Toward the improvement of the ^{238}U level scheme thanks to γ-spectroscopy

ν-ball2 Workshop

Carole Chatel

Philippe Dessagne, Greg Henning, Maëlle Kerveno, Jonathan Wilson

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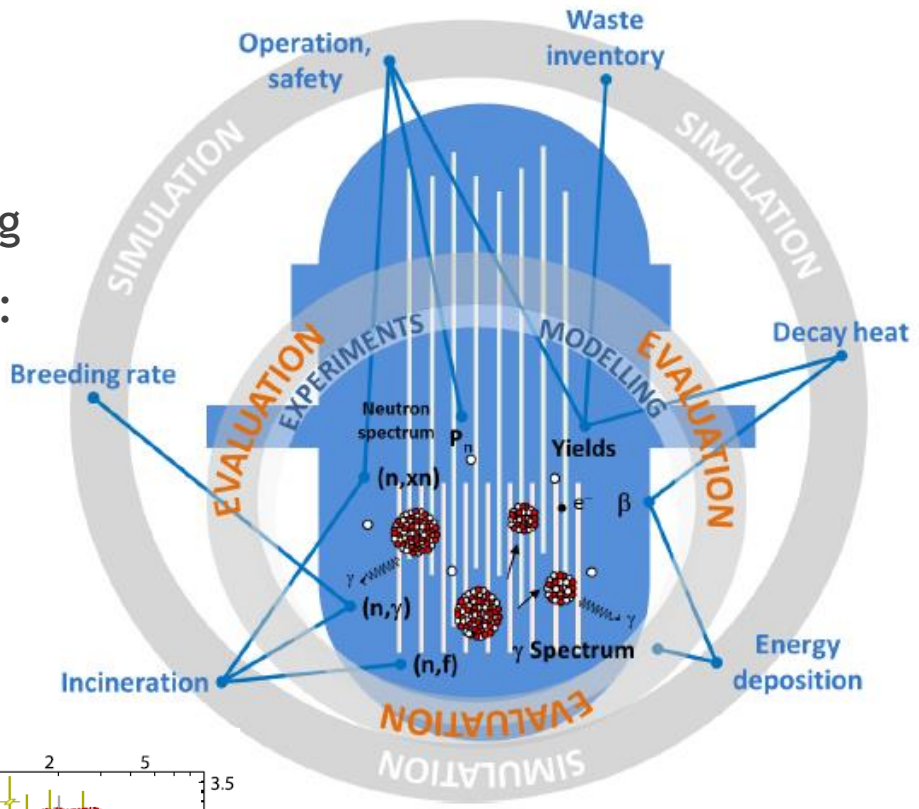
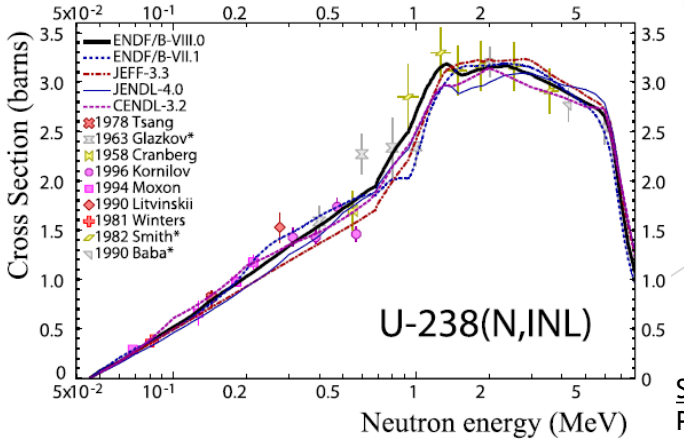
Need of measuring (n, xn) cross sections

- Improvement of actual or future reactor cores simulations requires a better knowledge of the neutron population which is partially driven by (n, xn) reactions, including inelastic scattering
- Neutronics codes for fast neutron reactors or large core reactors:
  - Use evaluated nuclear data files as input based on:
    - experimental data
    - state of the art of theoretical modeling
  - Have uncertainties mainly due to ^{238}U(n, n')
    - XS uncertainties target: 2-3% (HPRL); currently overestimated ~10% in the 2-5 MeV energy region (source: A. Santamarina, et al., Nucl. Data Sheet 118, (2014))

→ Need to make a new accurate ^{238}U(*n*, *n'*) cross section measurement



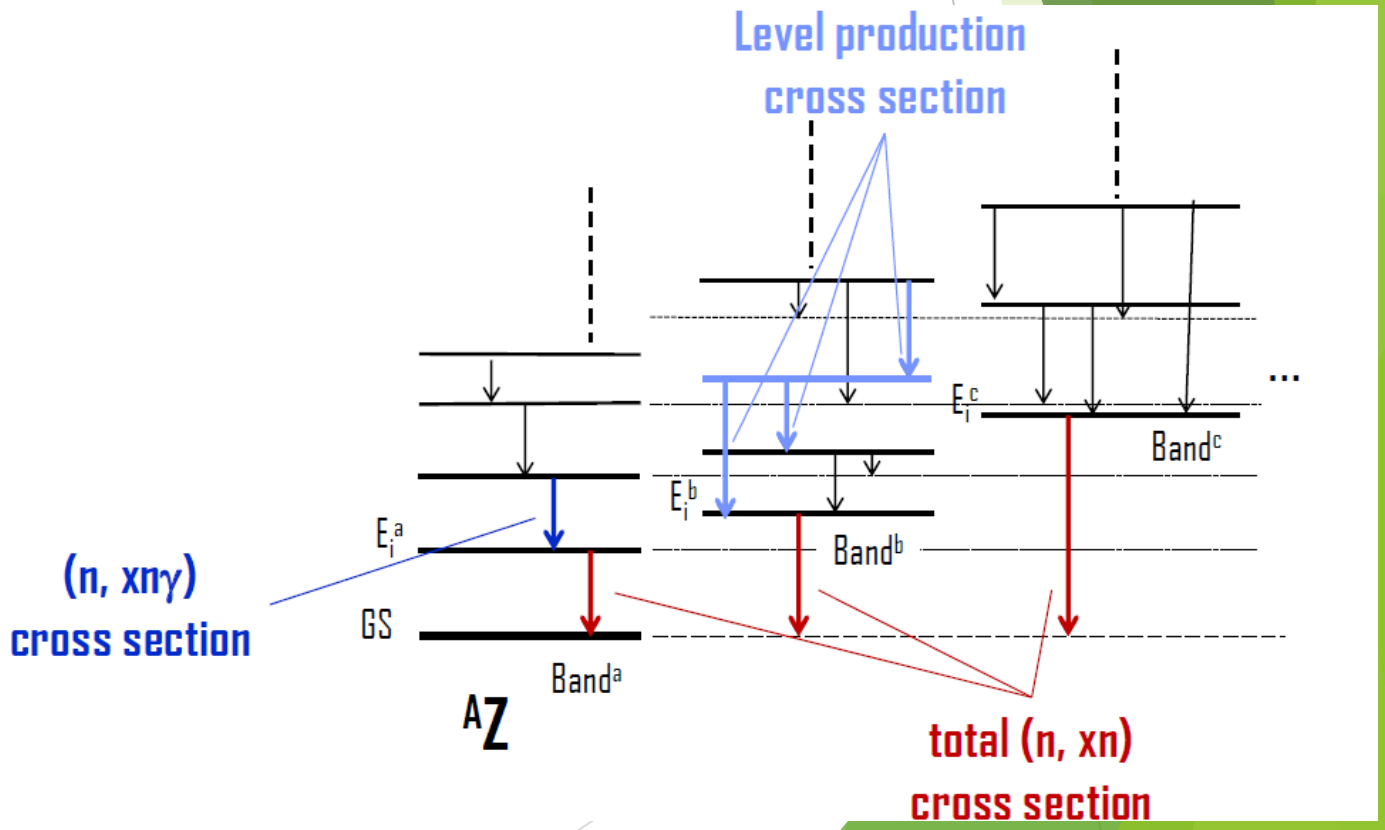
Source : M. Kerveno et al. ND2022 - presentation



Source : M. Kerveno et al. PRC 104, 044605-2, 2021

Why studying the ^{238}U level scheme

- Prompt γ-ray spectroscopy is a powerful method which provides a lot of cross sections:
  - (n, xnγ)
  - Level production
  - Total (n, xn)



Source : M. Kerveno et al.
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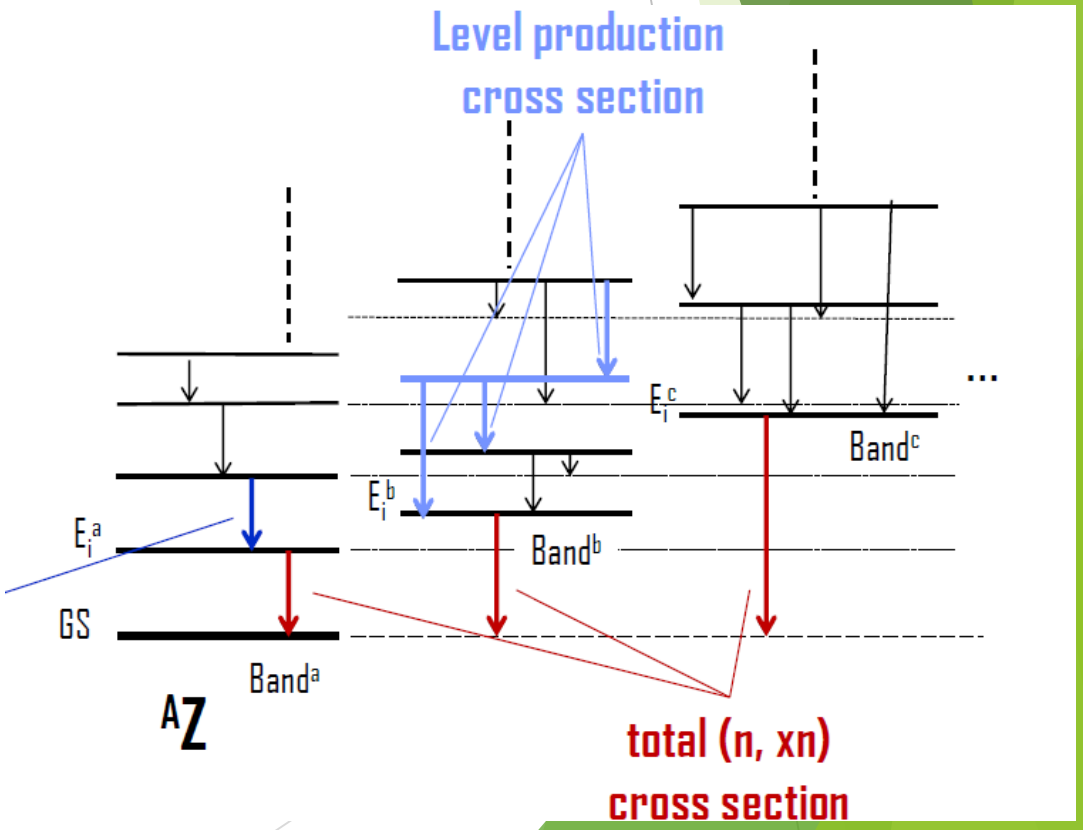
Why studying the ^{238}U level scheme

- Prompt γ-ray spectroscopy is a powerful method which provides a lot of cross sections:
  - (n, xnγ)
  - Level production
  - Total (n, xn)
- For neutronics needs: accurate neutron inelastic scattering of ^{238}U cross section
  - Large uncertainties in the current modeling are related to the knowledge of the decay scheme: poorly known BR and an incomplete information of the discrete states above 1.3 MeV
  - Uncertainties in level schemes induce uncertainties in inelastic cross sections (e.g. 10% on BR can have an impact of around 4% on (n, n'γ) XS) (Sensitivity analysis made by Greg Henning with the TALYS code, M. Kerveno et al. PRC 104, 044605, 2021))

→ Need to improve the level scheme knowledge to infer the total (n, n') XS



Source : M. Kerveno et al. ND2022 - presentation

^{238}U level scheme state of the art

Around 165 articles

- ^{238}Pa ß-decay
- ^{242}Pu α-decay
- ^{238}U(n,n'γ)
- Coulomb excitation
- ^{238}U(d,d')
- ^{238}U(γ,γ')
- ^{236}U(t,p)
- ^{238}U(n,n')
- ^{238}U IT decay (280 ns)

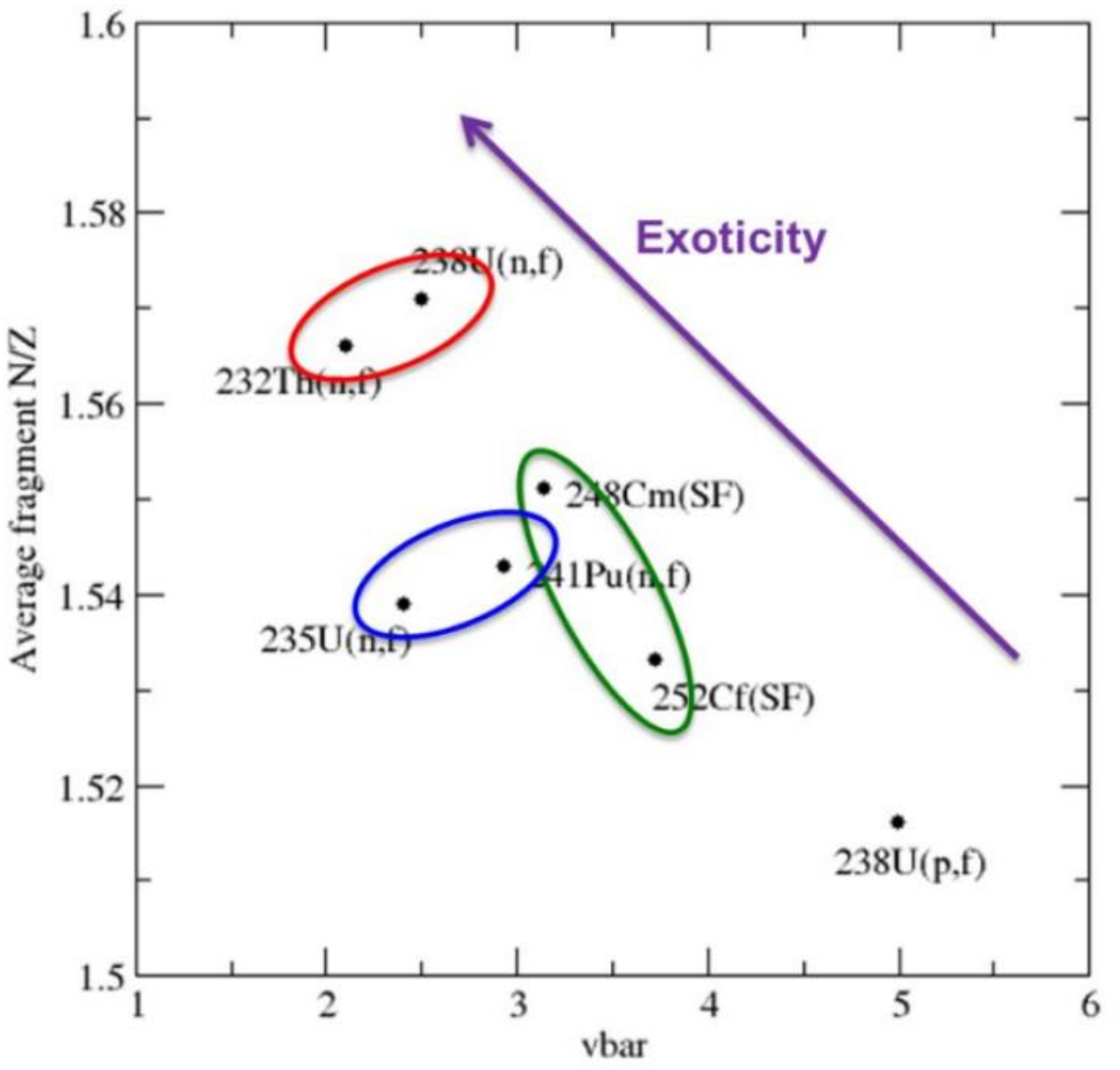
- Study of the main publication for each technique
- Often: the level scheme is not the first aim of the article
- Depending on the experimental technique, different states are observed
- When done by ^{238}U(n,n'γ), has never been done by γ-γ coincidences

ν-Ball experiments

- Realized in 2018 and 2022
- ALTO accelerator
- Neutrons beam LICORNE (Lithium Inverse Cinematiques ORsay NEUtron source) mono-energetic and pulsed (400 ns) focused forward

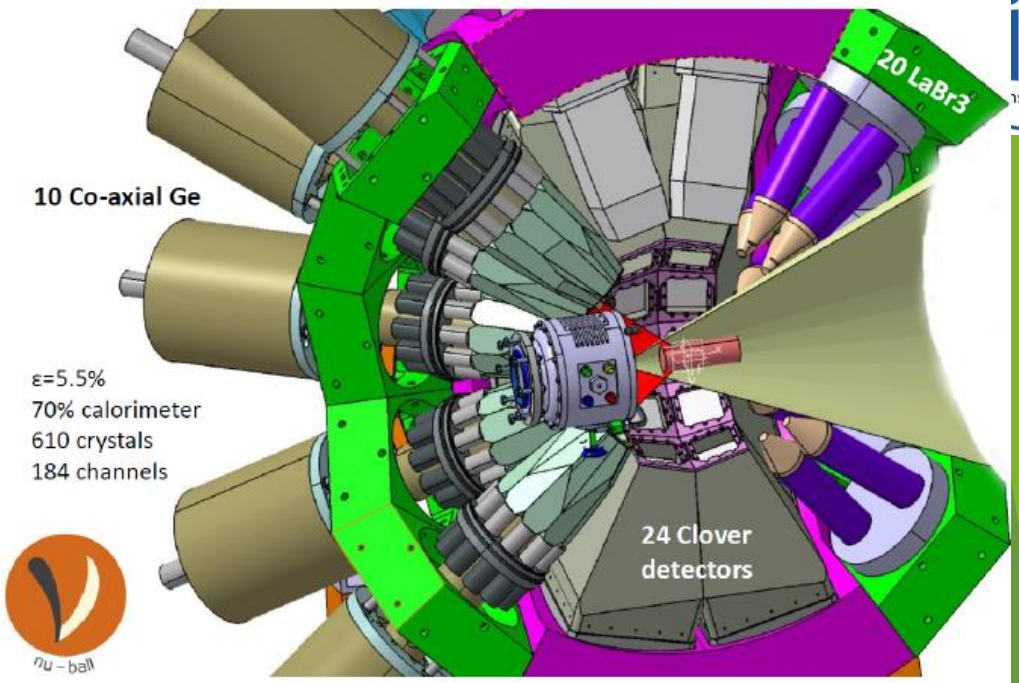
Experiments goal

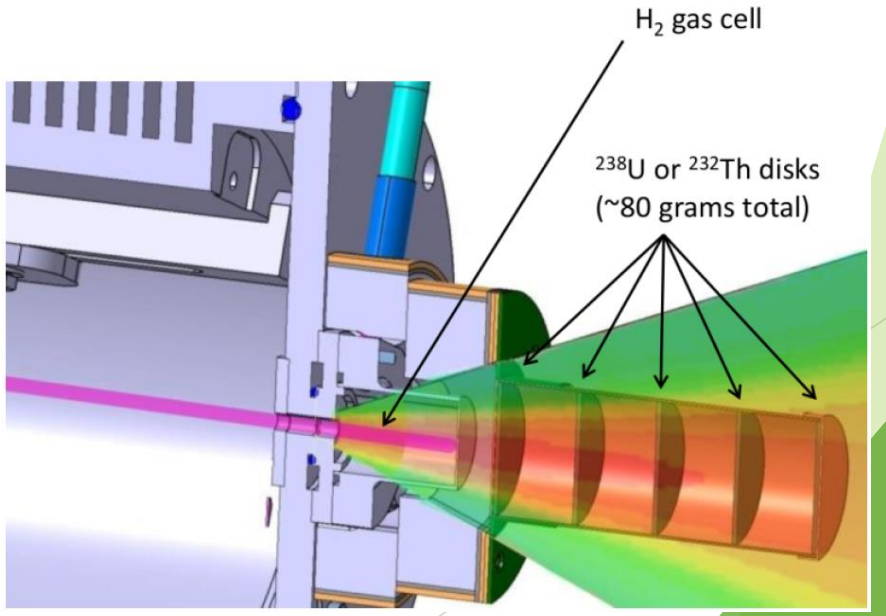
- Neutron-rich fission fragments
- Possibility of studying the structure of the target nucleus ^{238}U



ν-Ball experiment

- Detectors around the target 34 HPGe
  - 24 CLOVER
  - 10 HPGe
  - BGO (scintillators) around each Ge
- 5 ^{238}U or ^{232}Th disks
- Neutron production target: H_2
  Pressure: 1.4 bar
- 3 data set
  - ^{238}U, E_n=1,9 MeV – 9 days of data
  - ^{238}U, E_n=3,3 MeV – 5 days of data
  - ^{232}Th, E_n=1,9 MeV – 19 days of data

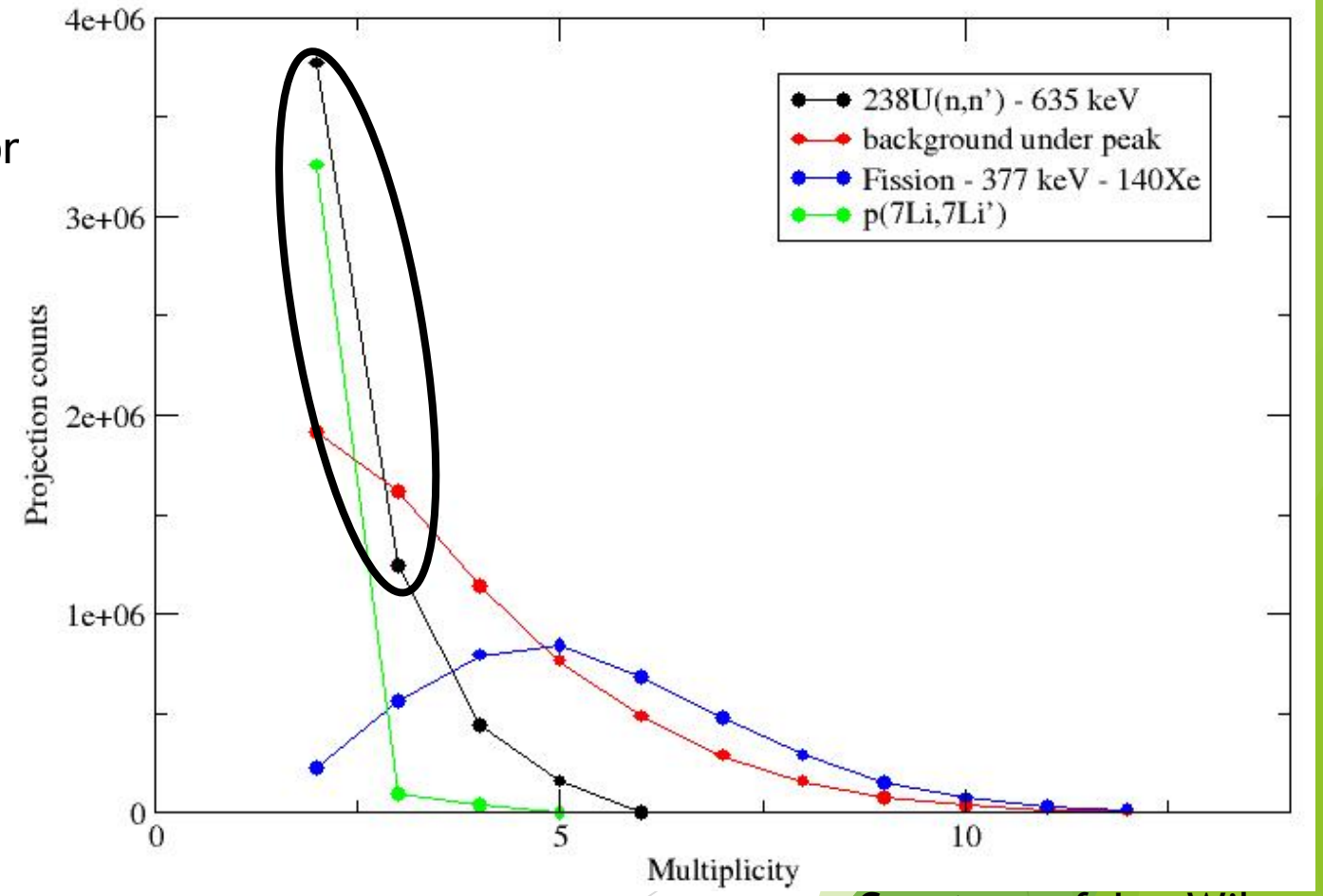




Data used to start the analysis

- Coincidences of γ with a multiplicity of 2 or 3 selection mostly the γ from the (n, n'γ)

→ Disregard most of the γ from fission (mean multiplicity of 5) and other parasitic γ



Courtesy of Jon Wilson

Data analysis– use of Radware escl8r

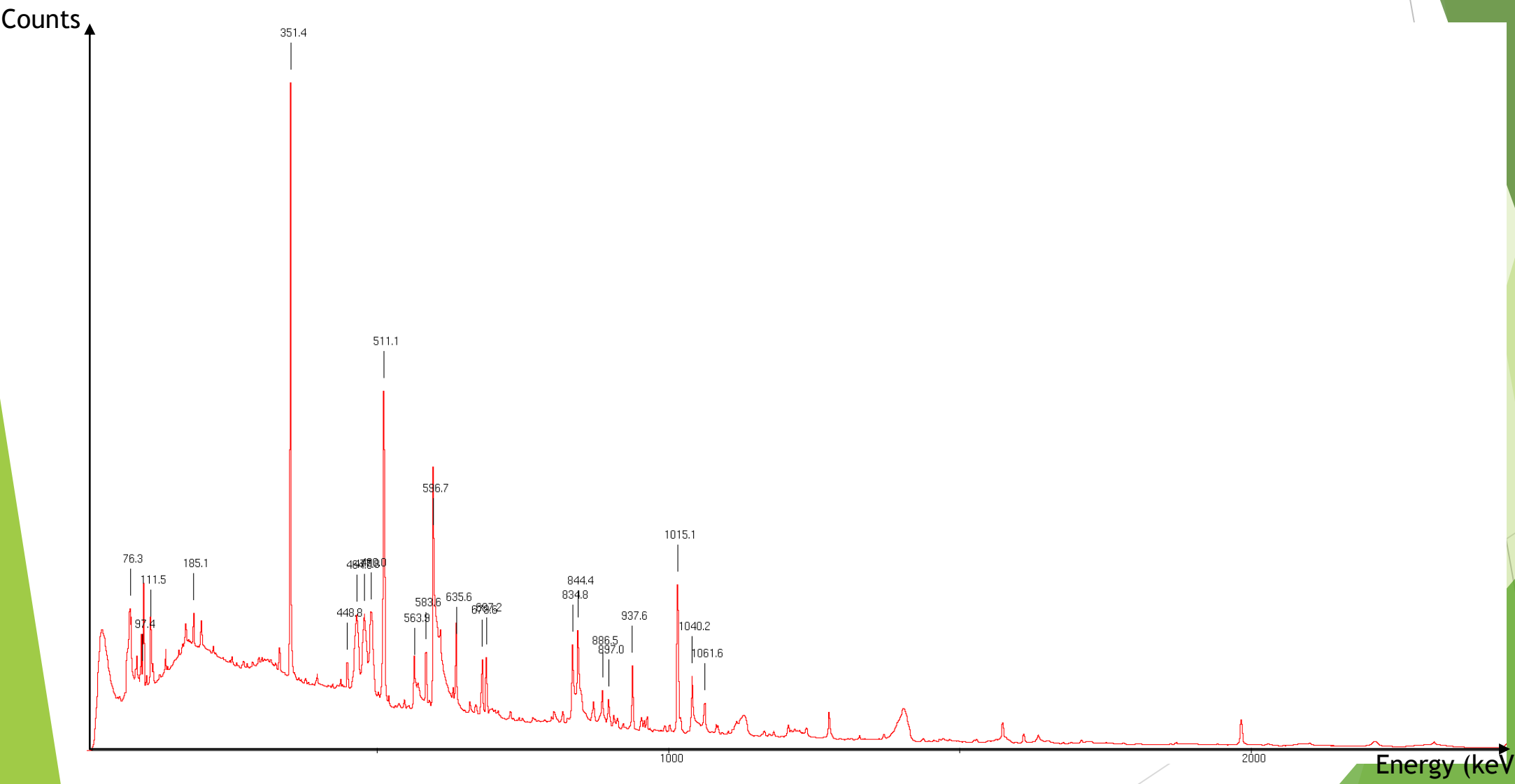
- Developed to **reproduce level scheme from a γ–γ coincidence matrix**
- Allows to make a gate by specifying energy for all axes but one to see the γ in coincidence
- Can work with background subtracted gated spectra

- To reproduce the level scheme:
  - Electron conversion coefficients, detection efficiency and γ-ray energy calibrations are taken into account
  - Lest-squares global fit on the level scheme is performed:
    - To reproduce the experimental spectrum and coincidence matrix
      - Including determination of level energies
      - Including determination of intensities of transitions

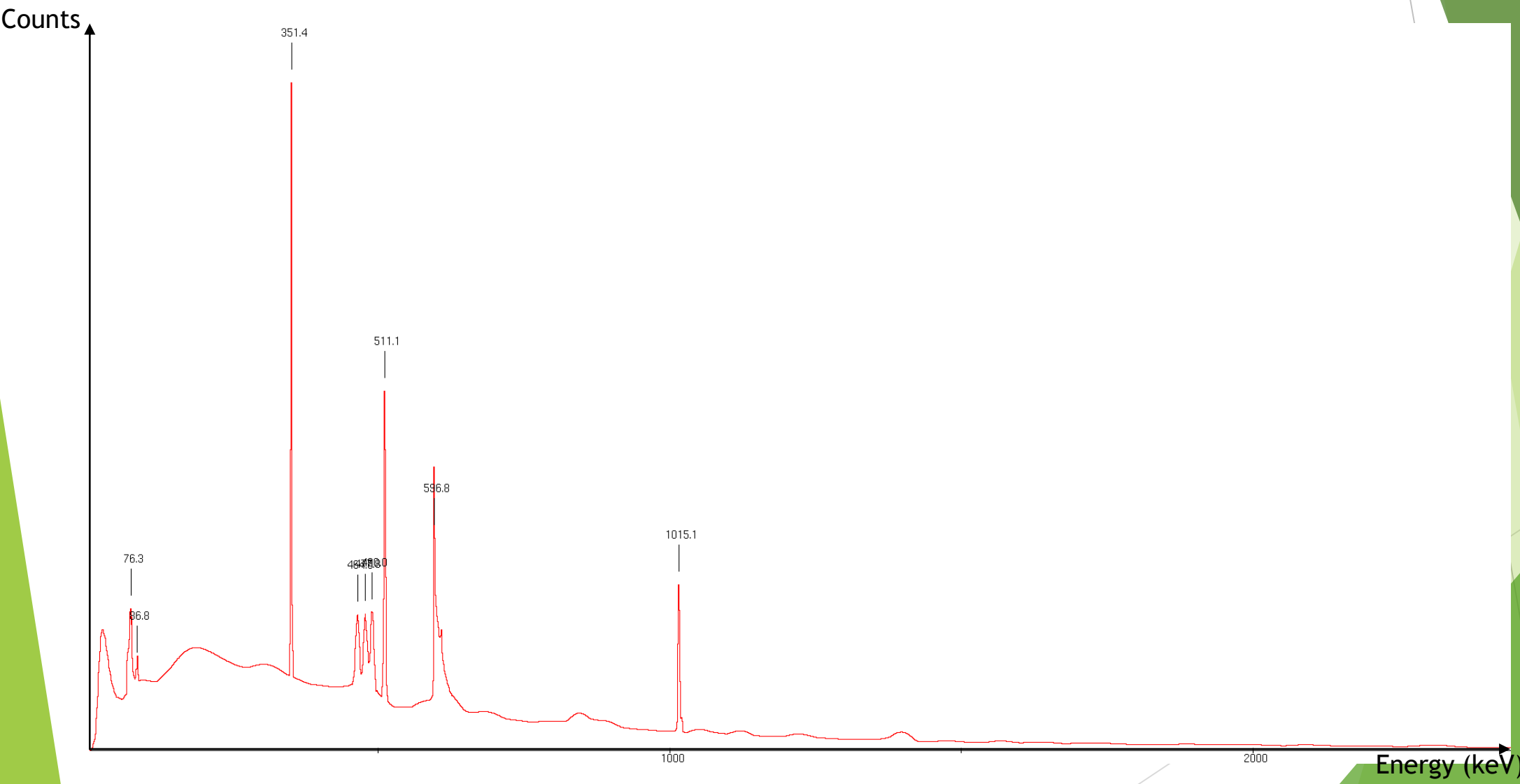
Data analysis – methodology

- Transitions in ENSDF
- Identification of the γ in the Govor *et al.* publication (*Investigation of the ^{238}U in the (n, n'γ) Reaction*, Physics of Atomic Nuclei **volume 77**, pages 131–166 (2014))
- Identification of the γ in Andi Messingschlager's bachelor thesis (done at IKP TU Darmstadt, private communication)
- Coincidences checking

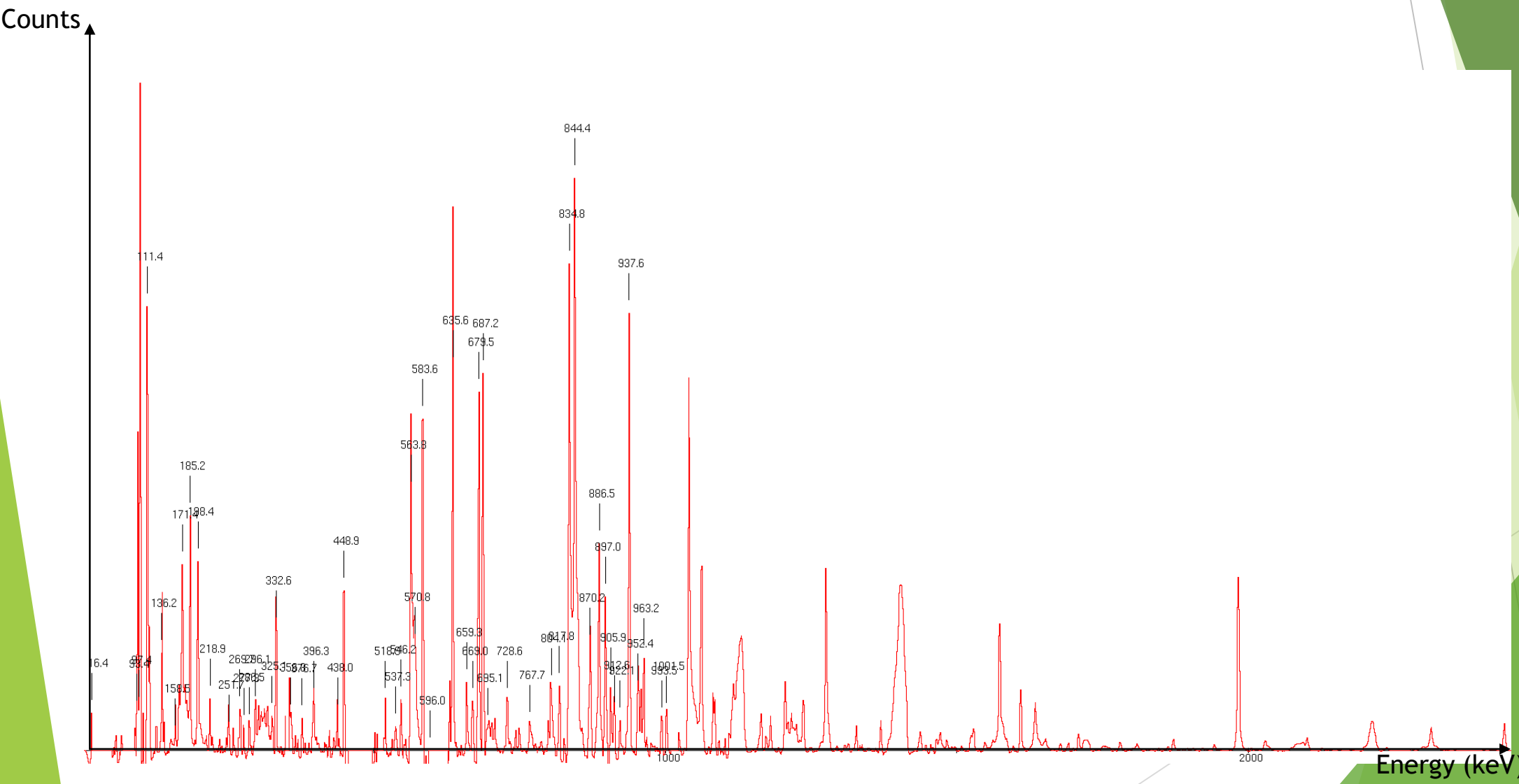
Total γ-spectrum



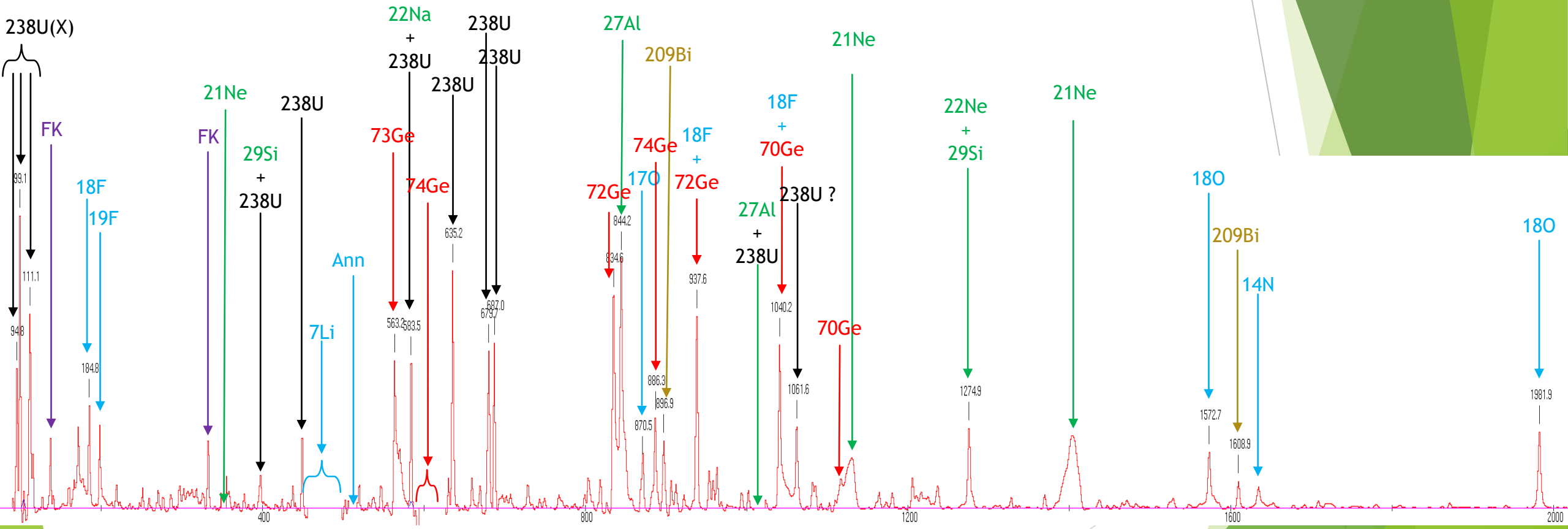
Background profile



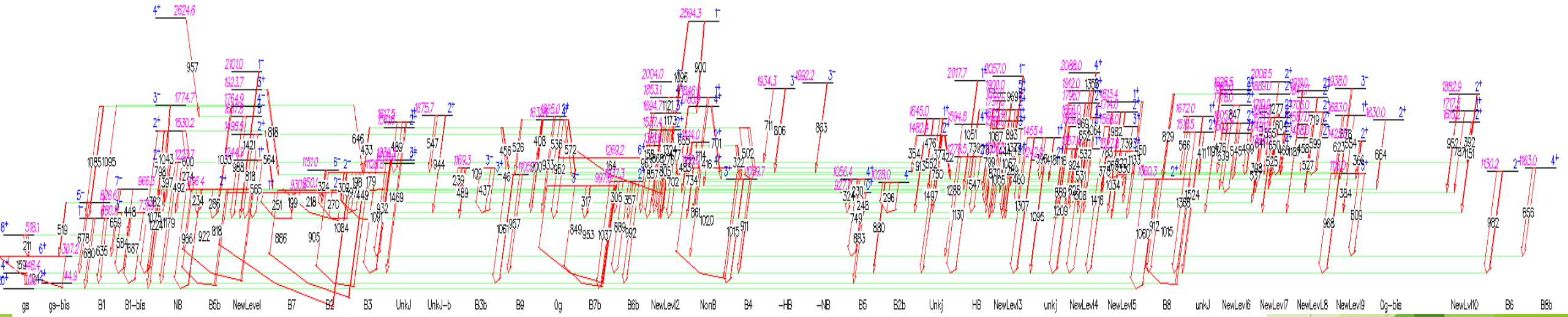
Background subtraction spectrum



Contamination analysis

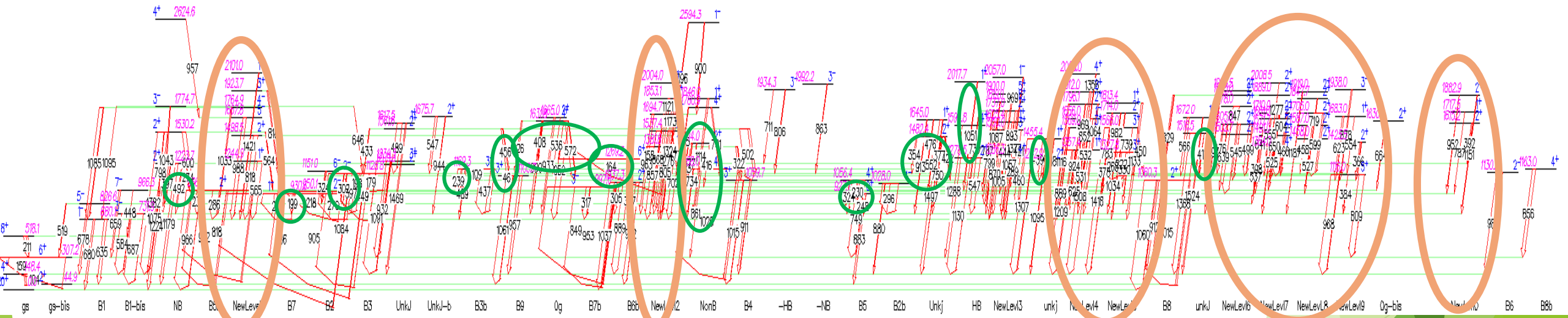


Analysis of the ν-Ball data - ^{238}U level scheme - obtained results



- 103 levels identified
  - Including 52 already listed in ENSDF
- 211 γ identified
  - Including 86 already listed in ENSDF

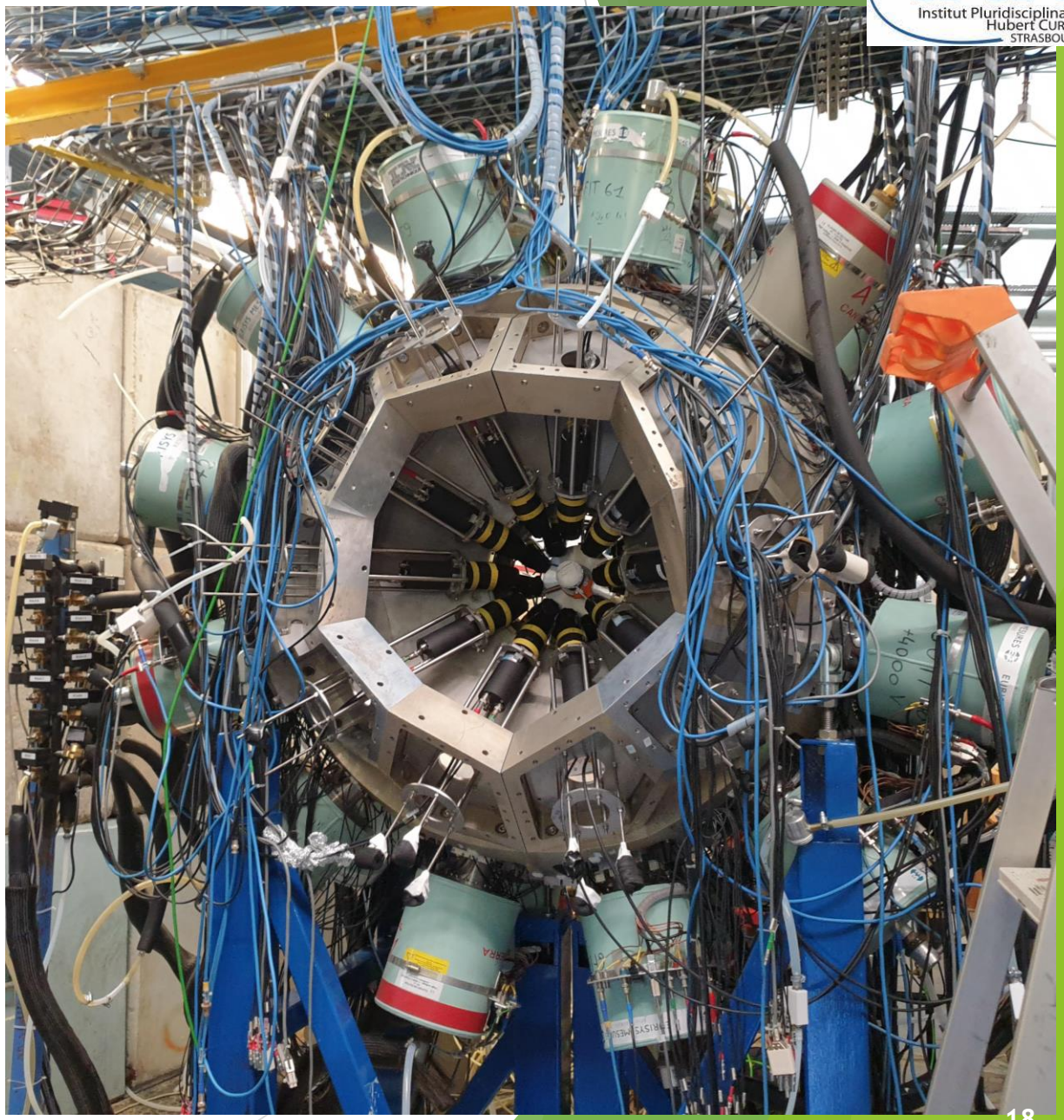
Analysis of the ν-Ball data - ^{238}U level scheme - obtained results



- 39 new γ depopulating levels already known in ENSDF ; including 13 in common with Andi's work
- 51 new levels (not known in ENSDF) ; including 32 in common with Andi's work
- 86 new γ (de)populating these new levels ; including 38 in common with Andi's work

ν-Ball2

- Increased statistics (8 times)
- Remove of some contamination by changing the beam dump and the target
  - The main contamination of ν-Ball (^{21}Ne) has been deleted in ν-Ball2
  - 3 new rays of contamination appear linked to the Au



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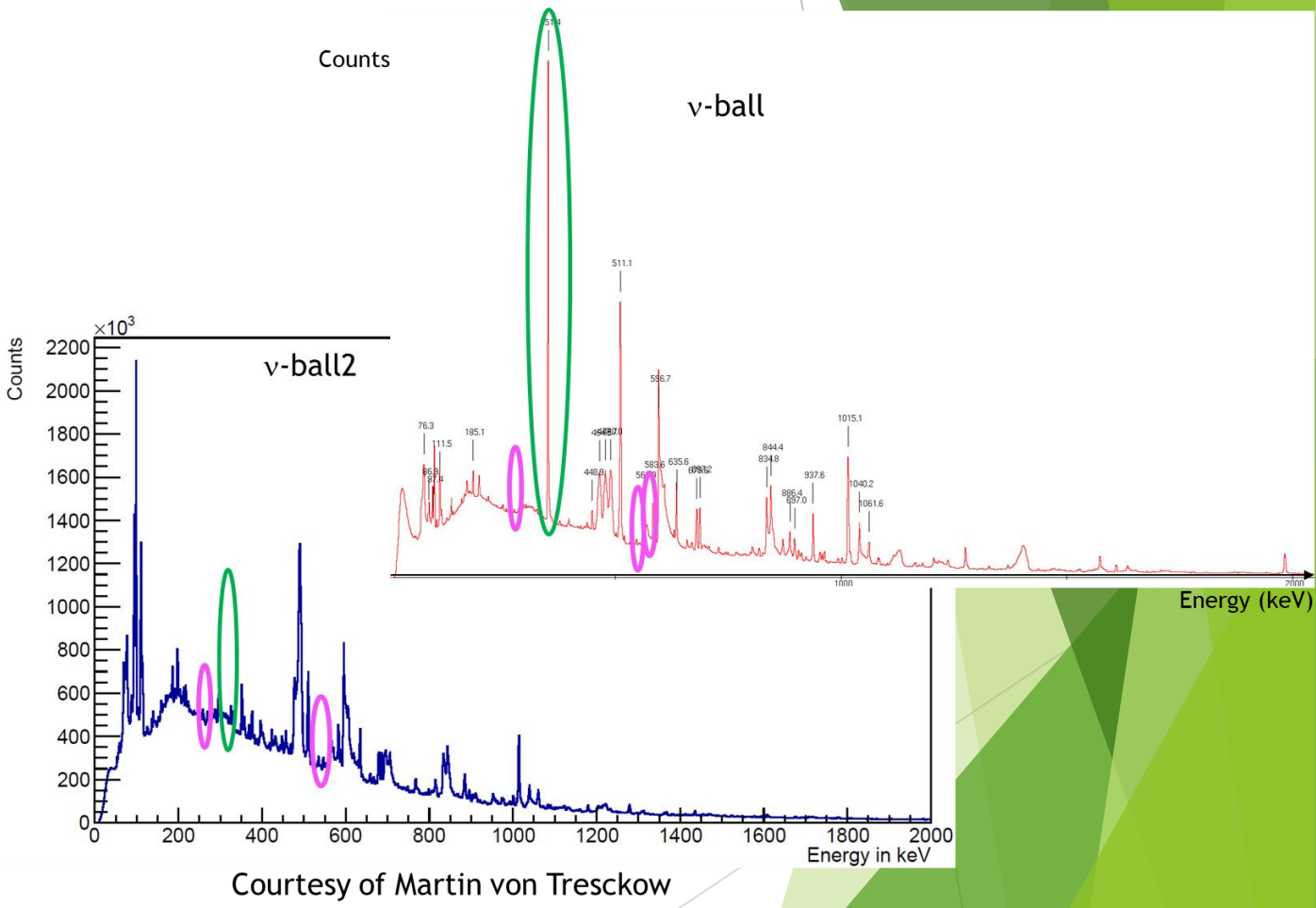
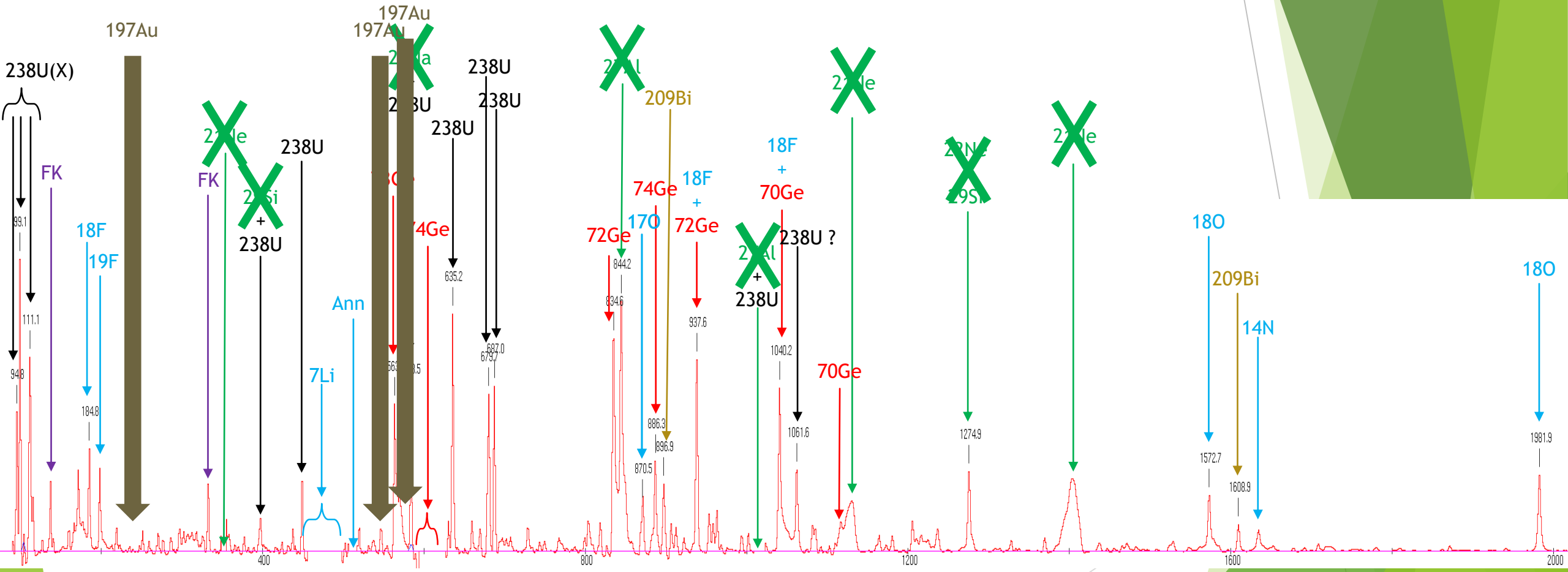
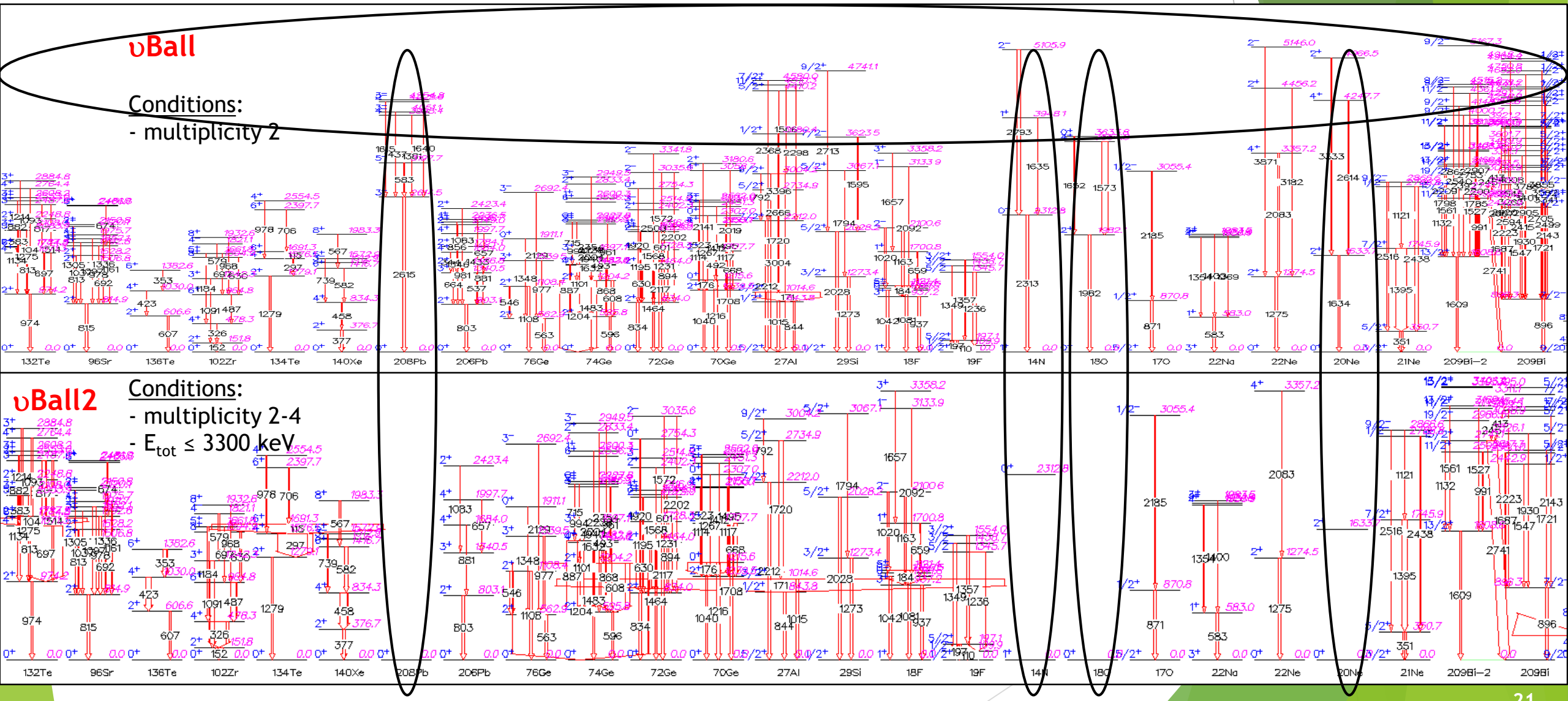


Courtesy of Martin von Tresckow

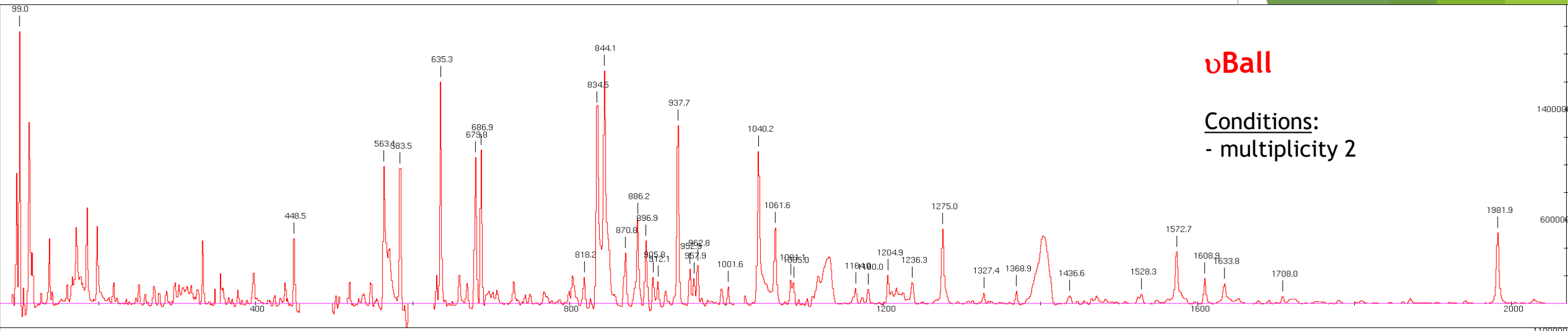
Contamination analysis



Contamination analysis

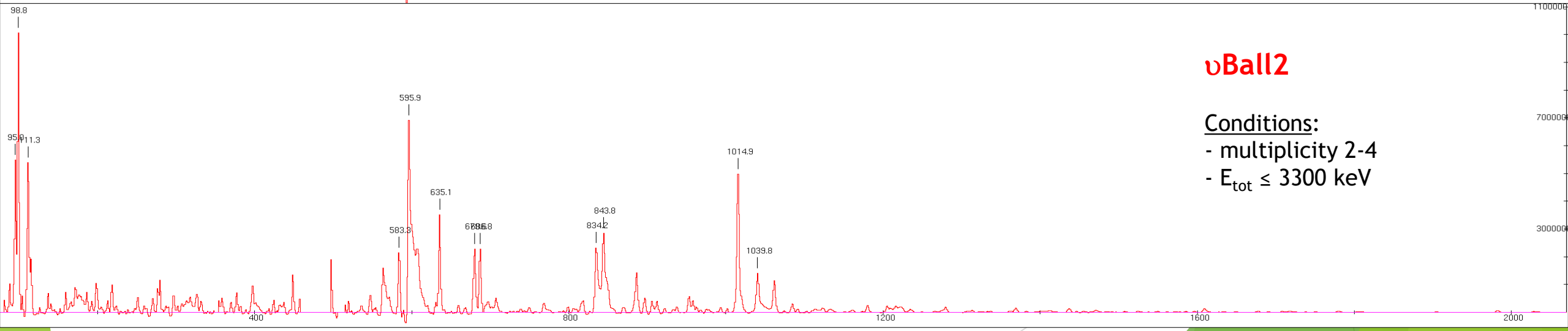


υBall2: Background subtraction spectrum



υBall

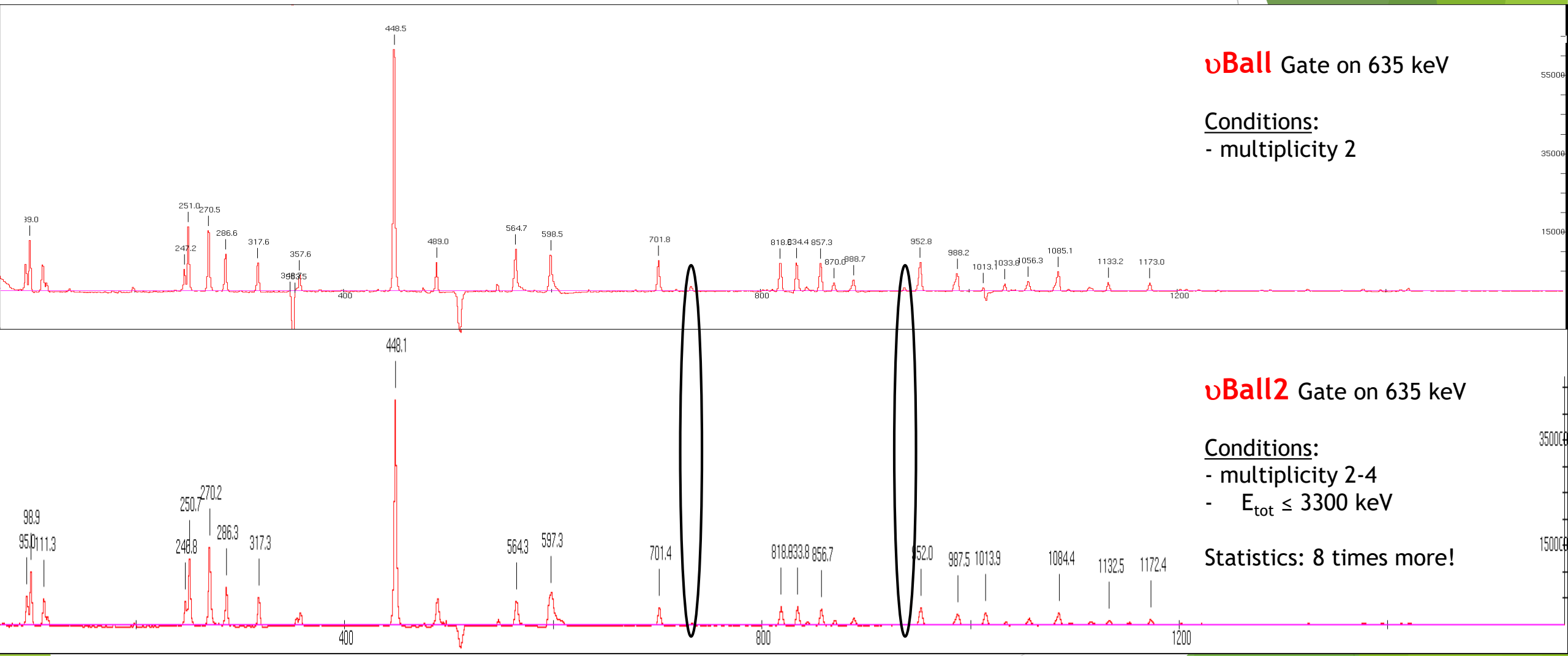
Conditions:
- multiplicity 2



υBall2

Conditions:
- multiplicity 2-4
- $E_{tot} \leq 3300$ keV

Comparison ν-Ball and ν-Ball2– γ 635 keV



υBall Gate on 635 keV

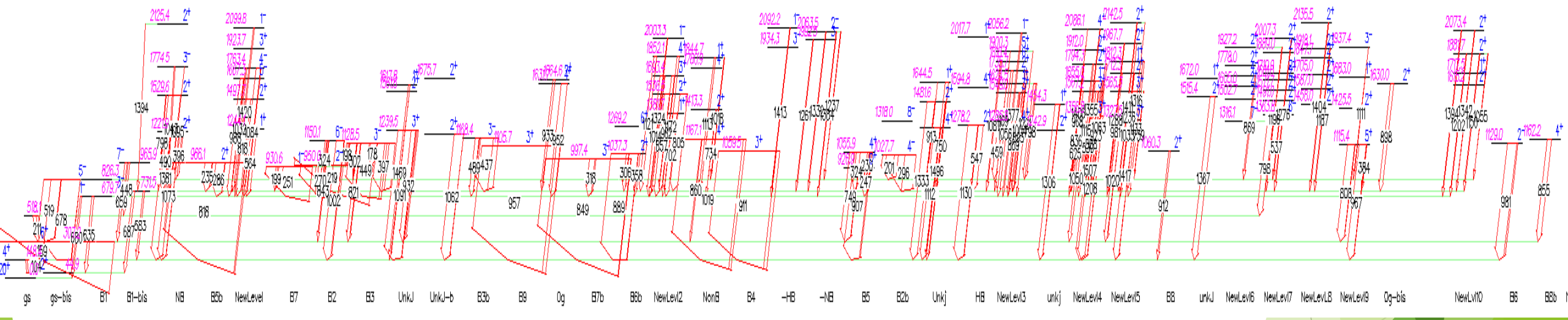
Conditions:
- multiplicity 2

υBall2 Gate on 635 keV

Conditions:
- multiplicity 2-4
- $E_{tot} \leq 3300$ keV

Statistics: 8 times more!

Analysis of the ν-Ball2 data - ^{238}U level scheme - obtained results



- 91 levels identified
  - Including 50 already listed in ENSDF
- 162 γ identified
  - Including 67 already listed in ENSDF

Branching ratios (PRELIMINARY)

Level	Gamma	ENSDF	This work	Kerveno *et al.* (2021)	Govor *et al.* (2014)	Messingschlager (2020)
731.93	687	100 (20)	100 (3)	100	100	100 (3.7)
	583	81.4 (16)	78.1 (24)	84 (3)	84.6	78.9 (111)
826.64	678	100 (6)	100 (4)	100	100	100 (16)
	519	50 (3)	53.7 (20)	55 (2)	55.6	60.4 (49)
930.55	251	13.1 (14)	9.5 (3)	11 (2)	8.7	
	885	100 (4)	100 (6)	100	100	100 (14)
997.58	953	56.8 (13)	58.5 (6)	64 (9)	55.1	52.2 (159)
	849	100 (3)	100 (5)	100	100	100 (13)

Kerveno *et al.* and Govor *et al.*: BR done by simple γ, without coincidences
Messingschlager: BR done by γ-γ coincidence with the υBall data with no conditions

Branching ratios of this work in rather good agreement with the 3 publications and with ENSDF within the uncertainties ranges

Branching ratios (PRELIMINARY)

Level	Gamma	ENSDF	This work	Kerveno *et al.* (2021)	Govor *et al.* (2014)	Messingschlager (2020)
680.11	680	79 (4)	61.5 (19)	61 (7)	61	69.6 (126)
	635	100 (20)	100 (3)	100	100	100 (35)

Branching ratios of this work in rather good agreement with the 3 publications.

The 4 works have found a BR much lower than the one given in ENSDF.

The impact of the BR on the (n, n'γ) cross section has been analyzed by Kerveno *et al.* and the low BR seems to improve the agreement between theory and experimental

Conclusions

ν-ball

- 86 γ confirmed (ENSDF)
- 52 confirmed levels (ENSDF)
- 125 new γ indentified
- 51 new levels identified
- 97 γ listed in ENSDF for which no coincidences have been found
  - Including 35 feeding the ground state or the first 2^+ level which were impossible to check

ν-ball2

- 67 γ confirmed (ENSDF)
- 50 confirmed levels (ENSDF)
- 95 new γ indentified
- 41 new levels identified
- 54 γ listed in ENSDF for which no coincidences have been found
  - Including 35 feeding the ground state or the first 2^+ level which were impossible to check
- **STILL ONGOING!**

Most of contaminations have been analyzed

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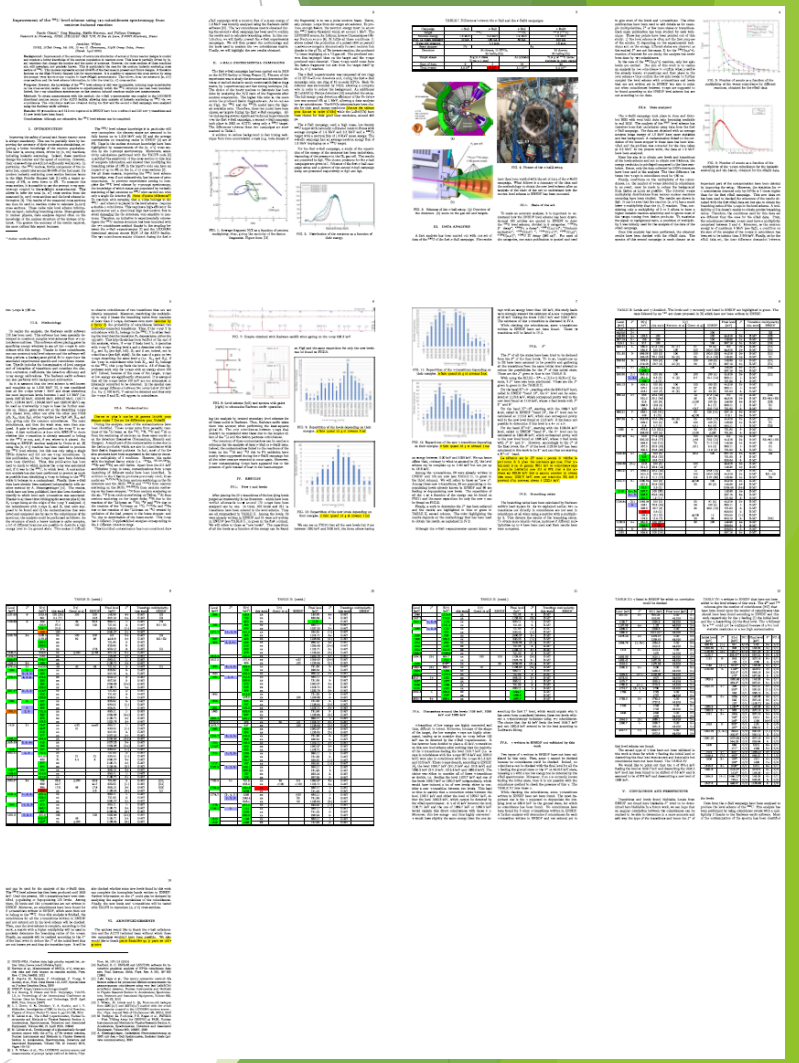
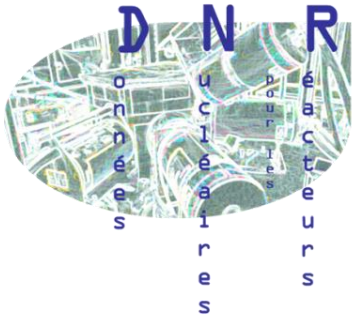
Outlook

- Few γ must be reanalyzed to decide of their existence (~12)
- Branching ratios will be extracted
- Article in progress
- **The new levels and transitions will be used with TALYS to be tested to reproduce (n, n'γ) cross sections**





Thank you ☺

Thank to the ν-Ball collaboration

Particularly thank to:

Jon Wilson

Andi Messingschlager

Martin von Tresckow