Gamma-ray analysis of the strong β-decay contributors to the antineutrino spectrum

Samuel Kim

National Nuclear Data Center, BNL

2nd IAEA Technical Meeting On Nuclear Data Needs for Antineutrino Spectra

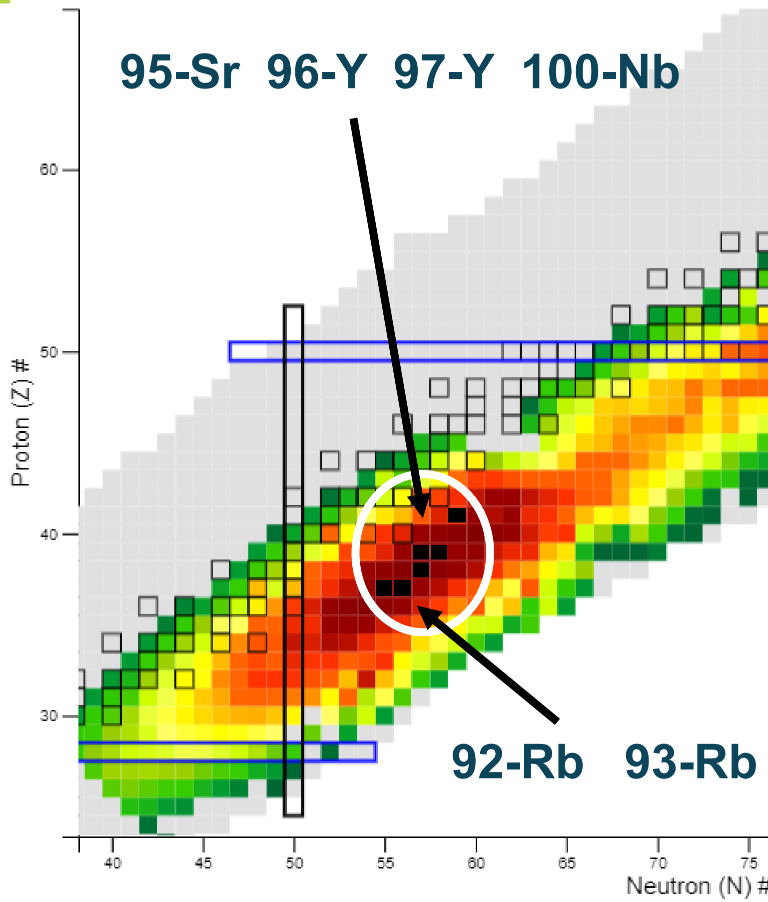
1/19/2023

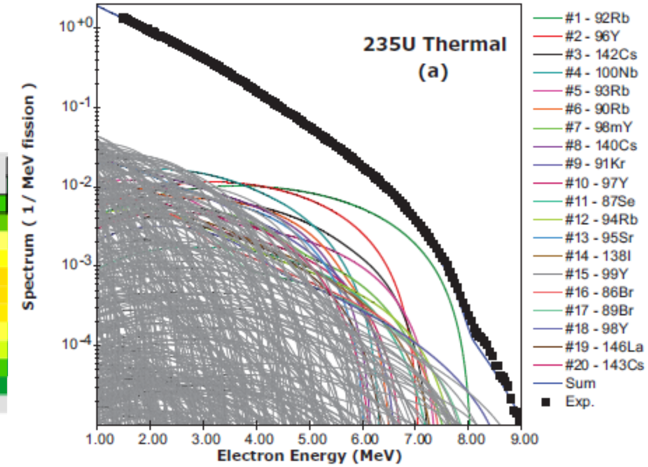
Motivation

- Better understand a role of the fission yield data and decay data in analyzing antineutrino spectrum
- Specifically, their potential contributions to the spectral bump appearing at 5 to 7 MeV region of $\bar{\nu}_e$ spectrum
  - A.A. Sonzogni et al, PRL 116, 132502 (2016)
  - Dwyer and Langford, PRL 114, 012502 (2015)
- Alternate analysis using γ-rays
- Measure the gamma ray yields from 8 fission product / daughter nuclides identified as significant β-decay contributors in the same energy region
- JEFF3.3 fission yield library
  - Changed from ENDF VIII
- ENDF decay data library

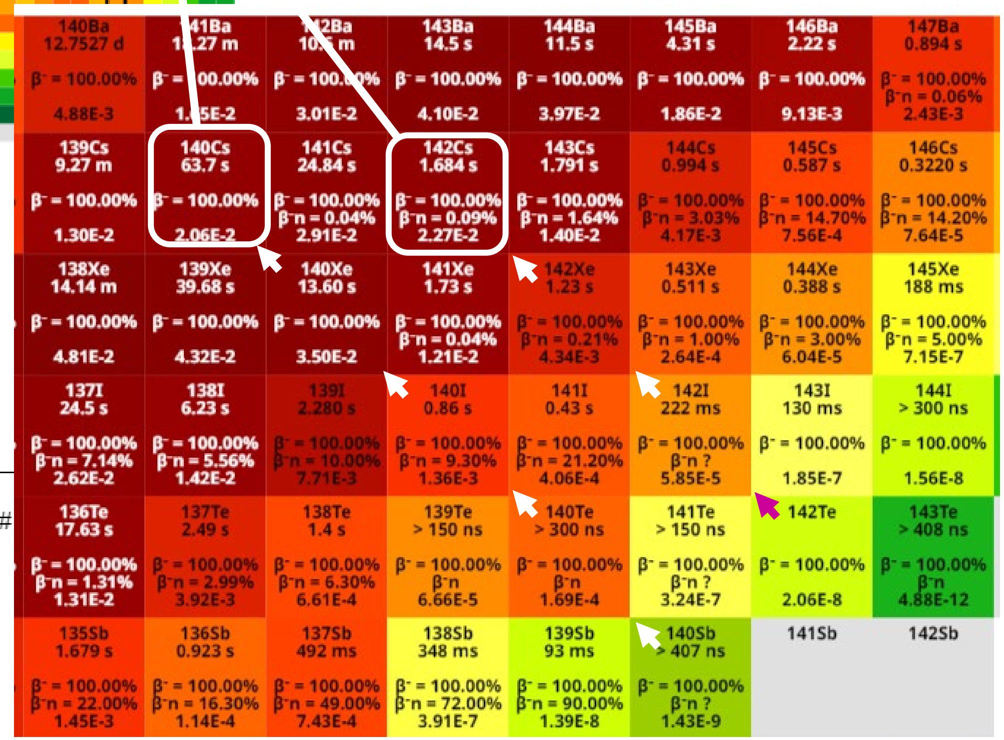
Brookhaven National Laboratory

Fission Yields (235-U)





A. A. Sonzogni et al. Phys. Rev. C 91, 011301(R) (2015)



140Ba 12.7527 d β^- = 100.00% 4.88E-3	1[illegible]1Ba 1[illegible].27 m β^- = [illegible]00.00% 1.[illegible]5E-2	1[illegible]2Ba 10.[illegible] m β^- = 100.[illegible]% 3.01E-2	143Ba 14.5 s β^- = 100.00% 4.10E-2	144Ba 11.5 s β^- = 100.00% 3.97E-2	145Ba 4.31 s β^- = 100.00% 1.86E-2	146Ba 2.22 s β^- = 100.00% 9.13E-3	147Ba 0.894 s β^- = 100.00% $\beta^- n$ = 0.06% 2.43E-3
139Cs 9.27 m β^- = 100.00% 1.30E-2	140Cs 63.7 s β^- = 100.00% 2.06E-2	141Cs 24.84 s β^- = 100.00% $\beta^- n$ = 0.04% 2.91E-2	142Cs 1.684 s β^- = 100.00% $\beta^- n$ = 0.09% 2.27E-2	143Cs 1.791 s β^- = 100.00% $\beta^- n$ = 1.64% 1.40E-2	144Cs 0.994 s β^- = 100.00% $\beta^- n$ = 3.03% 4.17E-3	145Cs 0.587 s β^- = 100.00% $\beta^- n$ = 14.70% 7.56E-4	146Cs 0.3220 s β^- = 100.00% $\beta^- n$ = 14.20% 7.64E-5
138Xe 14.14 m β^- = 100.00% 4.81E-2	139Xe 39.68 s β^- = 100.00% 4.32E-2	140Xe 13.60 s β^- = 100.00% 3.50E-2	141Xe 1.73 s β^- = 100.00% $\beta^- n$ = 0.04% 1.21E-2	142Xe 1.23 s β^- = 100.00% $\beta^- n$ = 0.21% 4.34E-3	143Xe 0.511 s β^- = 100.00% $\beta^- n$ = 1.00% 2.64E-4	144Xe 0.388 s β^- = 100.00% $\beta^- n$ = 3.00% 6.04E-5	145Xe 188 ms β^- = 100.00% $\beta^- n$ = 5.00% 7.15E-7
137I 24.5 s β^- = 100.00% $\beta^- n$ = 7.14% 2.62E-2	138I 6.23 s β^- = 100.00% $\beta^- n$ = 5.56% 1.42E-2	139I 2.280 s β^- = 100.00% $\beta^- n$ = 10.00% 7.71E-3	140I 0.86 s β^- = 100.00% $\beta^- n$ = 9.30% 1.36E-3	141I 0.43 s β^- = 100.00% $\beta^- n$ = 21.20% 4.06E-4	142I 222 ms β^- = 100.00% $\beta^- n$? 5.85E-5	143I 130 ms β^- = 100.00% 1.85E-7	144I > 300 ns β^- = 100.00% 1.56E-8
136Te 17.63 s β^- = 100.00% $\beta^- n$ = 1.31% 1.31E-2	137Te 2.49 s β^- = 100.00% $\beta^- n$ = 2.99% 3.92E-3	138Te 1.4 s β^- = 100.00% $\beta^- n$ = 6.30% 6.61E-4	139Te > 150 ns β^- = 100.00% $\beta^- n$ 6.66E-5	140Te > 300 ns β^- = 100.00% $\beta^- n$ 1.69E-4	141Te > 150 ns β^- = 100.00% $\beta^- n$? 3.24E-7	142Te β^- = 100.00% 2.06E-8	143Te > 408 ns β^- = 100.00% $\beta^- n$ 4.88E-12
135Sb 1.679 s β^- = 100.00% $\beta^- n$ = 22.00% 1.45E-3	136Sb 0.923 s β^- = 100.00% $\beta^- n$ = 16.30% 1.14E-4	137Sb 492 ms β^- = 100.00% $\beta^- n$ = 49.00% 7.43E-4	138Sb 348 ms β^- = 100.00% $\beta^- n$ = 72.00% 3.91E-7	139Sb 93 ms β^- = 100.00% $\beta^- n$ = 90.00% 1.39E-8	140Sb > 407 ns β^- = 100.00% $\beta^- n$? 1.43E-9	141Sb	142Sb

https://www.nndc.bnl.gov/nudat3/

Brookhaven National Laboratory

Experiment

Irradiation (30 sec)

- Uranium 235 (253 ng) Uranyl Nitrate ICP calibration solution
- Plutonium 239 (301 ng), CRM

Transport (20 sec)

- RABBIT delay

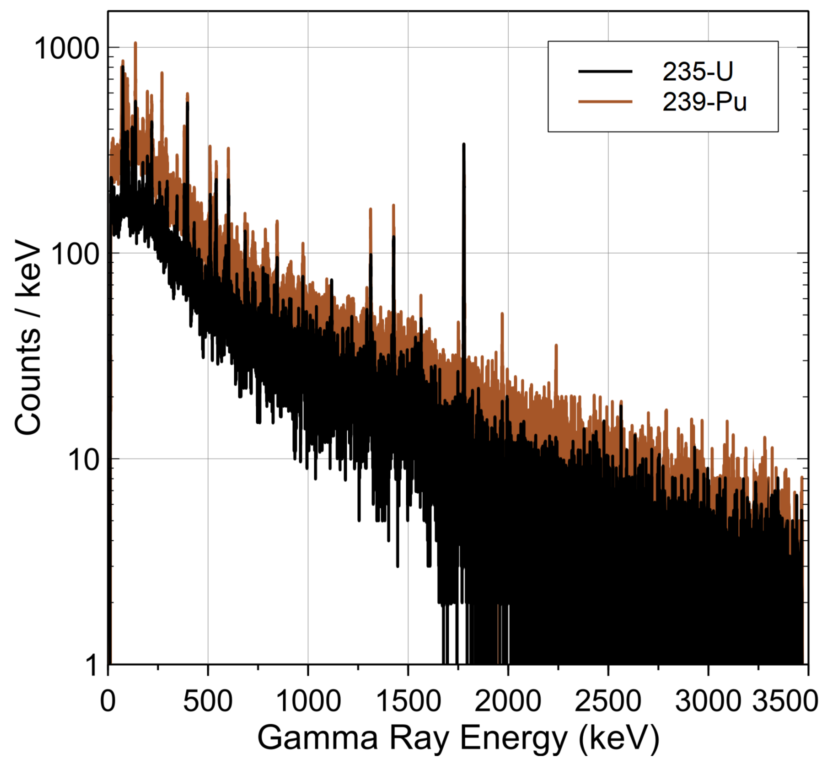
Measurement (30 sec)

- ORTEC P-type 44% HPGe

High Flux Isotope Reactor

- NAA, ORNL
- PT-2 port
- Thermal neutron flux
  - ~ 4.5E+13 n/cm^2/sec

Isotope	t_half (s)	keV	Intensity
142-Cs	1.68	359.60	0.270
93-Rb	5.84	432.61	0.202
100-Nb	1.50	535.67	0.460
140-Cs	63.70	602.25	0.530
95-Sr	23.90	685.60	0.226
92-Rb	4.49	814.98	0.032
96-Y	5.34	1749.68	0.024
97-Y	3.75	3287.60	0.181



Brookhaven National Laboratory

Expected Gamma Ray Quantification

Nuclide production per fission

$$N_f = \underline{Y_{IF}} \sigma_f \varphi \frac{mN_A}{M}$$

Y_{IF}	93-Se	93-Br	93-Kr	93-Rb
JEFF3.3 (2017)	No data	6.25E-05	6.14E-03	2.71E-02
ENDF/B-VIII.0 (2018)	2.46E-08	3.08E-05	4.86E-03	3.07E-02

93-Se > 93-Br > 93-Kr > 93-Rb
93-Br > 93-Kr > 93-Rb
93-Kr > 93-Rb
93-Rb

A set of coupled linear differential equations

- To account for production and decay during 30-sec irradiation

Expected

$$N_\gamma = \lambda N \, \varepsilon \, I_\gamma$$

N- Integrated number of undecayed nuclides, decay corrected for 30-sec measurement

Uncertainty

$$\frac{dN_\gamma}{N_\gamma} = \sqrt{\left(\frac{dN}{N}\right)^2 + \left(\frac{dY_{IF}}{Y_{IF}}\right)^2 + \left(\frac{d\varepsilon}{\varepsilon}\right)^2}$$

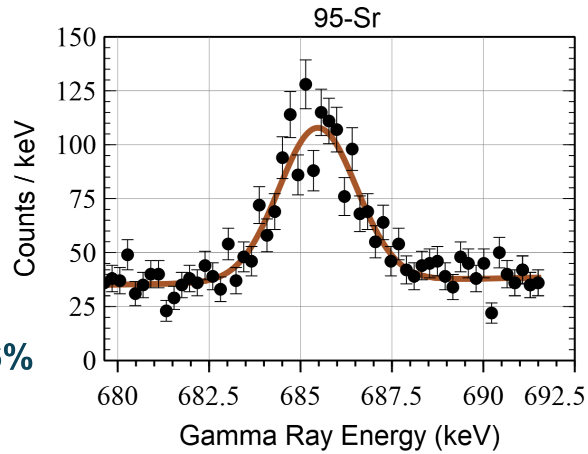
	dN / N	dY_{IF} / Y_{IF}
93-Rb	1%	18%
100-Nb	9%	35%
140-Cs	1%	24%
95-Sr	1%	10%
92-Rb	1%	18%
96-Y	1%	24%
97-Y	2%	15%
142-Cs	4%	20%

Measured Gamma Ray Quantification

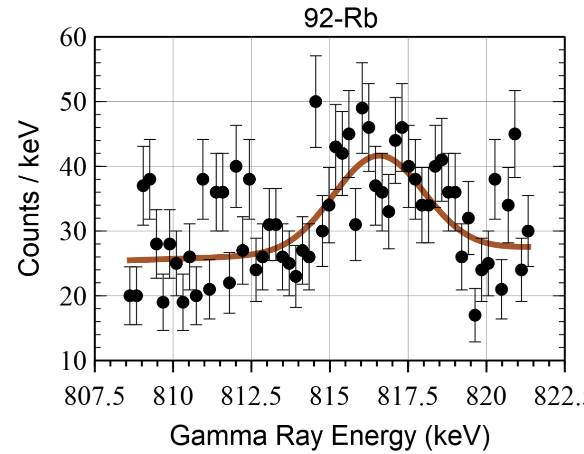
Good Statistics (140-Cs, 100-Nb, 95-Sr)

Poor Statistics (96-Y, 92-Rb, 93-Rb)

235-U



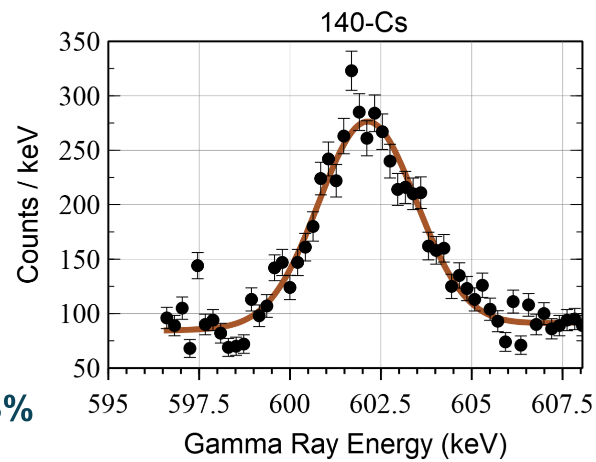
I_γ = 22.6%



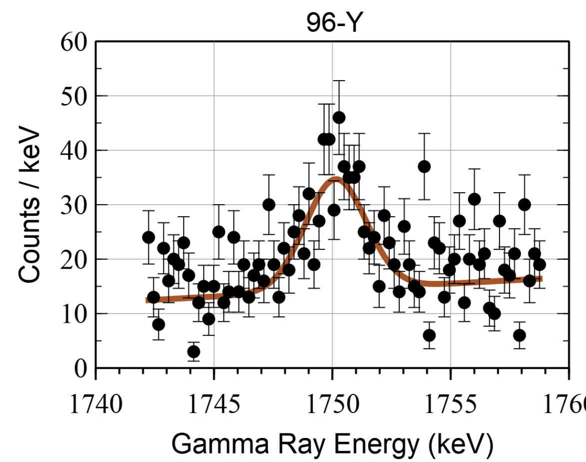
I_γ = 3.2%

92-Rb / 30 strongest γ yields ~ 1.4%

239-Pu



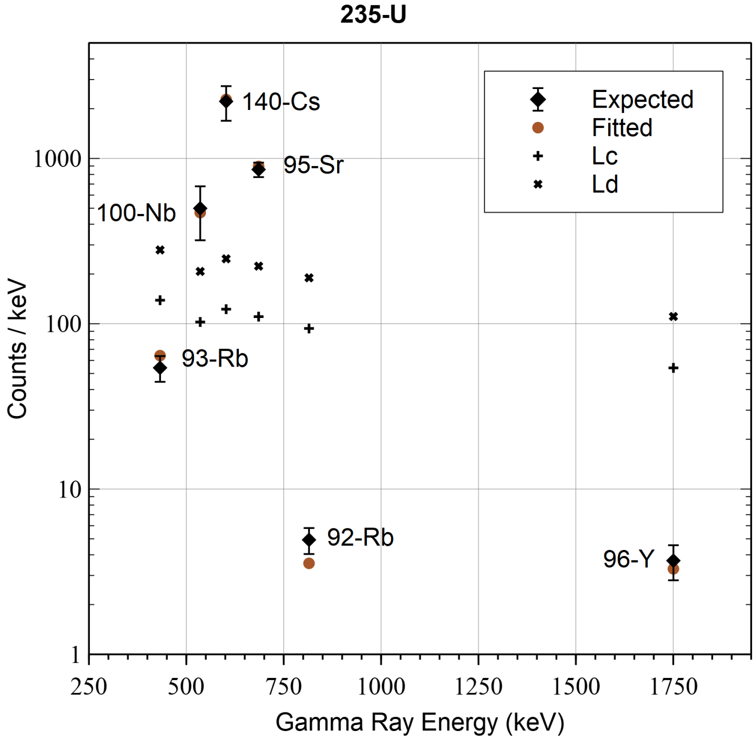
I_γ = 53%



I_γ = 2.4%

96m-Y (1750.06 keV, I_γ = 88%)

Results

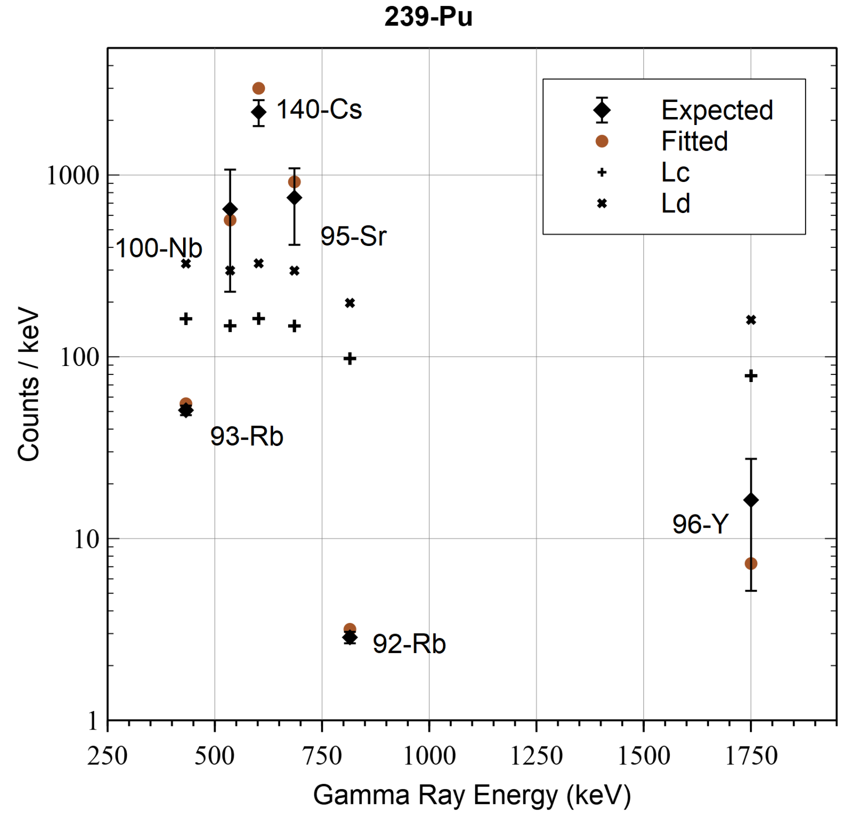


97-Y and 142-Cs

- Fission yields of the nuclides are too low

95-Sr, 100-Nb (235-U, 239-Pu)

- Within 1-σ of the expected



140-Cs

- **235-U** : within 1-σ of the expected
- **239-Pu** : **2-σ** above the expected

Brookhaven National Laboratory

Lc : α = 0.05 (false positive), Ld : β = 0.05 (false negative)

Conclusion

100-Nb and 95-Sr

- Measured gamma rays are consistent with the expected values for 235-U and 239-Pu
- This indicates that Y_{IF} (JEFF3.3 fission yield library) and I_{γ} (ENDF decay data library) are reliable for these nuclides.

140-Cs

- Measured gamma ray is consistent with the expected value for 235-U,
- But it is **NOT** consistent for 239-Pu.
    - Potential errors in Y_{IF}?
    - Follow up: improve expected calculation and uncertainty

96-Y, 92-Rb and 93-Rb

- Measured gamma rays are statistically insignificant.
- Follow up: improve statistics - continuum reduction, better deconvolution method

97-Y and 142-Cs

- Fission yields are too low for the gamma rays to be measured sufficiently.
- Follow up: a larger sample is needed.

Acknowledgement

Collaborators: S. Kim (BNL), C. J. Martoff (Temple), M. Dion (ORNL), D. Glasgow (ORNL)

The authors would like to thank A. Sonzongi (BNL) and E. McCutchan (BNL) for valuable comments and suggestions.

The work at Temple University was funded by the U. S. National Science Foundation under grant NSF-PHY1242611, NSF-1812504, 1747523, and 1314483.

The work at Brookhaven National Laboratory was sponsored by the Office of Nuclear Physics, Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-98CH10886 with Brookhaven Science Associates, LLC.

Thank you for your attention!