De-excitation after neutron captures : application of the FIFRELIN code to neutrinos and bolometers

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CEA Saclay

GDR Deep underground physics plenary meeting – 30 Nov 2021

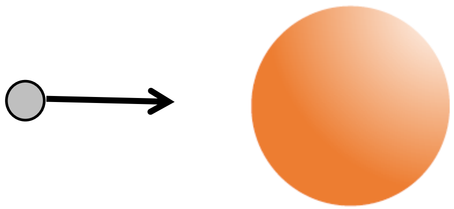
Introduction

neutron background : cosmic-ray produced neutron
Fast neutrons leading to nuclear recoils through elastic scattering
Here : neutrons at the end of their track, thermalized

Capture of thermalized neutrons :

$\sigma_{capture} \sim 1/v$

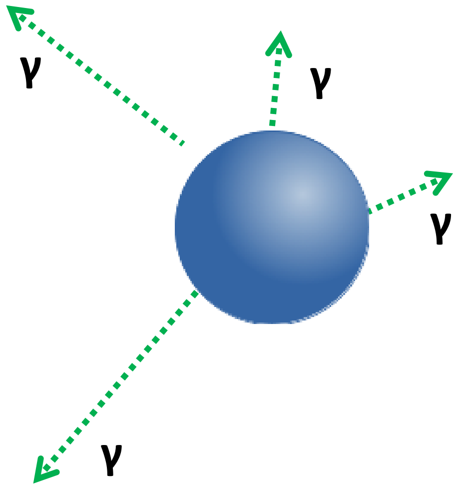
De-excitation of the nucleus
Simulated by FIFRELIN



thermal neutron
E ≈ 25meV

Nucleus $^{A}_{Z}X$

Compound nucleus $^{A+1}_{Z}X$
Excited state



Of interest for :

- Neutrino detection : $\bar{\nu}_e + p \rightarrow e^+ + n$
- Bolometer backgrounds

Contents

FIFRELIN

FIFRELIN : FIssion **FR**agment **E**vaporation **L**eading to an **In**vestigation of Nuclear data.
O. Litaize et al., Eur. Phys. J. A (2015) 51: 177
D. Regnier et al., Computer Physics Communications 201(2016)19–28

Eur. Phys. J. A (2015) **51**: 177
DOI 10.1140/epja/i2015-15177-9

Regular Article – Theoretical Physics

Fission modelling with FIFRELIN*

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Computer Physics Communications 201 (2016) 19–28

Contents lists available at ScienceDirect

Computer Physics Communications

journal homepage: www.elsevier.com/locate/cpc

ELSEVIER

An improved numerical method to compute neutron/gamma deexcitation cascades starting from a high spin state

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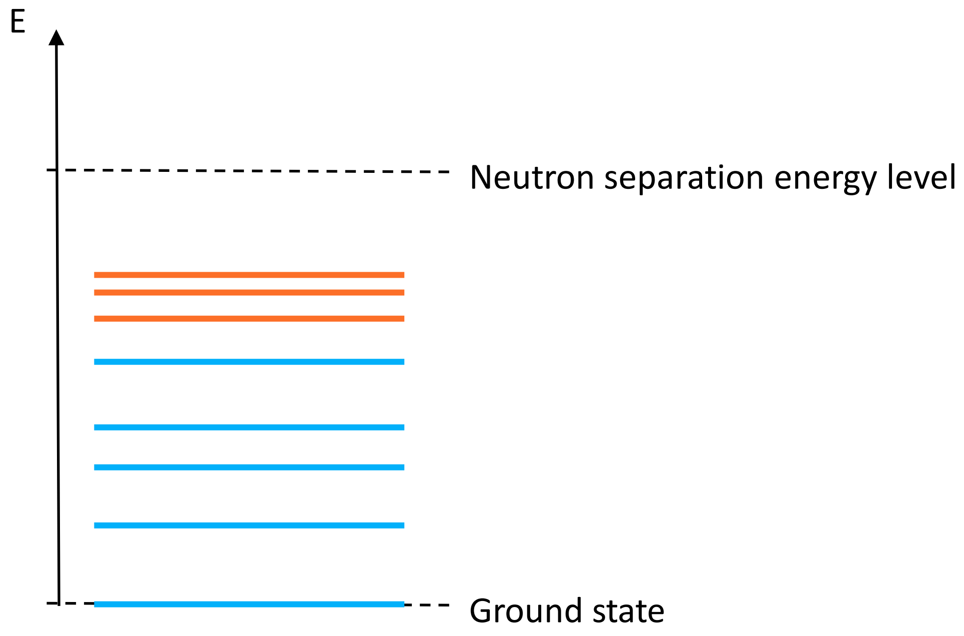
[b] Nuclear and Chemical Science Division, Lawrence Livermore National Laboratory, Livermore, CA 94551, USA

- Developpers : **O. Litaize, O. Serot, A. Chebboubi**
- All FIFRELIN results presented in this talk are courtesy of **A. Chalil, L. Thulliez, T. Materna**

FIFRELIN : level scheme



Energy levels from RIPL3
Energy levels from EGAF

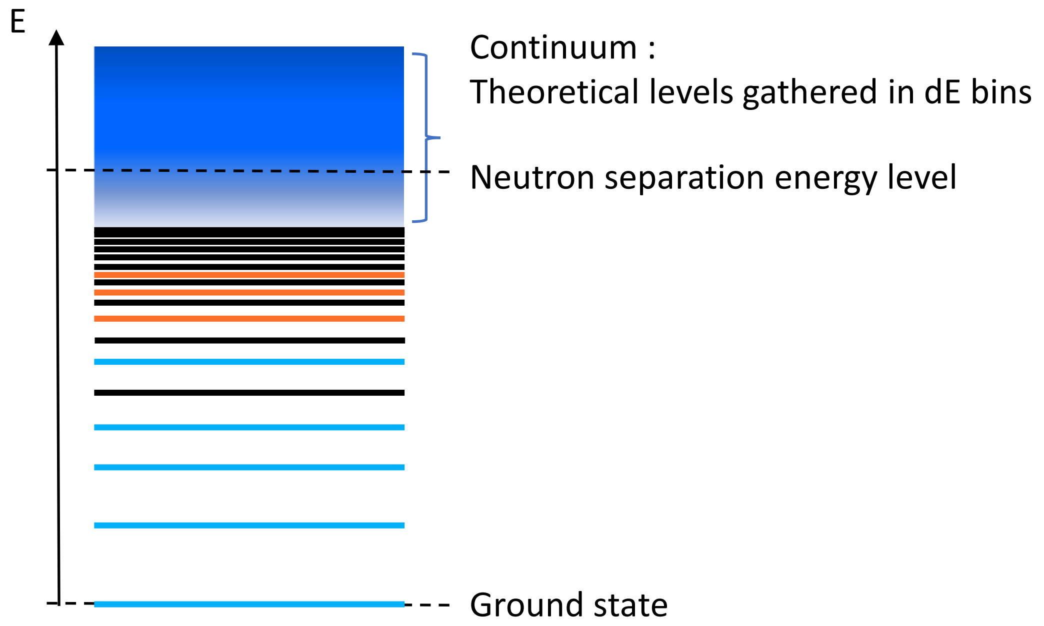
- Information on levels :
  - Energy E
  - Spin J
  - Parity π
  - Level to level transition probabilities

- FIFREFLIN incorporates evaluated nuclear data
  - Low-lying states : **RIPL-3**
  - Levels accessible from S_n : **EGAF**

RIPL-3 : Reference Input Parameter Libray
Nucl. Data Sheets 110 (2009) 3107
Database updated in September 2020

EGAF : The Evaluated Gamma-Ray Activation File
Nucl. Data Sheets 119 (2014) 79

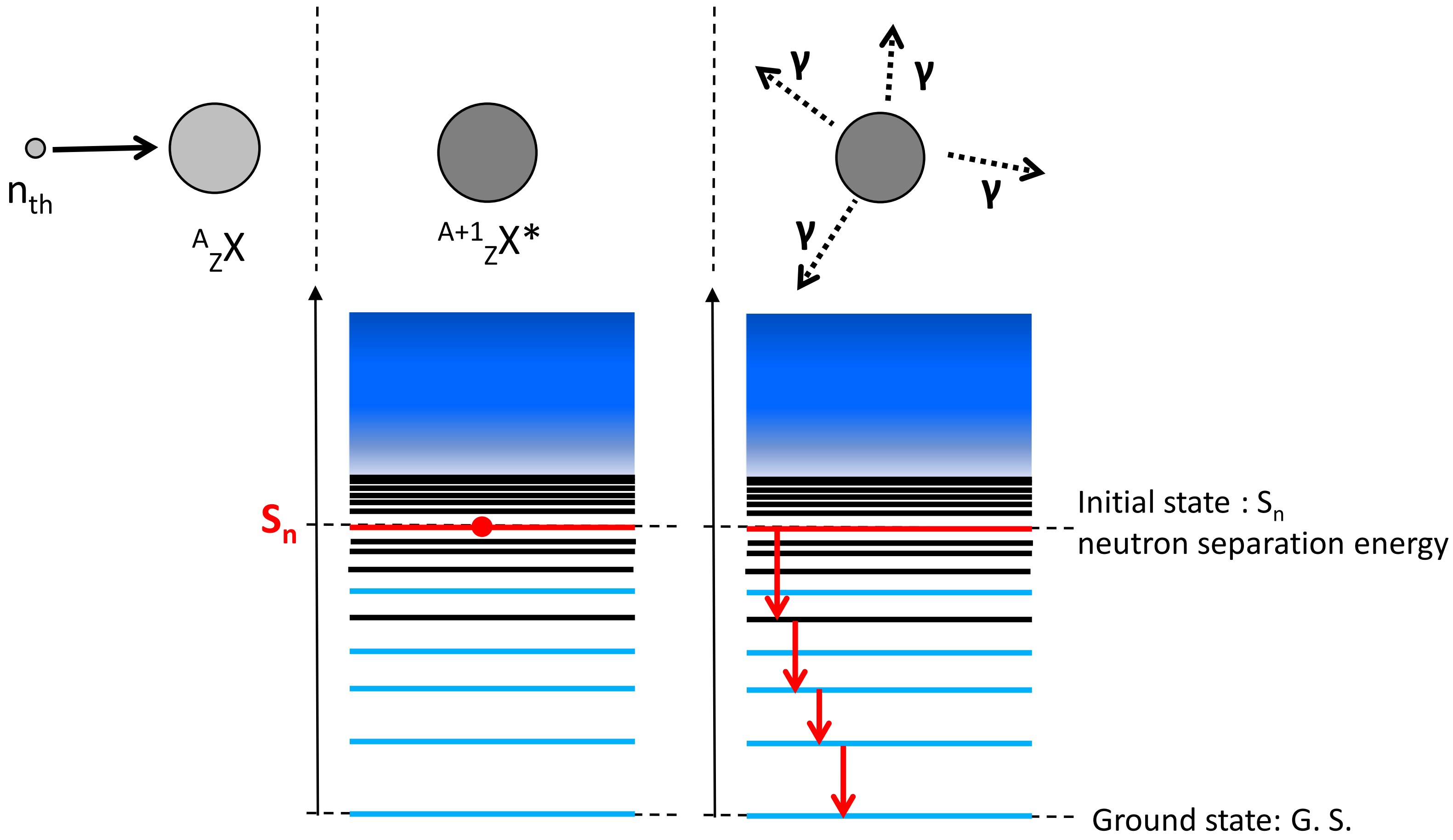
FIFRELIN : level scheme



Energy levels from RIPL3
Energy levels from EGAF
Theoretical levels from models

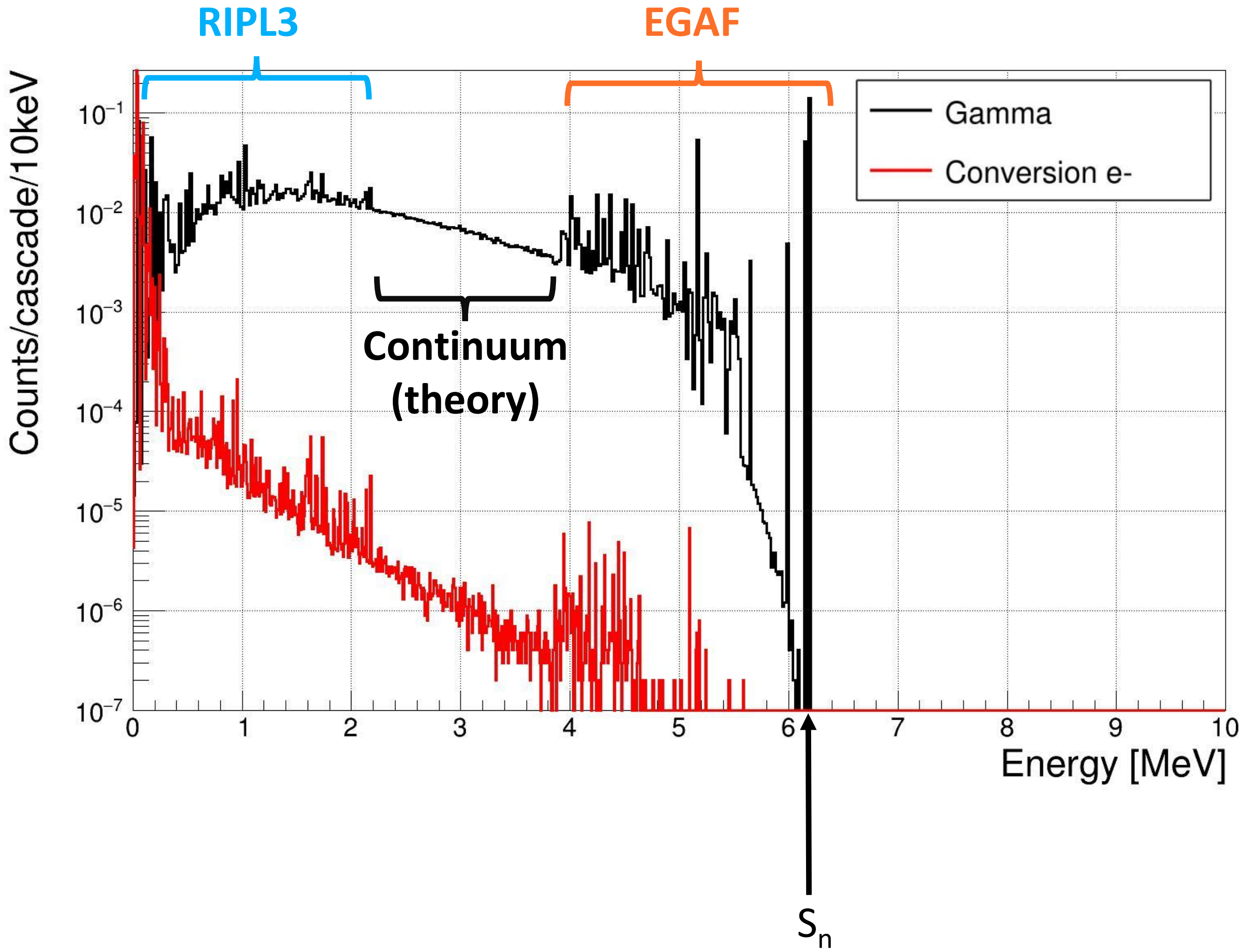
- Some evaluated levels are not completely known : models are used to complete missing information
- Some discreet energy levels + the continuum are missing from evaluated data
- FIFRELIN completes the evaluated level scheme with theoretical level density models

FIFRELIN : γ-cascades



- Following neutron capture, compound nucleus is in a state close to S_n
- Then de-excitates towards ground state emitting **γ**
- **FIFRELIN** generates **γ** cascades with a Monte Carlo process from S_n to G.S.

FIFRELIN : example for ^{183}W



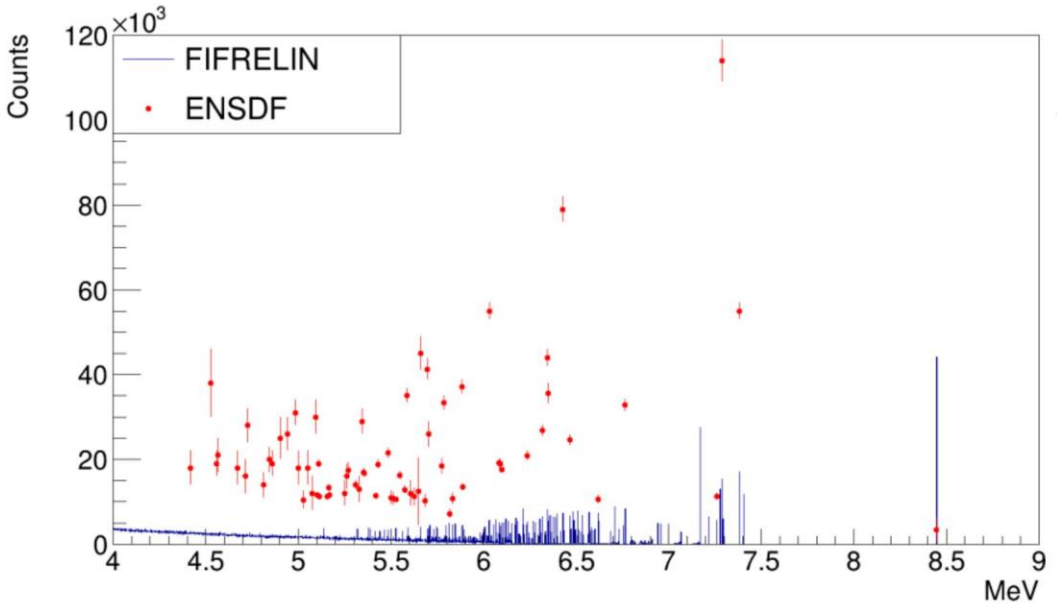
Output for each cascade :

- Number of **γ**
- Number of conversion e^-
- Energies
- Isotropic momenta
- Timing (RIPL3 or Weisskopf estimate)

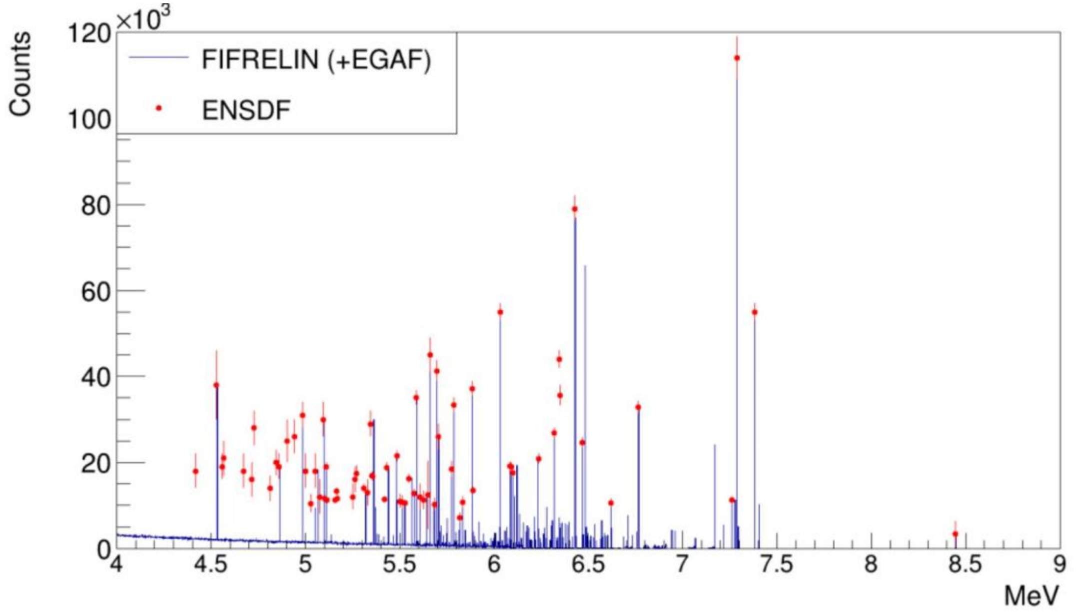
Improvement of FIFRELIN results

Courtesy of A. Chalil

Comparison with experimental results for the **γ** de-excitation of ^{156}Gd



Older FIFRELIN version based on RIPL-3

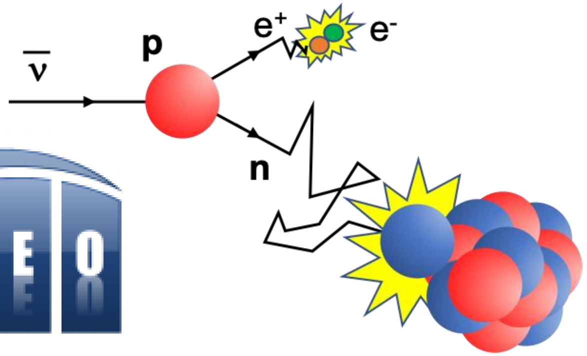


FIFRELIN based on updated RIPL3 + EGAF

Contents

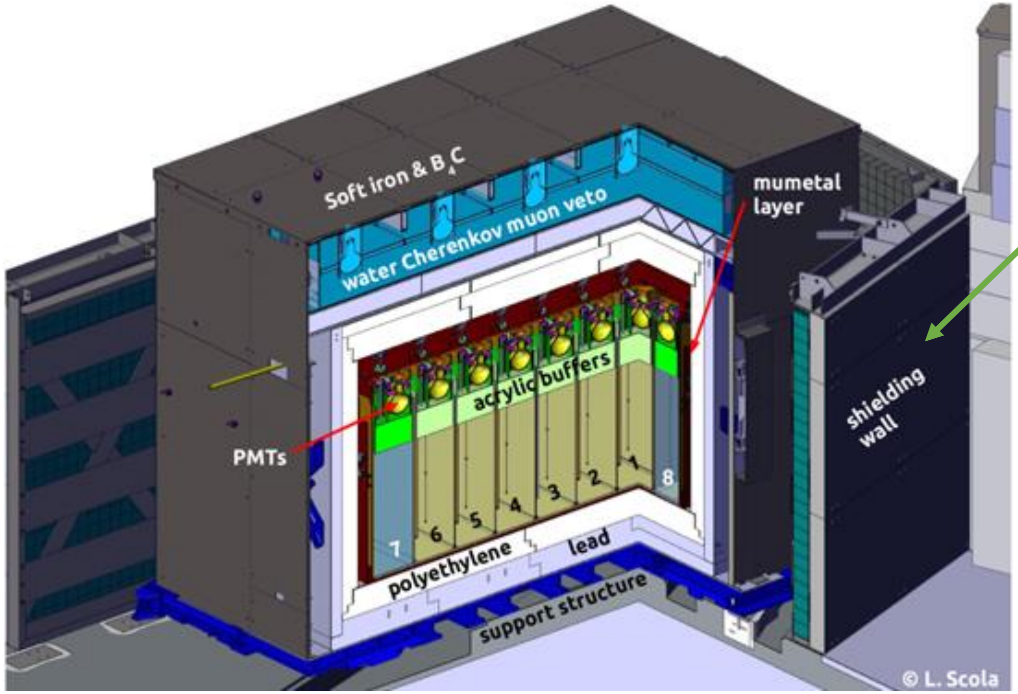
https://www.stereo-experiment.org/scientific.php?

Neutrino detection : STEREO



STEREO = Search for Sterile Reactor Neutrino Oscillations

- near ILL research reactor
- 6 cells filled with Gd-loaded liquid scintillator (0.2wt% Gd)



STEREO collaboration, Phys .Rev. D 102 (2020) 5, 052002
STEREO collaboration , Phys. Rev. Lett. 125 (2020) 20, 201801
PROSPECT and STEREO collaborations, 2021, arXiv:2107.03371 [nucl-ex]

Inverse Beta decay :

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Used for neutrino detection :

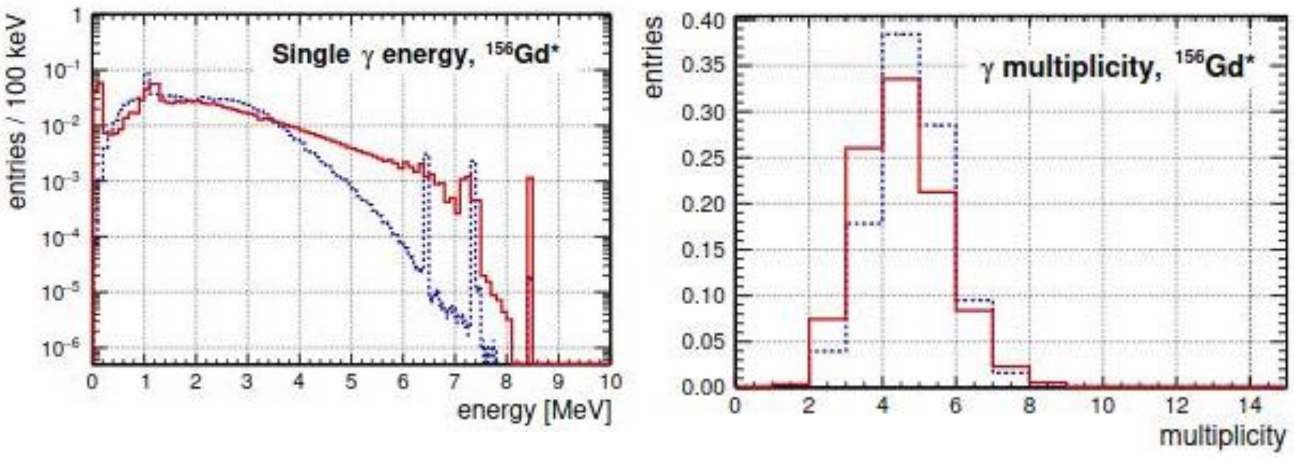
- e^+ detected via scintillation and annihilation
- n detected via capture on Gd after thermalization

$$n + {}^{155,157}Gd \rightarrow {}^{156,158}Gd + \boldsymbol{\gamma}$$
$$\boldsymbol{\sigma}_{(n,\gamma)}\,({}^{155}Gd)=60\ 000b$$
$$\boldsymbol{\sigma}_{(n,\gamma)}\,({}^{157}Gd)=250\ 000b$$

- delayed coincidence between these signals is used to reject background

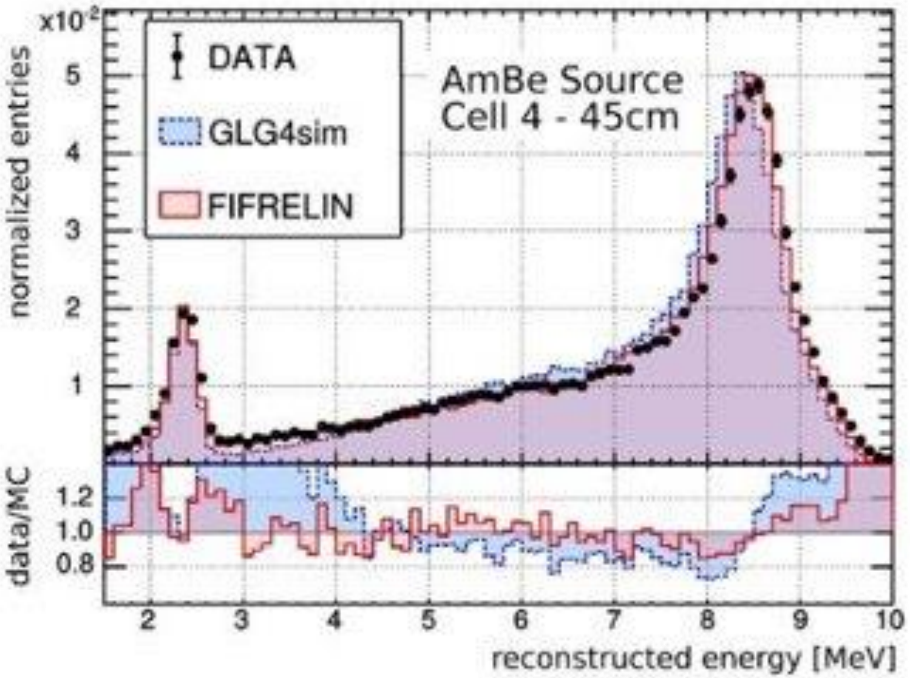
STEREO + FIFRELIN

- Detector response depends on the de-excitation of ^{156,158}Gd (neutron signal)
- Using FIFRELIN de-excitation schemes helped the Monte-Carlo simulation better fit the experimental data



FIFRELIN data (red) on ^{156}Gd de-excitation compared to Geant4 simulation (blue)

H. Almazán et al., Zenodo, 2653786 (2019)

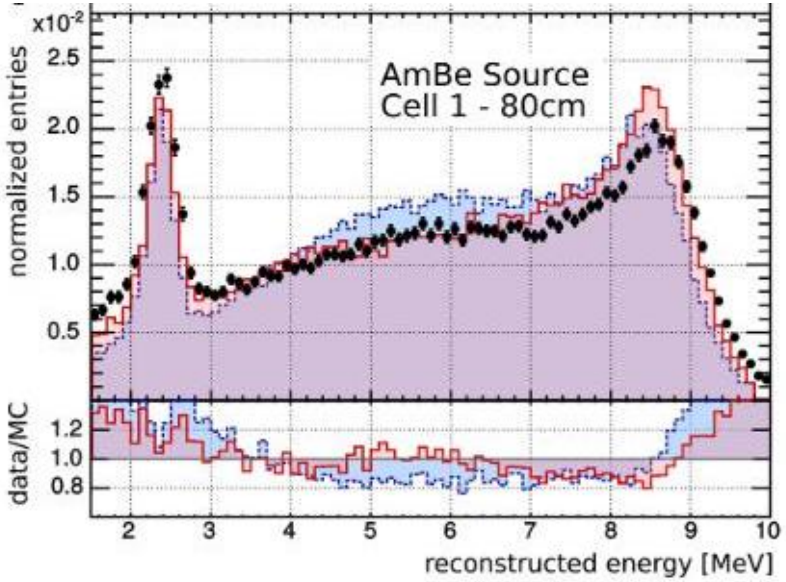


AmBe source placed at the **center of the cell**
Reconstructed energy spectra from neutron captures

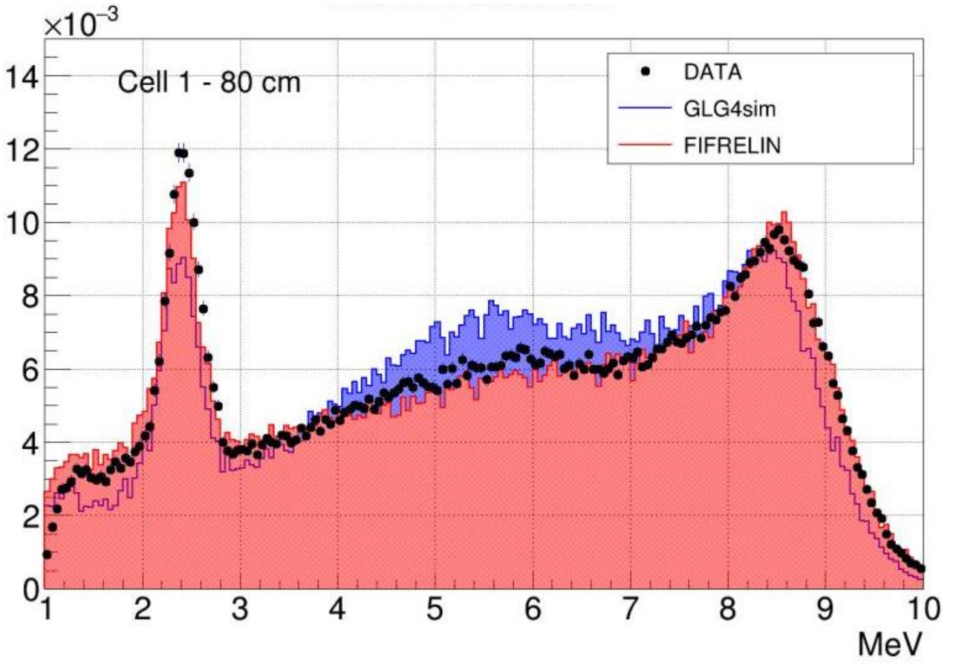
Eur. Phys. J. A (2019) 55: 183

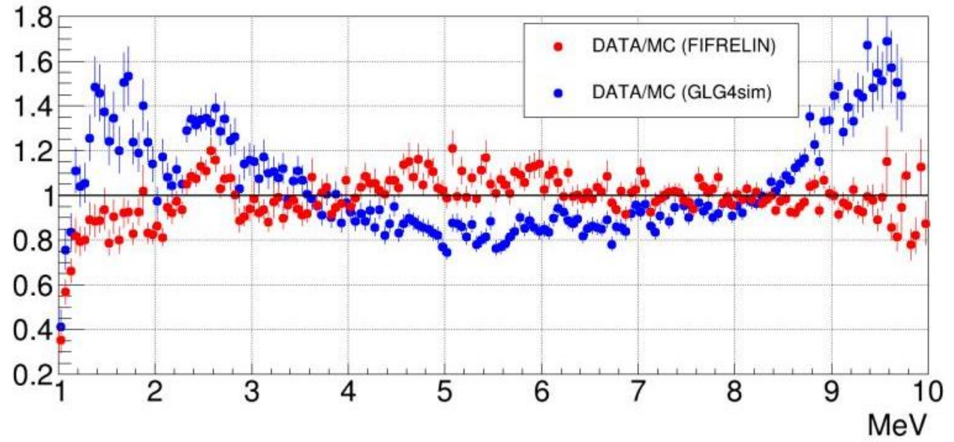
STEREO+FIFRELIN

AmBe source placed at the **top of a side cell**
Reconstructed energy spectra from neutron captures
Eur. Phys. J. A (2019) 55: 183



- AmBe source at the top of a side cell = more **γ** escape the cell without depositing all their energy
- Response of the detector more sensitive to the Gd **γ-**cascade details
- Simulations with FIFRELIN better fit the data, especially after database updates

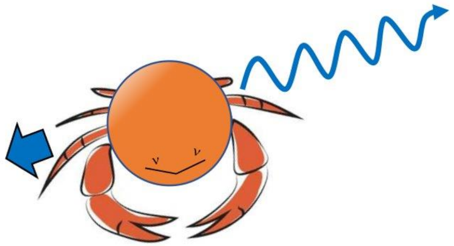




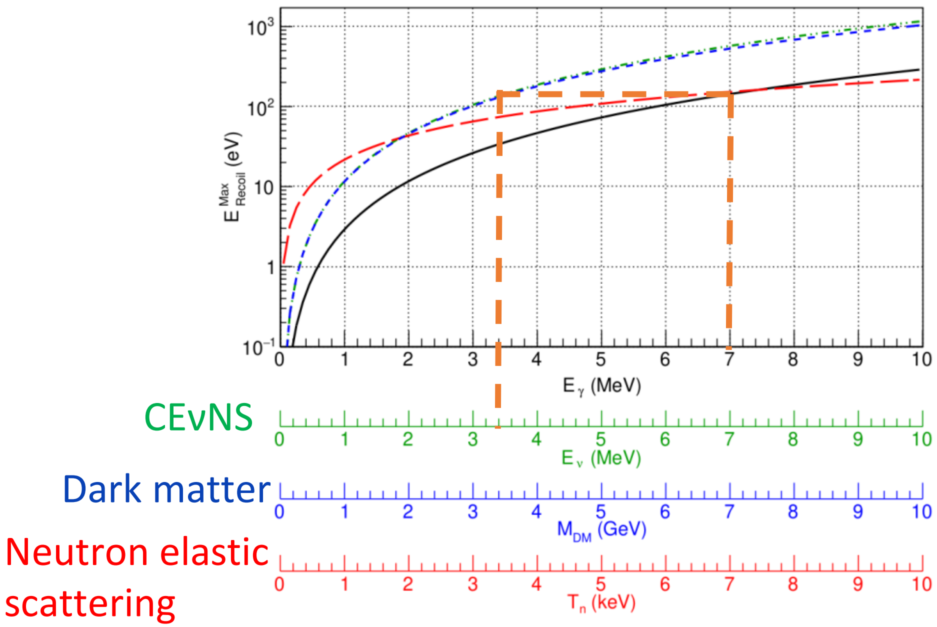
Same plot with FIFRELIN+EGAF
Courtesy of A. Chalil

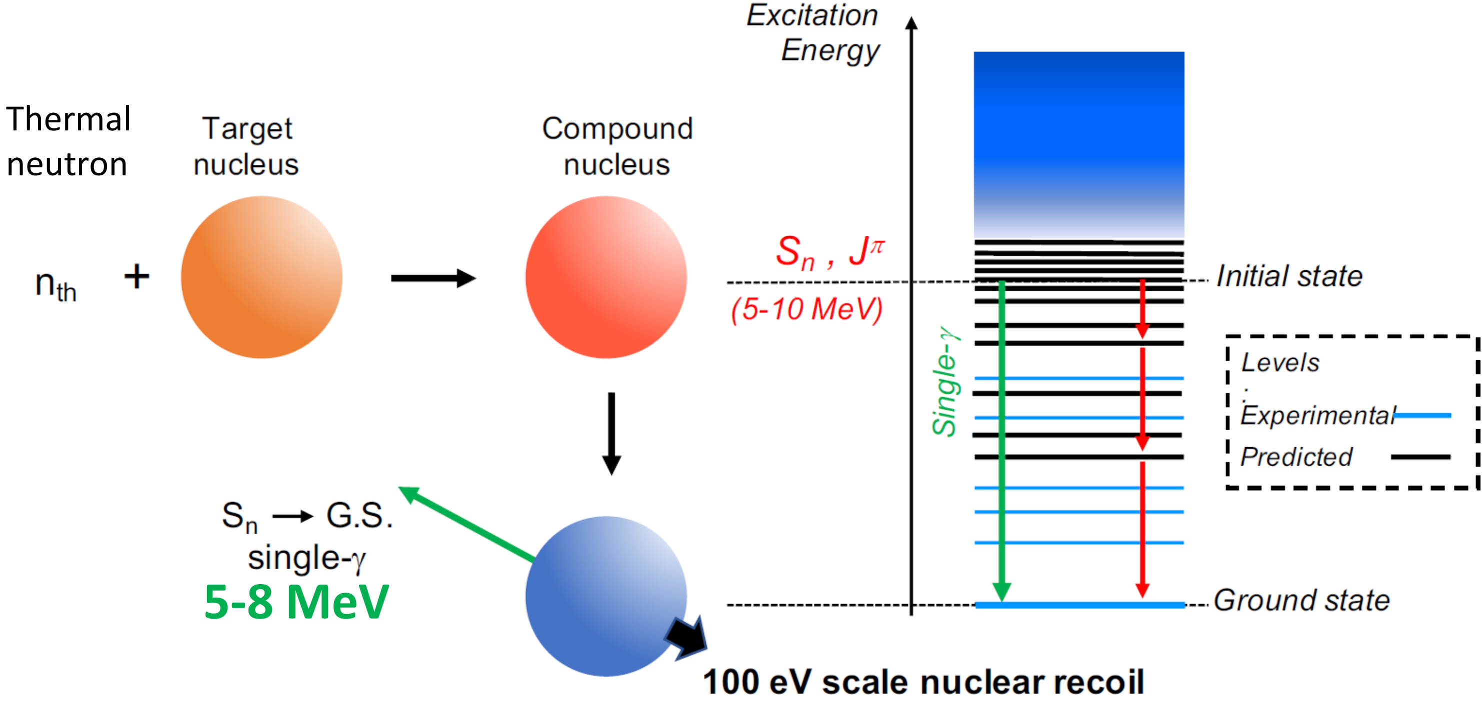
Contents

CRAB : Bolometer calibration method



Maximum nuclear recoil energy for different processes (target = W)





Defined recoil energy : $\frac{E_\gamma^2}{2Mc^2}$

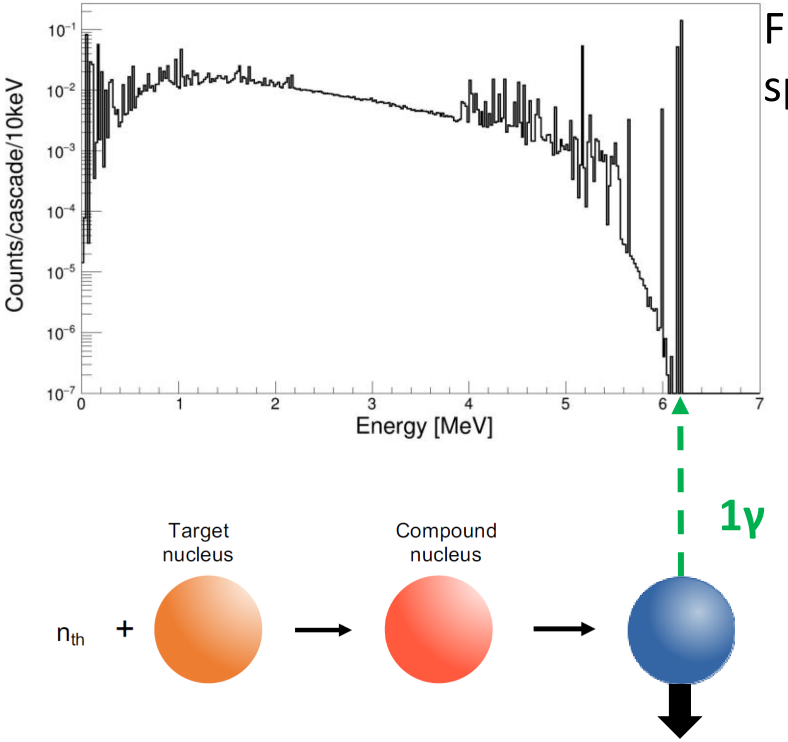
Only method combining :

- Pure nuclear recoils
- in the bulk of bolometer
- in the 100 eV energy range

L. Thulliez, D. Lhuillier et al 2021 JINST 16 P07032

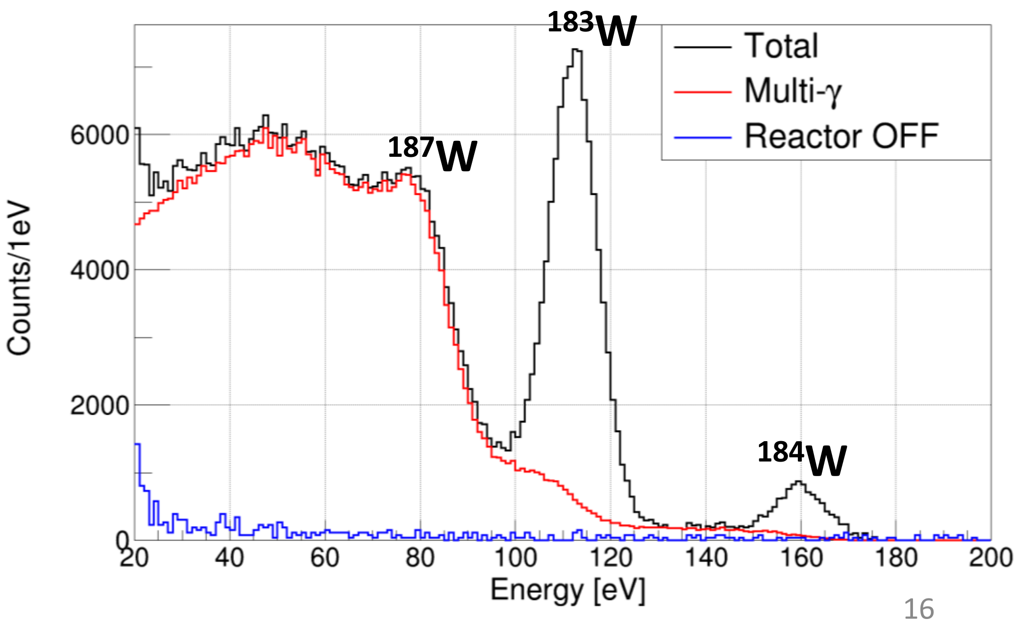
$CaWO_4$ bolometer

FIFRELIN **γ** de-excitation spectrum for ^{183}W

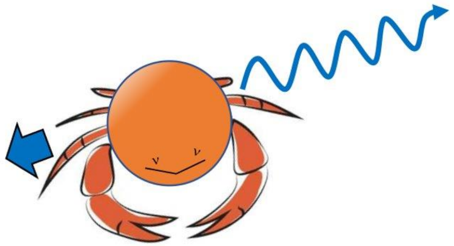


1γ-transition : Sn=6.2MeV
112eV recoil

- Multi-**γ** transitions dominate the recoil spectrum below 100eV
- CRAB needs precise description of the **γ**-cascades
- Third calibration peak hidden in the multi-**γ** background

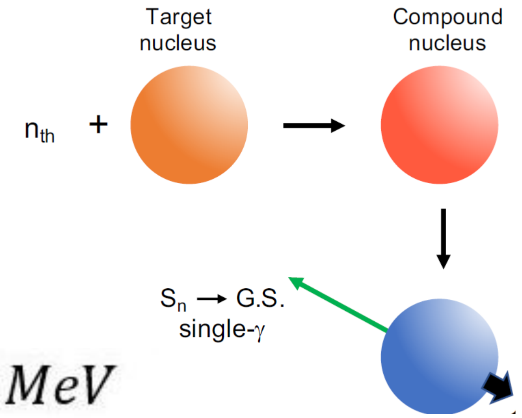


Recoil energy spectrum
simulation GEANT4+FIFRELIN
5 × 5 × 5 mm3 CaWO4 bolometer
Resolution : σ = 5eV

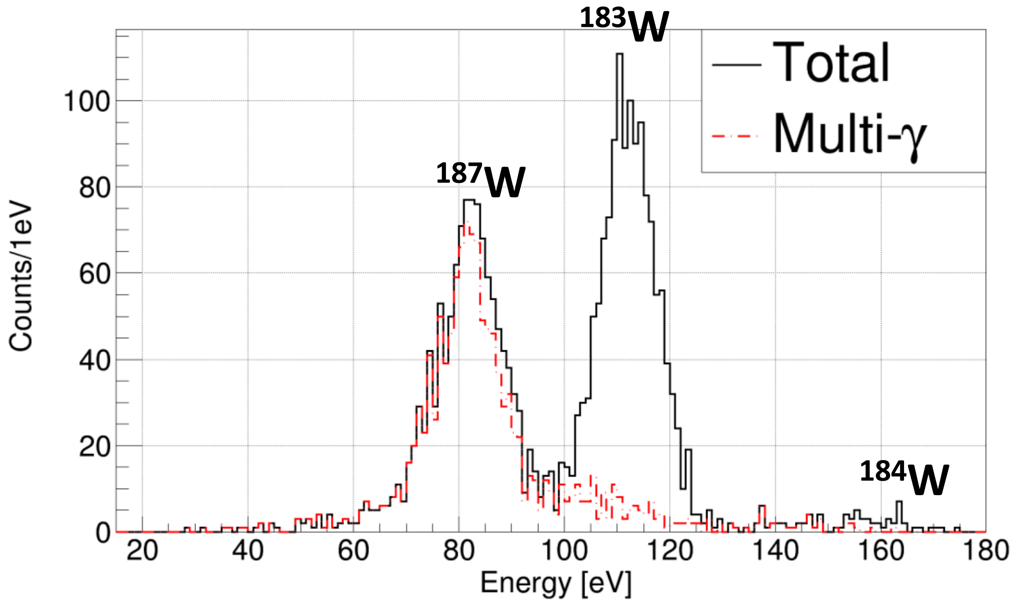


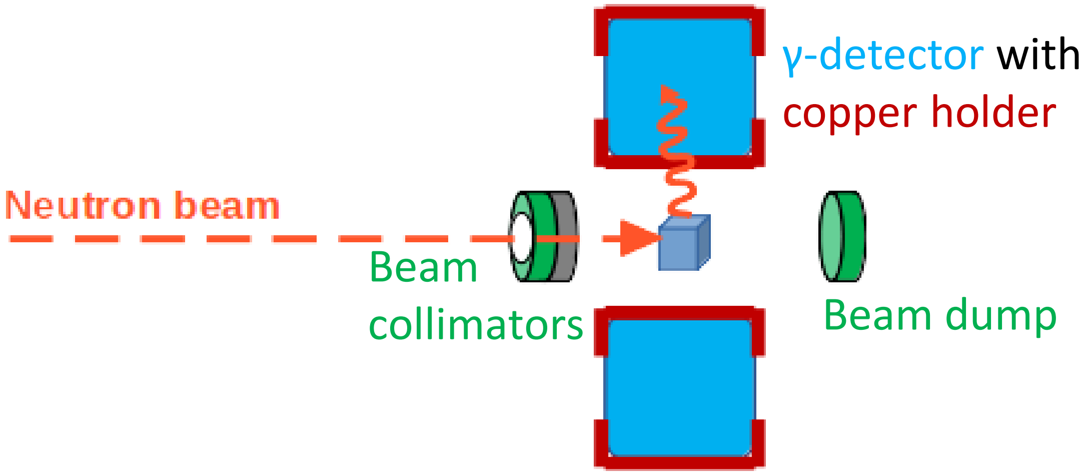
L. Thulliez, D. Lhuillier et al 2021 JINST 16 P07032

Measures in coincidence



$$E_\gamma = 5{,}47 \pm 0{,}2\ MeV$$

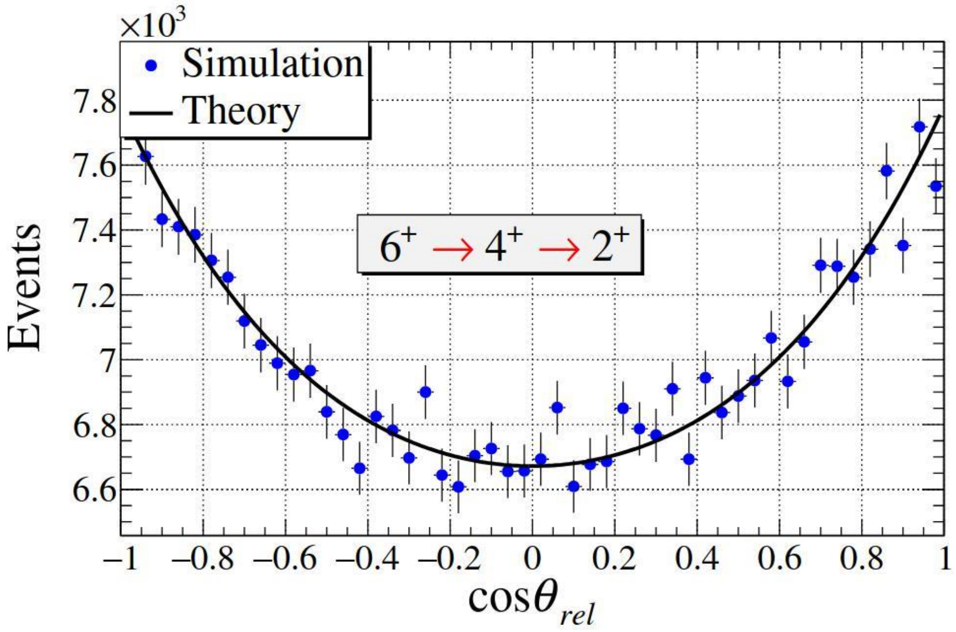




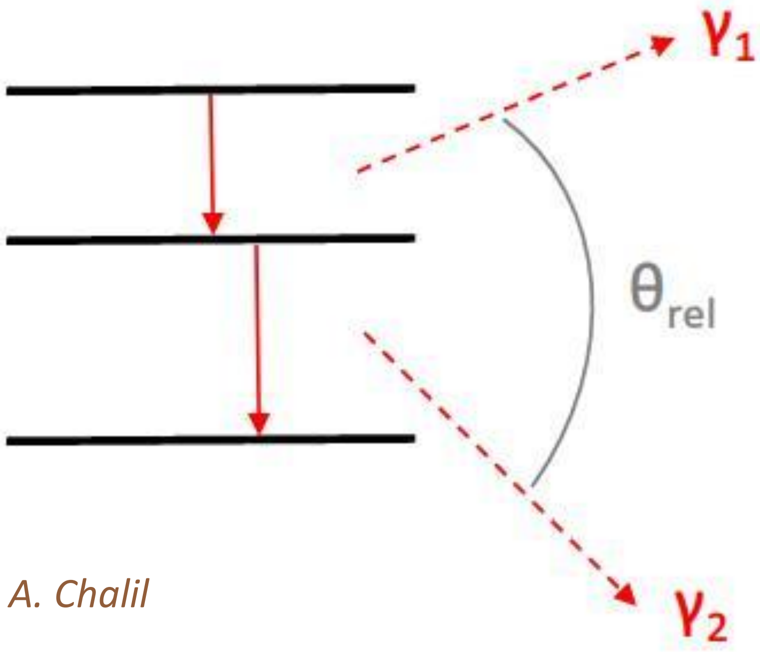
- Measure in coincidence the emitted **γ** and the corresponding nuclear recoil in the bolometer
- Allows to get a third calibration peak @85eV
- Use the two **γ** detectors for triple coincidence **γ-γ-recoil** : access to multi-**γ** transitions (calibration @lower energy)

FIFRELIN developments : angular correlations

- Direction of emission is isotropic for the first **γ**
- But directions are correlated for the following **γ**
- It has been recently implemented in FIFRELIN



A. Chalil et al., arXiv:2110.00619 [nucl-th]
Under review for Eur. Phys. J A



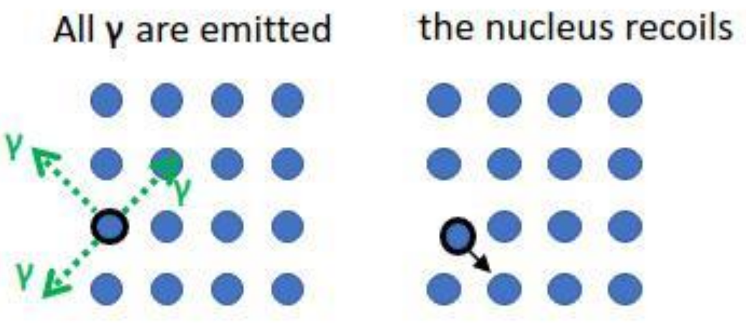
after A. Chalil

FIFRELIN developments : timing

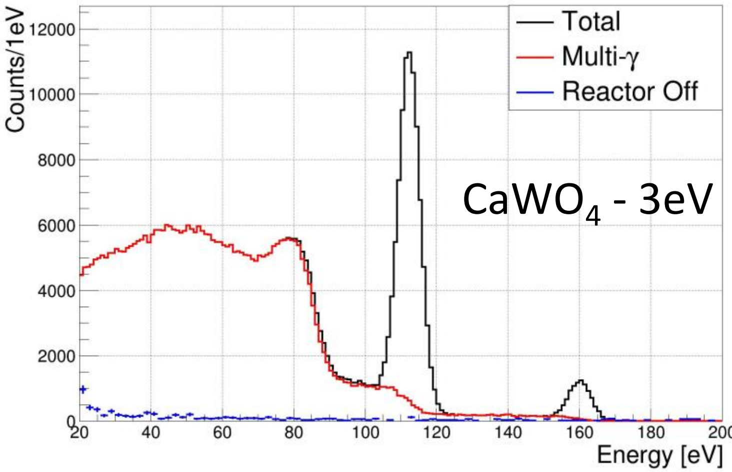
For CRAB, two timing to be compared :

- Emission of the **γs** : $\boldsymbol{\tau_\gamma}$ (FIFRELIN)
- Recoil in the crystal lattice : $\boldsymbol{\tau_{recoil}}$

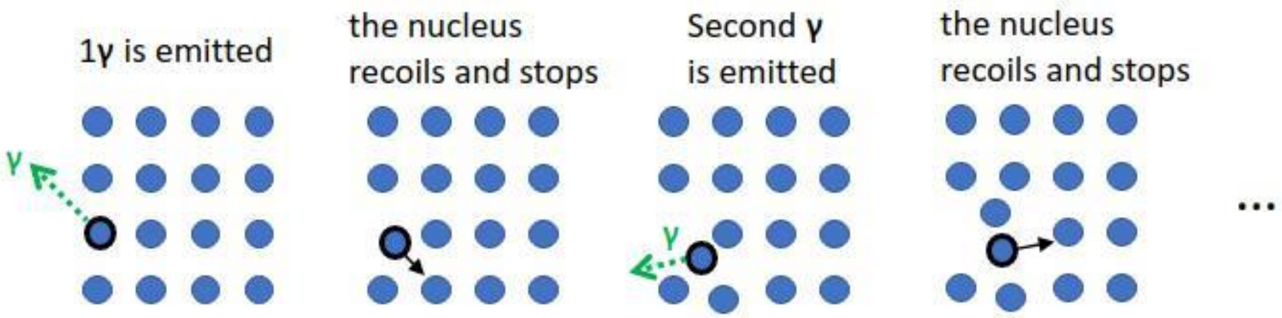
$\tau_\gamma \ll \tau_{recoil}$

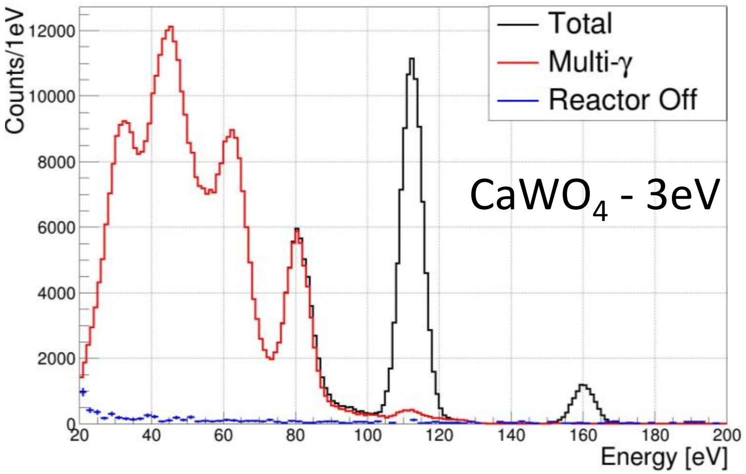


$\vec{p}_{tot} = \sum \vec{p}_{rec\,i}$



$\tau_\gamma \gg \tau_{recoil}$





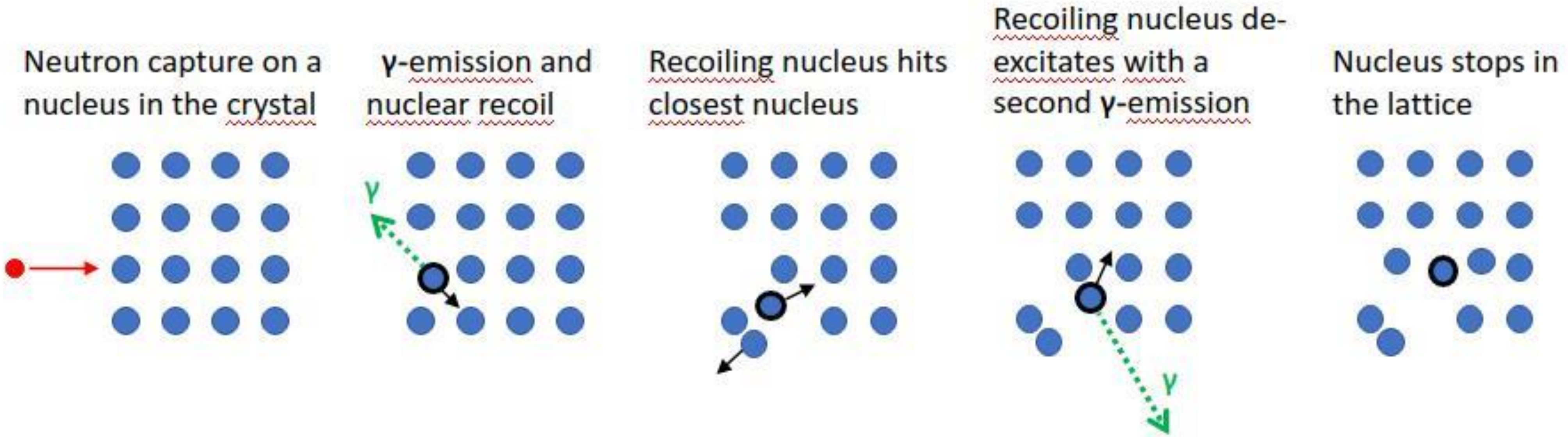
$p^2_{tot} = \sum p^2_{recoil\ i}$

FIFRELIN developments : timing

- Timing changes the energy deposited in the bolometer, but calibration peaks do not move

- Ongoing studies on both timings
  - **τ_γ :** FIFRELIN with models taking collective effects into account (rotational bands)
  - **τ_{recoil} :** Binary Collision Approximation simulations with code IRADINA (C. Borschel, C. Ronning/Nucl. Instrum. Methods B 269 (2011) 2133)

$\tau_\gamma \approx \tau_{recoil}$



Conclusion

- FIFRELIN uses both experimental and theoretical data to precisely predict de-excitation of nuclei after thermal neutron capture
  - Effort to incorporate more evaluated databases (updated RIPL3, EGAF, …)
  - Angular correlations
  - Timing of cascades

- A useful tool for the community : a lot of possible applications
  - neutrino detection
  - Bolometers
  - ...

- Not open source (code CEA), but possible to get cascade samples

(already avalaible online for Gd : https://zenodo.org/record/3384633#.YaSr8rvjKAk)