Calculated antineutrino spectra from nuclear reactor fuel isotopes fission fragments conformed with experimentally measured ones

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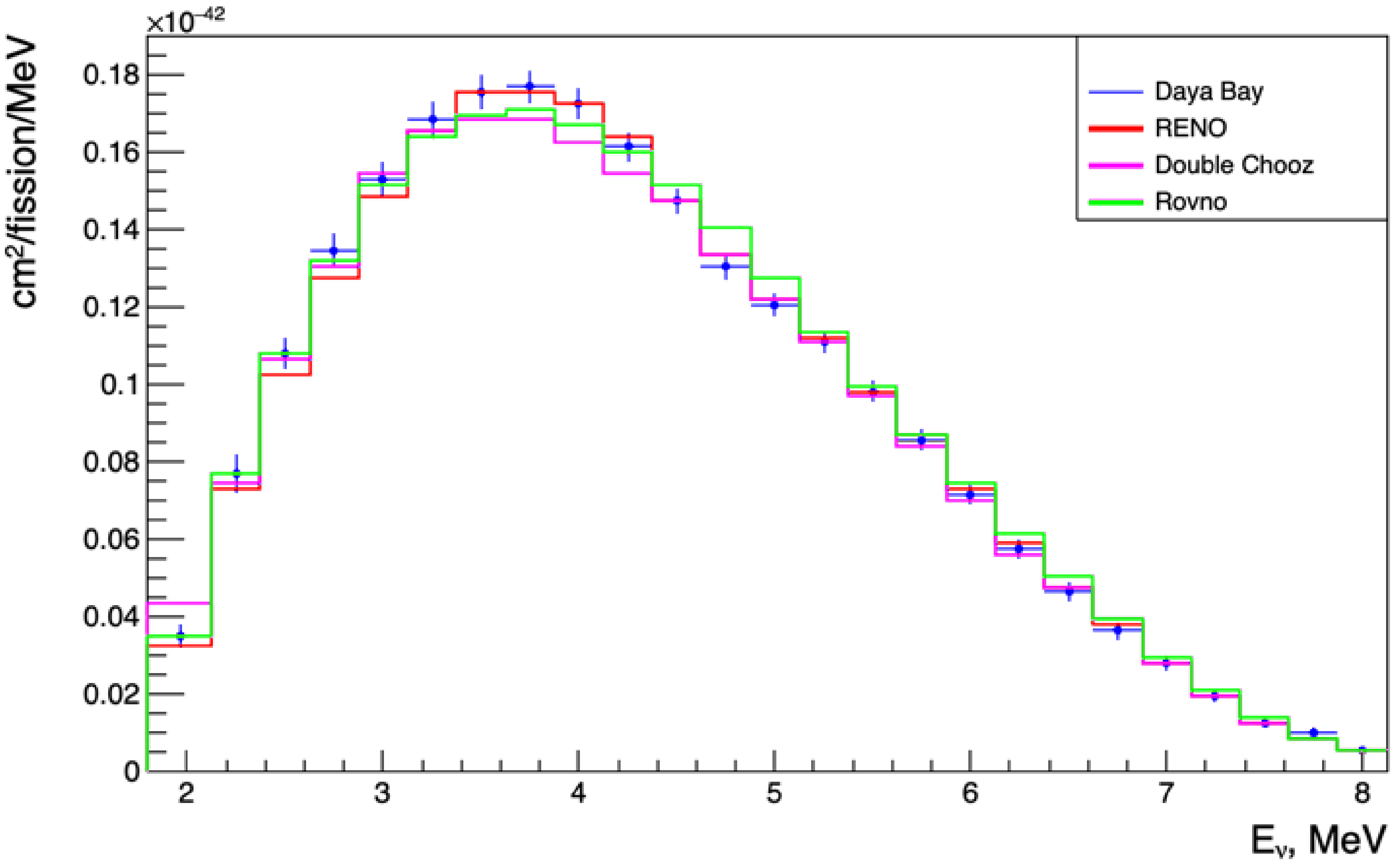
When doing experiments with reactor antineutrinos one needs to have exact antineutrino spectrum from nuclear reactor.

How to get it?

Most exact method is direct measurement.

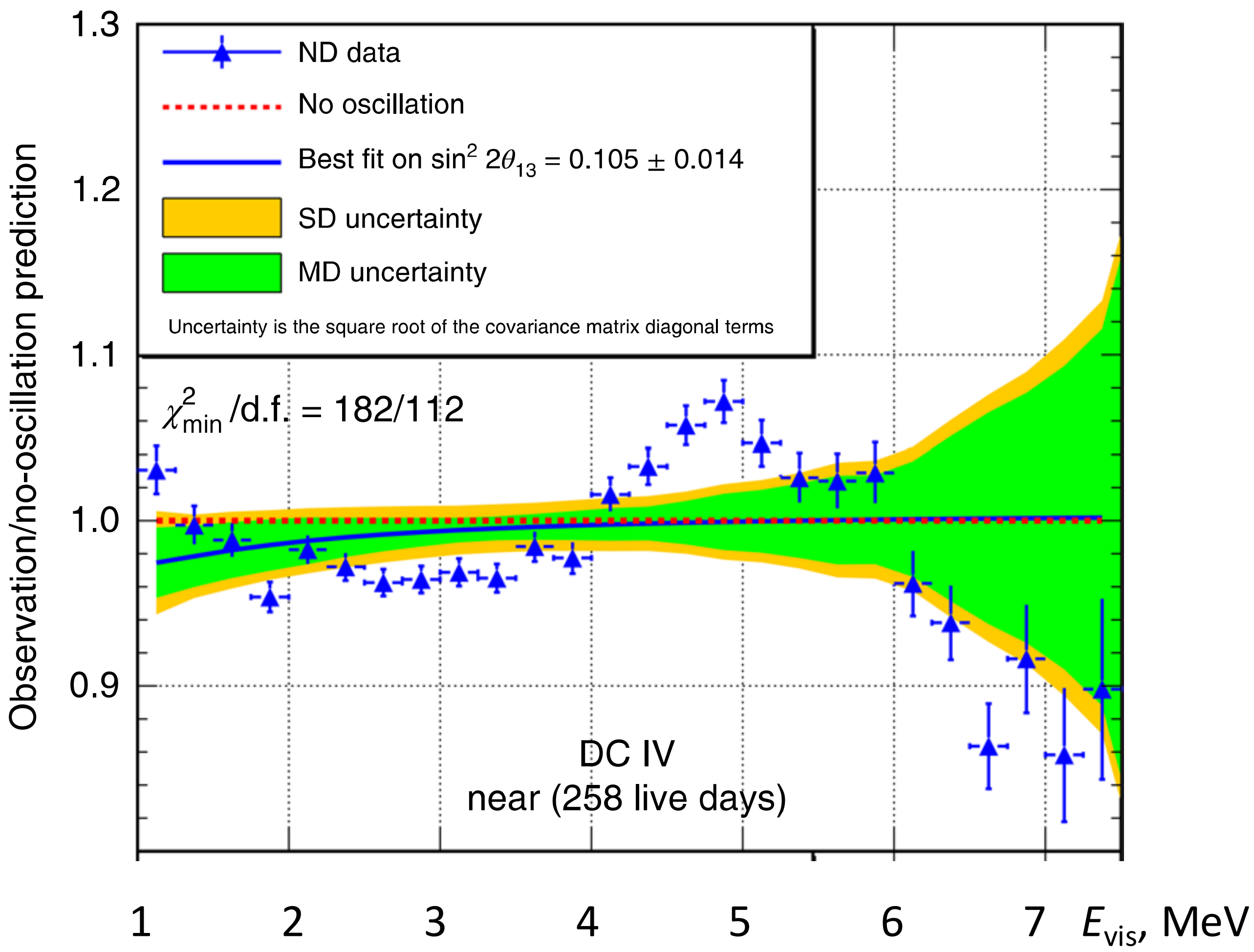
4 experimental antineutrino spectra weighted with cross section



Daya Bay	> 2 000 000
RENO	~ 800 000
Double Chooz	~200 000
Rovno	174 000

We use summation method spectrum to fit the experimental one.
For fitting there was developed the procedure allowing to change summed spectrum shape.

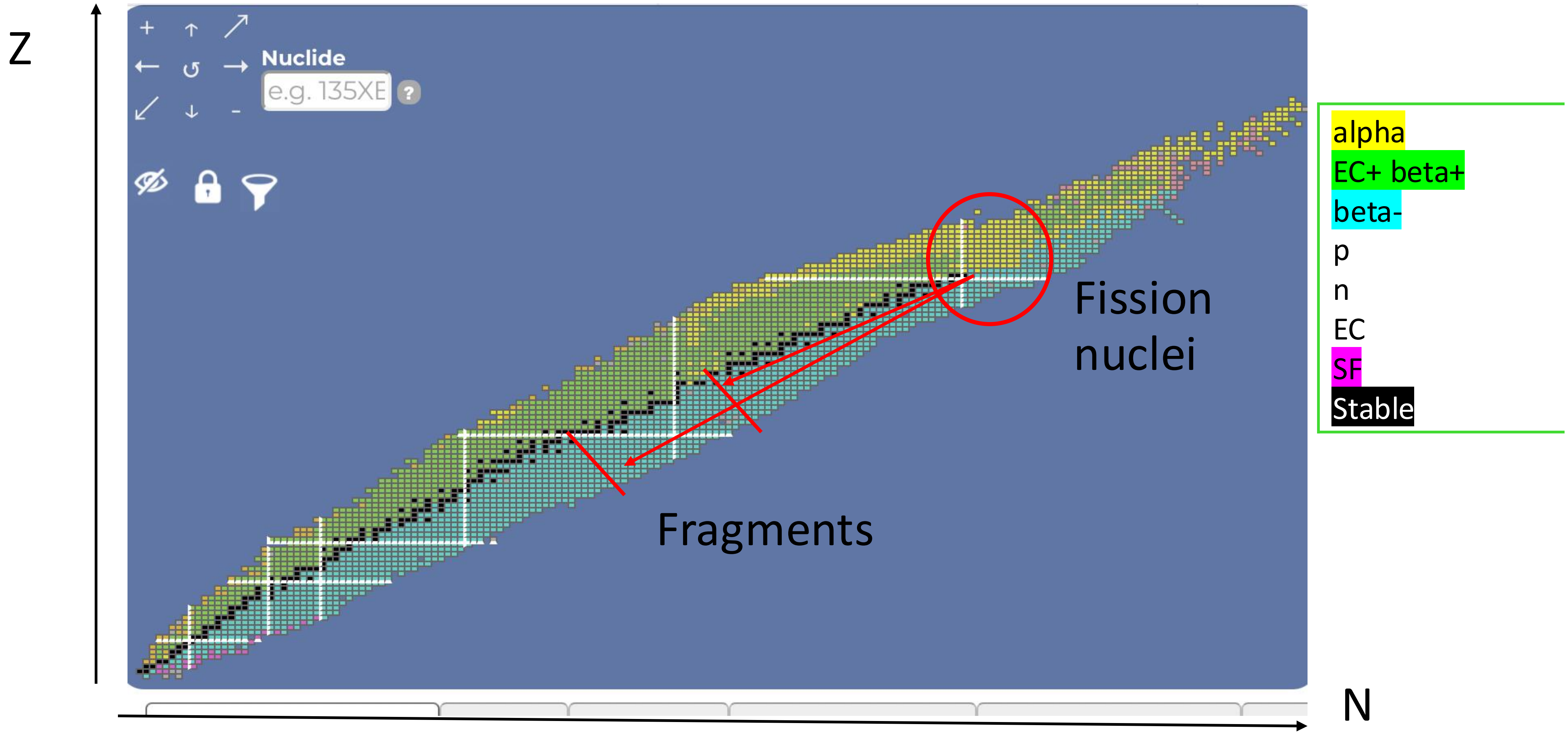
Double Chooz experimental and calculated spectra ratio



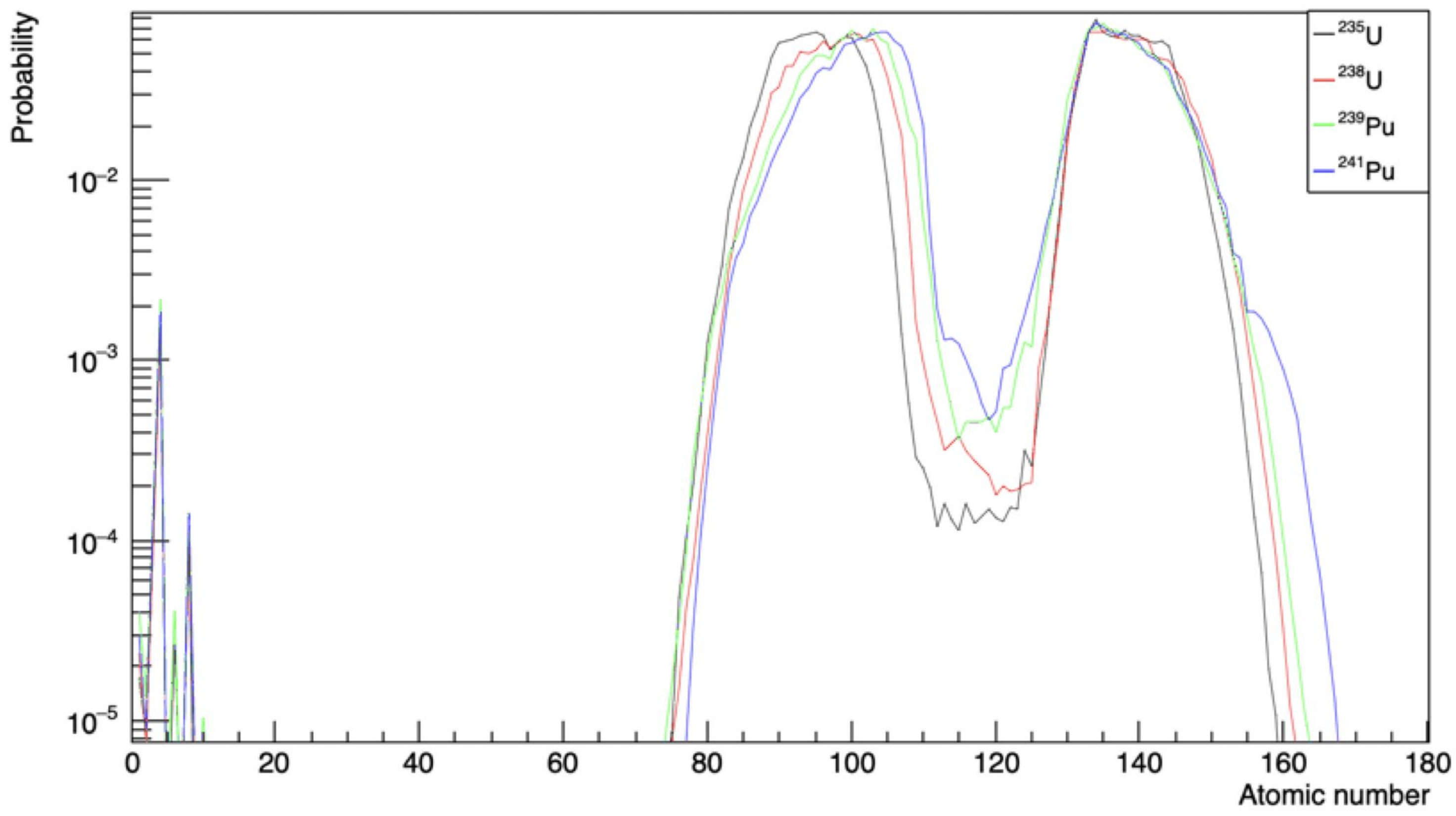
To calculated antineutrinos spectra we use standard data base for decay schemes of nuclei-fragments.

But the question : how exact they are?

The fission of heavy nucleus on two fragments



Mass distribution of fragments for fission of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu



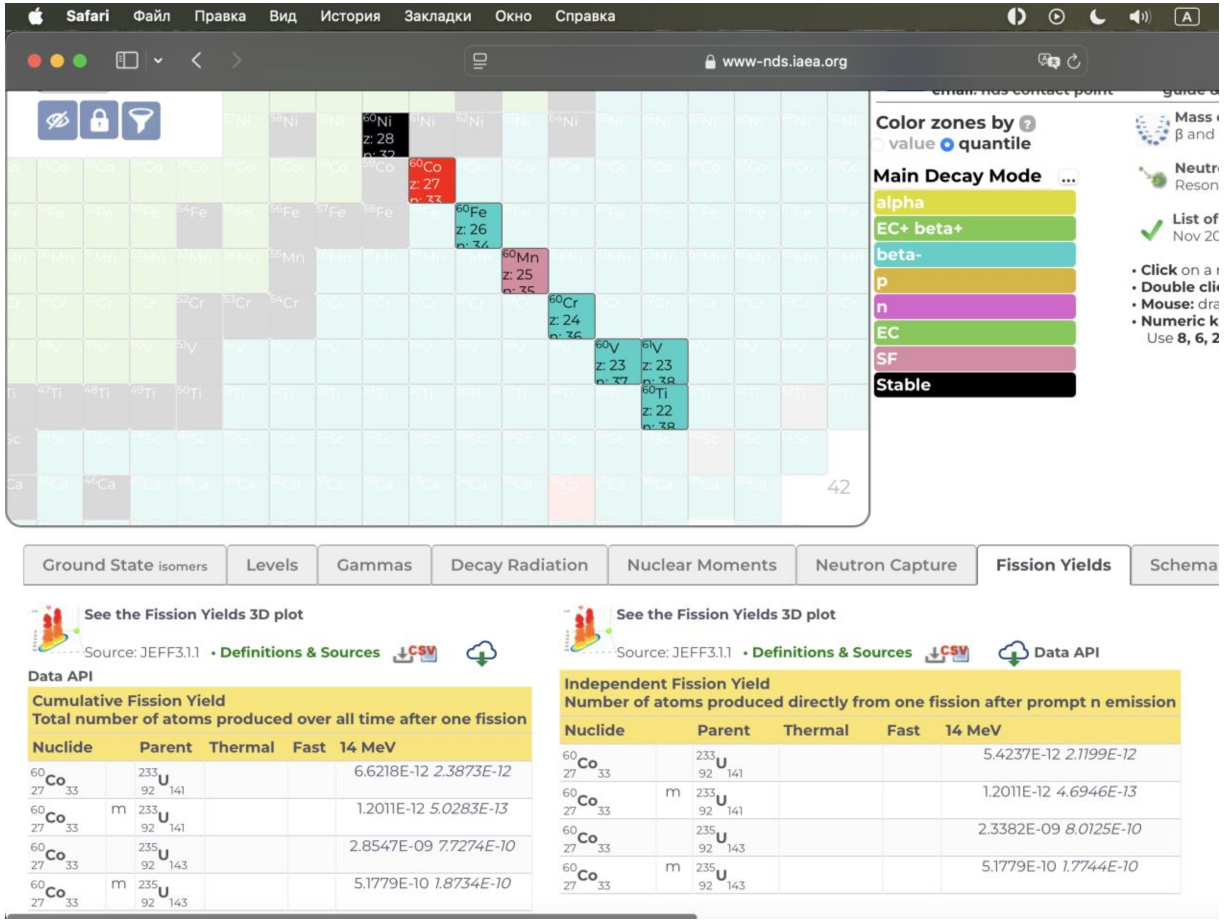
If to analyze data bases on fission fragments one can find that only one third part of all fragments is totally known, how they decay.

Another one third part has estimated decay schemes.

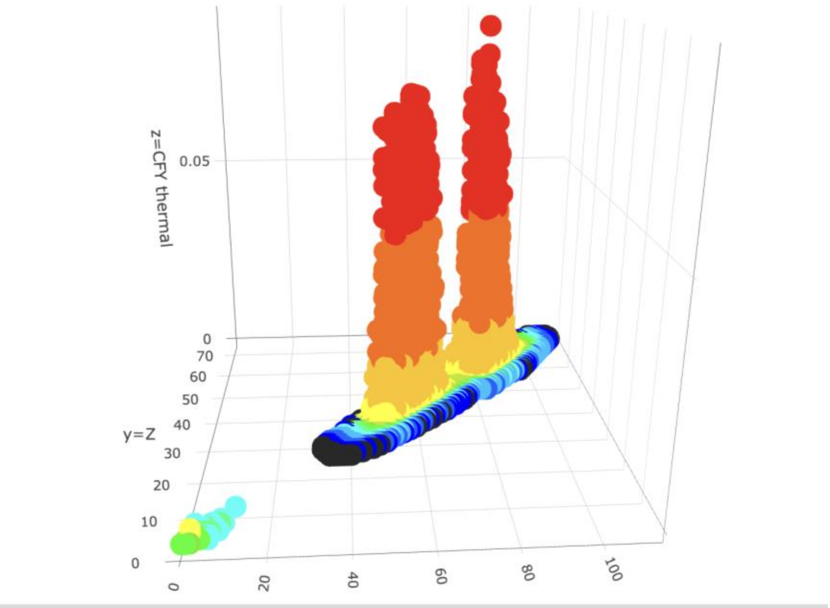
And last one third part is totally unknown.

The example of charge chain with mass A = 60

Cr 60 24 0.49 s 0 0 2.6138e-12 1.0211e-11 3 1 2
5701 0.102
6059 0.886
6111 0.012
Mn 60 25 1.77 s 0 0 2.7318e-12 5.2985e-12 8 0.885 1
5217 0.00503
5229 0.0302
5362 0.00591
5522 0.02391
5643 0.03523
5923 0.81792
6416 0.05537
6601 0.02643
Mn 60 25 0.28 s 0 0 3.0759e-13 5.9658e-13 4 1 1
6088 0.02994
6470 0.0499
7621 0.04192
8445 0.87824
Fe 60 26 2.62e+06 y 0 0 0 0 1 1 1
178 1
Co 60 27 10.467 m 0 0 0 0 2 0.0025 1
722.78 0.03459
1548.88 0.95641
Co 60 27 1925.28 d 0 0 0 0 2 1 1
317.88 0.9988
1492 0.12
Ni 60 28 1e+30 y 0 0 0 0 0 0 1



Our data base contains information on beta-decays of nuclei with masses A = 58 до A = 191
In total more than 1000 nuclei.
for ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu



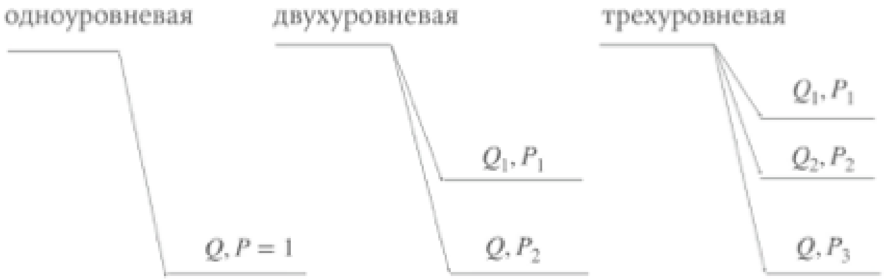
Трехмерная картинка кумулятивных выходов ядер – осколков при делении тяжелых ядер, содержащиеся в базе Live Chart of Nuclides.

Proposed method vary the probabilities of beta-decay branches to fit experimental antineutrino spectrum.

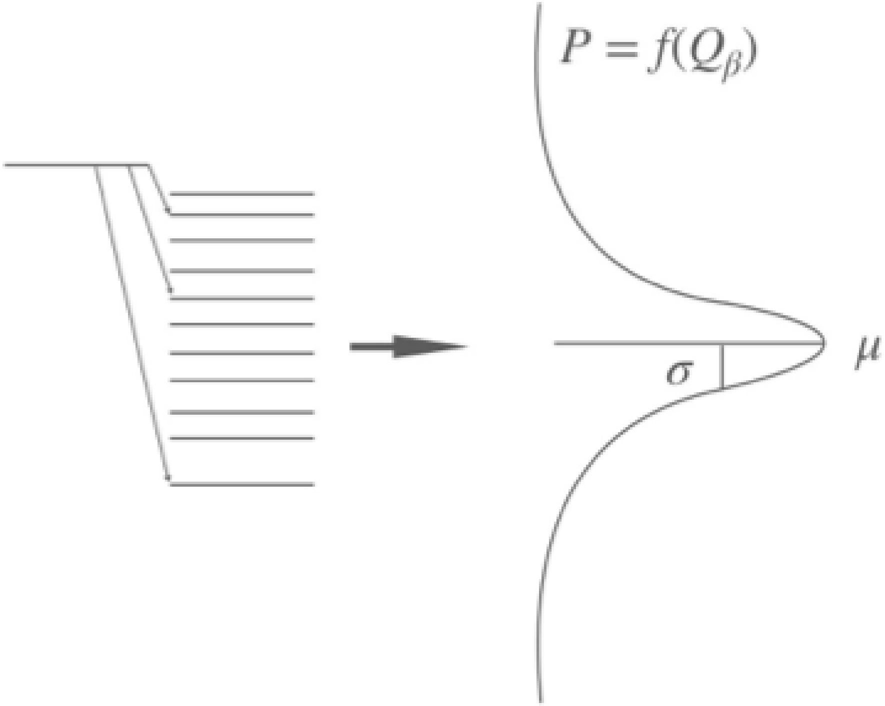
We vary probabilities of beta-decay branches for unknown fragments.

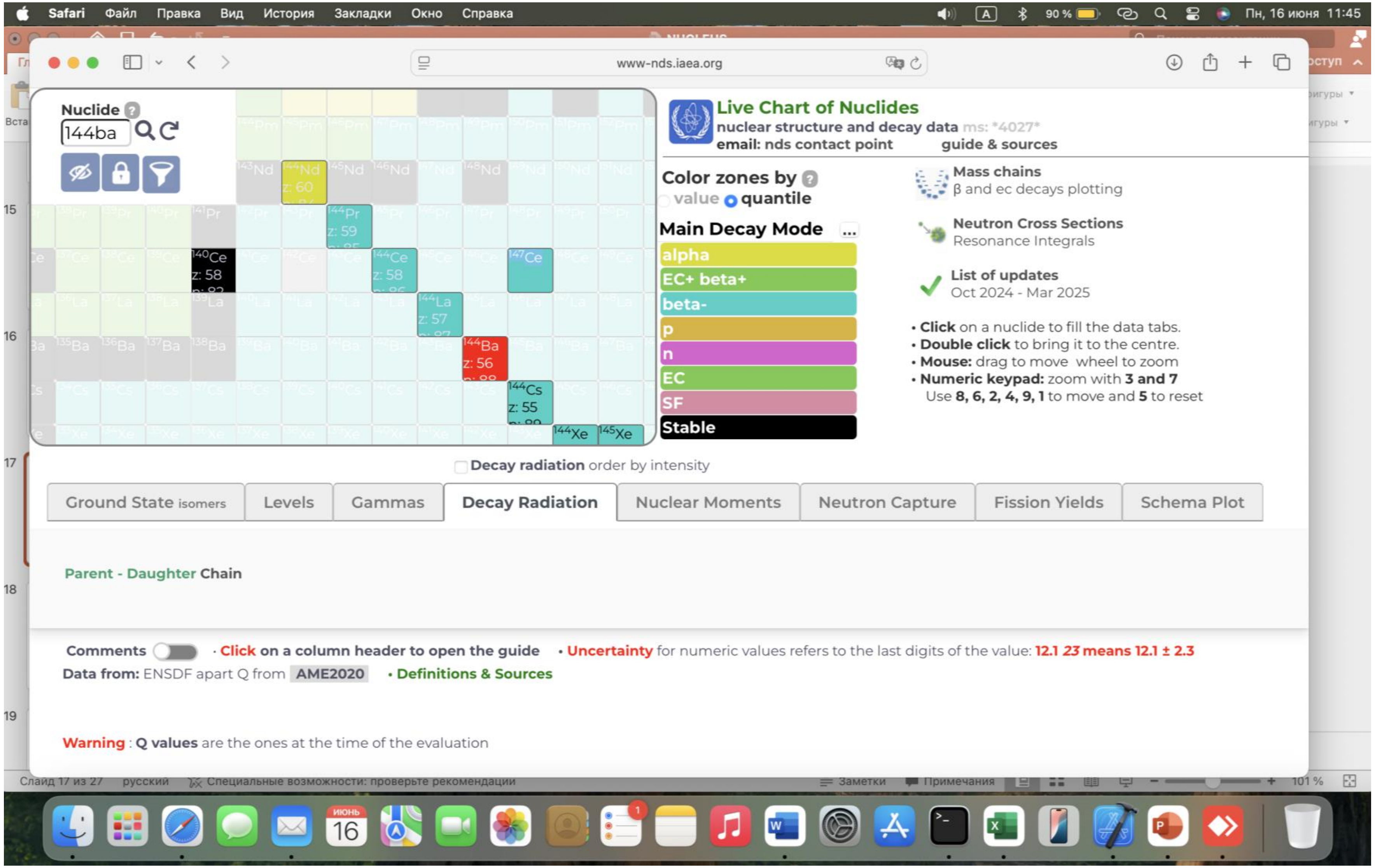
Schemes used for beta and antineutrino spectra of individual nucleus

1, 2 or 3 level equally distributed on probability



Power function levels distribution on probability

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Mass chains
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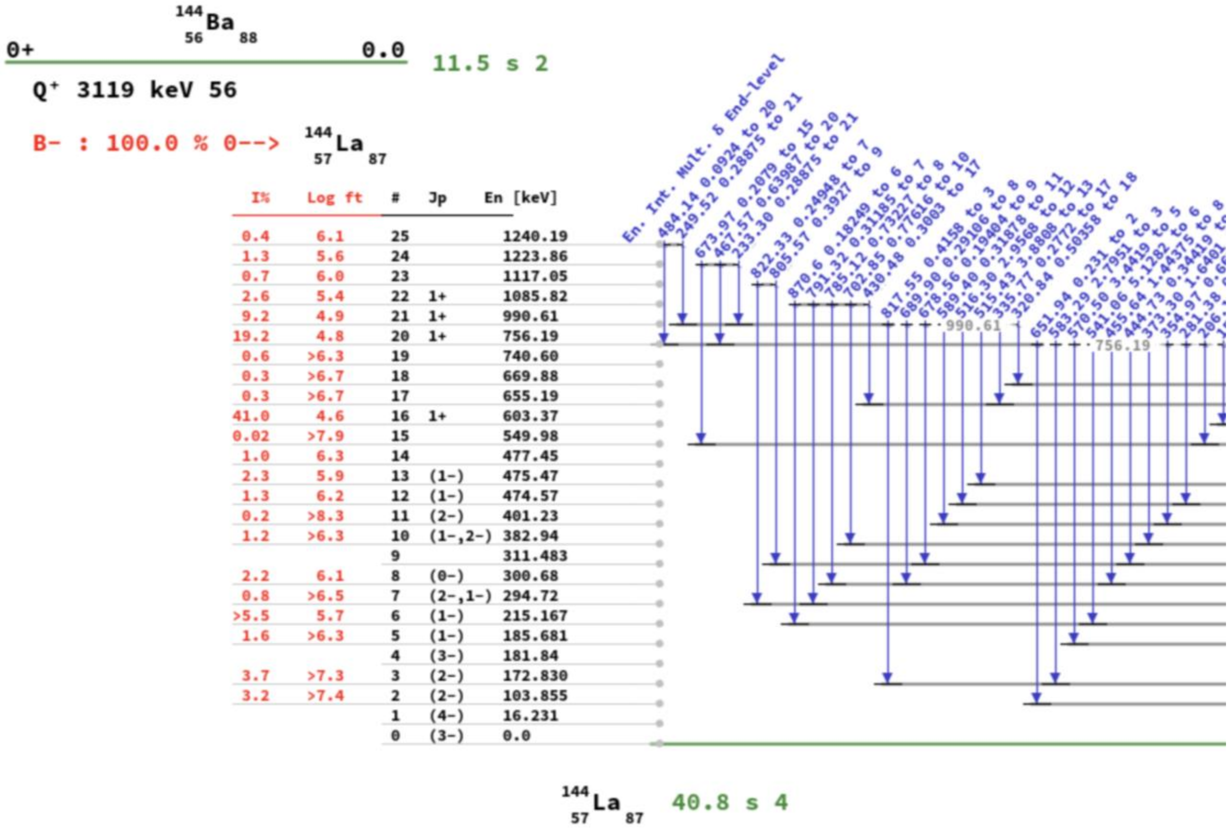
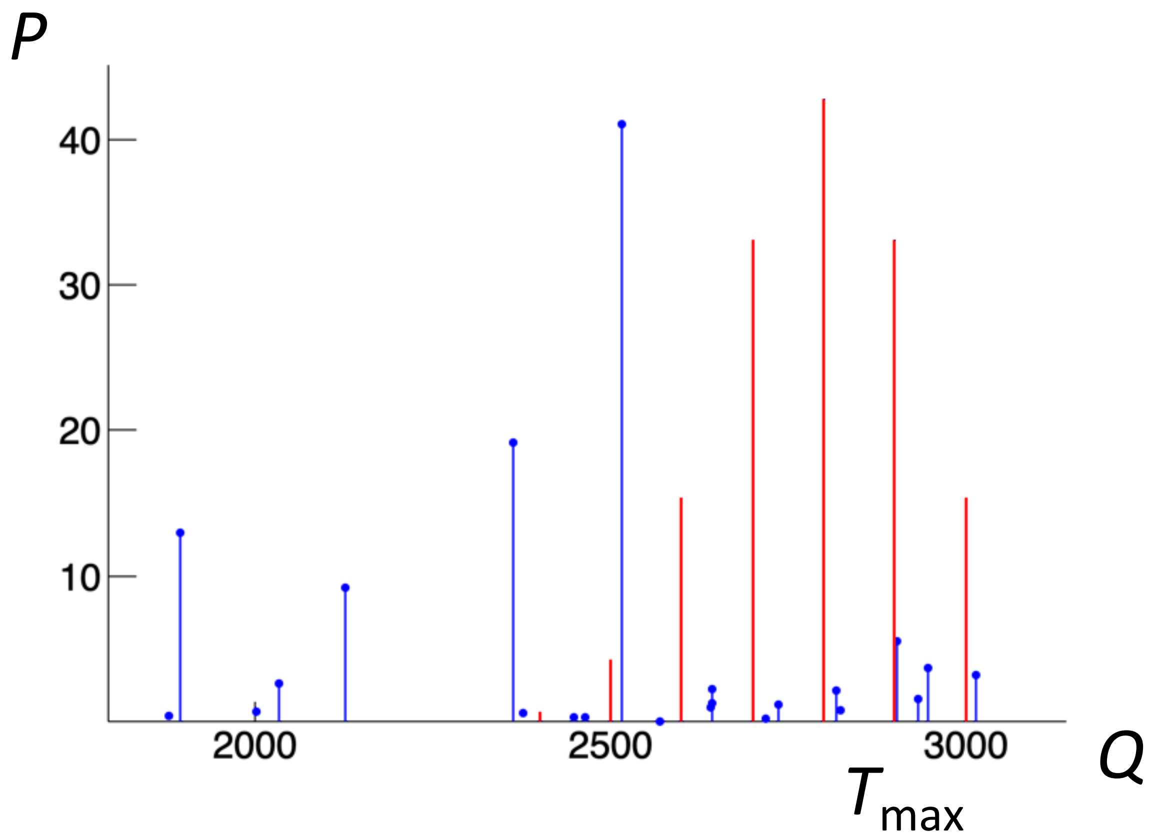
Neutron Cross Sections
Resonance Integrals
List of updates
Oct 2024 - Mar 2025
• Click on a nuclide to fill the data tabs.
• Double click to bring it to the centre.
• Mouse: drag to move wheel to zoom
• Numeric keypad: zoom with 3 and 7
Use 8, 6, 2, 4, 9, 1 to move and 5 to reset
Decay radiation order by intensity
Ground State isomers
Levels
Gammas
Decay Radiation
Nuclear Moments
Neutron Capture
Fission Yields
Schema Plot
Parent - Daughter Chain
Comments
· Click on a column header to open the guide
• Uncertainty for numeric values refers to the last digits of the value: 12.1 23 means 12.1 ± 2.3
Data from: ENSDF apart Q from AME2020
• Definitions & Sources
Warning : Q values are the ones at the time of the evaluation

Example: ^{144}Ba estimated decay scheme

#	$\langle E_{\beta-} \rangle$ [keV]	$I_{\beta-}$(abs) [%]	Daughter level [keV]	J^{π}	$E_{\beta-,\,max}$ [keV]	log*ft*	Transition type	Comments
1	720 *25*	0.4	1240.19 *10*		(1879)	6.1		
2	727 *25*	1.3	1223.86 *8*		(1895)	5.6		
3	775 *26*	0.7	1117.05 *9*		(2002)	6.0		
4	789 *26*	2.6	1085.82 *7*	1+	(2033)	5.4	allowed	
5	832 *26*	9.2	990.61 *5*	1+	(2128)	4.9	allowed	
6	938 *26*	19.2	756.19 *4*	1+	(2363)	4.8	allowed	
7	945 *26*	< 0.6	740.60 *6*		(2378)	> 6.3		
8	977 *26*	< 0.3	669.88 *5*		(2449)	> 6.7		
9	984 *26*	< 0.3	655.19 *5*		(2464)	> 6.7		
10	1007 *26*	**41.0**	603.37 *3*	1+	(2516)	4.6	allowed	
11	1032 *26*	< 0.02	549.98 *9*		(2569)	> 7.9	1st unique	
12	1065 *26*	1.0	477.45 *6*		(2642)	6.3		
13	1066 *26*	2.3	475.47 *4*	(1-)	(2644)	5.9	1st non-unique	
14	1066 *26*	1.3	474.57 *3*	(1-)	(2644)	6.2	1st non-unique	
15	1088 *26*	< 0.2	401.23 *4*	(2-)	(2718)	> 8.3	1st unique	
16	1108 *26*	< 1.2	382.94 *4*	(1-,2-)	(2736)	> 6.3		
17	1146 *26*	2.2	300.68 *4*	(0-)	(2818)	6.1	1st non-unique	
18	1149 *26*	< 0.8	294.72 *4*	(2-,1-)	(2824)	> 6.5		
19	1186 *26*	> 5.5	215.167 *6*	(1-)	(2904)	< 5.7	1st non-unique	
20	1191 *26*	< 3.7	172.830 *7*	(2-)	(2946)	> 7.3	1st unique	
21	1199 *26*	< 1.6	185.681 *6*	(1-)	(2933)	> 6.3	1st non-unique	
22	1223 *26*	< 3.2	103.855 *6*	(2-)	(3015)	> 7.4	1st unique	



We change Q the array of T_{max} for beta-decays



Method of fitting experimental spectrum with calculated one

$$= w_{235}\ y_{235} + w_{238} y_{238} + w_{239} y_{239} + w_{241} y_{241}$$

$$\chi_k^2 = \sum_{i=1}^{4} \sum_{j=1}^{26} \frac{\left(y_{exp,j} - y_{calc,j}\right)^2}{\sigma_j^2}$$

$$|\chi_k^2 - \chi_{k-1}^2| < \varepsilon$$

i – runs through antineutrino spectra (^{235}U, ^{238}U, ^{239}Pu , ^{241}Pu),
j – runs through experimental spectrum bins
k – runs through A charge chains

Criterium for fitting experimental spectra

$$\chi_k^2 = \sum_{i\,DC} \frac{\left(y_{exp,i} - y_{calc,i}\right)^2}{\sigma_i^2} + \sum_{j\,DB} \frac{\left(y_{exp,j} - y_{calc,j}\right)^2}{\sigma_j^2} + \sum_{l\,RENO} \frac{\left(y_{exp,l} - y_{calc,l}\right)^2}{\sigma_l^2} +$$

$$+ \sum_{j\,Rovno} \frac{\left(y_{exp,m} - y_{calc,m}\right)^2}{\sigma_m^2} + \frac{(\sigma_{DC} - \sigma_{calc\,DC})^2}{\Delta\sigma_{DC}^2} + \frac{(\sigma_{DB} - \sigma_{calc\,DB})^2}{\Delta\sigma_{DB}^2} + \frac{(\sigma_{RENO} - \sigma_{calc\,RENO})^2}{\Delta\sigma_{RENO}^2}$$

$$+ \frac{(\sigma_{Bugey} - \sigma_{calc\,Bugey})^2}{\Delta\sigma_{Bugey}^2}$$

$$|\chi_k^2 - \chi_{k-1}^2| < \varepsilon$$

Result of fitting makes it possible to conform calculated spectrum with the experimental one.

New calculated antineutrino spectra (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) produce cross sections that perfectly satisfy to the experimentally measured ones in Double Chooz, RENO and Daya Bay experiments as well as in the experiment Bugey-3 that was for a long time most exact experimental cross section.

Cross sections

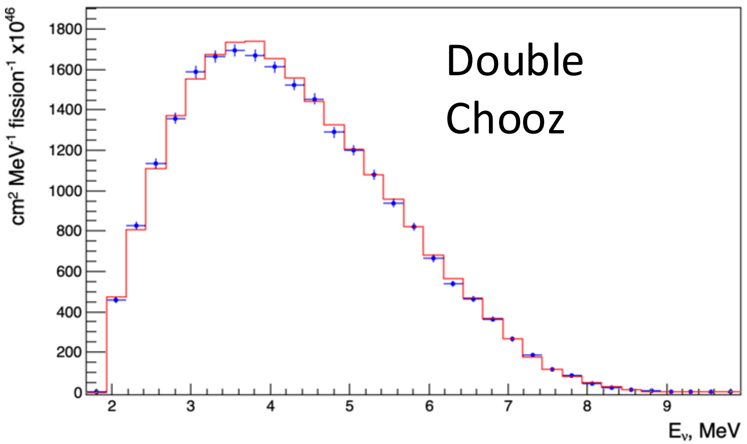
	^{235}U	^{238}U	^{239}Pu	^{241}Pu	DC
This work	**5.794**	**10.64**	**4.139**	**6.262**	**5.820**
ILL	6.426	8.929	4.204	5.796	5.866
Vogel	6.502	9.109	4.526	6.515	6.072
MEPhI	6.395	9.213	4.388	6.478	5.977
Huber & Mueller	6.681	10.12	4.387	6.081	6.180
Kopeikin et al.	6.308	9.395	4.33*	6.01*	5.900

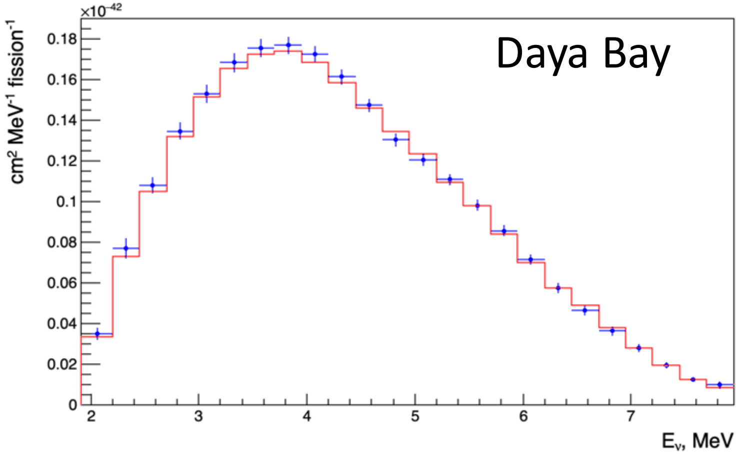
Experimental Double Chooz $\sigma_f = (5.71 \pm 0.06) \cdot 10^{-43}$ cm^2/fission

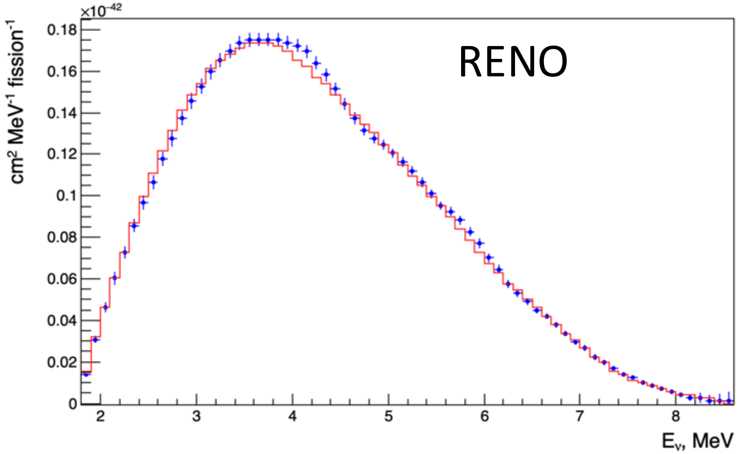
Comparison of experimental and calculated cross sections through our ^{235}U, ^{238}U, ^{239}Pu , ^{241}Pu individual spectra

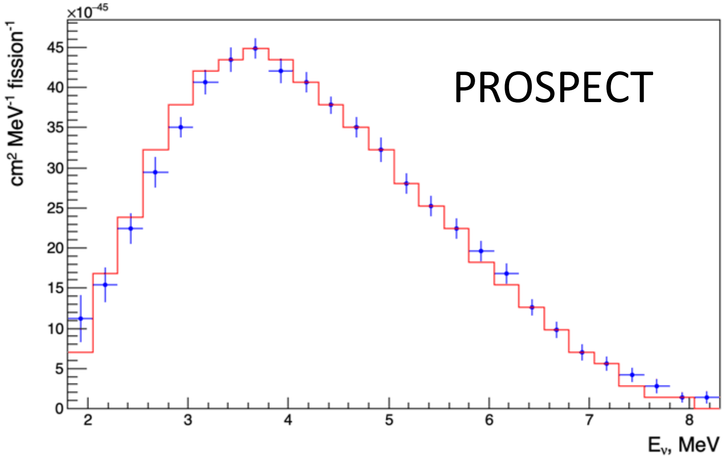
experiment	Core content				${}^{i}\sigma_f$ x10^{43} [cm²/fission]	${}^{INR}\sigma_f$ x10^{43} [cm²/fission]	R_{INR}	H-M	R_{H_M}
	^{235}U	^{238}U	^{239}Pu	^{241}Pu					
Double Chooz	0.520	0.087	0.333	0.060	**5.71** ± 0.06	5.82	0.988	6.180	0.924
Bugey-4	0.538	0.078	0.328	0.056	**5.752** ± 0.081	5.782	0.995	6.163	0.933
Daya Bay	0.561	0.076	0.307	0.056	**5.84** ± 0.07	5.804	1.006	6.204	0.927
RENO	0.571	0.073	0.300	0.056	**5.852** ± 0.094	5.801	1.009	6.210	0.926

Measured antineutrino spectra and predicted (INR) ones



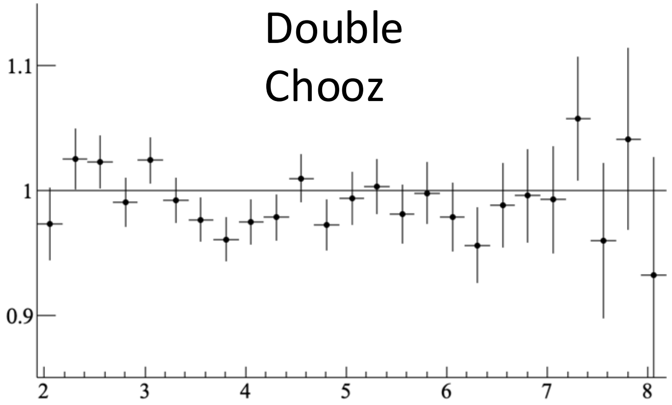




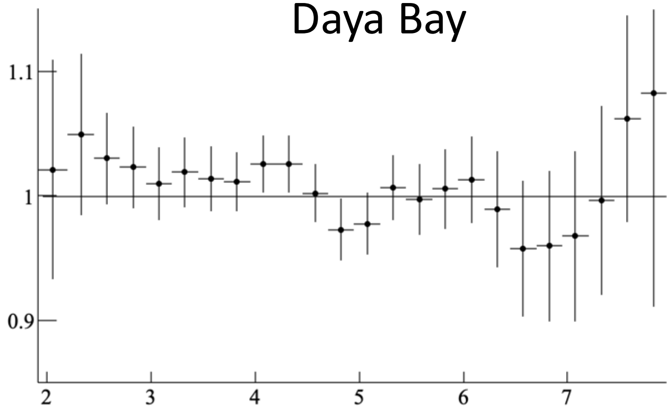


Ratio of experimental and predicted (INR) spectra

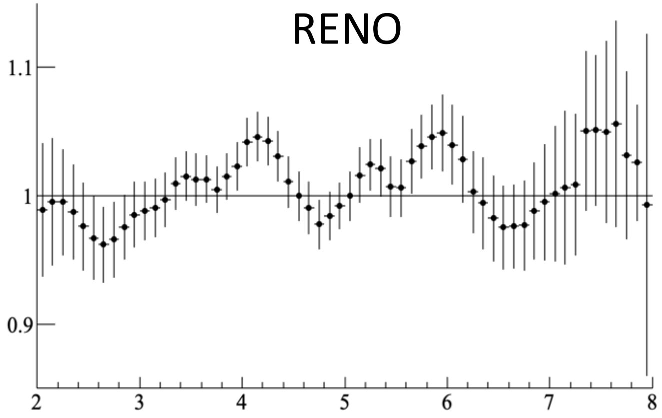
Double Chooz



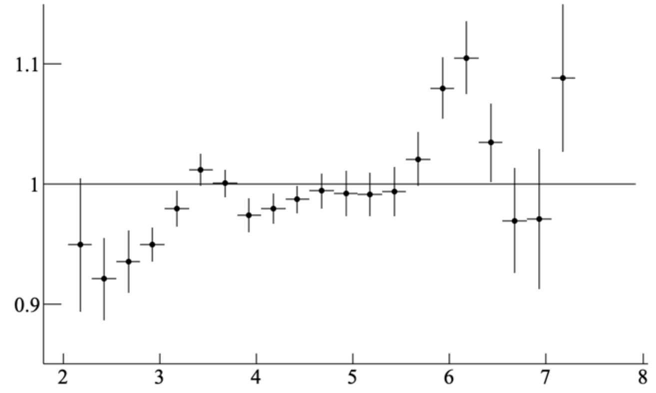
Daya Bay

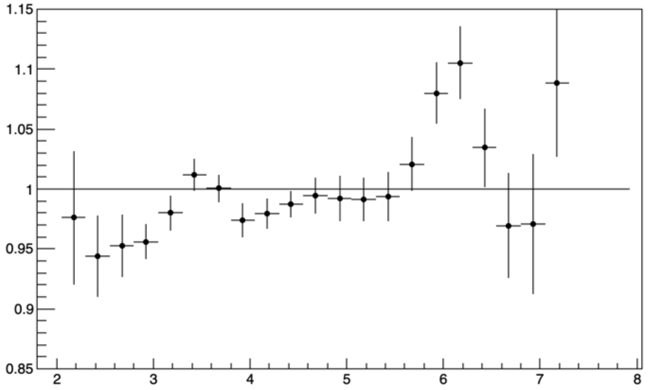


RENO



PROSPECT
with ^{235}U spectrum
for 2 years after
fission





PROSPECT
with ^{235}U spectrum
for several days after
fission

Conclusion

New method of calculation antineutrino spectra, producing by fissile isotopes of nuclear fuel placed in a reactor core, is developed. The method is based on fitting experimental spectrum by the calculated one.

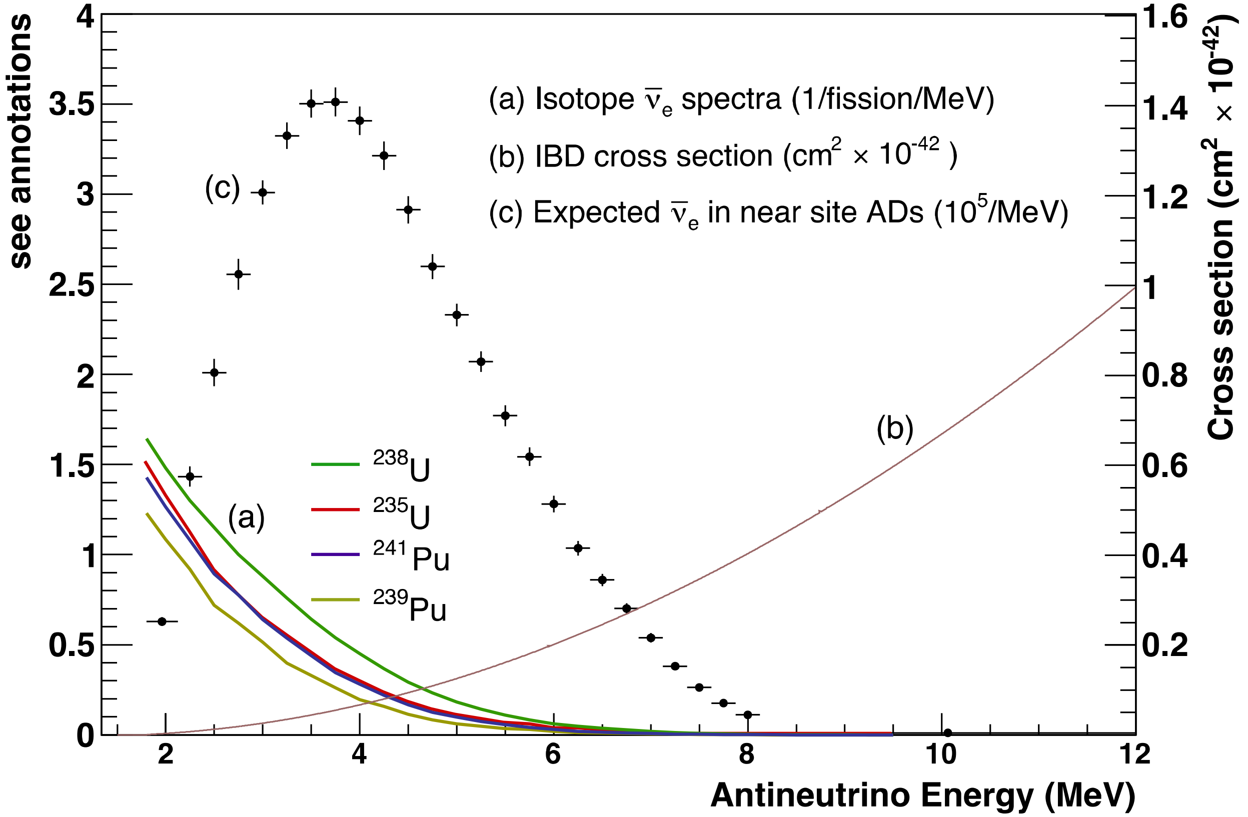
In a number of experiments reactor antineutrino spectrum was measured with high statistics. It corresponds to the standard core content on fission number from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.

During the fitting experimental antineutrino spectrum possible decay schemes for unknown fragments can be found.

Getting of exact antineutrino spectra from fissile isotopes of nuclear fuel (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) opens a real way for distant nuclear reactor monitoring.

Thank you for attention!

Experimental cross section



$$\sigma_f = \int \frac{dn}{dE}(E)\sigma(E)dE$$