Study Of Exotic Nuclei Of Interest For Applied And Fundamental Nuclear Physics With Total Absorption Gamma-ray Spectroscopy (TAGS)

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For the TAGS Collaboration

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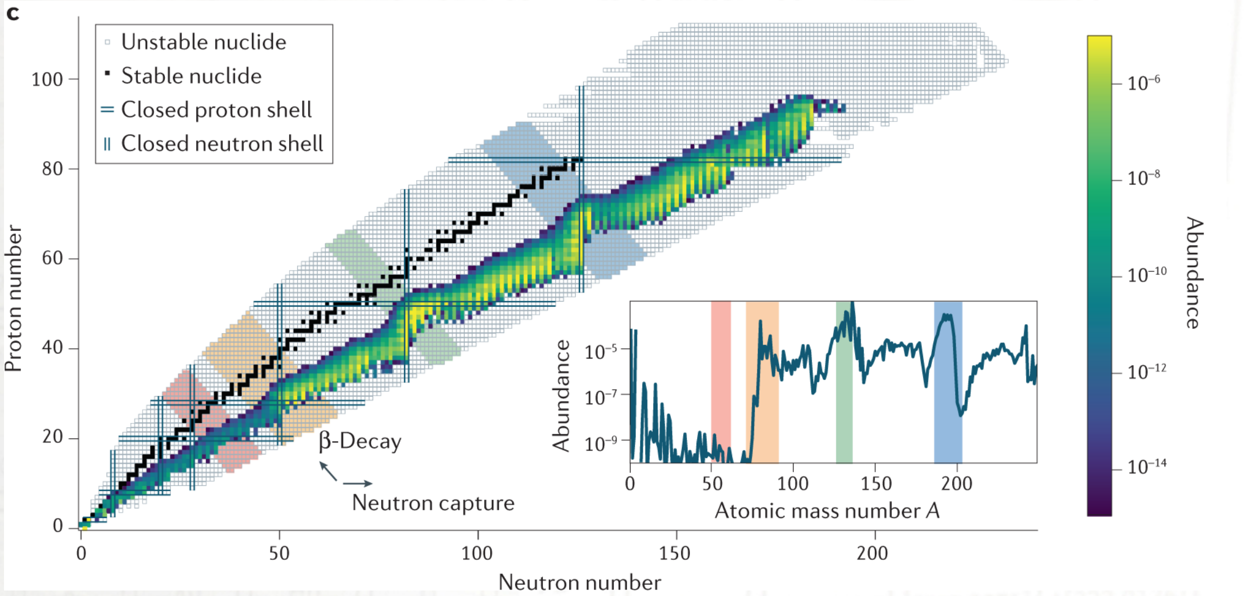
Table Of Content

« Dans le vie, rien n'est à craindre, tout est à comprendre. »
Marie Curie

Nuclear Astrophysics: R-Process

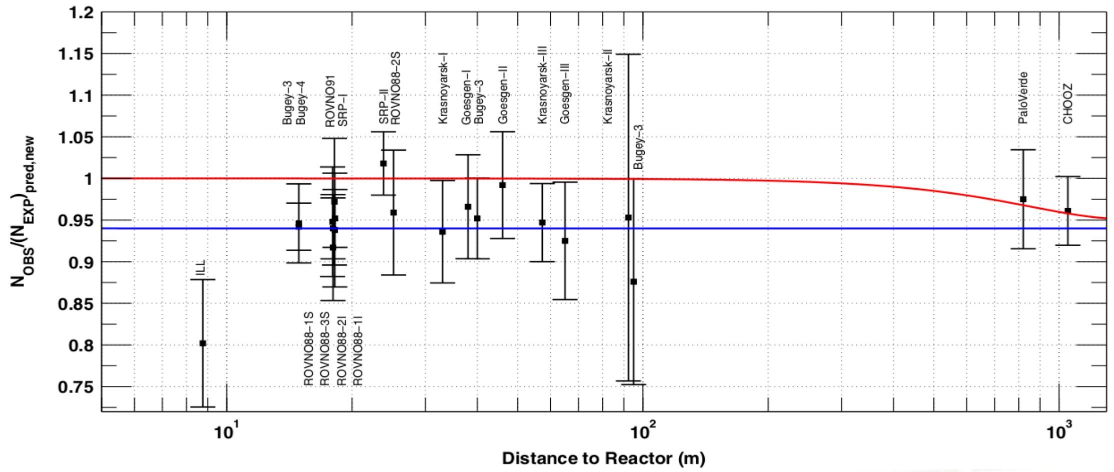
- Nucleosynthesis process producing half of the nuclei heavier than iron
- Need very hot ($T \sim 10^9 K$) and very neutron dense ($\sim 10^{24}/cm^3$) environments
- Core-collapse supernovae and binary neutron star mergers
- Competition between 3 processes :
  - Neutron capture (n,γ)
  - Photo-disintegration (γ,n)
  - β-decay

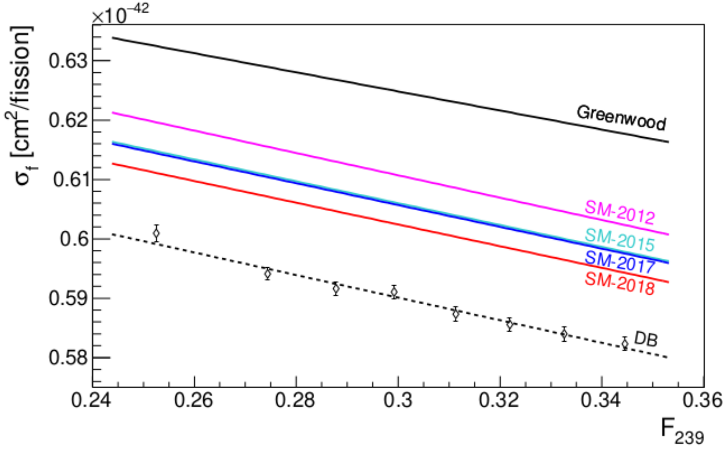


D.M.Siegel, nature review physics, 2022

Reactor Neutrino Studies

- β decays lead to (anti)neutrino emission
- Several fields of neutrino physics:
  - Energy spectrum computation
  - Reactor anomalies
    - Flux
    - Shape of energy distribution
  - Neutrino oscillations
  - Applied neutrino physics
    - Reactor monitoring
    - Non-proliferation



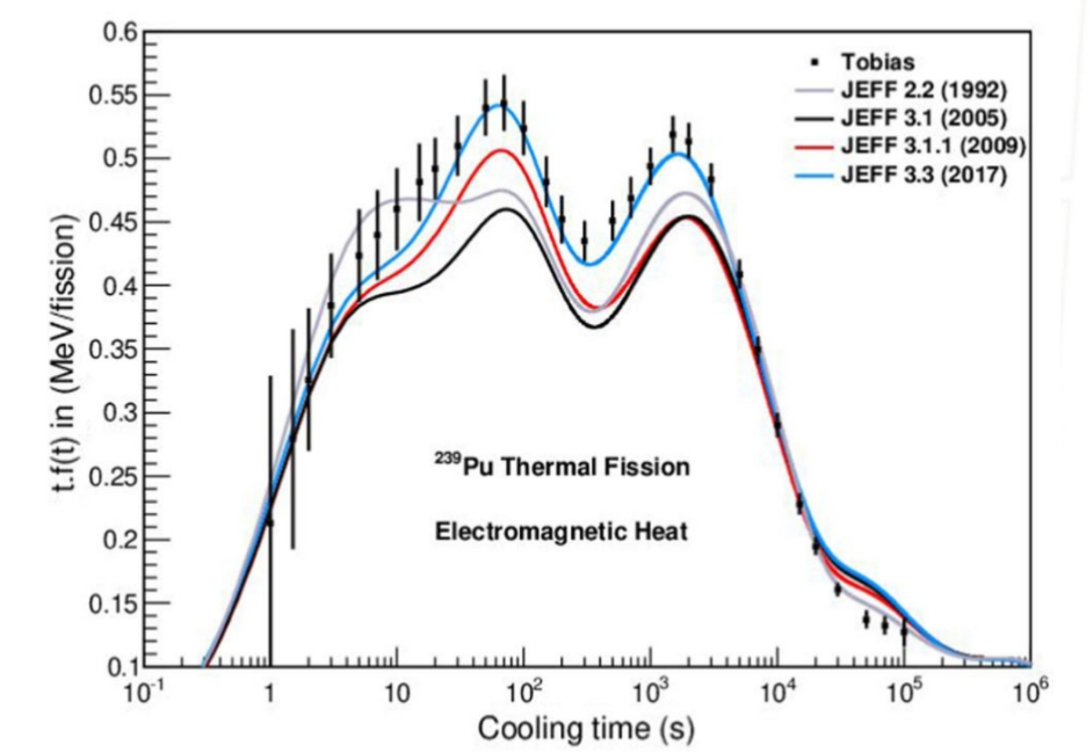


Upper panel: G. Mention et al, Physical Review D 83, 2011

Lower panel: M. Estienne et al, Physical Review Letters 123, 2019

Reactors: Decay Heat

- Decay of fission products from fuel ≈ 7% of operating reactor power
- Main power source after shutdown
- Better knowledge of the decay heat can lead to a better prevention of serious accident risks
- Economic reasons for fuel cooling (more important for future reactors)
- Better safety when dismantling reactors and for processing spent fuel

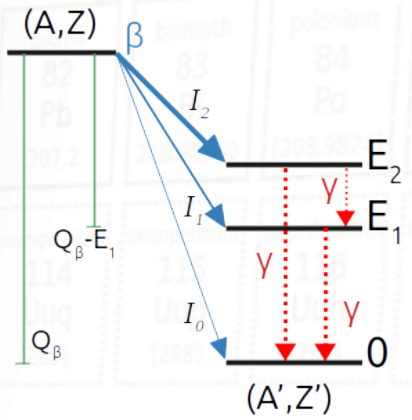


A.L. Nichols et al, European Physics Journal A, 59:78, 2023

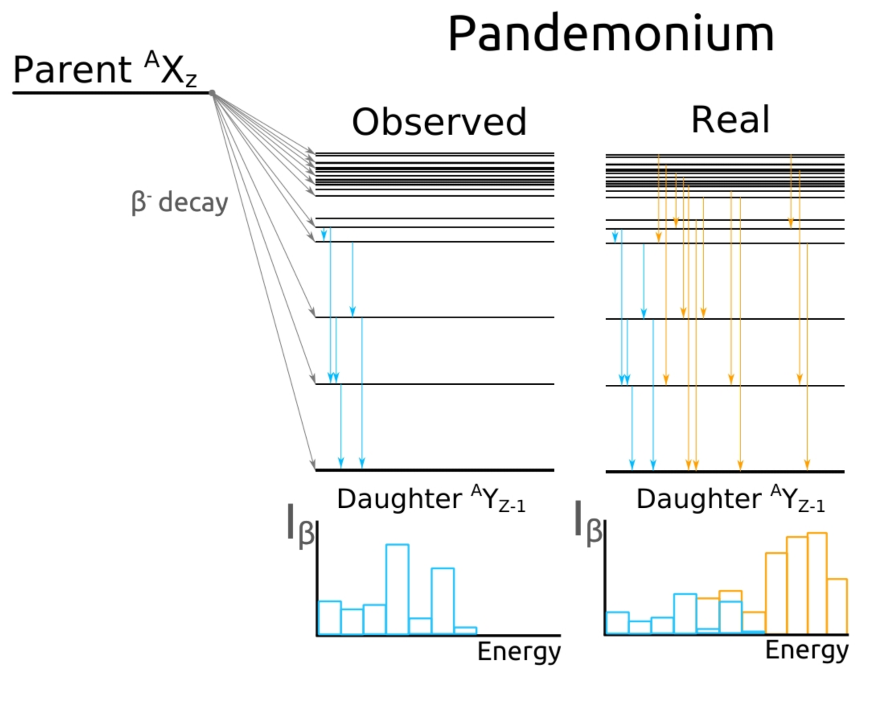
Interest of TAGS Measurements

- Common points between those scientific interests : β-decay
- Theoretical models are validated with experimental measurements through the β-strength S_β
- β-strength obtained from β-Intensity (I_β) obtained form β-feeding
- Need for a reliable database
- Previous data measurements performed with high-resolution detectors (HPGe …)

$$S_i = \frac{I_i}{f(Q_\beta - E_i)\, T_{1/2}} \qquad I_i = \frac{f_i}{\sum_k f_k}$$



Pandemonium Effect

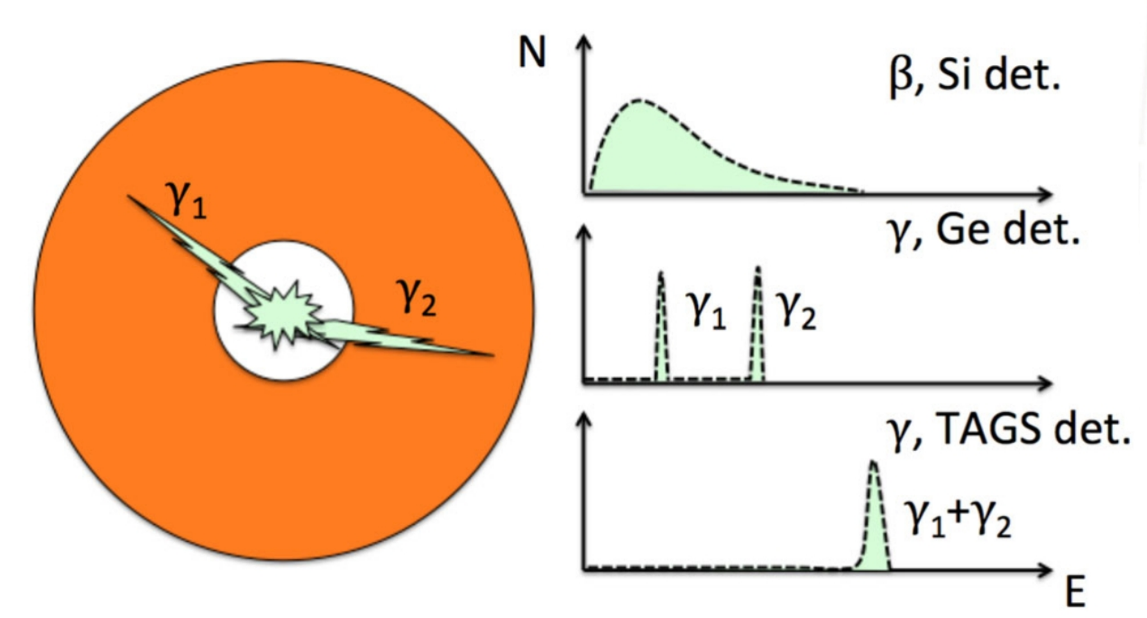


- May affect measurements performed with high-resolution detectors (e.g. HPGe)
- Due to low detection efficiency for high energy gamma-rays
- Also due to low angular coverage of high-resolution detectors
- Leads to an overestimation of feeding to low energy levels
- More important effect with a large Q_β

J.C.Hardy et al. Physics Letters Volume 71B, number 2, 1977

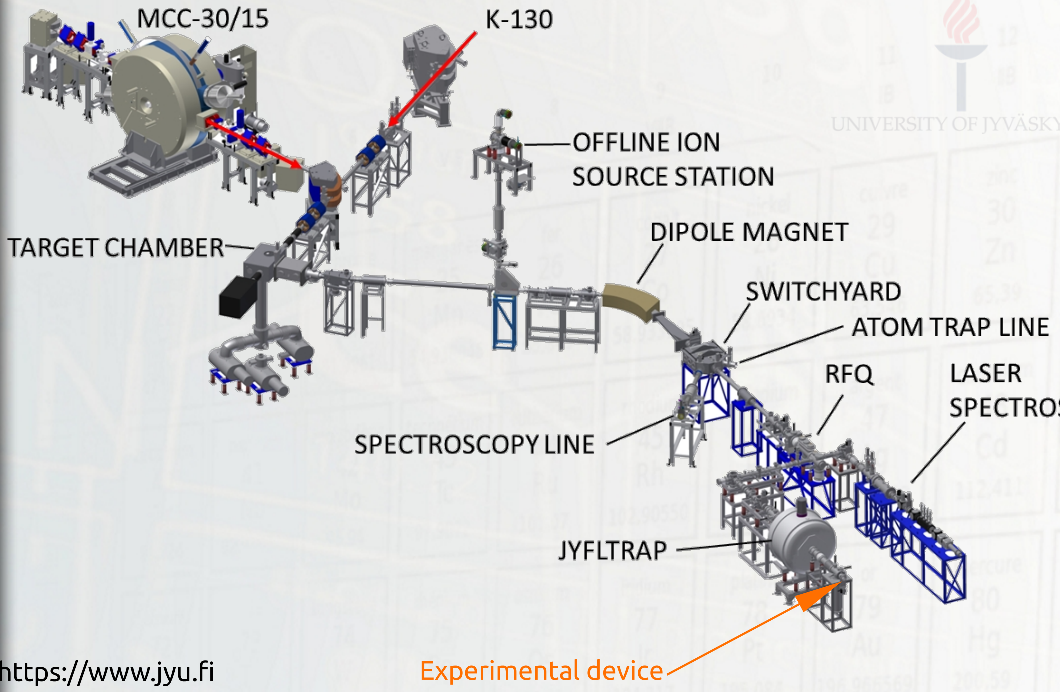
Total Absorption Gamma-Ray Spectroscopy

- Avoid Pandemonium effect
- Detect all γ-rays from the de-excitation cascade
  - Energy of the detected peak should correspond to the energy of the fed level
- Need a calorimeter, 4π detector with a material having a detection efficiency as high as possible (BaF_2, NaI…)



A.Algora et al. The European Physical Journal A, 2021

I241 Experiment



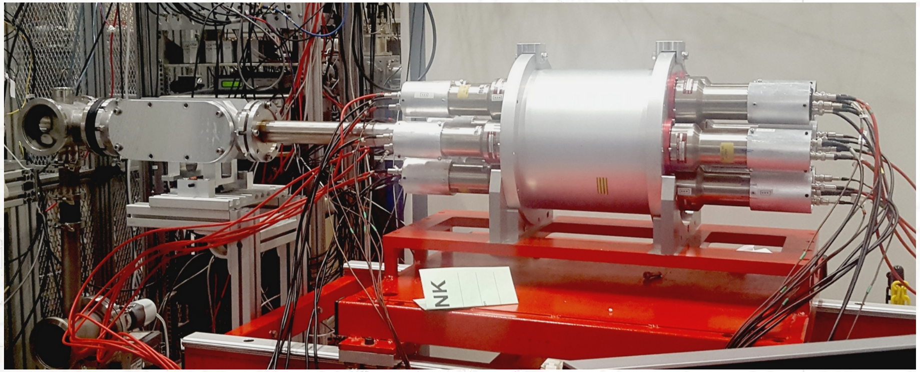
https://www.jyu.fi

- Sept 2022 in Jyväskylä University, Finland, in JYFL Accelerator Laboratory
- IGISOL (Ion Guide Isotope Separation On-Line) can produce refractory elements
- Very precise mass separation thanks to JYFLTRAP double Penning trap (~10^5 - 10^6)

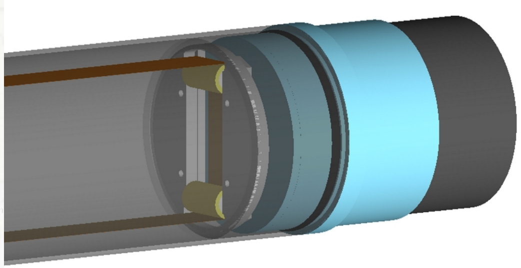
J.Äystö et al. Nuclear Physics A 693.1, 2001
T. Eronen et al. The European Physical Journal A 48, 2012

Rocinante Detector

- Total Absorption Spectrometer composed of 12 BaF_2 crystals
- Segmented detector for the multiplicity of the gamma cascade
- Beam implanted on a magnetic tape
- Plastic scintillator in the detector center used for β/γ coincidences
- $CeBr_3$ detector with higher resolution for better identification of contaminants
- Internal contamination of BaF_2 by ^{238}U and ^{232}Th leads to α background signals used for alignment



Rocinante detector, Sept 2022
Plastic detector and beam tube

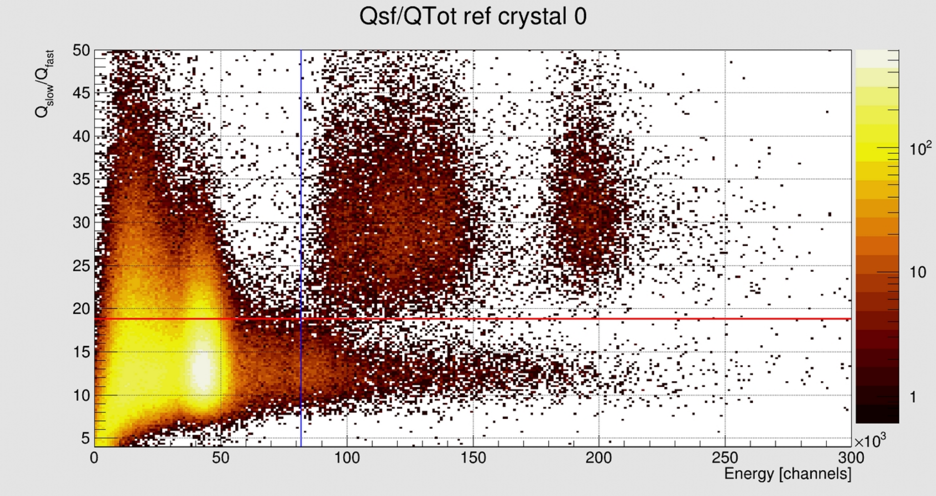


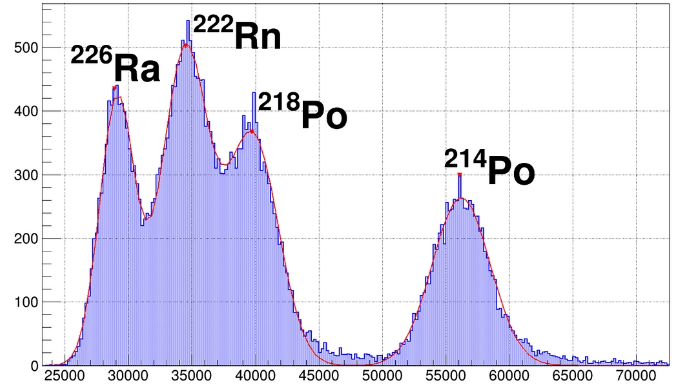
E. Valencia et al., Phys. Rev. C 95, 024320 (2017)

Data Treatment & Data analysis

Data Treatment: Alignment

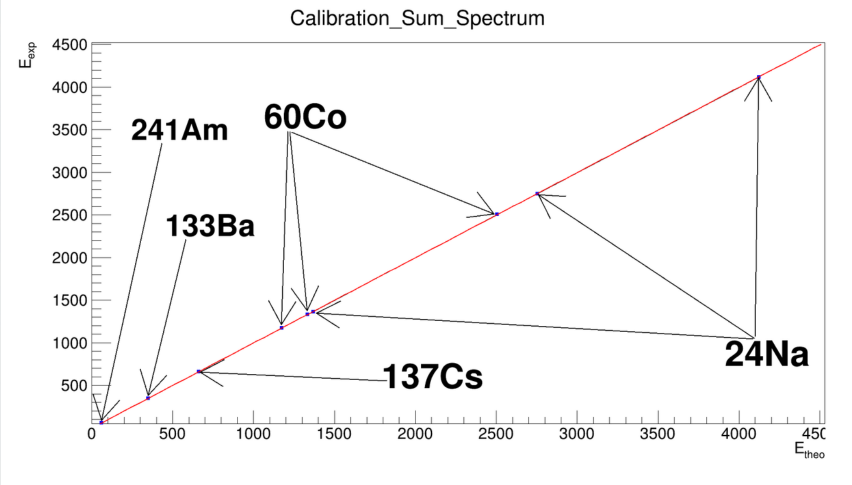
- Compensates PMT gain drifts
- Discrimination possible thanks to two scintillation times of BaF_2:
  - 630ns (slow)
  - 0.7ns (fast)
- Performing α/γ discrimination to obtain clean α peaks
- Using α events coming from internal contamination for reference

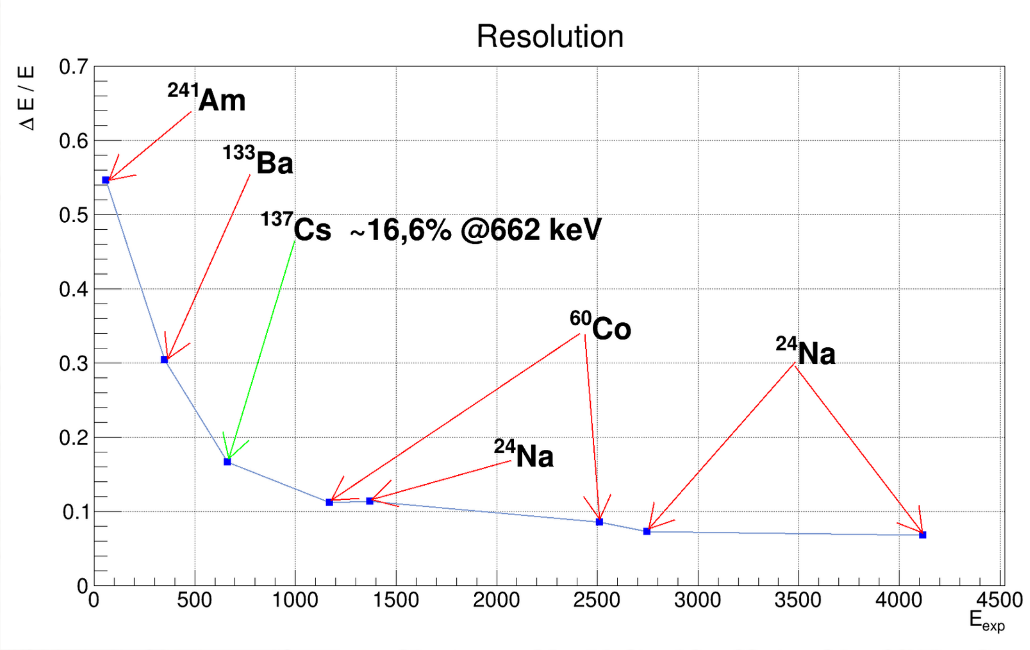




Data Treatment: Calibration

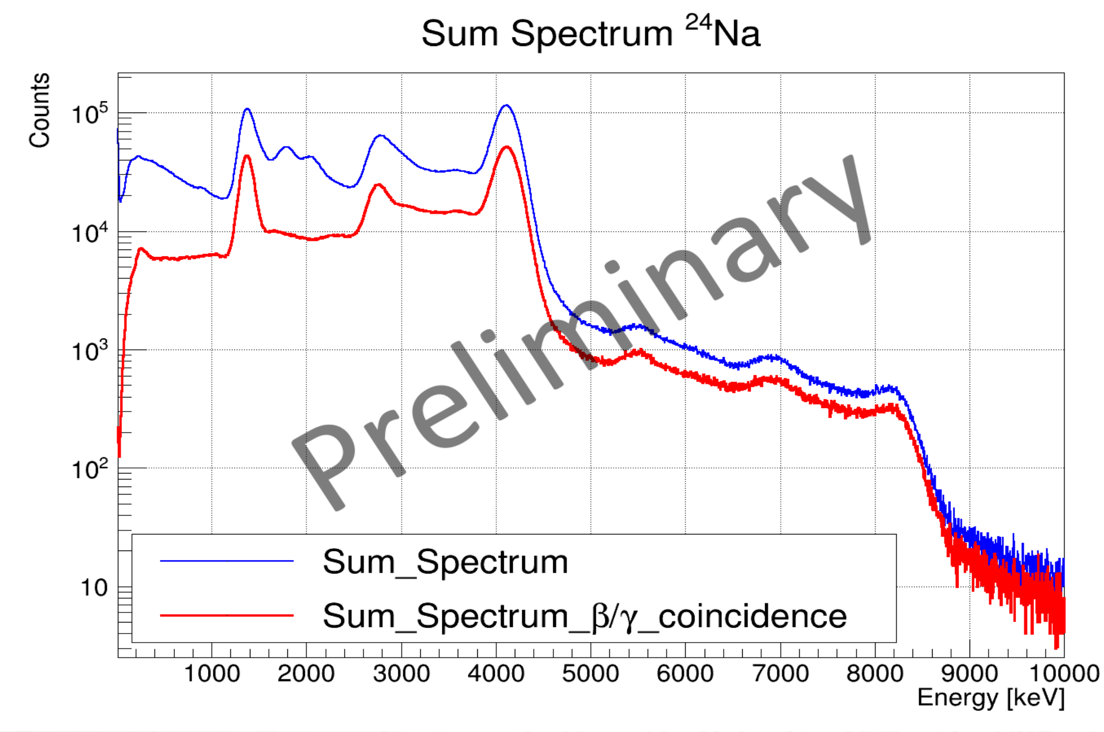
- Converts channels into energy
- ^{24}Na gives access to high energy point (4122 keV)
- Calibration in energy resolution





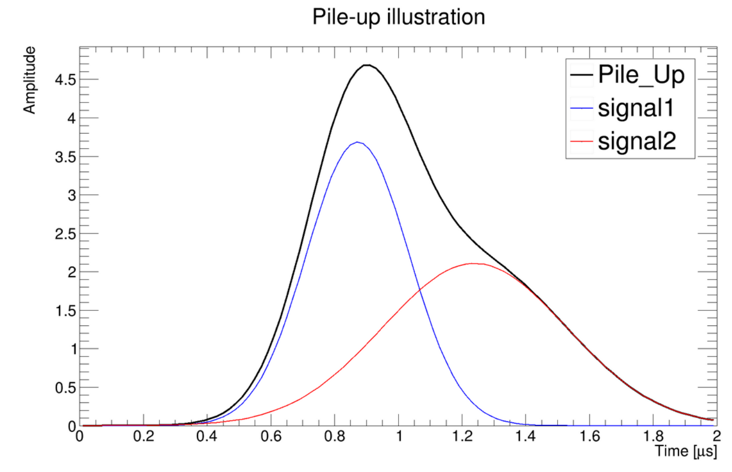
Contaminants: Background

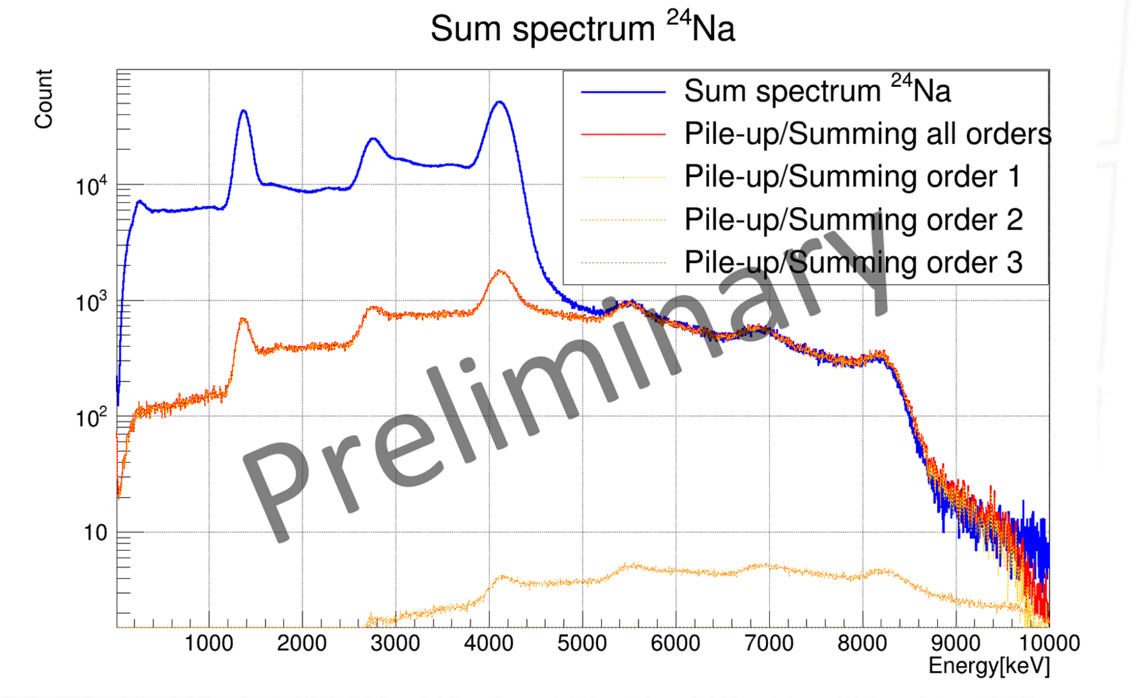
- β/γ coincidences allow to exclude contaminants
- Depends on plastic scintillator detection efficiency
- Loss of statistics
- Background run subtraction in case of sealed source



Contaminants: Pile-up/Summing

- Sum of 2 signals detected in the same time window
- Same crystal = pile-up otherwise = summing
- Frequency depends on the duration of the time window, efficiency of the detector and activity of the source/beam





D. Cano-Ott,Nuclear Inst. And Methods in Physics Reasearch, A 430 (1999) 488-497
V. Guadilla, Nuclear Inst. And Methods in Physics Reasearch, A 910 (2018) 79-89

Computation of Detector Response Matrix

- We have to find **f** given **d** and a known **R**
- Solve the inverse problem represented by **d = R** x **f**
  - d = clean data
  - f = feeding
  - R = detector response matrix
- Detector response matrix is calculated from Monte Carlo simulations of the detector with GEANT4 code
  - R_j = response for bin *j*
  - $\mathbf{e}_j$ = response to the decay particle emission
  - r_j = response to the cascade
  - b_{jk} = branching ratio for the transition from level *j* to *k*
  - $\mathbf{g}_{jk}$ = response to emitted γ-ray

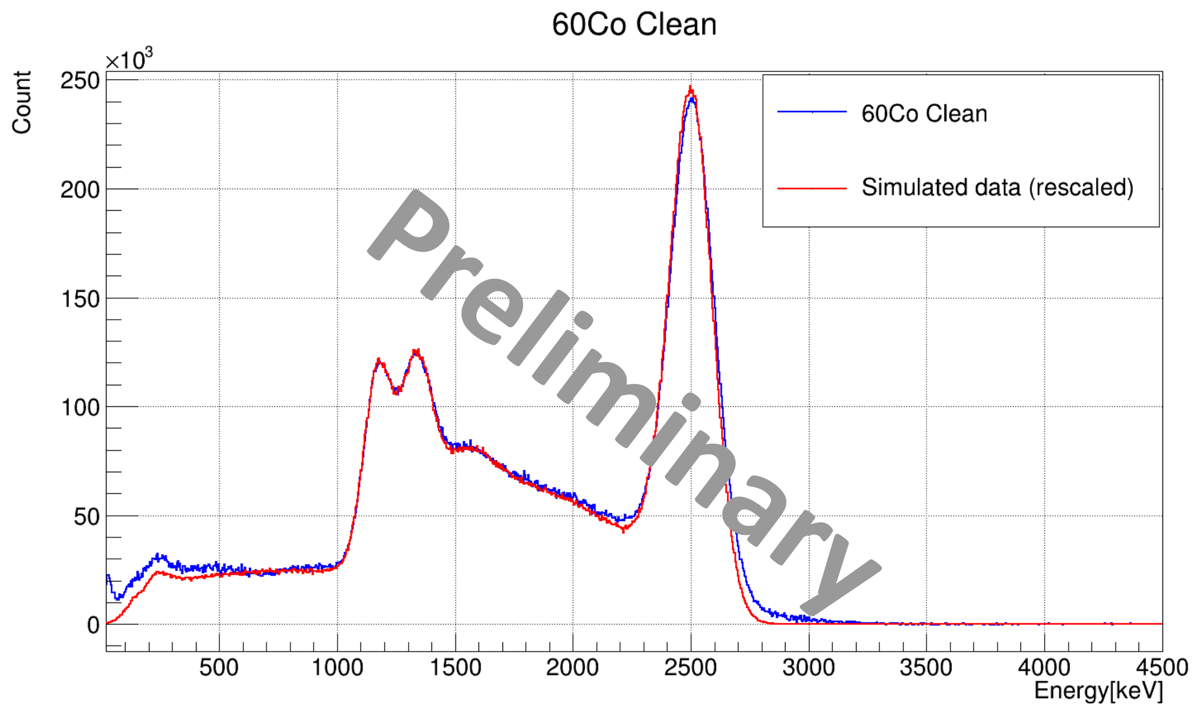
$$d_i = \sum_j^{levels} R_{ij}(B) f_j$$

$$\boldsymbol{R}_j = \boldsymbol{e}_j \otimes \boldsymbol{r}_j$$

$$\boldsymbol{r}_j = \sum_k b_{jk} \boldsymbol{g}_{jk} \otimes \boldsymbol{r}_k$$

J.L.Tain, Physics Research A 571 (2007) 728–738

Monte Carlo simulations

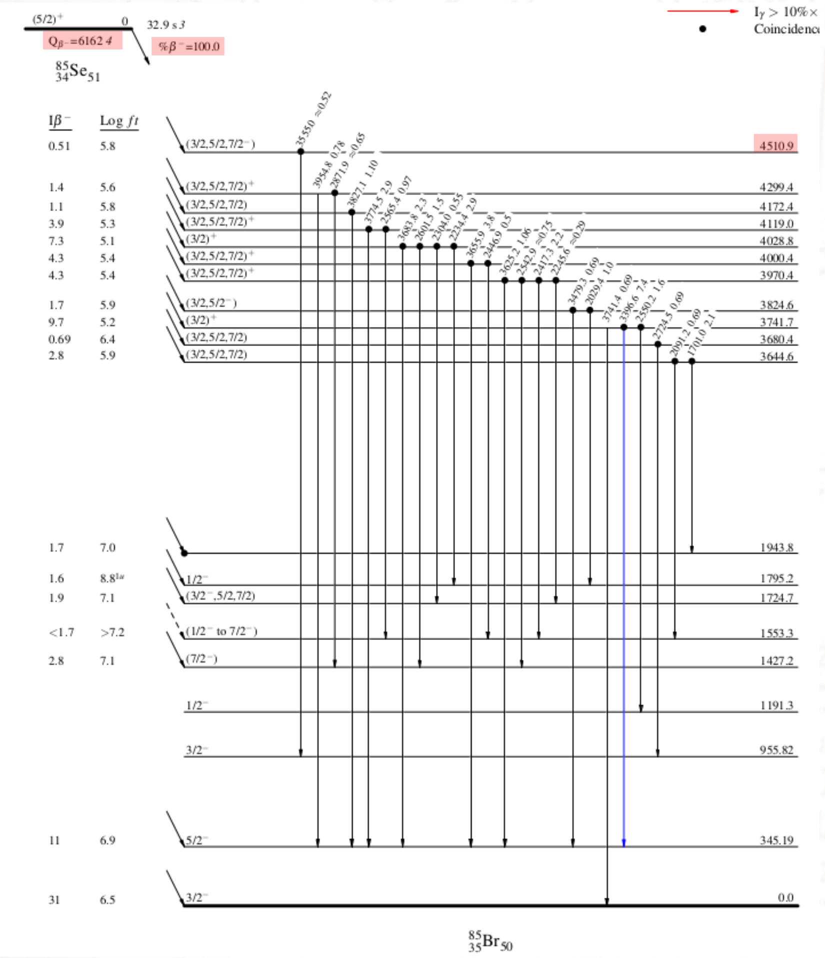


- Updated version of an already existing geometry of this detector
- Geometry has been validated by comparing source simulation and data
- Simulation used to calculate the response to electrons and gammas from the studied nucleus

E.Valencia Marin, Master,University of Valencia, 2010
S.J. Rice, PhD, University of Surrey, 2014
A-A. Zakari, PhD, University of Nantes, 2015

Physics Case: ^{85}Se

- ^{85}Se identified as priority 1 by IAEA for predictions of the decay heat (^{233}U/^{232}Th)
- 0,99 % of contribution to the total decay heat after 10s and 1,24 % after 100s following shut down.
- $Q_{\beta-}$ = 6162 keV but last fed level known = 4510.9 keV → Pandemonium candidate
- Interesting case :
  - Neutron emission threshold above the Q_β value
  - No isomeric states known
  - Half-life of daughter nucleus ^{85}Br (~2min54s) feeding at 96% a ~4h29min level
  - Half-life of grand-daughter nucleus more than 10 years

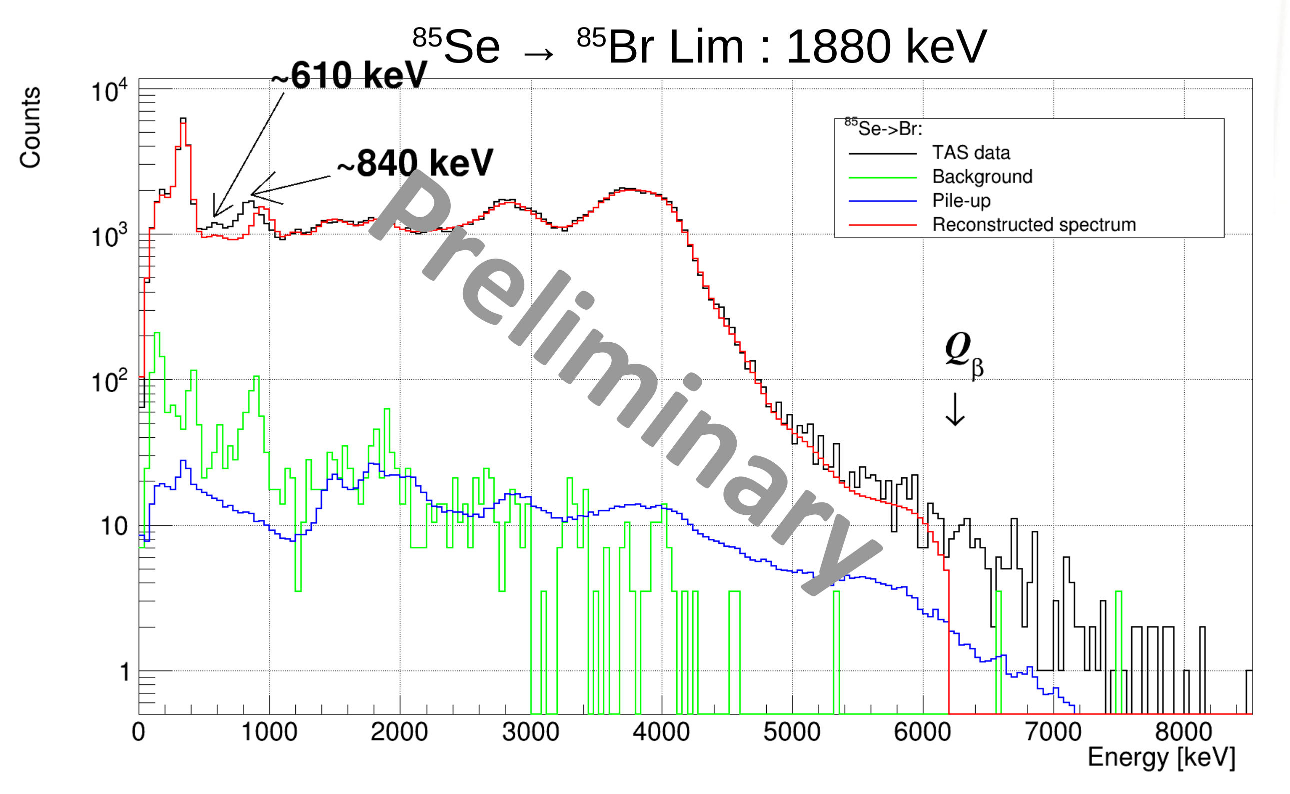


M. Gupta et al, INDC (NDS)-0577,2010

ENSDF – Evaluated Dec 2013

First Results

- Based on ENSDF database
- Reconstruction failed from 500 to 850 keV
- Not any levels but γ-rays in the decay scheme:
  - 840 keV (1795 to 955)
  - 609 keV (955 to 345)



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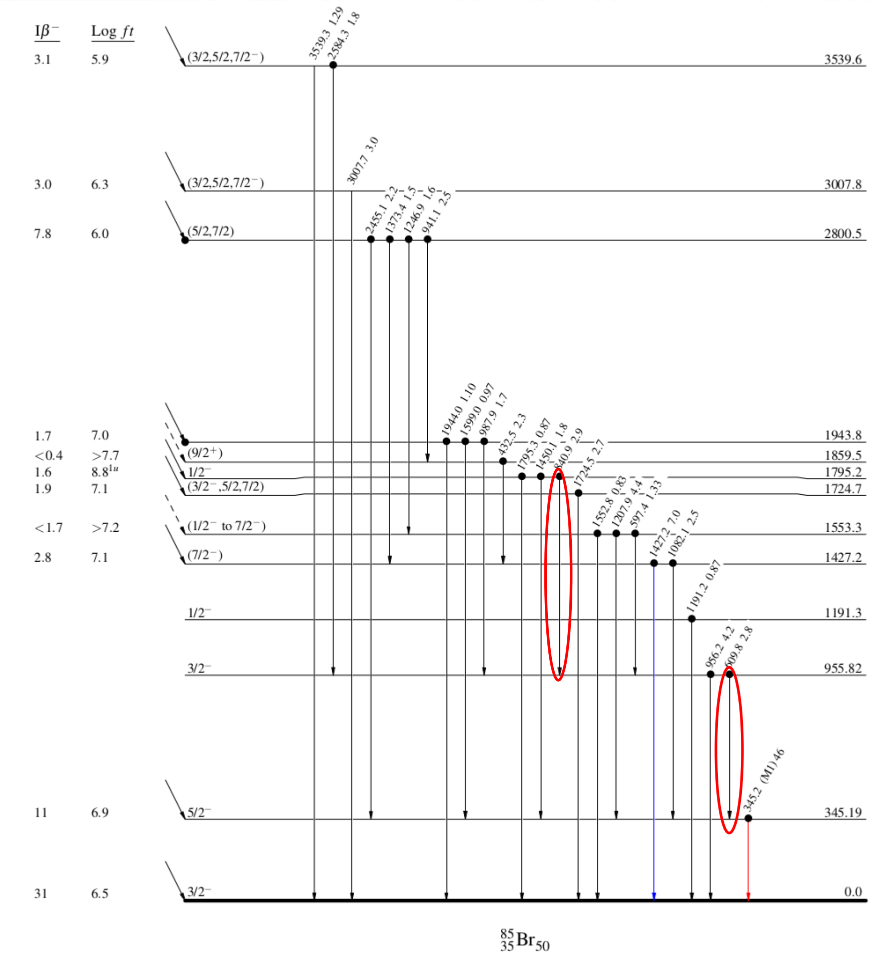

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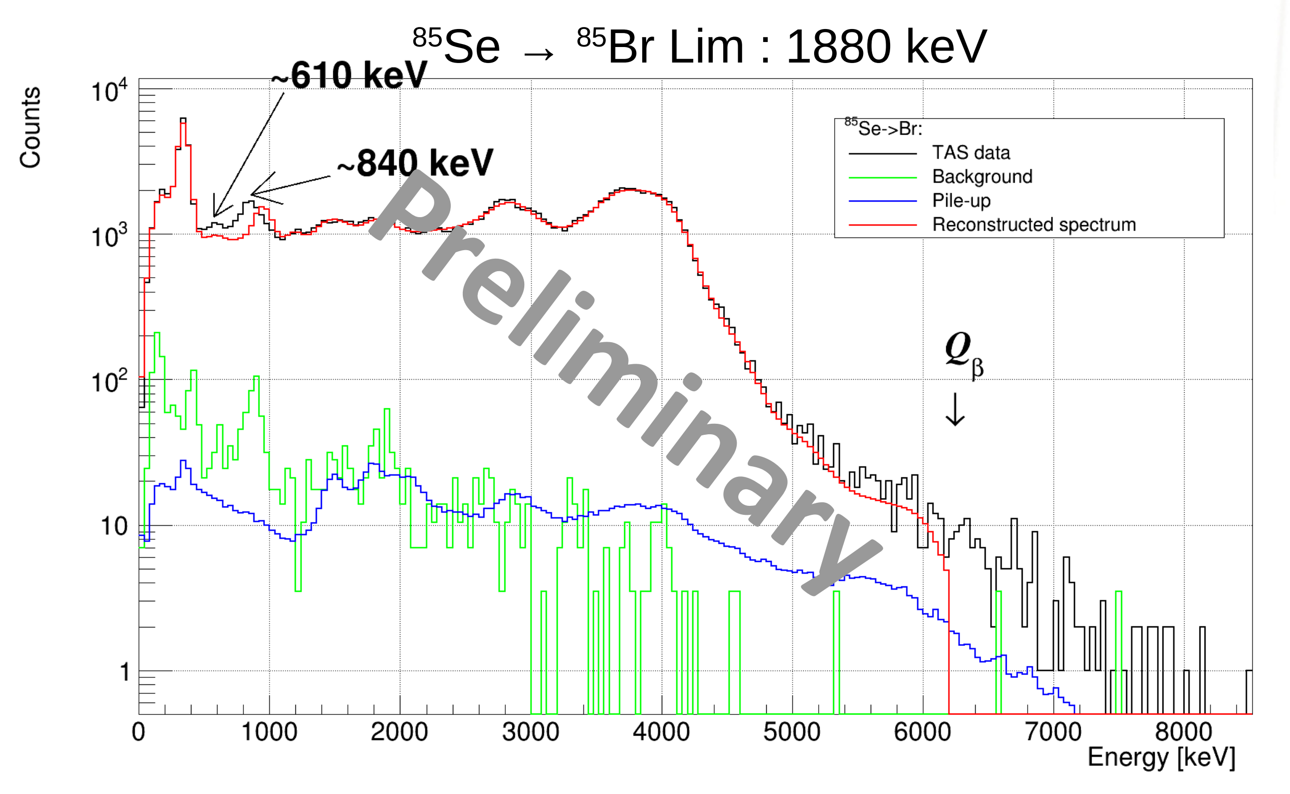

Conclusion

- Importance of β-decay and good knowledge of β properties of nuclei involved in several fields of physics
- Measurements performed in the past may be affected by the Pandemonium Effect
- The TAGS method is now used to complete and correct databases
- Sept 2022, new TAGS experiments for 17 nuclei of interest performed in Jyväskylä
- Data treatment and preparation finished
- Analysis on-going and results soon

Thank you for your attention

The TAGS Collaboration

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