors
- DC far detector @ 1050 m from cores
- rock overburden: 300 m.w.e.

Detection via inverse beta decay (IBD)

- $\bar{\nu}_\mathrm{e} + p \rightarrow e^+ + n$
- $E_\mathrm{prompt} = E_{\bar{\nu}_\mathrm{e}} - \underbrace{(M_n - M_p)}_{=\Delta} + m_e$

$$\rightarrow E_{\bar{\nu}_\mathrm{e}} = E_\mathrm{prompt} + 0.78\,\mathrm{MeV}$$

Coincidence signal

- prompt γ-signal from positron annihilation
- delayed $\sim$ 8 MeV γ-signal from neutron capture on H or Gd

$\rightarrow\ t_{e^+n} \sim 30\ \mu\mathrm{s}$

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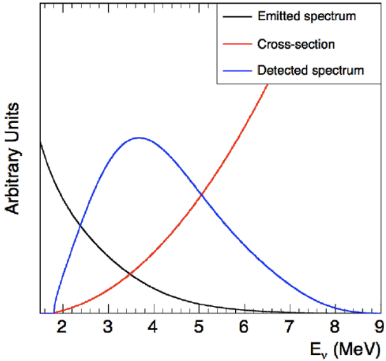
Event rate at a detector and mean cross-section per fission

$$N_\nu^{\text{pred}}(s^{-1}) = \frac{1}{4\pi L^2} N_p \frac{P_{\text{th}}}{\langle E_f \rangle} \sigma_f^{\text{pred}}$$

$$\sigma_f^{\text{pred}} = \int_0^\infty S_{\text{tot}}(E_\nu)\sigma_{\text{V-A}}(E_\nu)dE_\nu = \sum_k f_k \sigma_{f,k}^{\text{pred}}$$



V-A cross section

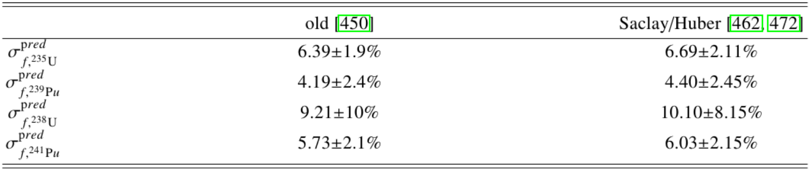
- $\sigma_{\text{V-A}}(E_e) = \kappa p_e E_e(1+\delta_{\text{rec}}+\delta_{\text{wm}}+\delta_{\text{rad}})$
- $\kappa \sim \frac{1}{\tau_n}$
- $E_{\bar{\nu}_e} = E_e + \Delta + \frac{E_e(E_e+\Delta)}{M} + \frac{1}{2}\frac{(\Delta^2 - m_e^2)}{M}$

Mean cross-section per fission

Effects responsible for increased σ_f^{pred}

- $\bar{\nu}_e$-flux: $^{235}\mathrm{U} + 3.7\%$, $^{239}\mathrm{Pu} + 4.2\%$, $^{241}\mathrm{Pu} + 4.7\%$, $^{238}\mathrm{U} + 9.8\%$
- Neutron lifetime (τ_n) decrease by a few percent
- Off-equilibrium effects included

Updated cross-sections

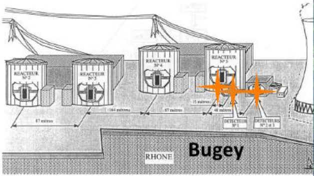


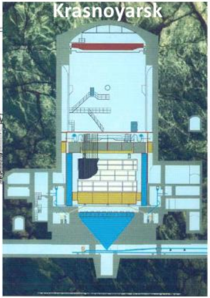
	old [450]	Saclay/Huber [462, 472]
$\sigma^{pred}_{f,^{235}\mathrm{U}}$	6.39±1.9%	6.69±2.11%
$\sigma^{pred}_{f,^{239}\mathrm{P}u}$	4.19±2.4%	4.40±2.45%
$\sigma^{pred}_{f,^{238}\mathrm{U}}$	9.21±10%	10.10±8.15%
$\sigma^{pred}_{f,^{241}\mathrm{P}u}$	5.73±2.1%	6.03±2.15%

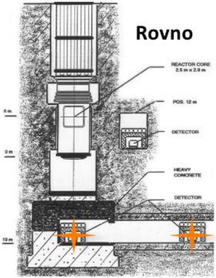
Values in units of $10^{-43}\mathrm{cm}^2$ / fission

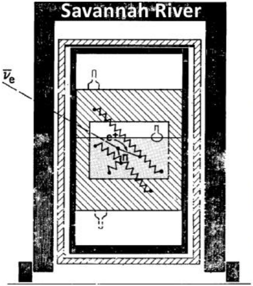
Short baseline experiments

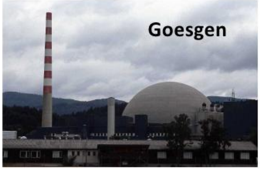
19 measuremens @ L < 100m

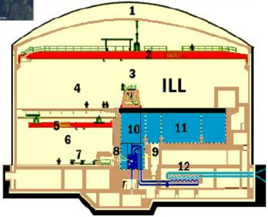












Short baseline experiments

Reevaluation

result	Det. type	τ_n (s)	^{235}U	^{239}Pu	^{238}U	^{241}Pu	old	new	err(%)	corr(%)	L(m)
Bugey-4	^{3}He+H$_2$O	888.7	0.538	0.328	0.078	0.056	0.987	0.926	3.0	3.0	15
ROVNO91	^{3}He+H$_2$O	888.6	0.614	0.274	0.074	0.038	0.985	0.924	3.9	3.0	18
Bugey-3-I	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.988	0.930	4.8	4.8	15
Bugey-3-II	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.994	0.936	4.9	4.8	40
Bugey-3-III	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.915	0.861	14.1	4.8	95
Goesgen-I	^{3}He+LS	897	0.620	0.274	0.074	0.042	1.018	0.949	6.5	6.0	38
Goesgen-II	^{3}He+LS	897	0.584	0.298	0.068	0.050	1.045	0.975	6.5	6.0	45
Goesgen-II	^{3}He+LS	897	0.543	0.329	0.070	0.058	0.975	0.909	7.6	6.0	65
ILL	^{3}He+LS	889	$\simeq 1$	—	—	—	0.832	0.7882	9.5	6.0	9
Krasn. I	^{3}He+PE	899	$\simeq 1$	—	—	—	1.013	0.920	5.8	4.9	33
Krasn. II	^{3}He+PE	899	$\simeq 1$	—	—	—	1.031	0.937	20.3	4.9	92
Krasn. III	^{3}He+PE	899	$\simeq 1$	—	—	—	0.989	0.931	4.9	4.9	57
SRP I	Gd-LS	887	$\simeq 1$	—	—	—	0.987	0.936	3.7	3.7	18
SRP II	Gd-LS	887	$\simeq 1$	—	—	—	1.055	1.001	3.8	3.7	24
ROVNO88-1I	^{3}He+PE	898.8	0.607	0.277	0.074	0.042	0.969	0.901	6.9	6.9	18
ROVNO88-2I	^{3}He+PE	898.8	0.603	0.276	0.076	0.045	1.001	0.932	6.9	6.9	18
ROVNO88-1S	Gd-LS	898.8	0.606	0.277	0.074	0.043	1.026	0.955	7.8	7.2	18
ROVNO88-2S	Gd-LS	898.8	0.557	0.313	0.076	0.054	1.013	0.943	7.8	7.2	25
ROVNO88-3S	Gd-LS	898.8	0.606	0.274	0.074	0.046	0.990	0.922	7.2	7.2	18

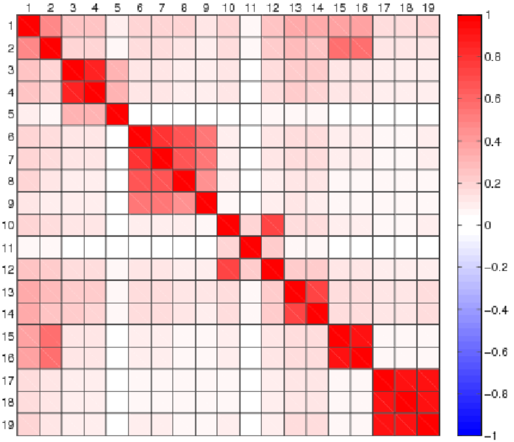
Short baseline experiments

Correlation matrix

(in %)

$\vec{R}$	$\Sigma_{\text{tot.}}$	$\Sigma_{\text{cor.}}$
Bugey-4 15m	3.0	3.0
Rovno91 18m	3.9	3.0
Bugey-3 15m	5.0	5.0
Bugey-3 40m	5.1	5.0
Bugey-3 92m	14.1	5.0
Goesgen 38m	6.5	6.0
Goesgen 45m	7.6	6.0
Goesgen 65m	9.5	6.0
ILL 9m	5.1	4.1
Krasno 33m	5.1	4.1
Krasno 92m	20.3	4.1
Krasno 57m	4.1	4.1
SRP I 18m	3.7	3.7
SRP II 25m	3.8	3.7
Rovno88 1I 18m	6.9	6.9
Rovno88 2I 18 m	6.9	6.9
Rovno88 1S 18m	7.8	7.2
Rovno88 2S 25m	7.8	7.2
Rovno88 3S 18m	7.2	7.2

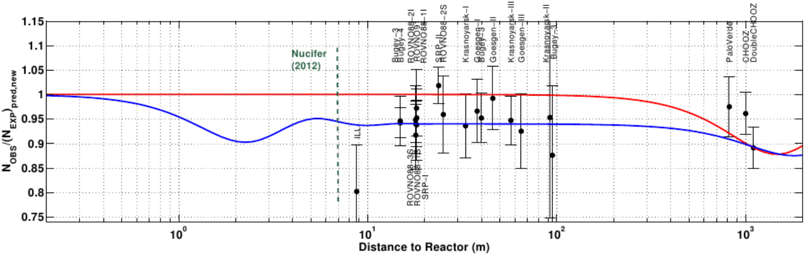
C (correlation matrix on Ratios)



- Global **2% correlated norm error of ILL β-spectra**
- Block correlations come from identical detector, technology or ν source

Short baseline experiments

Reevaluation



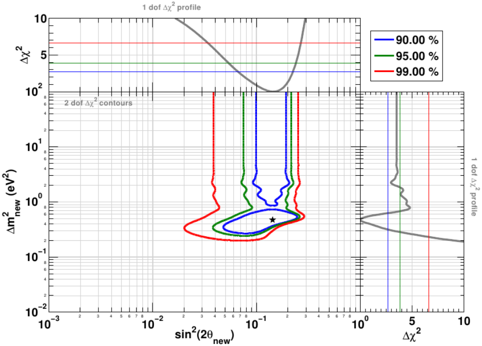
- Experimental errors and $\bar{\nu}_e$ spectra errors added in quadrature
- Average ratio including possible correlations is 0.927 ± 0.023

Short baseline experiments

4th neutrino hypothesis – rate only analysis

$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta_{\text{new}} & \sin\theta_{\text{new}} \\ -\sin\theta_{\text{new}} & \cos\theta_{\text{new}} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_{\text{new}} \end{pmatrix}$$

$$P_{\nu_e\to\nu_e}(L,E) = |\langle\nu_e(L)|\nu_e(L=0)\rangle|^2 = 1 - \sin^2(2\theta_{\text{new}})\sin^2\left(\frac{\Delta m^2_{\text{new}} L}{E}\right)$$



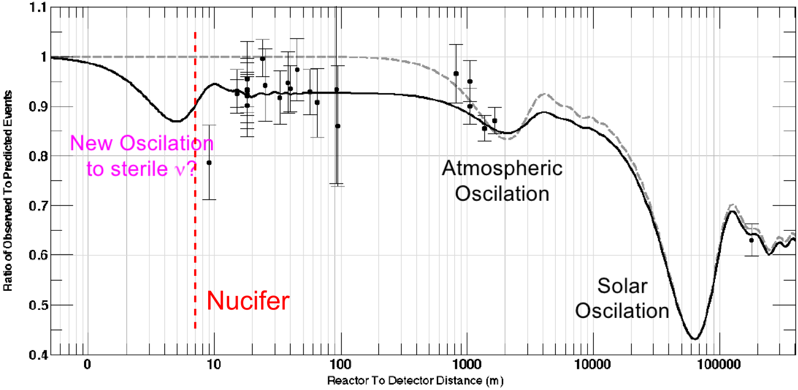
Best fit:

- $\Delta m^2_{\text{new,R}} = 0.5\,\text{eV}^2$
- $\sin^2(2\theta_{\text{new,R}} \sim 0.14$
- No-oscillation analysis excluded at 99.8%

Outline

1. Fission reactors
   - A clean antineutrino-source
   - Fuel composition
2. Reference antineutrino spectra
   - Ab initio calculation
   - Conversion of beta spectra
   - New antineutrino spectra
3. Short baseline experiments
   - An IBD detector example: Double Chooz
   - Reevaluation using updated cross-sections per fission
   - What comes next?

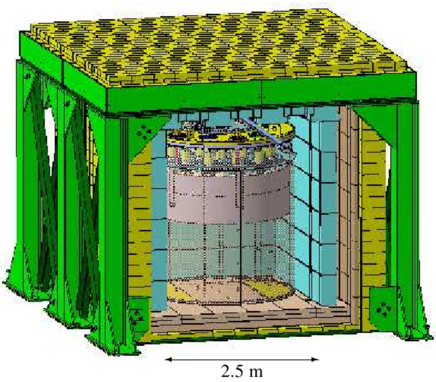
Reactor Antineutrino Anomaly

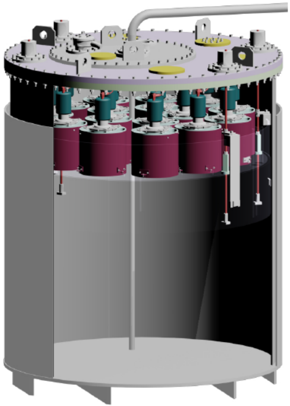


Nucifer @ Osiris-Saclay

- Designed for non-proliferation studies
- Osiris reactor: 70 $\mathrm{MW_{th}}$, core size of 57 × 57 × 60 cm
- Nucifer target: 0.85 $\mathrm{m^3}$ of Gd-LS
- Baseline distribution $\mathrm{L} = 7.0 \pm 3$ m

  → $\mathrm{eV^2}$ Oscillations are not washed out!





Reactor Antineutrino Anomaly

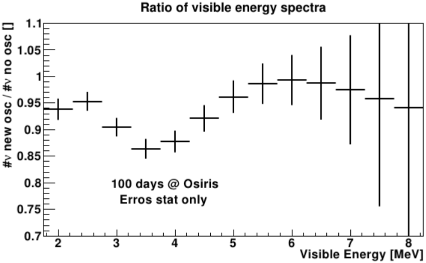


Figure 120. Expected distortion of neutrino spectrum in Nucifer with a new oscillation controlled by $\Delta m^2_{new} = 2.3$ and $\theta_{new} = 0.17$

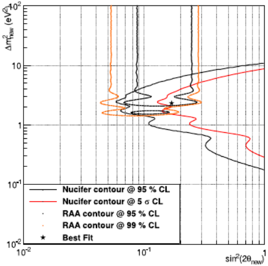


Figure 121. Discovery potential of Nucifer compared to Reactor Antineutrino Anomaly

Appendix

References I found useful putting together this:

- K. N. Abazajian et al., arXiv:1204.5379 (2012)
- Talk D. Lhuillier @ Neutrino 2012
- Mueller et al., Phys. Rev. C83, 054615 (2011)
- Huber, Phys. Rev. C84, 024617 (2011)
- Mention et al., Phys. Rev. D83, 073006, (2011)
- Y. Abe et al., Phys. Rev. Lett. 108. 131801 (2012)