Precise Determination of the ^{235}U Reactor Antineutrino Cross Section per Fission

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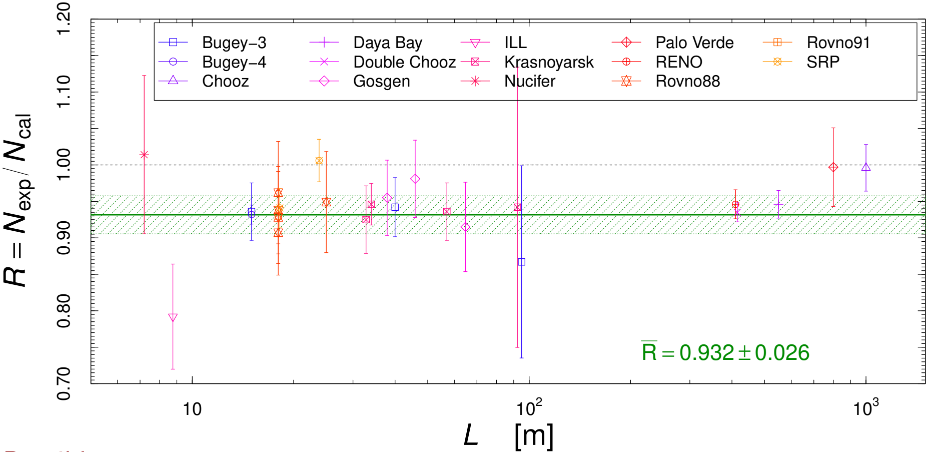
Talk based on arXiv:1608.04096

Reactor Electron Antineutrino Anomaly

[Mention et al (Saclay), PRD 83 (2011) 073006]

New reactor $\bar{\nu}_e$ fluxes [Mueller et al (Saclay), PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



Possible causes:

- Short-Baseline Neutrino Oscillations: see the talk by Yufeng Li.
- An excess of the reactor $\bar{\nu}_e$ flux estimation.

- Detection reaction: $\bar{\nu}_e + p \to n + e^+$

- Experimental event rate: $N_a = \frac{1}{4\pi L_a^2} N_p^a \frac{P_{th}^a}{\langle E_f \rangle_a} \sigma_{f,a}$ a: experiment index

- Experimental cross section per fission: $\sigma_{f,a} = \sum_k f_k^a \sigma_{f,k}$

  $k = 235, 238, 239, 241$: index of the four fissile isotopes ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

- Calculated cross sections per fission of the four fissile isotopes:

	Saclay (S)	Huber (H)	Saclay+Huber (SH)	uncertainty
$\sigma_{f,235}$	6.61	+1.2%	6.69	2.11%
$\sigma_{f,238}$	10.10		10.10	8.15%
$\sigma_{f,239}$	4.34	+1.4%	4.40	2.45%
$\sigma_{f,241}$	5.97	+1.0%	6.03	2.15%

- We investigate which of the four fluxes could be the cause of the reactor antineutrino anomaly.

Mention et al (Saclay), PRD 83 (2011) 073006

#	result	Det. type	τ_n (s)	^{235}U	^{239}Pu	^{238}U	^{241}Pu	old	new	err(%)	corr(%)	L(m)
1	Bugey-4	^{3}He + H_2O	888.7	0.538	0.328	0.078	0.056	0.987	0.942	3.0	3.0	15
2	ROVNO91	^{3}He + H_2O	888.6	0.614	0.274	0.074	0.038	0.985	0.940	3.9	3.0	18
3	Bugey-3-I	^{6}Li − LS	889	0.538	0.328	0.078	0.056	0.988	0.946	4.8	4.8	15
4	Bugey-3-II	^{6}Li − LS	889	0.538	0.328	0.078	0.056	0.994	0.952	4.9	4.8	40
5	Bugey-3-III	^{6}Li − LS	889	0.538	0.328	0.078	0.056	0.915	0.876	14.1	4.8	95
6	Goesgen-I	^{3}He + LS	897	0.620	0.274	0.074	0.042	1.018	0.966	6.5	6.0	38
7	Goesgen-II	^{3}He + LS	897	0.584	0.298	0.068	0.050	1.045	0.992	6.5	6.0	45
8	Goesgen-II	^{3}He + LS	897	0.543	0.329	0.070	0.058	0.975	0.925	7.6	6.0	65
9	ILL	^{3}He + LS	889	≃ 1	—	—	—	0.832	0.802	9.5	6.0	9
10	Krasn. I	^{3}He + PE	899	≃ 1	—	—	—	1.013	0.936	5.8	4.9	33
11	Krasn. II	^{3}He + PE	899	≃ 1	—	—	—	1.031	0.953	20.3	4.9	92
12	Krasn. III	^{3}He + PE	899	≃ 1	—	—	—	0.989	0.947	4.9	4.9	57
13	SRP I	Gd-LS	887	≃ 1	—	—	—	0.987	0.952	3.7	3.7	18
14	SRP II	Gd-LS	887	≃ 1	—	—	—	1.055	1.018	3.8	3.7	24
15	ROVNO88-1I	^{3}He + PE	898.8	0.607	0.277	0.074	0.042	0.969	0.917	6.9	6.9	18
16	ROVNO88-2I	^{3}He + PE	898.8	0.603	0.276	0.076	0.045	1.001	0.948	6.9	6.9	18
17	ROVNO88-1S	Gd-LS	898.8	0.606	0.277	0.074	0.043	1.026	0.972	7.8	7.2	18
18	ROVNO88-2S	Gd-LS	898.8	0.557	0.313	0.076	0.054	1.013	0.959	7.8	7.2	25
19	ROVNO88-3S	Gd-LS	898.8	0.606	0.274	0.074	0.046	0.990	0.938	7.2	7.2	18

Zhang, Qian, Vogel, PRD 87 (073018) 2013

#	Result	Detector type	^{235}U	^{239}Pu	^{238}U	^{241}Pu	Ratio	σ_{err} (%)	σ_{corr} (%)	L(m)	P_{sur}	Year
1	Bugey-4	^{3}He + H_2O	0.538	0.328	0.078	0.056	0.942	3.0	3.0	15	0.999987	1994
2	ROVNO91	^{3}He + H_2O	0.614	0.274	0.074	0.038	0.940	3.9	3.0	18	0.999981	1991
22	Double Chooz	Gd-LS	0.496	0.351	0.087	0.066	0.860	3.7	3.0	998–1115	0.954	2012
23	Double Chooz	LS (n-H)	0.496	0.351	0.087	0.066	0.920	4.0	3.0	998–1115	0.954	2012
3	Bugey-3-I	^{6}Li − LS	0.538	0.328	0.078	0.056	0.946	4.8	4.8	15	0.999987	1995
4	Bugey-3-II	^{6}Li − LS	0.538	0.328	0.078	0.056	0.952	4.9	4.8	40	0.999907	1995
5	Bugey-3-III	^{6}Li − LS	0.538	0.328	0.078	0.056	0.876	14.1	4.8	95	0.999479	1995
6	Goesgen-I	^{3}He + LS	0.620	0.274	0.074	0.042	0.966	6.5	6.0	38	0.999916	1986
7	Goesgen-II	^{3}He + LS	0.584	0.298	0.068	0.050	0.992	6.5	6.0	45	0.999883	1986
8	Goesgen-III	^{3}He + LS	0.543	0.329	0.070	0.058	0.925	7.6	6.0	65	0.999756	1986
9	ILL	^{3}He + LS	≈1	···	···	···	0.802	9.5	6.0	9	0.999995	1981
10	Krasnoyarsk I	^{3}He + PE	≈1	···	···	···	0.936	5.8	4.9	33	0.999937	1987
11	Krasnoyarsk II	^{3}He + PE	≈1	···	···	···	0.953	20.3	4.9	92	0.999511	1987
12	Krasnoyarsk III	^{3}He + PE	≈1	···	···	···	0.947	4.9	4.9	57	0.999812	1987
13	SRP-I	Gd-LS	≈1	···	···	···	0.952	3.7	2.7	18	0.999981	1996
14	SRP-II	Gd-LS	≈1	···	···	···	1.018	3.8	2.7	24	0.999967	1996
15	ROVNO88-1I	^{3}He + PE	0.607	0.277	0.074	0.042	0.917	6.9	5.7	18	0.999981	1988
16	ROVNO88-2I	^{3}He + PE	0.603	0.276	0.076	0.045	0.948	6.9	5.7	18	0.999981	1988
17	ROVNO88-1S	Gd-LS	0.606	0.277	0.074	0.043	0.972	7.8	7.2	18	0.999981	1988
18	ROVNO88-2S	Gd-LS	0.557	0.313	0.076	0.054	0.959	7.8	7.2	25	0.999964	1988
19	ROVNO88-3S	Gd-LS	0.606	0.274	0.074	0.046	0.938	7.2	7.2	18	0.999981	1988
20	Palo Verde	Gd-LS	0.60	0.27	0.07	0.06	0.975	6.0	2.7	750–890	0.967	2001
21	Chooz	Gd-LS	0.496	0.351	0.087	0.066	0.961	4.2	2.7	998–1115	0.954	1999

White Paper, arXiv:1204.5379

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_2O	888.7	0.538	0.328	0.078	0.056	0.987	0.926	3.0	3.0	15
ROVNO91	^{3}He+H_2O	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	≃ 1	—	—	—	0.832	0.7882	9.5	6.0	9
Krasn. I	^{3}He+PE	899	≃ 1	—	—	—	1.013	0.920	5.8	4.9	33
Krasn. II	^{3}He+PE	899	≃ 1	—	—	—	1.031	0.937	20.3	4.9	92
Krasn. III	^{3}He+PE	899	≃ 1	—	—	—	0.989	0.931	4.9	4.9	57
SRP I	Gd-LS	887	≃ 1	—	—	—	0.987	0.936	3.7	3.7	18
SRP II	Gd-LS	887	≃ 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

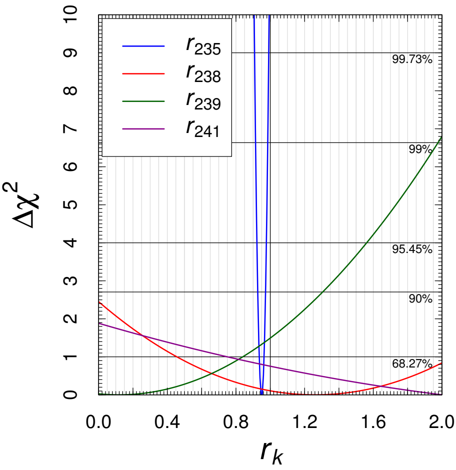
←NO!

Rescaling from Saclay to Saclay+Huber ratios:

$$R^{\text{exp}}_{a,\text{SH}} = R^{\text{exp}}_{a,\text{S}} \frac{\sum_k f^a_k \sigma^{\text{S}}_{f,k}}{\sum_k f^a_k \sigma^{\text{SH}}_{f,k}}$$

a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$R^{exp}_{a,SH}$	σ^{exp}_a [%]	σ^{cor}_a [%]	L_a [m]
1	Bugey-4	0.538	0.078	0.328	0.056	0.932	1.4	1.4	15
2	Rovno91	0.606	0.074	0.277	0.043	0.930	2.8		18
3	Rovno88-1I	0.607	0.074	0.277	0.042	0.907	6.4	3.8	18
4	Rovno88-2I	0.603	0.076	0.276	0.045	0.938	6.4		18
5	Rovno88-1S	0.606	0.074	0.277	0.043	0.962	7.3	2.2	18
6	Rovno88-2S	0.557	0.076	0.313	0.054	0.949	7.3	3.8	25
7	Rovno88-2S	0.606	0.074	0.274	0.046	0.928	6.8		18
8	Bugey-3-15	0.538	0.078	0.328	0.056	0.936	4.2		15
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942	4.3	4.0	40
10	Bugey-3-95	0.538	0.078	0.328	0.056	0.867	15.2		95
11	Gosgen-38	0.619	0.067	0.272	0.042	0.955	5.4		37.9
12	Gosgen-46	0.584	0.068	0.298	0.050	0.981	5.4	2.0	45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	0.915	6.7	3.8	64.7
14	ILL	1	0	0	0	0.792	9.1		8.76
15	Krasnoyarsk87-33	1	0	0	0	0.925	5.0	4.1	32.8
16	Krasnoyarsk87-92	1	0	0	0	0.942	20.4		92.3
17	Krasnoyarsk94-57	1	0	0	0	0.936	4.2	0	57
18	Krasnoyarsk99-34	1	0	0	0	0.946	3.0	0	34
19	SRP-18	1	0	0	0	0.941	2.8	0	18.2
20	SRP-24	1	0	0	0	1.006	2.9	0	23.8
21	Nucifer	0.926	0.061	0.008	0.005	1.014	10.7	0	7.2
22	Chooz	0.496	0.087	0.351	0.066	0.996	3.2	0	$\approx$ 1000
23	Palo Verde	0.600	0.070	0.270	0.060	0.997	5.4	0	$\approx$ 800
24	Daya Bay	0.561	0.076	0.307	0.056	0.946	2.0	0	$\approx$ 550
25	RENO	0.569	0.073	0.301	0.056	0.946	2.1	0	$\approx$ 410
26	Double Chooz	0.511	0.087	0.340	0.062	0.935	1.4	0	$\approx$ 415

- Theoretical ratios: $R_a^{\text{th}} = \dfrac{\sum_k f_k^a r_k \sigma_{f,k}^{\text{SH}}}{\sum_k f_k^a \sigma_{f,k}^{\text{SH}}}$ Unknowns: $r_{235}, r_{238}, r_{239}, r_{241}$
- Least-squares function: $\chi^2 = \sum_{a,b} \left(R_a^{\text{th}} - R_{a,\text{SH}}^{\text{exp}}\right) \left(V^{-1}\right)_{ab} \left(R_b^{\text{th}} - R_{b,\text{SH}}^{\text{exp}}\right)$



$r_{235} = 0.950 \pm 0.014$

Precise determination of the ^{235}U cross section per fission:

$$\sigma_{f,235} = (6.35 \pm 0.09) \times 10^{-43} \, \frac{\text{cm}^2}{\text{fission}}$$

2.0σ smaller than

$$\sigma_{f,235}^{\text{SH}} = (6.69 \pm 0.14) \times 10^{-43} \, \frac{\text{cm}^2}{\text{fission}}$$

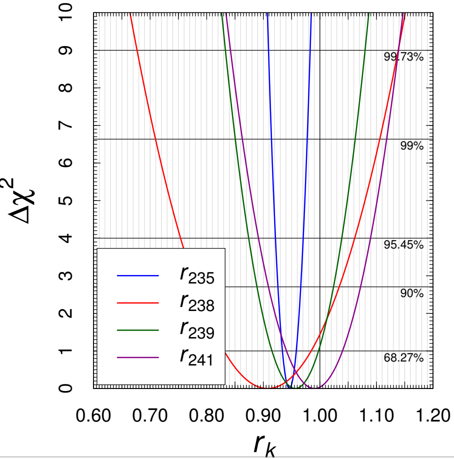
Note however the unrealistic deviations of the other fluxes, e.g.

$r_{239}^{\text{bf}} = 0.118$ and $r_{241}^{\text{bf}} = 3.490$

In order to keep under control the values of r_{238}, r_{239}, r_{241}, we add a penalty term to the least-squares function:

$$\widetilde{\chi}^2 = \chi^2 + \sum_k \left(\frac{1 - r_k}{\Delta r_k} \right)^2$$

with $\Delta r_{235} = \Delta r_{239} = \Delta r_{241} = 0.05$, and $\Delta r_{238} = 0.1$.



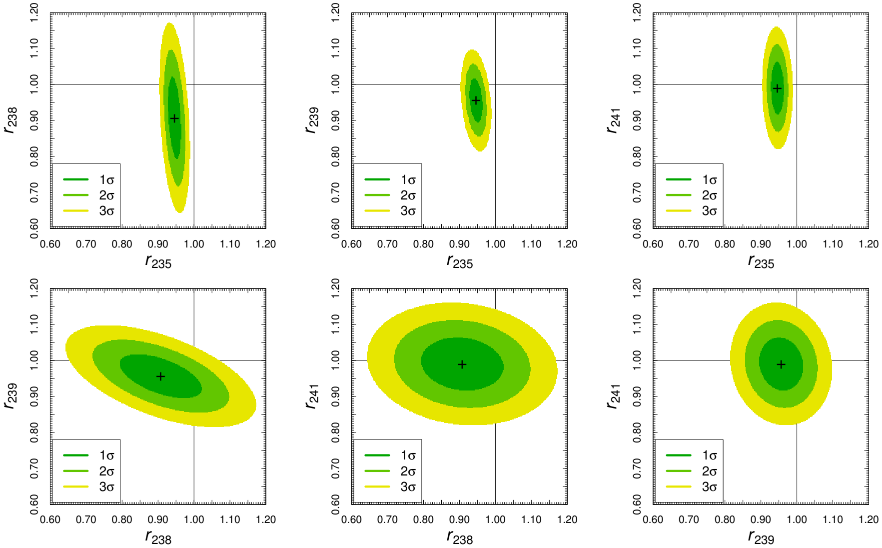
$$r_{235} = 0.946 \pm 0.012$$
$$r_{238} = 0.908 \pm 0.077$$
$$r_{239} = 0.956 \pm 0.041$$
$$r_{241} = 0.990 \pm 0.049$$

Precise and reliable determination of the ^{235}U cross section per fission:

$$\sigma_{f,235} = (6.33 \pm 0.08) \times 10^{-43} \frac{\text{cm}^2}{\text{fission}}$$

2.2σ smaller than

$$\sigma_{f,235}^{\text{SH}} = (6.69 \pm 0.14) \times 10^{-43} \frac{\text{cm}^2}{\text{fission}}$$



- Small anticorrelation of r_{235} with r_{238} and r_{239}.
- Sizable anticorrelation between r_{238} and r_{239}.
- r_{241} is practically uncorrelated with the other ratios.

- Uncertainty due to the uncertainties of the fission fractions f_k^a?

[see: Djurcic, Detwiler, Piepke, Foster, Miller, Gratta, JPG 36 (2009) 045002]

- Difficult to calculate due to the large number of experiments with mostly unknown fission fractions uncertainties and correlations.
- The most significant effect on the determination of $\sigma_{f,235}$ could come from a non-pure ^{235}U antineutrino spectrum in research reactor experiments.
- The SRP collaboration reported that "during the data collection period of this experiment, ^{239}Pu fissions constituted less than 8% of the total fissions and ^{238}U fissions less than 4%." [PRD 53 (1996) 6054]
- Considering $f_{235}^a = 0.88$, $f_{238}^a = 0.04$, $f_{239}^a = 0.08$, $f_{241}^a = 0$ for the research reactor experiments ($a = 14, \ldots, 20$) we obtained

$$r_{235} = 0.947 \pm 0.016 \qquad \sigma_{f,235} = (6.33 \pm 0.11) \times 10^{-43} \, \frac{\text{cm}^2}{\text{fission}}$$

- Result compatible with that in previous slide:

$$r_{235} = 0.946 \pm 0.012 \qquad \sigma_{f,235} = (6.33 \pm 0.08) \times 10^{-43} \, \frac{\text{cm}^2}{\text{fission}}$$

- Therefore, the determination of $\sigma_{f,235}$ is robust.

Conclusions

- If the reactor neutrino anomaly is due to an overestimation of the antineutrino fluxes, it is very likely that at least the calculation of the ^{235}U flux must be revised.

- This analysis does not give information on the cause of the theoretical excess for $\sigma_{f,235}$.

Speculations

- The theoretical excess for $\sigma_{f,235}$ could be due to an unknown imperfection in the 1985 measurement of the ^{235}U electron spectrum at ILL. [Schreckenbach, Colvin, Gelletly, Von Feilitzsch, PLB 160 (1985) 325]

- It may be possible that the reactor antineutrino anomaly and the 5 MeV bump are somewhat related and due to the ^{235}U antineutrino flux. Intriguing indications:
  - From a comparison of the NEOS and Daya Bay data P. Huber found that ^{235}U is the preferred source of the 5 MeV bump. [arXiv:1609.03910 and previous talk]
  - RENO found that the 5 MeV bump may be correlated with ^{235}U fuel fission fraction. [Hyunkwan Seo talk]