Accurate antineutrino spectra from fission fragments of ^{235}U,^{238}U,^{239}Pu,^{241}Pu

and some consequences followed from the spectra obtaining procedure

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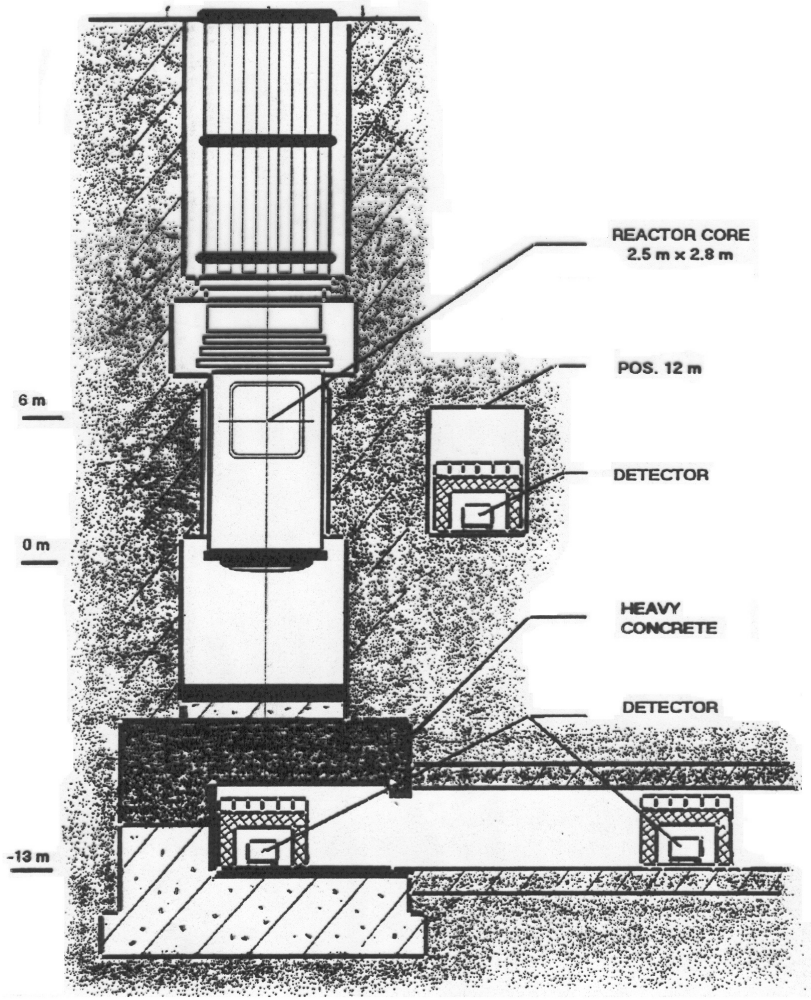
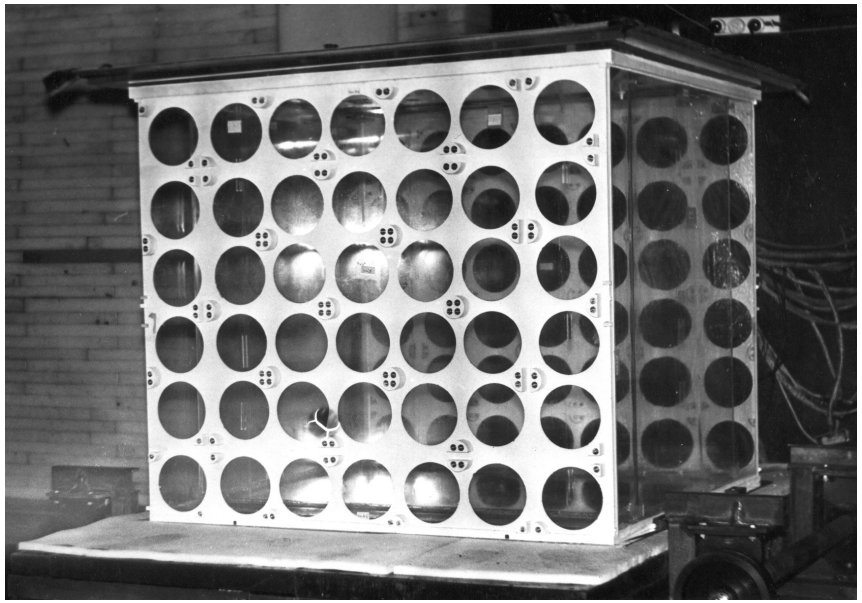
Content

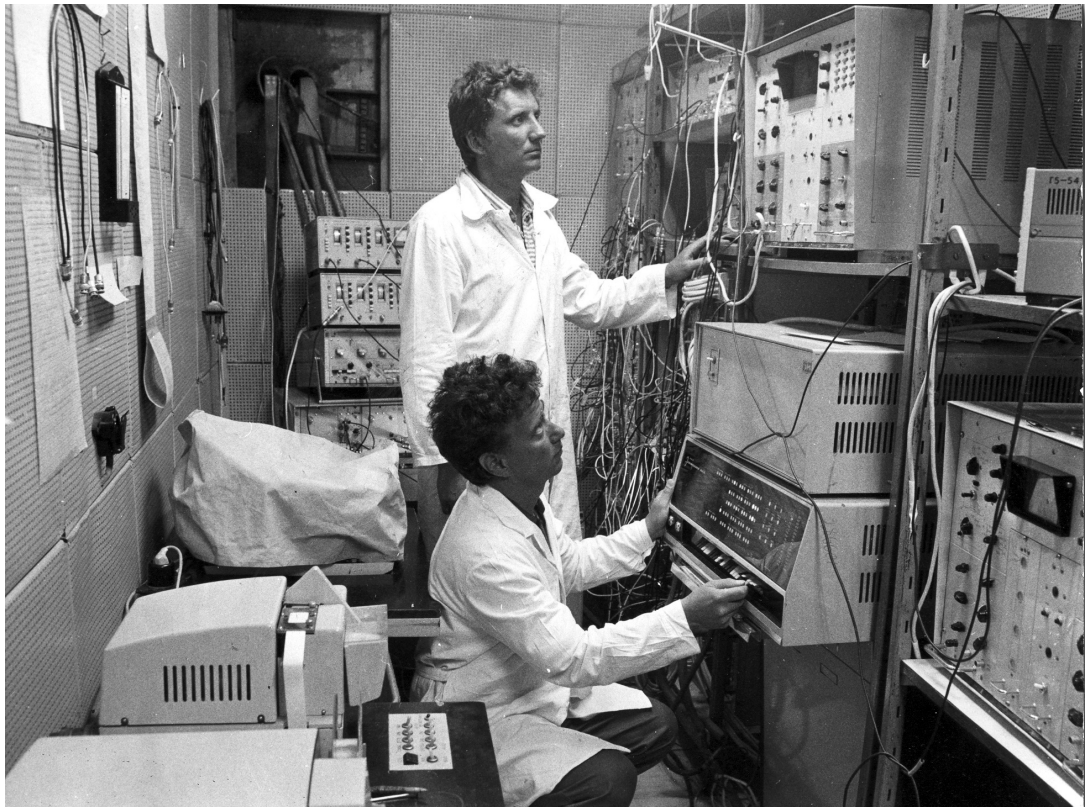
- Some history on antineutrino spectrum measurement (Rovno)
- Hugh statistics spectrum measurements Double Chooz, Daya Bay, RENO
- What individual antineutrino spectrum should be used?
- Combined method of antineutrino spectrum calculation
- Spectra ^{235}U,^{238}U,^{239}Pu,^{241}Pu
- What cross section for ^{235}U should be?
- How accurate spectra could be used?

Rovno NPP experiment in 1988-90

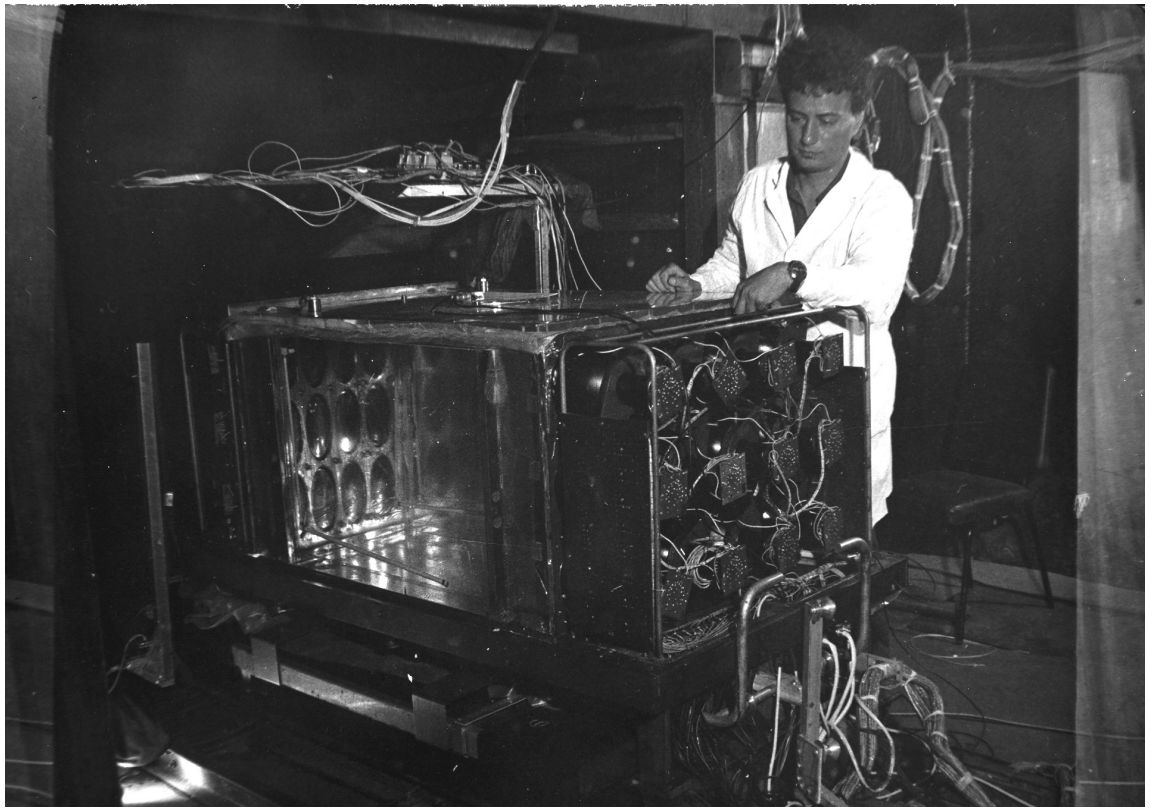




Spectrometer used in Rovno on the assembling stage



V.I. Kopeikin and A.N. Kheruvimov



Spectrometer prototype ND-1

Spectrum and cross section by RONS and WIND

Statistics 174 000 neutrino events

$$\frac{dN_\nu}{dE} = 5.09e^{-0.648E-0.0273E^2-1.411(\frac{E}{8})^{10}}$$

^{235}U	^{238}U	^{239}Pu	^{241}Pu
0.586	0.075	0.292	0.047

Cross section WIND: 5.828 ± 2.0%. Cross section RONS: 6.0 ± 3.0%

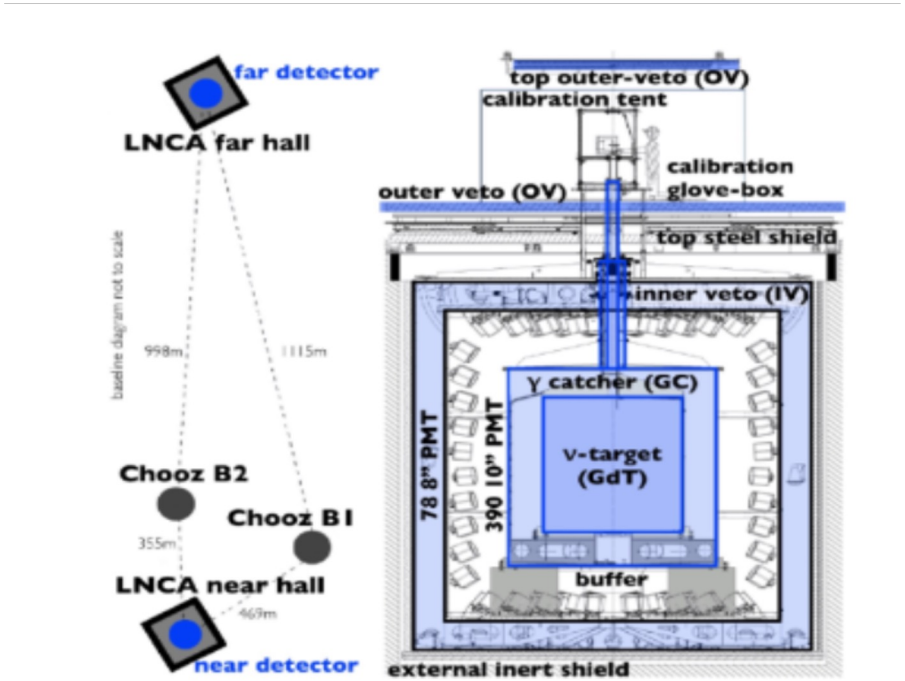
Cross section WIND: 5.85 ± 1.8% (А.А. Кувшинников, Л.А. Микаэлян, С.В. Николаев, М.Д. Скорохватов, А.В. Этенко, Письма в ЖЭТФ, 54(5), 259-262, 1991)

^{235}U	^{238}U	^{239}Pu	^{241}Pu
0.614	0.074	0.274	0.038

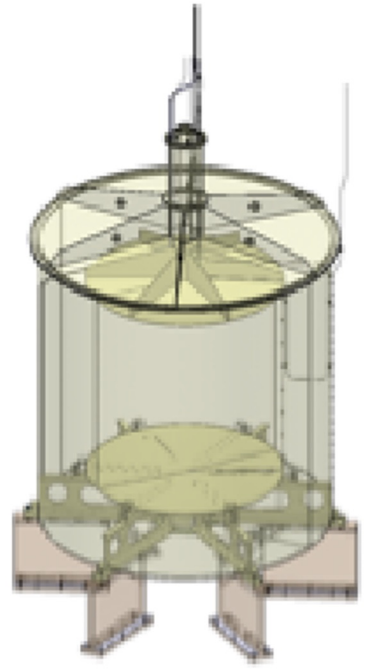
Modern high statistics reactor neutrino experiments

Double Chooz

Experiment Double Chooz has been working in 2010-2017 in France (Ardenne).
Red points mark the detector positions.



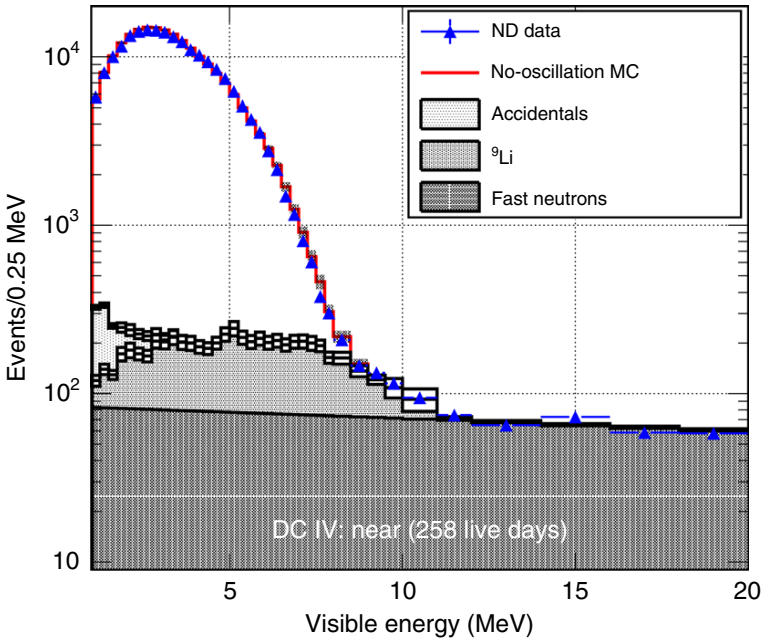
Detector Double Chooz scheme

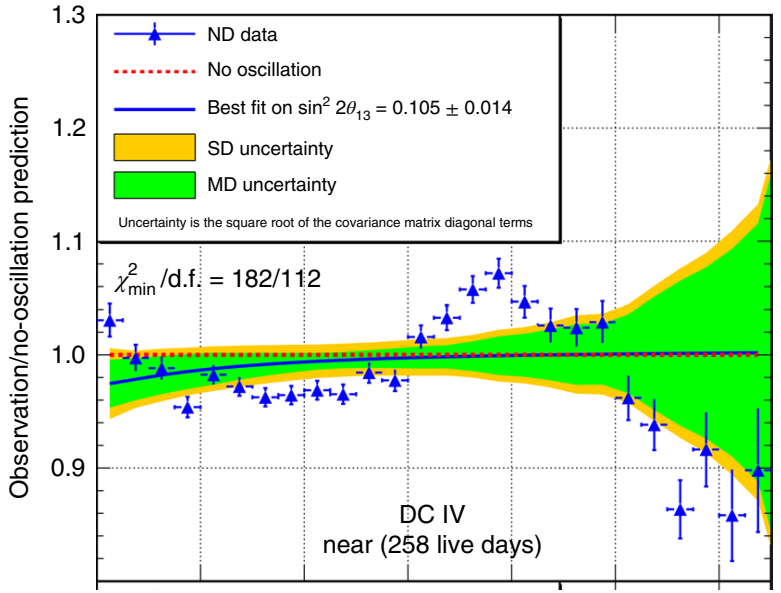


Acrylic cylinders of the target and gamma-catcher of Double Chooz detector

Double Chooz spectrum measurement by near detector

~210 000 neutrino events

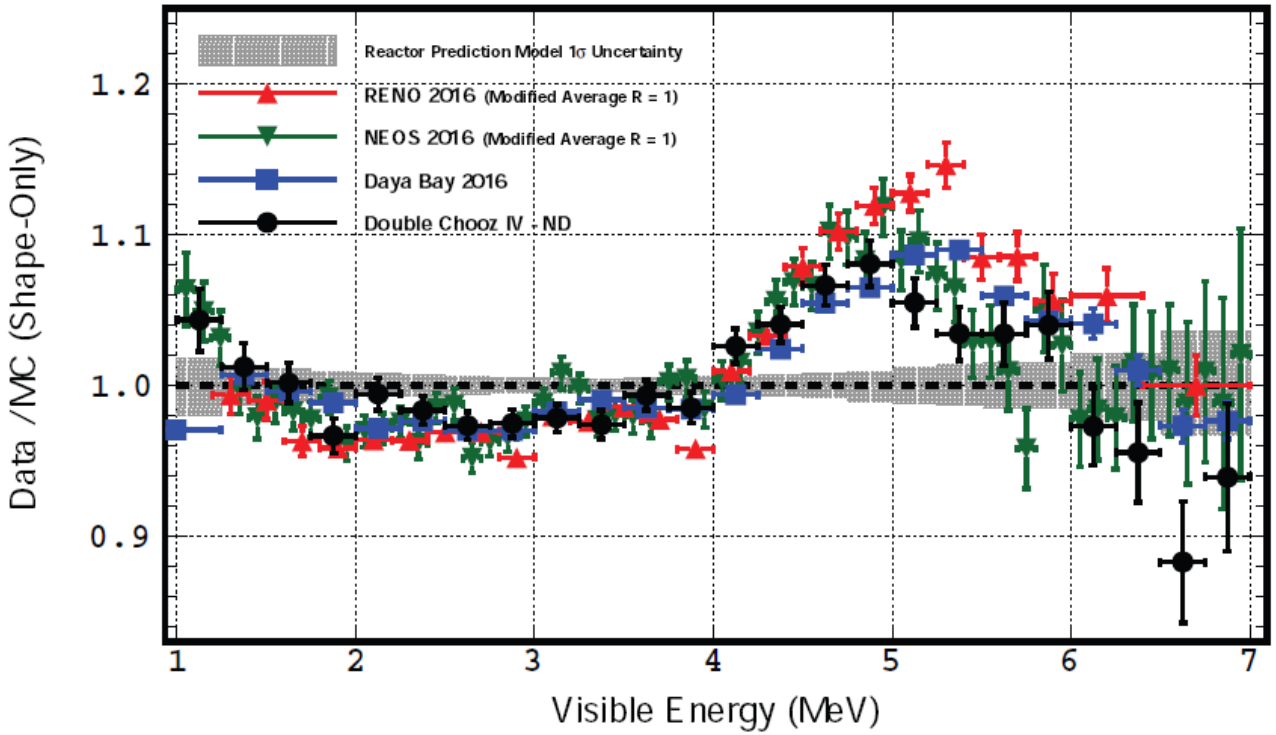




Measured spectrum ratio to the expected one calculated on base of Huber-Moeller.

BKG smaller than for RONS and energy resolution is better

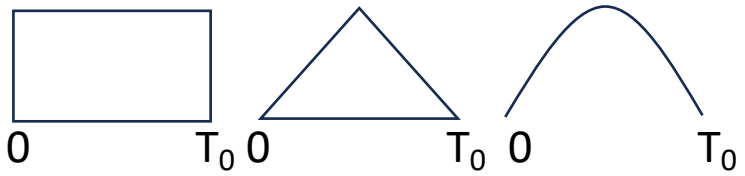
Bump at ~5 MeV of visible energy exists in all experiments: Double Chooz, Daya Bay, RENO, NEOS et al.



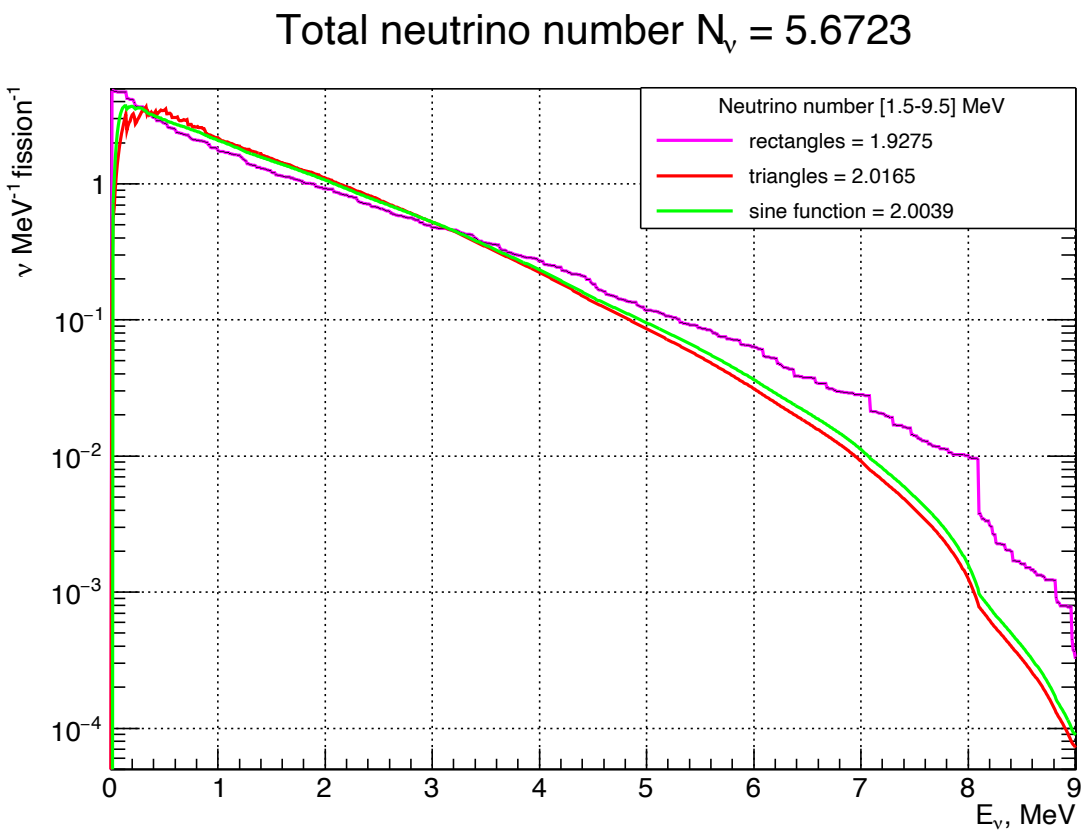
How one can correctly calculate an antineutrino spectrum?

The standard is summation method.

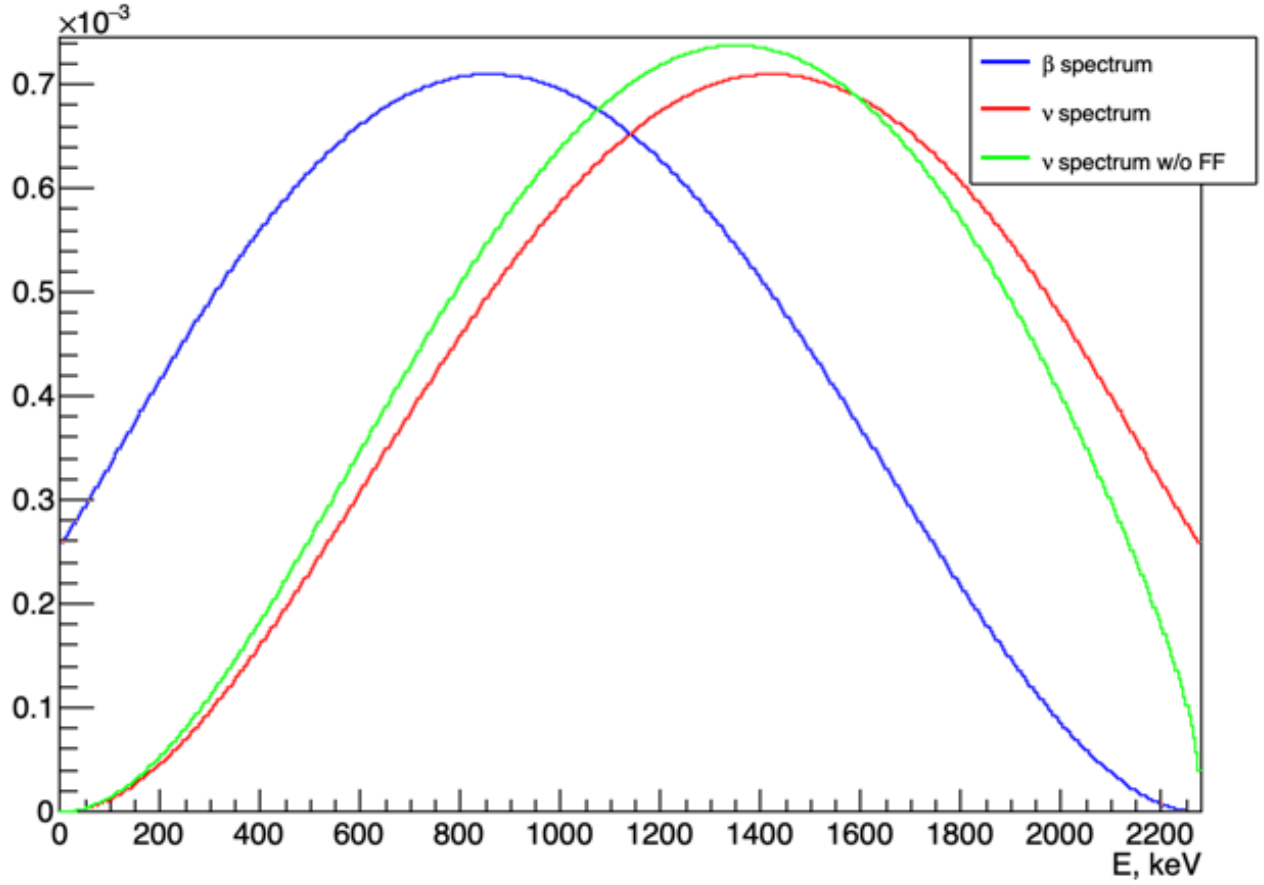
The question – if we need to know exactly the individual fragment spectrum?



If the number of individual spectra is large – the shape of separate spectrum does not important



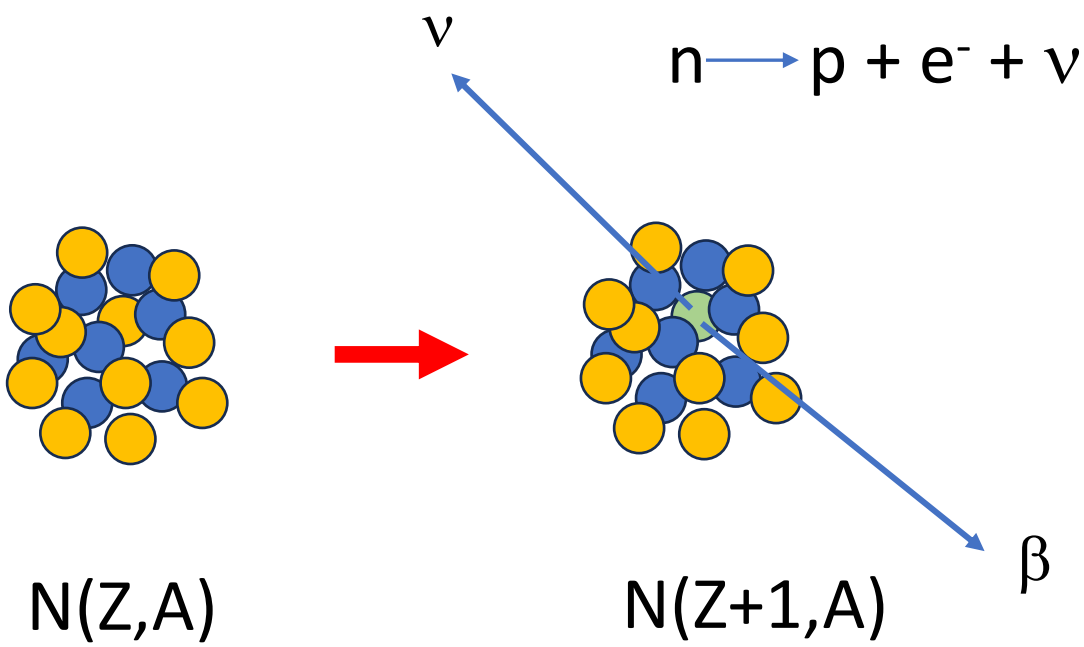
Which individual spectrum one should use?



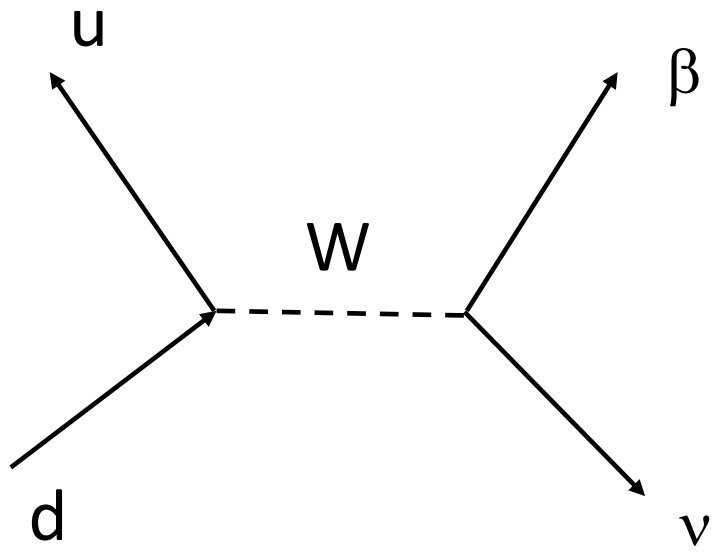
The energy conservation law acts in the moment of particles production.

But later each particle has its individual fate.

Beta-decay



$\tau_W = 3\ 10^{-25}$ c



Distance at which W decays on electron and antineutrino, is about 10^{-14} cm. Neutron radius is estimated as $1.2\text{-}1.3 \cdot 10^{-13}$ cm.

This means that decay happens inside a neutron.

Usually a calculation uses data on decay-schemes keeping in databases. These data contain multiple branches of beta-decay.

How accurate these data?

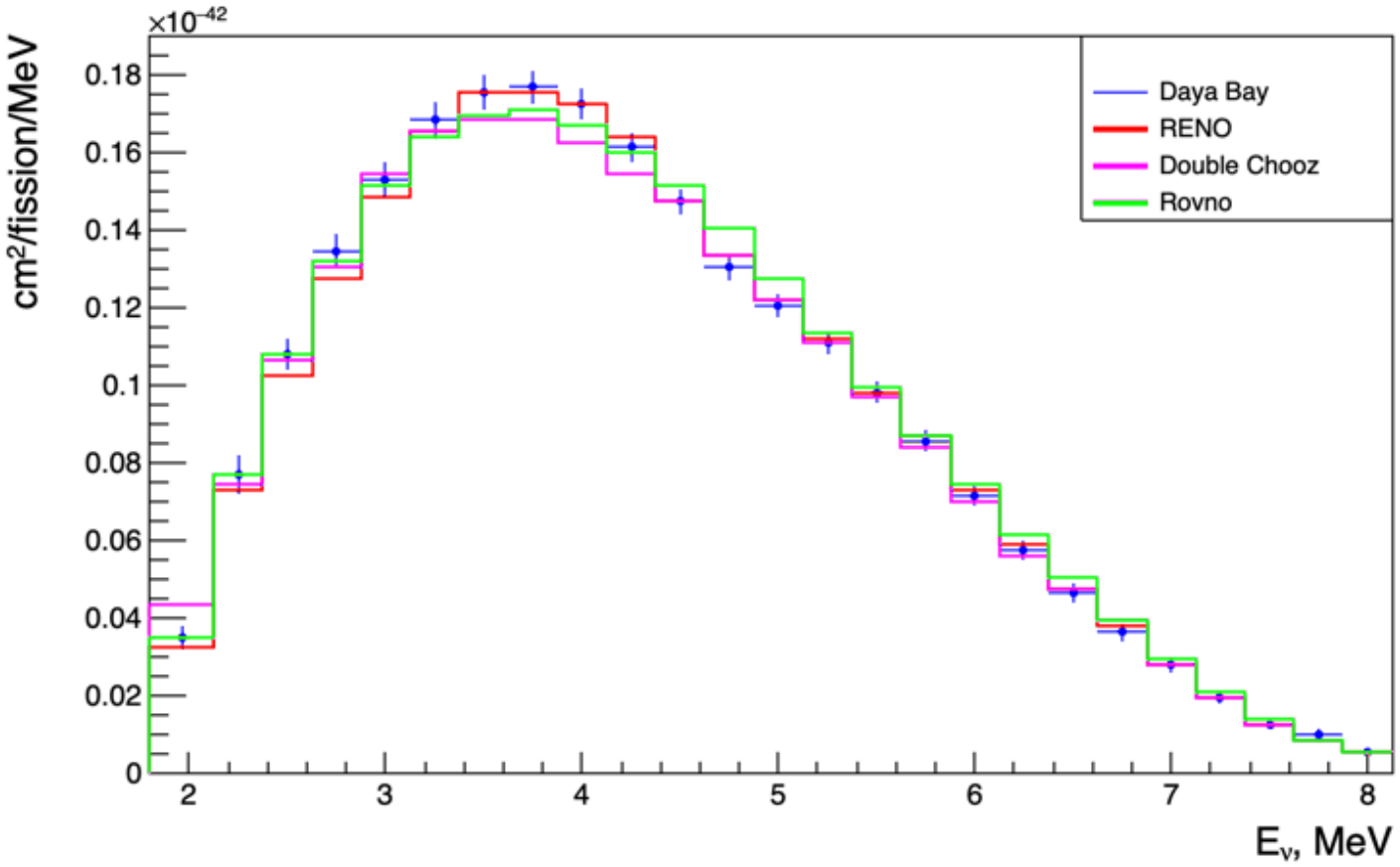
Fission fragment yields are known with uncertainty estimated as 5%

We surely know branching for about 1/3 of all known fragments. These are mainly long-lived nuclei.

For about 1/3 of fragments branching is totally unknown. These nuclei are far from the line of beta-stability.

And about 1/3 of fragments have branching calculated, we can say estimated.

Experimental antineutrino spectra weighted with IBD cross section



χ^2 square for minimization

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

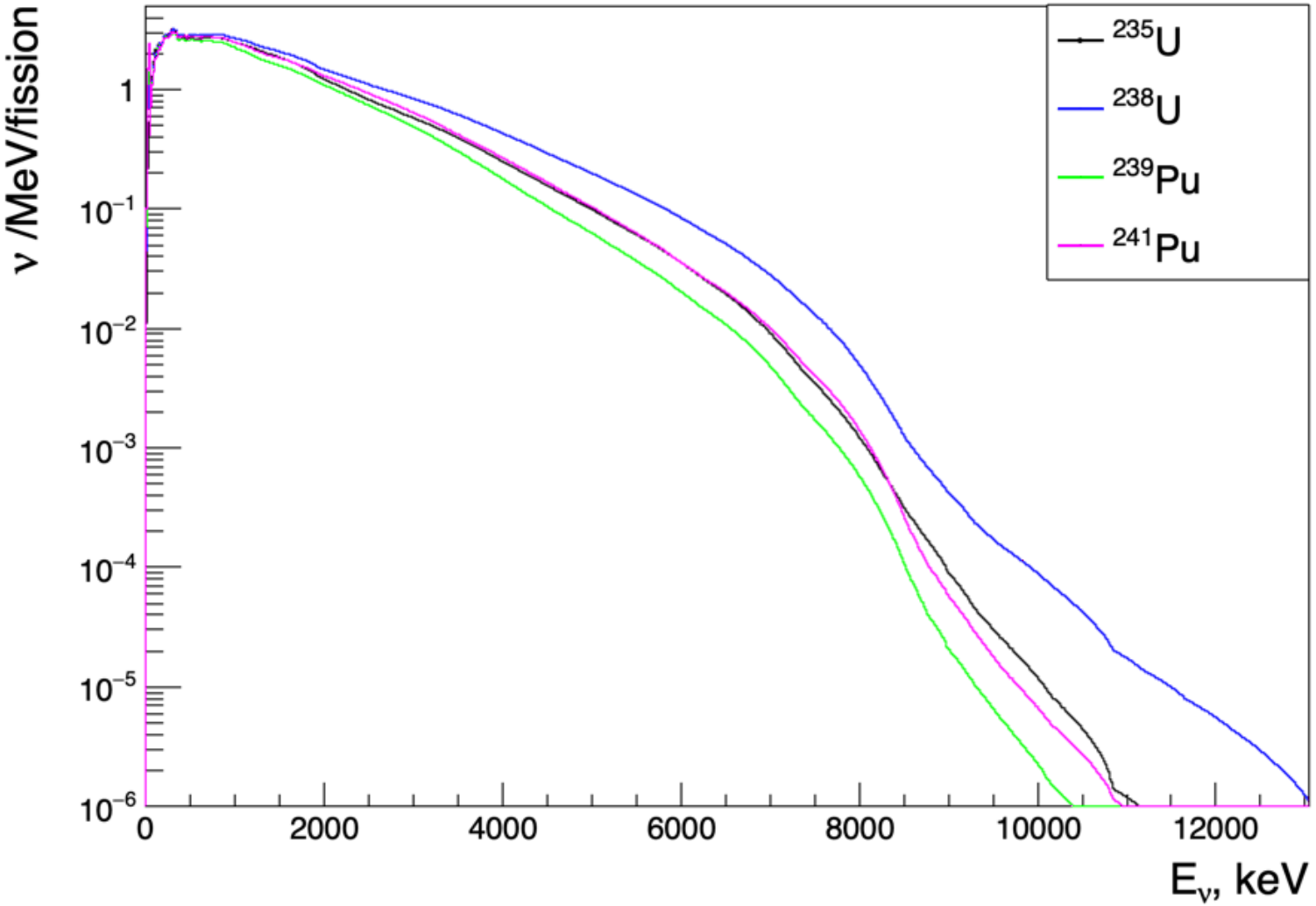
$$+ \frac{(\sigma_{DC} - \sigma_{calc\,DC})^2}{\Delta\sigma_{DC}^2} + \frac{(\sigma_{DB} - \sigma_{calc\,DB})^2}{\Delta\sigma_{DB}^2} + \frac{(\sigma_{RENO} - \sigma_{calc\,RENO})^2}{\Delta\sigma_{RENO}^2} + \frac{(\sigma_{Bugey} - \sigma_{calc\,Bugey})^2}{\Delta\sigma_{Bugey}^2} +$$

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

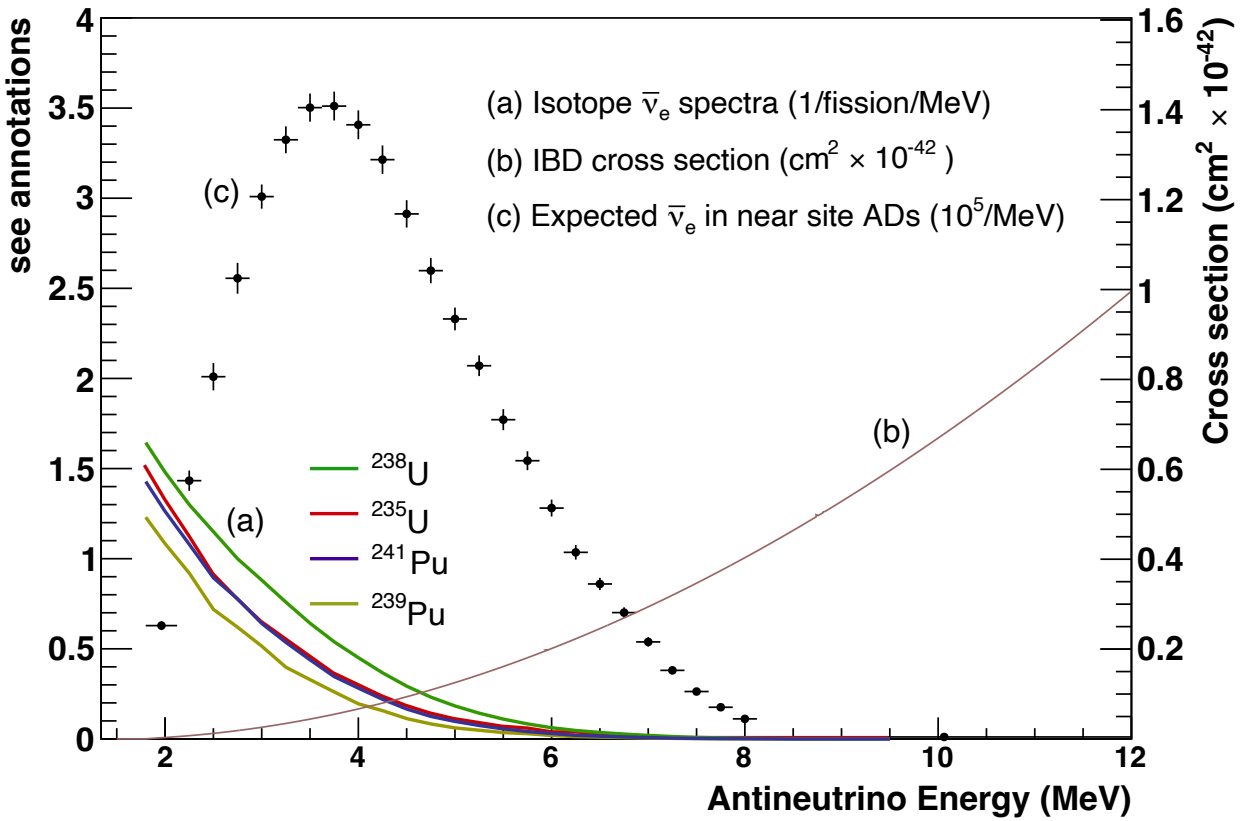
$$|\chi_k^2 - \chi_{k-1}^2| < \varepsilon$$

As a result of minimization we conform experimental antineutrino spectrum and obtain four spectra of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu. Obtained spectra perfectly describe all experimental spectra. Calculated on their base cross sections for core content of Double Chooz, RENO, Daya Bay, Bugey-3 have the smallest differences.

Antineutrino Spectra ^{235}U,^{238}U,^{239}Pu,^{241}Pu



What is experimental cross section of IBD?



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

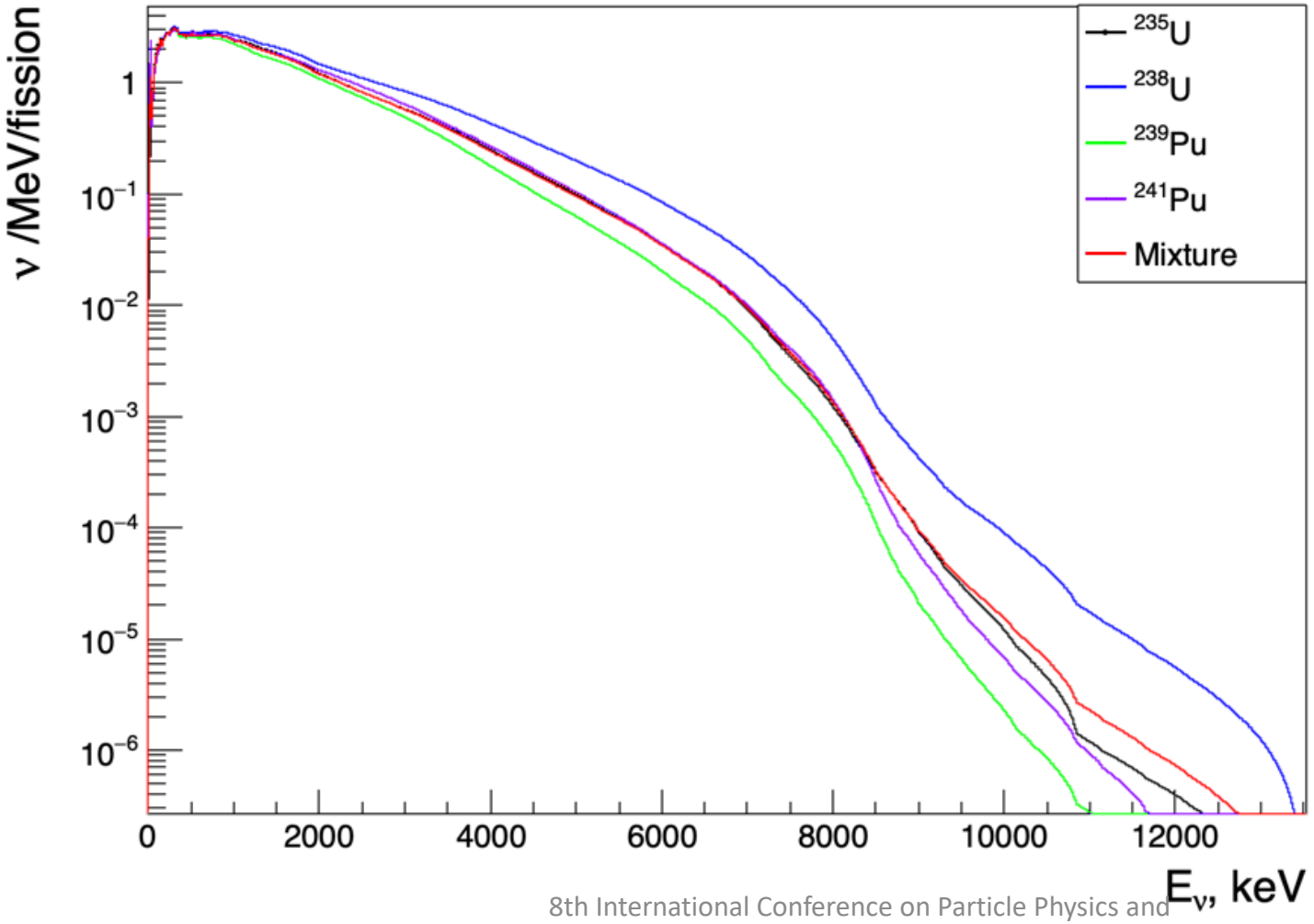
IBD cross sections for U and Pu isotopes in units 10^{-43} cm^2

	^{235}U	^{238}U	^{239}Pu	^{241}Pu
This work	**5.917**	**10.95**	**4.220**	**6.347**
ILL	6.426	8.929	4.204	5.796
Vogel	6.502	9.109	4.526	6.515
MEPhI	6.395	9.213	4.388	6.478
Huber & Mueller	6.681	10.12	4.387	6.081
Kopeikin et al.	6.308	9.395	4.33*	6.01*

before	now
σ_5 = **6.2 - 6.5**	σ_5 = **5.92**
σ_8 = 9.58 - 10.50	σ_8 = 10.95
σ_9 = 4.2 - 4.5	σ_9 = 4.22
σ_1 = **5.95 - 6.1**	σ_1 = **6.35**

What value of cross section for the spectrum of ^{235}U should be in reality ?

Antineutrino Spectra ^{235}U,^{238}U,^{239}Pu,^{241}Pu and mixed spectrum for Double Chooz



Mixed spectrum practically coincides with ^{235}U and ^{241}Pu

Measured with the best accuracy cross sections

	Experimental cross section
Double Chooz	**5.74** $\pm$ 0.06
Daya Bay	**5.84** $\pm$ 0.08
Bugey-4	**5.752** $\pm$ 0.081
RENO	**5.852** $\pm$ 0.094
WIND	**5.85** $\pm$ 0.105

Fitting of Bugey-4 cross section

$$\sigma_f = \mathbf{5.752} \pm 0.081 \quad = \quad 0.538\ \sigma_5 + 0.078\ \sigma_8 + 0.328\ \sigma_9 + 0.056\ \sigma_9$$

$$\chi^2 = \frac{(\sigma \quad -\sigma_{calc})^2}{\Delta\sigma^2}$$

σ_5 = **5.91** $\pm$ 0.77
σ_8 = 9.58 $\pm$ 1.90
σ_9 = 4.52 $\pm$ 0.59
σ_1 = 6.11 $\pm$ 0.76

Results of fitting measured with best accuracy cross sections

Cross section	experimental	^{235}U	^{238}U	^{239}Pu	^{241}Pu
Double Chooz	**5.74** ± 0.06 5.89	5.89±0.63 5.97±0.52	9.46±1.73 10.0±1.92	4.49±0.75 4.60±0.70	5.95±0.62 6.38±0.53
Daya Bay	**5.84** ± 0.08	5.94±0.56	9.85±1.92	4.57±0.72	6.36±0.52
Bugey-4	**5.752** ± 0.081	5.91±0.77	9.58±1.90	4.52±0.59	6.11±0.76
RENO	**5.852** ± 0.094	5.94±0.67	9.92±1.63	4.58±0.78	6.39±0.51
WIND	**5.85** ± 0.105	5.92±0.78	9.72±1.71	4.55±0.59	6.49±0.90
INR		5.92	10.95	4.22	6.35

Comparison of measured and calculated through INR spectra cross sections

experiment	Core content				$^{i}\sigma_f$ x10^{-43} [cm^2/fiss.]	$^{INR}\sigma_f$ x10^{-43} [cm^2/fiss.]	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** $\pm$ 0.06 **5.74** $\pm$ 0.06	5.817	0.982 0.987	6.180	0.924
Bugey-4	0.538	0.078	0.328	0.056	**5.752** $\pm$ 0.081	5.779	0.995	6.163	0.933
Daya Bay	0.561	0.076	0.307	0.056	**5.84** $\pm$ 0.08	5.804	1.006	6.204	0.927
RENO	0.571	0.073	0.300	0.056	**5.852** $\pm$ 0.094	5.801	1.009	6.210	0.926

Conclusion

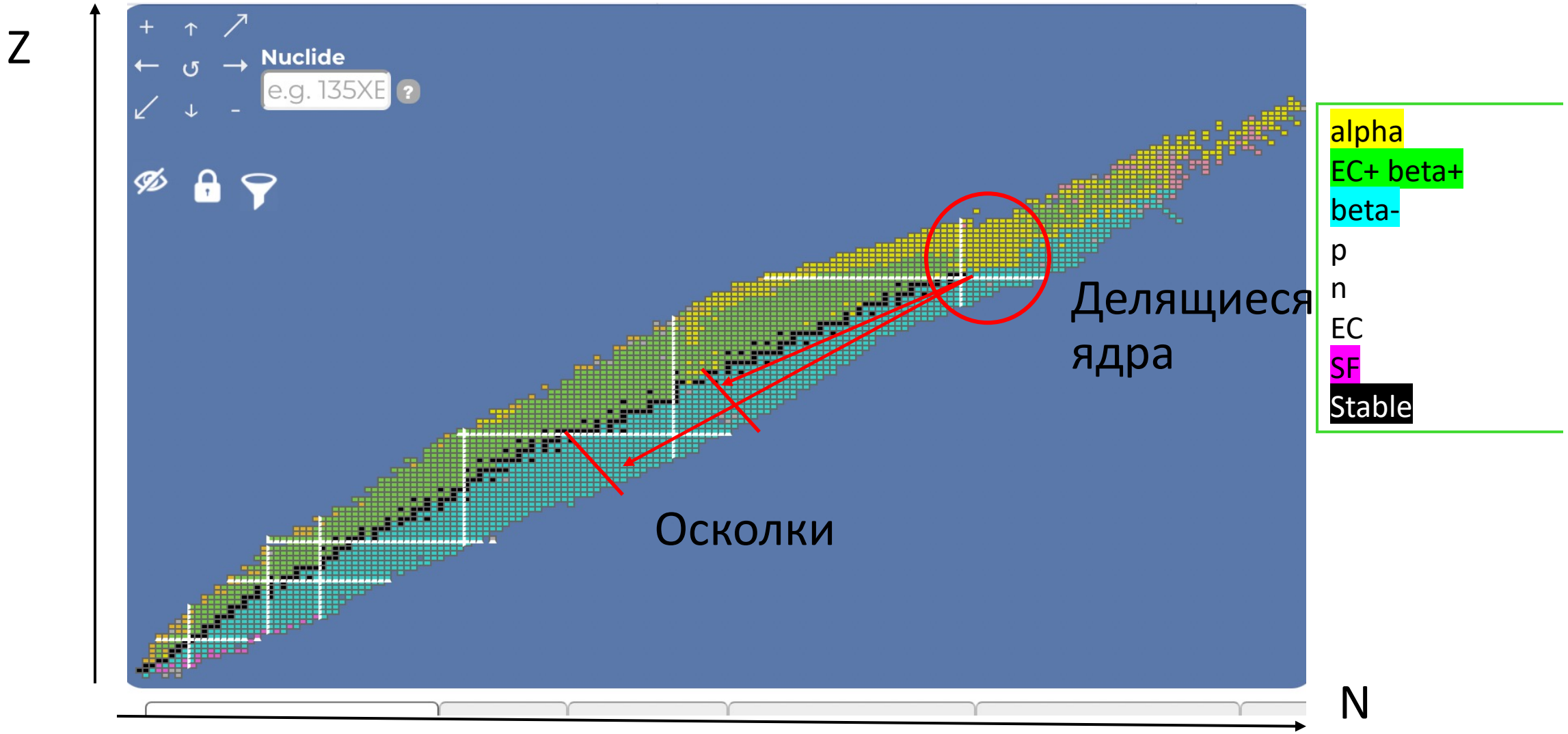
We applied new method of obtaining fission isotopes antineutrino spectra from high statistics experimental data.

Found four antineutrino spectra (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) allow to predict reactor antineutrino spectrum at any moment of its operation and at any core content.

Having exact (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) antineutrino spectra makes it possible to make online monitoring of reactor core during its cycle.

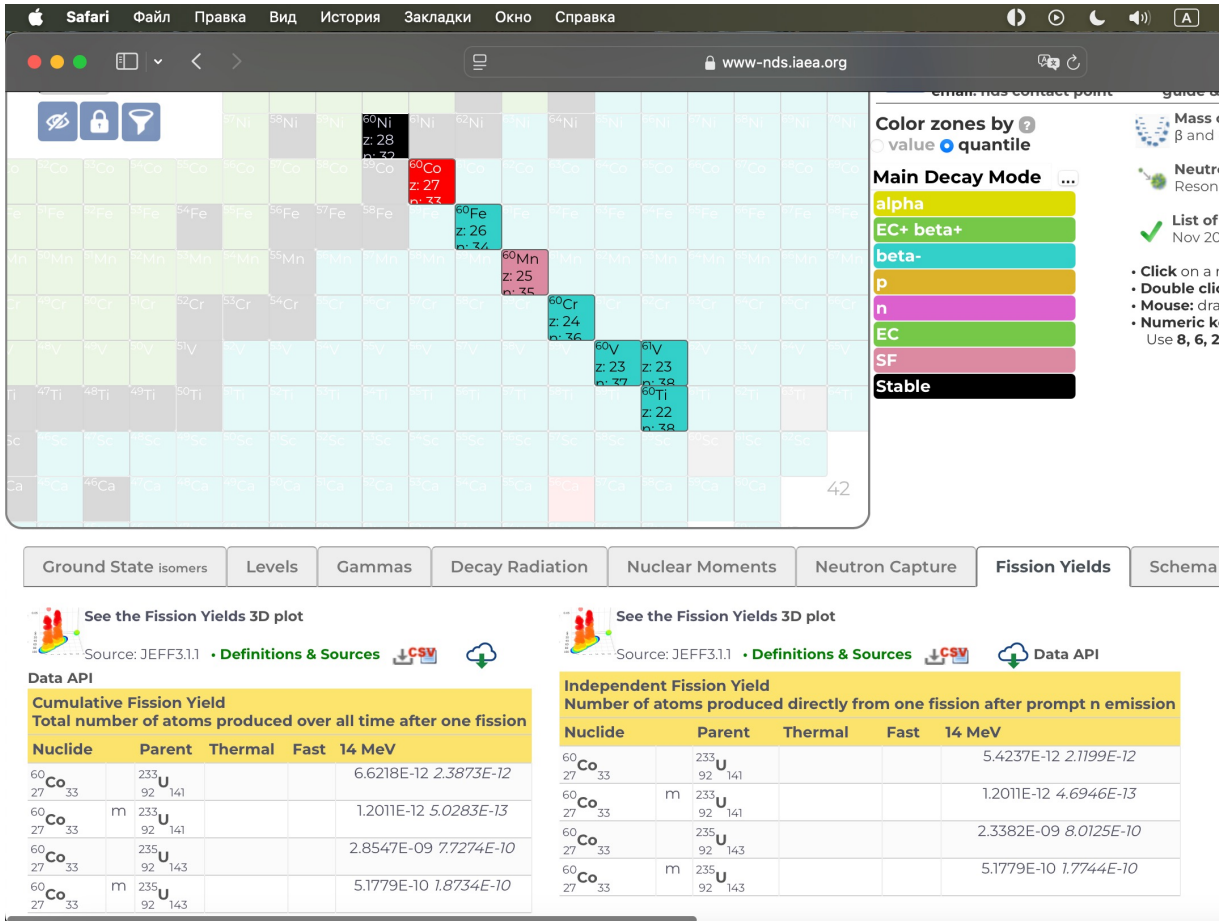
Thank you for the attention!

Деление тяжелых ядер происходит на два осколка неравной массы



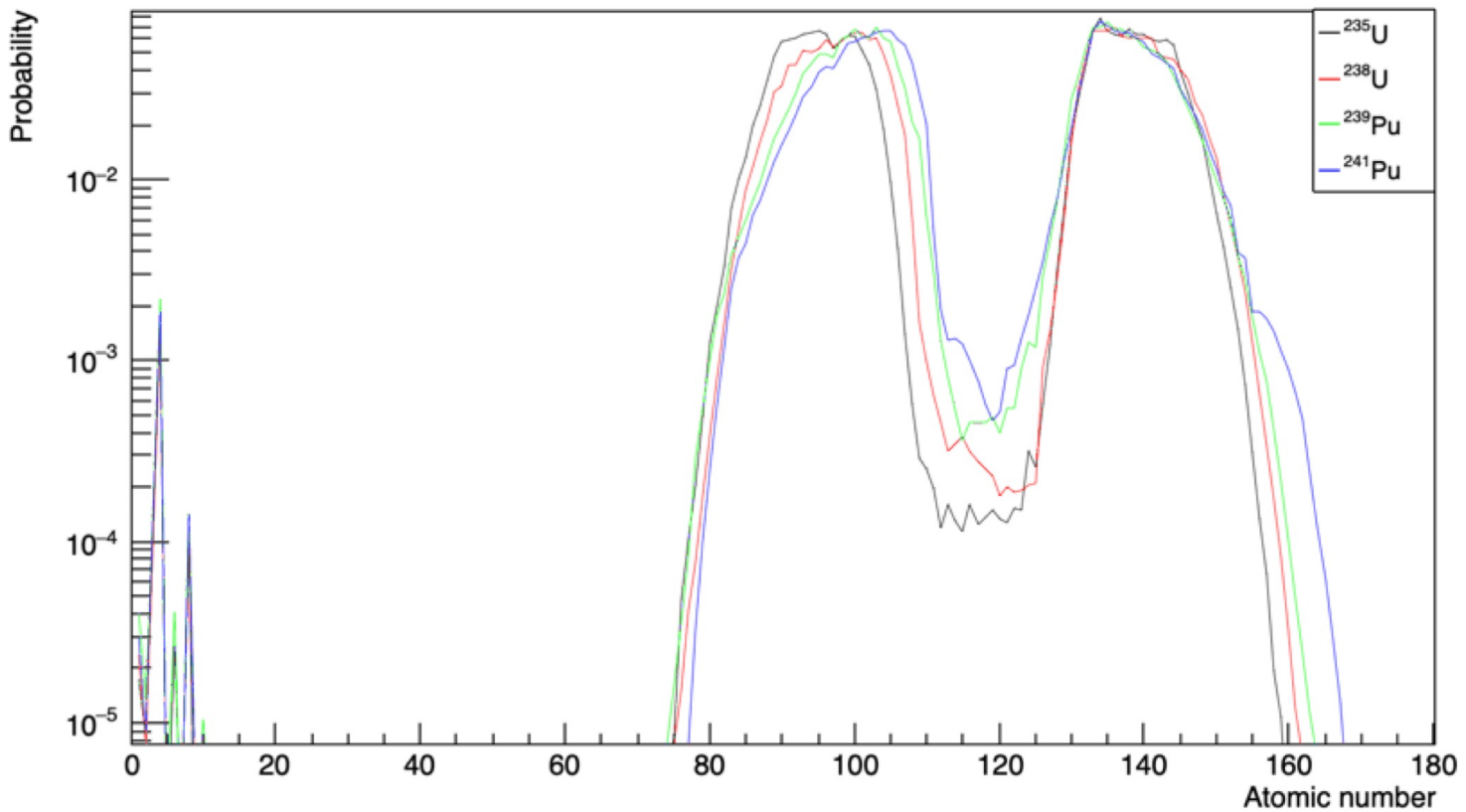
The example of charge chain with mass A = 60

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



Анализ показал, что в базах данных только треть всех осколков имеет полностью известные схемы распада. Одна треть является полностью неизвестной, и еще одна треть имеет схемы распада, основанные на расчете по известным моделям ядра.

Массовое распределение осколков деления



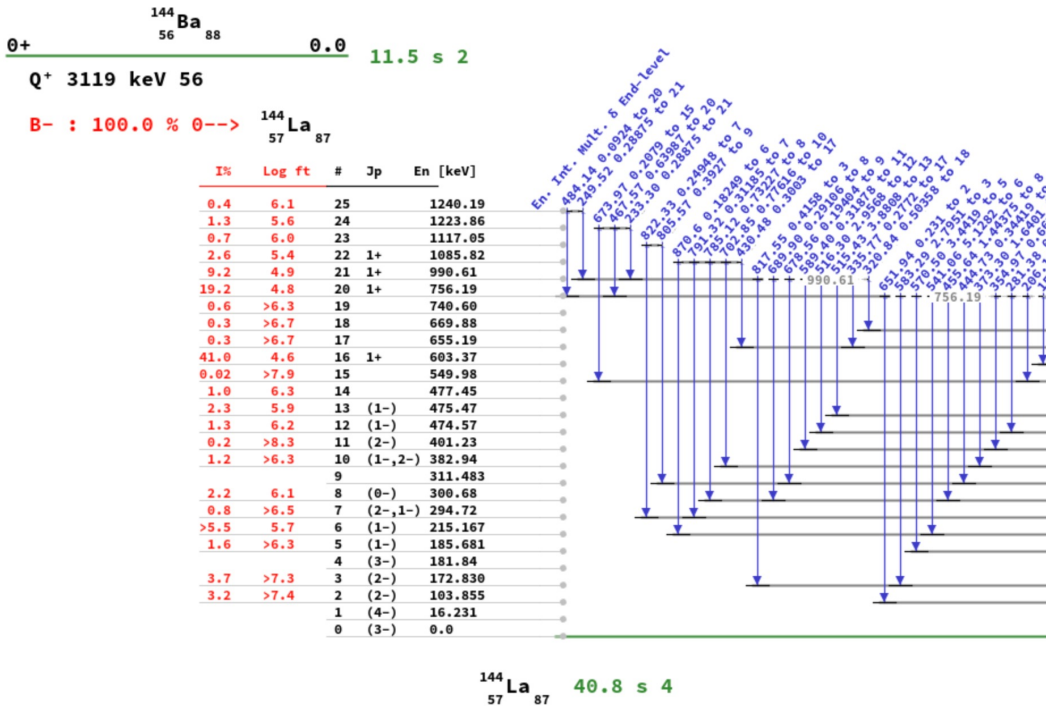
Предлагаемый метод расчета:

Берем экспериментальный спектр или несколько
Рассчитываем спектр по базе данных
Вычисляем χ^2. Если
Меняем схему распада у неизвестного ядра
Опять вычисляем χ^2. Если χ^2меньше предыдущего, то сохраняем нашу схему, если нет – восстанавливаем старую.
Переходим к следующему ядру.
Выполняем итерации пока разница χ^2 не станет меньше наперед заданного значения, например 10^{-5}.

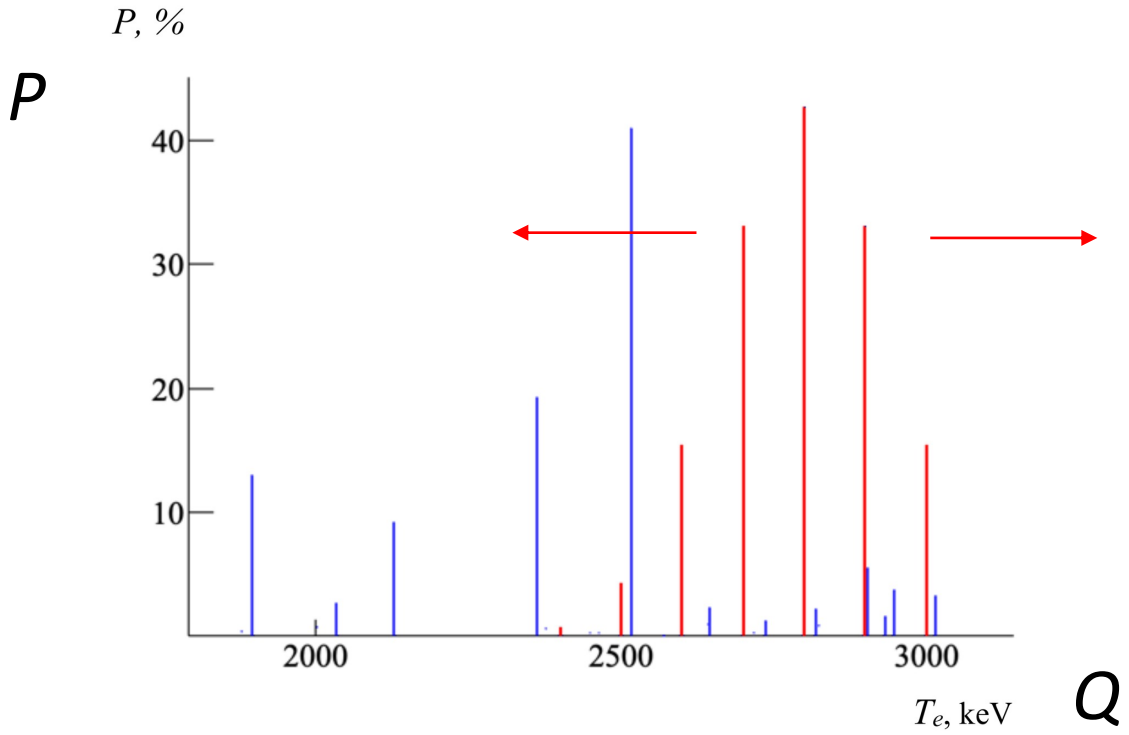
Описываются экспериментальные точки (~25-30 точек) и получается хи-2 с большим количеством параметров

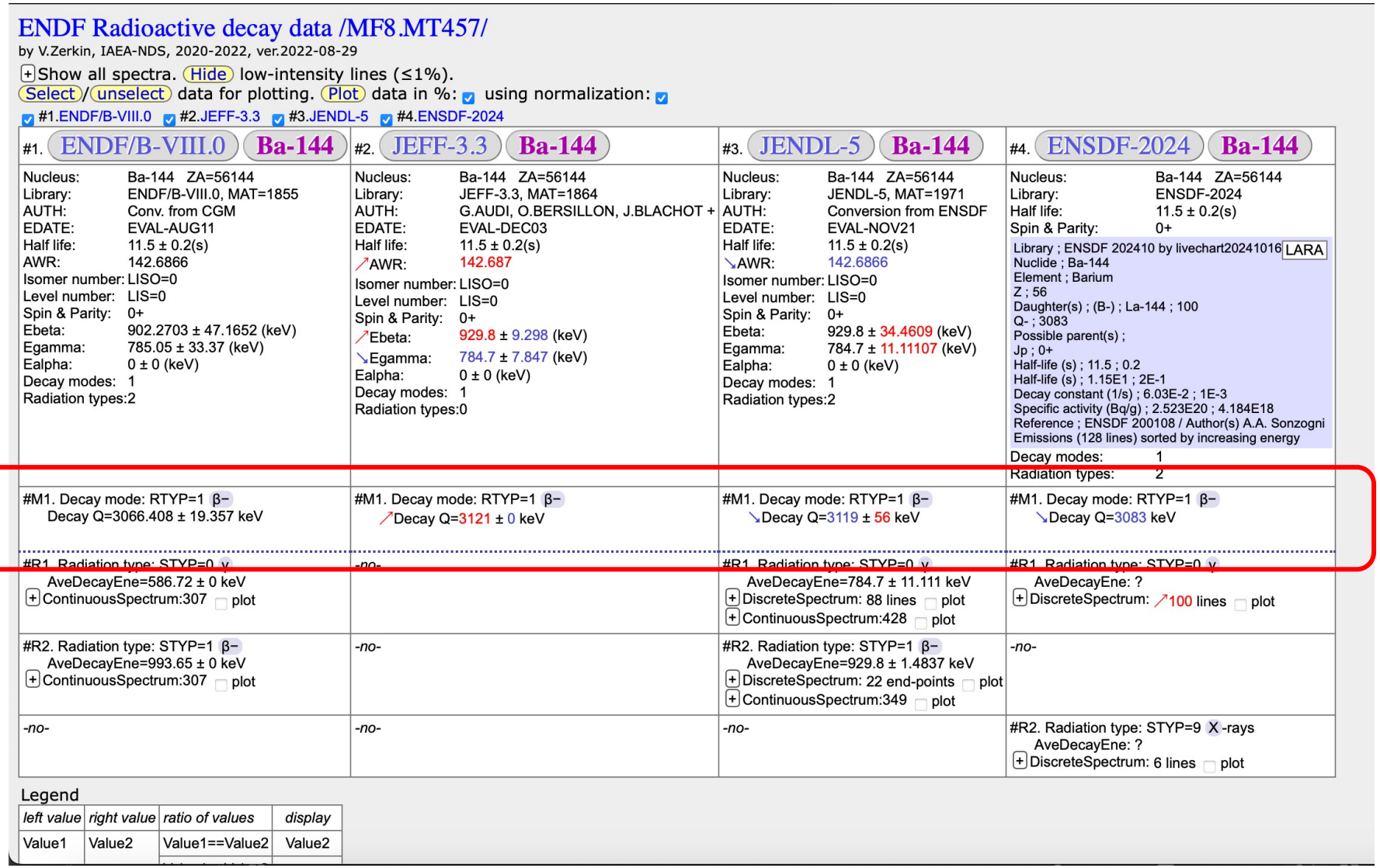
Пример варьирования вероятностей распада для ^{144}Ba

#	<E_{β^-}> [keV]	I_{β^-}(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





ENDF Radioactive decay data /MF8.MT457/

by V.Zerkin, IAEA-NDS, 2020-2022, ver.2022-08-29

[+]Show all spectra. Hide low-intensity lines (≤1%).
Select/unselect data for plotting. Plot data in %: using normalization:

#1.ENDF/B-VIII.0 #2.JEFF-3.3 #3.JENDL-5 #4.ENSDF-2024

#1. ENDF/B-VIII.0 Ba-144	#2. JEFF-3.3 Ba-144	#3. JENDL-5 Ba-144	#4. ENSDF-2024 Ba-144
Nucleus: Ba-144 ZA=56144 Library: ENDF/B-VIII.0, MAT=1855 AUTH: Conv. from CGM EDATE: EVAL-AUG11 Half life: 11.5 ± 0.2(s) AWR: 142.6866 Isomer number: LISO=0 Level number: LIS=0 Spin & Parity: 0+ Ebeta: 902.2703 ± 47.1652 (keV) Egamma: 785.05 ± 33.37 (keV) Ealpha: 0 ± 0 (keV) Decay modes: 1 Radiation types:2	Nucleus: Ba-144 ZA=56144 Library: JEFF-3.3, MAT=1864 AUTH: G.AUDI, O.BERSILLON, J.BLACHOT + EDATE: EVAL-DEC03 Half life: 11.5 ± 0.2(s) ↗AWR: 142.687 Isomer number: LISO=0 Level number: LIS=0 Spin & Parity: 0+ ↗Ebeta: 929.8 ± 9.298 (keV) ↘Egamma: 784.7 ± 7.847 (keV) Ealpha: 0 ± 0 (keV) Decay modes: 1 Radiation types:0	Nucleus: Ba-144 ZA=56144 Library: JENDL-5, MAT=1971 AUTH: Conversion from ENSDF EDATE: EVAL-NOV21 Half life: 11.5 ± 0.2(s) ↘AWR: 142.6866 Isomer number: LISO=0 Level number: LIS=0 Spin & Parity: 0+ Ebeta: 929.8 ± 34.4609 (keV) Egamma: 784.7 ± 11.11107 (keV) Ealpha: 0 ± 0 (keV) Decay modes: 1 Radiation types:2	Nucleus: Ba-144 ZA=56144 Library: ENSDF-2024 Half life: 11.5 ± 0.2(s) Spin & Parity: 0+ Library ; ENSDF 202410 by livechart20241016 LARA Nuclide ; Ba-144 Element ; Barium Z ; 56 Daughter(s) ; (B-) ; La-144 ; 100 Q- ; 3083 Possible parent(s) ; Jp ; 0+ Half-life (s) ; 11.5 ; 0.2 Half-life (s) ; 1.15E1 ; 2E-1 Decay constant (1/s) ; 6.03E-2 ; 1E-3 Specific activity (Bq/g) ; 2.523E20 ; 4.184E18 Reference ; ENSDF 200108 / Author(s) A.A. Sonzogni Emissions (128 lines) sorted by increasing energy Decay modes: 1 Radiation types: 2
#M1. Decay mode: RTYP=1 β− Decay Q=3066.408 ± 19.357 keV	#M1. Decay mode: RTYP=1 β− ↗Decay Q=3121 ± 0 keV	#M1. Decay mode: RTYP=1 β− ↘Decay Q=3119 ± 56 keV	#M1. Decay mode: RTYP=1 β− ↘Decay Q=3083 keV

#R1. Radiation type: STYP=0 γ
AveDecayEne=586.72 ± 0 keV
[+]ContinuousSpectrum:307 plot
	-no-	#R1. Radiation type: STYP=0 γ
		AveDecayEne=784.7 ± 11.111 keV
		[+]DiscreteSpectrum: 88 lines plot
		[+]ContinuousSpectrum:428 plot
			#R1. Radiation type: STYP=0 γ
			AveDecayEne: ?
			[+]DiscreteSpectrum: ↗100 lines plot

#R2. Radiation type: STYP=1 β−
AveDecayEne=993.65 ± 0 keV
[+]ContinuousSpectrum:307 plot
	-no-	#R2. Radiation type: STYP=1 β−
		AveDecayEne=929.8 ± 1.4837 keV
		[+]DiscreteSpectrum: 22 end-points plot
		[+]ContinuousSpectrum:349 plot
			-no-

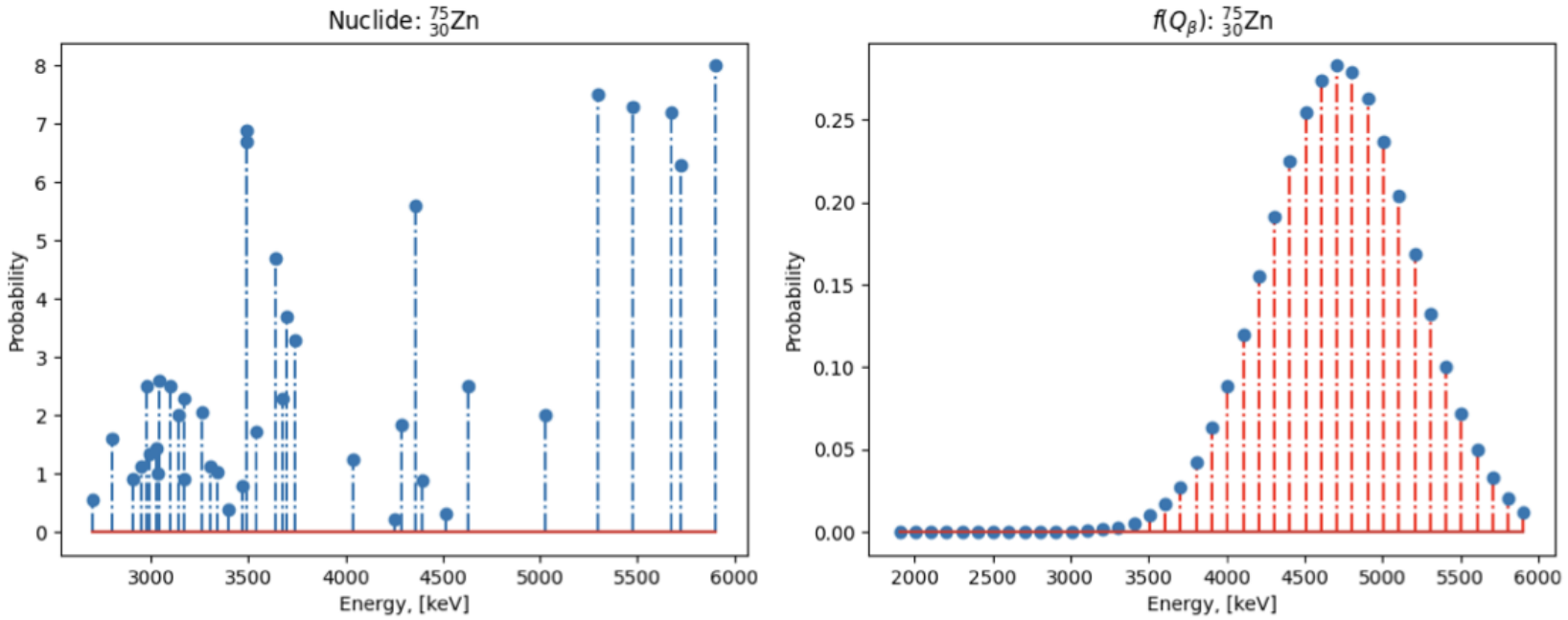
-no-	-no-	-no-	#R2. Radiation type: STYP=9 X-rays AveDecayEne: ? [+]DiscreteSpectrum: 6 lines plot

Legend

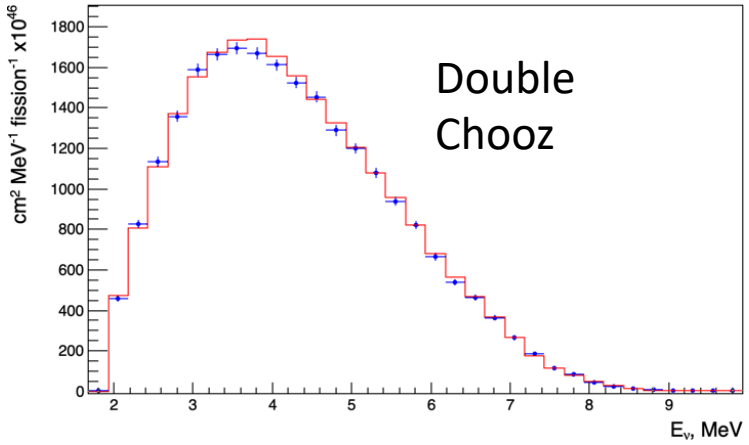
left value	right value	ratio of values	display
Value1	Value2	Value1==Value2	Value2

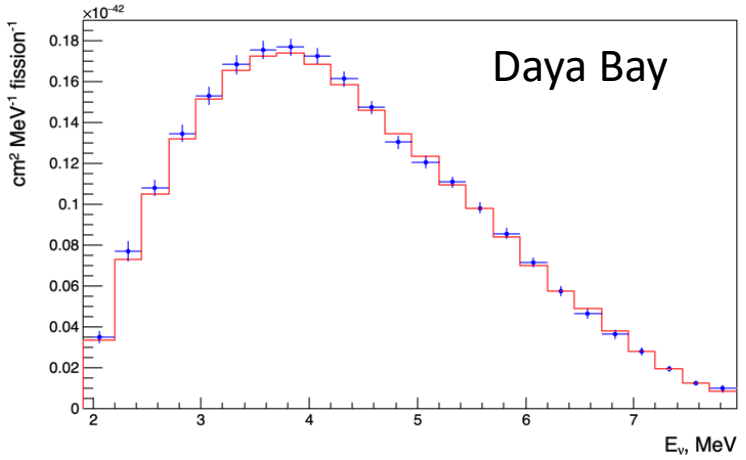
Еще пример ^{75}Zn

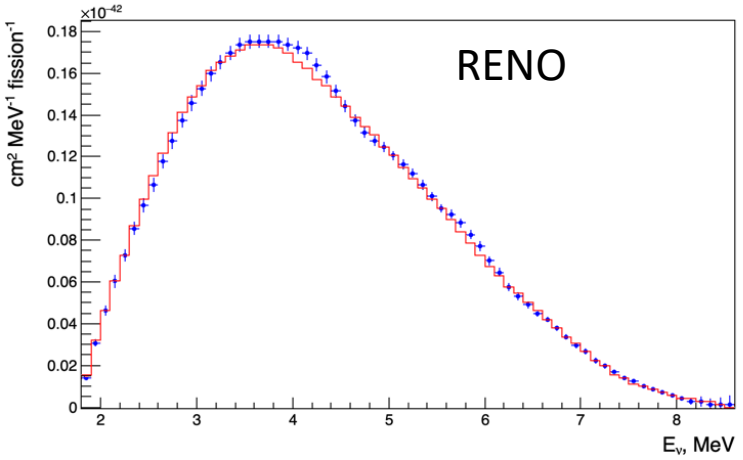
$^{75}_{30}$Zn - estimated, статус 2

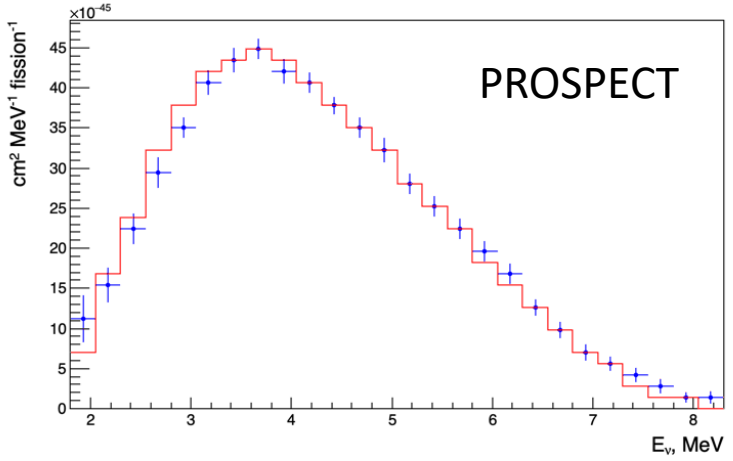
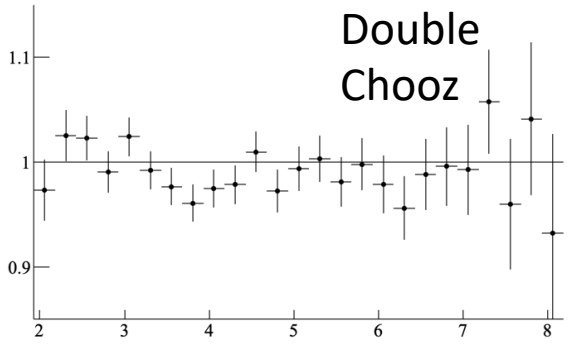
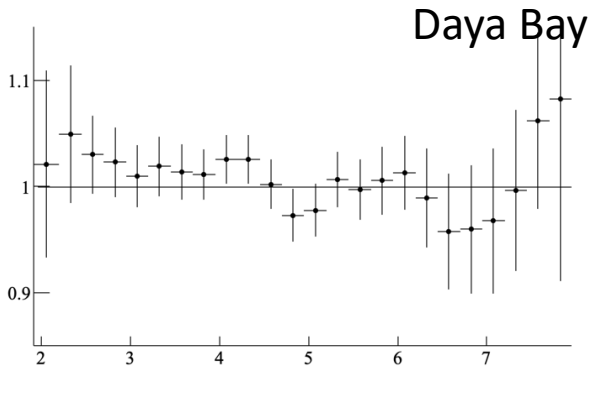
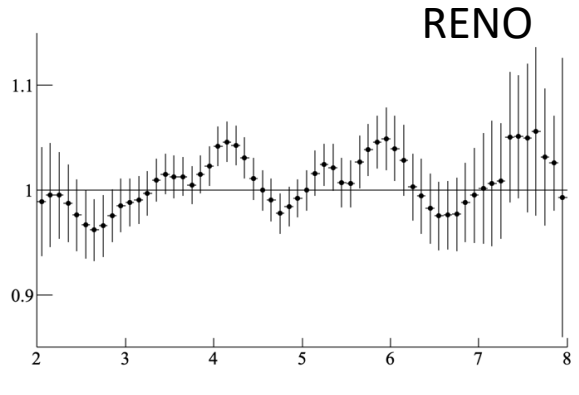
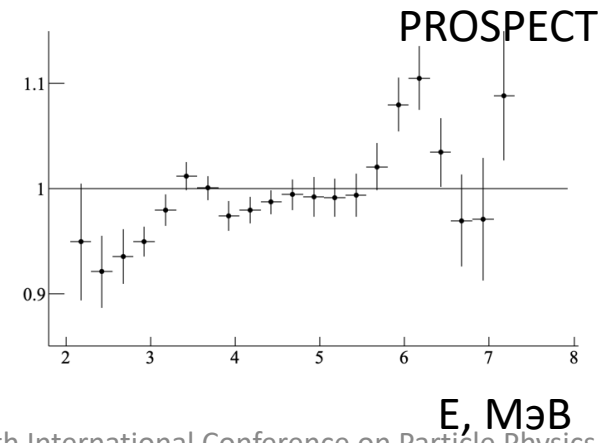


Измеренные спектры антинейтрино и расчетные









Отношение измеренных спектров антинейтрино к нашему спектру