Strasbourg, France
January 23 2023

Le détecteur e-Shape pour les mesures de forme des spectres d’électron

M. Estienne pour le groupe
Structure et Energie Nucléaire de Subatech
Contributions to the WP3

Workshop NACRE, IPHC

Subatech, CNRS/IN2P3, Univ. Nantes, IMT Atlantique, France

Outline

WP3 : décroissance des fragments de fission

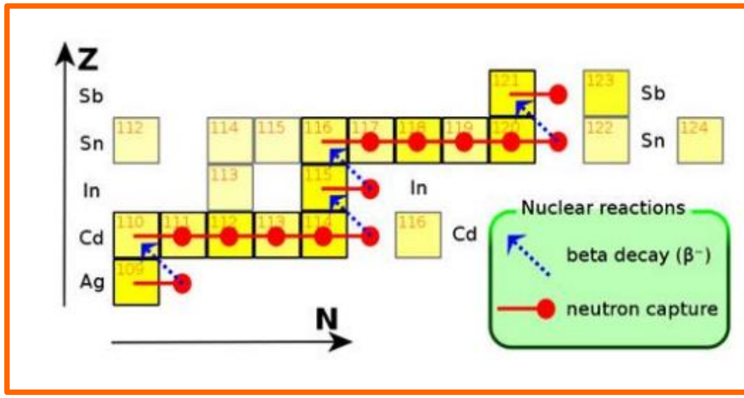
Task 3.1.3 Mesures forme des spectres d'électrons (e-Shape)
Task 3.4.1 Développement des détecteurs d'e-Shape
Tâche 3.2.1 Comparaison expérience / théorie pour l'amélioration des modèles

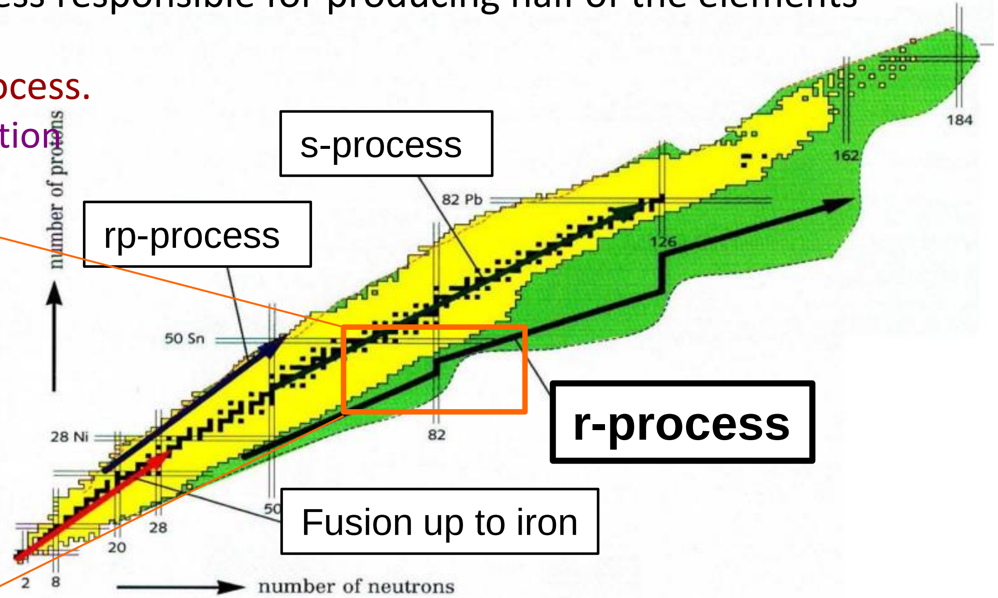
- Motivations for 1st Forbidden Beta Decay Study
- The e-Shape Detector
- e-Shape for Electron Spectra Measurement
- Conclusions and Outlooks

Motivations for 1st Forbidden Beta Decay Study

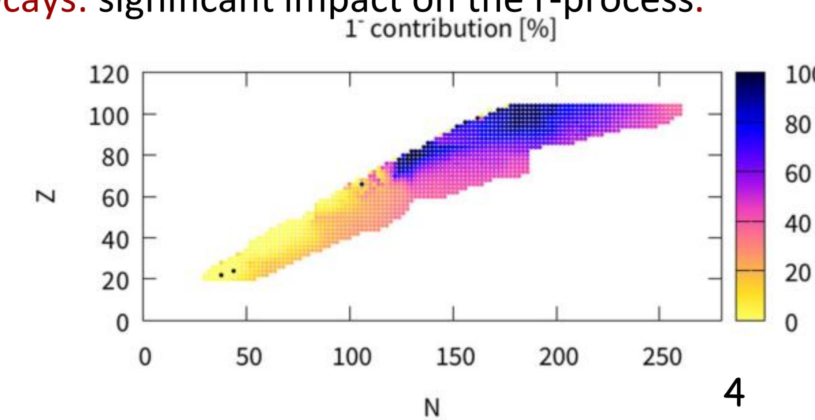
Nucleosynthesis and r-process

- Understanding nucleosynthesis: the r-process responsible for producing half of the elements heavier than iron in the universe
- ß decay plays an important role in the r-process.
  - n-capture (n,γ) and (γ,n) photodisintegration equilibrium and β-decay





- Half-life is an important parameter in r-process models. It represents an integral measure of β-strength.
- First forbidden β decays account for 1⁄3 to ½ of β decays: significant impact on the r-process.



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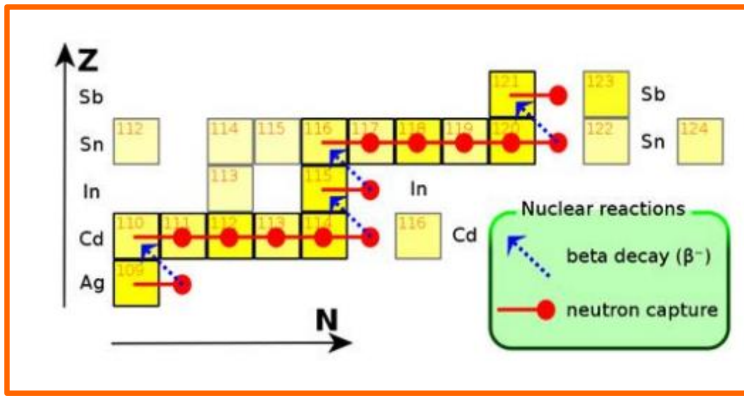

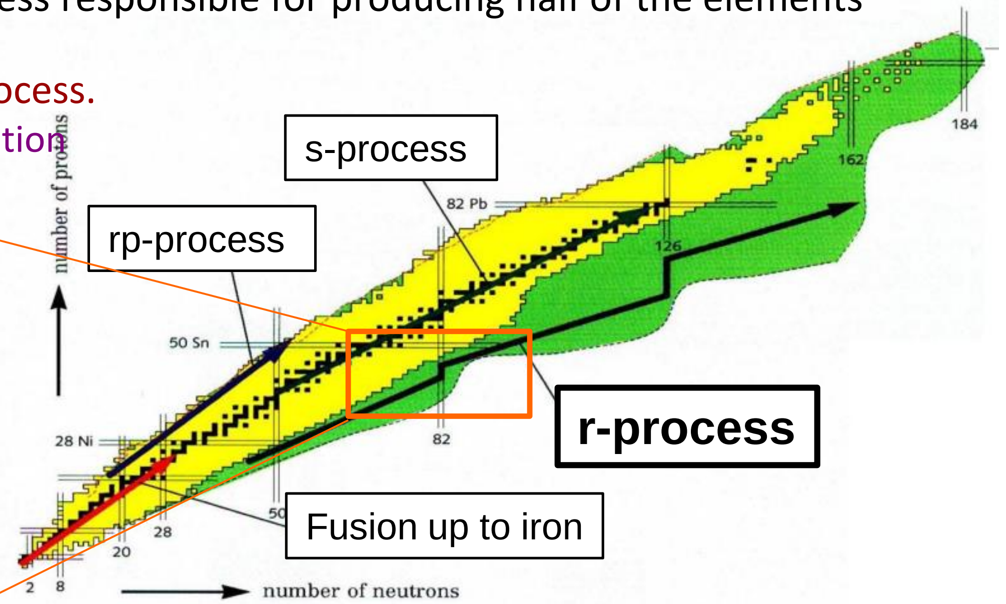

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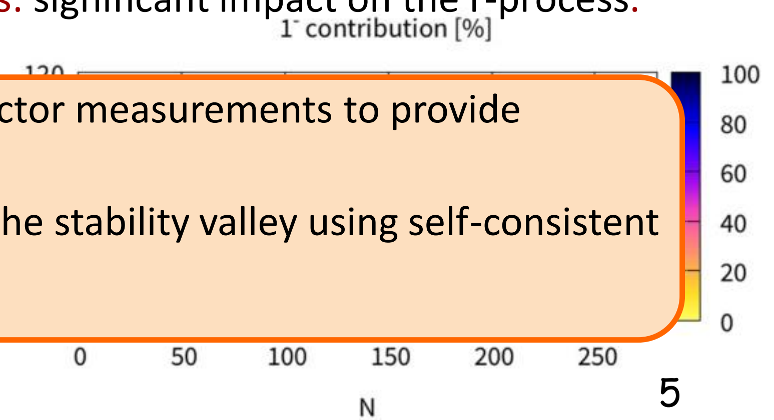


- Experimental requirements: new ß-strength and form factor measurements to provide additional constraints on models
- Theoretical needs: make predictions for nuclei far from the stability valley using self-consistent models that include 1st forbidden transitions

Shape Anomaly of Reactor Antineutrino Energy Spectra

- Measurement of the θ_{13} oscillation parameter by Double Chooz, Daya Bay, Reno in 2012
  - Independent evaluation of anti-ν energy spectra using BDNs
  - 6% deficit in the absolute value of the measured flux compared with the best prediction based on ILL data: reactor anomaly
  - Numerous projects in search of the existence of sterile neutrinos

Y. Abe et al Phys. Rev. Lett. 108, 131801, (2012)
F. P. An et al., Phys. Rev. Lett. 108, 171803 (2012)
J. K. Ahn et al., Phys. Rev. Lett. 108, 191802 (2012)

- In 2014, the same three experiments highlighted a spectrum distortion between 4.8-7.3 MeV compared to nuclear models again! (Shape anomaly)

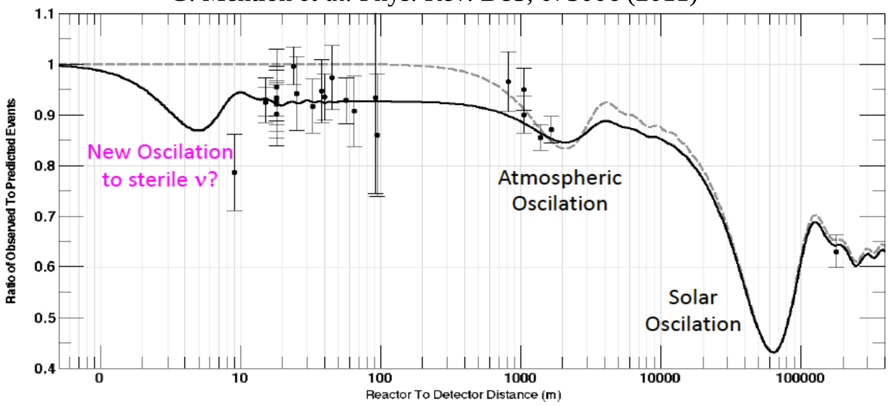
- **Research path put forward: first forbidden β-decays could be responsible for the distortion.**

- Experimental requirement: direct measurement of electron energy spectra of β decays of well-identified fission products (also known as form factors).

  ⇨ e-Shape experiment

- Theoretical requirement: take these form factors into account in our calculations for summing antineutrino energy spectra.

G. Mention *et al.* Phys. Rev. D83, 073006 (2011)



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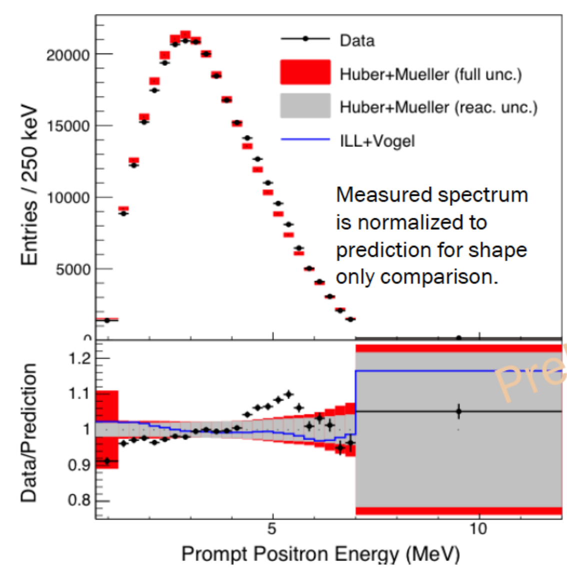
- Absolute shape comparison of data and prediction: $\chi^2/ndf = 41.8/21$



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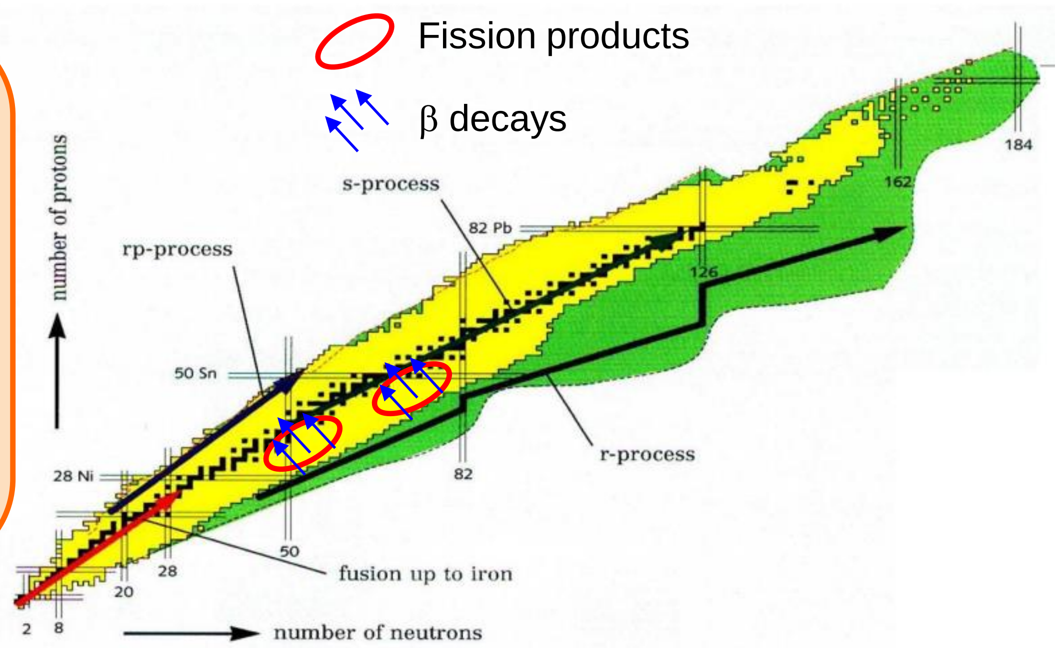

Beta Decay for Present and Future Reactors

- Getting access to the β decay properties and to antineutrino energy spectra

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y^{*} + e^{-} + \overline{\nu}_{e} $$

$$ \hookrightarrow {}^{A}_{Z+1}Y^{*} \rightarrow {}^{A}_{Z+1}Y + \gamma s $$

- The exploitation of the products of the beta decay is multifold:
  - The **antineutrinos** escape and can be detected → reactor monitoring, potential non-proliferation tool and essential for fundamental physics
  - **In laboratory, γ or β** measurements of well identified fission products → characterize the weak interaction properties, several physics topics in nuclear structure or nuclear astrophysics but also indirect access to antineutrino energy spectra

- Beta decay driven by some selection rules regarding the isospin and the spin-parity between the parent and daughter nuclei
  - Fermi in the 30s: $\lambda = \frac{2\pi}{\hbar}\left|V_{fi}\right|^2 \rho(E_f), \qquad V_{fi} \equiv \langle \psi_f | O_\beta | \psi_i \rangle$
  - β decay first formalized for ΔL=0 (allowed transitions):
    - ✓ Fermi transitions (super-allowed) : isospin change and ΔS=0: $O_\beta = O_F = g_V \tau^{\pm}$
    - ✓ Gamow-Teller transitions: ΔS=1: $O_\beta = O_F = g_A \hat{\sigma}_\mu \tau^{\pm}$
  - Forbidden transitions later identified and characterized: ΔL>=1
    - ✓ For first forbidden transitions: O_β includes 6 operators

Getting access to the $\bar{\nu}$ energy spectra of a fp

- Measurement of well identified fission product:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y^{*} + e^{-} + \bar{\nu}_{e} $$

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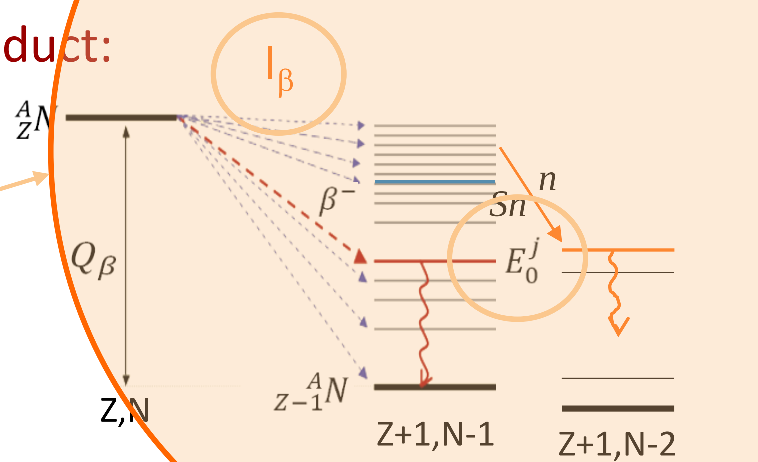

TAGS measurements
A. Porta's presentation

- Total energy spectrum of a fission product:

$$ S_{fp}(Z,A,p) \propto \sum_{b=1}^{N_b} I_{\beta\,fp}^{\;b} \times S_{fp}^{\;b}\left(Z_{fp}, A_{fp}, E_{0\,fp}^{\;b}, E\right) $$

- Energy spectrum of a b branch of a fission product:

$$ S^b_{fp}(p) \propto \underbrace{p^2 (Q - T_e)^2}_{\text{Phase space}} \underbrace{F(Z',p)}_{\text{Fermi function}} \underbrace{\mathbf{C(Z,p)}}_{\text{Shape factor}} \underbrace{(1 + \delta(Z,A,p))}_{\text{Subdominant corrections}} $$

A. Beloeuvre's PhD thesis : collaboration with S. Péru (CEA, DAM) and M. Martini (IPSA)

eShape measurements

Getting access to the $\bar{\nu}$ energy spectra of a fp

- Measurement of well identified fission product:

$$ {}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y^{*} + e^{-} + \bar{\nu}_{e} $$

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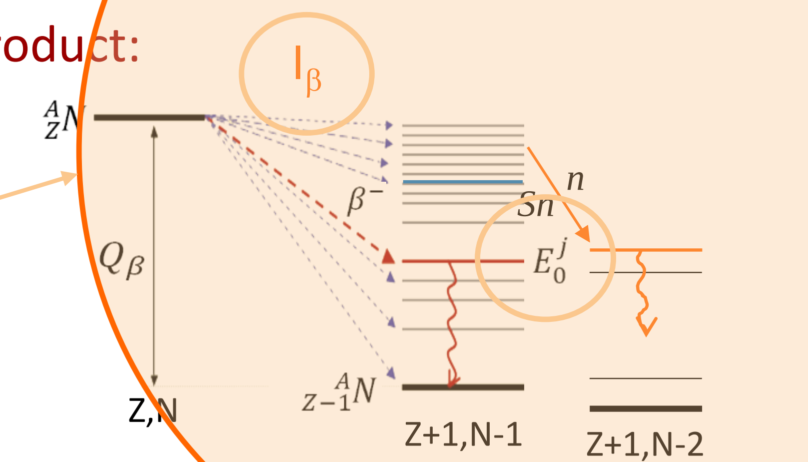

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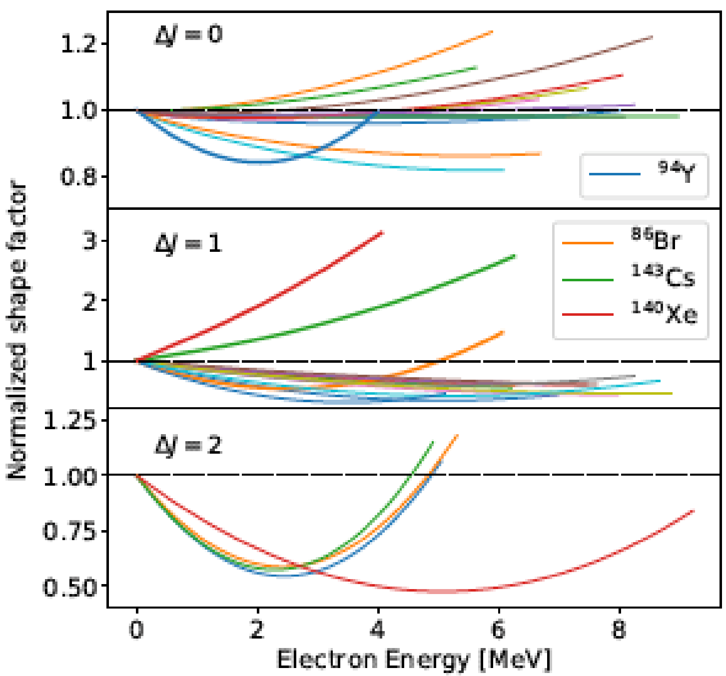
A. Beloeuvre's PhD thesis : collaboration with S. Péru

Tâche 3.2.1 Comparaison expérience / théorie pour l'amélioration des modèles

eShape measurements

Several Form Factor Predictions

- Form factor calculations for forbidden transitions: several models disagree, with the broadest predictions coming from L. Hayen et al.



L. Hayen et al., PRC.100.054323

- Predictions not all in agreement...:
  - A. Hayes et al. Phys. Rev. Lett. 112, 202501 (2014),
  - D.-L. Fang and B. A. Brown, Phys. Rev. C 91, 025503 (2015),
  - X.B. Wang, J. L. Friar and A. C. Hayes Phys. Rev. C 95 (2017) 064313 and Phys. Rev. C 94 (2016) 034314,
  - L. Hayen et al. Phys. Rev. C 031301(R)(2019)
  - J. Petković, T. Marketin, G. Martínez-Pinedo, N. Paar, J. of Physics G: NPP 2019, ISSN: 1361-6471

- Some of these groups also perform large-scale r-process calculations.

Ex.: T. Marketin, L. Huther, and G. Martínez-Pinedo, Phys. Rev. C 93, 025805 (2016).

➡ **Form factor measurements for the most important forbidden decays are needed to constrain the models.**

The e-Shape detector

The e-Shape experiment: Nantes-Surrey-Valencia Collaboration

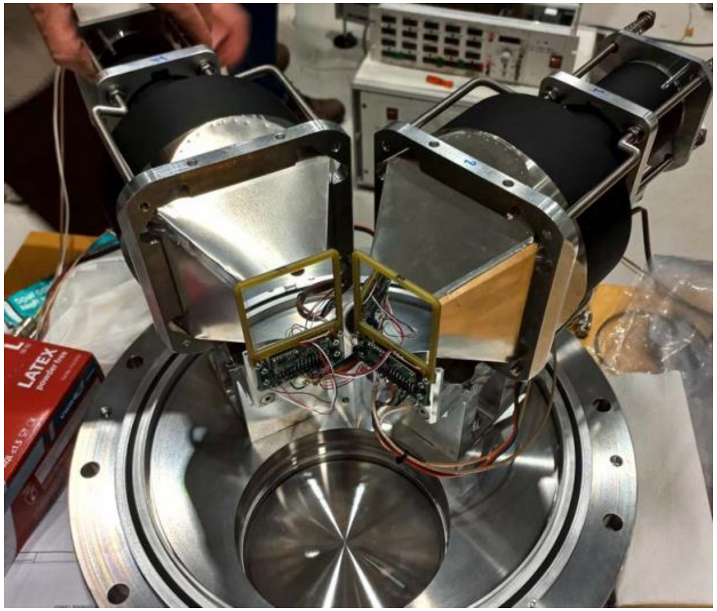
- ΔE – E telescopes to measure the beta spectrum of selected decays using isotopically pure beams at Jyväskylä with Si and plastic detectors in coincidence

- In vacuum chamber: two **ΔE-E telescopes** as close as possible (solid angle and better efficiency)

- Description of the telescopes:
  - **ΔE**: 500μm thickness Si detector, active area 50x50 mm2
  - **E**: Pl truncated cones, height 110 mm

- Ancillary detectors for gammas: HPGe and CeBr3

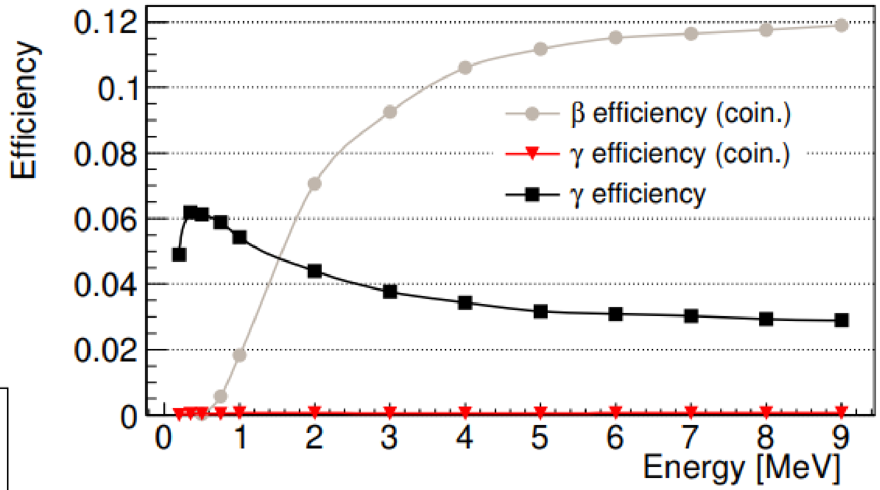
- DAQ: successful use of FASTER from LPC Caen

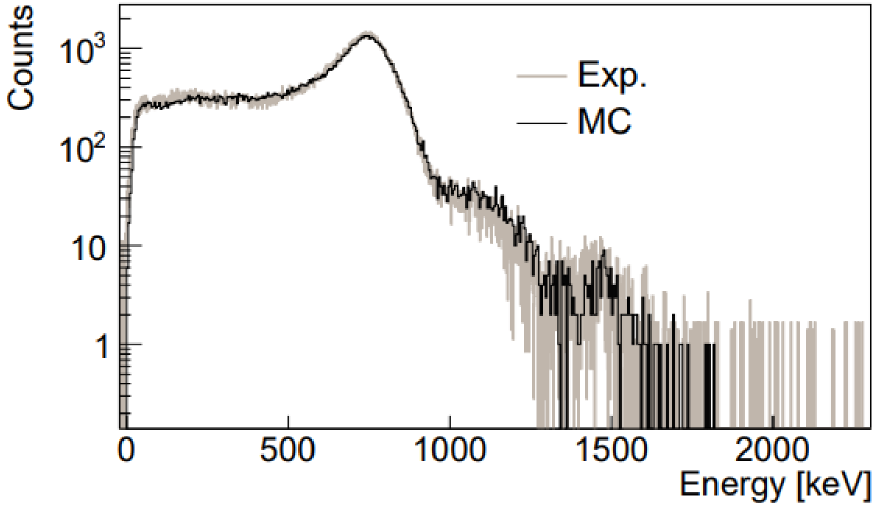


Task 3.4.1 Développement des détecteurs d'e-Shape

The e-Shape experiment: Detection principle

- Detection principle:
  - ΔE-E system provides very high gamma rejection efficiency
  - 12% efficiency for β measurements using coincidences





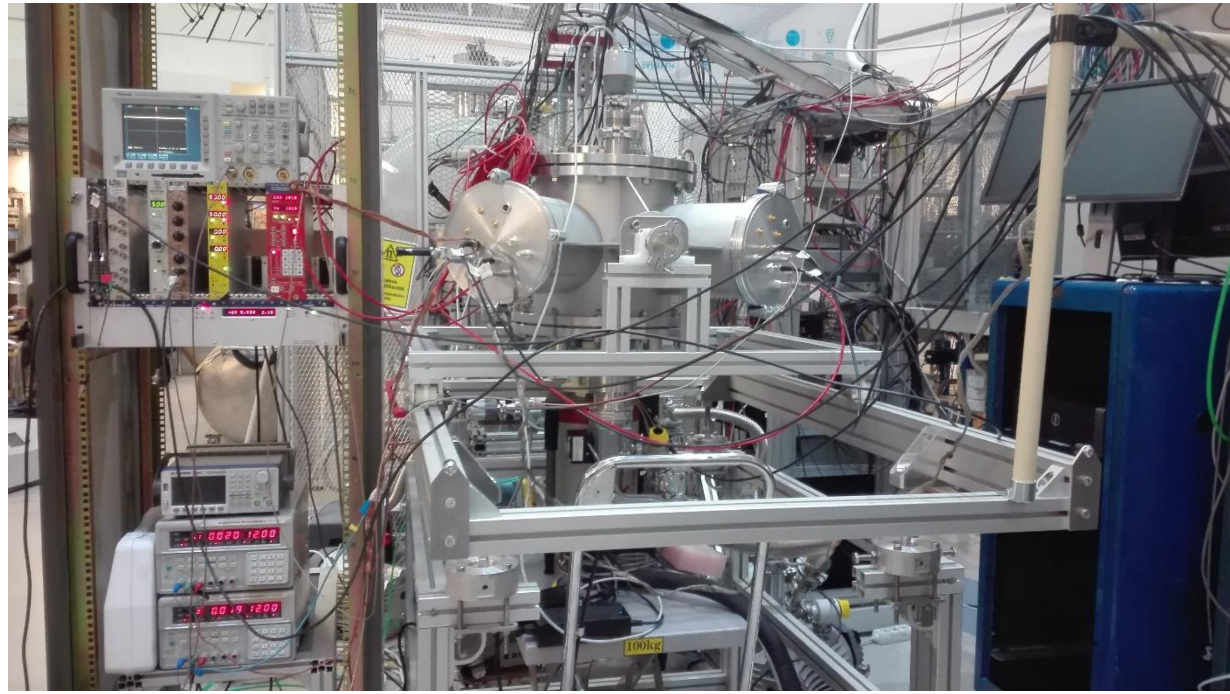
MC reproduction of the ^{207}Bi source at the lab. Plastic detector in coincidence with the silicon detector

- First commissioning @ex-CENBG Bordeaux, March 2019.
  - Monoenergetic electron sources
  - V. Guadilla *et al.*, accepted to JINST in 2024 (arXiv:2305.13832 [physics.ins-det])

Task 3.4.1 Développement des détecteurs d'e-Shape

e-Shape Assembly and Commissioning

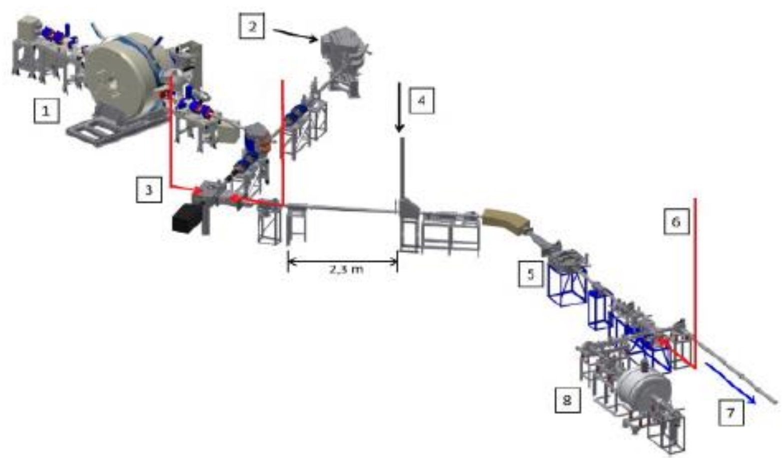
- What has been done so far?

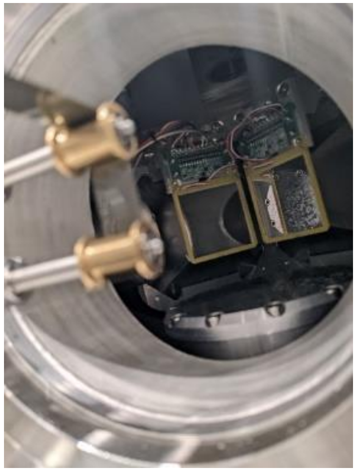


- Mechanical design, electronics and detector assembly @Subatech
- First tests @CENBG in march 2019
- Commissioning experiment in may 2019 @Jyväskylä (Finlande), analyses (R. Kean, **G. Alcala PhD @Valencia**)

e-Shape for Electron Spectra Measurement

Experimental campaign in 2022



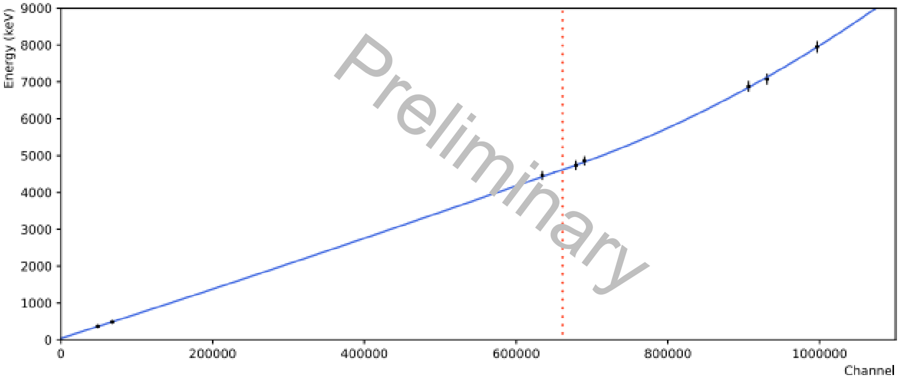


- IGISOL @ Jyväskylä for purified beams
  - Proton induced fission ion-guide source
  - Mass separator magnet
  - Double Penning trap system to clean the beams
- e-Shape experimental campaign **I233@IGISOL (Jyväskylä) in Jan. 2022**
- A dozen nuclei measured for first forbidden decay interest including nuclei for the detector calibration including ^{92}Rb et ^{96}Y.
- Analyses ongoing: 2 PhD thesis: G. Alcala (Valencia) and A. Beloeuvre (Subatech)

Task 3.1.3 Mesures forme des spectres d'électrons (e-Shape)

Ongoing Calibration of 2022 data

- E-Shape calibration: A. Beloeuvre and G. Alcala's PhD thesis
  - Several aspects covered (in A. Beloeuvre's thesis) due to COVID crisis including first forbidden ß-decay operators in the pnQRPA approach (see M. Fallot's talk) and e-Shape calibration.
  - A very tricky calibration close to be finalized
    - ✓ Several nuclei for several domains of energy
    - ✓ Iterative procedure and at least two calibration regions



Calibration in energy of the Plastic 1

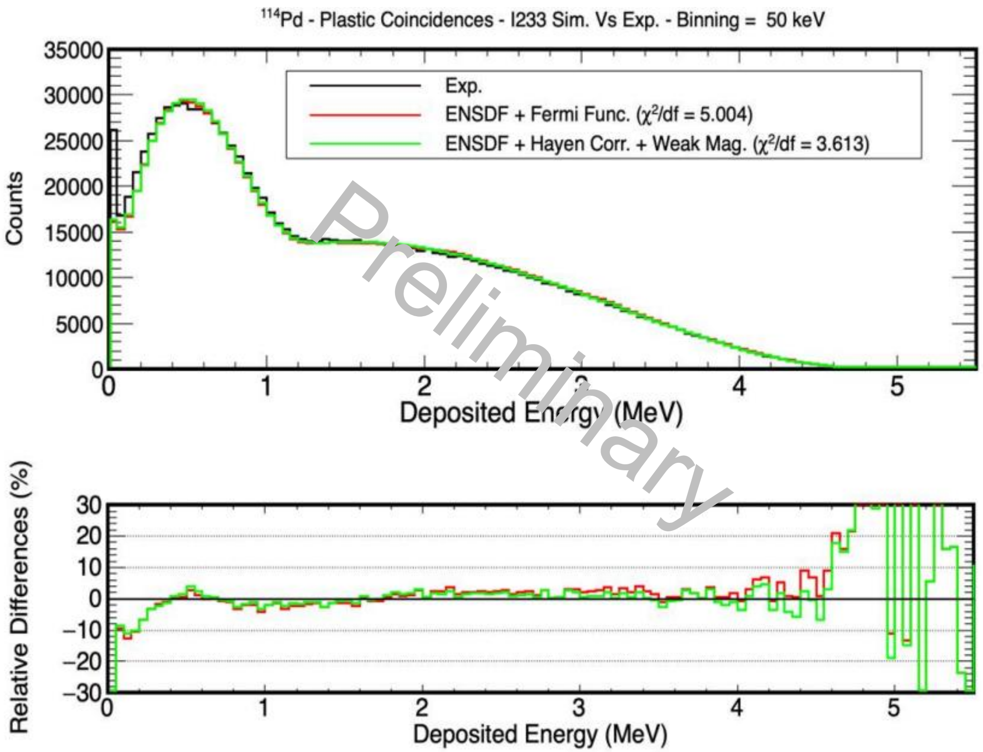
- Simulation: GEANT4 simulation to get the detector response. Validation of the MC for the ^{114}Ag.

- **A. Beloeuvre's PhD defense: October 19 2023, Nantes University**

- Next step: Analysis using deconvolution techniques of the most relevant contributors using our setup and deduce the spectrum shape for comparison with theoretical predictions.
  - Master 2 internship in 2024 and 1 PhD starting in fall 2024

Task 3.1.3 Mesures forme des spectres d'électrons (e-Shape)

Validation of MC



^{114}Pd $T_{1/2}$=2.42 min
Q=1.440(9) MeV

^{114}Ag $T_{1/2}$=4.6 s
Q=5.087(5) MeV

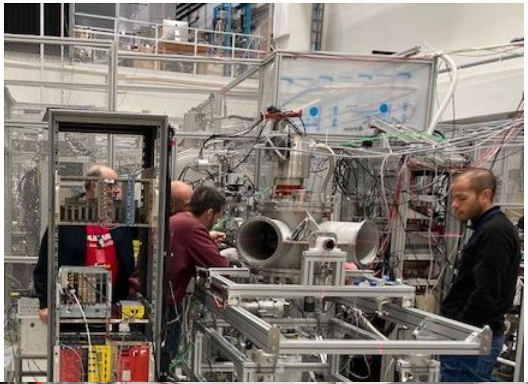
^{114}Cd
Stable

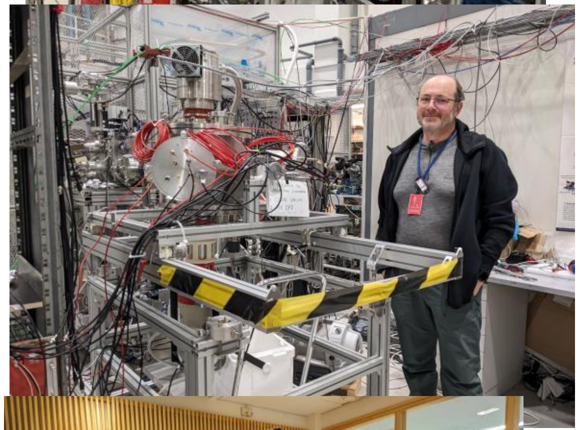
Courtesy of G. Alcala
PhD thesis IFIC Valencia

So far agreement within 2 and 3% between 0.8 and 4 MeV

Task 3.1.3 Mesures forme des spectres d'électrons (e-Shape)

New Experimental Campaign in Dec. 2023





- The IGISOL team had some issues in Jan. 2022 to tune properly the beam
- We were granted some extra-time for a new campaign in Dec. 2023 (I233 Addendum) to be able to measure the full list of nuclei of the initial proposal
- e-Shape with some small changes has been sent to Jyvaskylä last December
  - **Einzel lens** added to improve the beam focusing + extra collimator
  - **Small Silicon detector** to monitor the beam position
  - Buy a **new ^{207}Bi source** for the experiment
  - **Thinner Si detector:** 300μm thickness, same active area 50x50 mm2 => to lower the detection threshold
- Successful re-measurement of nuclei from 2022 and measurement of some new nuclei
- PhD thesis in Subatech starting in fall 2024 for the analysis of the data

Task 3.4.1 Développement des détecteurs d’e-Shape

Task 3.1.3 Mesures forme des spectres d’électrons (e-Shape)

Conclusions & Perspectives

- The theoretical and experimental studies of first forbidden β decays are important for several domains of physics including nucleosynthesis and antineutrinos from reactors

- e-Shape detector built to measured electron spectra from β branches of well identified fission products

- e-Shape detection principle exploits the coincidence between a plastic detector and a silicon detector.

- Two physics experimental campaigns in Jan. 2022 and Dec 2023.
  - ~15 nuclei measured for calibration and physics purpose

- Calibration in good progress and data analysis ongoing.
  - A. Beloeuvre's PhD thesis defended last October.
  - G. Alcala's PhD thesis in Valencia. Defense should take place in 2024
  - 1 PhD starting in Oct. 2024 at Subatech

- Upgrade of the e-Shape apparatus ongoing to improve its resolution

Thank you!

Structure et Energie Nucléaire

- 5 staff researchers/teaching researchers:
  - Eric Bonnet (CRCN) section 01
  - Magali Estienne (CRHC) section 01
  - Muriel Fallot (MCF, HDR) section 29
  - Lydie Giot (MA)
  - Amanda Porta (MA)
- 3 PhD students:
  - Yohannes Molla
  - Julien Pépin
  - Jad Halwani
- post-doc :
  - Suomen Nandi since nov. 2023
- Engineering support :
  - Stéphane Bouvier

The TAS/eShape Collaborati

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SUBATECH Nantes: M. Estienne, M. Fallot, J. Pepin, A

U. Surrey: W. Gelletly, S. Rice, M. Bowry, G.F. Farrelly, Z Podolyak, P.H. Regan

IGISOL Jyvaskyla: H. Penttilä, J.Äystö, T. Eronen, A. Ka V.-V. Elomaa, J. Hakala, A. Jokinen, I. Moore, J. Rissane Weber, P. Karvonen, V.S. Kolhinen

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BNL New-York: A. Sonzogni

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