UNIVERSITY OF OSLO

The Oslo Method at HIE-ISOLDE

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Outline

The Oslo Method and the Nuclear Level Density (NLD) and γ-ray Strength Function (γSF)

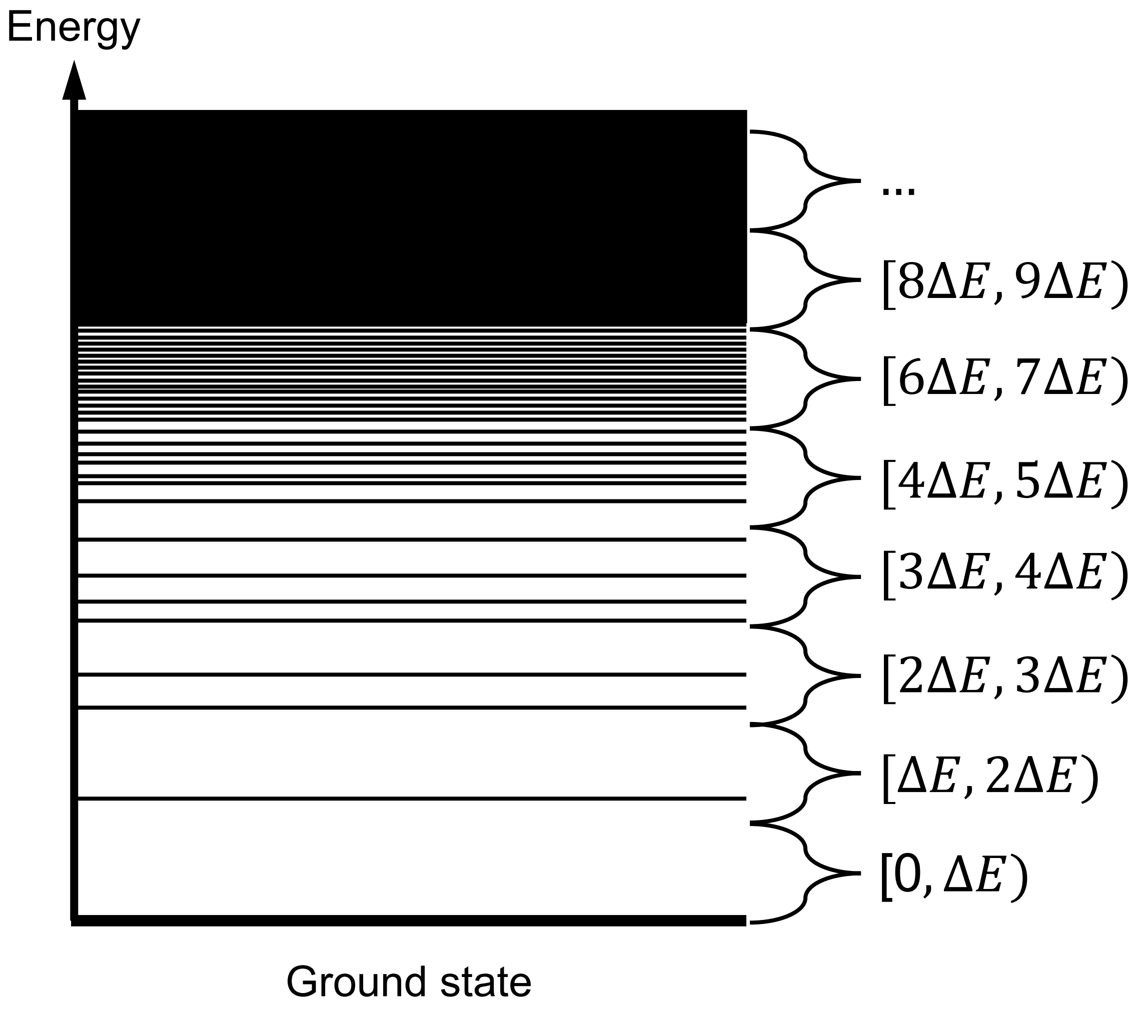
The Oslo Method in inverse kinematics

IS559 – $d(^{66}Ni, p)^{67}Ni$: Results

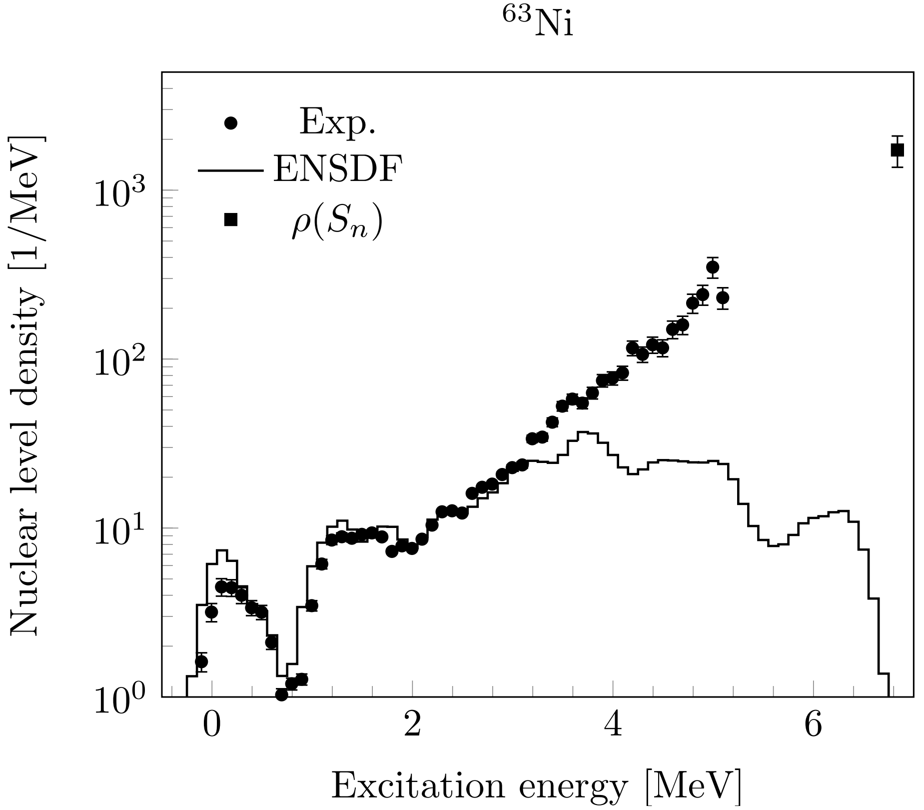
Future plans for Oslo Method experiments at HIE-ISOLDE

Preliminary results from experiment IS558

Nuclear Level Density

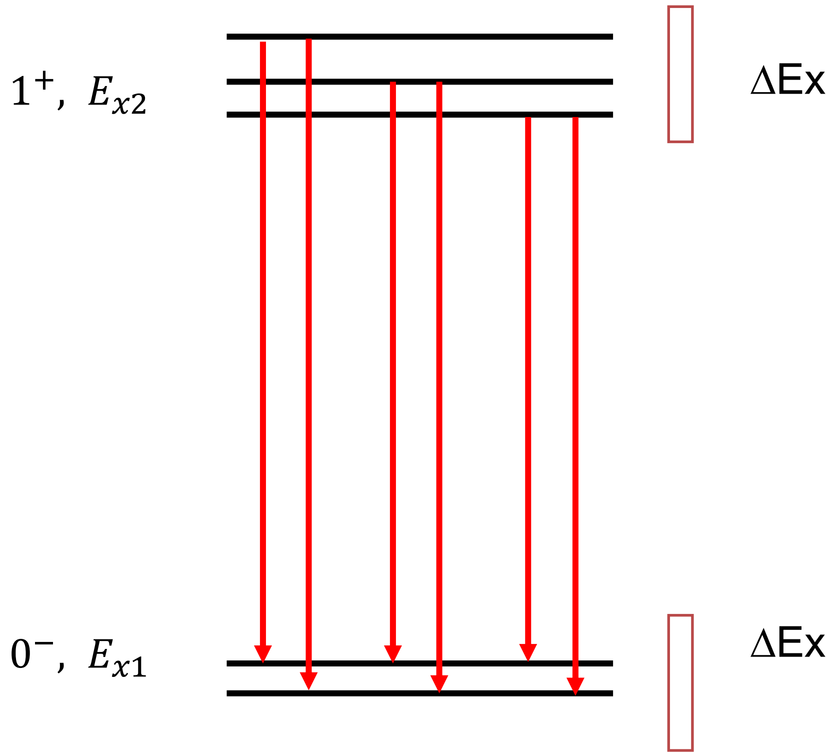


$$\rho(E, J, \pi) = \frac{\Delta N(E, J, \pi)}{\Delta E}$$



V. W. Ingeberg *et al.*, Phys Rev. C **106**, 054315 (2022)

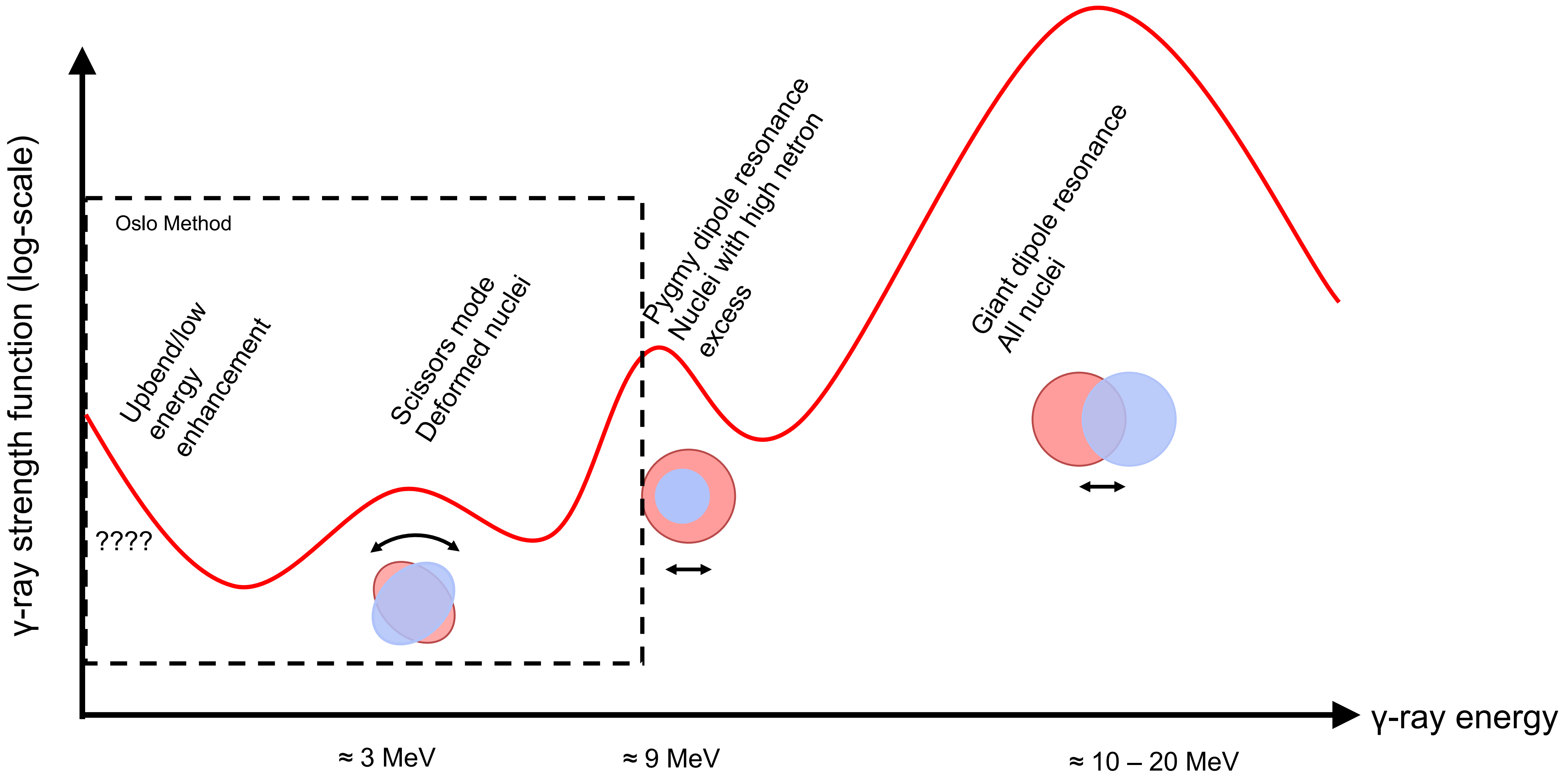
γ-ray strength function



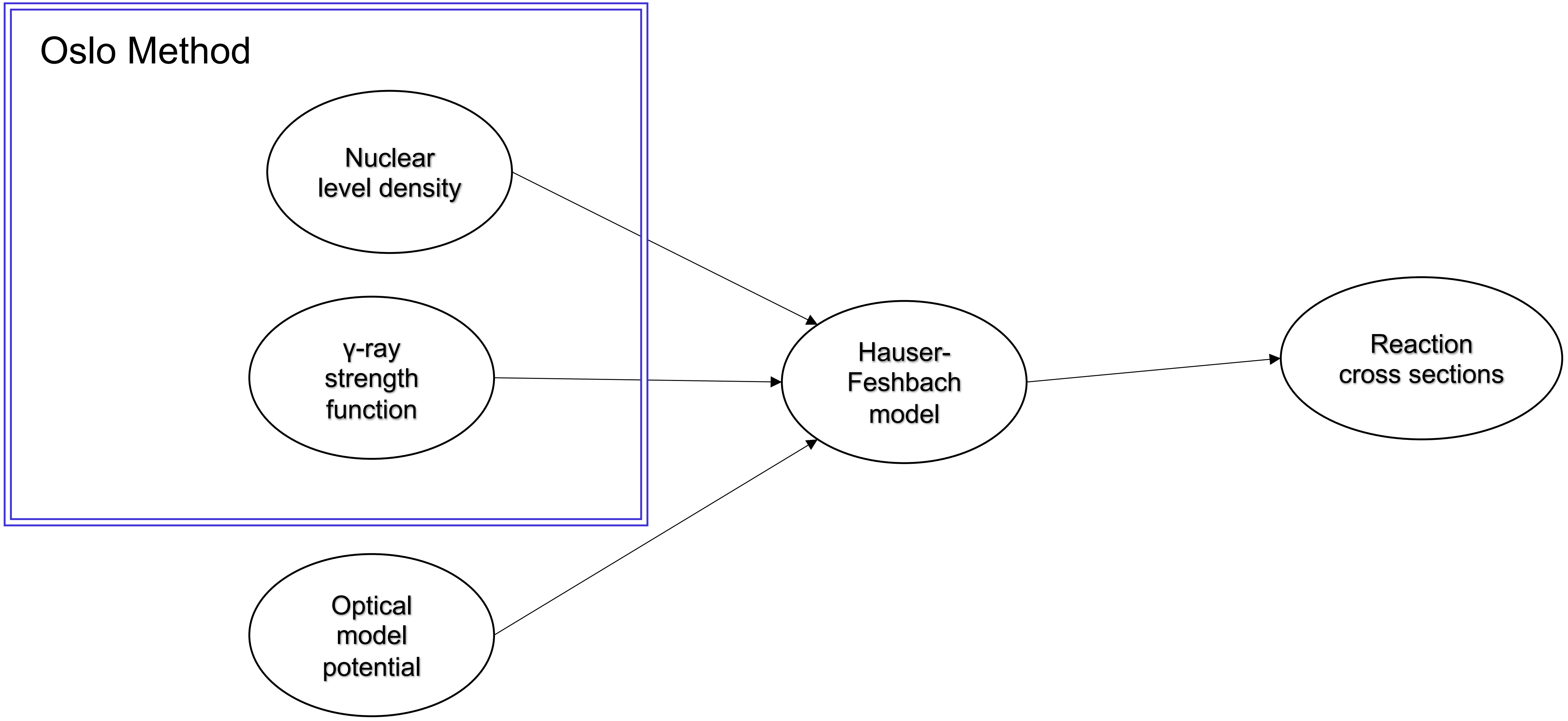
$$f_{XL}(E_\gamma, E_i, J_i, \pi_i) = \frac{\langle \Gamma_\gamma^{XL} \rangle (E_\gamma, E_i, J_i, \pi_i)}{E_\gamma^{2L+1}} \rho(E_i, J_i, \pi_i)$$

- $\langle \Gamma_\gamma^{XL} \rangle (E_\gamma, E_i, J_i, \pi_i)$: Average decay width with γ-ray energy E_γ from excitation bin with energy E_i, spin J_i and parity π_i
- $\rho(E_i, J_i, \pi_i)$: Level density
- X: Electric/magnetic
- L: Multipolarity, L=1,2,3,...
- In general: L=1 will dominate
- Upwards strength or downwards strength (excitation/de-excitation)

γ-ray strength function



Hauser-Feshbach calculations



Nucleosynthesis

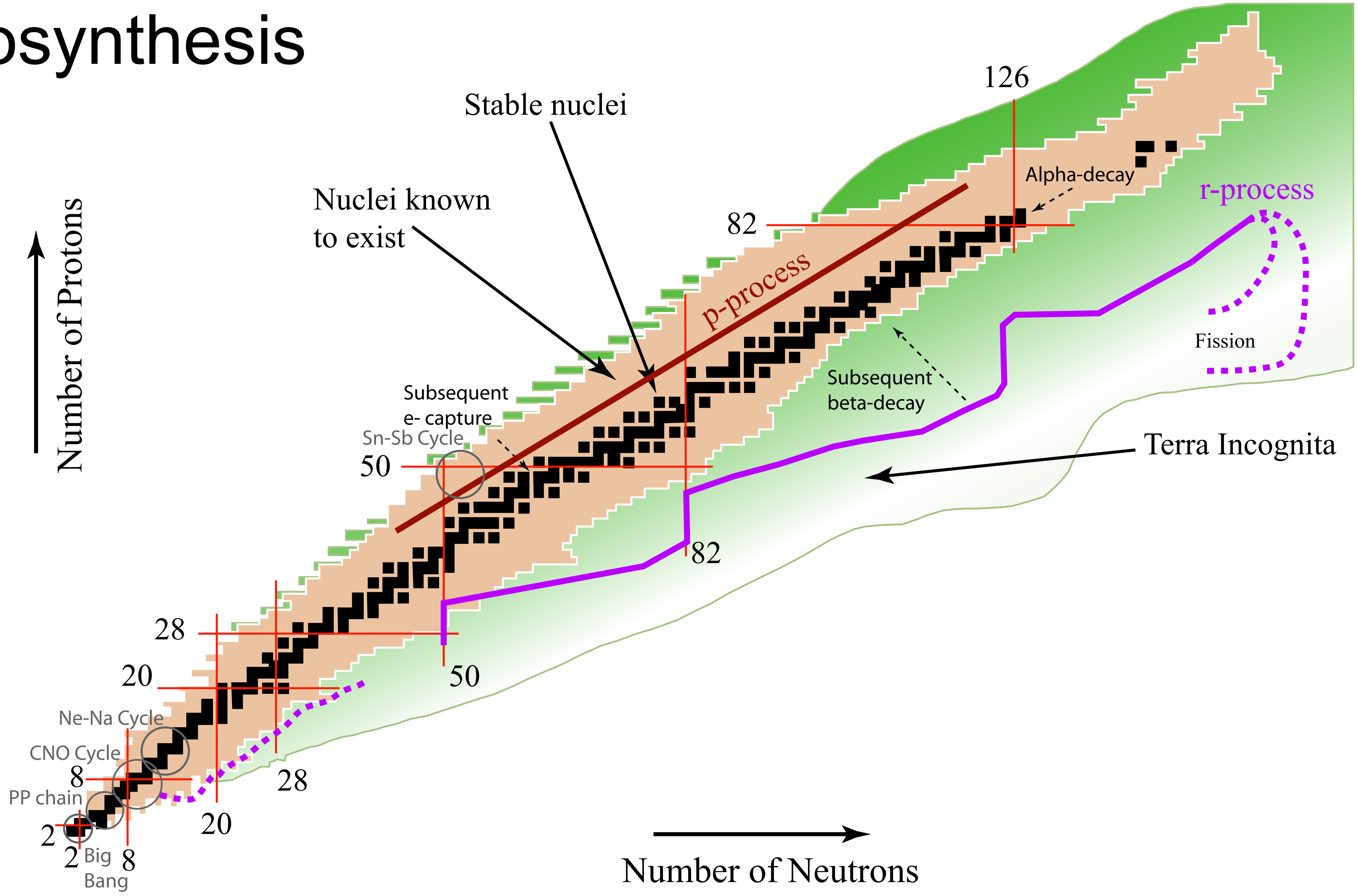


Figure credit: F. Timmes, http://cococubed.asu.edu/images/nuclide_chart/table_nuclei04.pdf

Nucleosynthesis

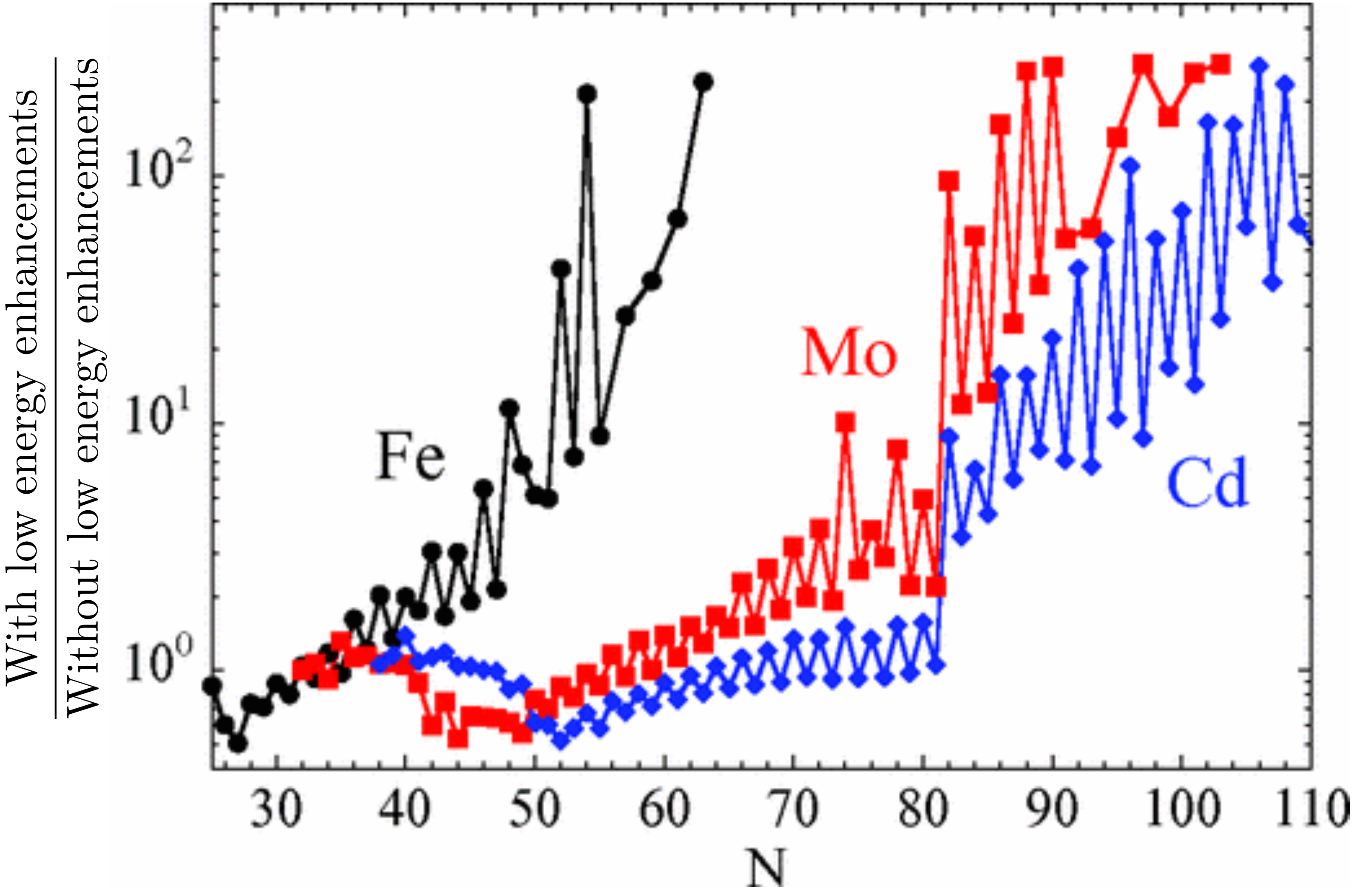
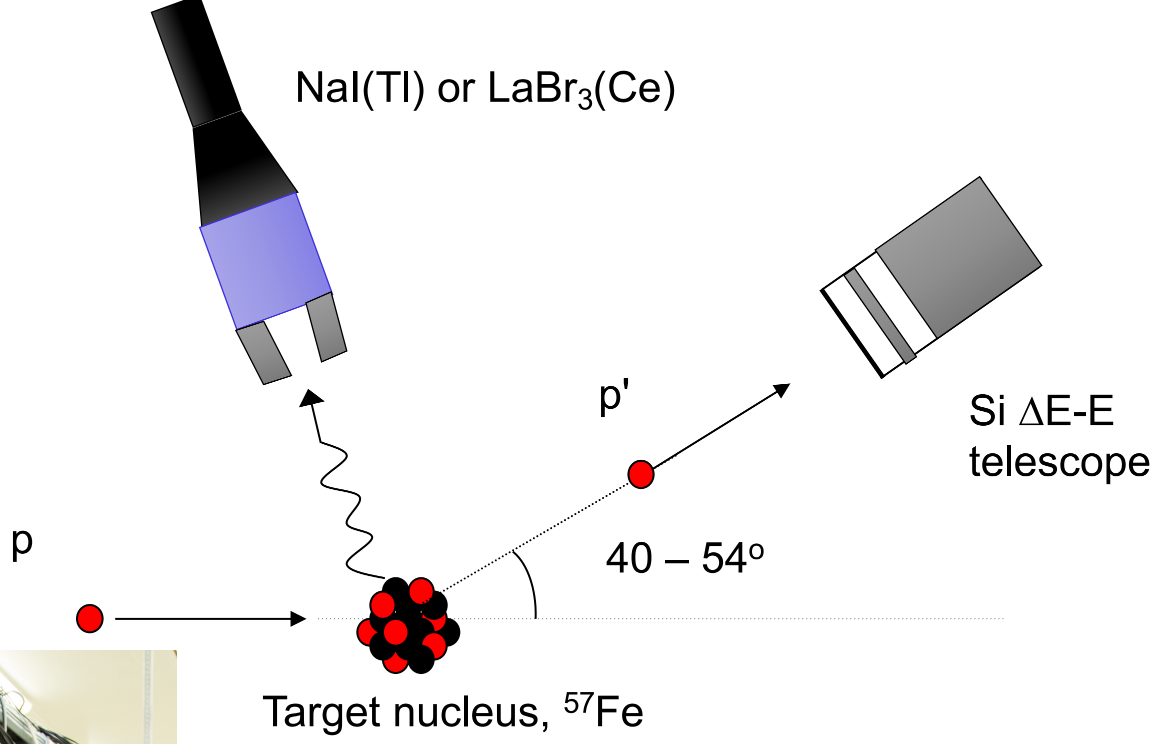
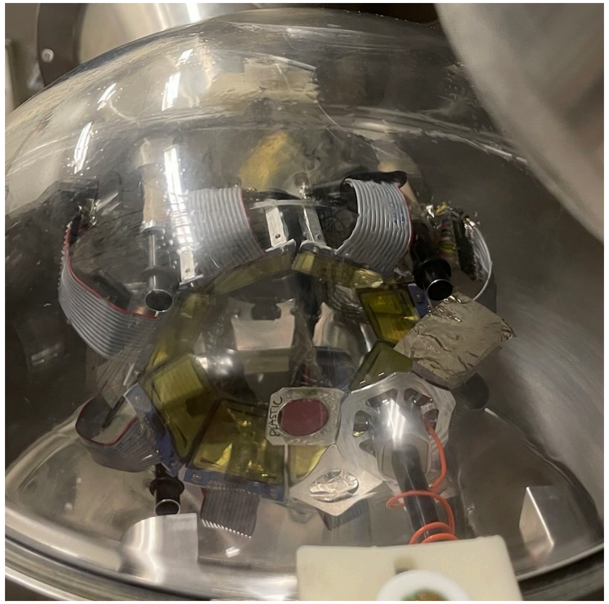


Figure credit: A. C. Larsen and S. Goriely, Phys. Rev. C **82**, 014318 (2010)

Oslo Method Experiment

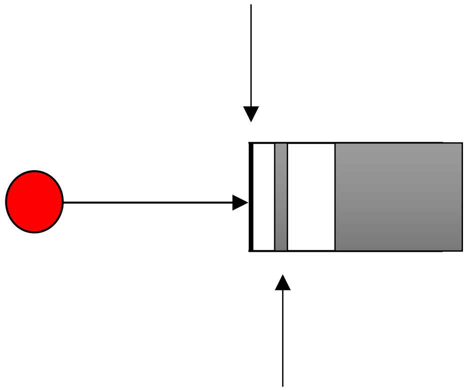
- Typical reactions
  - (p,p’), (d,p), (p,d), (α, p), (α, α’), (^{3}He, α), etc.
- Particle–γ coincidences
- Excitation energy found from kinematic reconstruction





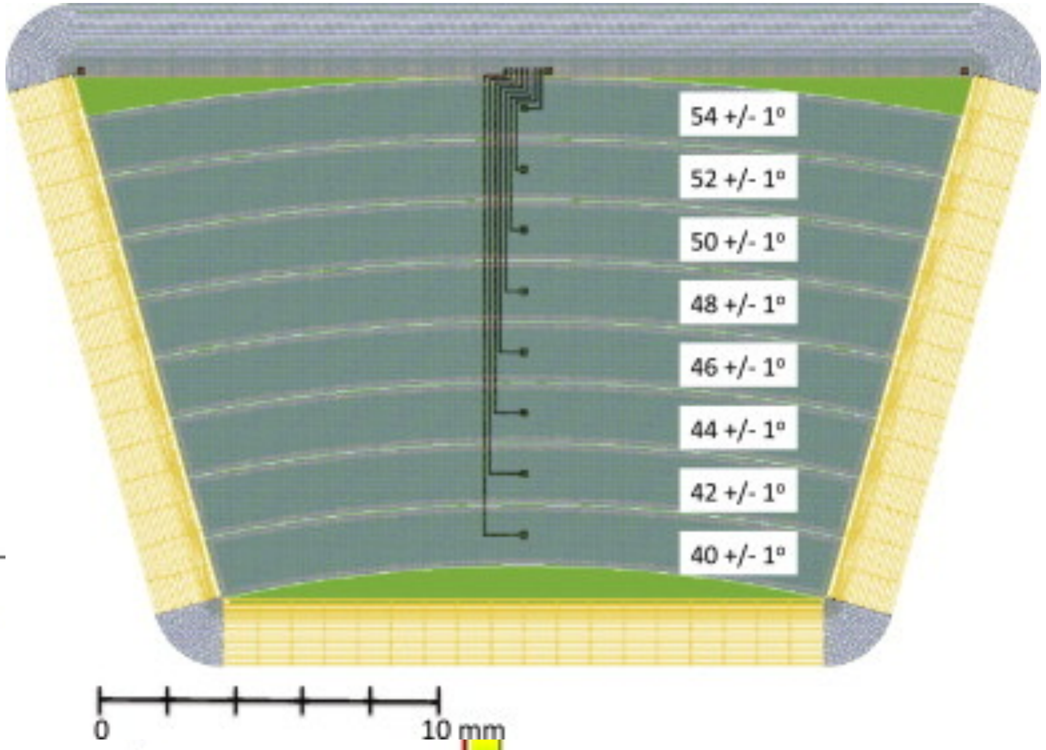
Oslo Method Experiment

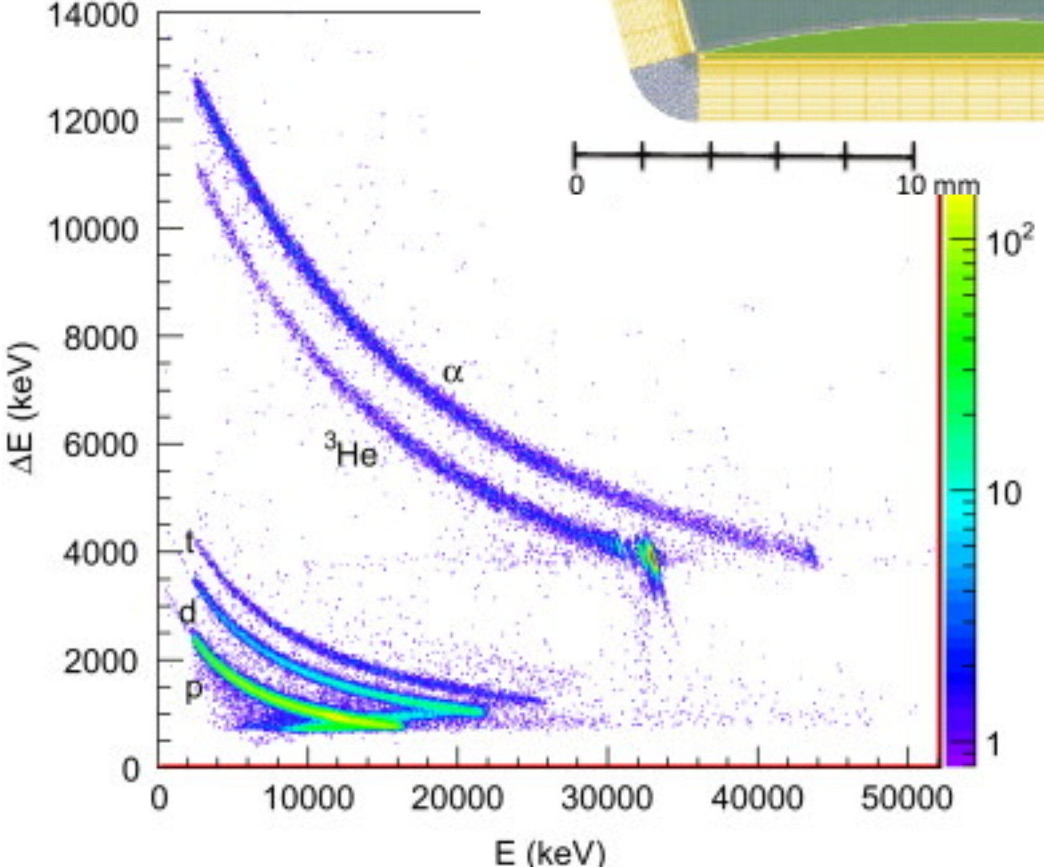
Absorber (Aluminum foil) 10 um
to shield from electrons



E silicon detector 1.55 mm
(single segments)

DE silicon detector 130 um
(eight segments)





We know:
1) Beam particle and energy
2) Target nucleus
3) Scattered particle, scattering angle and energy

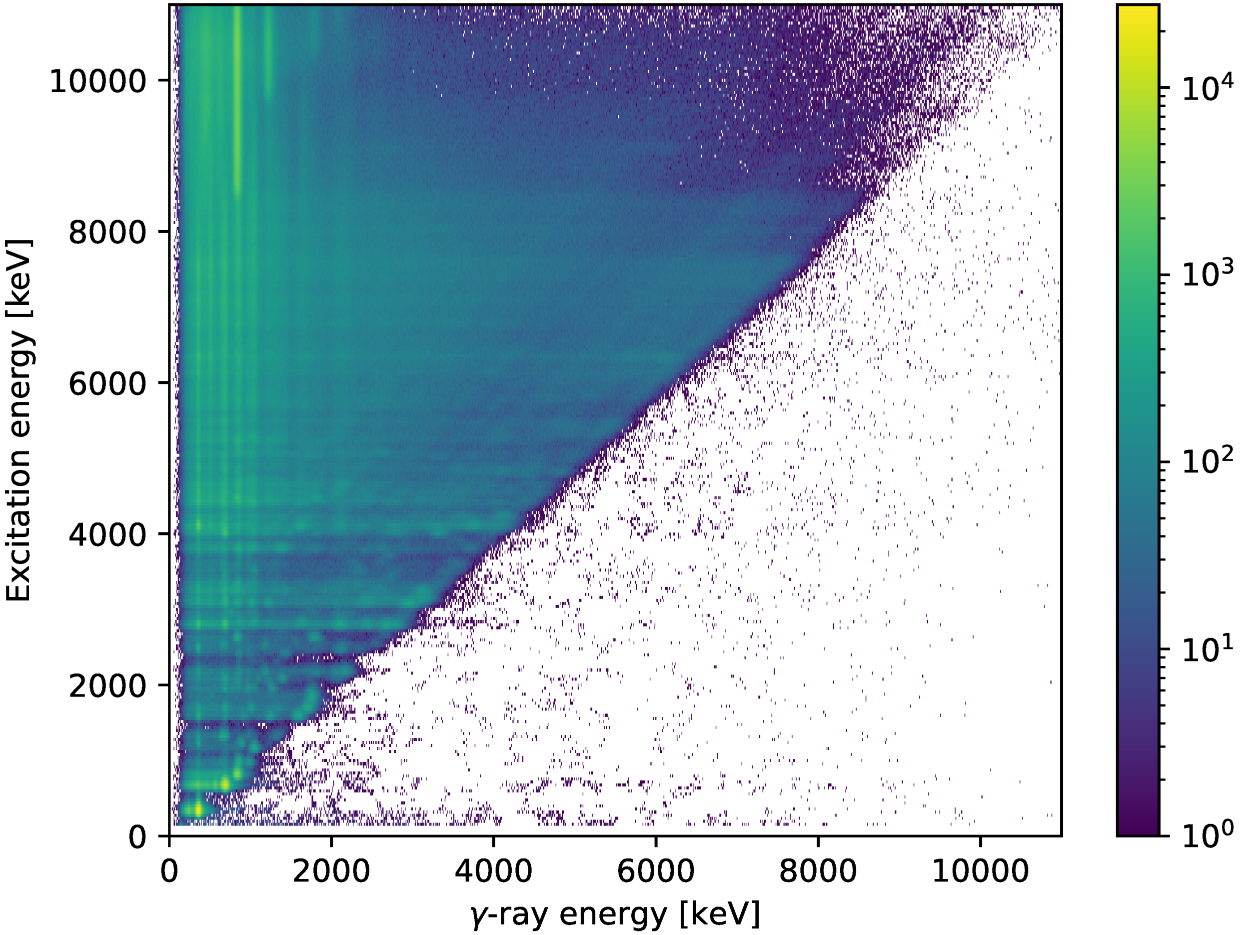
Can determine initial energy of excited nucleus!

M. Guttormsen *et al.*, Nucl. Instr. Methods A **648**,168 (2011)

The Oslo Method

- To extract NLD and γSF: Need the ***first-generation matrix***
  - Each excitation energy bin contains the distribution of the first gamma-ray emitted in cascades de-populating the bin
- Starting point for the Oslo Method: Raw excitation energy versus gamma-ray energy matrix
- 4 steps to get to the NLD and γSF:
  1. Unfolding Method
  2. First Generation Method
  3. Extraction of NLD and γSF from first-generation matrix
  4. Normalization

Raw excitation energy versus γ-ray energy matrix

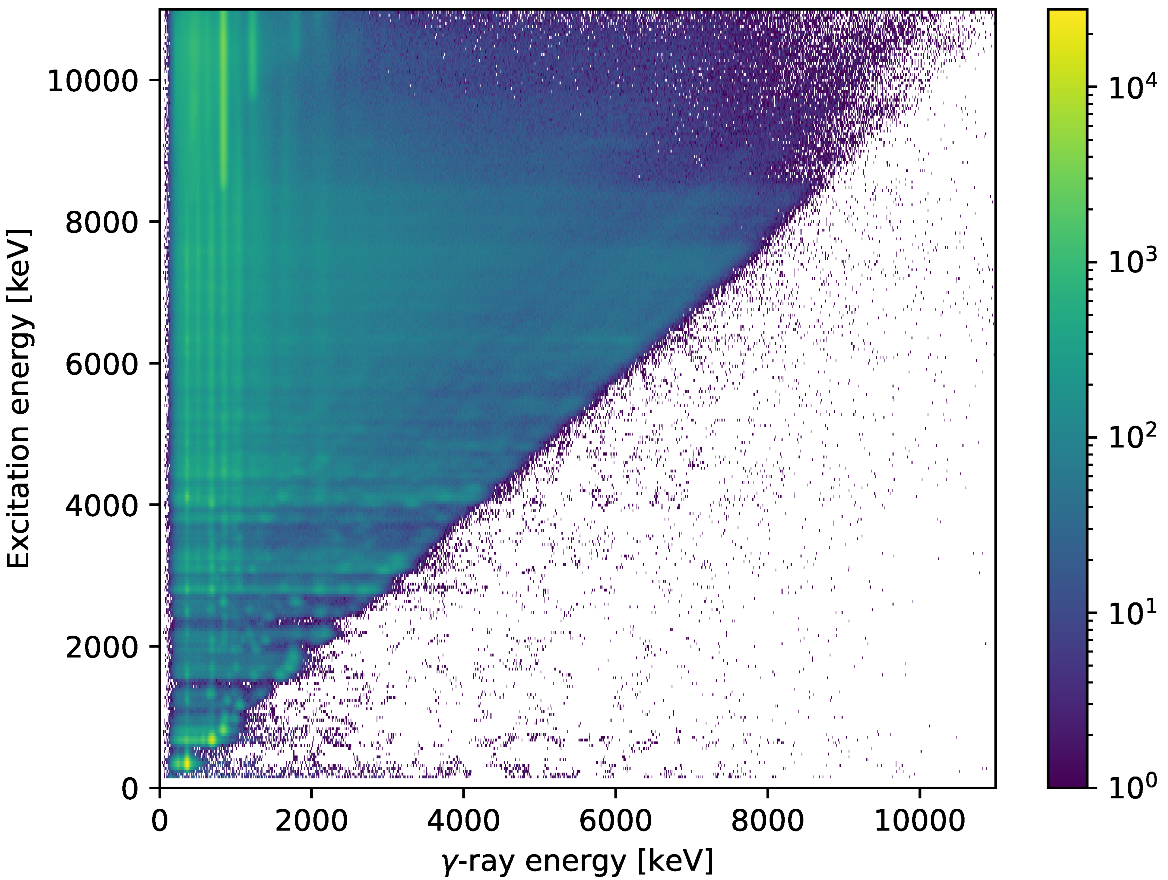


^{57}Fe(p,p'γ)^{57}Fe

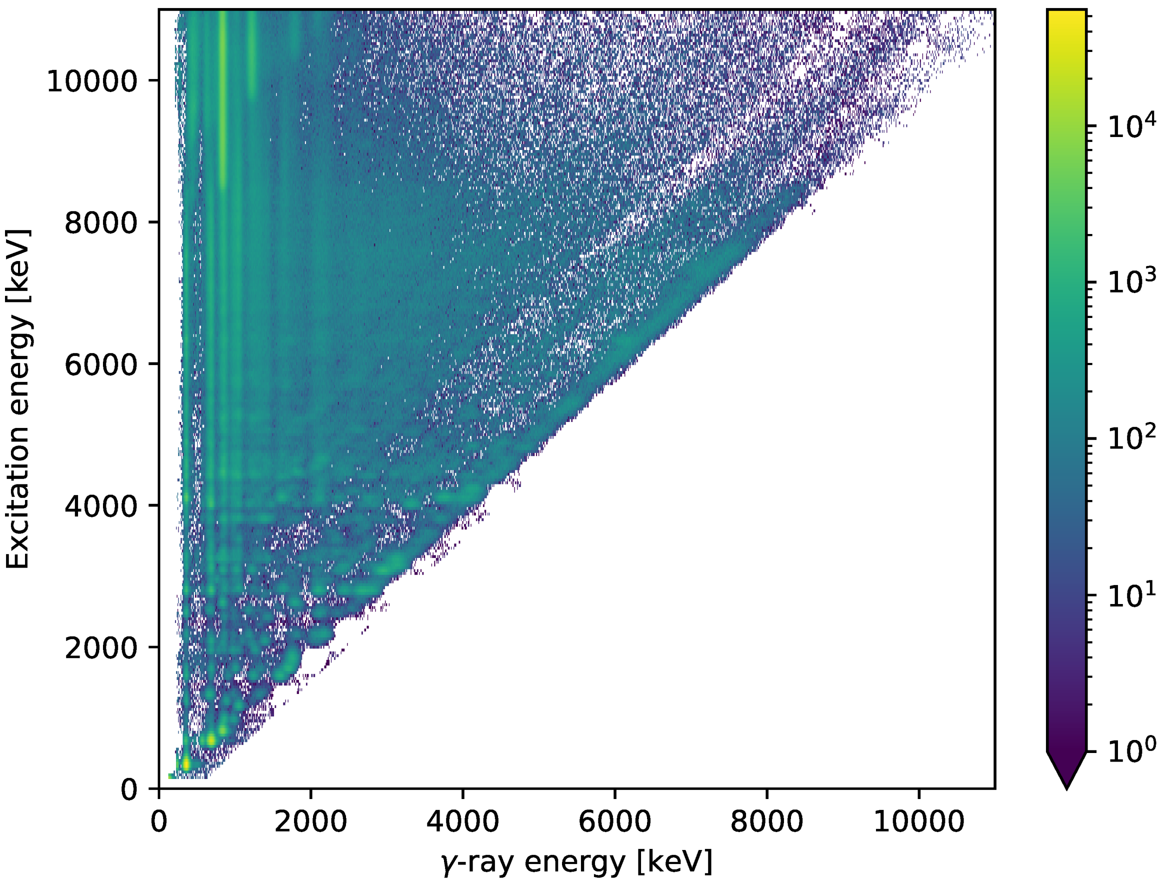
^{57}Fe data from Oslo Method Workshop 2016

Unfolding Method - Example $^{57}Fe(p,p'\gamma)^{57}Fe$

Raw Matrix



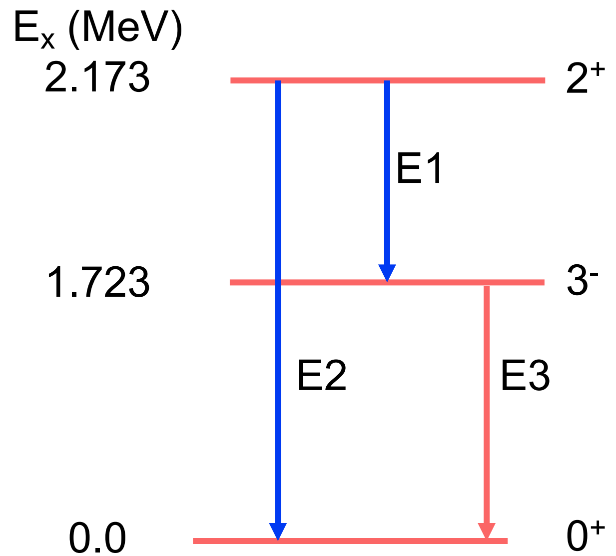
Unfolded Matrix

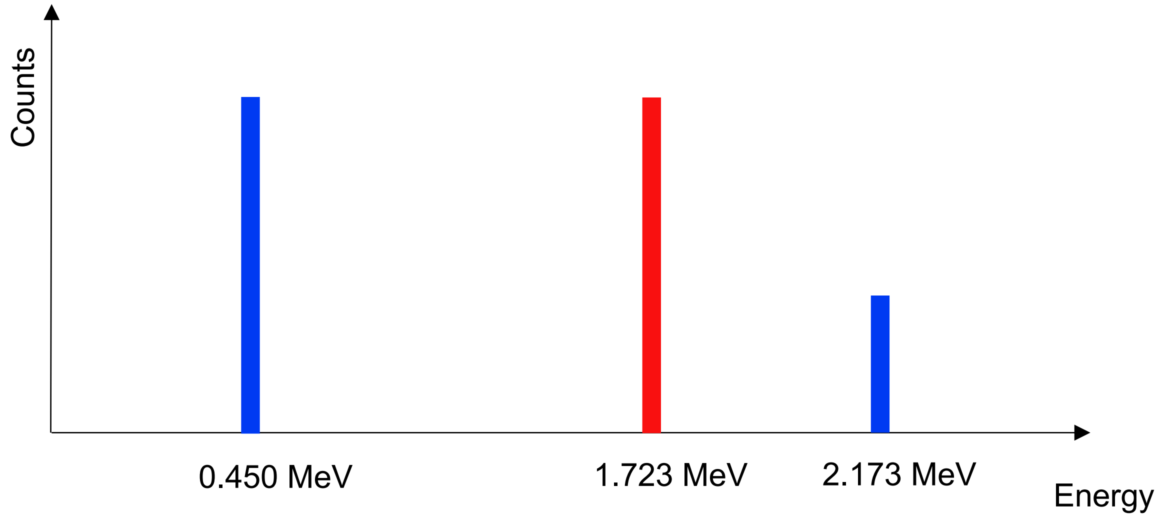


^{57}Fe data from Oslo Method Workshop 2016

First Generation Method

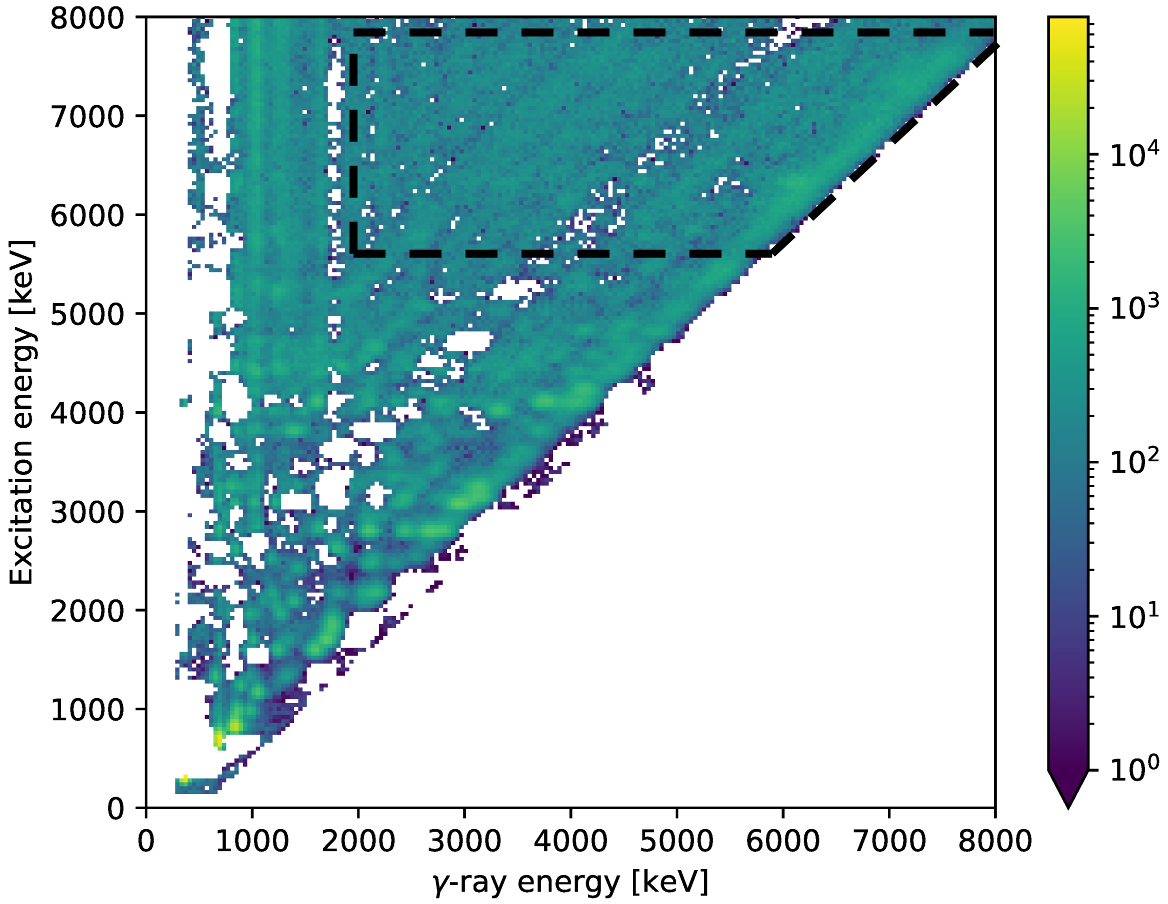
- **Why:** Each excitation bin in unfolded spectra contains all gamma-rays emitted in the cascades de-populating the bin. We only want the first transition in the cascades
- **Solution:** All excitation bins below a certain excitation bin will contain all transitions except those depopulating the bin.
- **How:** Iteratively subtract a weighted sum of all underlying bins





Extraction of NLD and gSF

First-generation Matrix (^{57}Fe(p,p'γ)^{57}Fe)



- $P(E_i, E_\gamma) \propto \mathcal{T}(E_\gamma) \cdot \rho(E_f = E_i - E_\gamma)$
- $\mathcal{T}(E_\gamma)$: γ-ray transmission coefficient
- $\rho(E_f = E_i - E_\gamma)$: Level density at final excitation energy E_f

$$P_{th}(E_x E_\gamma) = \frac{\mathcal{T}(E_\gamma)\rho(E_x - E_\gamma)}{\sum_{E_\gamma = E_\gamma^{min}}^{E_x} \mathcal{T}(E_\gamma)\rho(E_x - E_\gamma)}$$

$$f_{L=1}(E_\gamma) = [f_{E1}(E_\gamma) + f_{M1}(E_\gamma)] \approx \frac{\mathcal{T}(E_\gamma)}{2\pi E_\gamma^3}$$

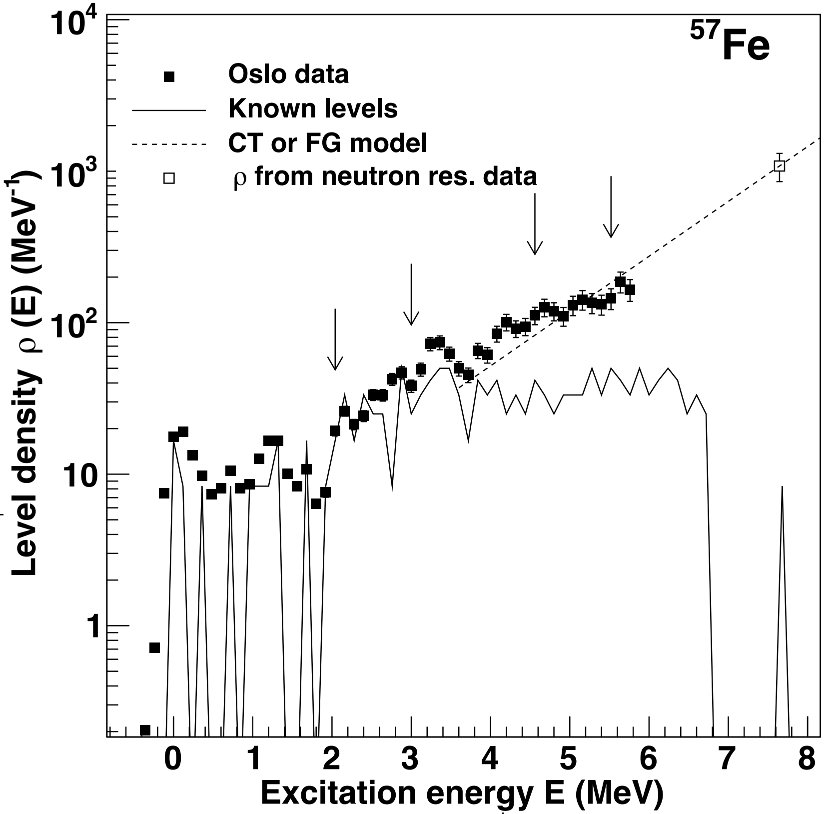
Normalization of NLD and gSF

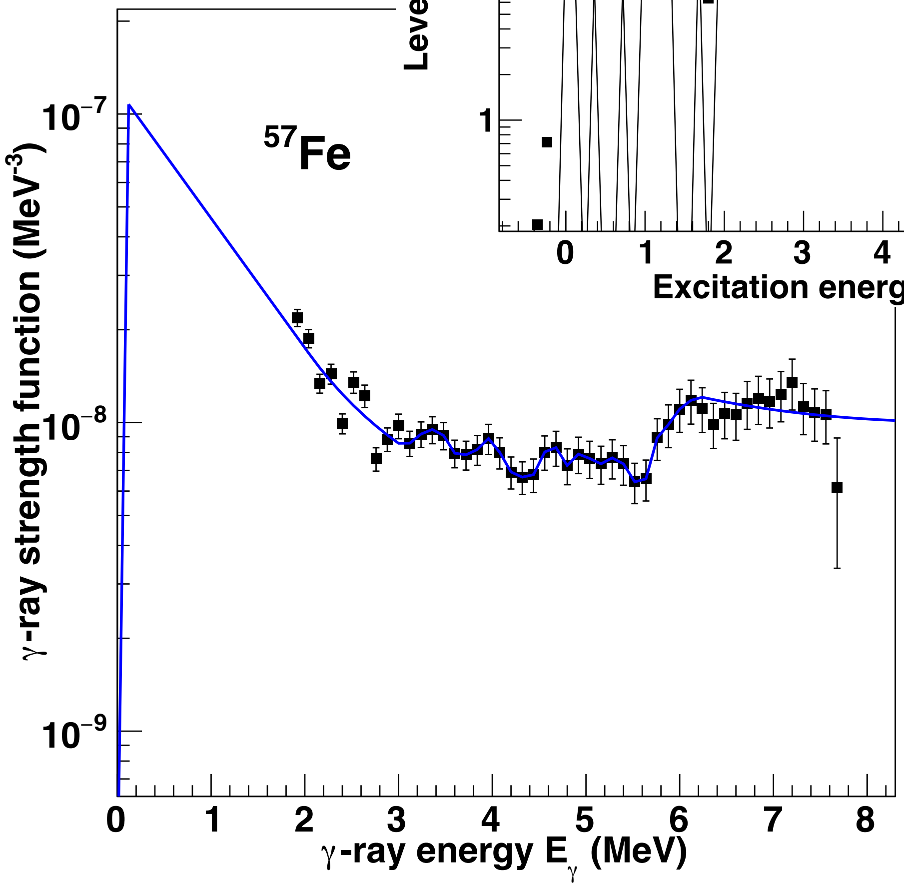
- **Why:** Theoretical FG matrix is invariant under transformation of NLD and transmission coefficient

$$\tilde{\rho}\left(E_x - E_\gamma\right) = A\rho\left(E_x - E_\gamma\right)e^{\alpha\left(E_x - E_\gamma\right)}$$
$$\tilde{\mathcal{T}}\left(E_x - E_\gamma\right) = B\mathcal{T}\left(E_\gamma\right)e^{\alpha E_\gamma}$$

- **Solution:** Compare with external data to find A, B, α coefficients that gives the physical transformation

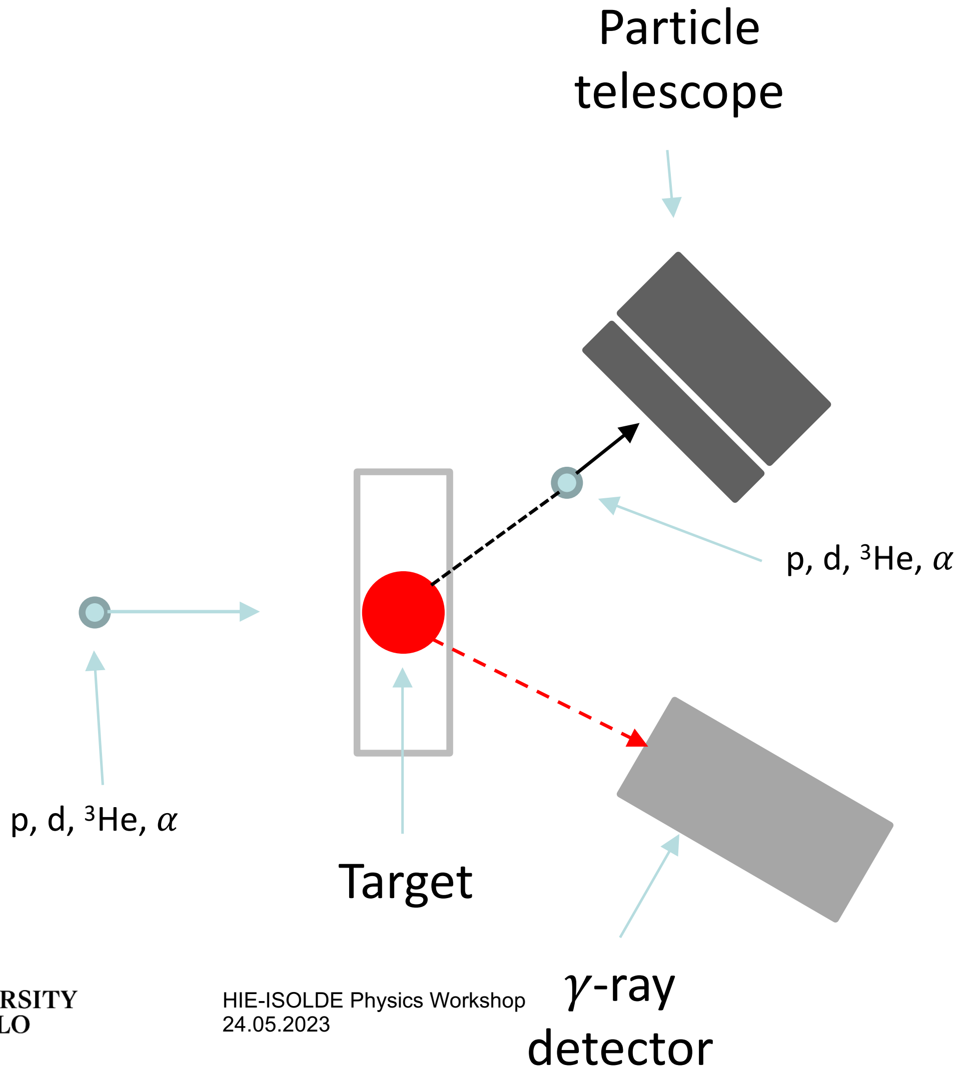
- **How:** Comparison with neutron resonance spacing, average radiative width and level density from discrete levels



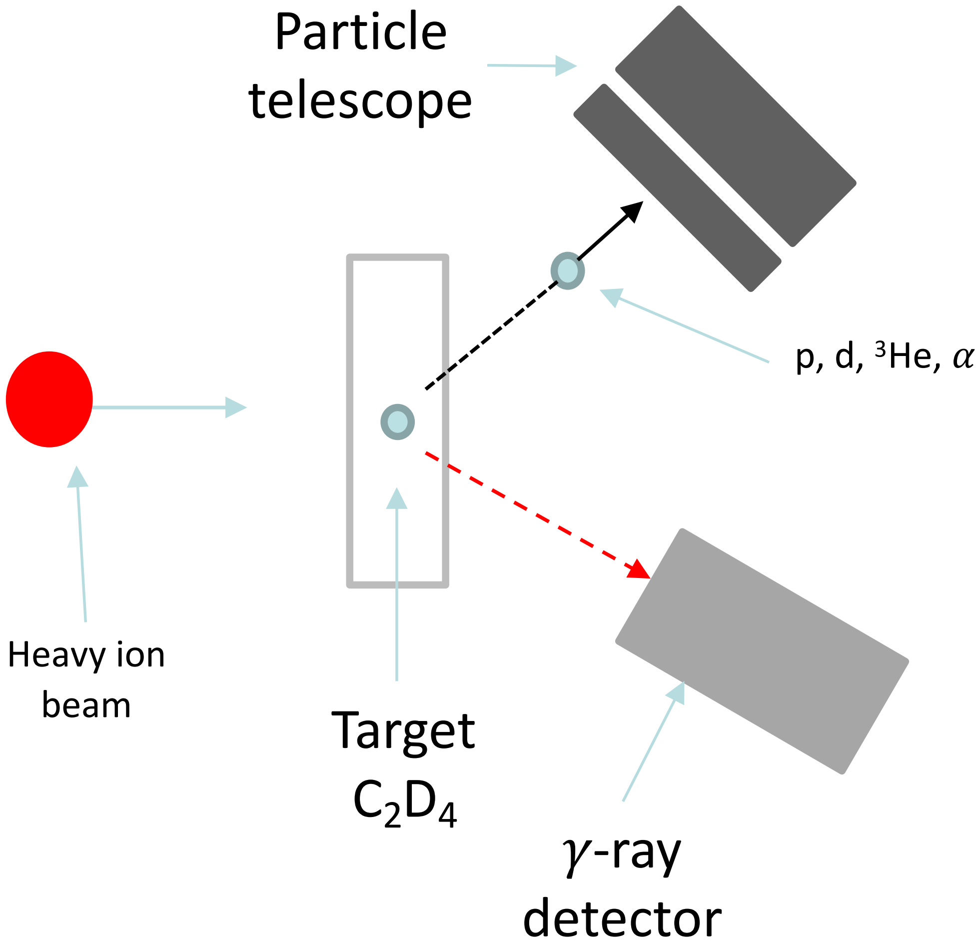


Oslo Method in Inverse Kinematics

"Normal" kinematics

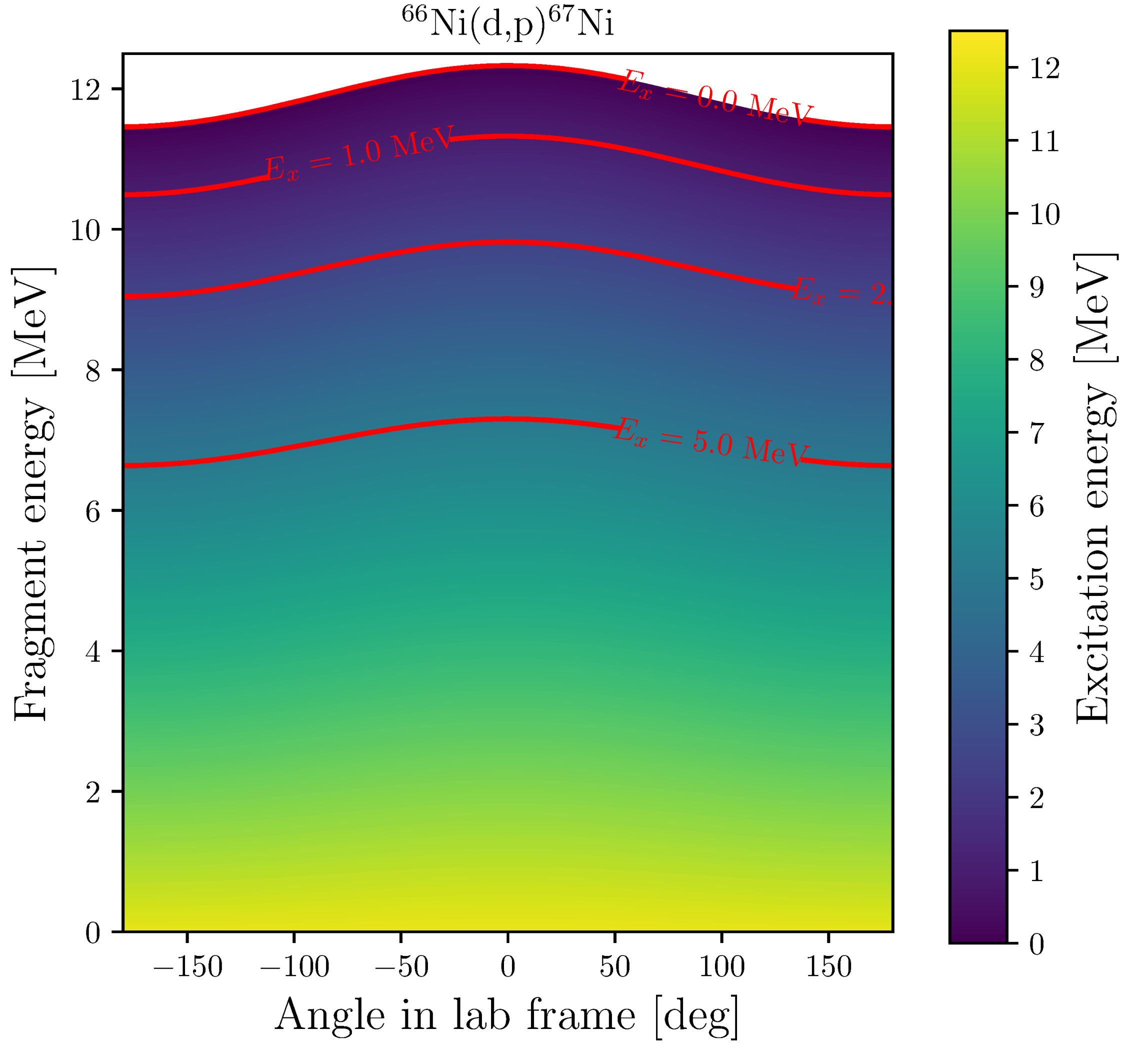


Inverse kinematics

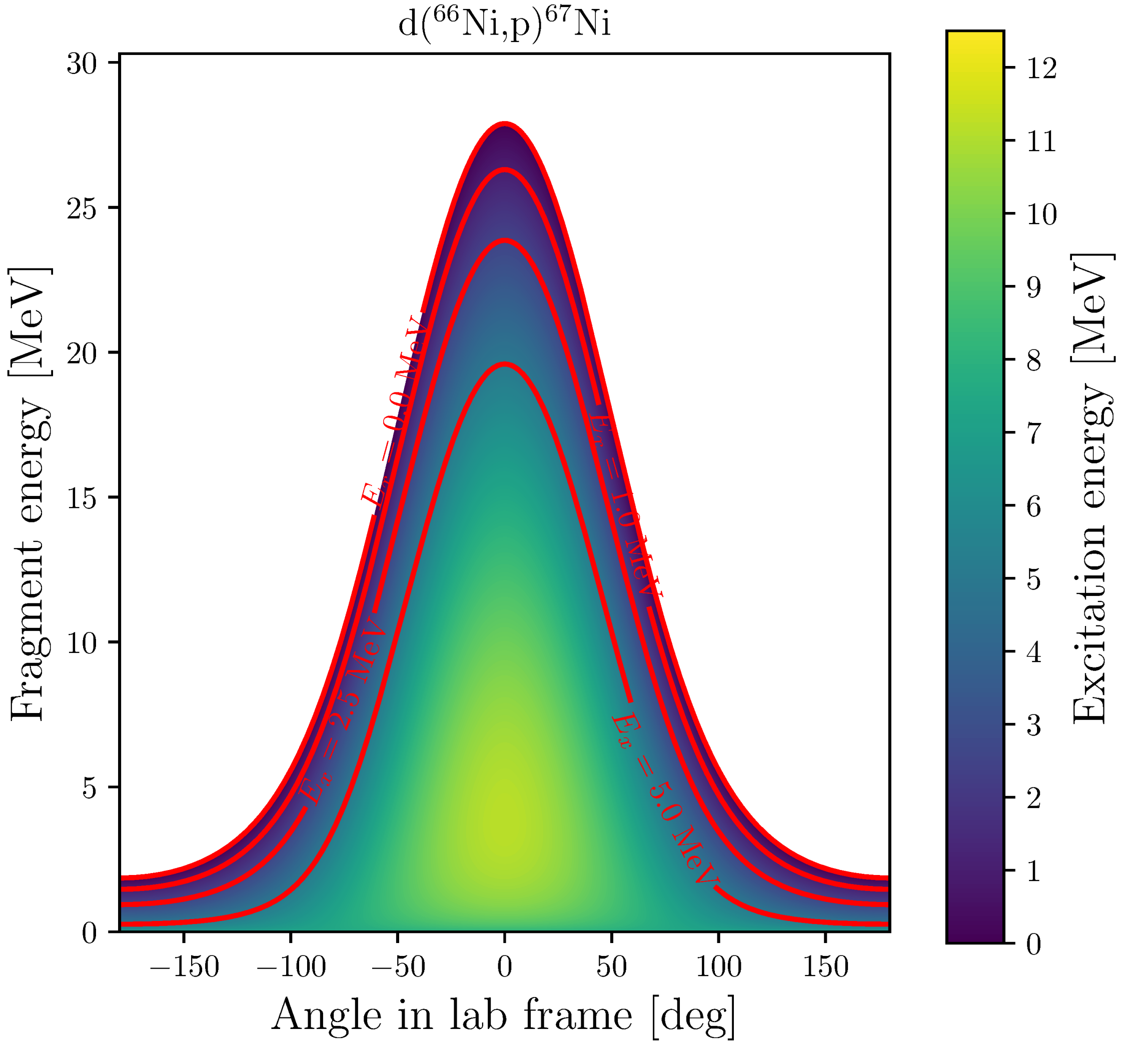


Oslo Method in Inverse Kinematics

“Normal” kinematics

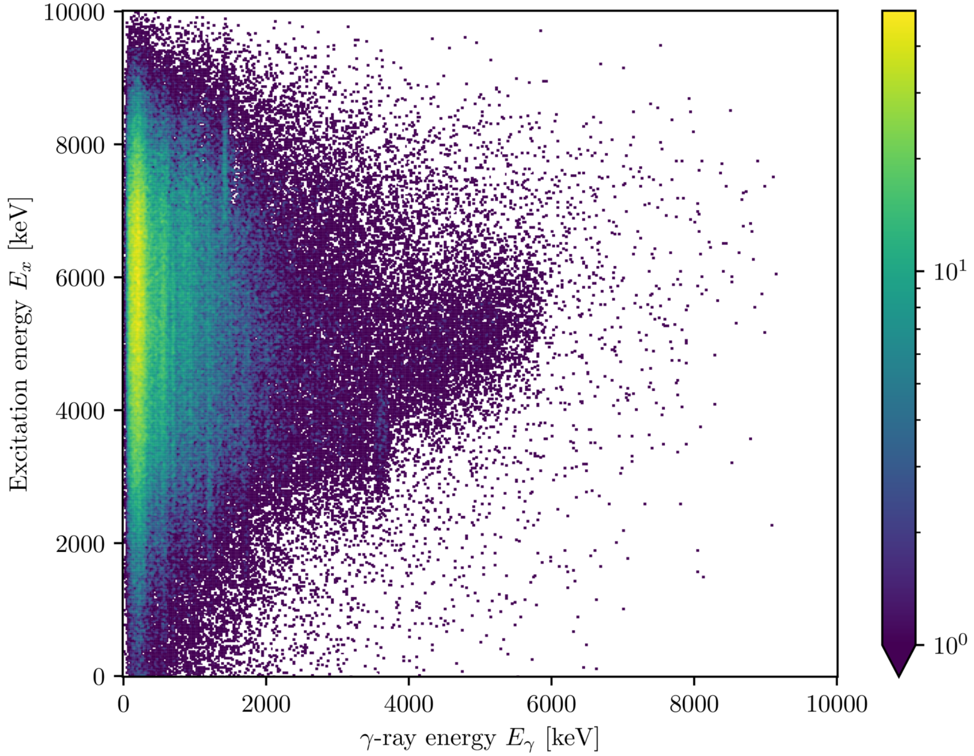


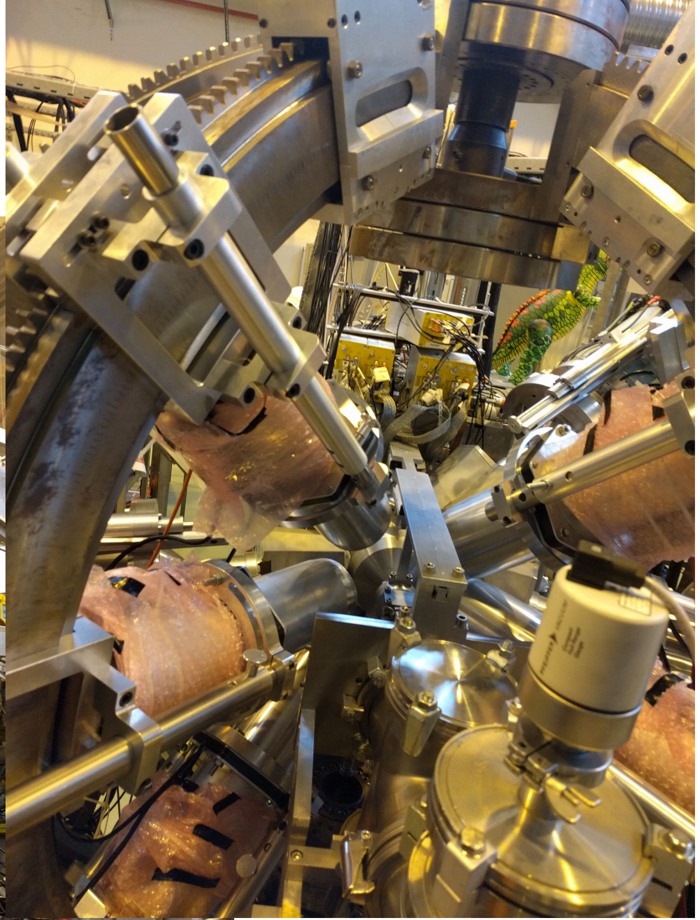
Inverse kinematics



IS559: Oslo Method with d(^{66}Ni, p)^{67}Ni

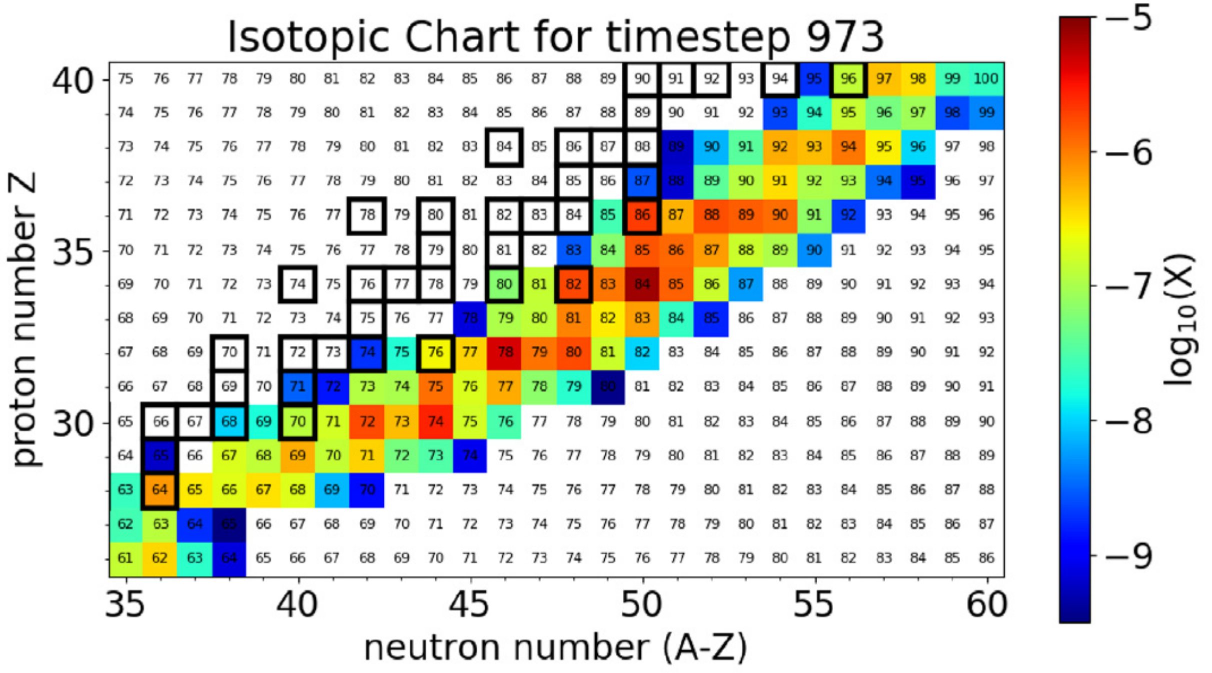
- MINIBALL array at HIE-ISOLDE
- C-REX particle array
- 6 large volume $LaBr_3$:Ce detectors
- 4.5 MeV/u ^{66}Ni beam
- About 11 pA for 140 hours



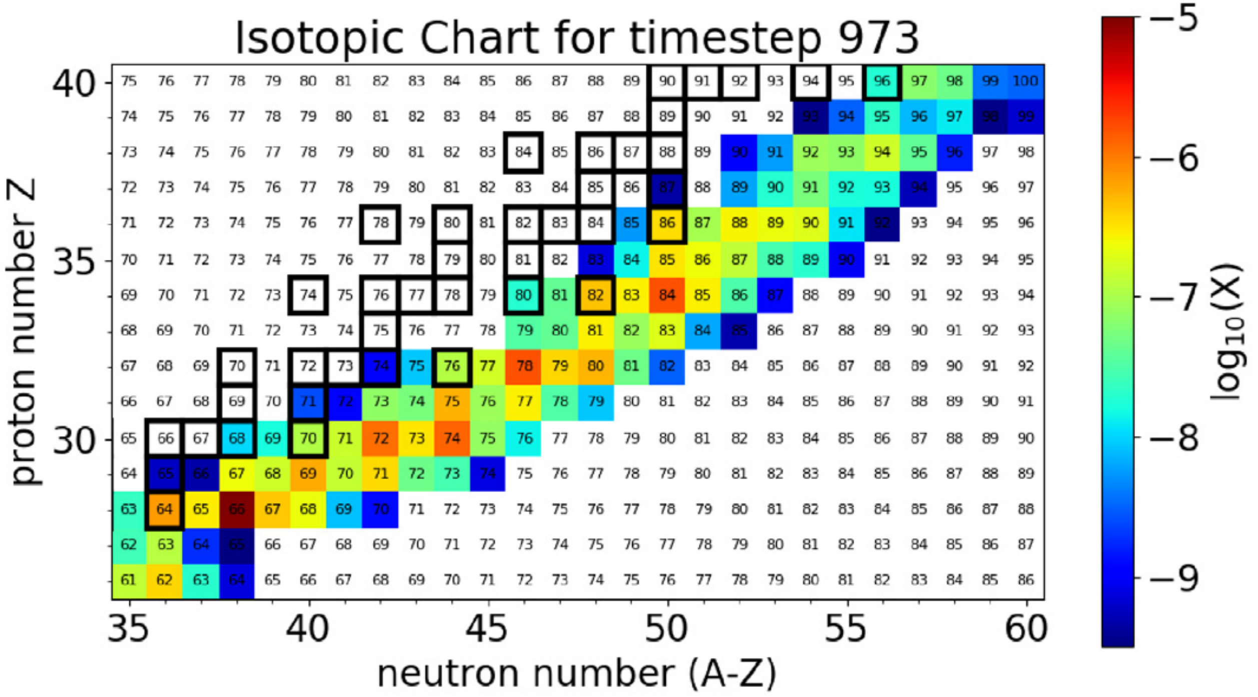


^{66}Ni(n,γ) – i-process bottleneck

High ^{66}Ni(n, γ) cross section



Low ^{66}Ni(n, γ) cross section

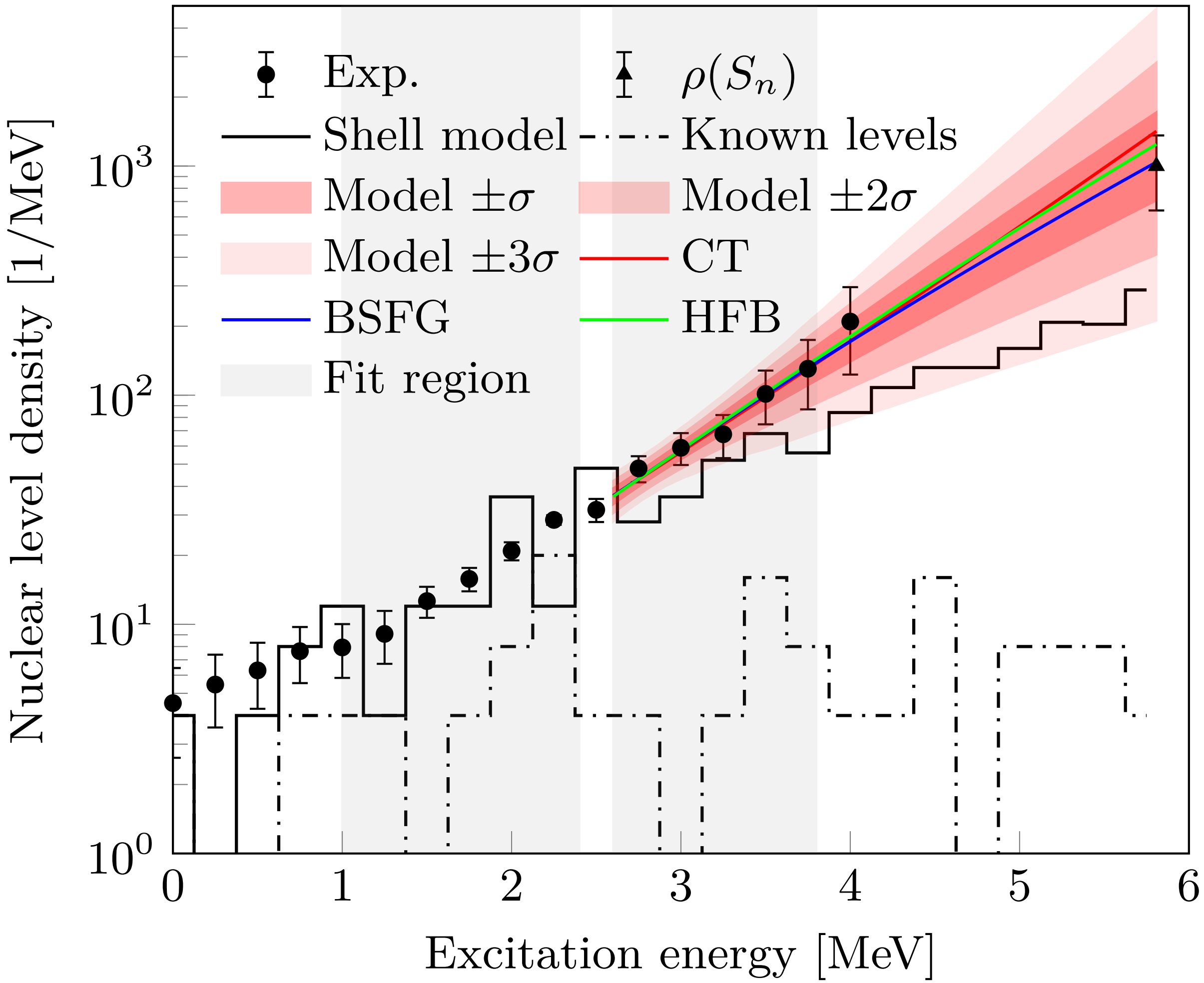


J. McKay *et al.*, MNRAS **491**, 5179 (2020)

Normalization of the NLD: ^{67}Ni

- No neutron resonance data
  - No NLD at neutron separation energy
- Incomplete level scheme
  - Few known levels

- Solution: Normalize to the NLD from large scale shell model calculation
- Use normalized NLD to estimate NLD at neutron separation energy



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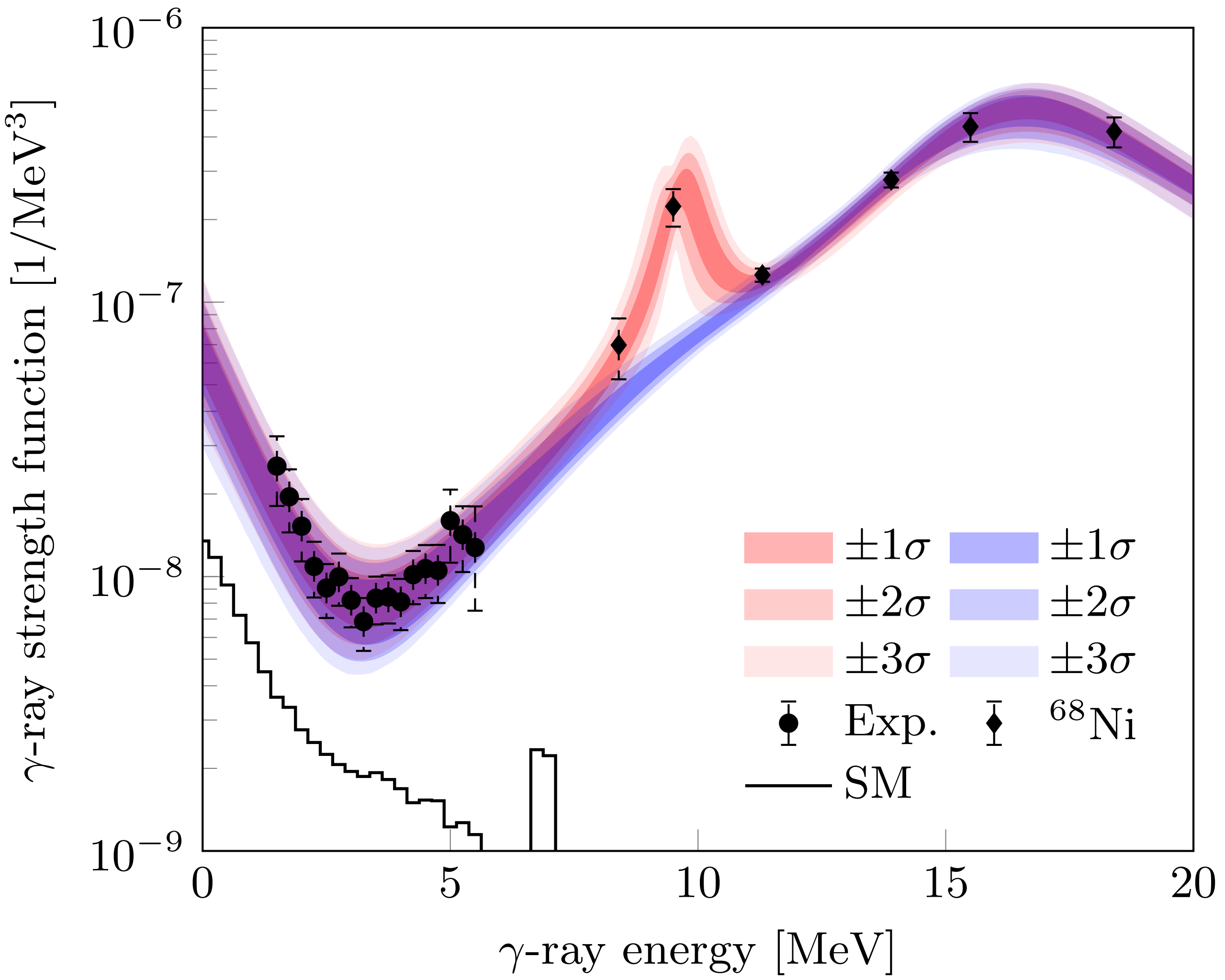
Normalization of gSF: ^{67}Ni

- No neutron resonance data
  - No average radiative width

- Luckily: E1 strength measurements from Coulomb excitation of ^{68}Ni
  - Can perform a model dependent extrapolation of the γSF



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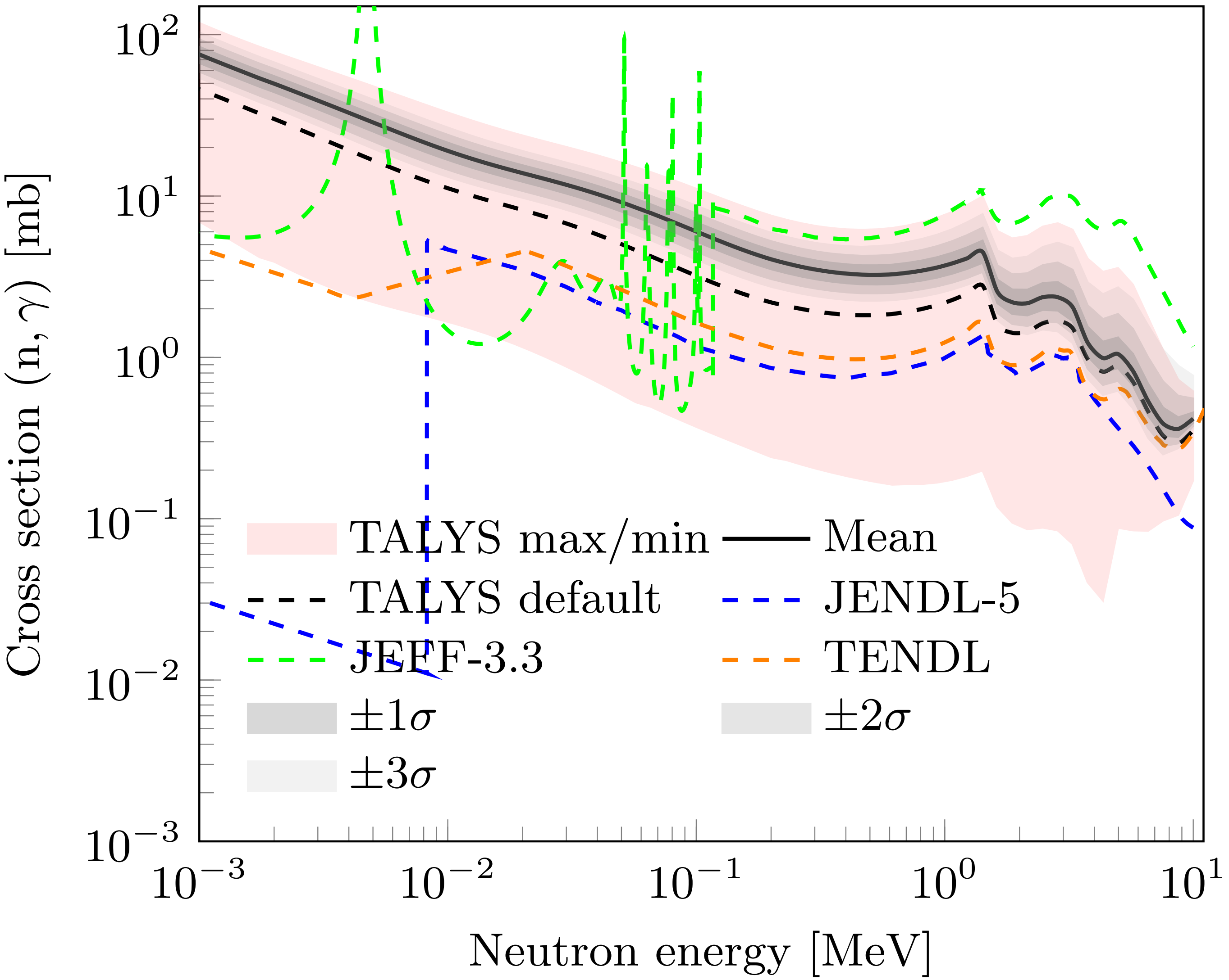
Neutron capture rate: ^{66}Ni



V. W. Ingeberg *et al.,* In preparation

New experiments at ISOLDE with Oslo Method

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Neutron-capture cross section for *i* process bottleneck ^{75}Ga: $^{75}\mathbf{Ga}(d,p\gamma)^{76}\mathbf{Ga}$

January 4, 2022

F. Pogliano[1], R. Gernhaeuser[2], A. C. Larsen[1], H. C. Berg[3], G. De Angelis[4], D. Gjestvang[1], S. Golenev[2], A. Görgen[1], M. Guttormsen[1], K. Hadyńska-Klęk[5], V. W. Ingeberg[1], P. Jones[6], K. C. W. Li[1], S. Liddick[3], D. Mücher[7], M. Markova[1], W. Paulsen[1], L. G. Pedersen[1], L. Pellegri[6], E. Sahin[1], S. Siem[1], A. Spyrou[3], M. Wiedeking[6], P. Reiter[8], K. Arnswald[8], M. Droste[8], H. Hess[8], H. Kleis[8]

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Evolution of $N = 50$ shell and neutron single-particle states towards ^{78}Ni: $^{79}\mathbf{Zn}(d,p)^{80}\mathbf{Zn}$

January 5, 2022

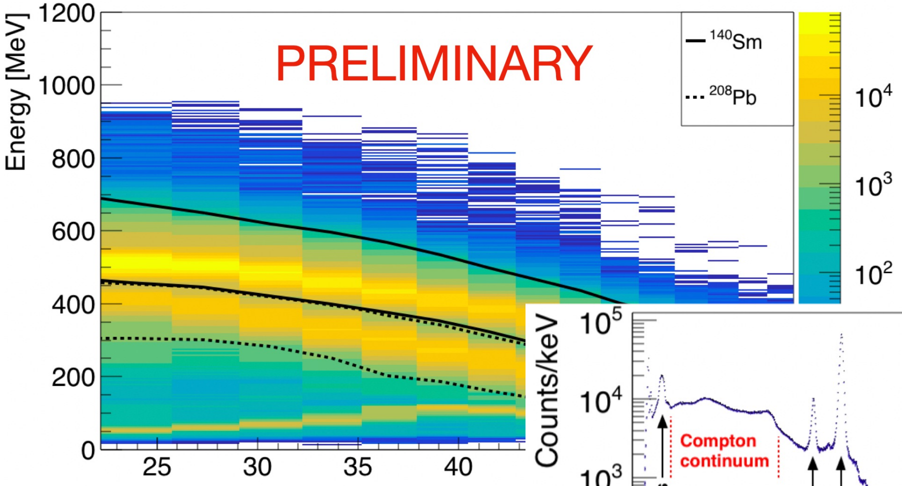
E. Sahin[1], G. de Angelis[2], H.C. Berg[3], V. Bildstein[4], N. Erduran[5], R. Gernhaeuser[6], D. Gjestvang[1], S. Golenev[6], A. Görgen[1], M. Guttormsen[1], K. Hadyńska-Klęk[7], A. Illana[8], V. W. Ingeberg[1], P. Jones[9], A.C.Larsen[1],K.C.W. Li[1], K.L. Malatji[9], M. Markova[1], A. Matta[10], J. Pakarinen[8], W. Paulsen[1], L.G. Pedersen[1], L.Pellegri[9], F. Pogliano[1], S. Siem[1], T. Tornyi[1], M. Yalcinkaya[11], M. Wiedeking[9], P. Reiter[12], K. Arnswald[12], M. Droste[12], H. Hess[12], H. Kleis[12],A. Spyrou[3], S. Liddick[3]

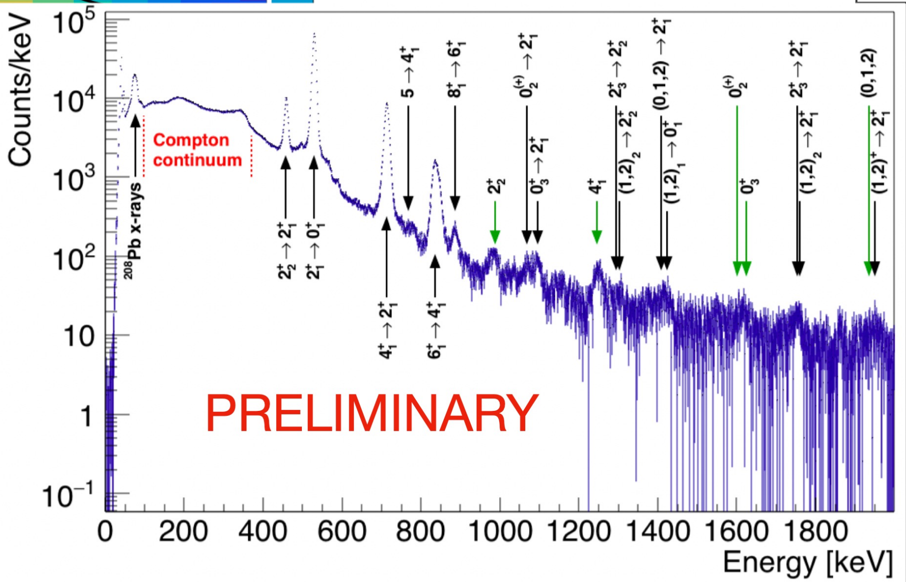
Bring OSCAR to ISOLDE?

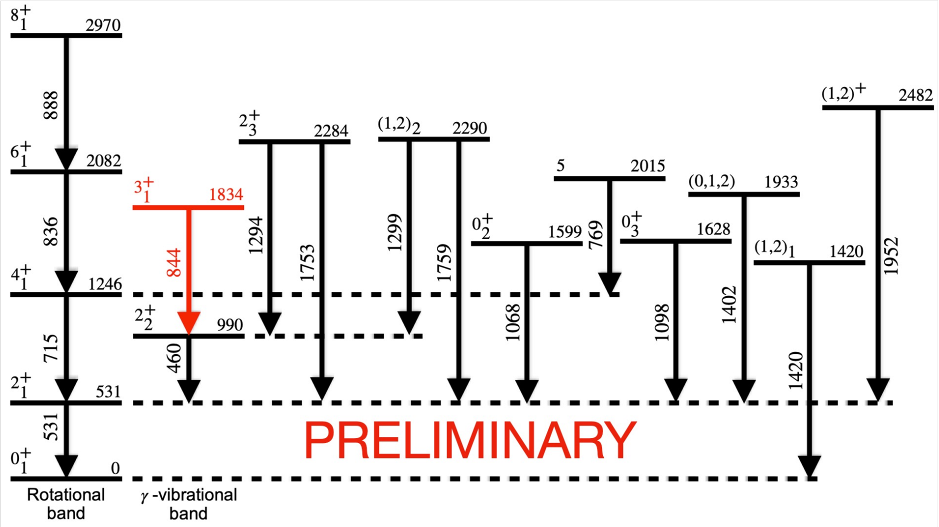
- Oslo Scintillator ARray
- World largest $LaBr_3$:Ce gamma detector array
- 30 large volume (3.5x8-inch) $LaBr_3$:Ce
- Superior efficiency at high energy
- Propose experiments at ISOLDE with OSCAR
- Still at the idea phase
- Lots of questions still needs to be answered (finance, logistics, etc.)
- Please let me know if you are interested in such a project

IS558 – Coulex of ^{140}Sm

"Shape Transition and Coexistence in Neutron-Deficient Rare Earth Isotopes"







Experiment	IS558
Target	208Pb
Particles/s	≈2x10^5
Beam energy	4.1A MeV
Separate angle ranges	23
Total angle coverage in COM	36.6°-136°
DSSD distance from target	27 mm

Currently analyzed by PhD student Wanja Paulsen

Summary

First ever Oslo Method analysis with ISOLDE data

Constrained the ^{66}Ni(n, g) cross section highly relevant for the i-process

Plan to propose new experiments where we may bring OSCAR to HIE-ISOLDE

Acknowlagement

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K. Arnswald, P. Reiter, D. Rosiak, B. Siebeck, M. Seidlitz, N. Warr

A. Choplin, S. Goriely, L. Siess

H. De Witte, A. Illana Sison,

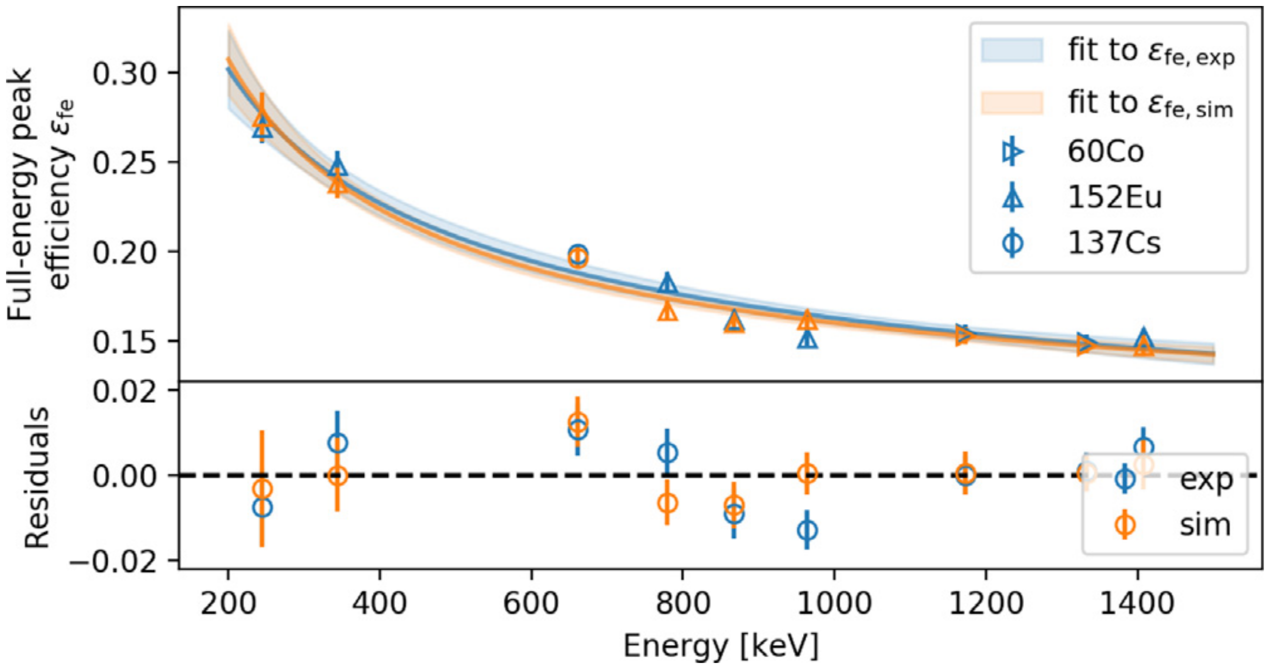
J. Cederkäll, J. Snäll

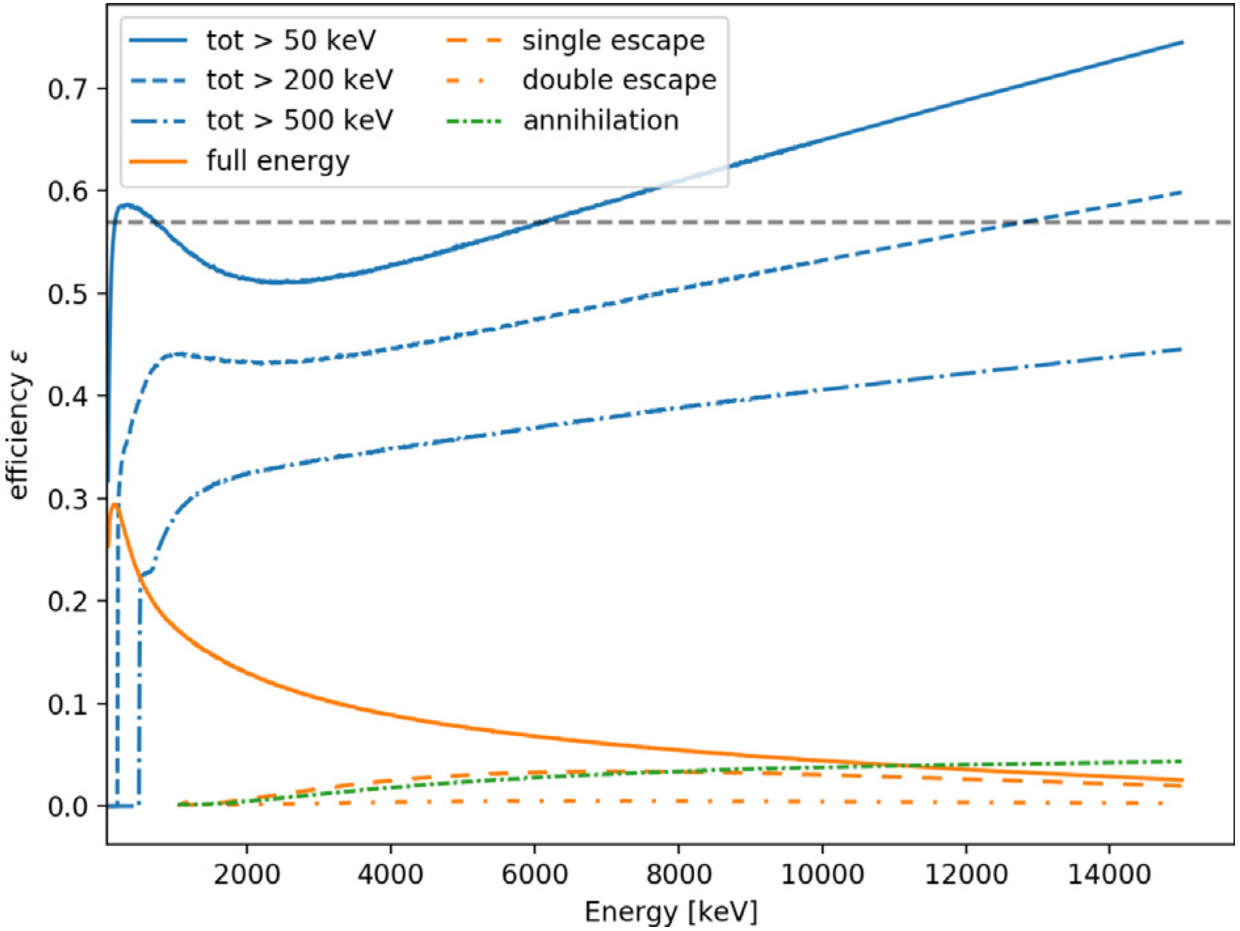
T. Berry

D. M. Cox, J. Pakarinen

OSCAR

Closest configuration: ≈ 16.4 cm
Angular coverage: 57% of 4π





F. Zeiser *et al.*, NIM A **985**, 164678 (2021)