ISOL – France VII

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 TAS collaboration

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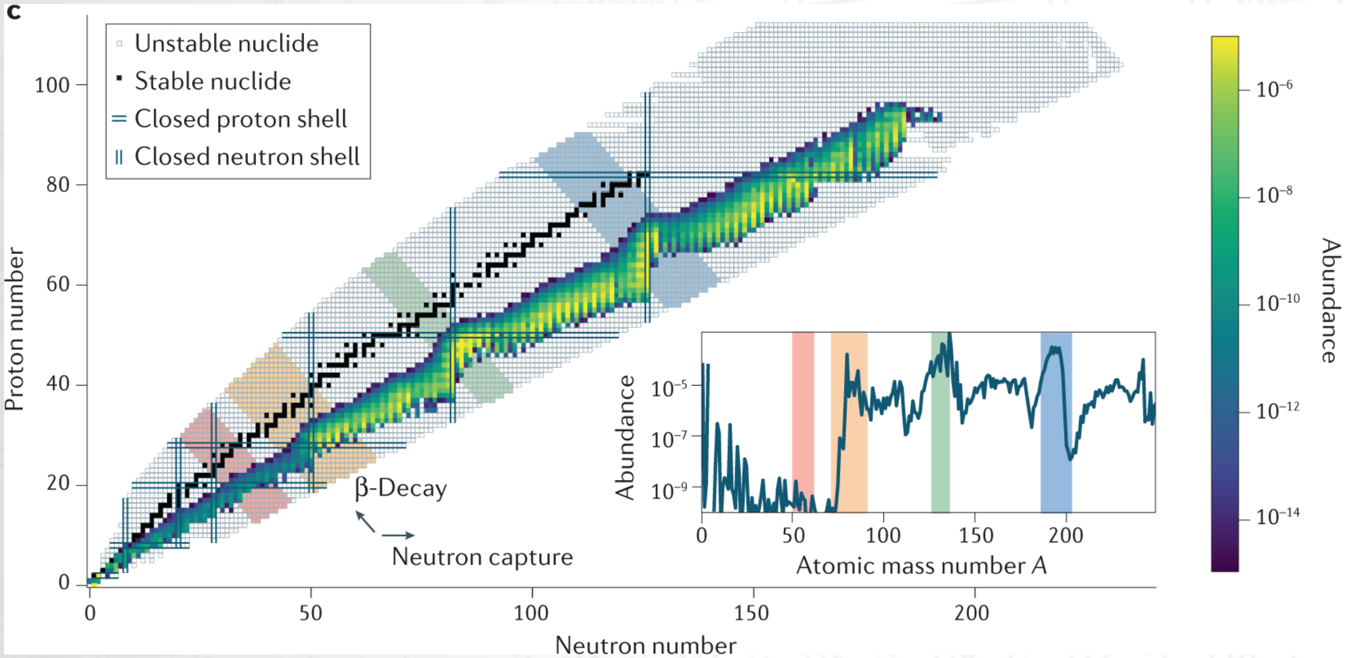
Summary

- Scientific interest
  - Nuclear astrophysics
  - Neutrino physics
  - Reactor physics
- Pandemonium effect
- Total absorption gamma-ray spectroscopy
  - Method
  - Experimental set-up
- Data treatment
  - Alignment
  - Calibration
  - Pile-up & Summing
- Data analysis
  - Detector response matrix
  - Simulation
  - Physics cases
    - 85Se
    - 136I

Nuclear astrophysics: r-process

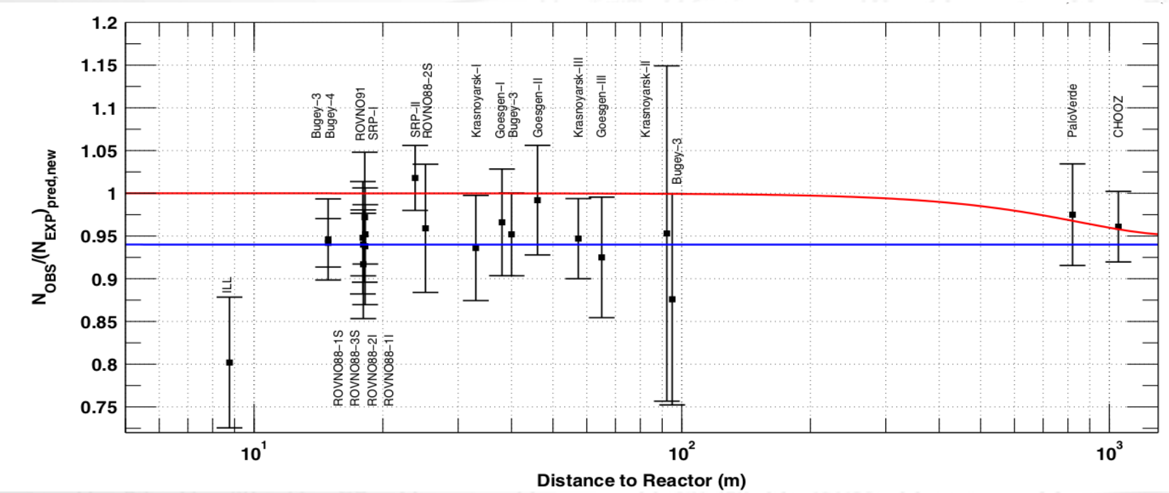
- Nucleosynthesis process producing half of the nuclei heavier than iron
- Need very hot ($T \sim 10^9$K) and very neutron dense ($\sim 10^{24}/cm^3$) environments
- Core-collapse supernovae and binary neutron star mergers
- Competition between 3 reactions :
  - Neutron captures (n,γ)
  - Photo-disitegration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



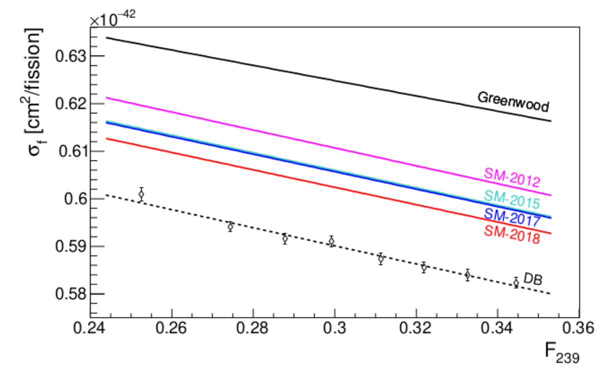
Source image : *"r-Process nucleosynthesis in gravitational-wave and other explosive astrophysical events", D.M.Siegel, nature review physics, 2022*

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
  - 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

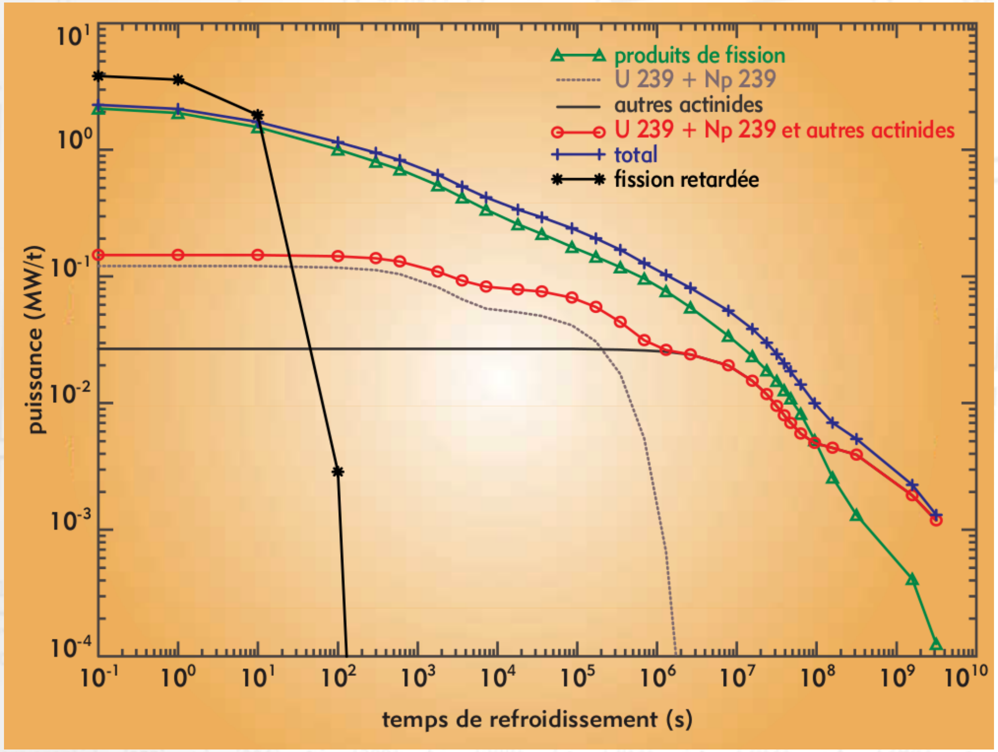
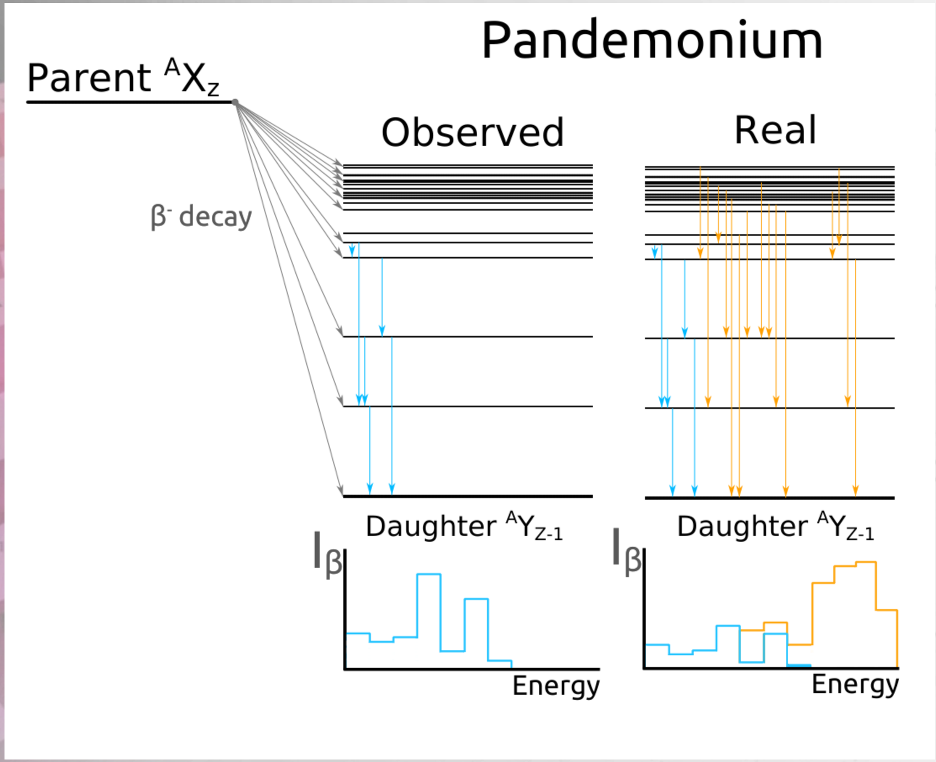


Image source : J.C.Nimal, Sureté et puissance résiduelle, 2001

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.

Total Absorption Gamma-Ray Spectroscopy

- Needs a calorimeter, 4π detector with a material having as high a detection efficiency 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

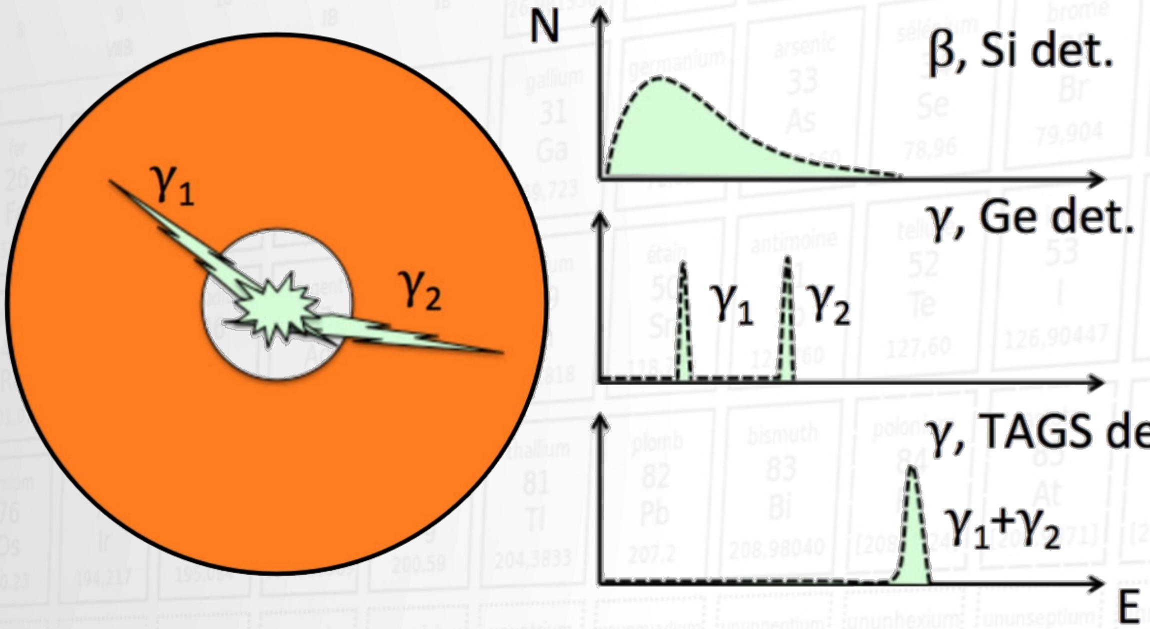


Image source : « Beta-decay studies for applied and basic nuclear physics » , A.Algora et al. The European Physical Journal A, 2021

Experimental set-up

- 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

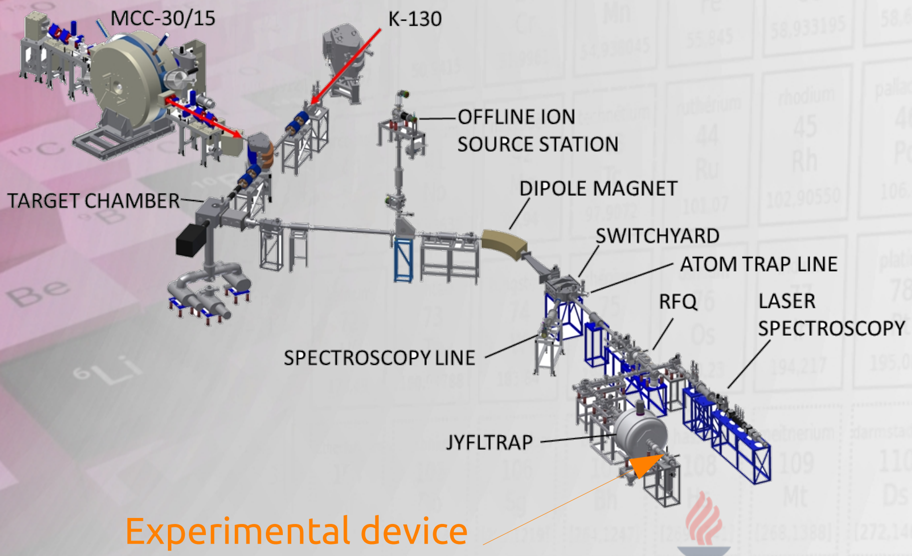
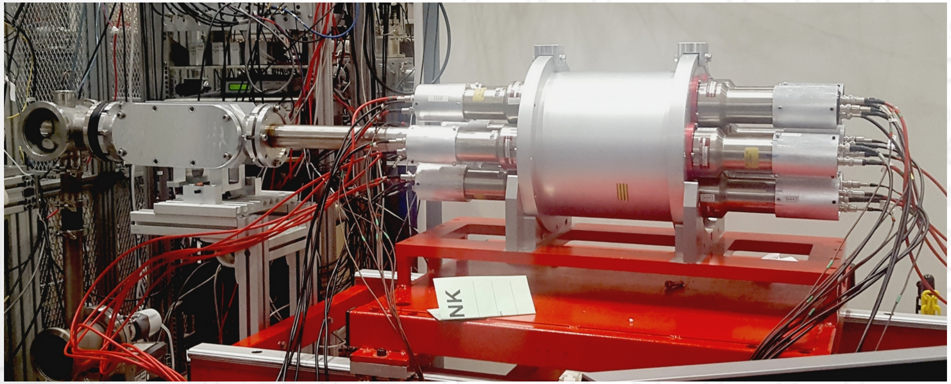


Image source : https://www.jyu.fi



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

- 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

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Data analysis

Data treatment

- Alignment
- Calibration
- Pile-up/summing
- Generic contaminants

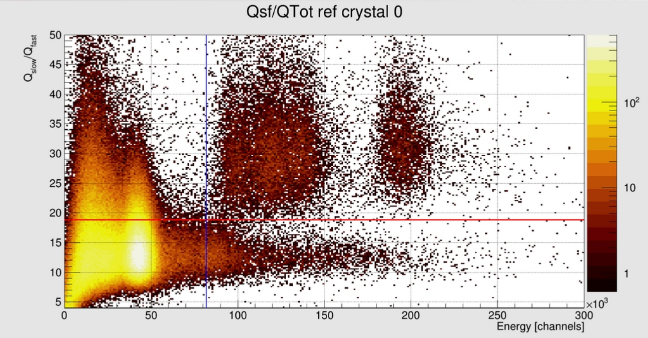
Data analysis

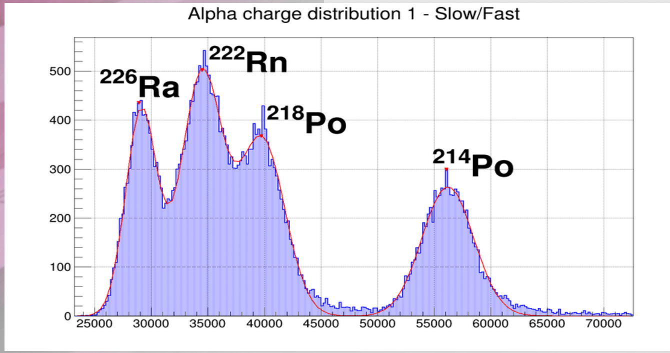
- Inverse problem
- Monte carlo simulations

Data treatment

Alignement

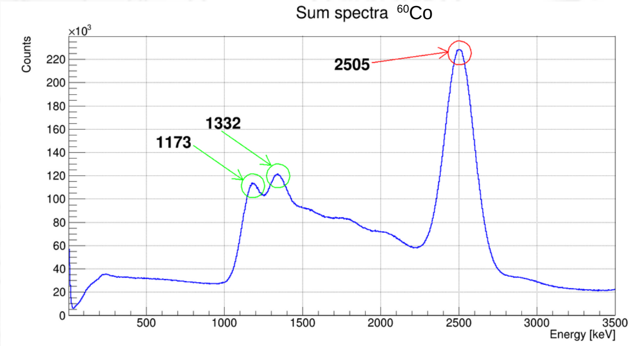
- Compensates PMT drifts and make calibration more efficient
- Using α events coming from internal contamination for reference
- Performing α/γ discrimination to obtain clean α peaks
- Discrimination possible thanks to two scintillation time of BaF_2 :
  - 630ns (slow)
  - 0.7ns (fast)

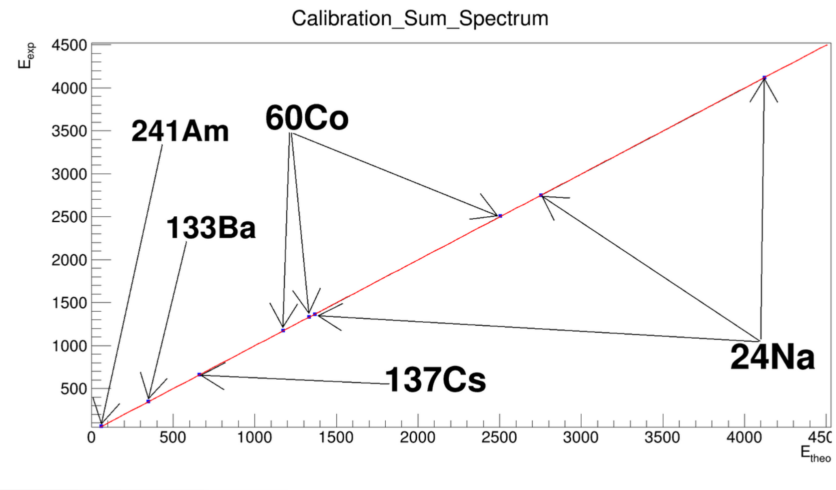




Calibration

- Converts channels into energy

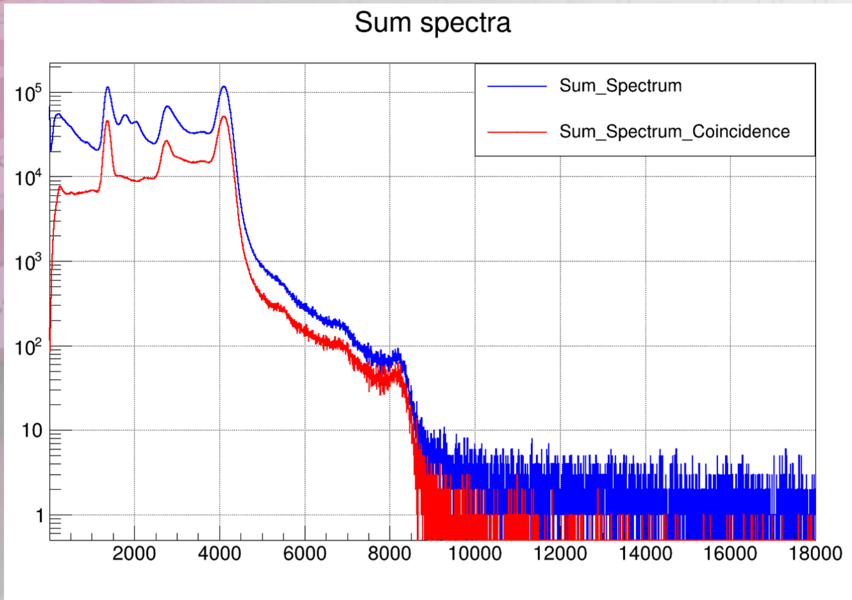




Contaminants

Background

- 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



Pile-up/Summing

- Sum of 2 signals detected in the same time window
- Produces a signal corresponding to the sum of the 2 signals

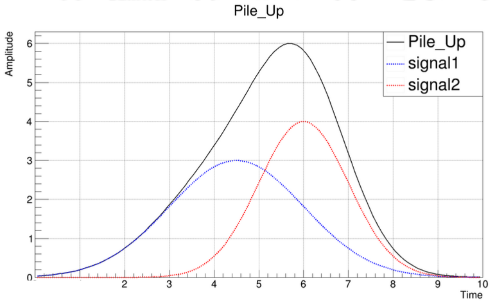
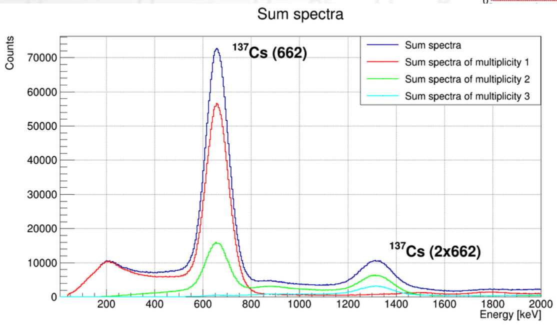


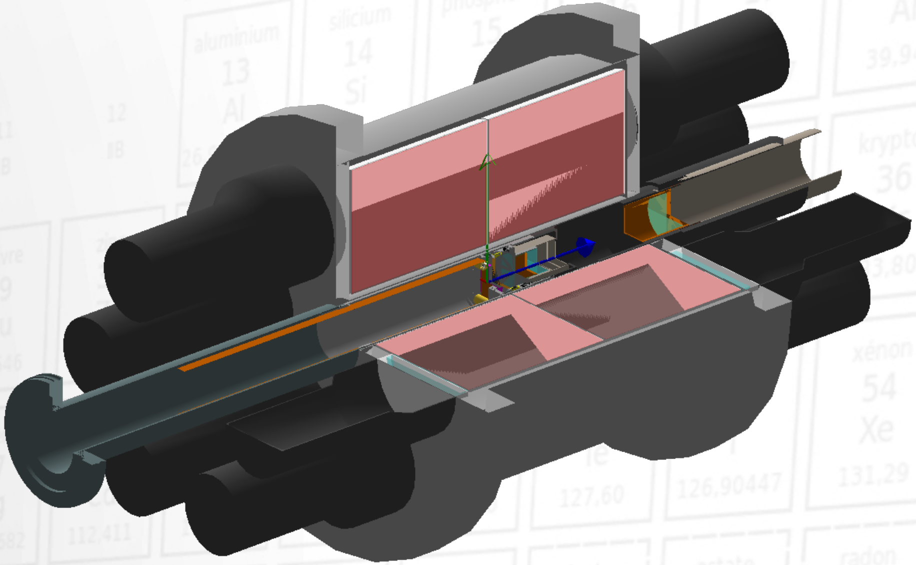
Image source : Thesis A-A Zakari



Detector response matrix

- We have to find **f** given **d** and a known **R**
- Solve the inverse problem represented by **d = R** x **f** [1]
- Detector response matrix is calculated from Monte Carlo simulations of the detector with GEANT4 Simulations

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



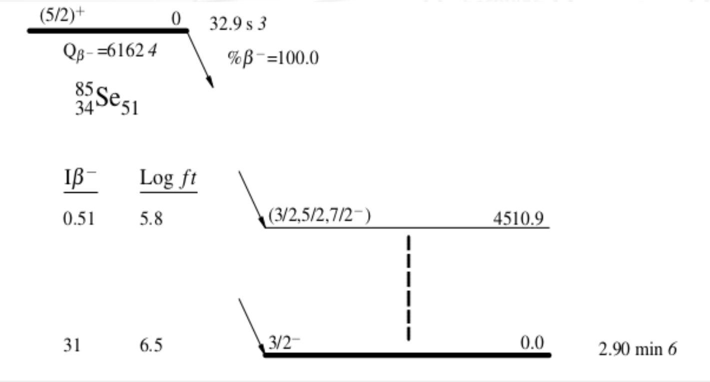
Geometry of our experimental device on GEANT4

- 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
- Geometry must be validated by comparing source simulation and data
- Simulation of the studied nucleus once the cleaning up has been validated

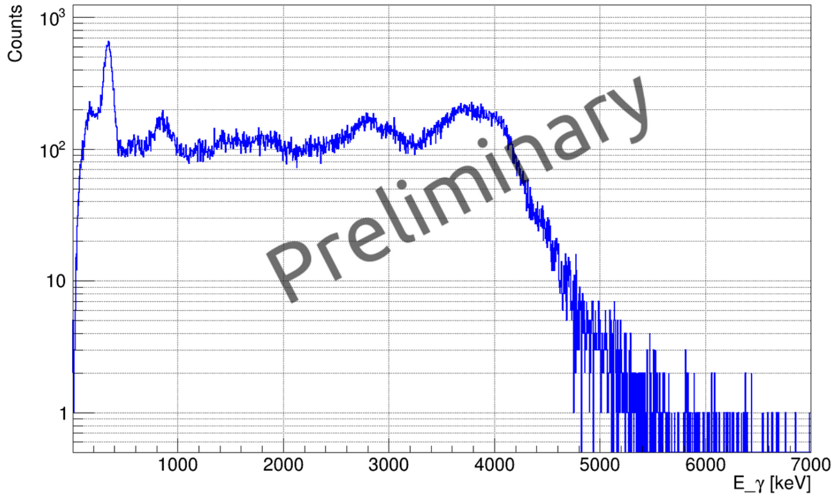
1) J.L.Tain, *Algorithms for the analysis of b-decay total absorption spectra*, Nuclear Instruments and Methods in Physics Research A 571 (2007) 728–738

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[2].
- $Q_{\beta-}$ = 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



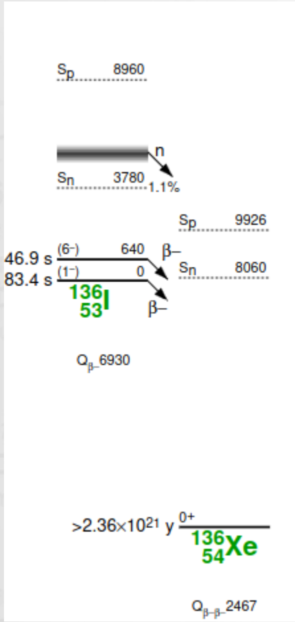
Coïncidence sum spectrum 85Se

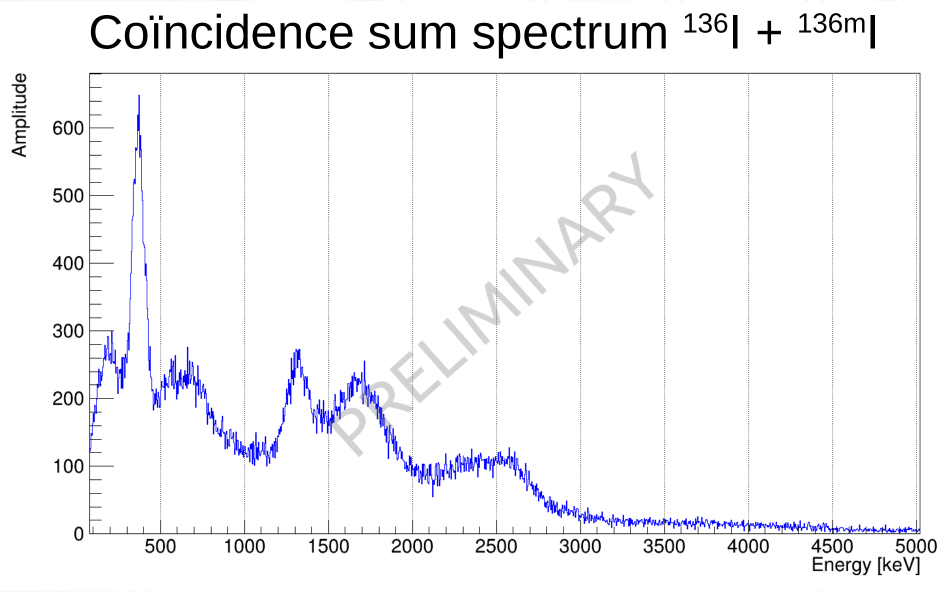


2) M. Gupta et al, "*Decay Heat Calculations: Assessment of Fission Product Decay Data Requirements for Th/U Fuel*" INDC International Nuclear Data Committee, INDC (NDS)-0577,2010

Physics case : ^{136}I

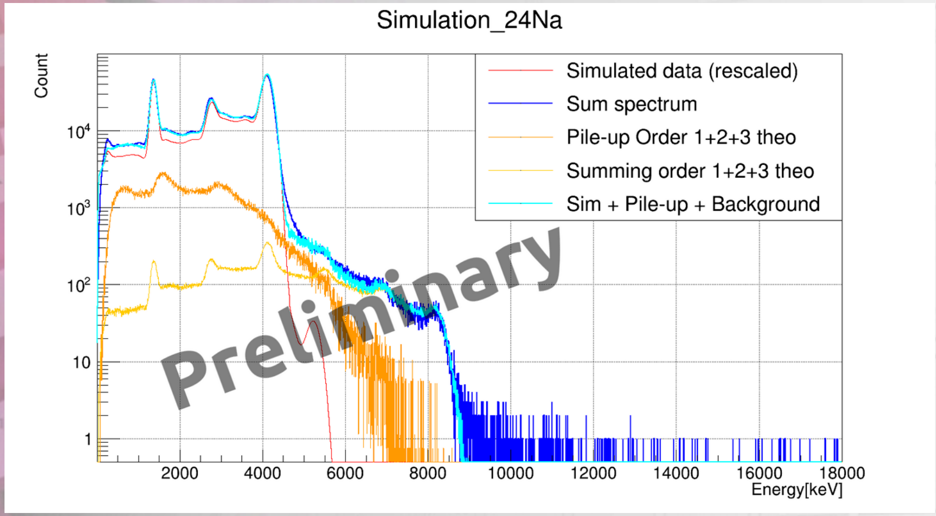
- ^{136m}I is high priority with contribution to total decay heat of 1.55 % and 3.69 % , 10 and 100s after reactor shut down
- ^{136}I contribution to total decay heat 100S after shut down = 2.74 % [3]
- Contribution of both into energy anti-neutrino spectra
- ^{136}I involved in r-process through pygmy 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





3) 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

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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