PhD hours

Study of exotic nuclei of interest for applied and fundamental nuclear physics with Total Absorption Gamma-ray Spectroscopy (TAGS)

Julien Pépin

Subatech (Nantes) – Instituto de Física Corpuscular (Valencia)

Supervisors :

Muriel Fallot (Subatech)

Amanda Porta (Subatech)

Alejandro Algora (IFIC)

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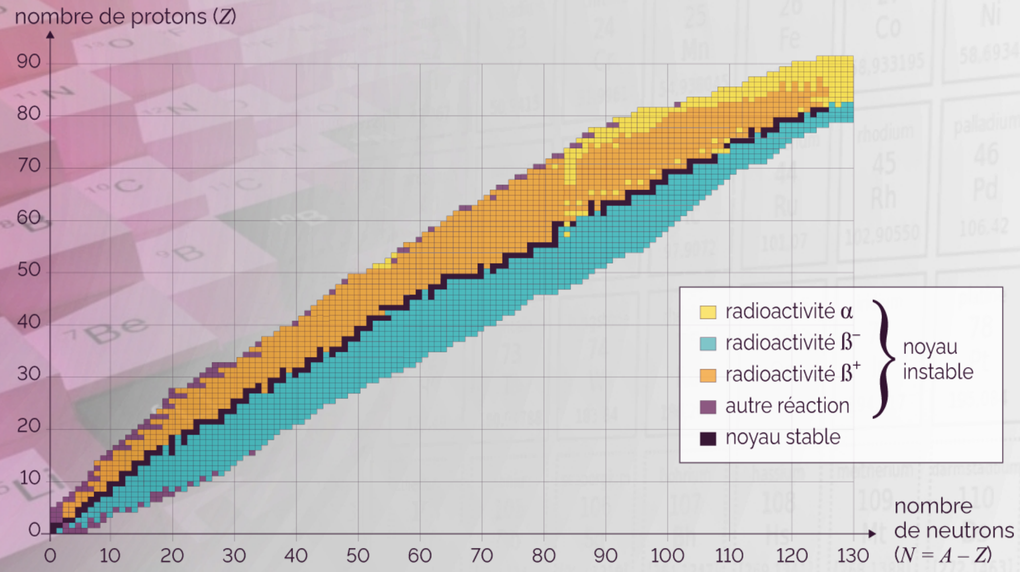
Summary

- Reminders
- Motivations
- Pandemonium effect
- TAGS technique
- Experimental setup
- Data treatment
- Physics cases

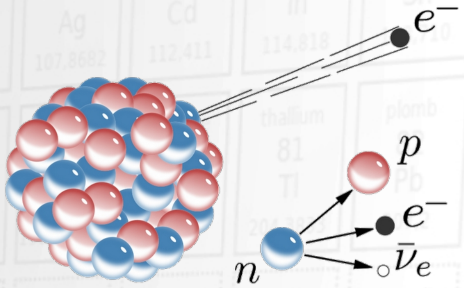
Exotic nuclei and β-decay

- Exotic nuclei = unstable nuclei far from stability valley
- Concerns a large majority of known nuclei



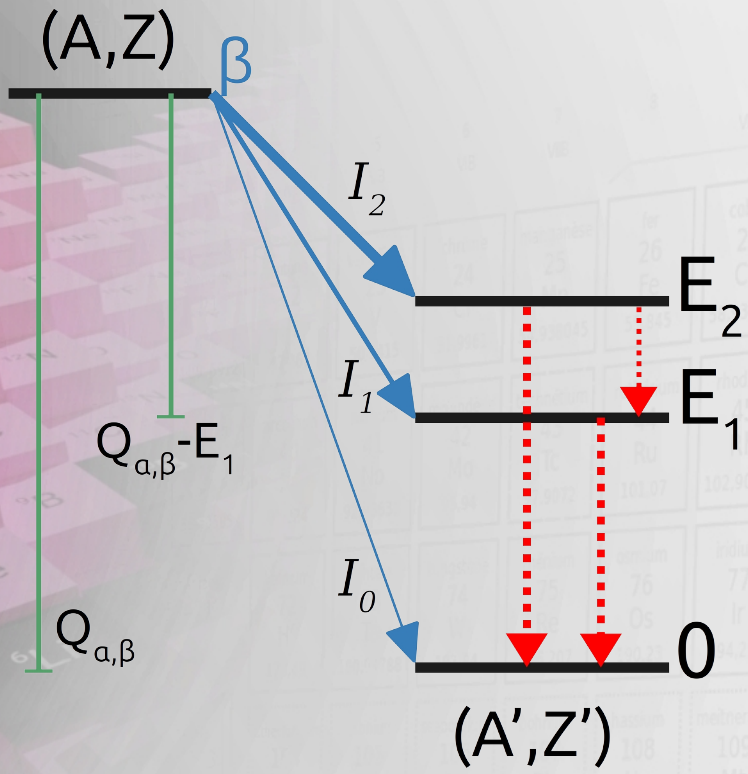
Source image: www.maxicours.com

- Three different types of β-decay:
  - β- $\quad {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu}_e$
  - β+ $\quad {}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + e^{+} + \nu_e$
  - Electron capture $\quad {}^{A}_{Z}X + e^{-} \rightarrow {}^{A}_{Z-1}Y + \nu_e$



- Emission of β particle and corresponding ν
- Feeding to levels of daughter nucleus
- Emission of γ-rays for de-excitation to lower energy levels

β strength and β intensity



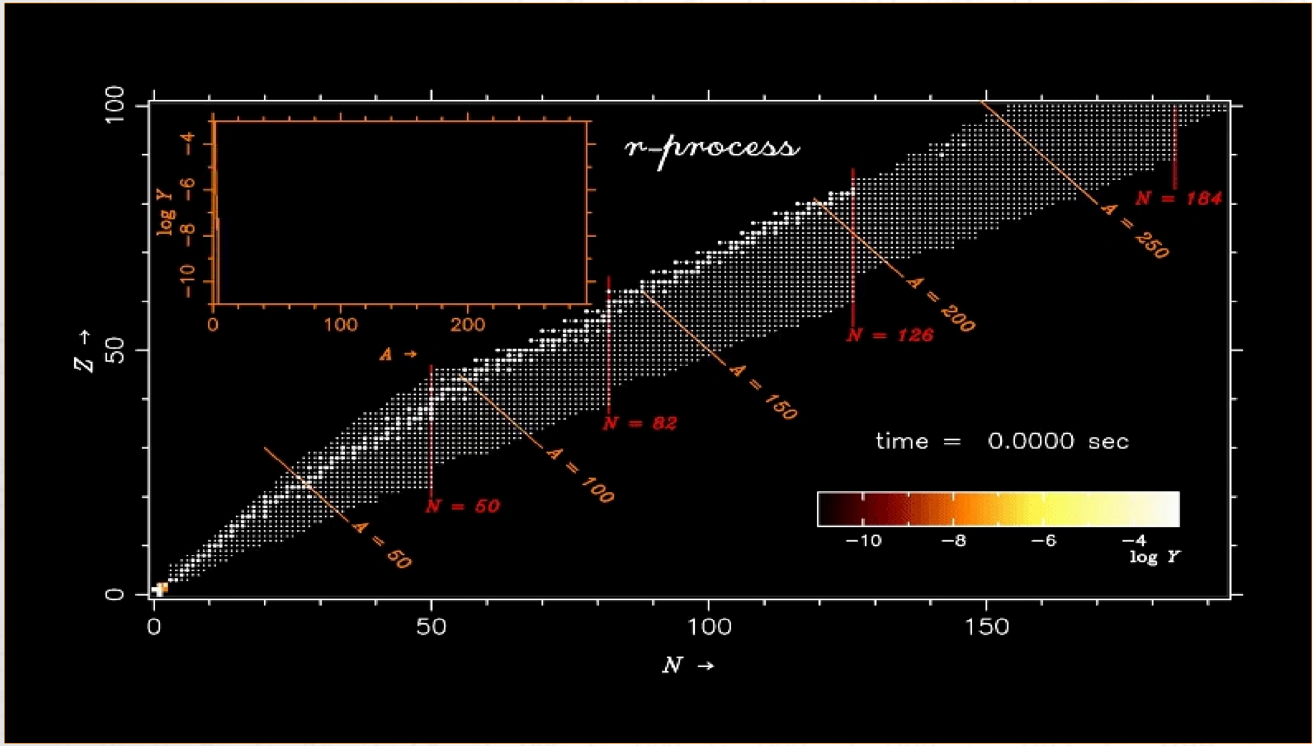
$$I_\beta(E_x) = \frac{N_\beta(E_x)}{\sum_{E_x} N_\beta(E_x)}$$

$$S_\beta(E_x) = \frac{\sum_{E_f \in \Delta E} \frac{1}{\Delta E} I_\beta(E_f)}{f(Q_\beta - E_x)\, T_{1/2}}$$

- $N_\beta(E_x)$ = number of β decay to level E_x
- $f(Q_\beta - E_x)$ = Fermi integral depending on the difference of energy between the fed excited level and the Q of the decay
- $T_{1/2}$ = half-life of the mother nucleus

Nuclear astrophysics: r-process

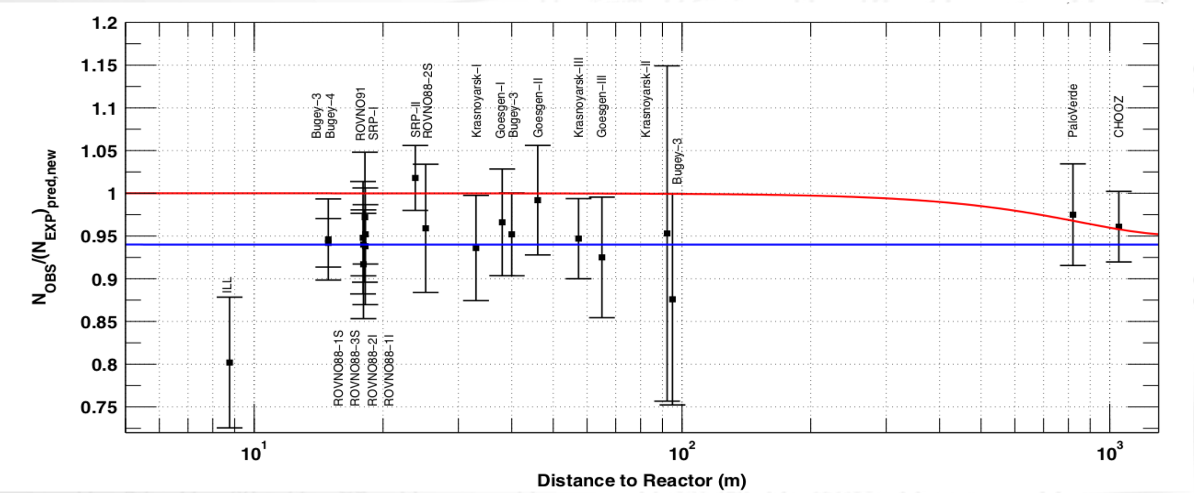
- Nucleosynthesis process producing half of the nuclei heavier than iron
- Need very hot ($T \sim 10^9$K) and very neutron dense ($\sim 10^{24}/cm^3$) environments
- Core-collapse supernovae and binary neutron star mergers
- Competition between 3 reactions :
  - Neutron capture (n,γ)
  - Photo-disintegration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



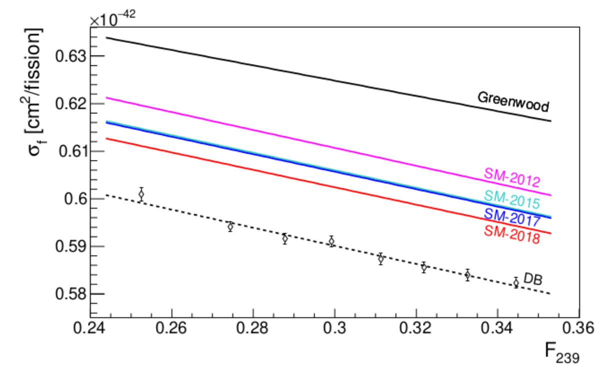
Animation of the r-process nucleosynthesis in supernovae.
Source : Shinya Wanajo, Stephane Goriely

Reactor neutrino studies

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



Source image: G. Mention et al. « Reactor antineutrino anomaly », Physical Review D 83, 2011



Source image: M. Estienne et al. « Updated Summation Model: An Improved Agreement with the Daya Bay Antineutrino Fluxes », 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

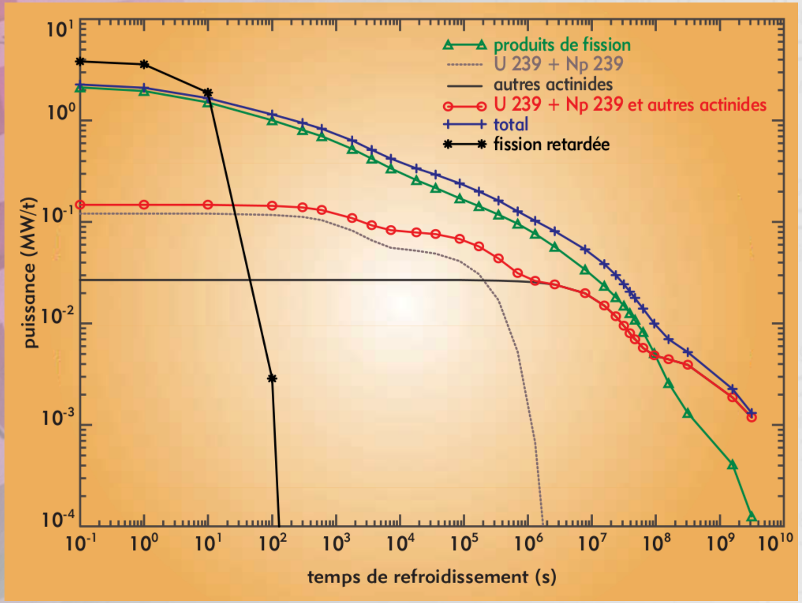


Image source : J.C.Nimal, Sureté et puissance résiduelle, 2001

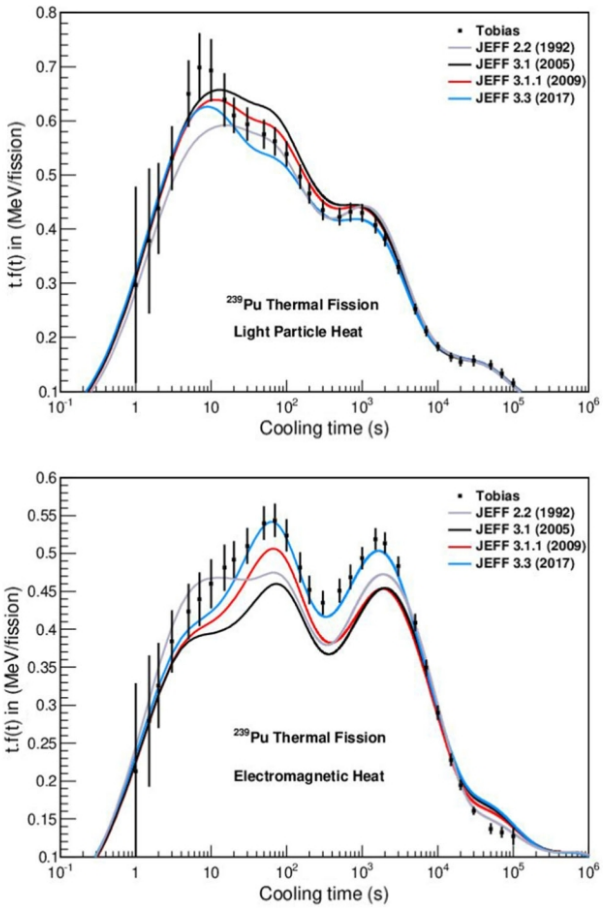
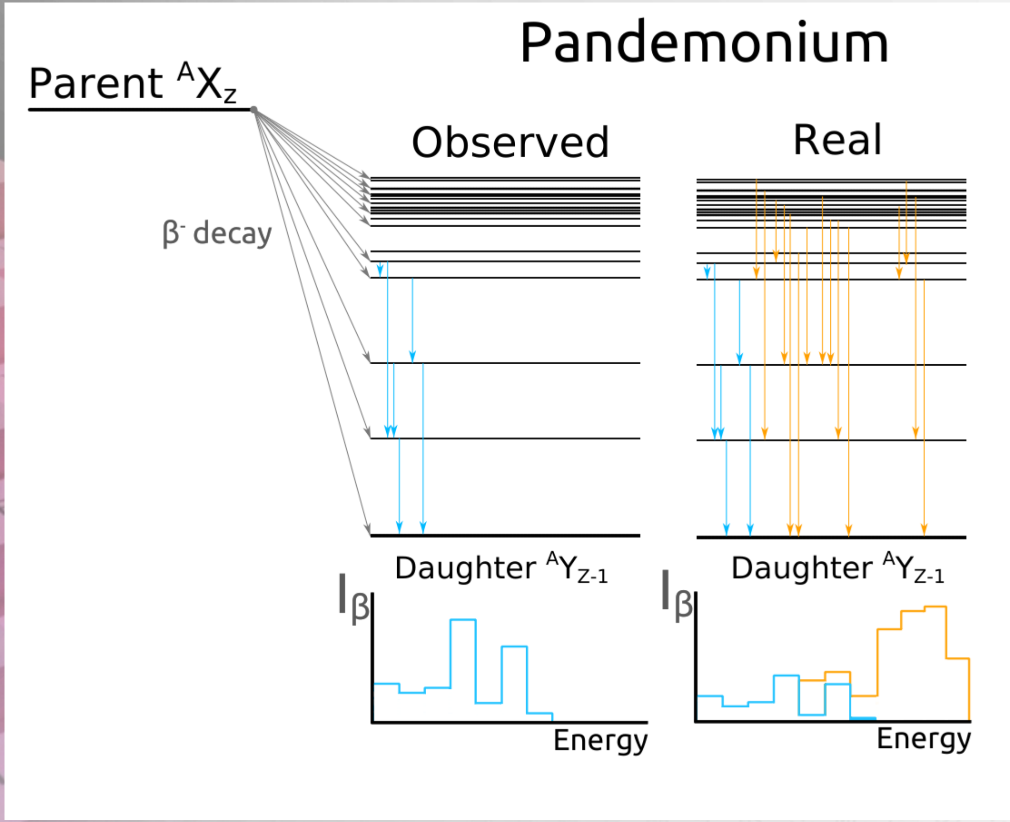


Image source : A.L. Nichols et al,"Improving fission-product decay data for reactor applications part I—decay heat", 2023

Interest of TAGS measurements

- Common points between those scientific interests: β-decay
- Study of β-decay can bring a lot of information
- Theoretical models are validated with experimental measurements
- Previous data measurements performed with high-resolution detectors (HPGe…)

Pandemonium effect



- Loss of detection efficiency affecting measurements done with high-resolution detectors (e.g. HPGe)
- High energy gamma-rays are unseen.
- High multiplicity cascades are incomplete.
- Leads to an underestimation of feeding towards high energy levels.
- Leads, thereby, to an overestimation of the feeding to lower energy levels.
- More important with nuclei with high Q-value.

J.C.Hardy et al. "The Essential Decay Of Pandemonium: A Demonstration Of Errors In Complex Beta-Decay Schemes". In: Physics Letters Volume 71B, number 2 (1977).

Total Absorption Gamma-Ray Spectroscopy

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

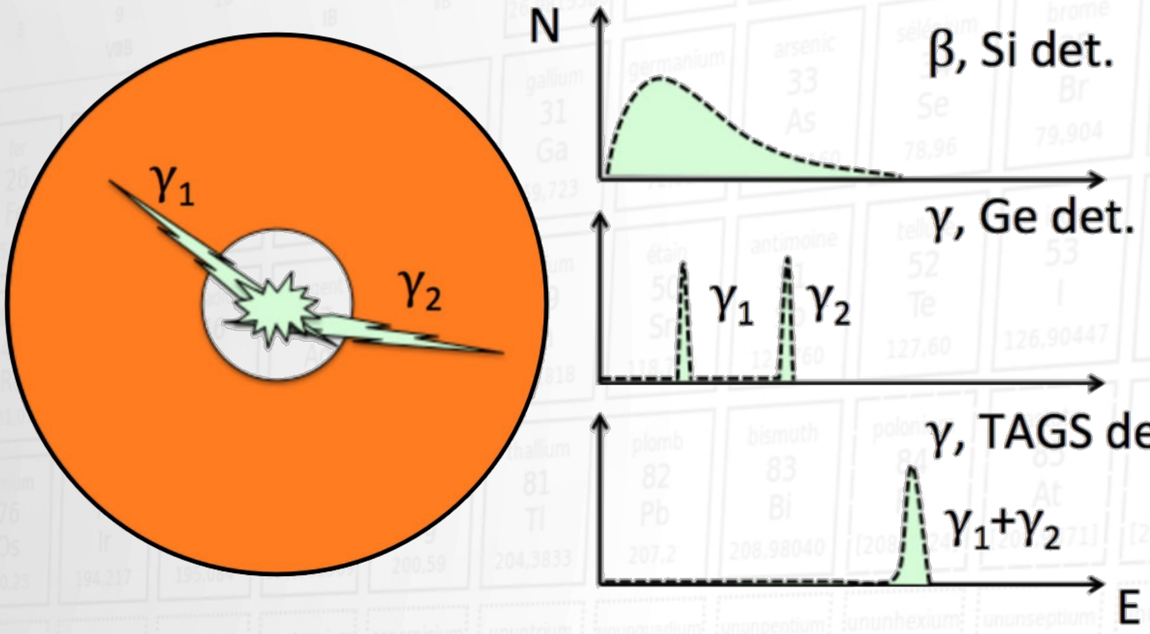
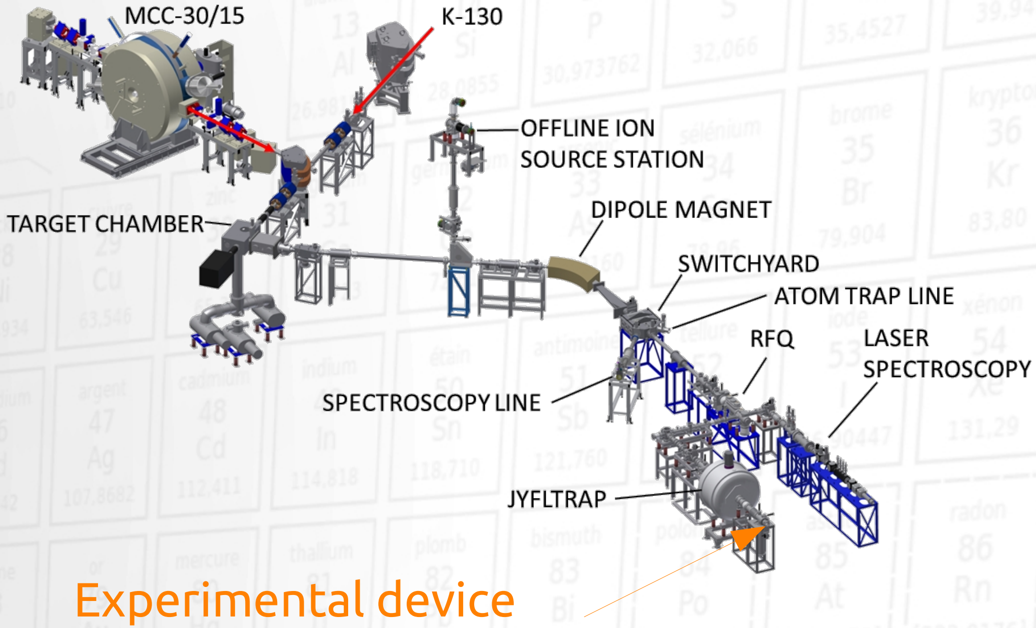


Image source : « Beta-decay studies for applied and basic nuclear physics » , A.Algora et al. The European Physical Journal A, 2021

Experimental set-up : Nuclei production

- From 7 to 29 september 2022 in Jyväskylä University, Finland, in JYFL Accelerator Laboratory
- IGISOL (Ion Guide Isotope Separation On-Line) can produce large range of stable and radioactive nuclei
- Very precise mass separation thanks to JYFLTRAP double Penning trap
- Beam implantation on a magnetic tape in the center of the detector. Rolling magnetic tape system avoids contamination of the measurement by daughter nucleus decays



Layout of the IGISOL facility in JYFL Accelerator Laboratory in Jyväskylä showing the path of beam particles from MCC-30/15 accelerator to JYFLTRAP. Our experimental setup was just at the end of JYFLTRAP.
Image source : https://www.jyu.fi

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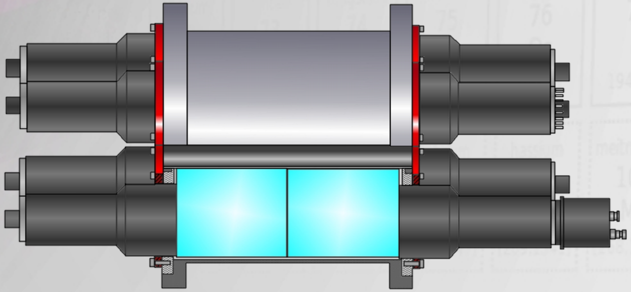
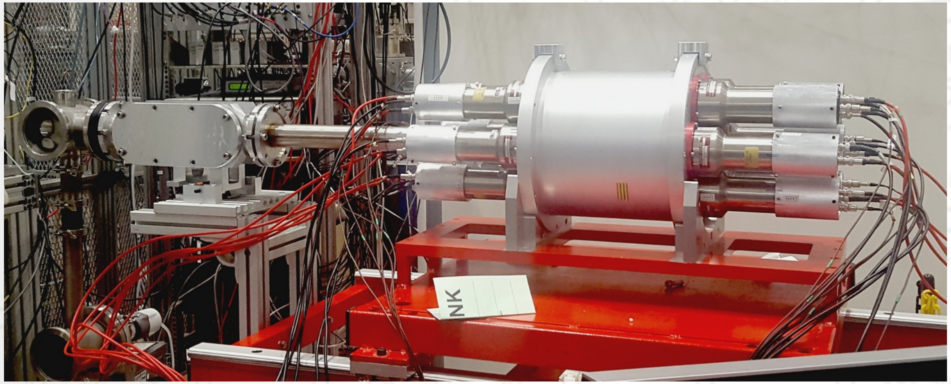
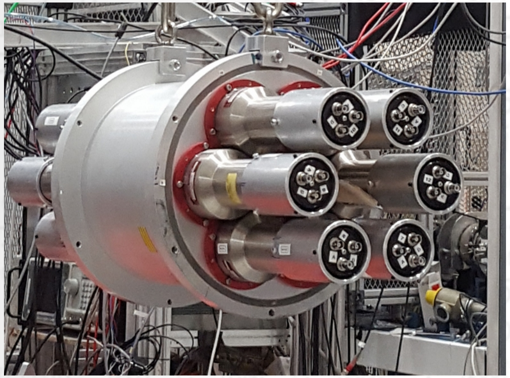
Experimental set-up : Rocinante detector

- Total Absorption spectrometer
- Composed of 12 Barium Fluoride crystals (BaF_2)
- Segmented detector for obtaining information on the multiplicity of the gamma cascade
- Plastic scintillator in the detector center used as trigger for β coincidence
- Cerium Bromine ($CeBr_3$) detector with higher resolution for better identification of contaminants
- Internal contamination of BaF_2 by ^{238}U and ^{232}Th leads to a characteristic α signal that can be useful for detector alignment







Rocinante detector from experiment I241 in September 2022 in Jyväskylä , Finland

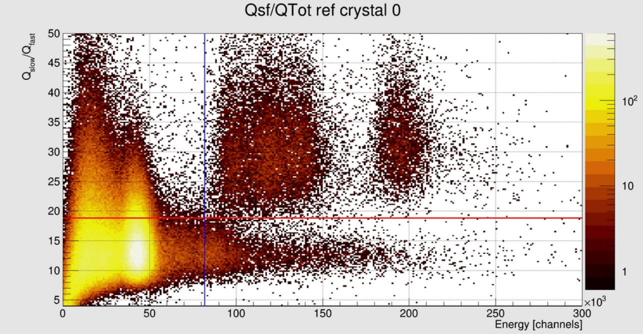
Data analysis

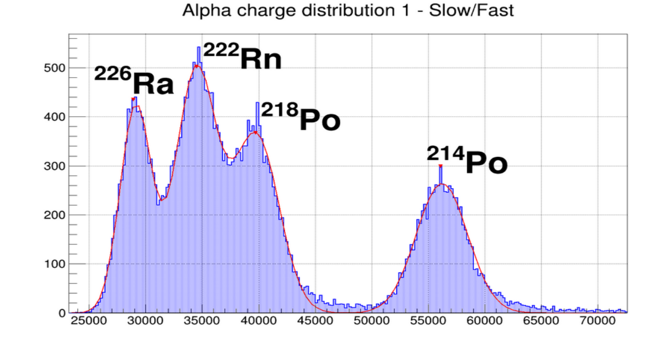
- Data treatment
  - Alignment
  - Calibration
  - Contaminants
- Data analysis
  - Monte Carlo simulations
  - Detector response matrix
  - Inverse problem

Data treatment

Alignment

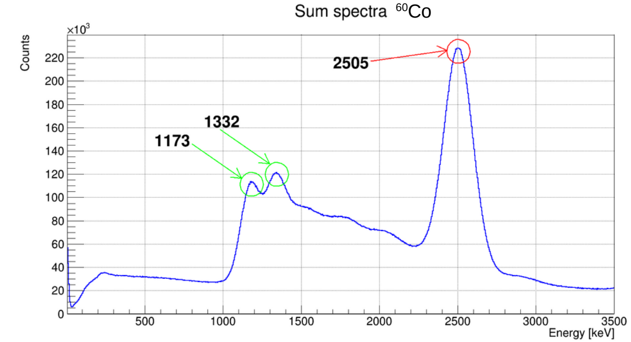
- Compensates PMT gain drifts and make calibration more efficient
- Using α events coming from internal contamination for reference
- Performing α/γ discrimination to obtain clean α peaks
- Discrimination possible thanks to two scintillation times of BaF_2:
  - 630ns (slow)
  - 0.7ns (fast)

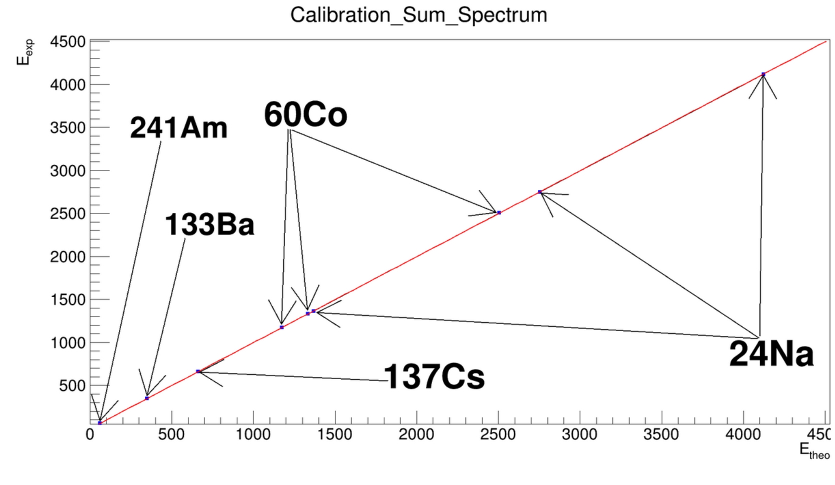




Calibration

- Converts channels into energy





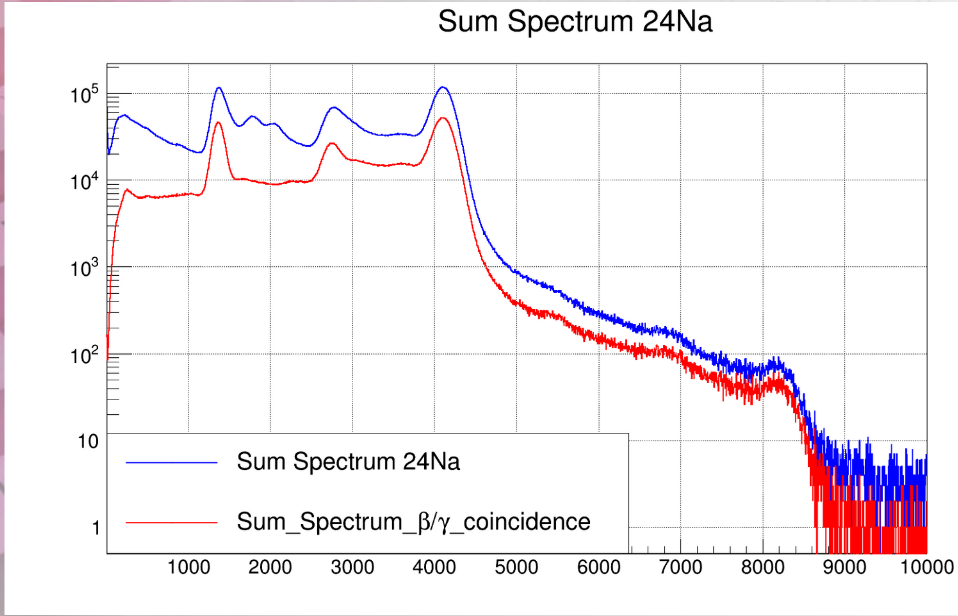
Background

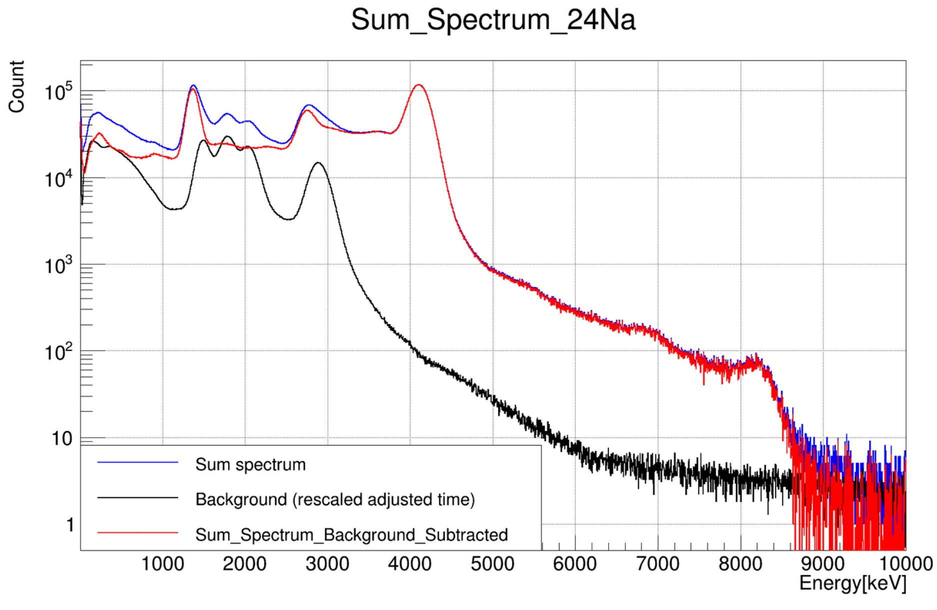
Coincidence

- β/γ coincidences allow to exclude un-wanted γ-rays
- Need that the plastics has been fired by a β particle
- Depends on plastic scintillator detection efficiency
- Loss of statistics

Subtraction

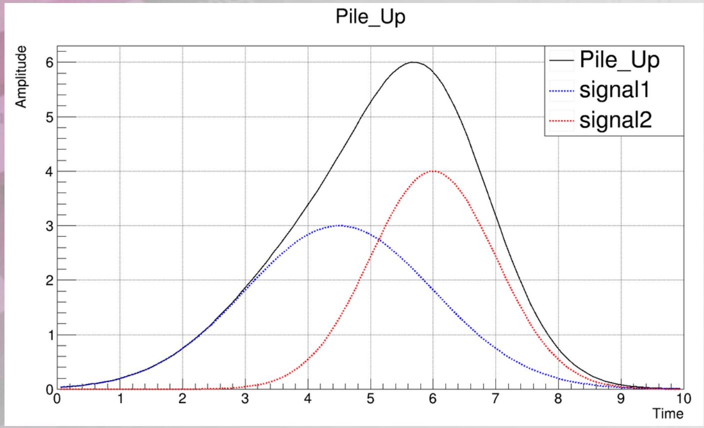
- When coincidence is not possible (sealed calibration sources)
- Normalization according to measurement time





Pile-up/Summing

- Sum of 2 signals detected in the same time window
- Can happen in the same crystal
- Produces a signal corresponding to the sum of the 2 signals
- Frequency depends on the duration of the time window, efficiency of the detector and activity of the source/beam



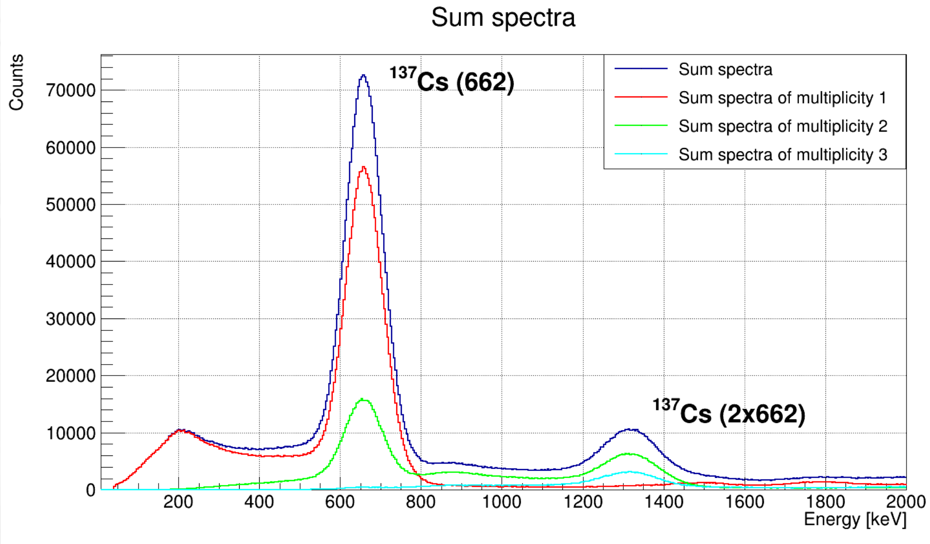


Image source : Thesis A-A Zakari

Data analysis

- 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**

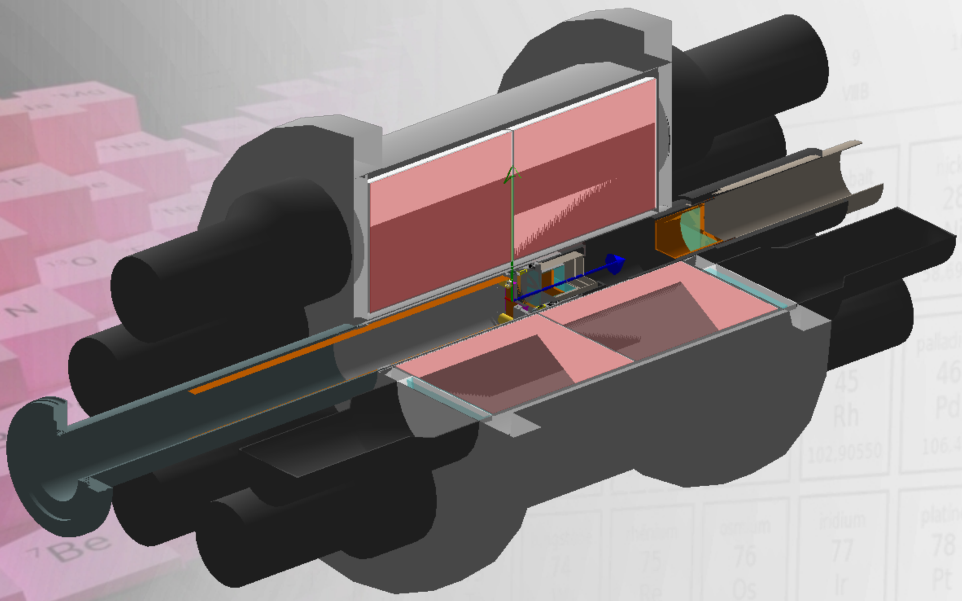
$$d_i = \sum_{j}^{levels} R_{ij}(B) f_j + C_i$$

- Detector response matrix is calculated from Monte Carlo simulations of the detector with GEANT4 code
  - b_{jk} = branching ratio for the transition from level j to k
  - $\mathbf{g}_{jk}$ = response to emitted γ-ray

$$\mathbf{R}_j = \sum_{k=0}^{j-1} b_{jk} \mathbf{g}_{jk} \otimes \mathbf{R}_k$$

J.L.Tain, *Algorithms for the analysis of b-decay total absorption spectra*, Nuclear Instruments and Methods in Physics Research A 571 (2007) 728–738

Monte Carlo simulations



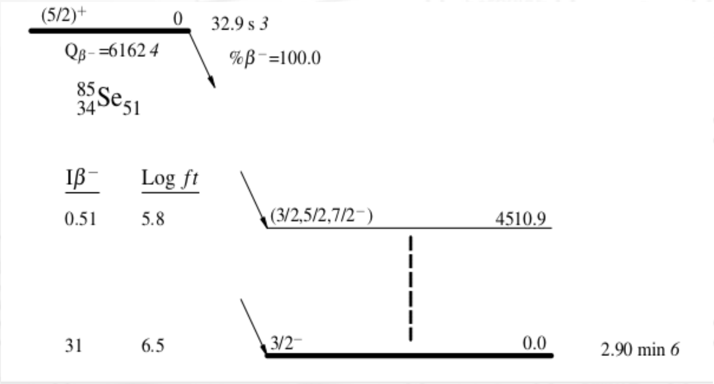
Geometry of Rocinante detector on GEANT4 simulation tookit. The $CeBr_3$, the tape rolling system, the beam pipe and the plastic detector have been added to previous geometry.

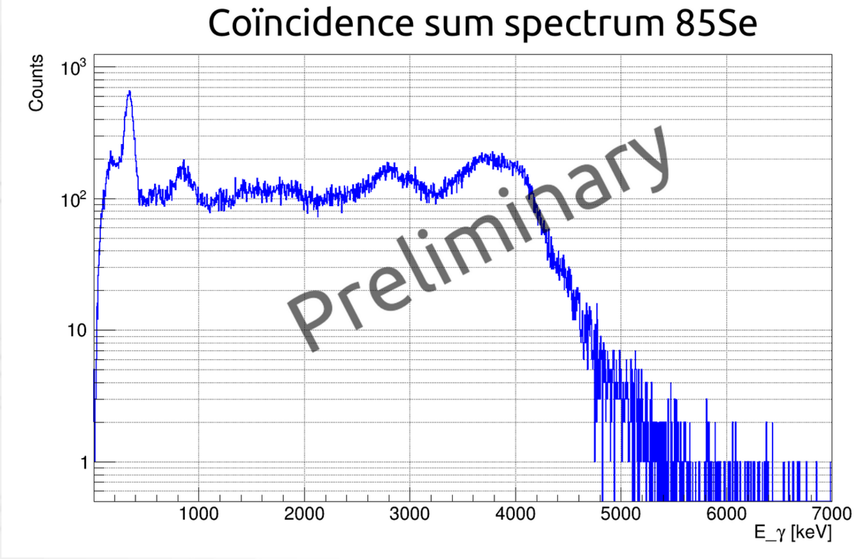
- Detector response matrix is calculated from Monte Carlo simulations of the Rocinante detector with Geant4
- Faithful representation of experimental conditions brings more precision in the calculation of the response matrix
- Updated version of an already existing geometry of this detector
- Geometry must be validated by comparing source simulation and data
- Simulation used to calculate the response to electrons and gammas from the studied nucleus

Physics case : ^{85}Se

- ^{85}Se identified as priority 1 by IAEA for improving the predictions of the decay heat in reactors based on $^{233}U/^{232}Th$ fuel
- 0,99 % of contribution to the total decay heat after 10 s and 1,24 % after 100s following shut down.
- Q_{β^-} = 6162 keV but last fed level known = 4510.9 keV
- → pandemonium candidate
- "Easy" case :
  - Neutron emission threshold above the Q_β value
  - No isomeric states
  - Half-life of daughter nucleus different

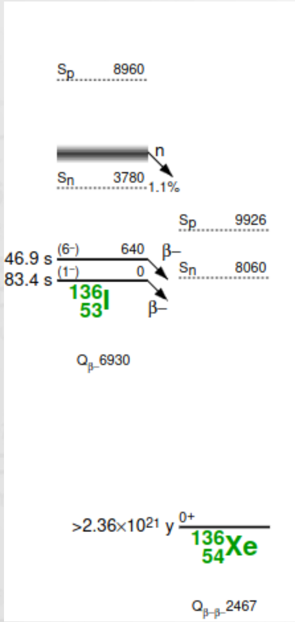
M. Gupta et al, "*Decay Heat Calculations: Assessment of Fission Product Decay Data Requirements for Th/U Fuel*"
INDC International Nuclear Data Committee, INDC (NDS)-0577,2010

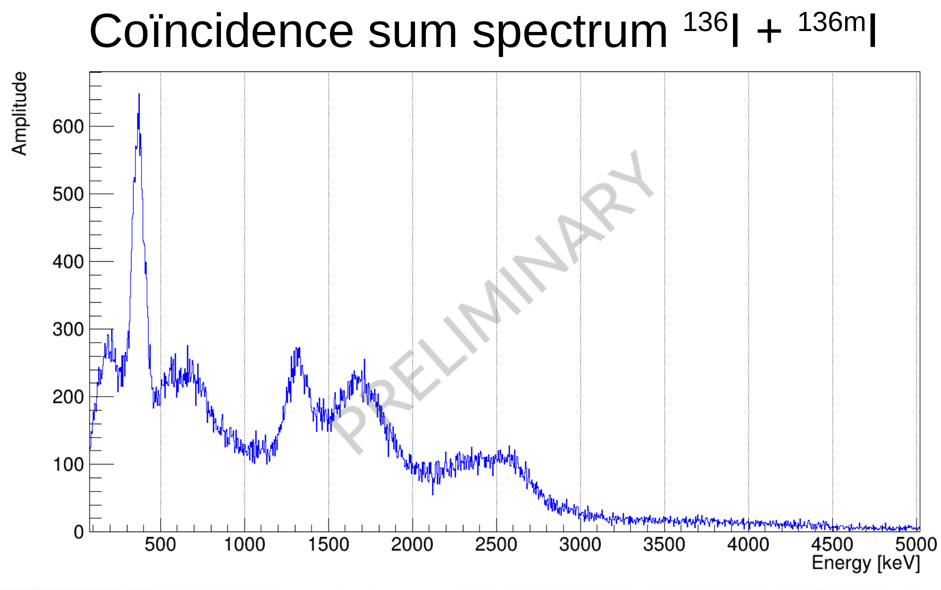




Physics case : ^{136}I

- ^{136m}I is high priority with contribution to total decay heat of 1.55 % and 3.69 % , 10 and 100s after reactor shut down
- ^{136}I contribution to total decay heat 100s after shut down = 2.74 %
- Contribution of both into energy anti-neutrino spectra
- ^{136}I involved in r-process through pygmy dipole resonance (PDR) affecting the cross-section of nuclear reactions involving photons
- ^{136m}I highly suspected to be pandemonium, ^{136}I moderately
- Isomeric states but different half-lives
- Daughter nucleus with long half-life, no contaminants





P.Dimitriou et A.Nichols, "*Total Absorption Gamma-ray Spectroscopy for Decay Heat Calculations and Other Applications*" INDC International Nuclear Data Committee, INDC (NDS)-0676,2015

Data analysis

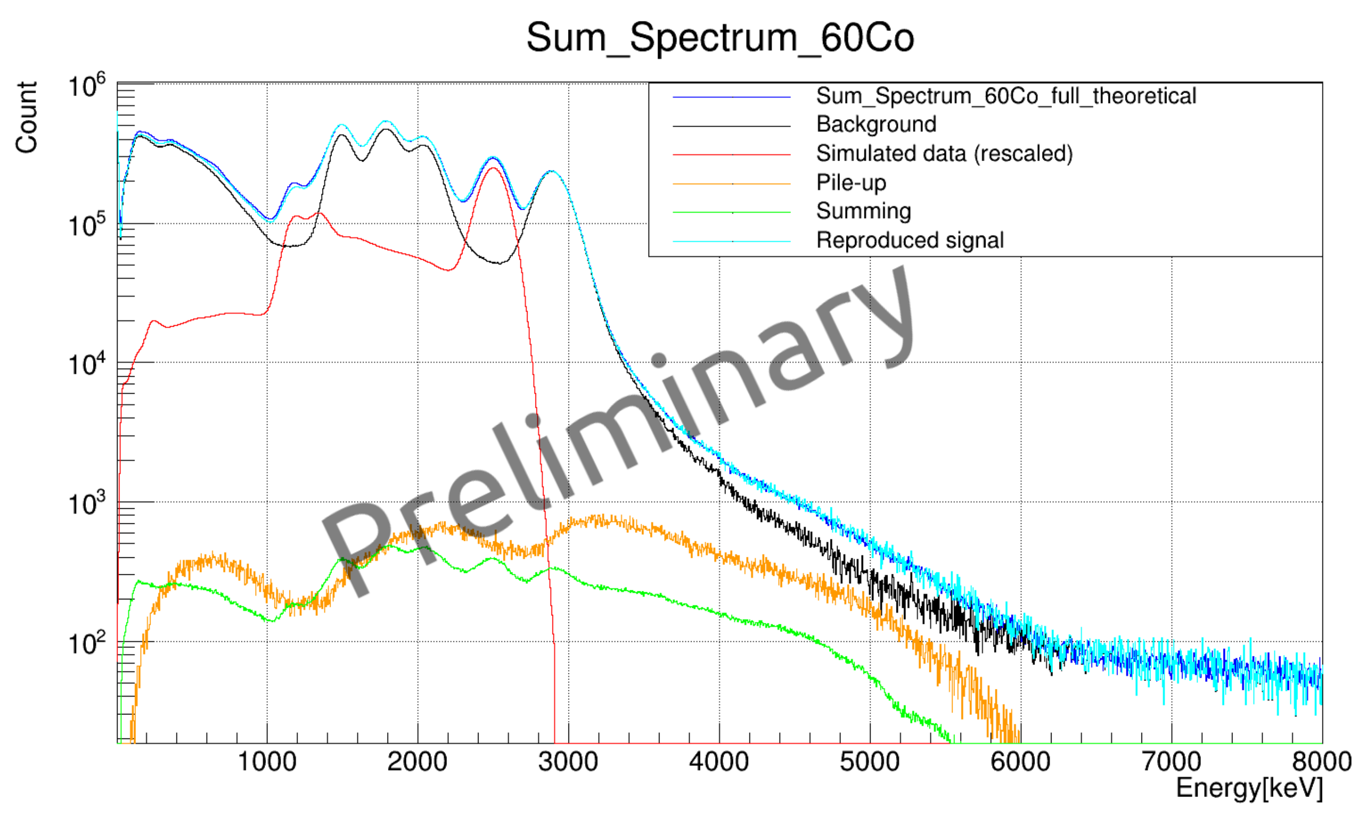
Data treatment

- ~~Alignment~~
- ~~Calibration~~
- ~~Contaminants~~

Data analysis

- ~~Monte Carlo simulations~~
- Detector response matrix
- Inverse problem

Perspectives of the work



- Validation of the simulation
- Simulation of measured nuclei
- Extraction of the detector response matrix
- Solving the inverse problem
- Study the impact of new data

Thank you for your attention!

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