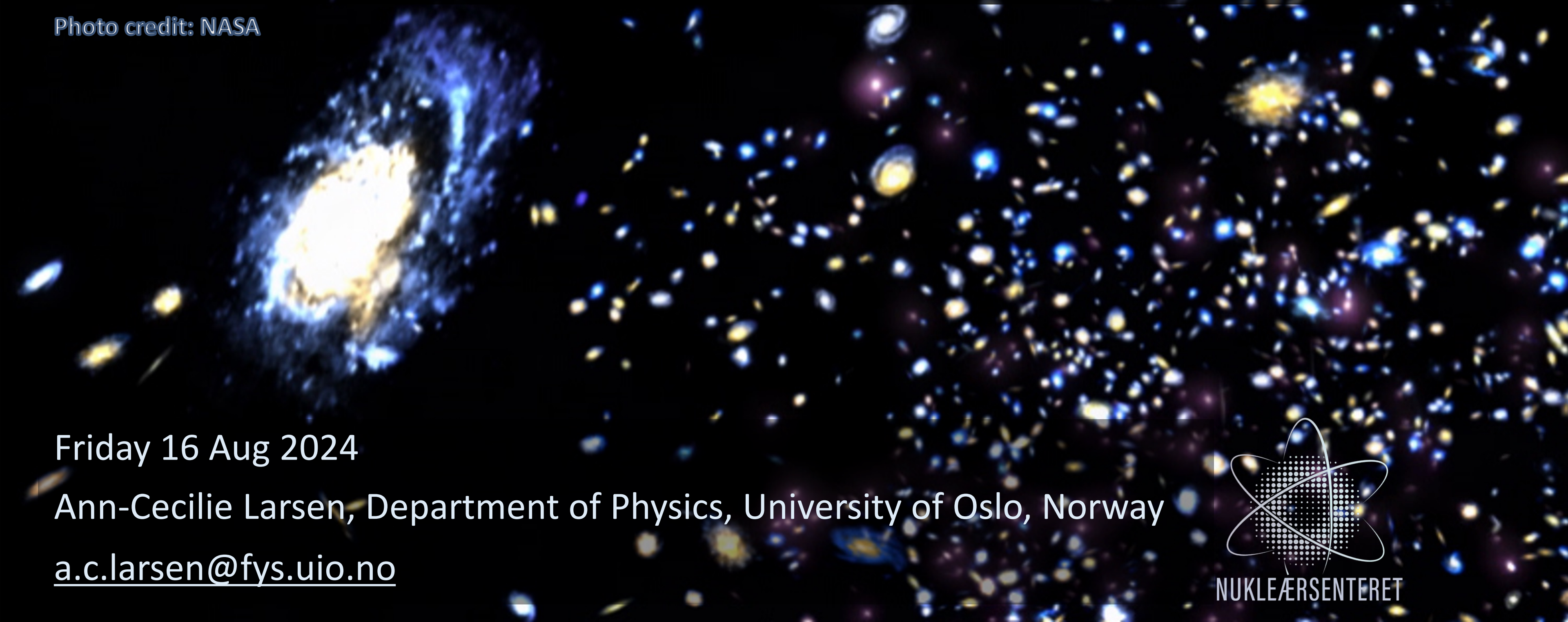
Lecture 2:
Nuclear-physics ingredients for heavy-element nucleosynthesis

Photo credit: NASA



Friday 16 Aug 2024

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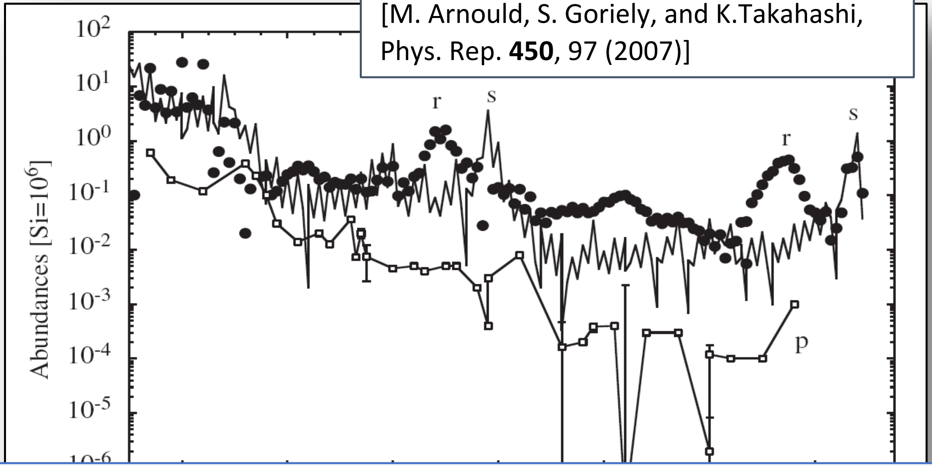
NUKLEÆRSENTERET

Overview of the lectures

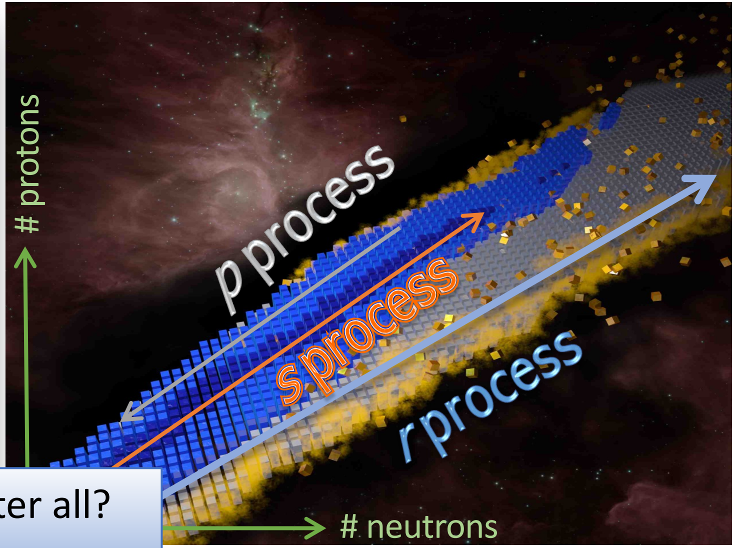
- **Yesterday**: A first introduction to nuclear astrophysics, with focus on heavy-element nucleosynthesis
- **Today**: (Some of the) Needed nuclear-physics input for heavy-element nucleosynthesis, brief intro to experimental methods to indirectly measure neutron-capture rates

Recap: how to "cook" heavy elements

Slow neutron-capture (*s*) process (≈50%)
Rapid neutron-capture (*r*) process (≈50%)
p process: proton capture, photodisintegration, νp-process, … (~0.1-1%)



[M. Arnould, S. Goriely, and K.Takahashi, Phys. Rep. **450**, 97 (2007)]

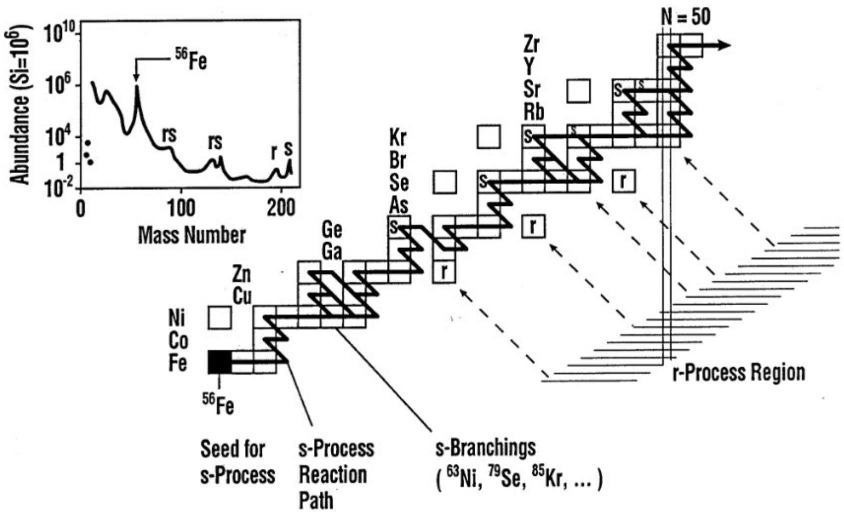


… maybe the *rp* process can contribute to the "p-nuts" after all?
See Sophie's talk on Tuesday!

Nuclear-physics needs for the *s* process

- Measure (n,γ) cross sections => calculate (n,γ) reaction rates
- Measure β^- decay half lives => calculate β^- decay rates

Almost all the needed nuclear-physics data are or can be measured, as the relevant nuclei are on or close to the valley of stability



Review article on the *s* process:
Käppeler et al., Rev. Mod. Phys. 83, 157 (2011)

In general, when an unstable nucleus is made in the *s* process, the following condition is fulfilled:

$\tau_{\beta-} << \tau_{n\gamma}$

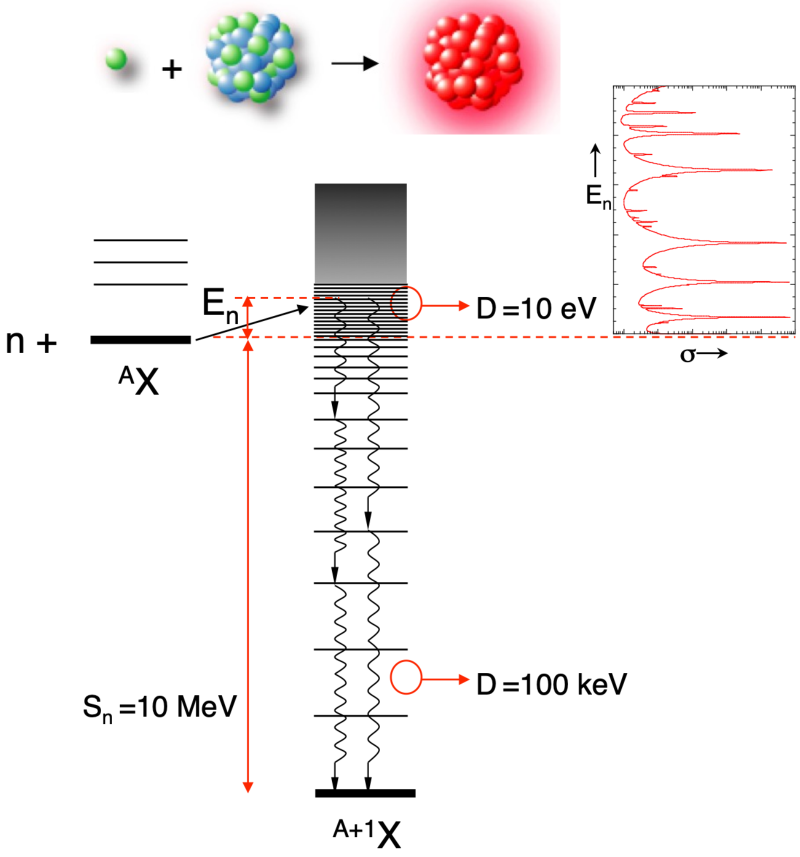
=>

$\lambda_{\beta-} >> \lambda_{n\gamma}$

Except at the branch points, where $\lambda_{\beta-} \approx \lambda_{n\gamma}$

Neutron-capture measurements for the *s* process

1) Shoot neutrons with a known flux & energy on a sample (isotopically enriched), measure transmission and γ rays
2) Place your sample in a neutron beam, then measure γ rays from the produced radioactive nuclei afterwards (activation technique)



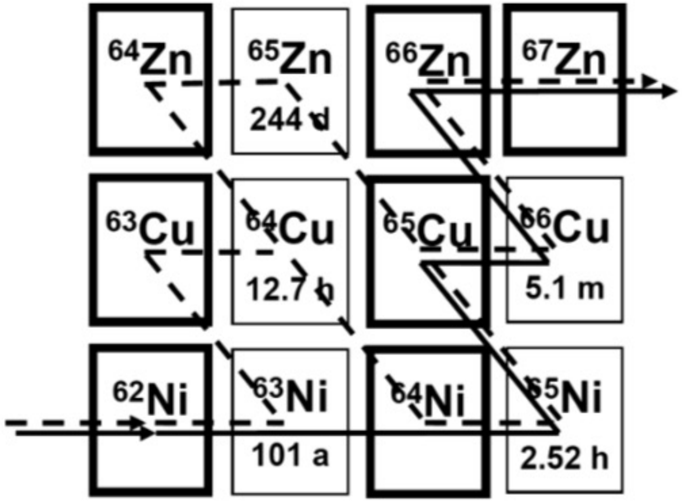
Facilities: n_TOF @ CERN, GELINA, Los Alamos National Lab,…

See Sec. IIA in Käppeler et al., Rev. Mod. Phys. 83, 157 (2011)

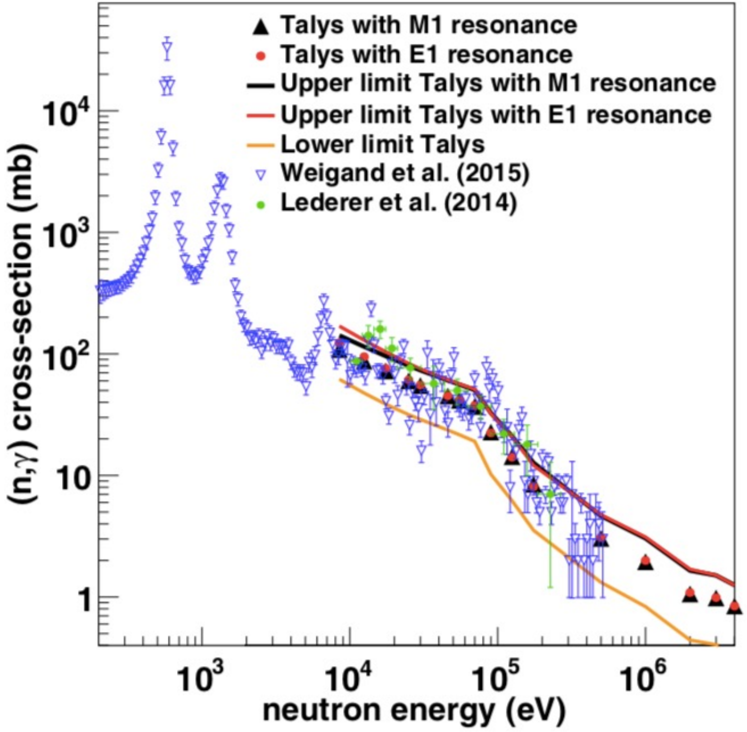
Pictures from Frank Gunsing

An example of a branch-point nucleus: ^{63}Ni 🌱

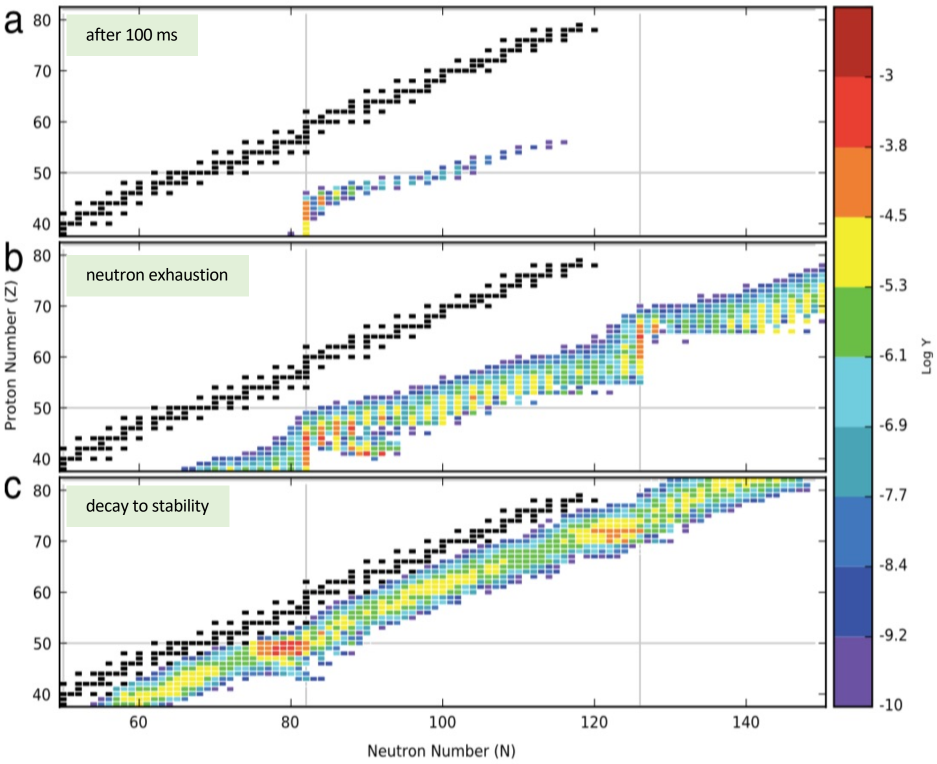
Lederer et al., PRL 110, 022501 (2013), Weigand et al., PRC 92, 045810 (2015),
Crespo Campo et al., PRC 94, 044321 (2016)
"Talys" [or TALYS]: open-source nuclear reaction code https://nds.iaea.org/talys/

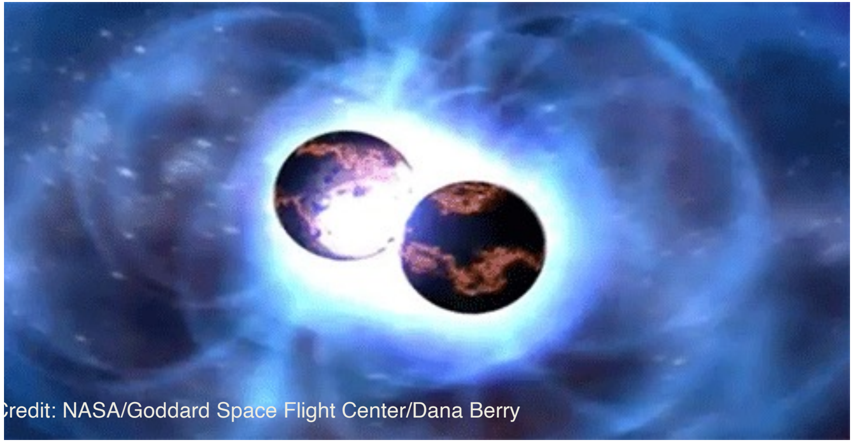


Dashed line: n density ≈10^7 cm^{-3}, kT ≈26 keV
Solid line: n density up to $10^{11\text{-}12}$ cm^{-3}, kT ≈90 keV



Nuclear-physics needs for the *r* process



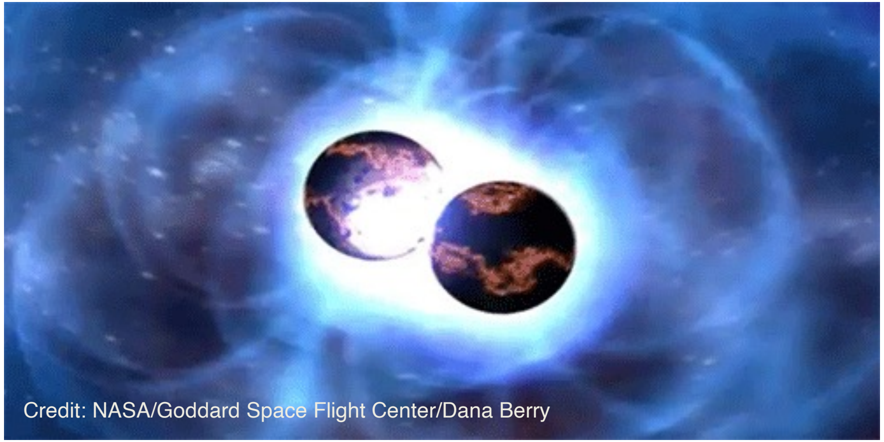


Snapshots , reaction network, neutron-star collision trajectory

Mumpower, Surman, McLaughlin, Aprahamian, Prog.Part. Nucl. Phys. 86, 86 (2016)

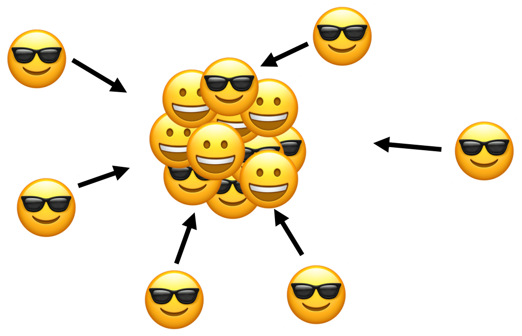
Nuclear-physics needs for the *r* process

- Masses!!! -> To get *Q*-values, separation energies
- β^- decay rates!
- (n,γ) rates!
- Fission rates!

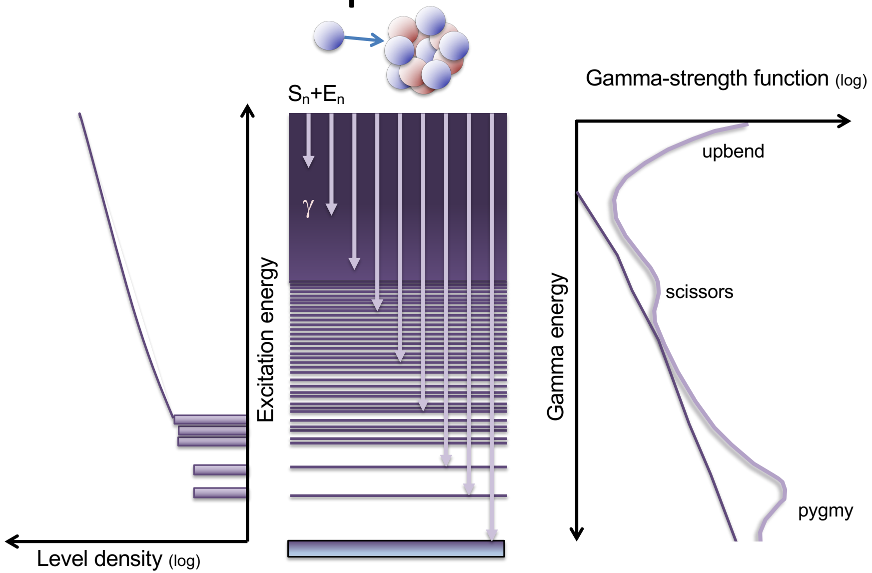


From an experimental point of view (**at least in my view**), the hardest ones to measure are the (n,γ) and the fission rates

If we cannot measure neutron-capture cross sections…



(Wolfenstein-)Hauser-Feshbach theory
-> “compound nucleus” picture of Bohr
[W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952)]



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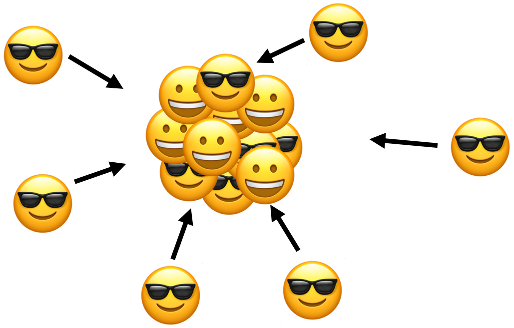
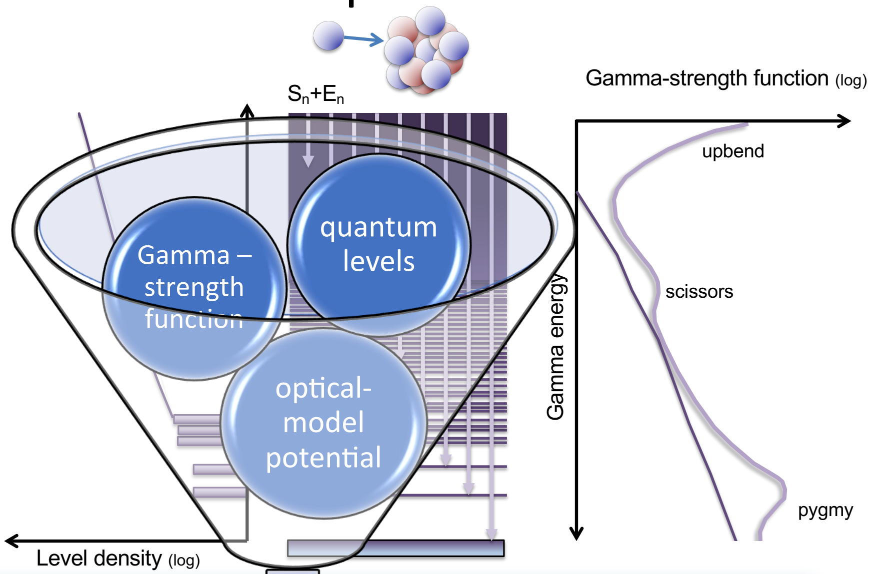




(Wolfenstein-)Hauser-Feshbach theory
-> "compound nucleus" picture of Bohr
[W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952)]

$$N_A\langle\sigma v\rangle(T) = \left(\frac{8}{\pi m}\right)^{1/2} \frac{N_A}{(kT)^{3/2} G(T)} \int_0^\infty \sum_\mu \frac{(2I^\mu+1)}{(2I^0+1)} \sigma^\mu(E)\, E \exp\left[-\frac{(E+E_x^\mu)}{kT}\right] dE$$

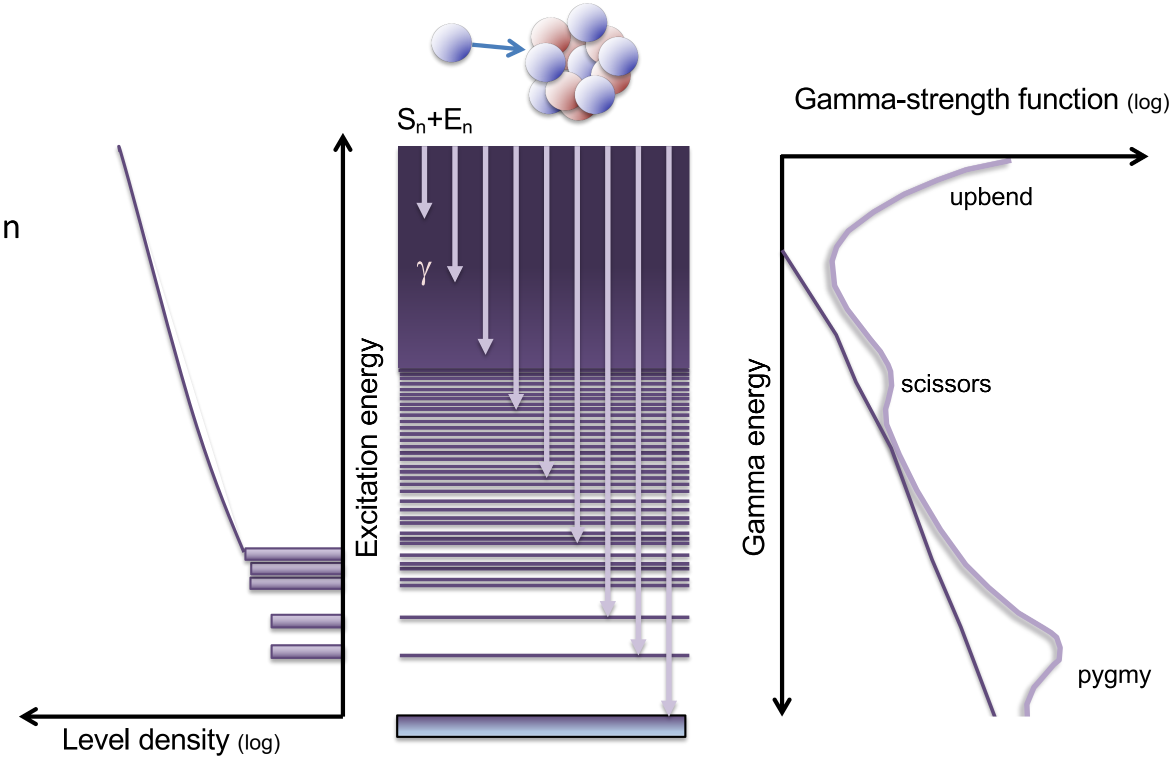
$$G(T) = \sum_\mu (2I^\mu+1)/(2I^0+1)\exp(-E_x^\mu/kT)$$

Why are nuclear level densities and γ-ray strength functions important for (n,γ) reaction rates?

Fermi's Golden Rule

[actually Dirac, Proc. R. Soc. London A 114, 243 (1927)]

$$\lambda_{i \to f} = \frac{2\pi}{\hbar} |\langle f|H'|i\rangle|^2 \rho_f$$



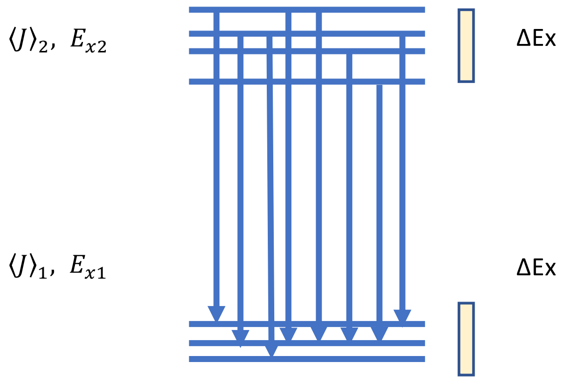
Matrix element for electric/magnetic decay in the case of gamma radiation

What are nuclear level densities and γ-ray strength functions?

Level density:

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

$$\rho(E_x) = \sum_J \sum_\pi \rho(E_x, J, \pi)$$



Gamma-ray strength function: [Bartholomew et al., chapter 4, Advances in Nuclear Physics 7, 229 (1972)]

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

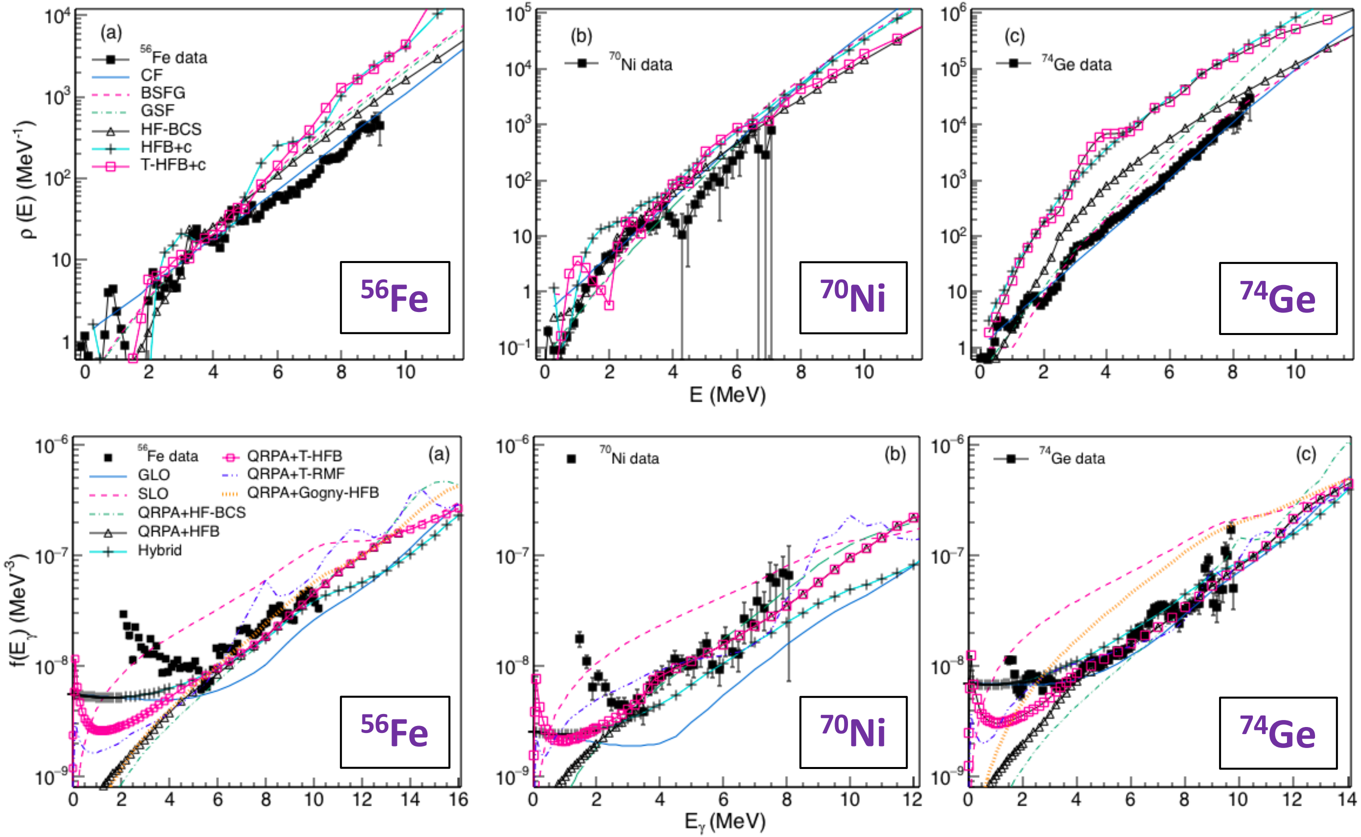
Also called photon strength function, radiative strength function, …
E1 and M1 transitions dominate at high excitation energies

Both these quantities are useful when we deal with ***many*** levels and ***many*** transitions

… but don't we know how to calculate level densities and γ-ray strength functions? 🤔

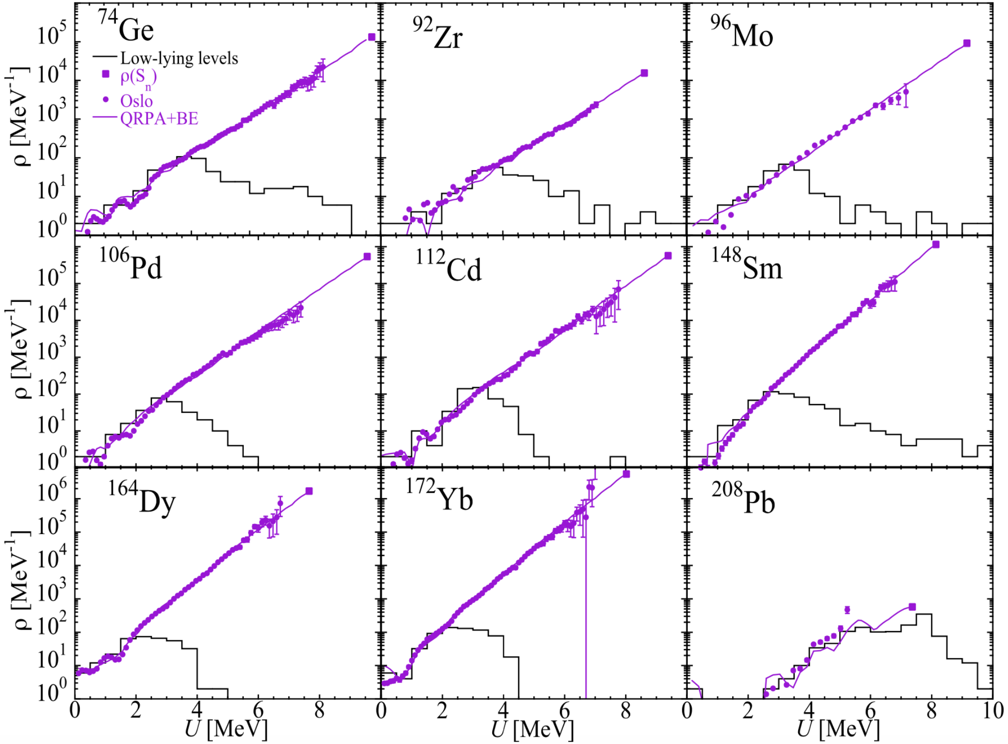
Data (+ all refs) available at ocl.uio.no

I have used models included in TALYS-1.8



Things are going in the right direction!

Hilaire, Goriely, Péru, Gosselin, PLB 843, 137989 (2023)



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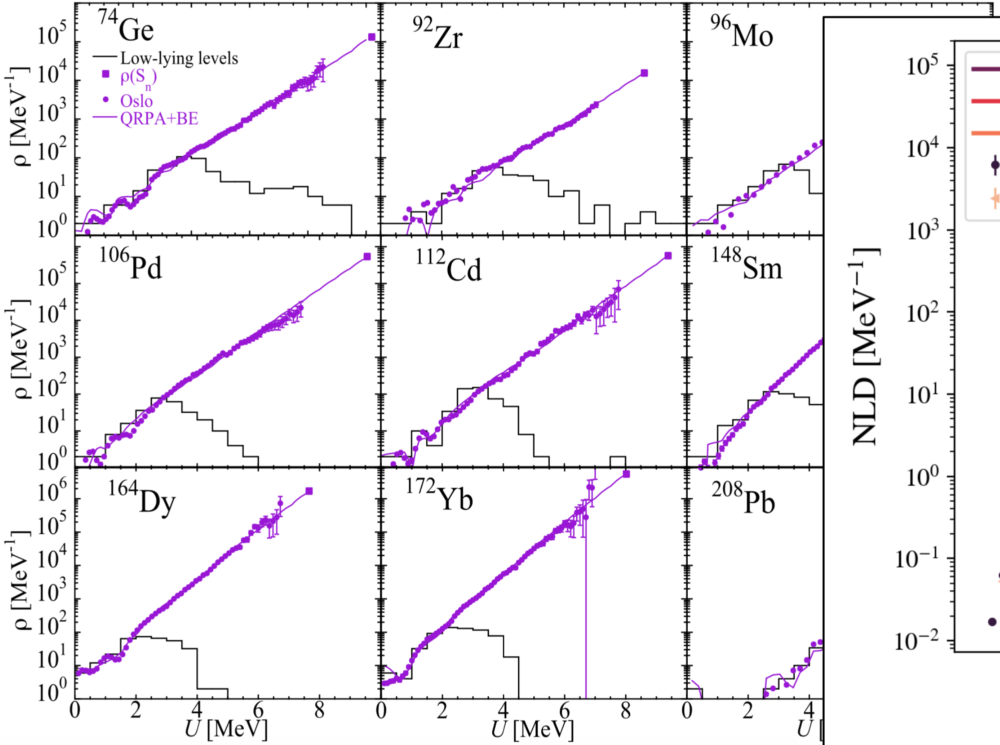
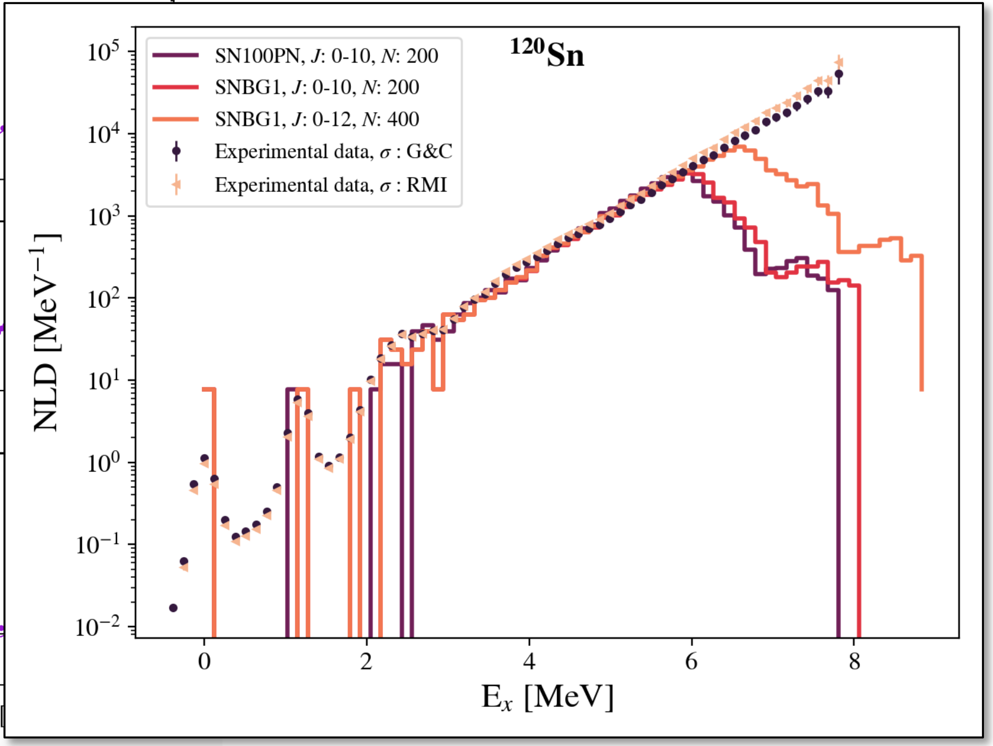
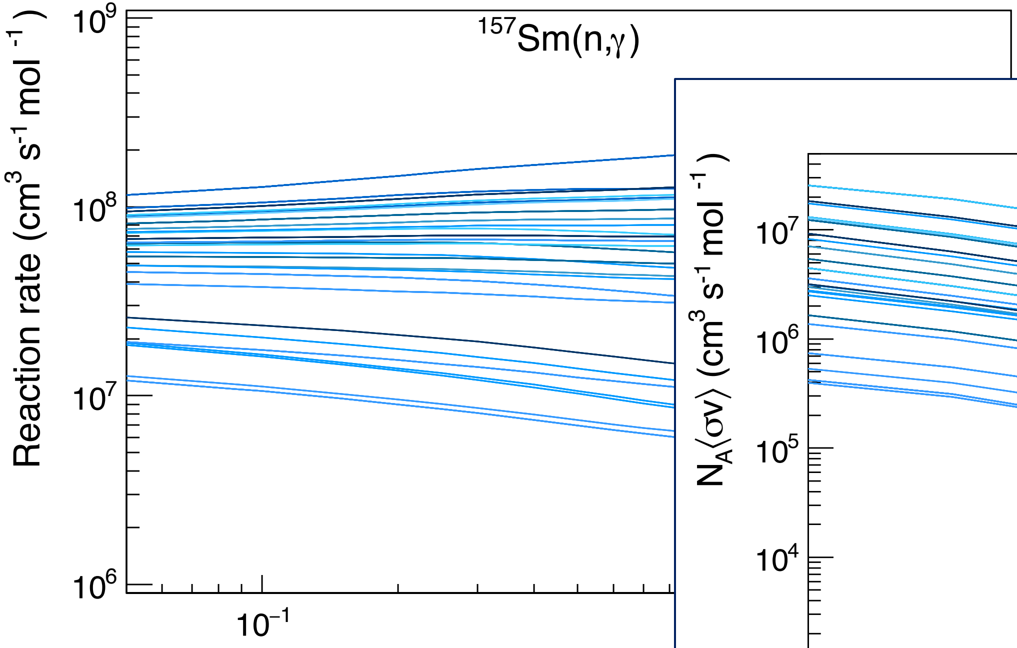
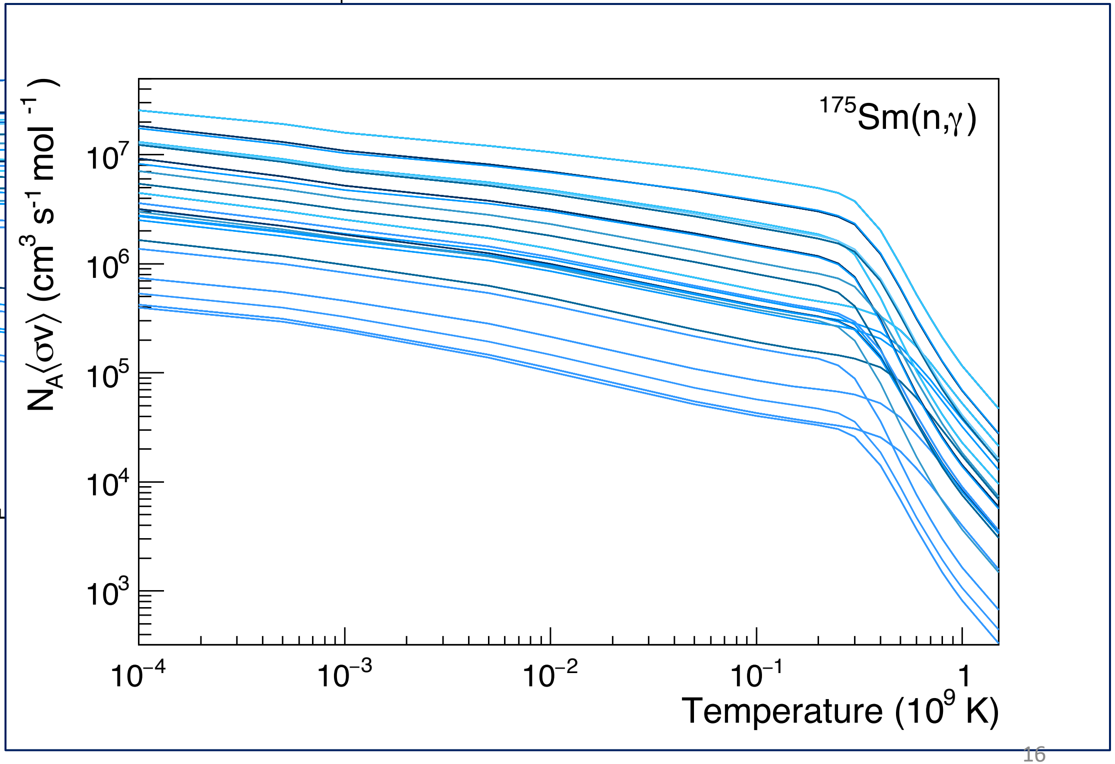


Jenny Finrud's Master thesis (2024): KSHELL calculations.
Exp. data from Maria Markova et al., PRC 106, 034322 (2022)



Theoretical $^{157}Sm(n,\gamma)$ and $^{175}Sm(n,\gamma)$ reaction rates

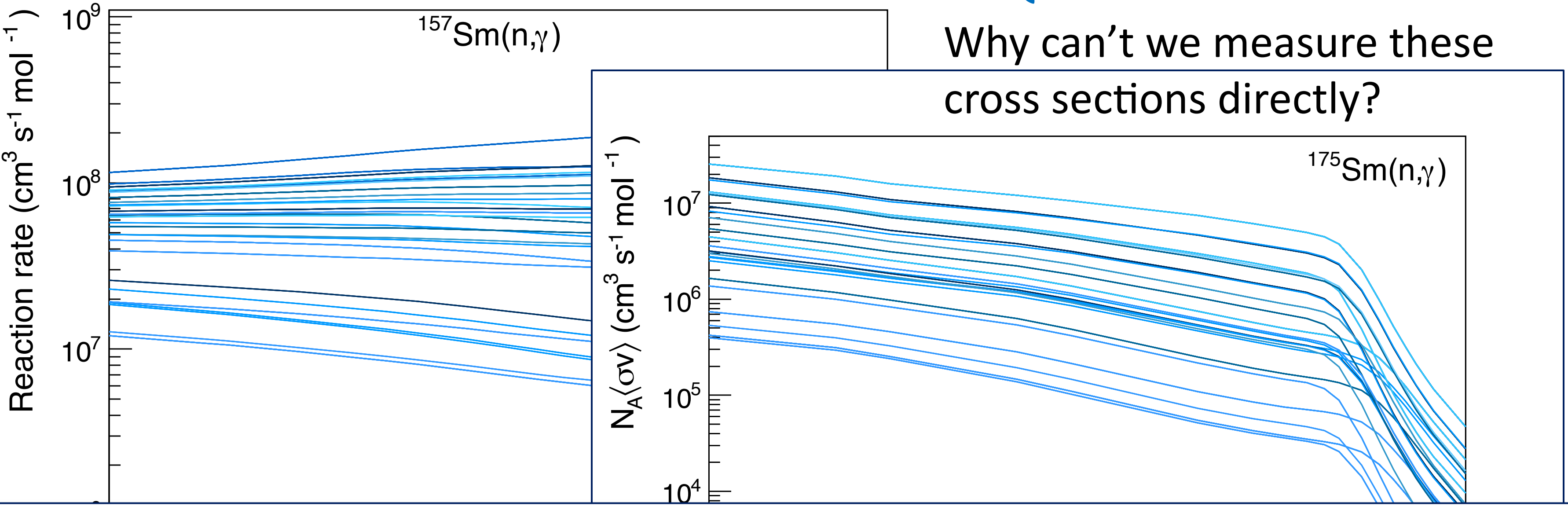




Theoretical ^{157}Sm(n,γ) and ^{175}Sm(n,γ) reaction rates

🤔 **Question:**

Why can't we measure these cross sections directly?



<u>How to treat these uncertainties?</u>

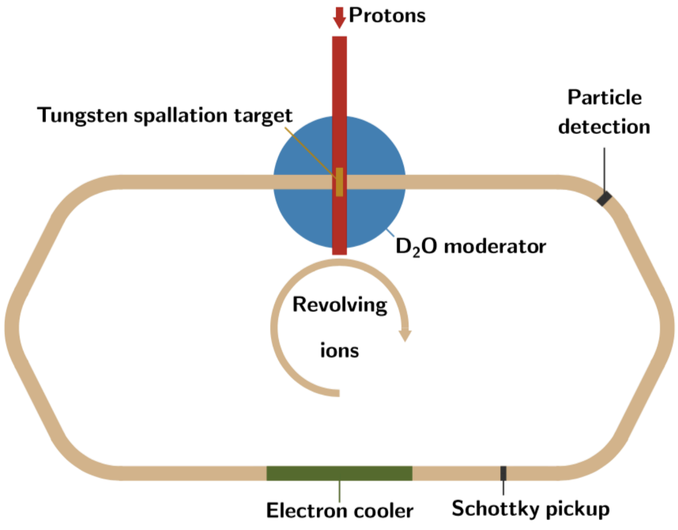
1) Monte Carlo approach: e.g. Mumpower et al., Prog. Part. Nucl. Phys. **86**, 86 (2016),
Denissenkov et al., J. Phys. G: Nucl. Part. Phys. **45**, 055203 (2018)
2) Systematic treatment, masses & β-decay, many trajectories: Kullmann et al., MNRAS 523, 2551 (2023)
3) Systematic treatment, level density and gamma-strength: Pogliano & Larsen, Phys. Rev. C 108, 025807 (2023)

Experimental efforts, neutron-capture reaction rates on neutron-rich nuclei

Direct approach:

combine a neutron source with a storage ring!

[Reifarth et al., Phys. Rev. Accel. Beams **20**, 044701 (2017)]



Indirect approaches:

- Surrogate method for direct capture

[e.g. Gaudefroy et al, Eur. Phys. J. A **27**, 309 (2006), Jones et al., Nature **465**, 454 (2010), Kozub et al., PRL **109**, 172501 (2012), ++]

- Surrogate method for "compound" capture

[e.g. Escher et al., PRL **121**, 052501 (2018), Ratkiewicz et al., PRL **122**, 052502 (2019), ++]

- Measure E1 strength with Coulomb dissociation

[e.g. Uberseder et al., PRL **112**, 211101 (2014)

- The Oslo method in inverse kinematics

[Ingeberg et al., EPJA 56, 68 (2020)]

- ***The Oslo and beta-Oslo methods: measure level density and γ-ray strength function***

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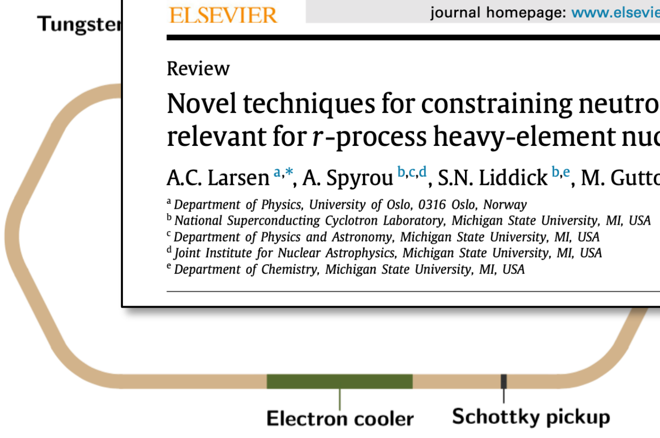

Progress in Particle and Nuclear Physics 107 (2019) 69–108

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Review

Novel techniques for constraining neutron-capture rates relevant for *r*-process heavy-element nucleosynthesis

A.C. Larsen [a,*], A. Spyrou [b,c,d], S.N. Liddick [b,e], M. Guttormsen [a]

[a] Department of Physics, University of Oslo, 0316 Oslo, Norway
[b] National Superconducting Cyclotron Laboratory, Michigan State University, MI, USA
[c] Department of Physics and Astronomy, Michigan State University, MI, USA
[d] Joint Institute for Nuclear Astrophysics, Michigan State University, MI, USA
[e] Department of Chemistry, Michigan State University, MI, USA

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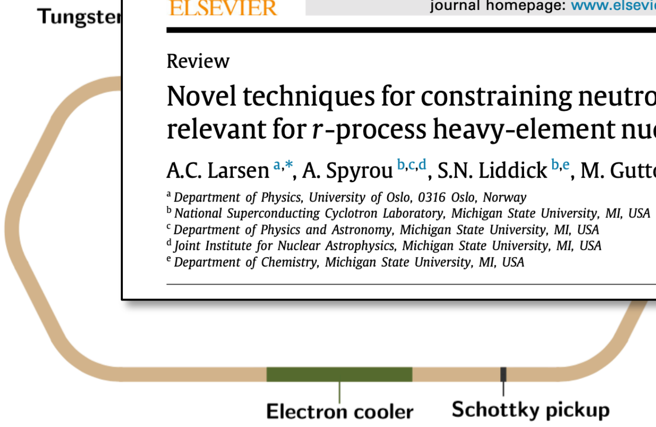

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Research

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Accepted: 22 January 2024

Photon strength functions and nuclear level densities: invaluable input for nucleosynthesis

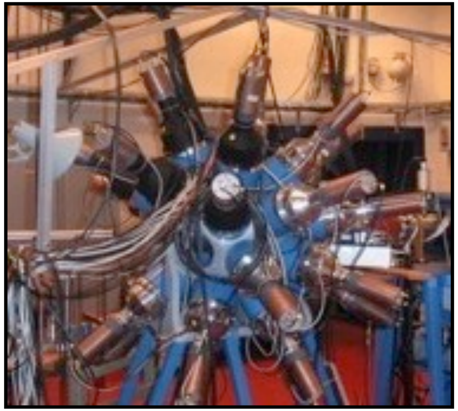
M. Wiedeking[1,2,3] and S. Goriely[4]

[1]SSC Laboratory, iThemba LABS, P.O. Box 722, Somerset West 7129, South Africa
[2]School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa
[3]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[4]Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Campus de la Plaine CP 226, Brussels 1050, Belgium

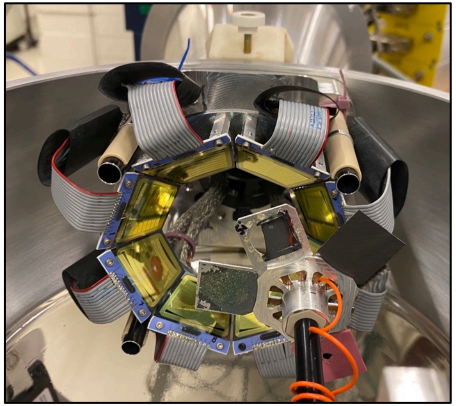
MW, 0000-0003-4983-3882

The pivotal role of nuclear physics in nucleosynthesis processes is being investigated, in particular the

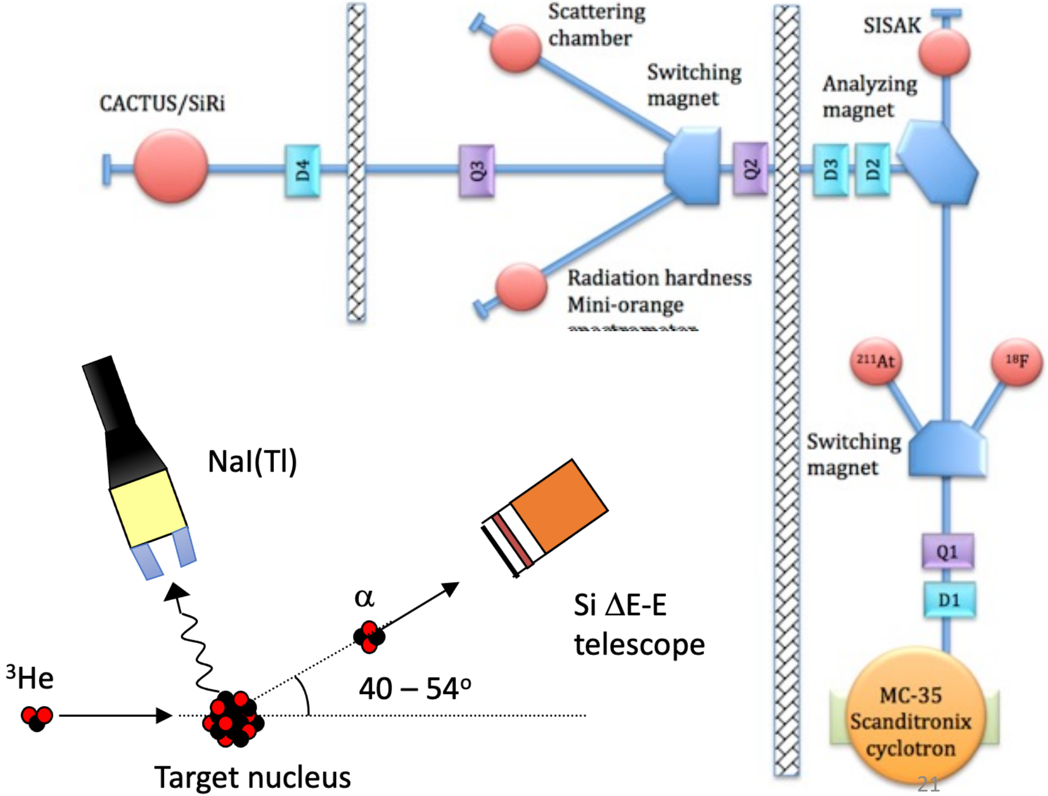
Experiments at the Oslo Cyclotron Lab, Univ. of Oslo



CACTUS:
26 (28) collimated NaI(Tl) crystals, 5’’ x 5’’



SiRi:
8x8 Si ΔE-E particle detectors (≈9% of 4π) [Guttormsen et al., NIM A 648, 168 (2011)]



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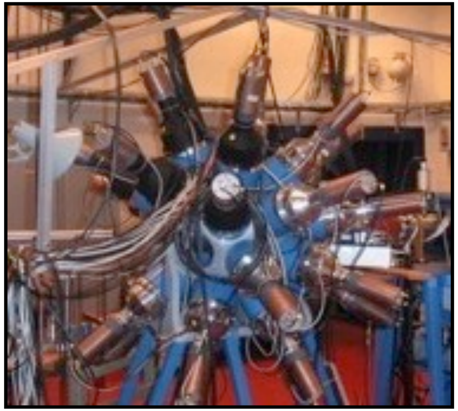

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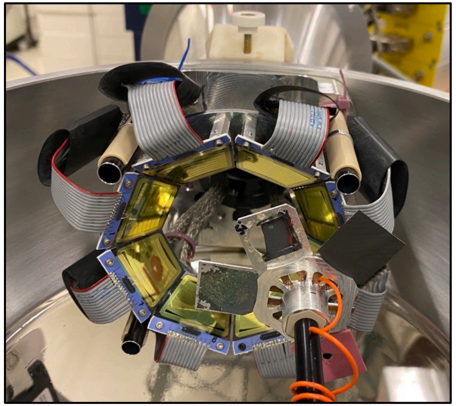

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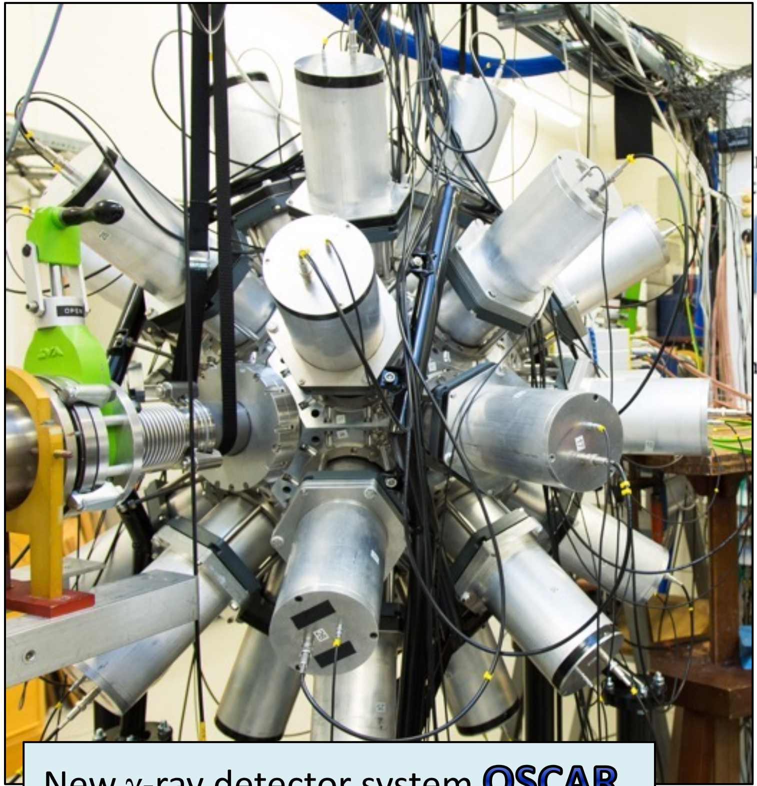
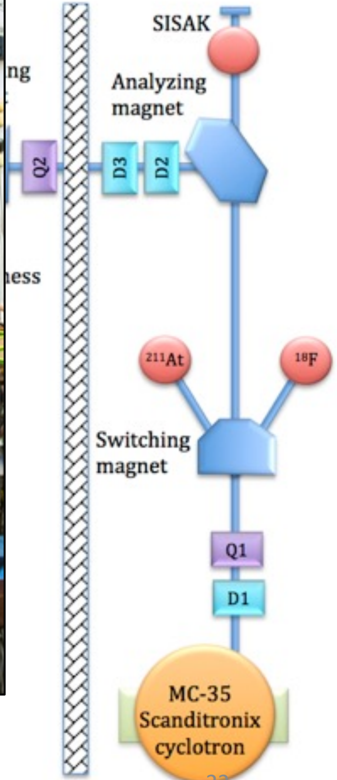


New γ-ray detector system **OSCAR**
30 $LaBr_3(Ce)$, 3.5'' x 8'' crystals
[Zeiser et al., NIM A 985, 164678 (2021)]



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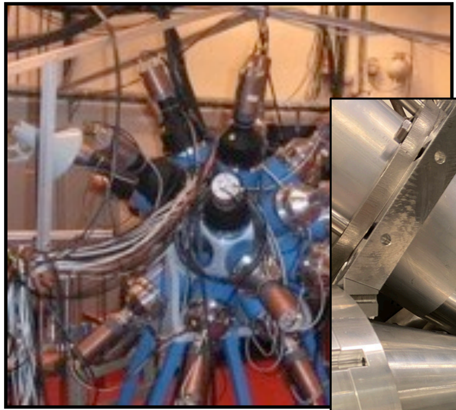

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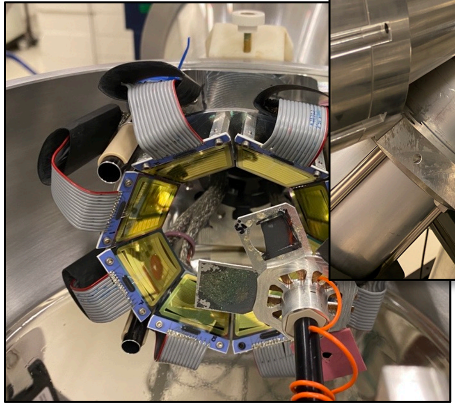

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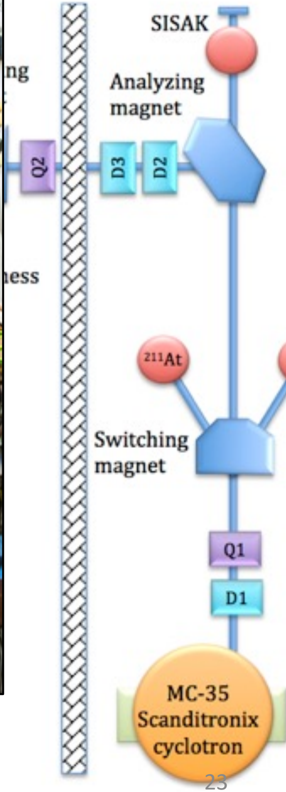
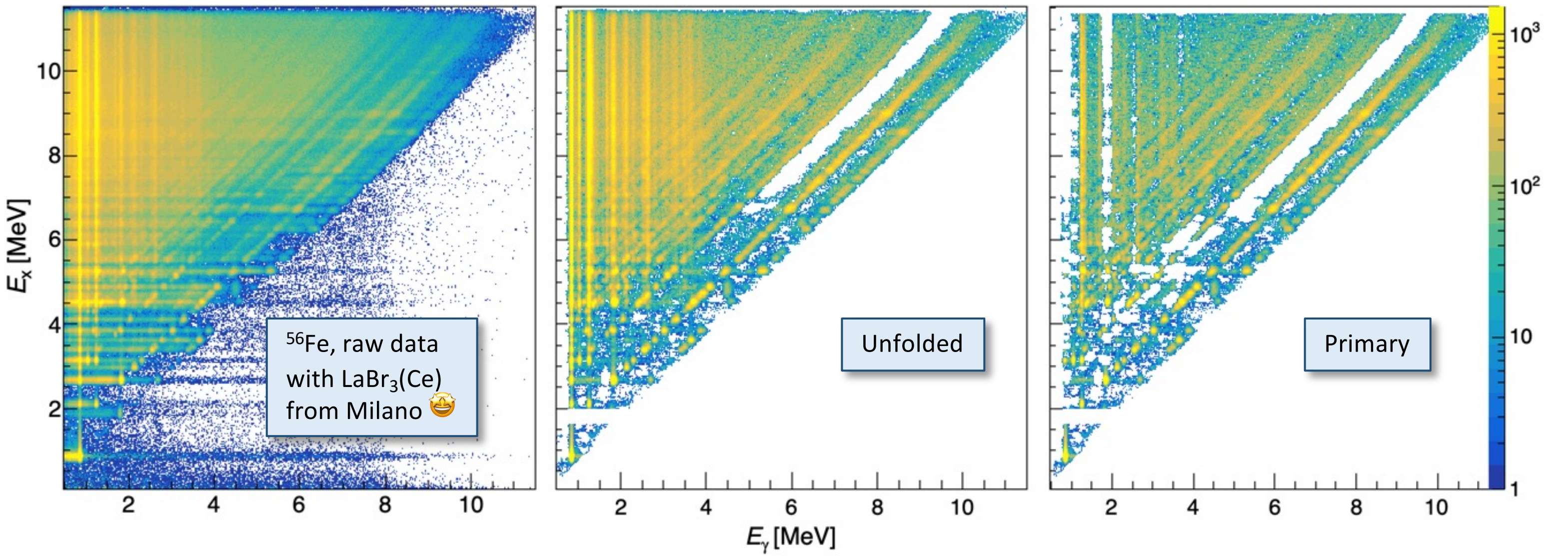


The Oslo method – a crash course 😎

[Data from Larsen et al., PRL **111**, 242504 (2013)
and J.Phys.G: Nucl. Part. Phys. 44, 064005 (2017)]



0. Get yourself an ($E\gamma$,E_x) matrix (>20 000 coincidences)
1. Correct for the γ-detector response [Guttormsen et al., NIM A 374, 371 (1996)]
2. Extract *distribution of* primary γs for each E_x [Guttormsen et al., NIM A 255, 518 (1987)]
3. Obtain level density and γ-strength from primary γ rays [Schiller et al., NIM A 447, 498 (2000)]
4. Normalize & evaluate systematic errors [Schiller et al., NIM A 447, 498 (2000), Larsen *et al.*, PRC **83**, 034315 (2011)]

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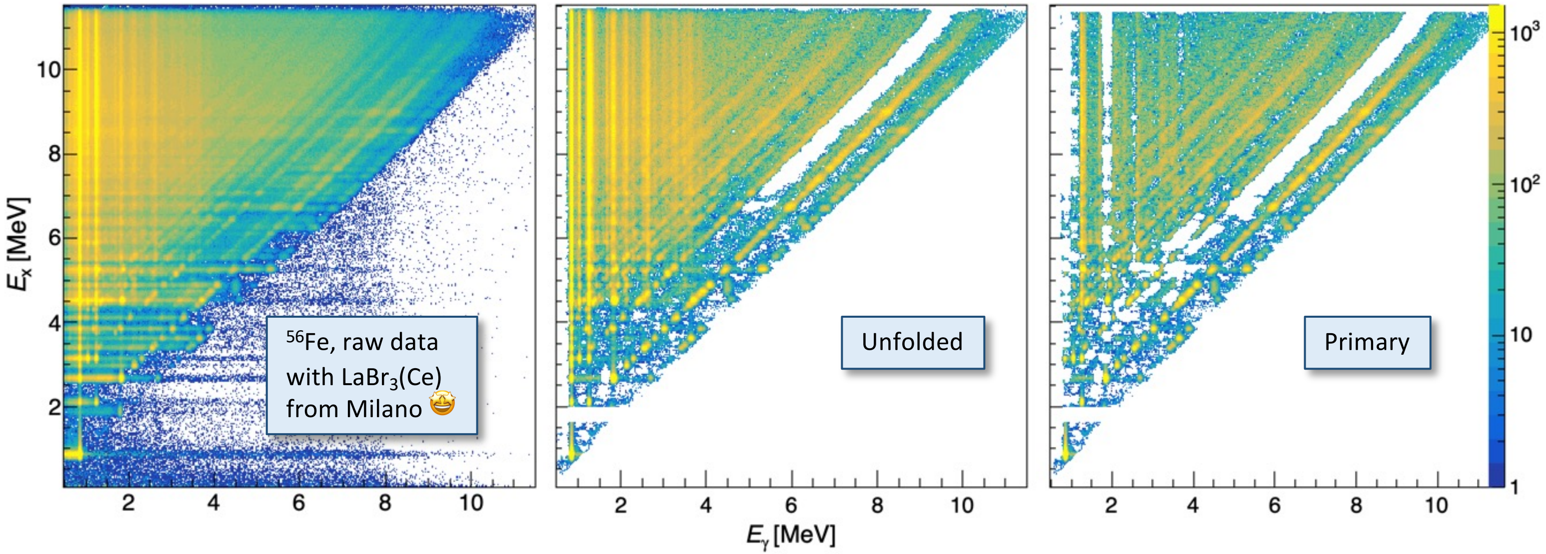

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Data and references (if something is missing, please let us know!):
https://ocl.uio.no/compilation/
Analysis codes and tools:
https://github.com/oslocyclotronlab/oslo-method-software
Python version OMpy (work in progress 🔨):
https://github.com/oslocyclotronlab/ompy

Measuring level density and γ-ray strength

Ansatz:

[generalization of Fermi´s Golden Rule]

Factorize the primary γ matrix:

$$P(E_\gamma, E_x) \propto \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$

where the gamma-decay strength (for dipole radiation)

$$f(E_\gamma) = \mathcal{T}(E_\gamma)/2\pi E_\gamma^3$$

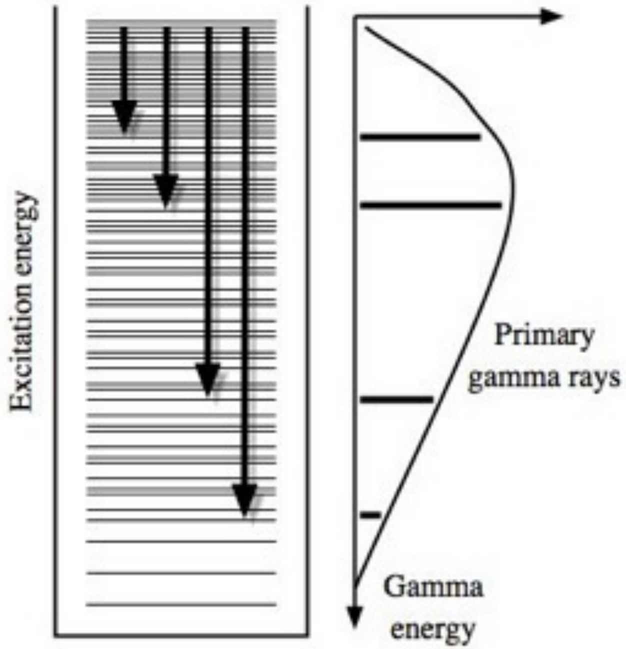
Two important assumptions:

✅ 1) The γ decay takes place *a long time* after the level is formed

🤔 2) The γ-ray strength function varies *slowly* with E_x (at high E_x – high level density)

-> the ***Brink hypothesis***

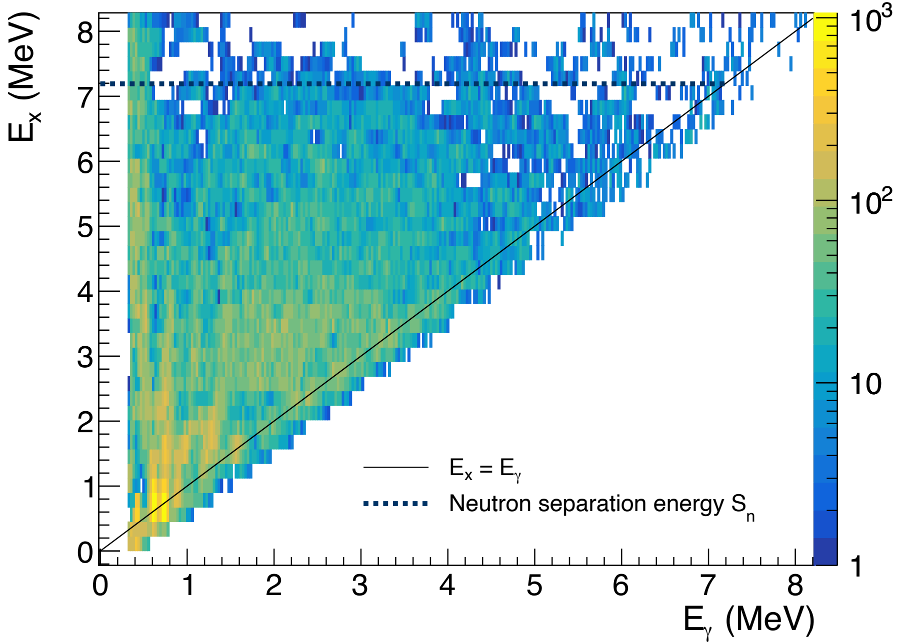
[Brink, Doctoral thesis, Oxford (1955) and Axel, Phys. Rev. **126**, 671 (1962)]

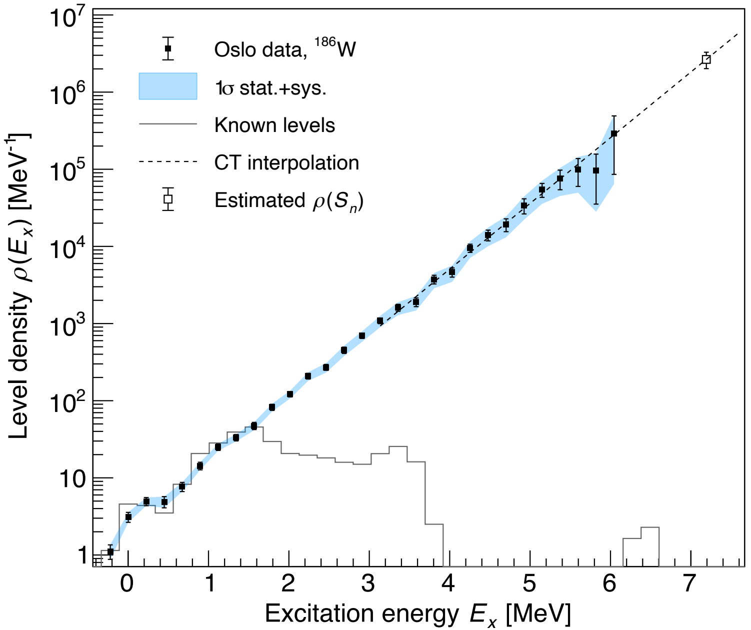


[Schiller et al., NIM A 447, 498 (2000)]

Using the data to calculate (n,γ) reaction rates

Primary γ rays

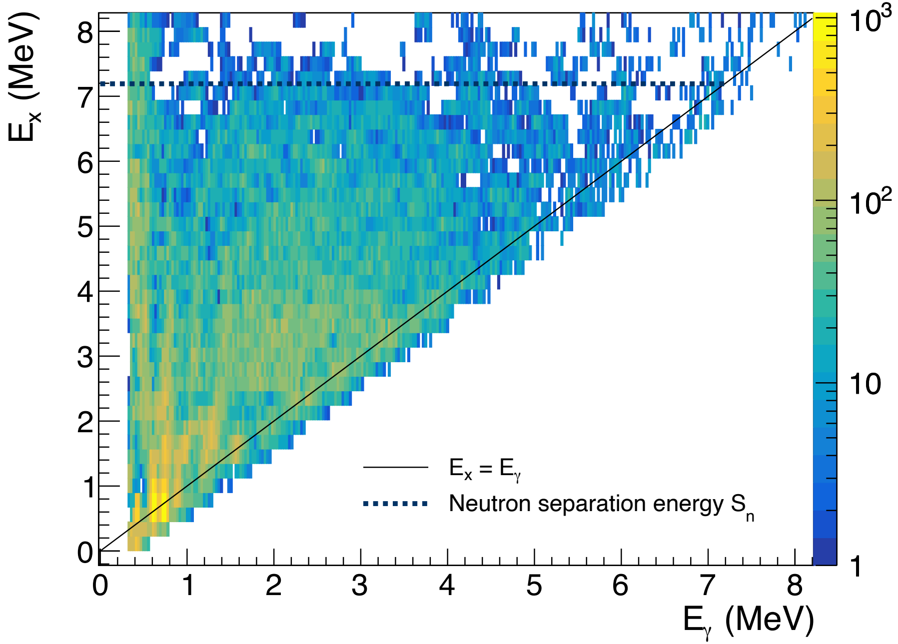


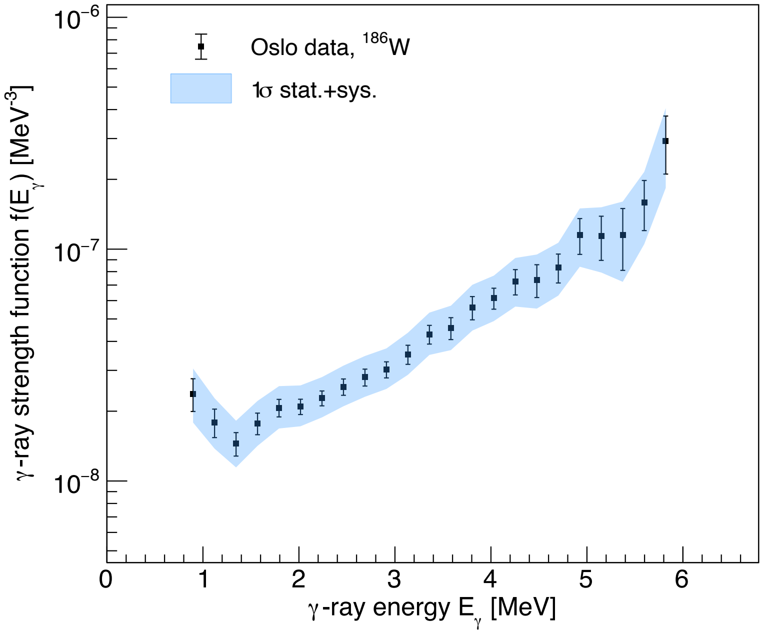


$^{186}W(\alpha,\alpha'\gamma)^{186}W$
[Larsen et al., PRC **108**, 025804 (2023)]

Using the data to calculate (n,γ) reaction rates

Primary γ rays





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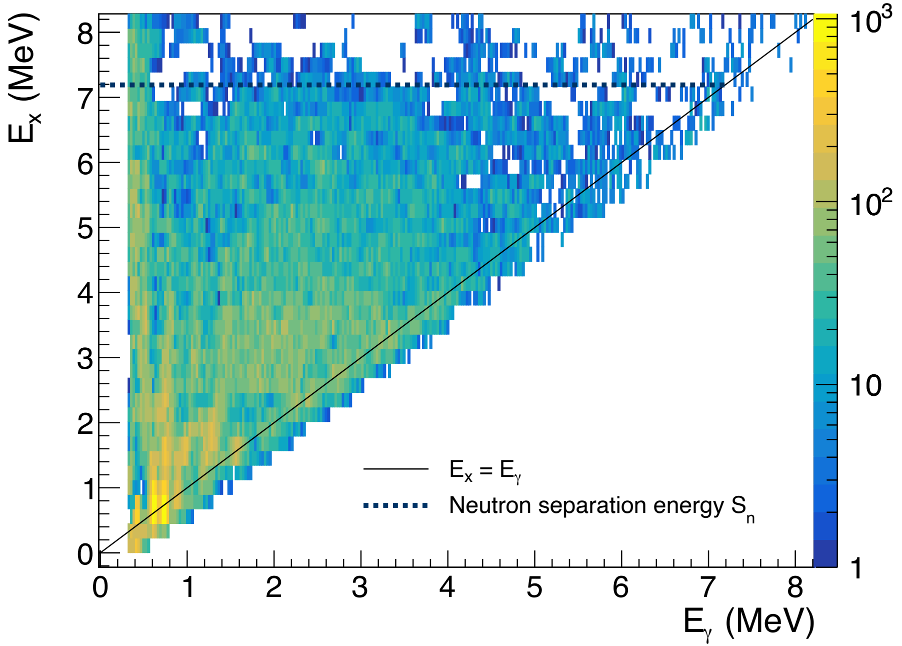
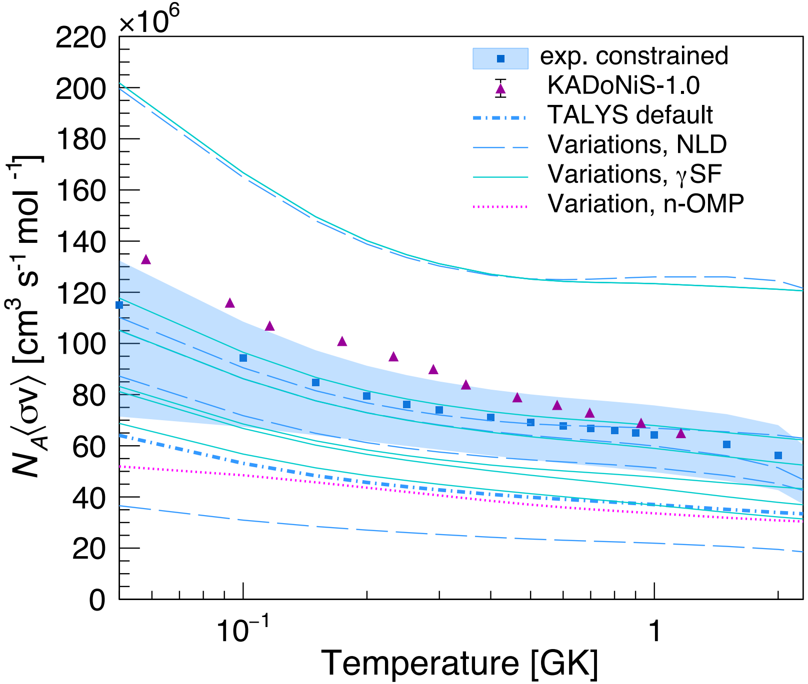
[Larsen et al., PRC **108**, 025804 (2023)]

Using the data to calculate (n,γ) reaction rates

Primary γ rays





$^{186}W(\alpha,\alpha'\gamma)^{186}W$
[Larsen et al., PRC **108**, 025804 (2023)]

Surprise! The low-energy upbend

VOLUME 93, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 1 OCTOBER 2004

Large Enhancement of Radiative Strength for Soft Transitions in the Quasicontinuum

A. Voinov,[1,2,*] E. Algin,[3,4,5,6] U. Agvaanluvsan,[3,4] T. Belgya,[7] R. Chankova,[8] M. Guttormsen,[8] G. E. Mitchell,[4,5] J. Rekstad,[8] A. Schiller,[3,†] and S. Siem[8]

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[4]*North Carolina State University, Raleigh, North Carolina 27695, USA*
[5]*Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA*
[6]*Department of Physics, Osmangazi University, Meselik, Eskisehir, 26480 Turkey*
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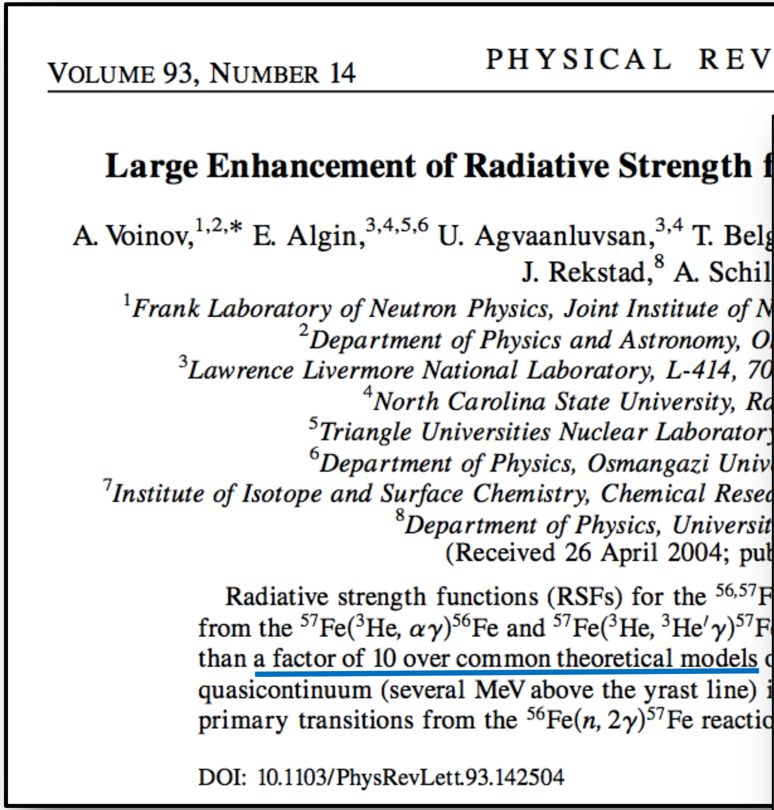
(Received 26 April 2004; published 29 September 2004)

Radiative strength functions (RSFs) for the ^{56,57}Fe nuclei below the separation energy are obtained from the ^{57}Fe(^{3}He, $\alpha\gamma$)^{56}Fe and ^{57}Fe(^{3}He, ^{3}He$'\gamma$)^{57}Fe reactions, respectively. An enhancement of more than a factor of 10 over common theoretical models of the soft ($E_\gamma \lesssim 2$ MeV) RSF for transitions in the quasicontinuum (several MeV above the yrast line) is observed. Two-step cascade intensities with soft primary transitions from the ^{56}Fe(n, 2γ)^{57}Fe reaction confirm the enhancement.

DOI: 10.1103/PhysRevLett.93.142504 PACS numbers: 25.40.Lw, 25.20.Lj, 25.55.Hp, 27.40.+z

Surprise! The low-energy upbend



VOLUME 93, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 1 OCTOBER 2004

Large Enhancement of Radiative Strength f

A. Voinov,[1,2,*] E. Algin,[3,4,5,6] U. Agvaanluvsan,[3,4] T. Belg
J. Rekstad,[8] A. Schil
[1]*Frank Laboratory of Neutron Physics, Joint Institute of N*
[2]*Department of Physics and Astronomy, O*
[3]*Lawrence Livermore National Laboratory, L-414, 70*
[4]*North Carolina State University, Ra*
[5]*Triangle Universities Nuclear Laborator*
[6]*Department of Physics, Osmangazi Univ*
[7]*Institute of Isotope and Surface Chemistry, Chemical Resea*
[8]*Department of Physics, Universit*
(Received 26 April 2004; pub

Radiative strength functions (RSFs) for the ^{56,57}F
from the ^{57}Fe(^{3}He, $\alpha\gamma$)^{56}Fe and ^{57}Fe(^{3}He, ^{3}He$'\gamma$)^{57}F
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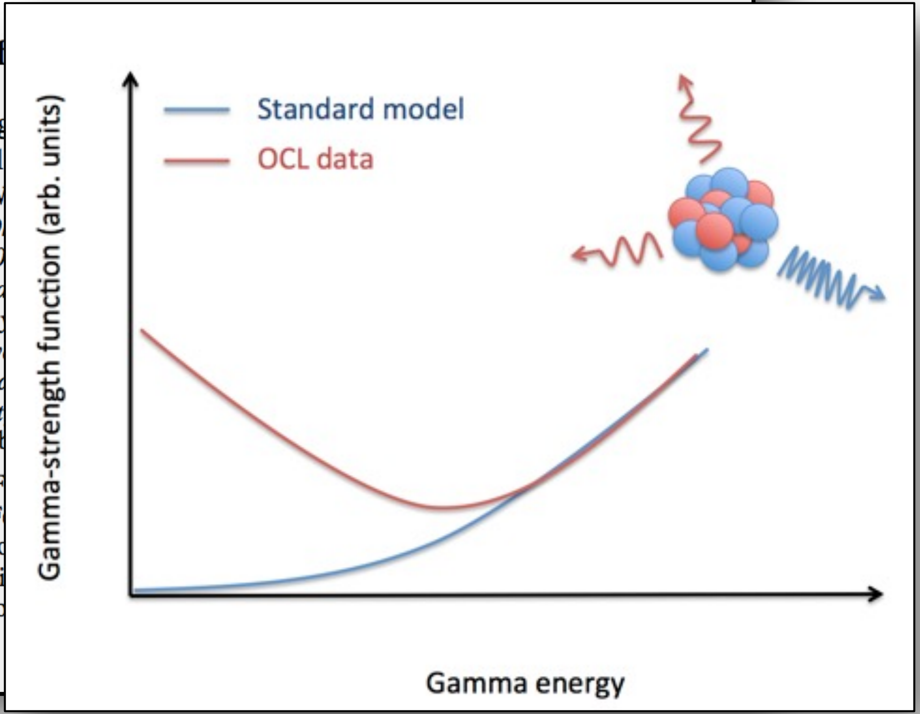
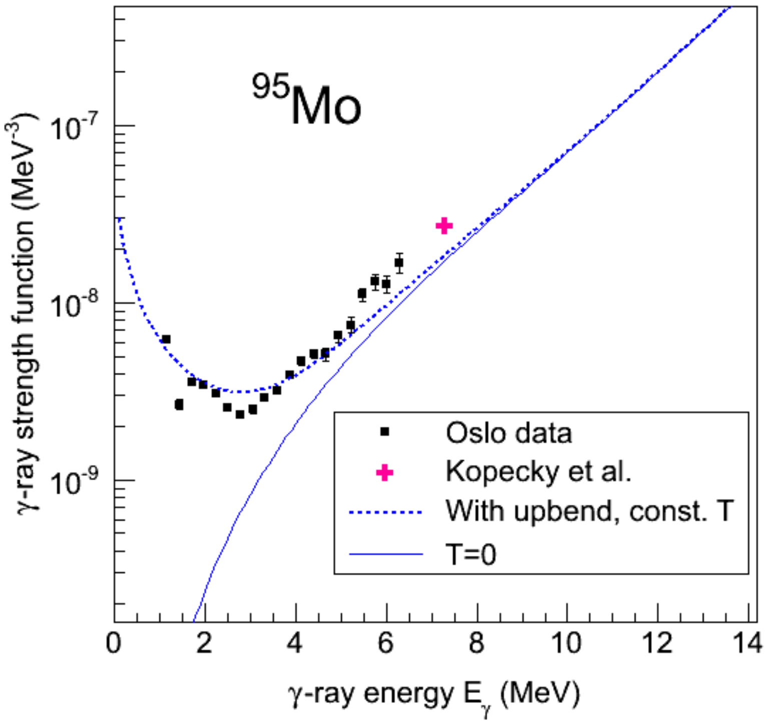
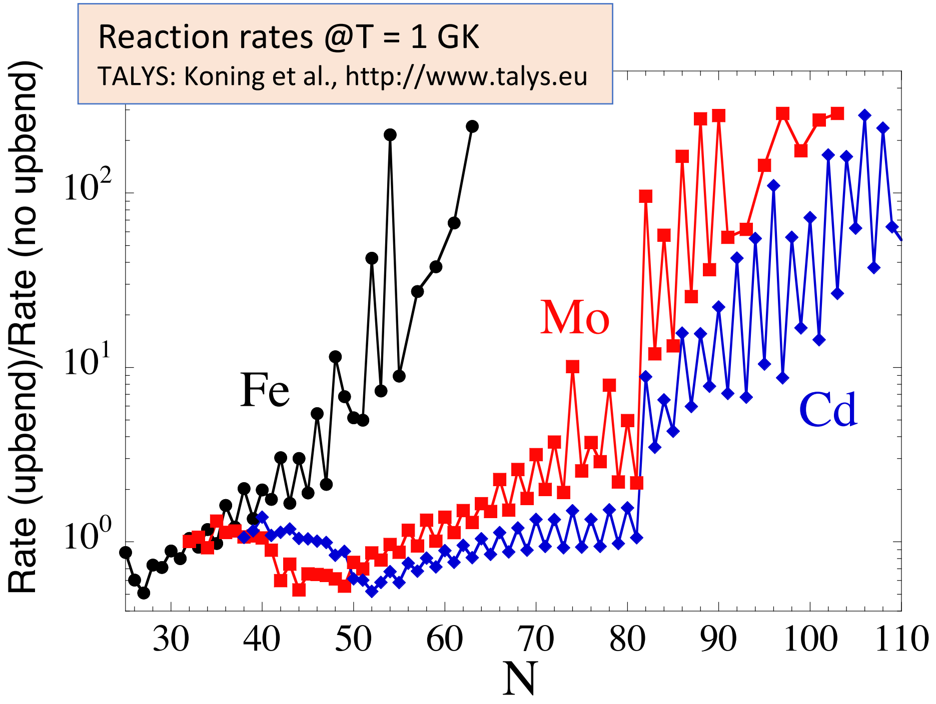
DOI: 10.1103/PhysRevLett.93.142504



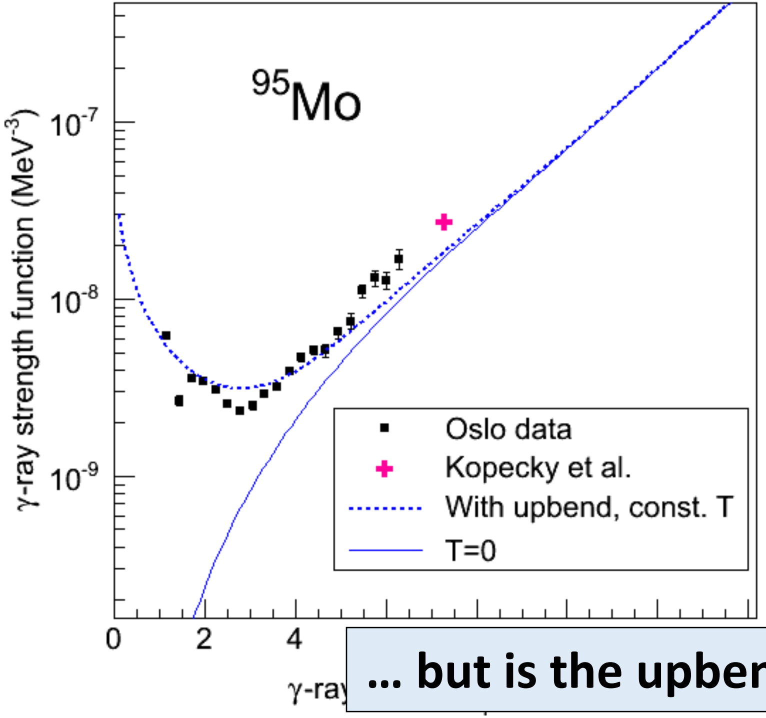
Impact on *r*-process (n,γ) reaction rates?

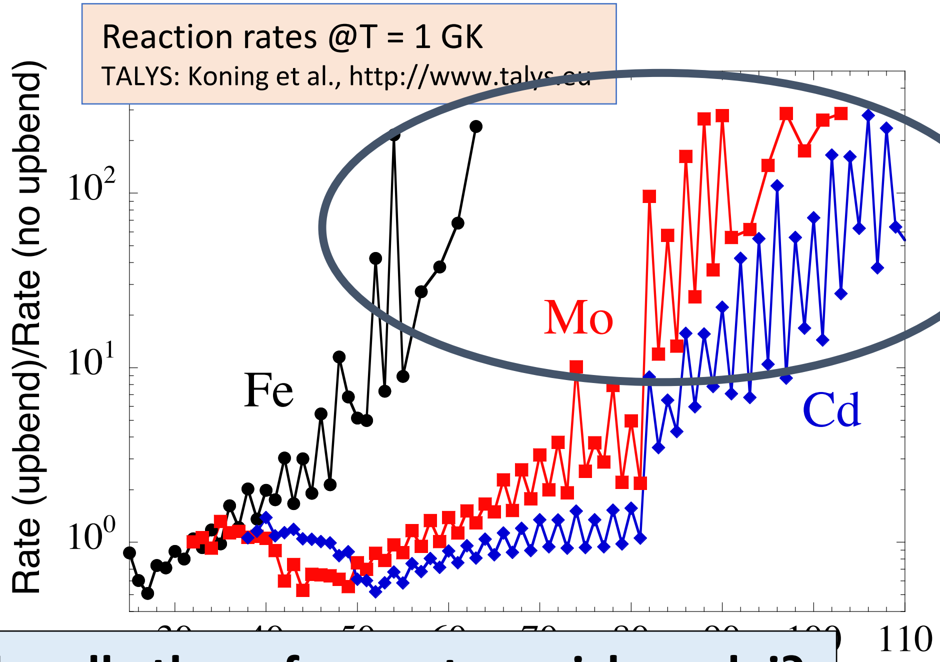




[A.C. Larsen and S. Goriely, Phys. Rev. C **82**, 014318 (2010)]

Impact on *r*-process (n,γ) reaction rates?





… but is the upbend really there for neutron-rich nuclei?

[A.C. Larsen and S. Goriely, Phys. Rev. C **82**, 014318 (2010)]

Overview of indirect experiments, unstable nuclei

- Surrogate method, direct capture
- Surrogate method, compound capture
- Coulomb dissociation
- Oslo method in inverse kinematics
- β-Oslo method

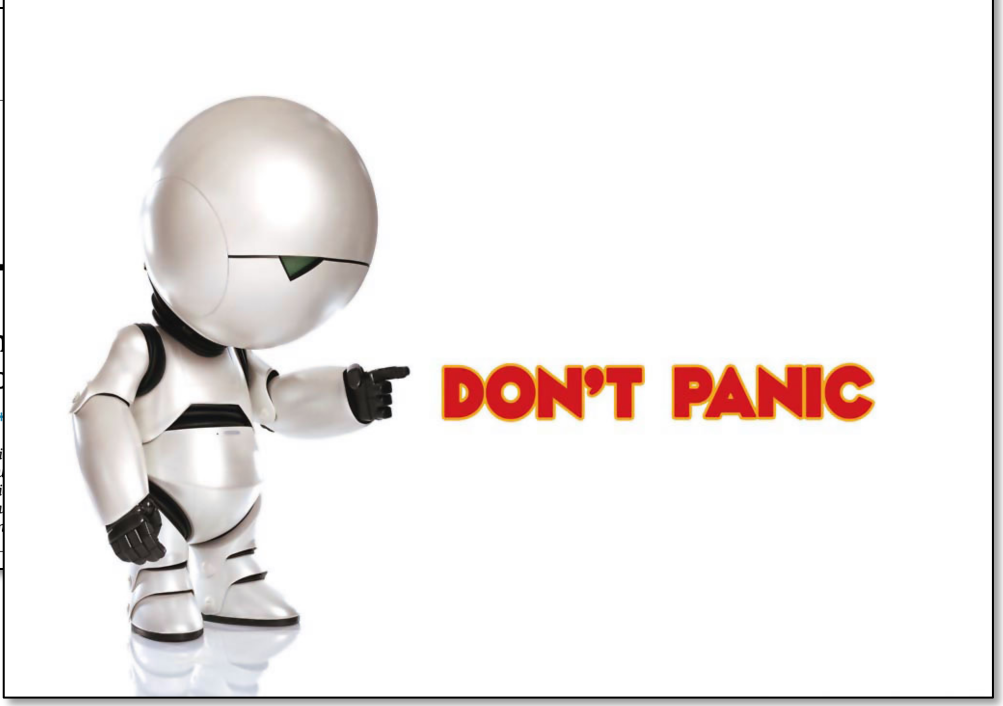

ELSEVIER

Review

Novel tech
relevant fo

A.C. Larsen [a,*]

[a] Department of Physi
[b] National Supercondu
[c] Department of Physi
[d] Joint Institute for Nu
[e] Department of Chem



Picture from qmediasolutions.com

More details in the refs on the slides, summarized in Larsen et
https://doi.org/10.1016/j.ppnp.2019.04.002

Overview of indirect experiments, unstable nuclei

- Surrogate method, direct capture
- Surrogate method, compound capture
- Coulomb dissociation
- Oslo method in inverse kinematics
- β-Oslo method

Progress in Particle and Nuclear Physics 107 (2019) 69–108

Contents lists available at ScienceDirect

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

Review

Novel techniques for constraining neutron-capture rates relevant for *r*-process heavy-element nucleosynthesis

A.C. Larsen [a,*], A. Spyrou [b,c,d], S.N. Liddick [b,e], M. Guttormsen [a]

[a] *Department of Physics, University of Oslo, 0316 Oslo, Norway*
[b] *National Superconducting Cyclotron Laboratory, Michigan State University, MI, USA*
[c] *Department of Physics and Astronomy, Michigan State University, MI, USA*
[d] *Joint Institute for Nuclear Astrophysics, Michigan State University, MI, USA*
[e] *Department of Chemistry, Michigan State University, MI, USA*

More details in the refs on the slides, summarized in Larsen et al., PPNP 107, 69 (2019)
https://doi.org/10.1016/j.ppnp.2019.04.002

First, you need to produce radioactive nuclei! 🤩

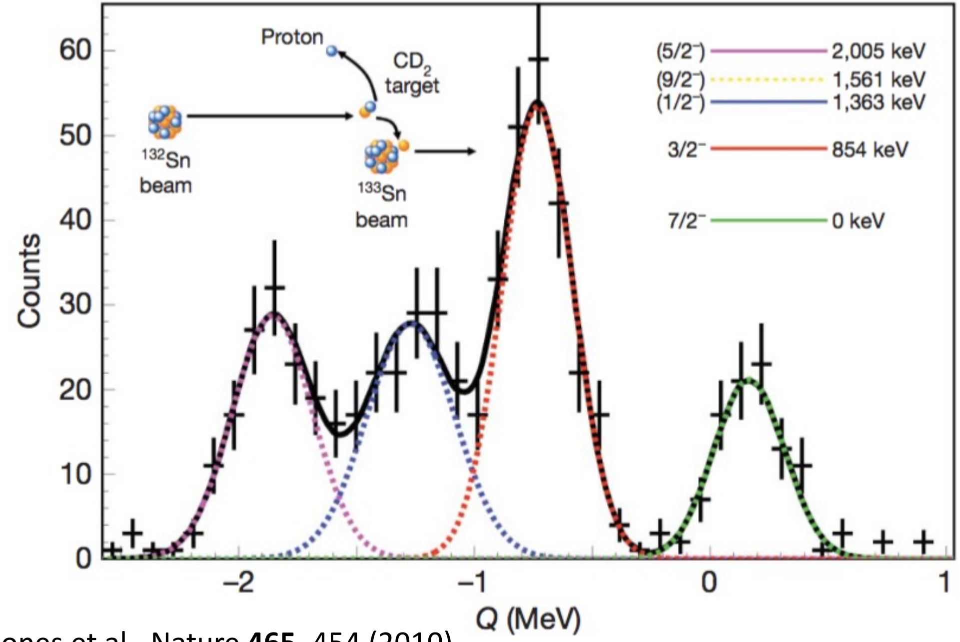
Stolen from Alexander Gottberg, IPAC 2018

🤔 **Question:**

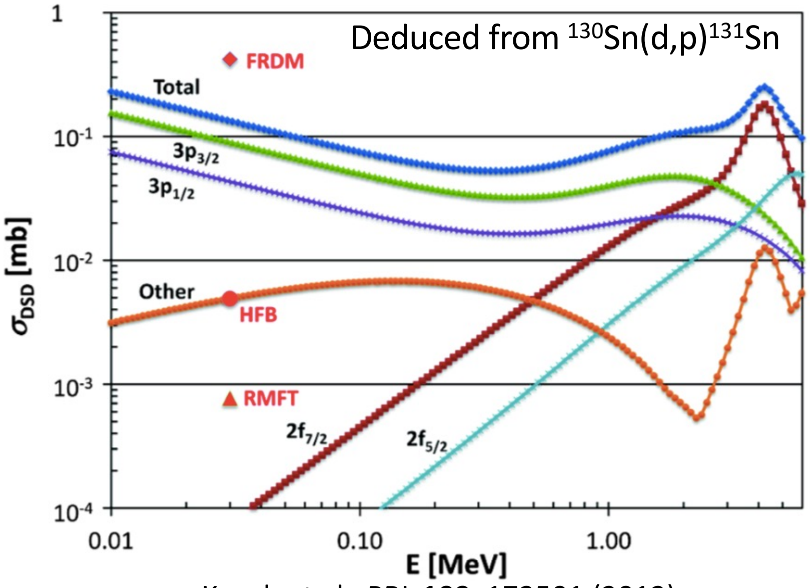
Can you find a missing lab in this map?

Surrogate method, direct capture via (d,p)

- Direct capture: “fast” ~10^{-22} s (similar to direct reaction), ≈pure wave functions
- Angular distributions of protons => dominant s.p. orbitals => spins



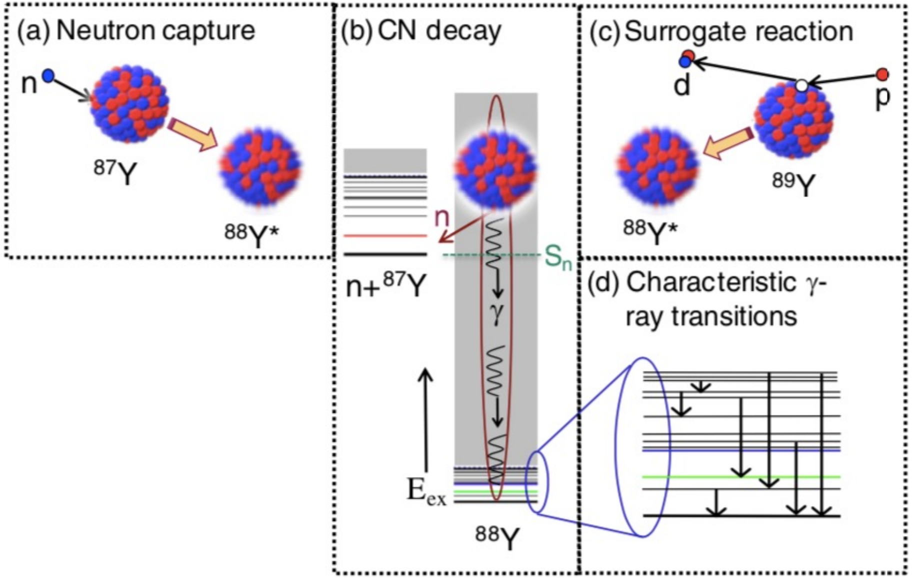
Jones et al., Nature **465,** 454 (2010)

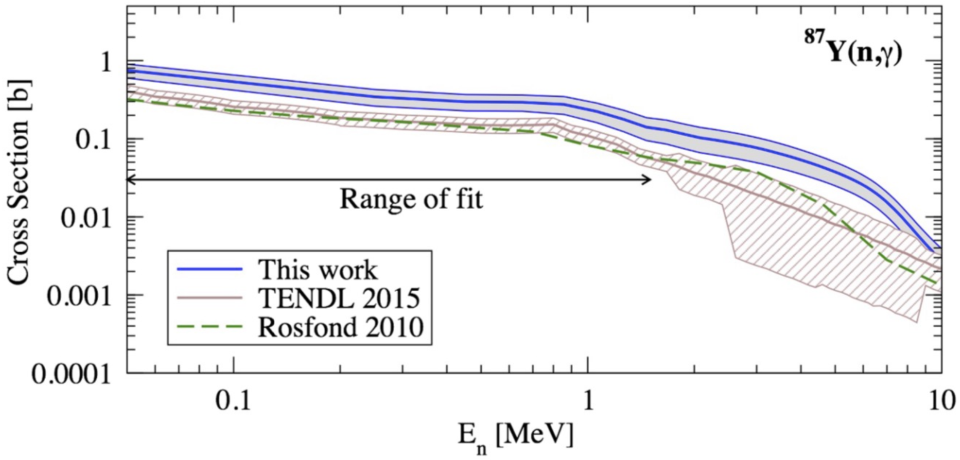


Kozub et al., PRL **109**, 172501 (2012)

Surrogate method, compound capture

- Compound capture: “long” time to thermalize (half life ~10^{-15-18} s), very complicated wave functions
- By gating on discrete levels in the residual nucleus, one can select different decay paths representing different initial spins

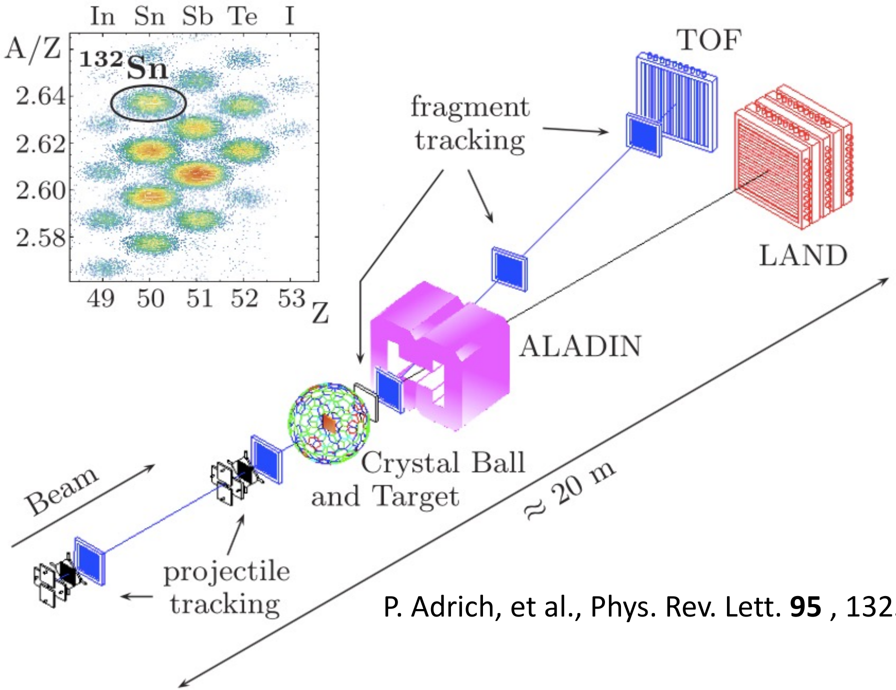


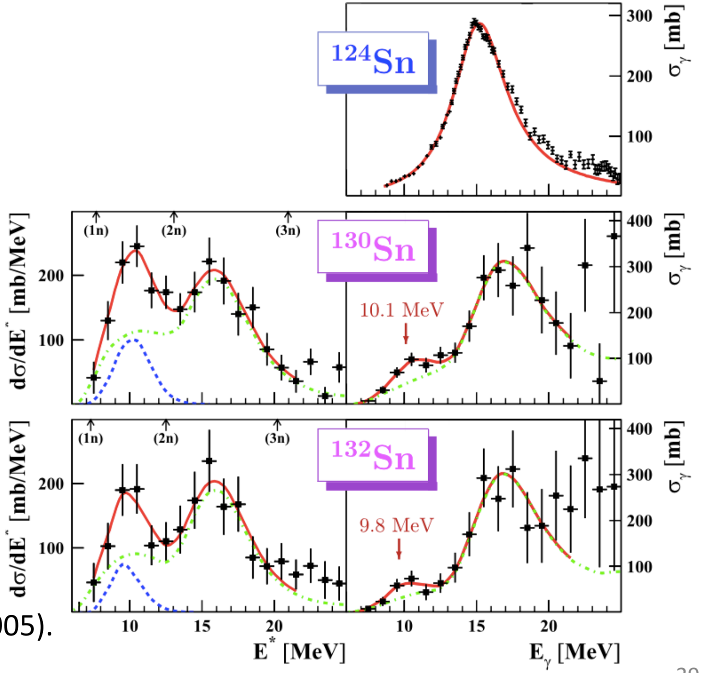


Escher et al., Phys. Rev. Lett. **121**, 052501 (2018).

Coulomb dissociation

- The radioactive nucleus gets excited by the Coulomb field of a high-Z target, leading to a (γ,n) reaction => γ-strength function above S_n

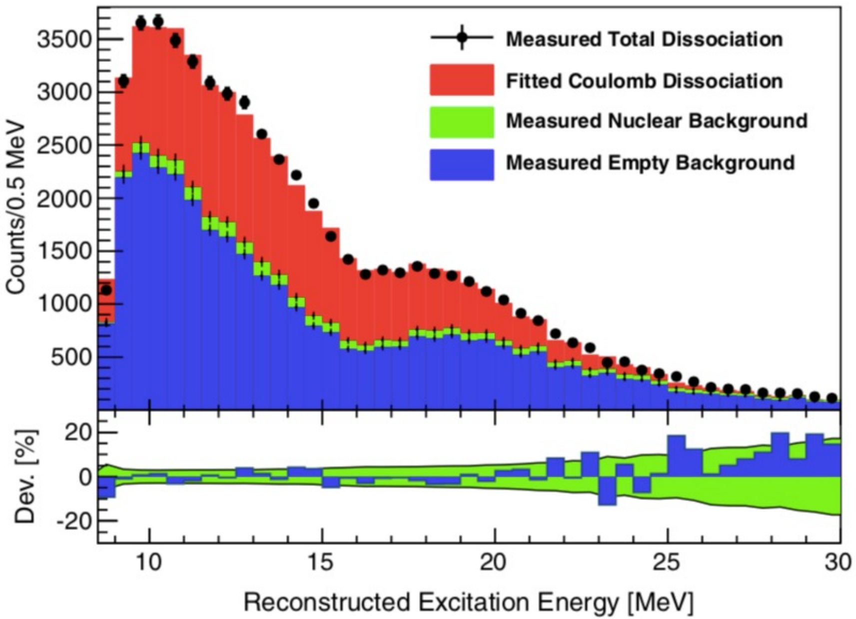


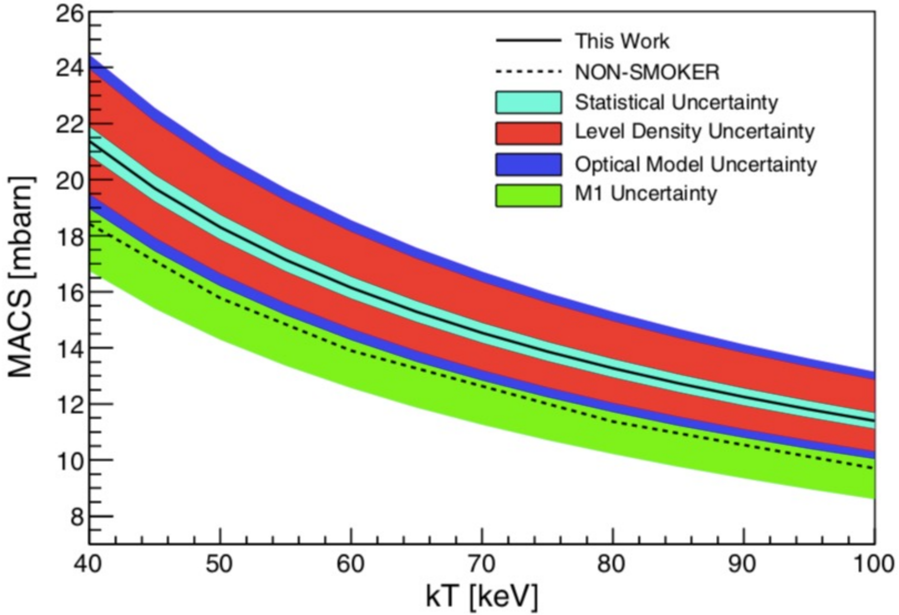


P. Adrich, et al., Phys. Rev. Lett. **95** , 132501 (2005).

Coulomb dissociation and derived $^{59}Fe(n,\gamma)$ rate

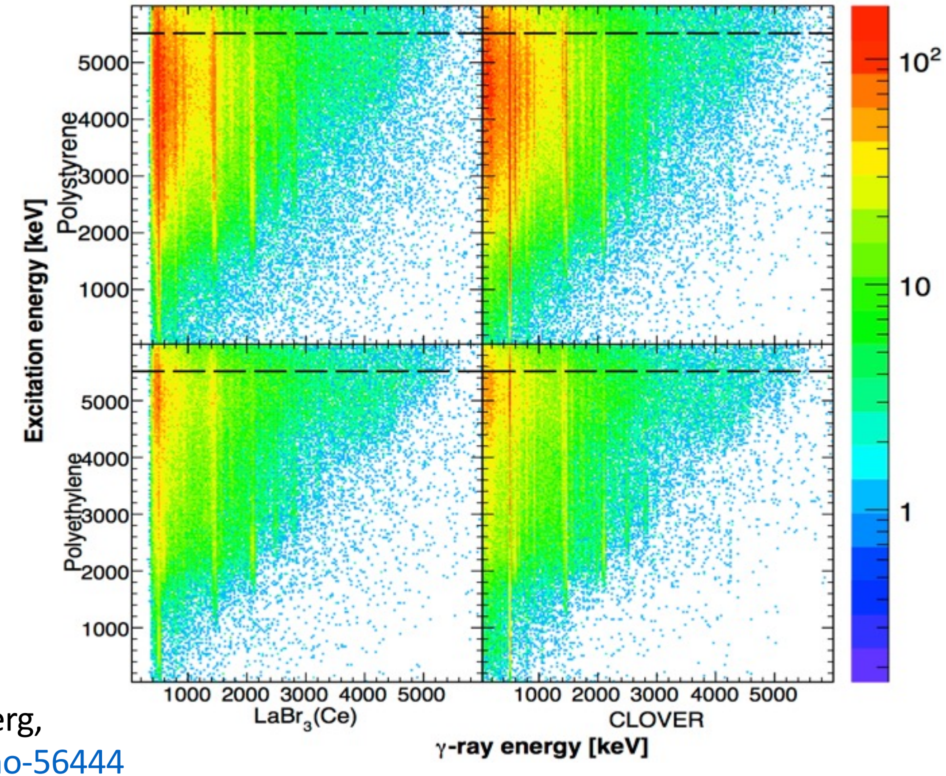
- Uberseder et al., PRL **112**, 211101 (2014)





The Oslo method in inverse kinematics

Proof-of-principle:
$^{86}Kr(d,p\gamma)^{87}Kr$,
inverse kinematics
iThemba LABS,
April/May 2015



MSc thesis of Vetle W. Ingeberg,
http://urn.nb.no/URN:NBN:no-56444

The Oslo method in inverse kinematics

Ingeberg et al., Eur. Phys. J. A **56**, 68 (2020)

Proof-of-principle:
^{86}Kr(d,pγ)^{87}Kr,
inverse kinematics
iThemba LABS,
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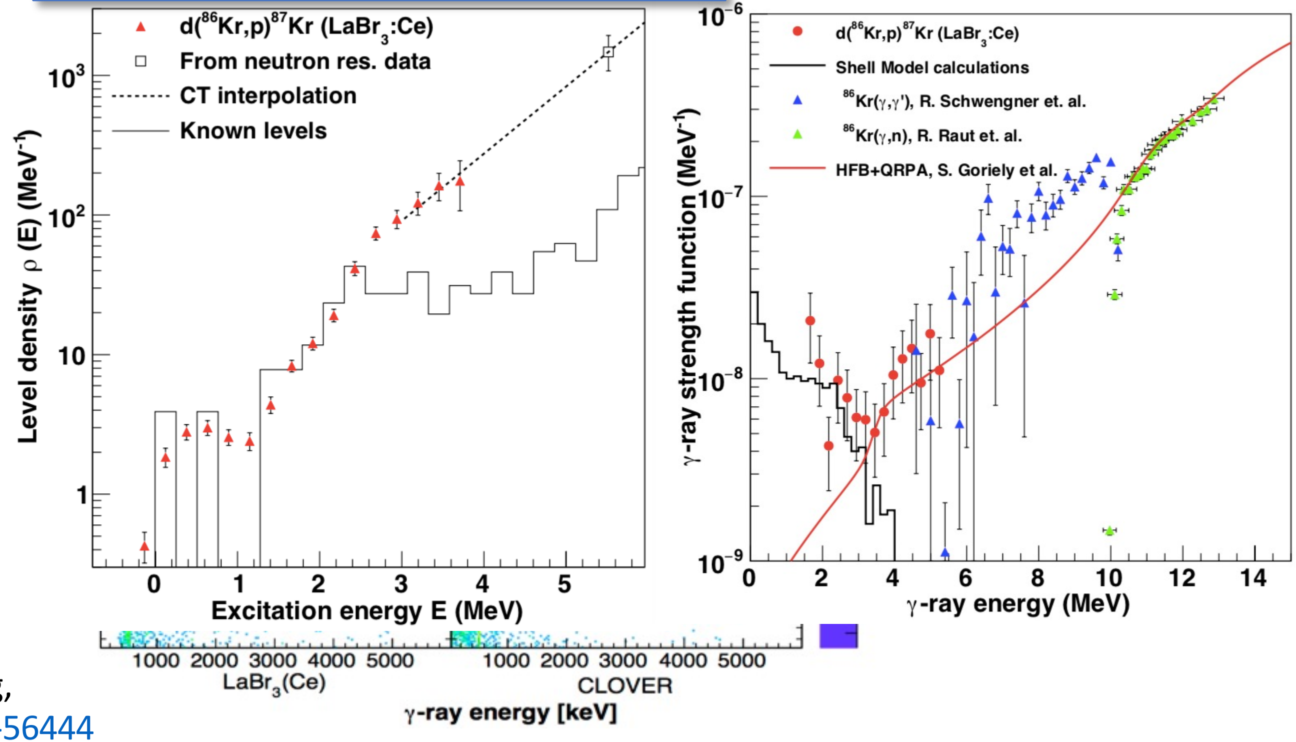
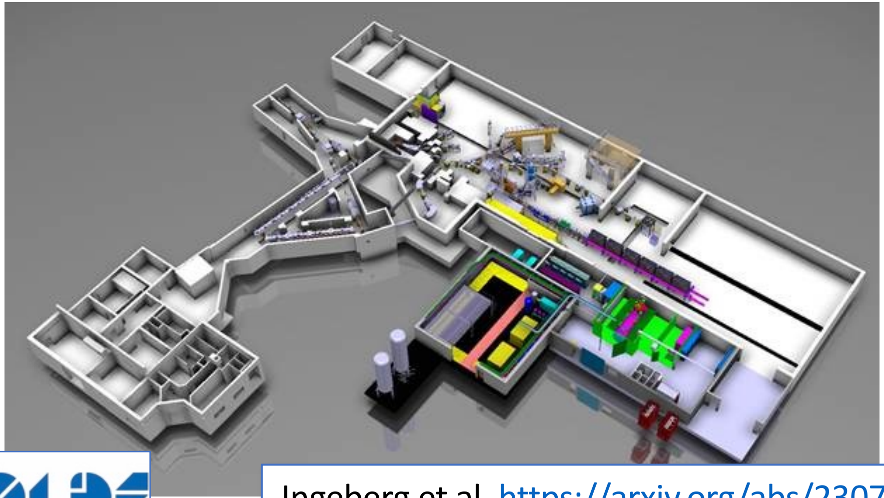


MSc thesis of Vetle W. Ingeberg,
http://urn.nb.no/URN:NBN:no-56444

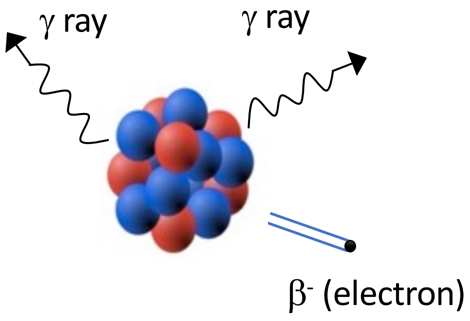
The Oslo method in inverse kinematics

HIE-ISOLDE experiment:
7-14 November 2016, $^{66}Ni(d,p\gamma)^{67}Ni$ in inverse kinematics
[Similar to Diriken et al., PRC **91**, 054321 (2015) but with ≈5MeV/nucleon]
MINIBALL array [P. Reiter et al., NPA 701, 209 (2002)]
+ two 3.5”x8” $LaBr_3(Ce)$ detectors from Oslo + CD detectors



Ingeberg et al. https://arxiv.org/abs/2307.07153 (in review, PRC)

The beta-Oslo method



Main idea:

Because the *Q*-value quickly gets large for neutron-rich nuclei (comparable to S_n):
populate highly excited states in the daughter nucleus by β^- decay of its mother

Recipe:

1) Implant a neutron-rich nucleus inside a *highly efficient* (≈4π), *segmented* total-absorption spectrometer (preferably with $Q_\beta \approx S_n$)
2) Measure β^- in coincidence with *all* γ rays from the daughter nucleus
3) Apply the Oslo method to the (E_x, E_γ) matrix to extract level density & γ- strength

A quick reminder about β⁻ decay & selection rules

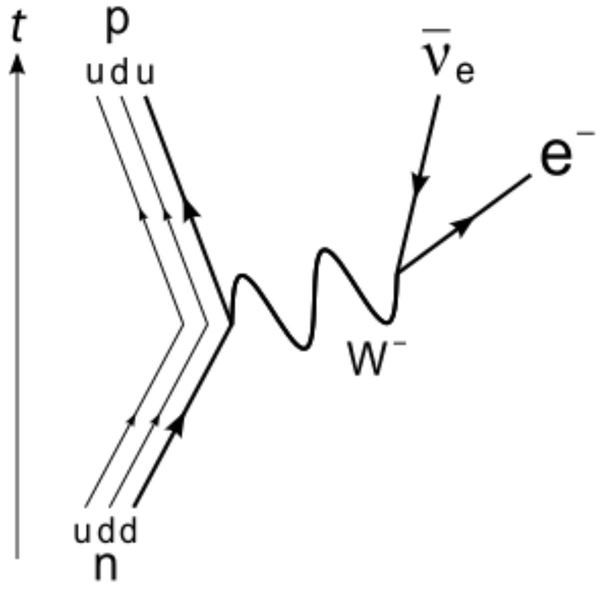


Figure from Wikipedia

- **Superallowed (Fermi) transitions: ΔJ = 0; Δπ= no**
- **Allowed (Gamow-Teller): ΔJ = 0,1; Δπ= no**
- First forbidden: ΔJ = 0,1,2; Δπ= yes
- Second forbidden: ΔJ = 1,2,3; Δπ= no
- …

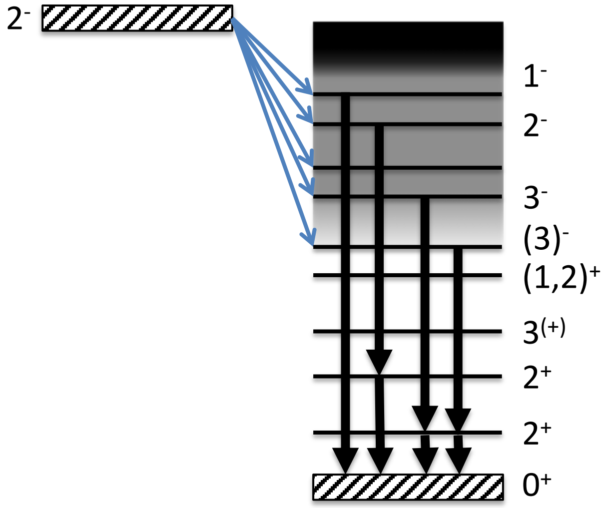
🤔 **Questions:**

1) Which initial spins and parity are populated after Gamow-Teller beta- decay from the ^{76}Ga ground state (spin/parity 2^-) into ^{76}Ge?
2) Which final spins and parity are reached in ^{76}Ge after one E1 transition?
3) Same as 2) but for one M1 transition?

The beta-Oslo method

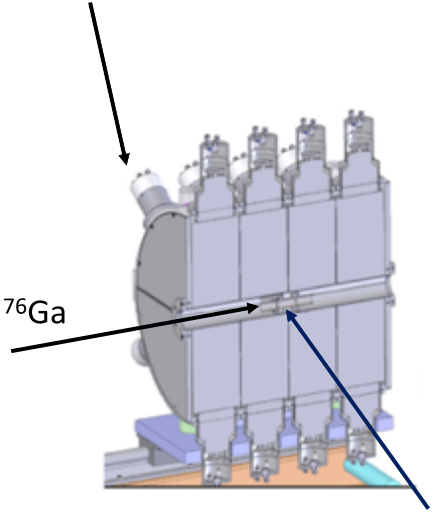
Segments give individual γ rays, the sum of all gives E_x

(a) Beta decay, ^{76}Ga



^{76}Ge

(b) Photomultiplier tubes



Si surface-barrier detector
to fit the 1.8'' borehole

(c) The Summing NaI detector (SuN)

@ NSCL/MSU

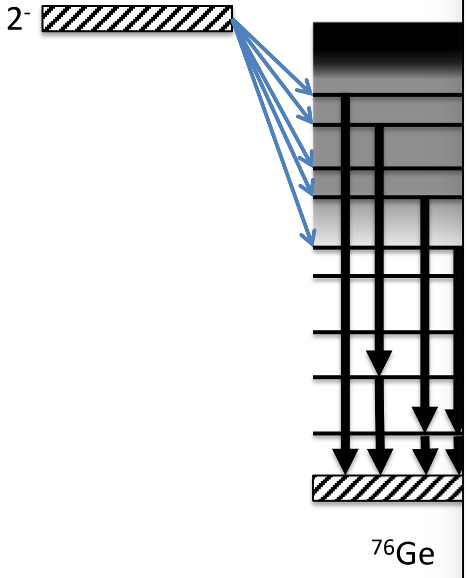
[A. Simon, S.J. Quinn, A. Spyrou et al., NIM A 703, 16 (2013)]

Larsen et al., PPNP 107, 69 (2019)

The beta-Oslo method

Segments give individual γ rays, the sum of all gives E_x

(a) Beta decay, ^{76}Ga



Larsen et al., PPNP 107, 69 (2019)

PRL **113,** 232502 (2014) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2014

Novel technique for Constraining *r*-Process (*n*, *γ*) Reaction Rates

A. Spyrou,[1,2,3,*] S. N. Liddick,[1,4,†] A. C. Larsen,[5,‡] M. Guttormsen,[5] K. Cooper,[1,4] A. C. Dombos,[1,2,3] D. J. Morrissey,[1,4] F. Naqvi,[1] G. Perdikakis,[6,1,3] S. J. Quinn,[1,7,3] T. Renstrøm,[5] J. A. Rodriguez,[1] A. Simon,[1,8] C. S. Sumithrarachchi,[1] and R. G. T. Zegers[1,7,3]

[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
[5]*Department of Physics, University of Oslo, NO-0316 Oslo, Norway*
[6]*Central Michigan University, Mount Pleasant, Michigan, 48859, USA*
[7]*Department of Physics & Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[8]*Department of Physics and The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA*

(Received 25 August 2014; published 2 December 2014)

A novel technique has been developed, which will open exciting new opportunities for studying the very neutron-rich nuclei involved in the *r* process. As a proof of principle, the *γ* spectra from the *β* decay of ^{76}Ga have been measured with the SuN detector at the National Superconducting Cyclotron Laboratory. The nuclear level density and *γ*-ray strength function are extracted and used as input to Hauser-Feshbach calculations. The present technique is shown to strongly constrain the ^{75}Ge$(n,\gamma)^{76}$Ge cross section and reaction rate.

DOI: 10.1103/PhysRevLett.113.232502 PACS numbers: 26.30.Hj, 21.10.Ma, 27.50.+e

The beta-Oslo method: $^{70}Co \rightarrow {}^{70}Ni$

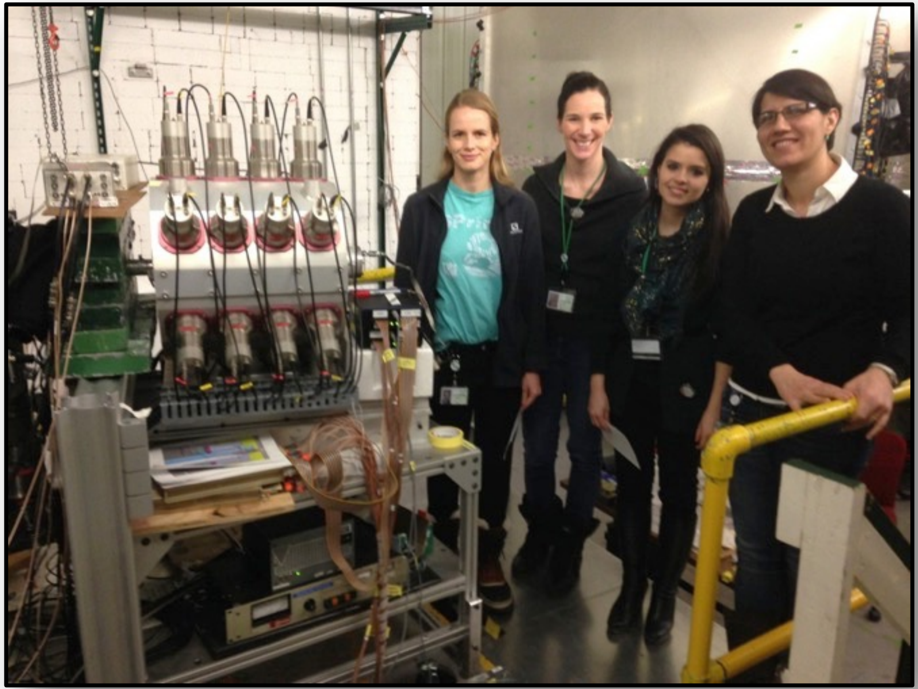
Discretionary beam time @ NSCL/MSU, Feb 2015; ^{70}Co beta-decaying into ^{70}Ni

^{86}Kr primary beam, 140 MeV/nucleon
^{70}Co implanted on DSSD detector in SuN

^{70}Co $T_{1/2}$: 105 ms
^{70}Co $I^{\pi} = 6^{-}$
Beta-decay Q-value: 12.3 MeV
S_n, ^{70}Ni: 7.3 MeV

🤔 **Question:**

Which initial spins and parity are populated after Gamow-Teller beta- decay into ^{70}Ni?



[S.N. Liddick A. Spyrou, B.P. Crider, F. Naqvi, A.C. Larsen, M. Guttormsen et al., PRL **116**, 242502 (2016)]

The beta-Oslo method: $^{70}\mathrm{Co} \rightarrow {}^{70}\mathrm{Ni}$

PRL **116,** 242502 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

Experimental Neutron Capture Rate Constraint Far from Stability

S. N. Liddick,[1,2] A. Spyrou,[1,3,4] B. P. Crider,[1] F. Naqvi,[1] A. C. Larsen,[5] M. Guttormsen,[5] M. Mumpower,[6,7] R. Surman,[6] G. Perdikakis,[8,1,4] D. L. Bleuel,[9] A. Couture,[10] L. Crespo Campo,[5] A. C. Dombos,[1,3,4] R. Lewis,[1,2] S. Mosby,[10] S. Nikas,[8,4] C. J. Prokop,[1,2] T. Renstrom,[5] B. Rubio,[11] S. Siem,[5] and S. J. Quinn[1,3,4]

[1]*National Superconducting Cyclotron Laboratory (NSCL), Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*
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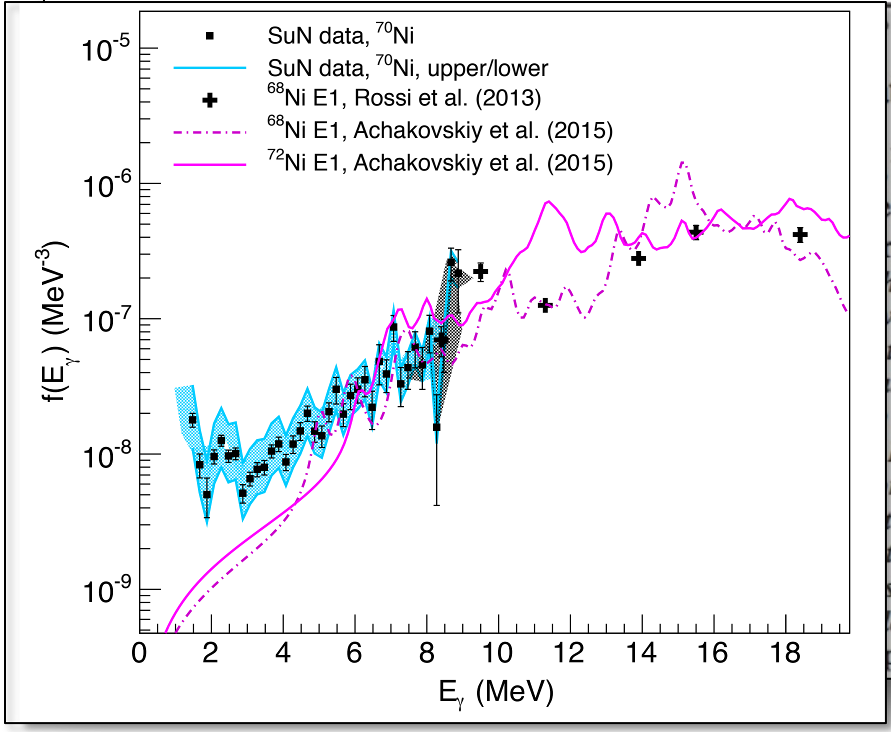
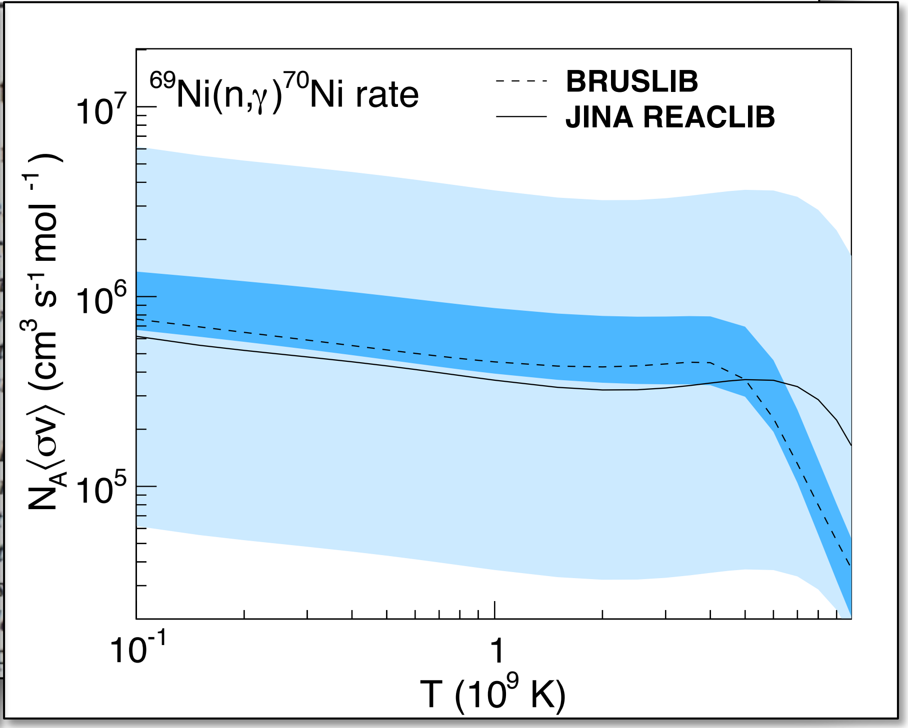
[6]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[7]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87544, USA*
[8]*Central Michigan University, Mount Pleasant, Michigan 48859, USA*
[9]*Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, California 94550-9234, USA*
[10]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[11]*IFIC, CSIC-Universidad de Valencia, 46071 Valencia, Spain*

(Received 5 January 2016; published 16 June 2016)

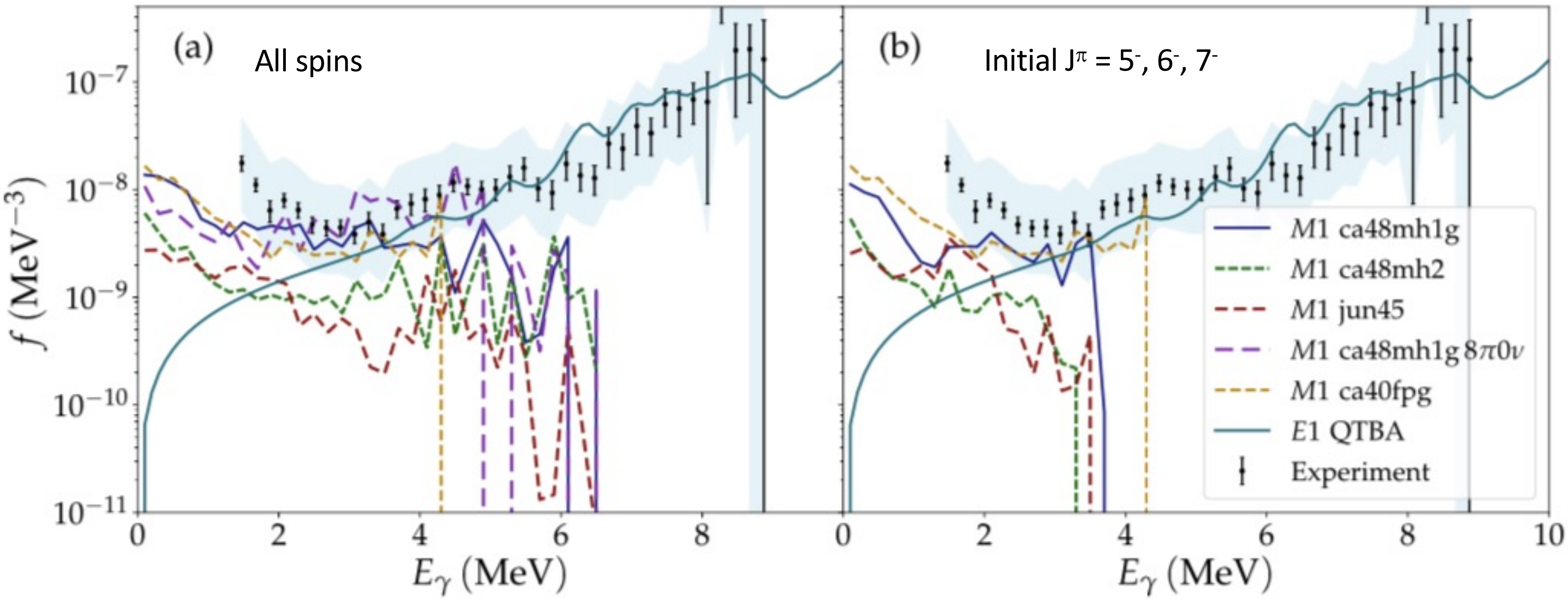
The beta-Oslo method: $^{70}Co \rightarrow {}^{70}Ni$

PRL 116, 242502 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016





The beta-Oslo method: ^{70}Ni results

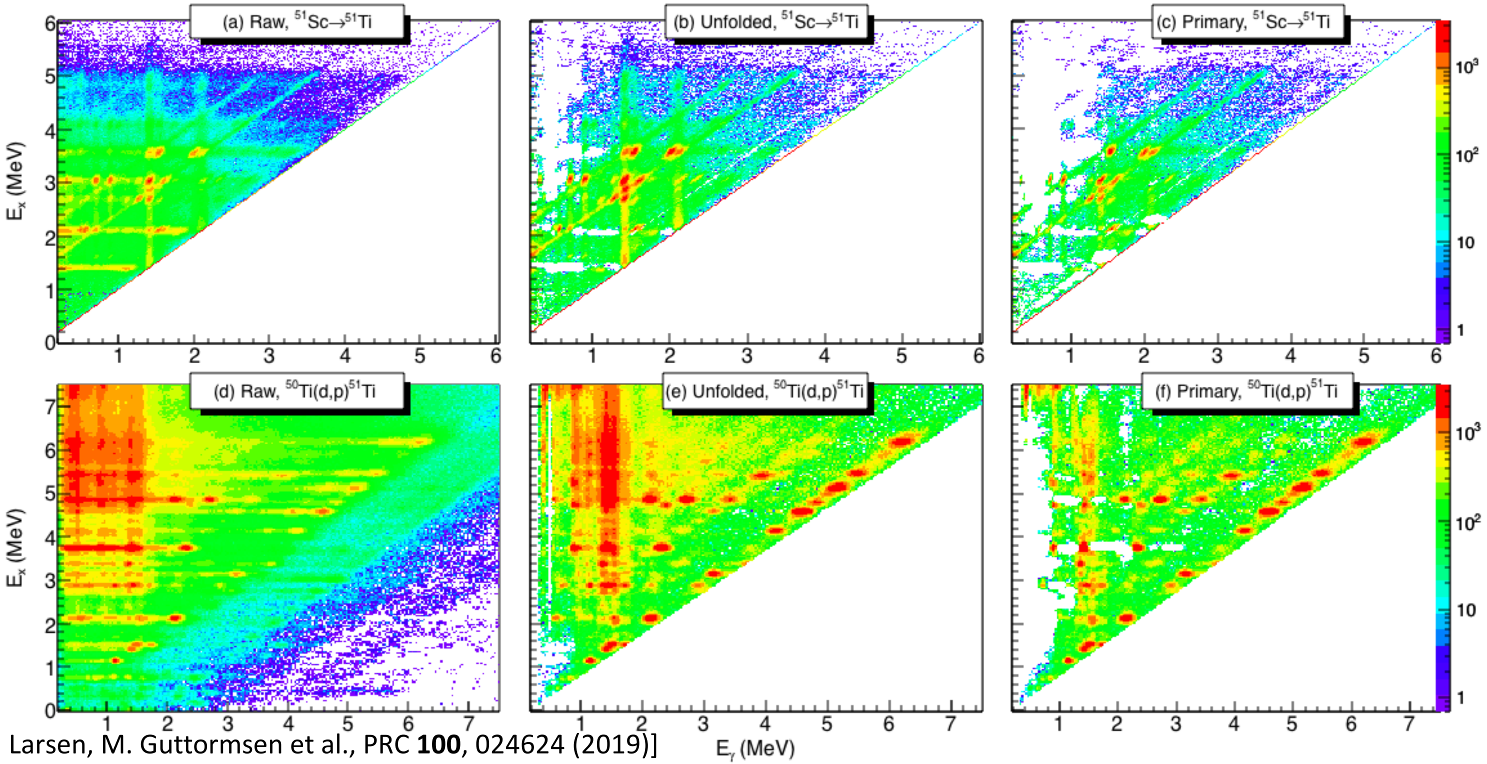


Improved data analysis: deconvolution of the E_x axis as well [M. Guttormsen et al., in preparation]

[Larsen, Midtbø, Guttormsen, Renstrøm, Liddick, Spyrou et al., PRC **97**, 054329 (2018)]

The beta-Oslo *and* Oslo method: ^{51}Ti

Discretionary beam time @ NSCL/MSU, February 2015; ^{51}Sc beta-decaying into ^{51}Ti
Q-value, beta-decay: 6.503 MeV; S_n = 6.372 MeV. Also: $^{50}Ti(d,p\gamma)^{51}Ti$ @ OCL.

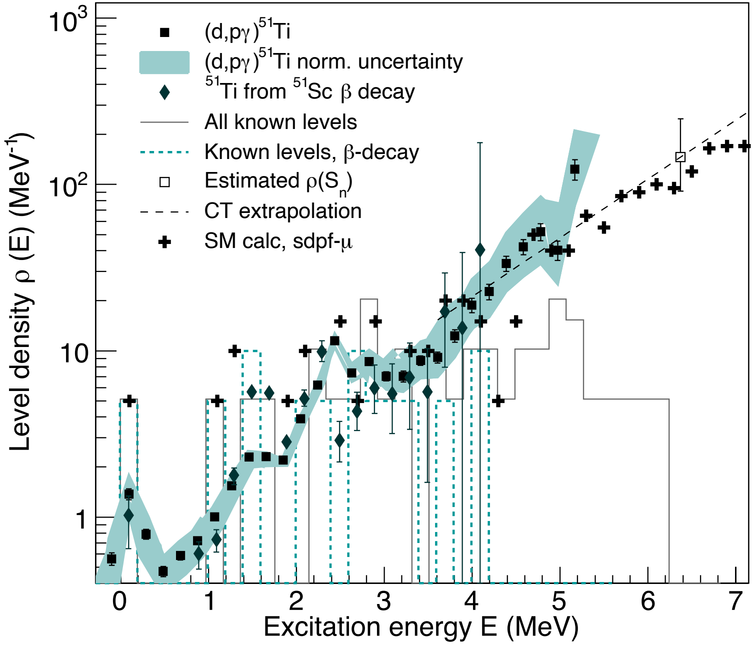


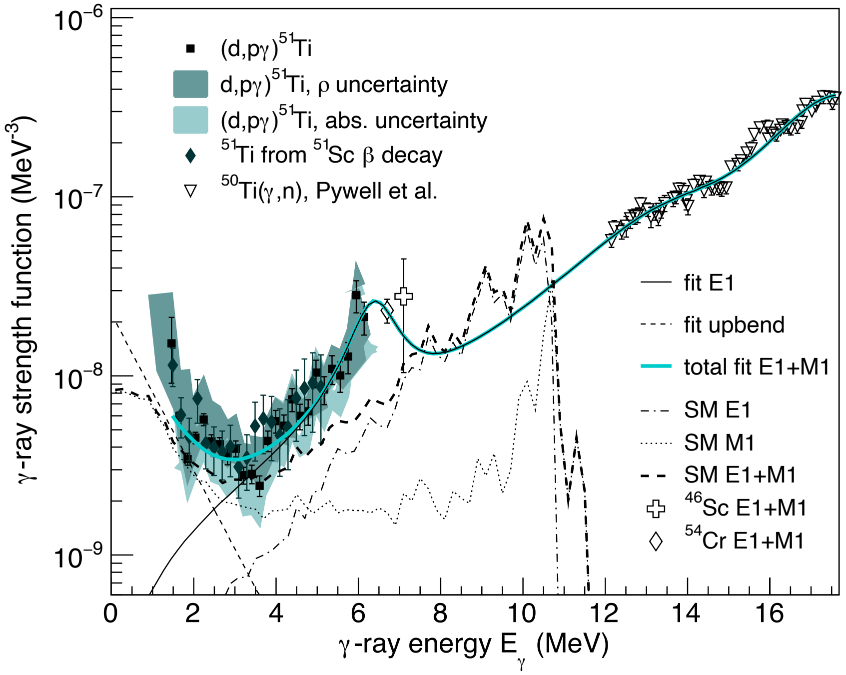
[S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRC **100**, 024624 (2019)]

The beta-Oslo *and* Oslo method: ^{51}Ti

Almost the same spin range of the final levels!

Shell-model calculations by Jørgen E. Midtbø using KSHELL (Shimizu, https://arxiv.org/abs/1310.5431)



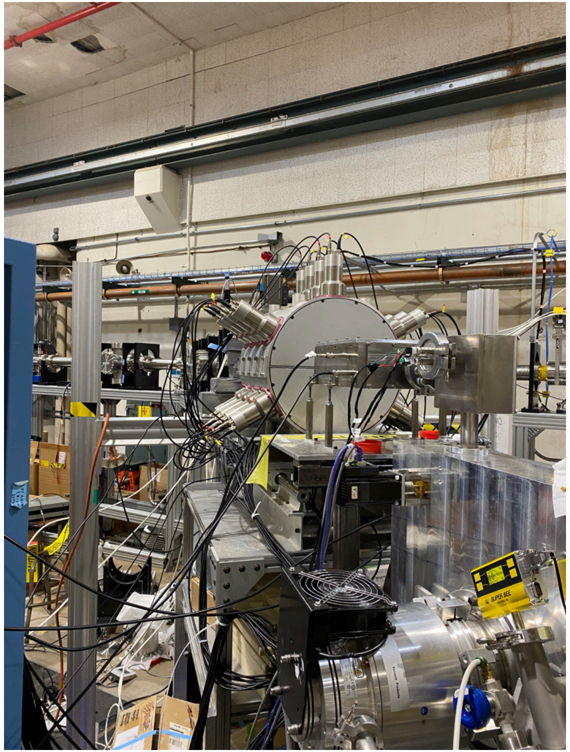


[S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRC **100**, 024624 (2019)]

The samarium experiment @ Argonne National Lab

CARIBU: ^{252}Cf spontaneous fission source → ^{156,158}Pm. SuN with SuNTAN (tape station) and a fiber detector for the electrons

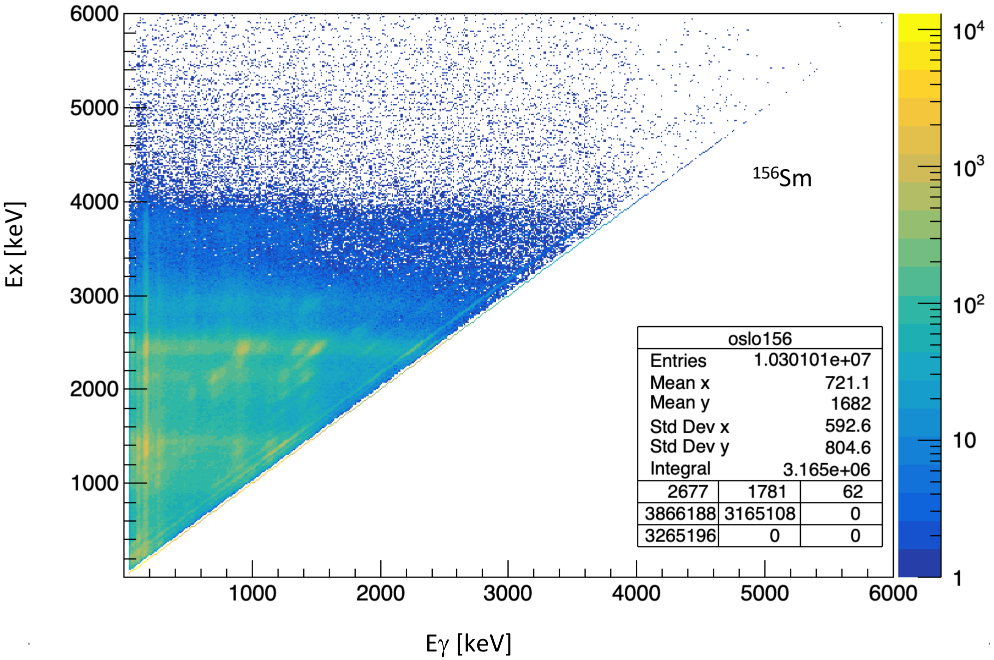
[CARIBU: G. Savard, et al, Nucl. Instr. Methods Phys. Res. B 266, 4086 (2008)]

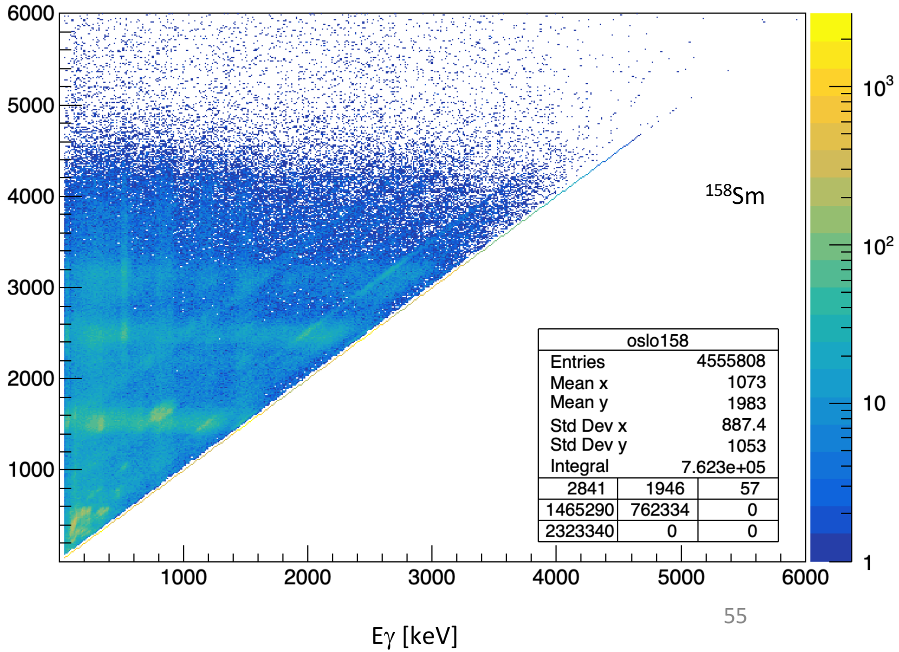


The samarium experiment @ Argonne National Lab

^{156}Pm -> ^{156}Sm: Q-value = 5.20 MeV, S_n = 7.24 MeV, $T_{1/2}$ = 26.7s

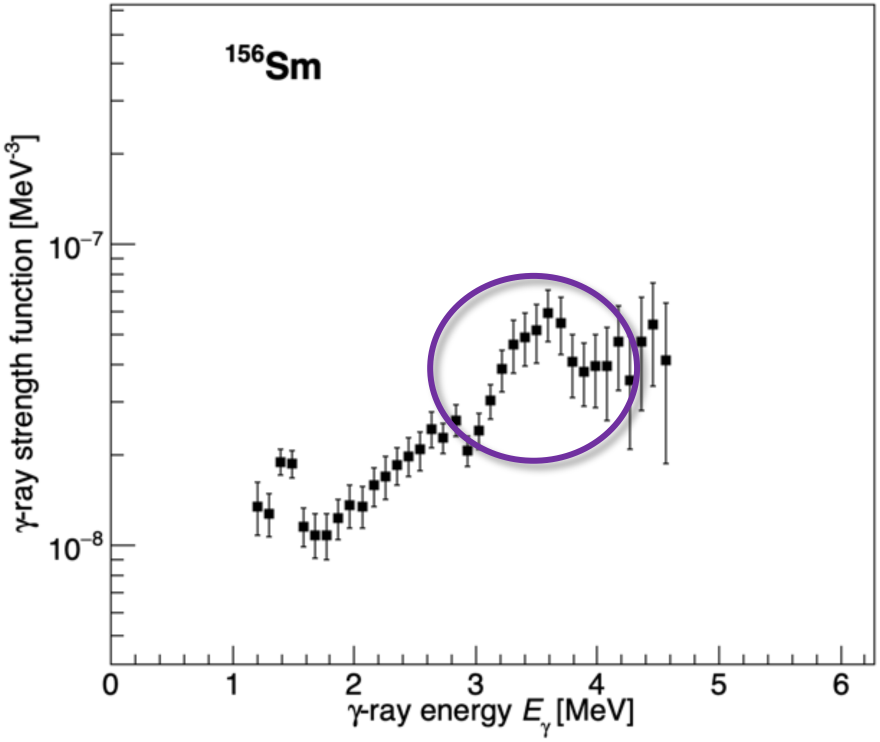
^{158}Pm -> ^{158}Sm: Q-value = 6.16 MeV, S_n = 6.64 MeV, $T_{1/2}$ = 4.8 s

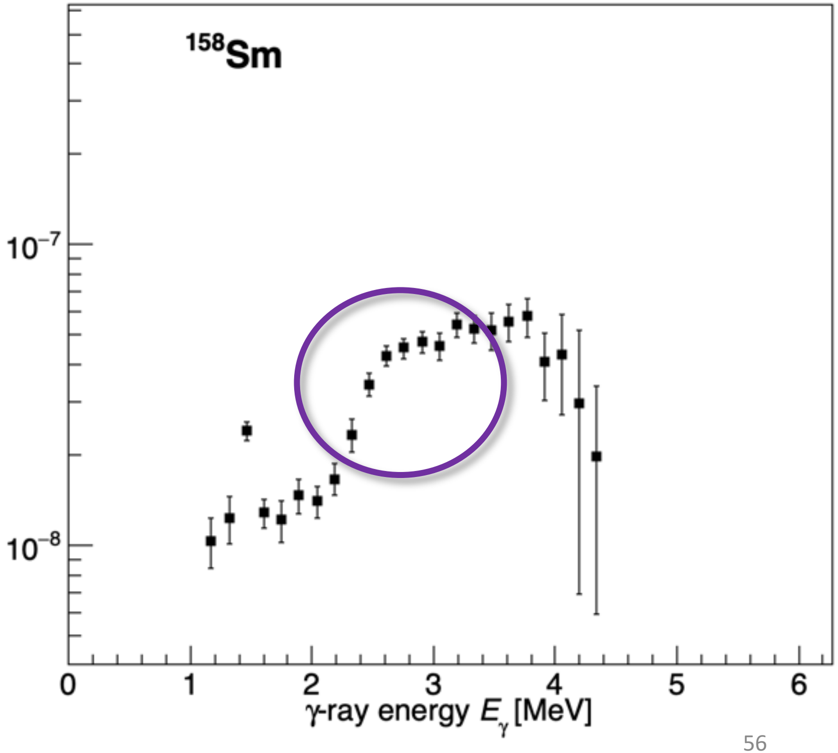




SUPER-preliminary results, ^{156,158}Sm

Deformation (beta2) ≈ 0.34-0.35 [Goriely, Chamel, and Pearson, PRL **102**, 152503 (2009)]





Summary – key points 🗝️

- Experimental data is needed to help constrain (n,γ) rates for unstable nuclei
- A low-energy enhancement in the γ-strength function may increase (n,γ) rates for neutron-rich nuclei
- There are several methods that can be applied to obtain (n,γ) rates indirectly, such as the surrogate method, Coulomb dissociation, the ***Oslo method in inverse kinematics***, and the ***β-Oslo method***

Picture from http://www.opnlttr.com/sites/default/files/cattura.png

Nuclear astrophysics is awesome 😍