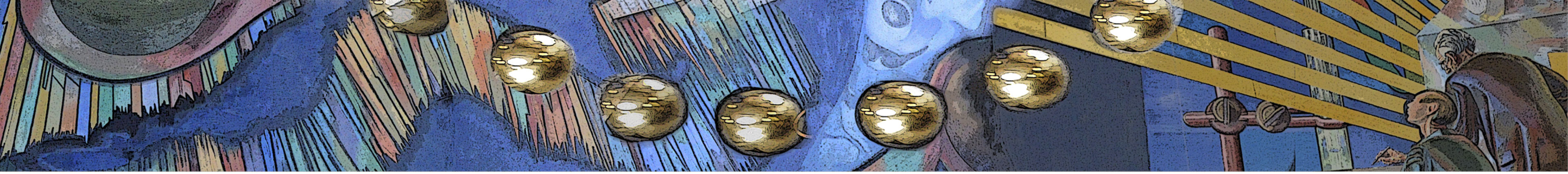


UiO : Department of Physics
University of Oslo

V. W. Ingeberg

Inverse-Oslo Method

A tool for expanding our understanding of the r-process

Outline

- Motivation
- What is the Oslo Method?
- Why Oslo Method with inverse kinematics
- Results

The neutron-capture process (s-/r-process)

- Responsible for most nuclei heavier than iron[1]
- Known to happen in kilonovas following neutron star mergers[2]
- Abundance calc. needs accurate nuclear input
  - Neutron capture rates
  - Decay rates, masses, etc.
- Alternative to surrogate & nTOF

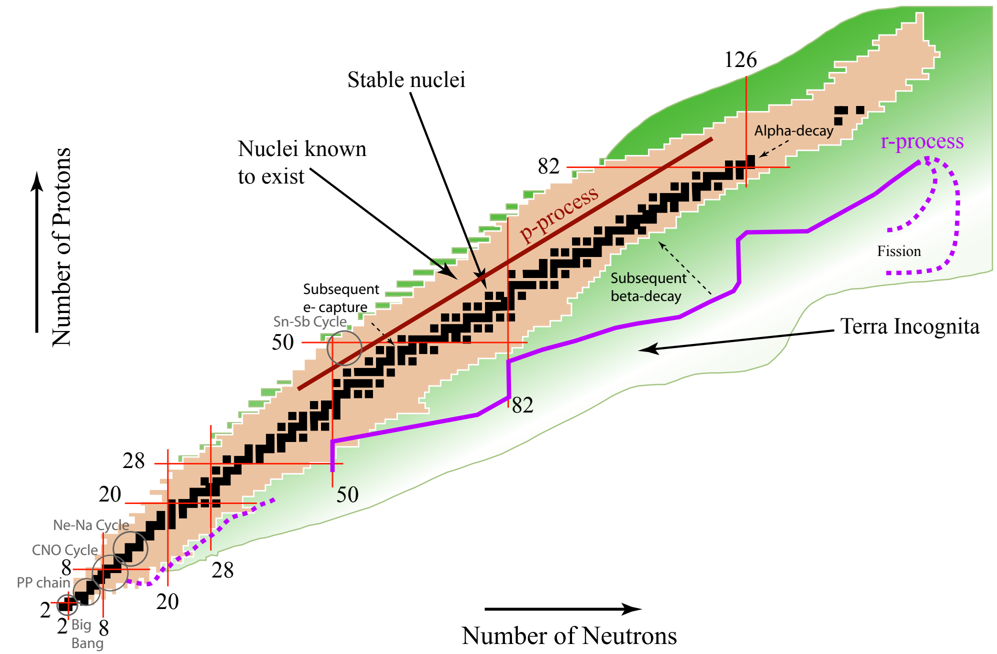
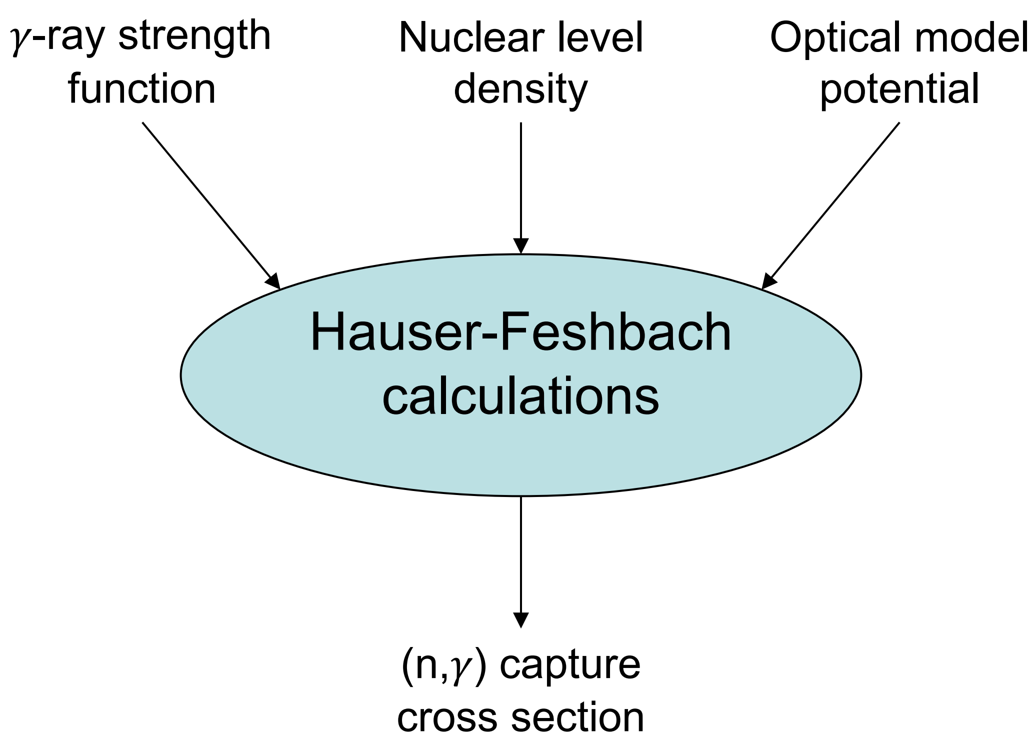


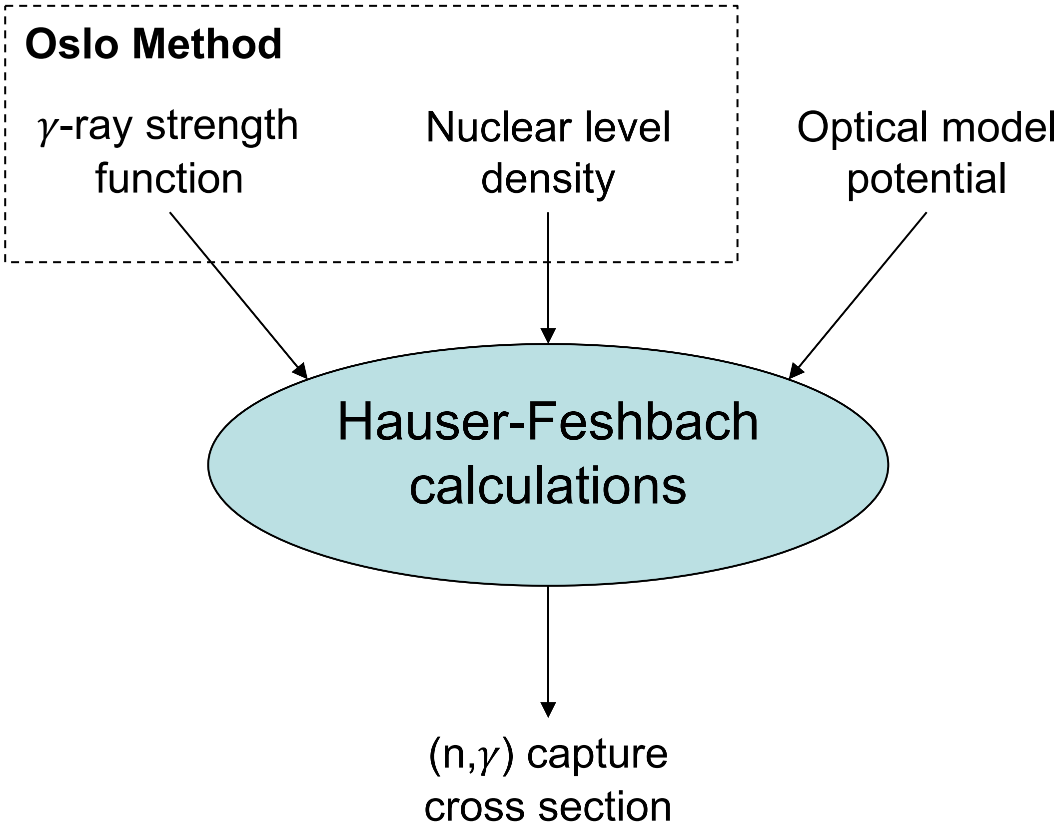
Figure credit: F. Timmes, http://cococubed.asu.edu/images/nuclide_chart/table_nuclei04.pdf

[1] M. Arnould, S. Goriely and K. Takahashi, Phys. Rep. **450**, 97-213 (2007)
[2] D. Kasen *et al.*, Nature **551**, 80-84 (2017)

Neutron capture

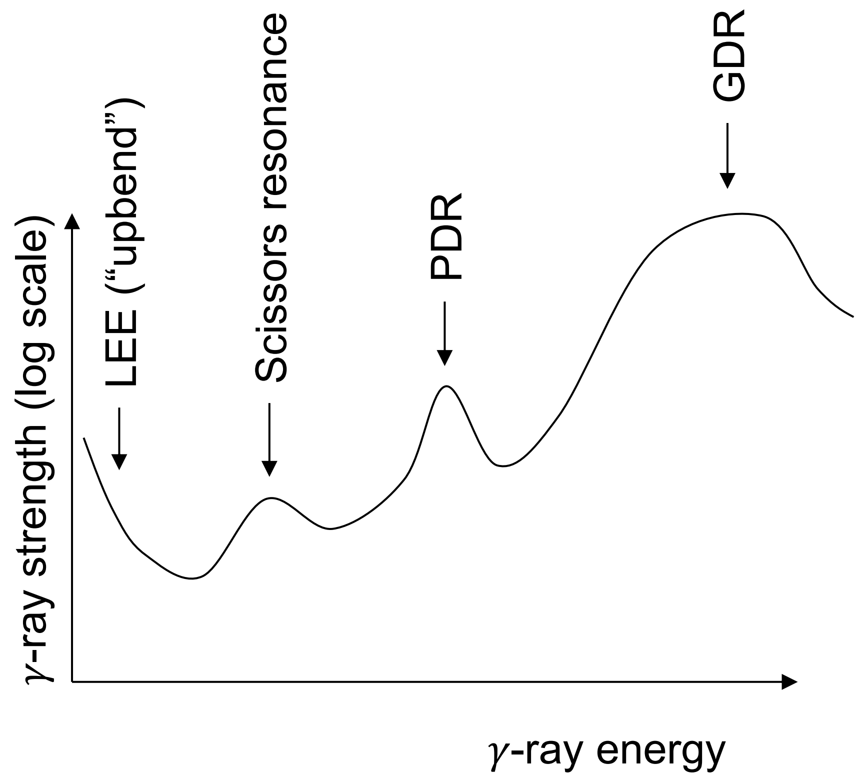


Neutron capture



γ-ray Strength Function

- Measure of the electromagnetic interaction of a nucleus
- Dominated by the E1 giant resonance (GDR)
- Low energy enhancement "upbend" (LEE)
- Scissors resonance
- Pygmy dipole resonance (PDR)



Effect of LEE on neutron capture

- Origin of LEE still not well understood
- The LEE can have a huge impact on (n,γ) cross section
- Experimental data is needed to refine theoretical models

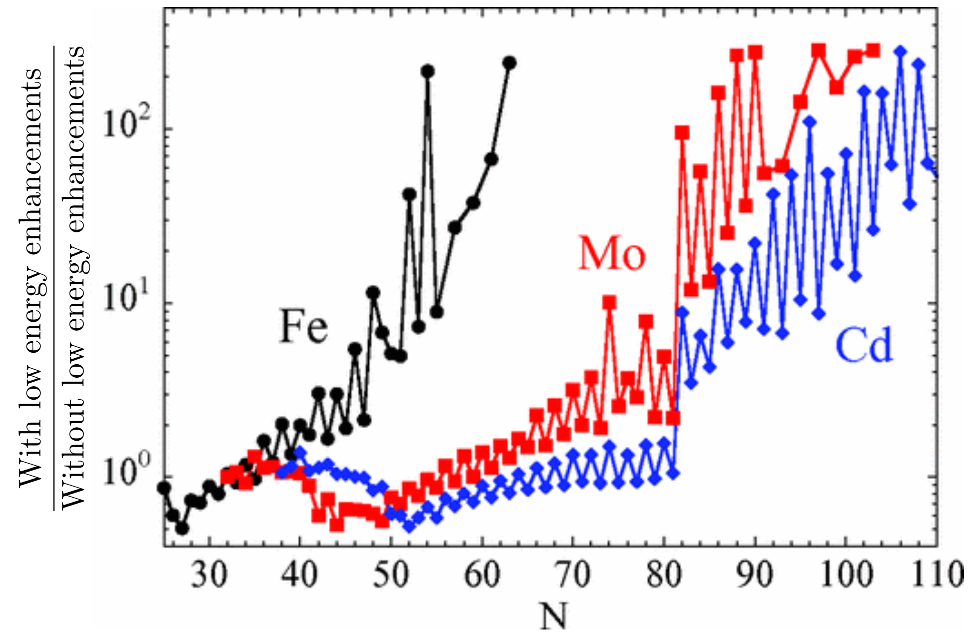
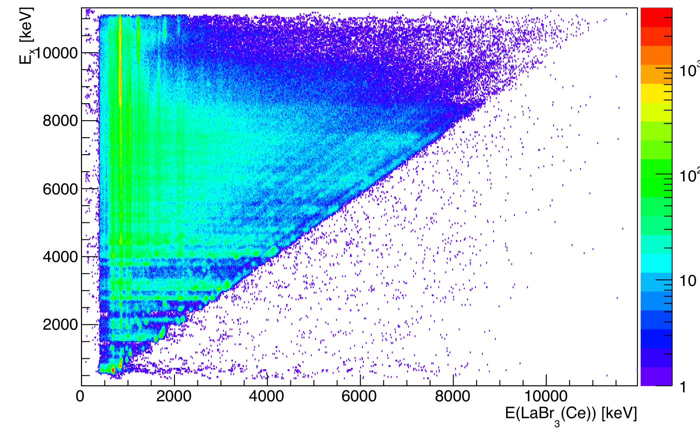


Figure credit: A. C. Larsen and S. Goriely, Phys. Rev. C **82**, 014318 (2010)

The Oslo Method

- Simultaneous measurement of
  - γ-ray strength function (γSF)
  - Nuclear Level Density (NLD)
- Relies on experimental E_γ vs E_x matrices from the quasi-continuum



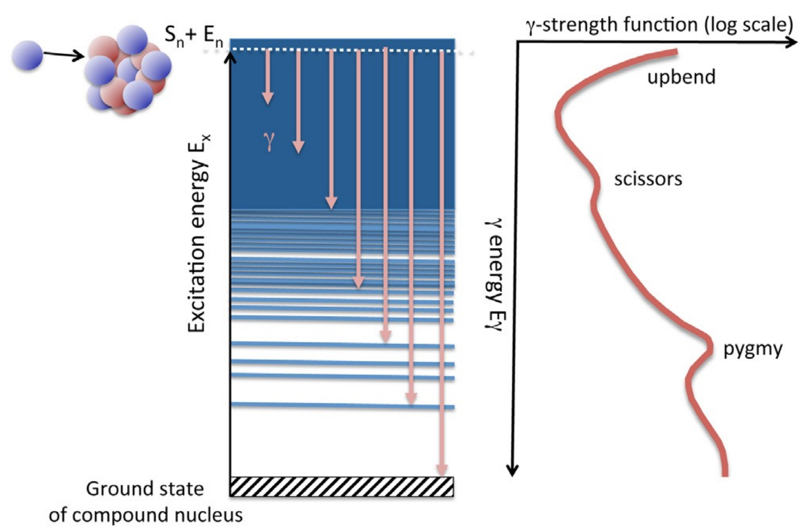
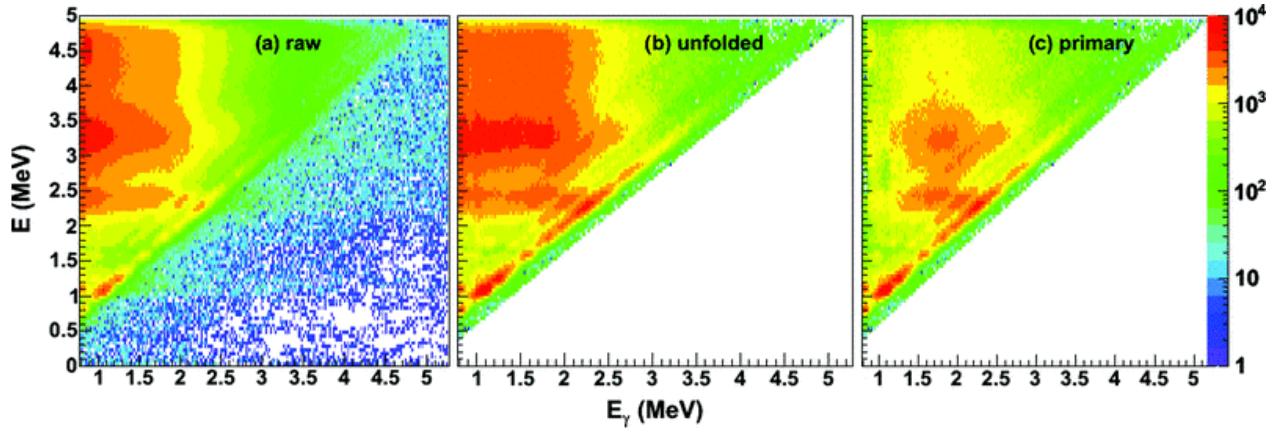


Figure credit: A. C. Larsen, A. Spyrou S. N. Liddick and M. Guttormsen, Prog. In Part. And Nucl. Phys. **107**, 69-108 (2019)

Oslo Method – In practice



1. Unfold with detector response
2. First generation method
3. Extract functional form of NLD & γSF

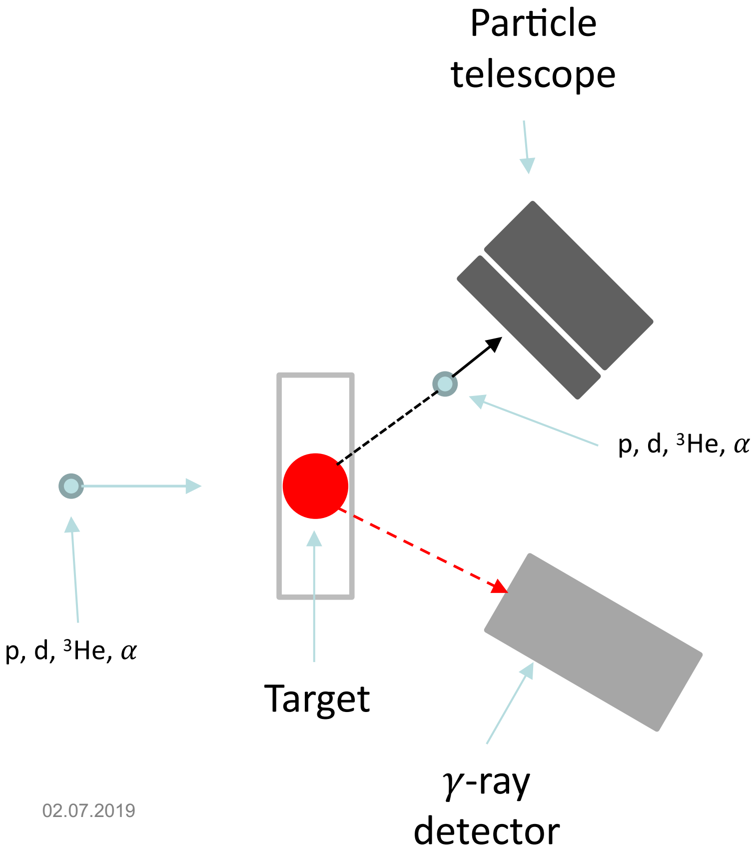
$$\tilde{\rho} = A\rho e^{\alpha E_x}$$

$$\tilde{\mathcal{T}} = B\mathcal{T}e^{\alpha E_\gamma}$$

- Transformation parameters A, B and α has to be determined
- Comparison to nuclear parameters
  – Experimental
  – Systematical

Figure credit: M. Guttormsen *et al.*, Phys. Rev. C **88**, 024307 (2013)

The Oslo Method – In practice



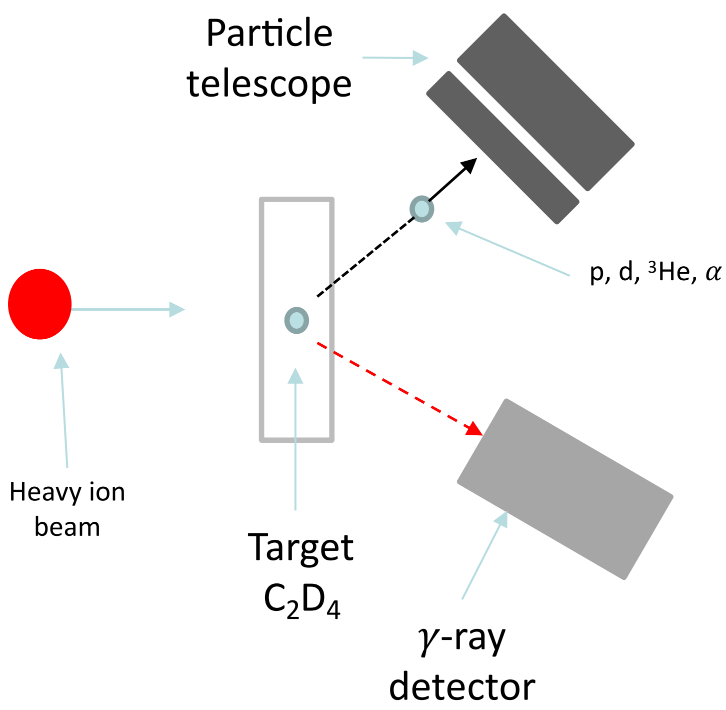
Typical experiments:

- Particle-γ coincidences
  - Light ion beam
  - (p,p'), (d,p), (^{3}He,α), etc.
  - Typical beam energy 12-34 MeV
  - Stable targets

To reach neutron rich:

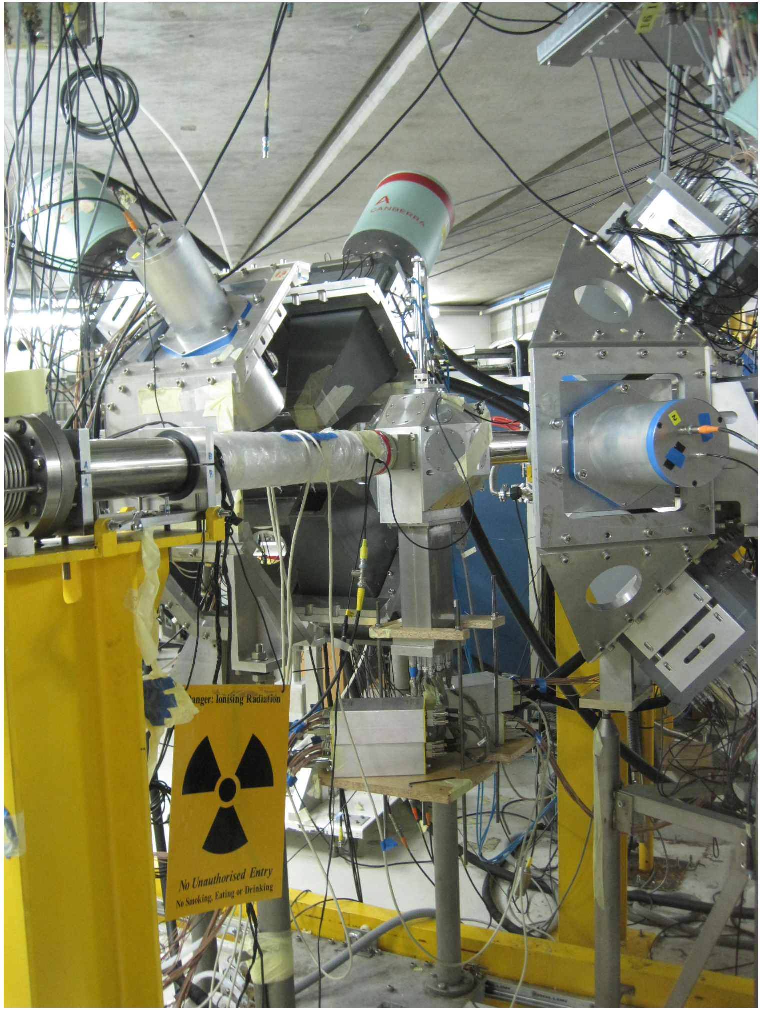
- β-Oslo
- **Inverse kinematics**

Oslo Method in inverse kinematics



- Interchange target & beam
- Deuterated plastic targets
- Radioactive beams, noble gases, alkali's, etc.
- Complements traditional Oslo Method and β-Oslo
- Doppler shift

Inverse-Oslo experiments



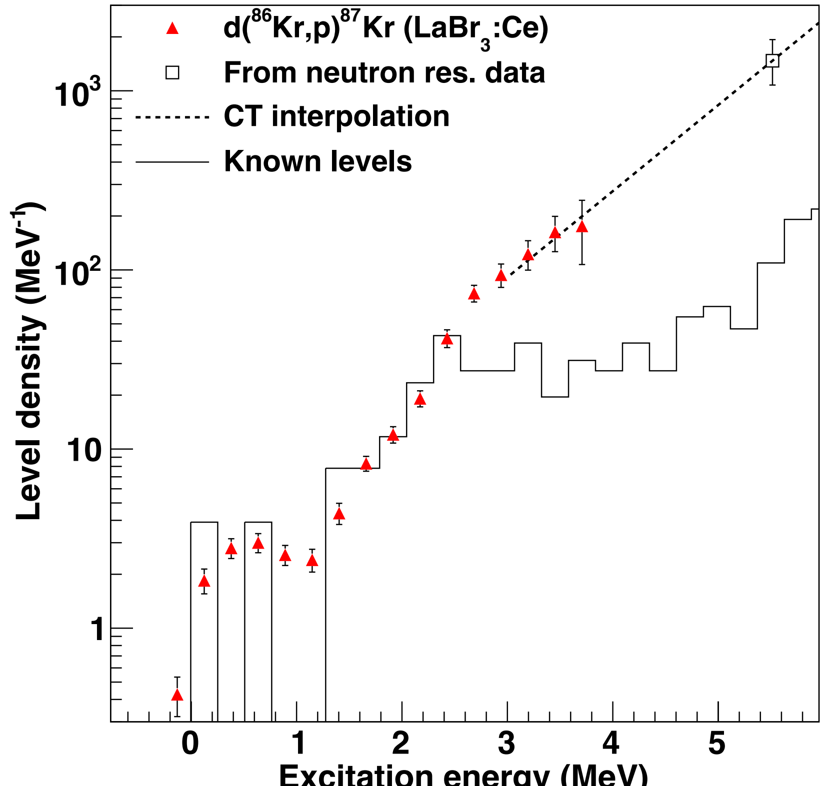
Completed experiments

- d(^{86}Kr, p)^{87}Kr – iThemba LABS
  - April/May 2015
  - Analysis finished
- d(^{84}Kr,p)^{85}Kr – iThemba LABS
  - November/December 2017
  - Analysis on-going
- d(^{132}Xe,p)^{133}Xe – iThemba LABS
  - November/December 2017
  - Analysis on-going
- **d(^{66}Ni,p)^{67}Ni – CERN ISOLDE**
  - November 2016
  - First inverse-Oslo with radioactive beam!
  - Analysis on-going

Proof-of-principle – ^{87}Kr

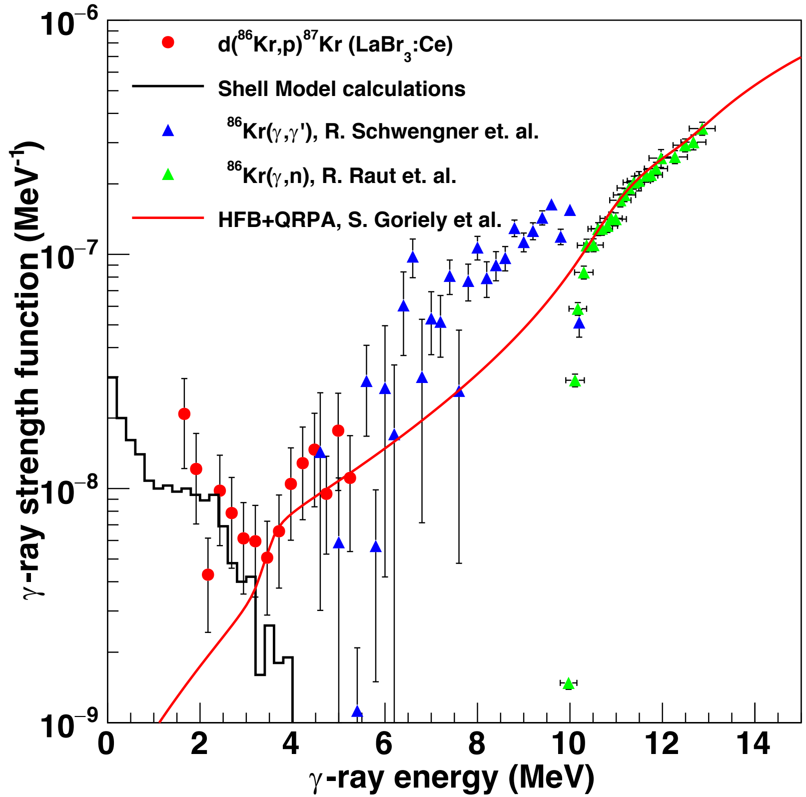
- 300 MeV ^{86}Kr beam
- d(^{86}Kr,p)^{87}Kr
- AFRODITE + 2 $LaBr_3$:Ce (3.5x8”)

^{87}Kr – Nuclear level density



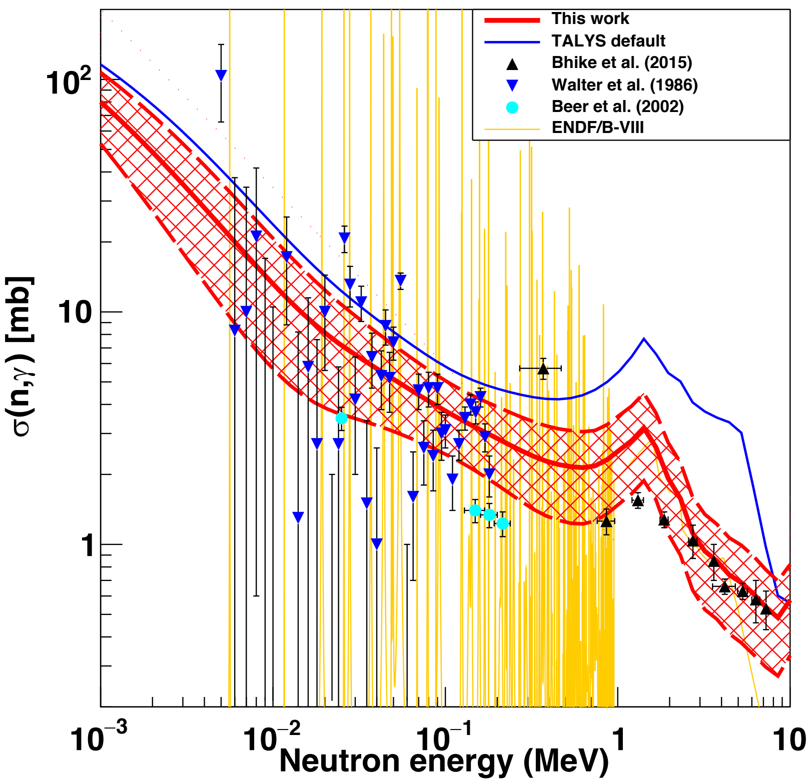
V. W. Ingeberg *et al.*, Submitted

^{87}Kr - γ-ray Strength Function



V. W. Ingeberg *et al.*, Submitted

87Kr – (n,γ) cross section

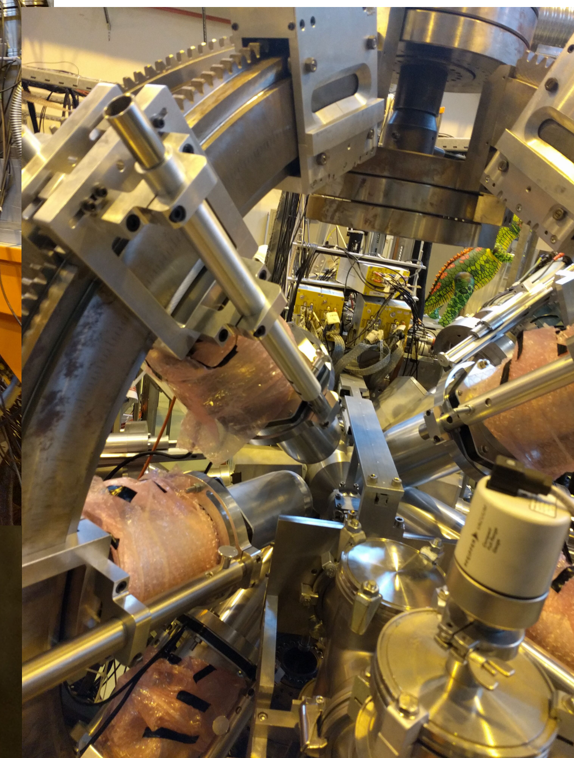


V. W. Ingeberg *et al.*, Submitted

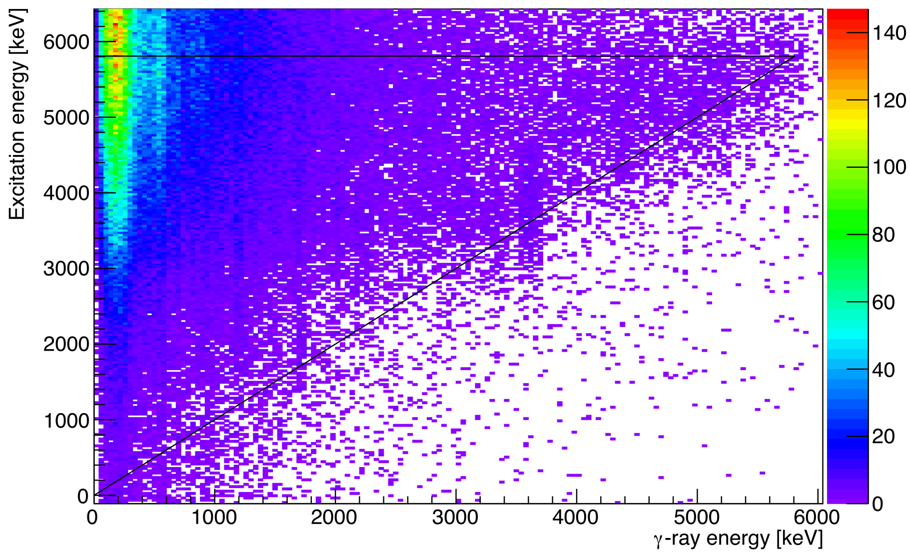
HIE-ISOLDE

- ^{66}Ni beam @ 4.5 MeV/u
- ≈11 pA for ~ 140 hours
- 669 μg/cm^2 C_2D_4 target

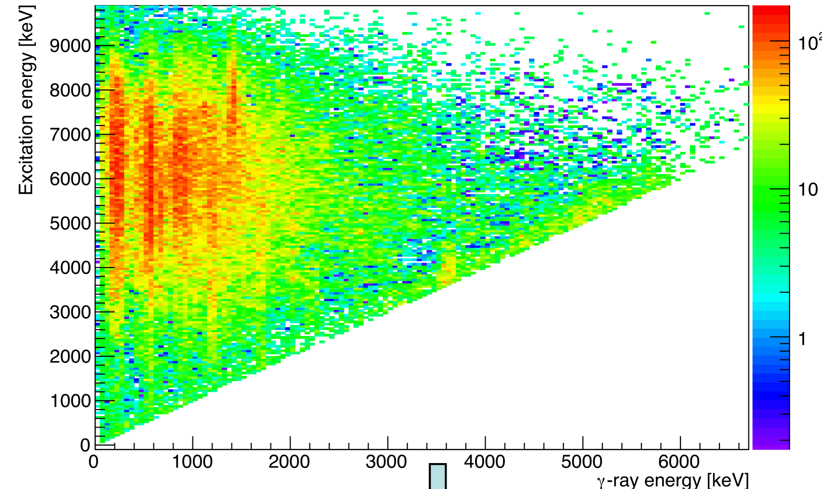
- Six Miniball clusters
- Six large volume (3.5x8”) LaBr3:Ce detectors
- C-REX particle array
- Look for particle-γ coincidences



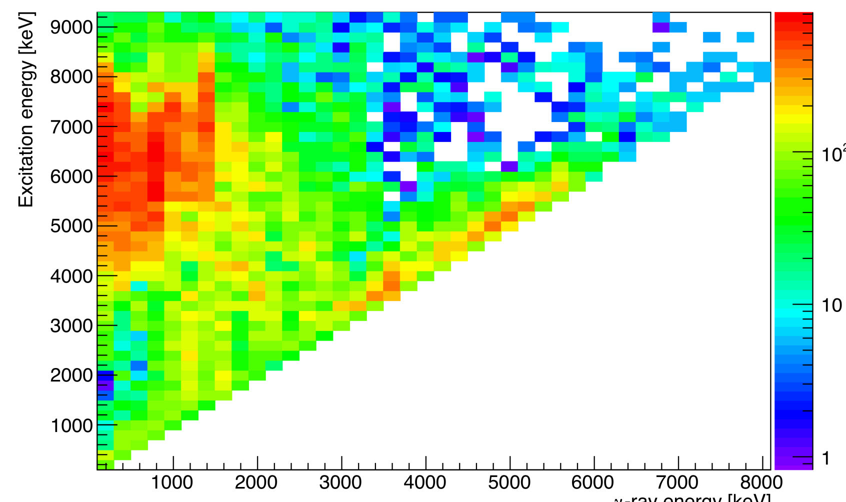
Results



Unfold



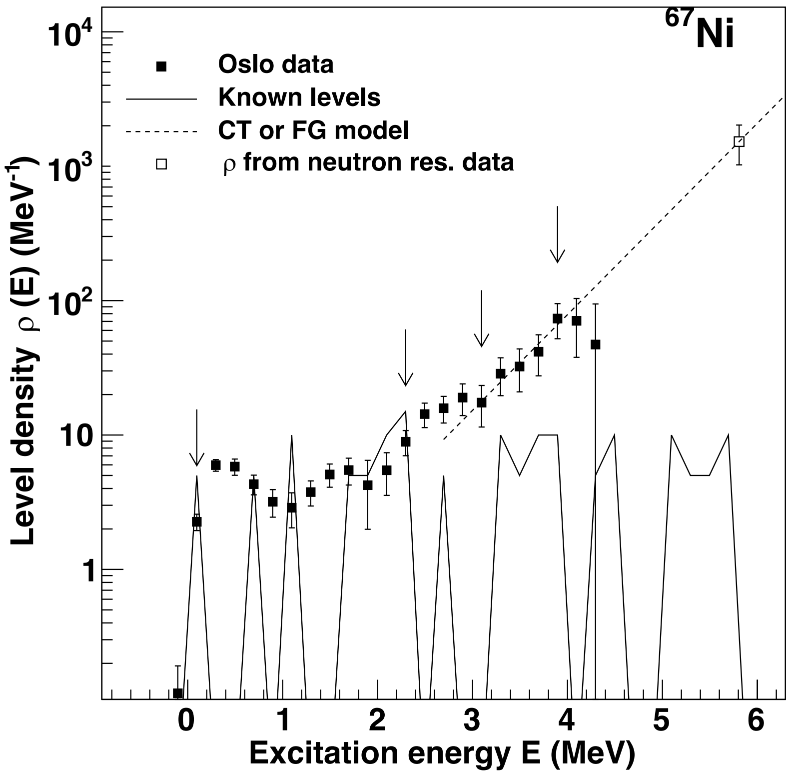
First generation

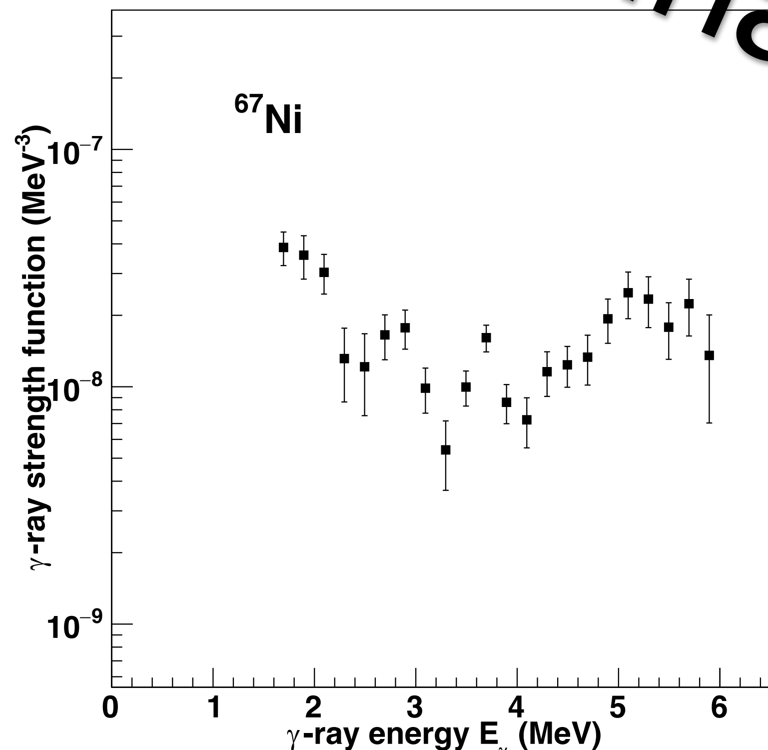


Preliminary!

Preliminary!

Results





Summary

- The inverse-Oslo Method
  - An indirect route to determine (n,γ) cross section
  - Allows measurements on nuclei with challenging chemical properties
  - Bridges the gap between traditional Oslo Method and the β-Oslo method

Thank you for listening!

ISOLDE experiment IS559

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Acknowledgement

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University of Oslo

NRF
National Research Foundation
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1999-2019

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Laboratory for Accelerator Based Sciences

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With funding from
The Research Council of Norway