



Investigating the low-energy enhancement in Zr isotopes

Artemis Spyrou



Amal Sebastian



National Science
Foundation



MICHIGAN STATE
UNIVERSITY

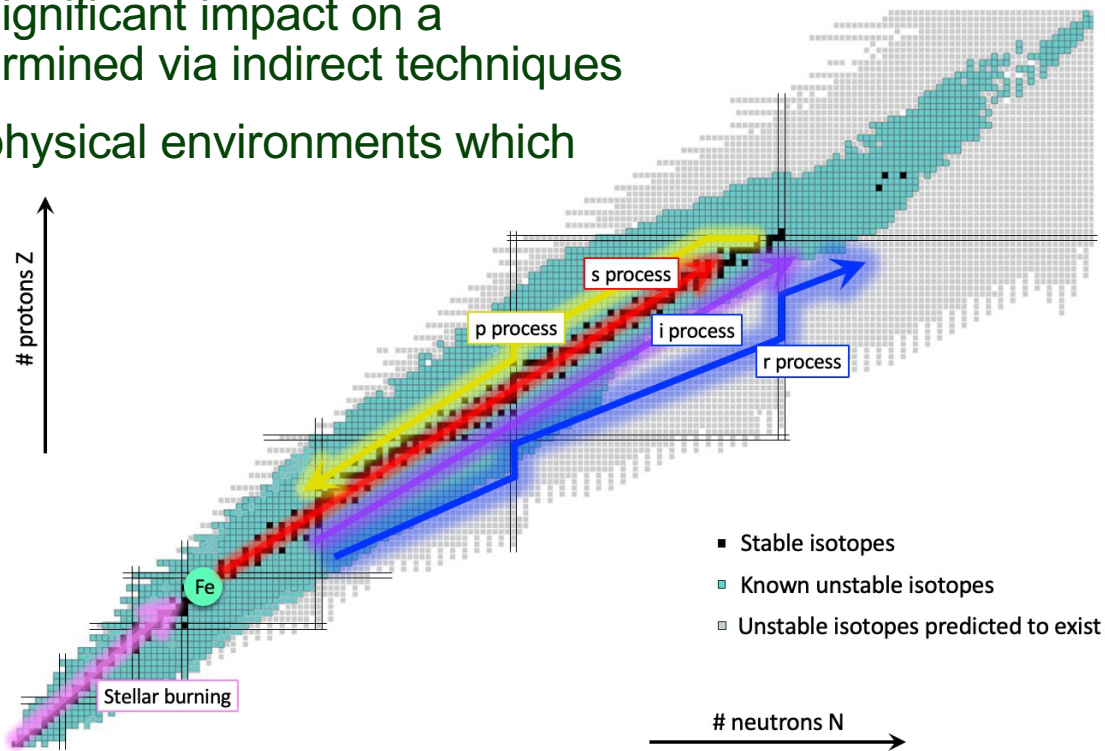
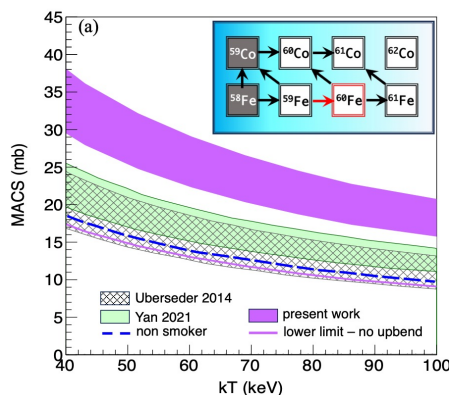
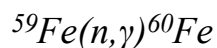
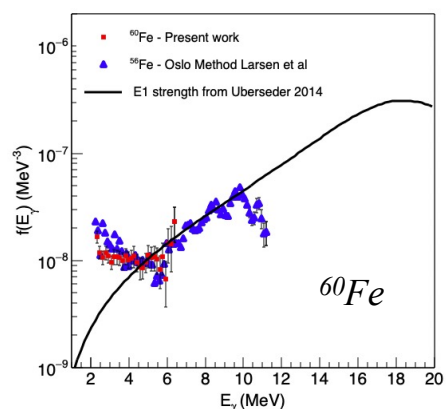


U.S. DEPARTMENT
of ENERGY | Office of
Science

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics and used resources of the Facility for Rare Isotope Beams (FRIB) Operations, which is a DOE Office of Science User Facility under Award Number DE-SC0023633.

Motivation

- The low energy enhancement can have significant impact on a neutron-capture cross sections when determined via indirect techniques
- Particularly important for explosive astrophysical environments which include nuclei far from stability



AS et al, Nature Comms 2024

Wiedeking et al, Nature Reviews 2025

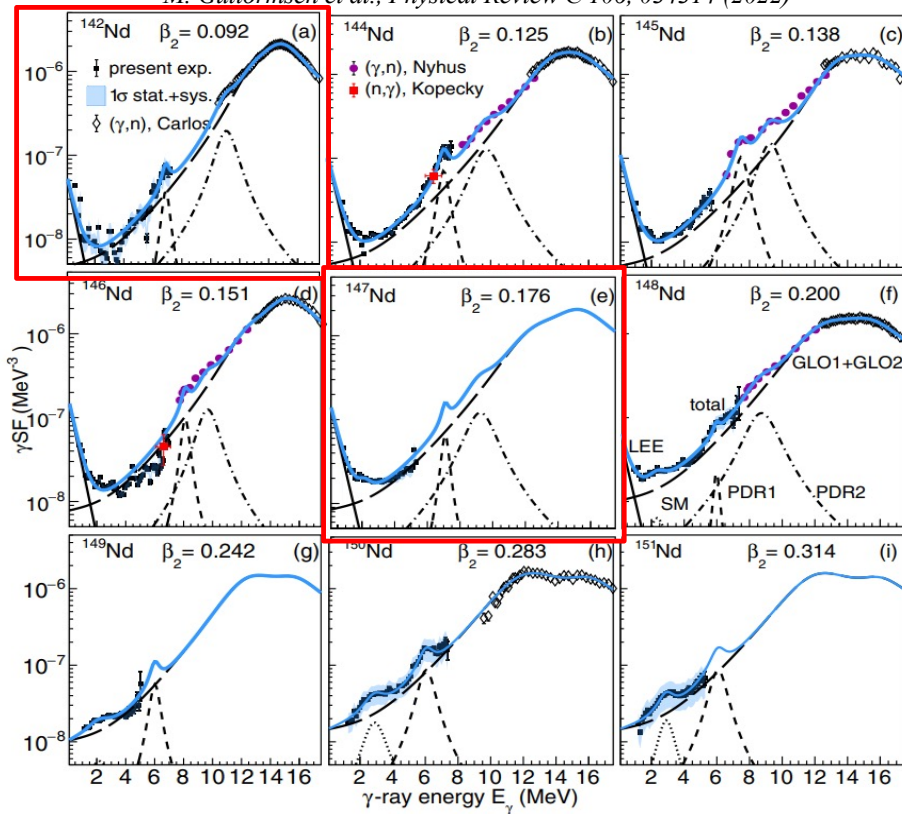


Facility for Rare Isotope Beams
 National Science Foundation

Artemis Spyrou – Oslo 2026

Evolution of upbend as a function of deformation

M. Guttormsen et al., *Physical Review C* 106, 034314 (2022)



Deformation in Nd isotopes

spherical

deformed

¹⁴² Nd	¹⁴³ Nd	¹⁴⁴ Nd	¹⁴⁵ Nd	¹⁴⁶ Nd	¹⁴⁷ Nd	¹⁴⁸ Nd	¹⁴⁹ Nd	¹⁵⁰ Nd
$\beta_2 = 0.092$	$\beta_2 = 0.109$	$\beta_2 = 0.125$	$\beta_2 = 0.138$	$\beta_2 = 0.151$	$\beta_2 = 0.176$	$\beta_2 = 0.200$	$\beta_2 = 0.242$	$\beta_2 = 0.283$

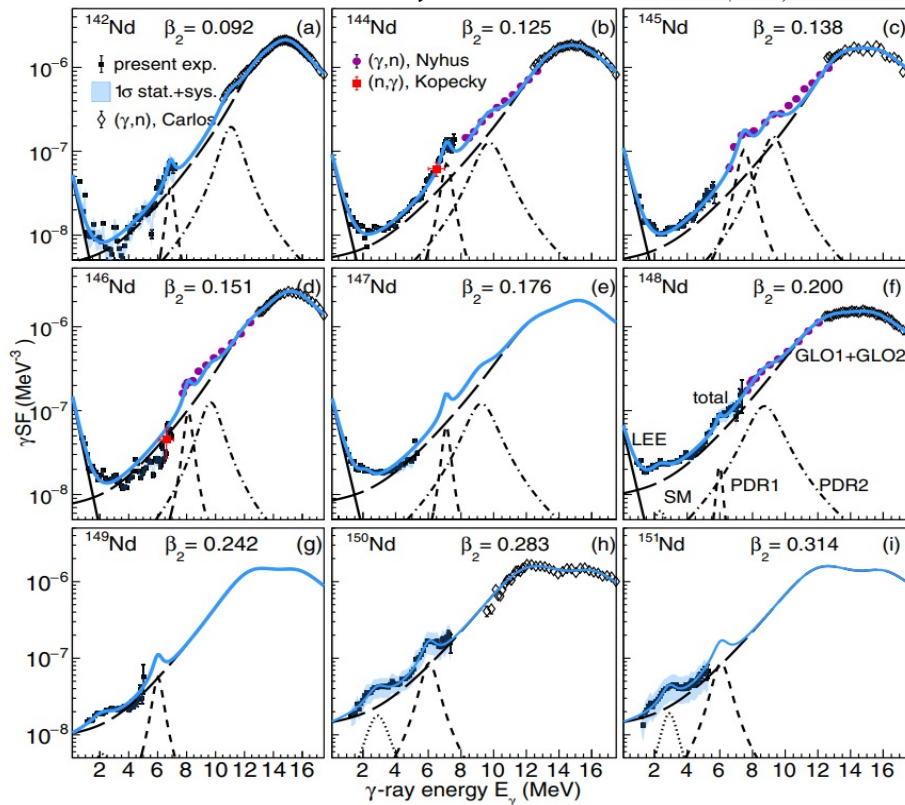


Facility for Rare Isotope Beams
National Science Foundation

Artemis Spyrou – Oslo 2026

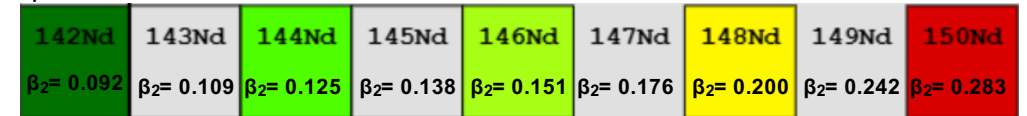
Evolution of upbend as a function of deformation

M. Guttormsen et al., *Physical Review C* 106, 034314 (2022)



Deformation in Nd isotopes

spherical



deformed

Deformation in Zr isotopes

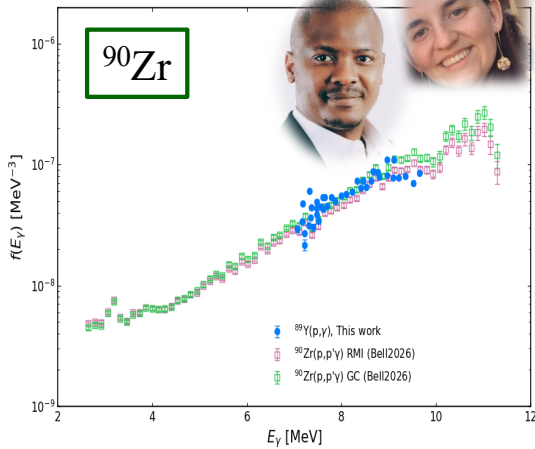


- $^{90-98}\text{Zr}$: $\beta_2 = 0.06 - 0.1$
- Abrupt change at ^{100}Zr : $\beta_2 = 0.36$

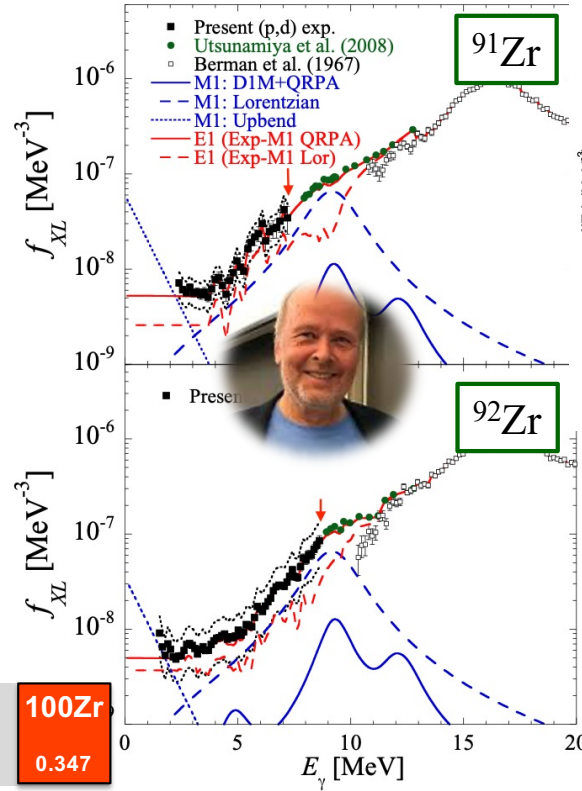


Existing measurements along the Zr isotopic chain

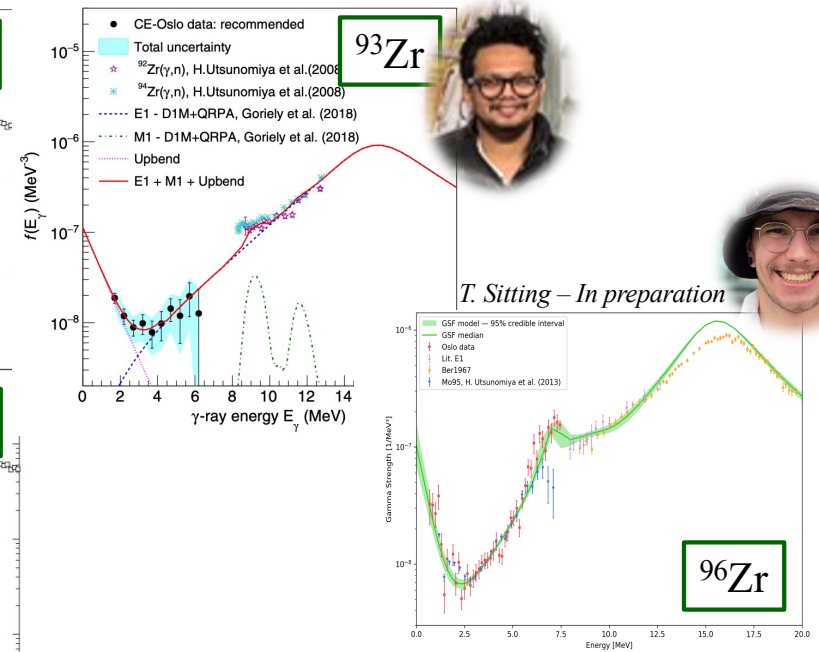
L. Bell – Submitted 2026
K. Malatji – Oslo 2026



Guttormsen et al. PRC 96, 024313 (2017)



Pathirana et al. PRC 113, 015801 (2026)



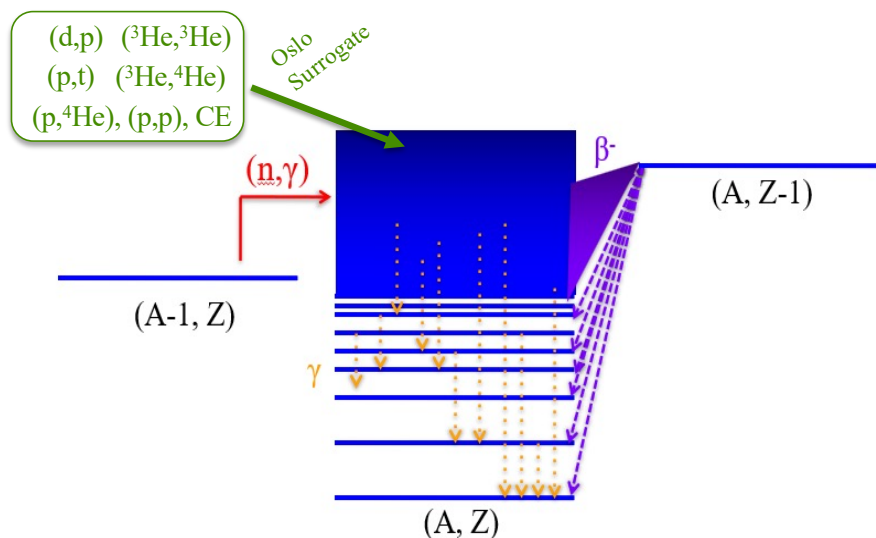
90Zr	92Zr	94Zr	96Zr	98Zr	100Zr
0.092	0.10	0.088	0.06	0.06	0.347



Facility for Rare Isotope Beams
National Science Foundation

Artemis Spyrou – Oslo 2026

Using the β Oslo method to populate neutron-rich Zr



97Mo	98Mo	99Mo	100Mo	101Mo	102Mo	103Mo	104Mo
96Nb	97Nb	98Nb	99Nb	100Nb	101Nb	102Nb	103Nb
95Zr	96Zr	97Zr	98Zr	99Zr	100Zr	101Zr	102Zr
94Y	95Y	96Y	97Y	98Y	99Y	100Y	101Y

Red arrows point from 96Y to 97Zr, from 97Y to 98Zr, and from 99Y to 100Zr.

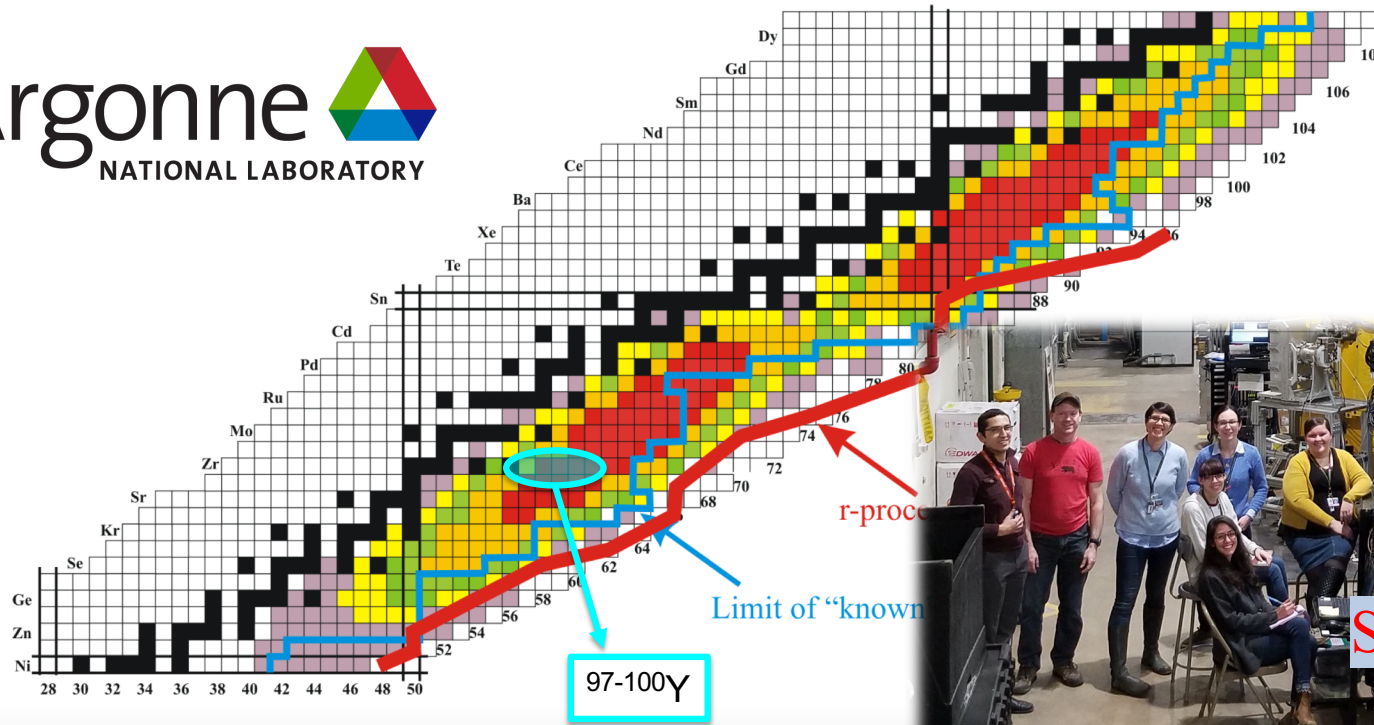
Extracting Nuclear Level Densities and γ -ray Strength Functions



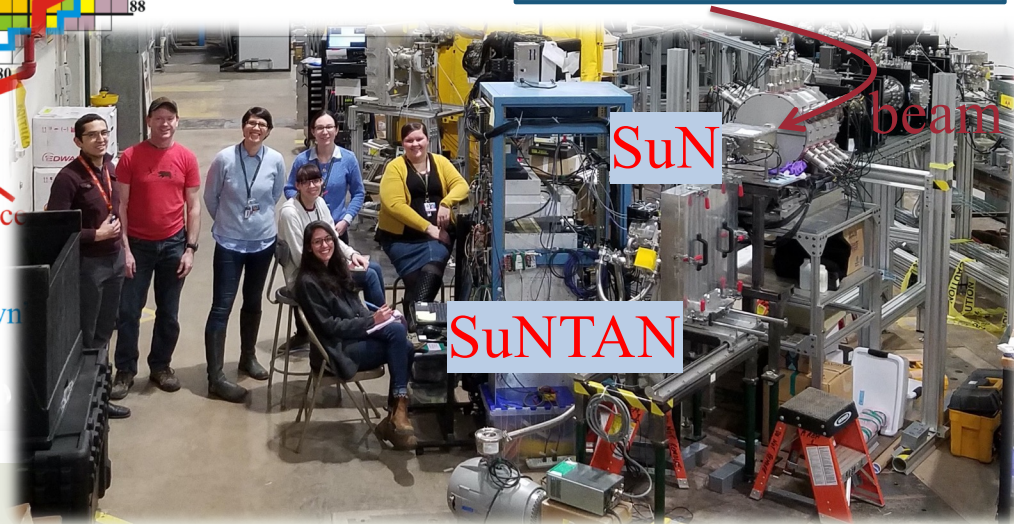
CARIBU Facility @ Argonne National Lab

^{252}Cf spontaneous fission yield from 1 Ci source

Exp. PI: Mallory Smith



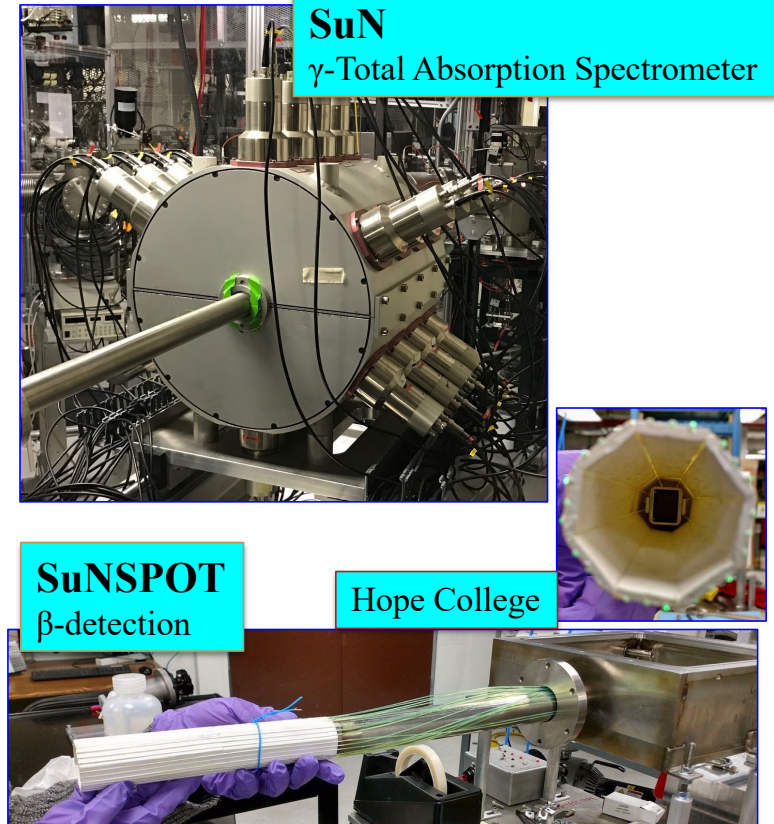
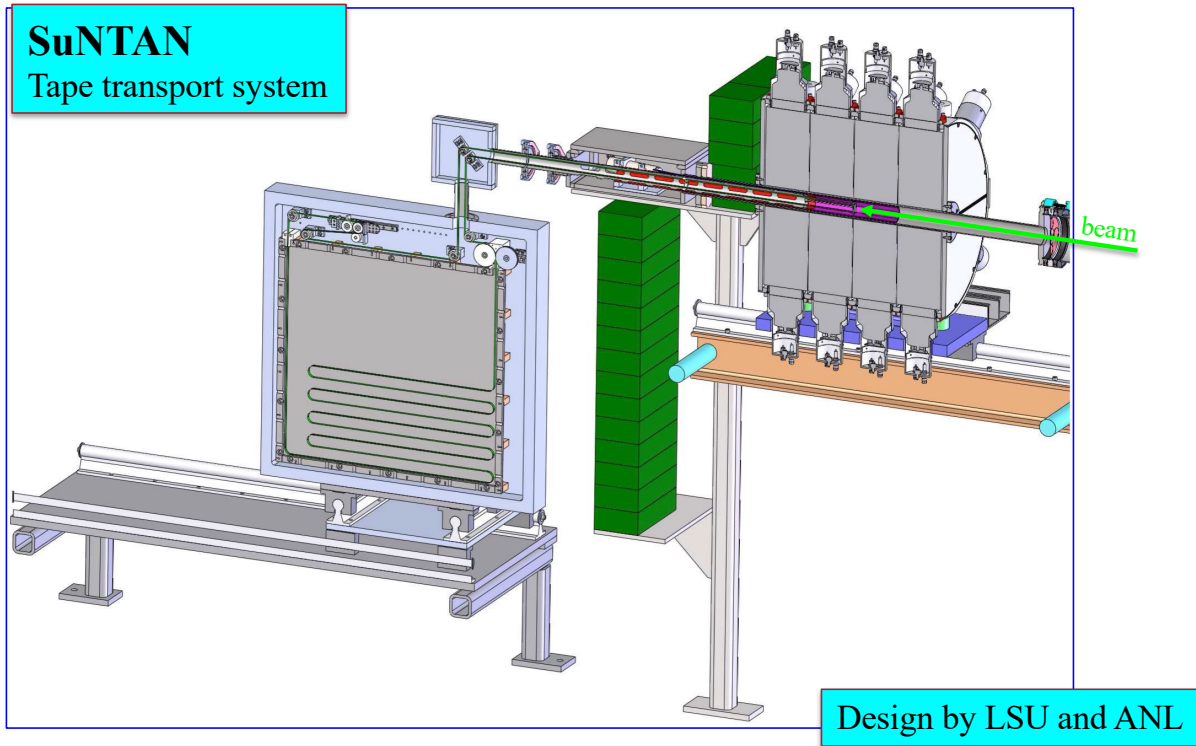
The SuN setup @ ANL



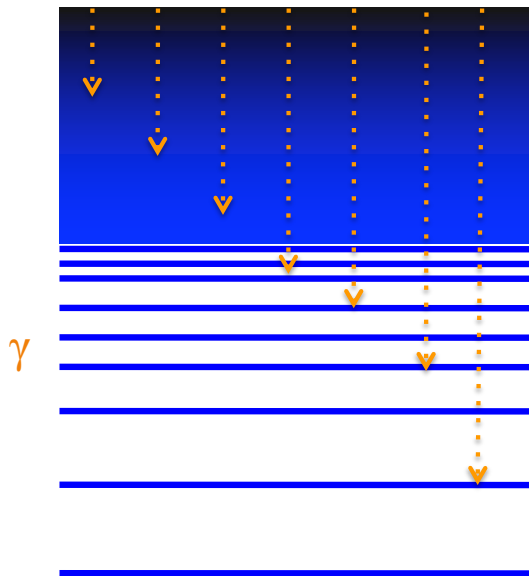
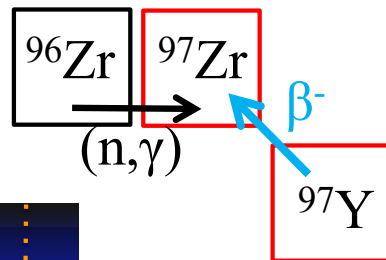
Facility for Rare Isotope Beams
National Science Foundation

Artemis Spyrou – Oslo 2026 7

The SuN setup

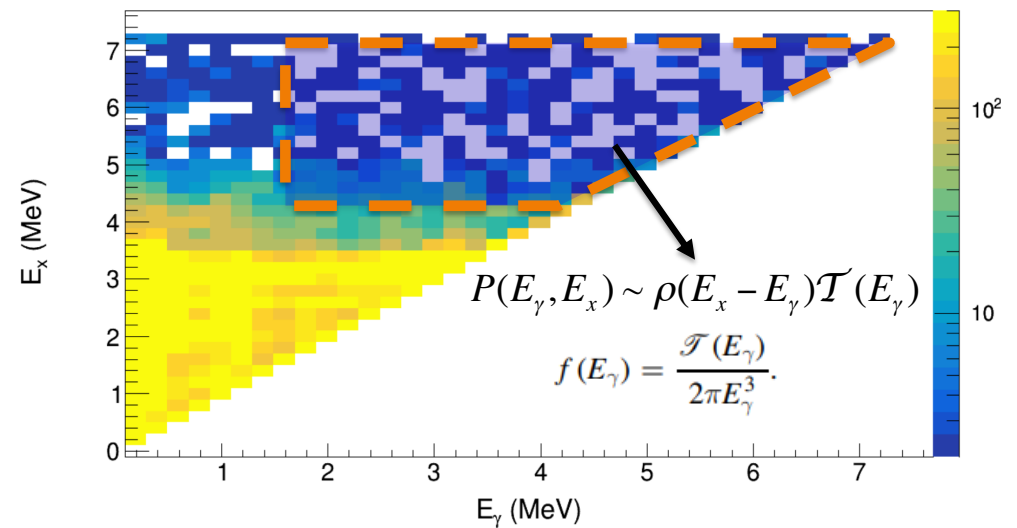


Results for ^{97}Zr



$^{97}\text{Y} \rightarrow ^{97}\text{Zr}$
 $Q_\beta = 6.8 \text{ MeV}$
 $S_n = 5.56 \text{ MeV}$

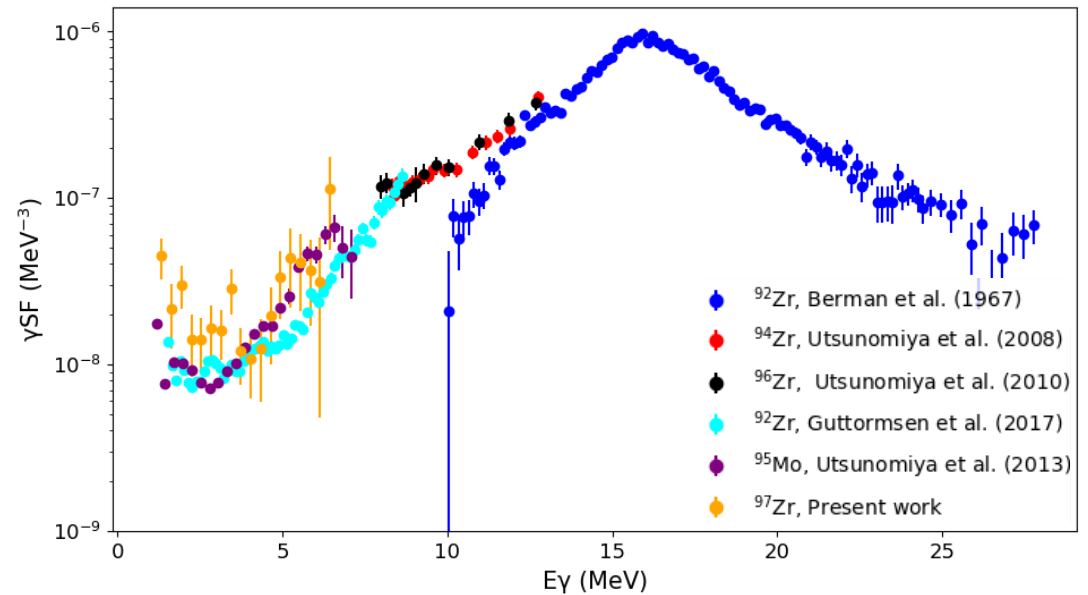
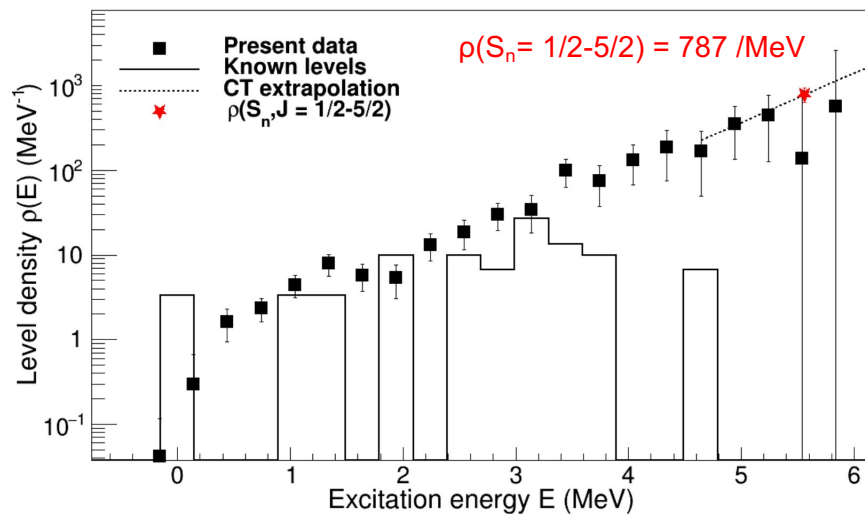
Raw matrix for β -oslo analysis



Extracted Partial NLD and γ SF

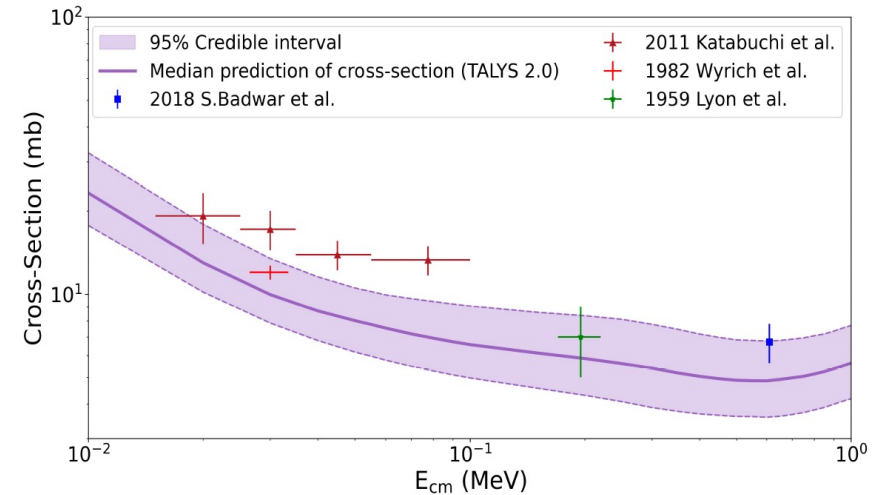
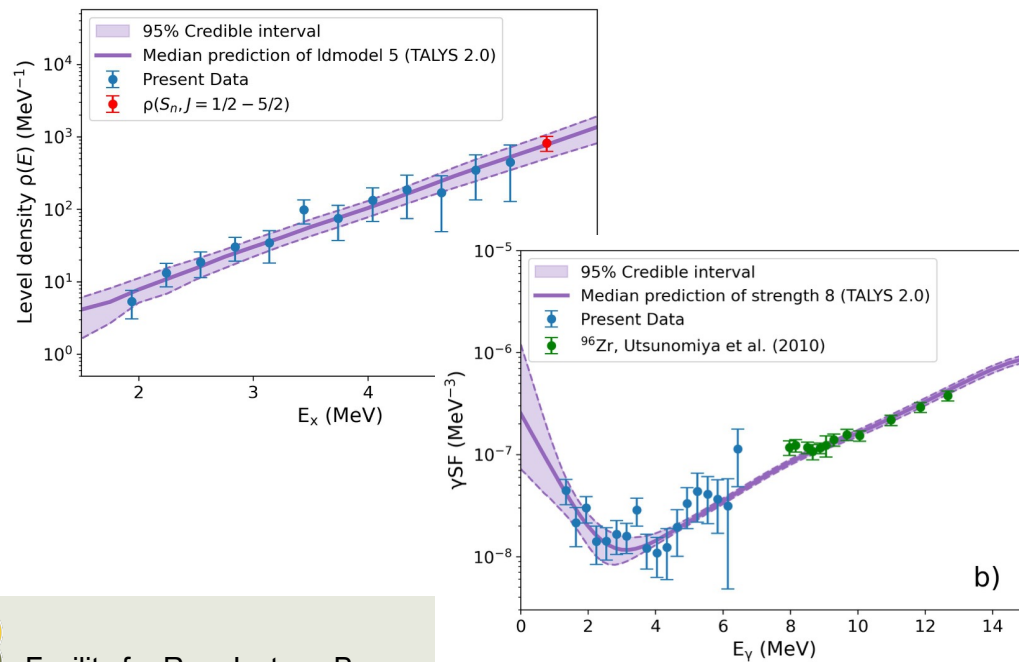
Normalization points:

- Low-lying discrete levels.
- D0 (converted to partial NLD@ S_n)
- Γ_γ



Bayesian Analysis to fit our data and input to TALYS

- A Bayesian framework in combination with Metropolis–Hastings Markov Chain Monte Carlo (MCMC) algorithm was used to fit the experimental data



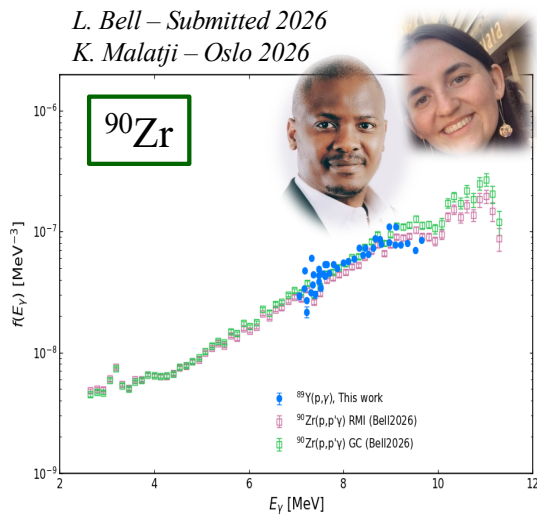
- Extracted $^{96}\text{Zr}(n,\gamma)^{97}\text{Zr}$ reaction cross section in good agreement with direct measurements

A. Sebastian et al. PRC - Submitted

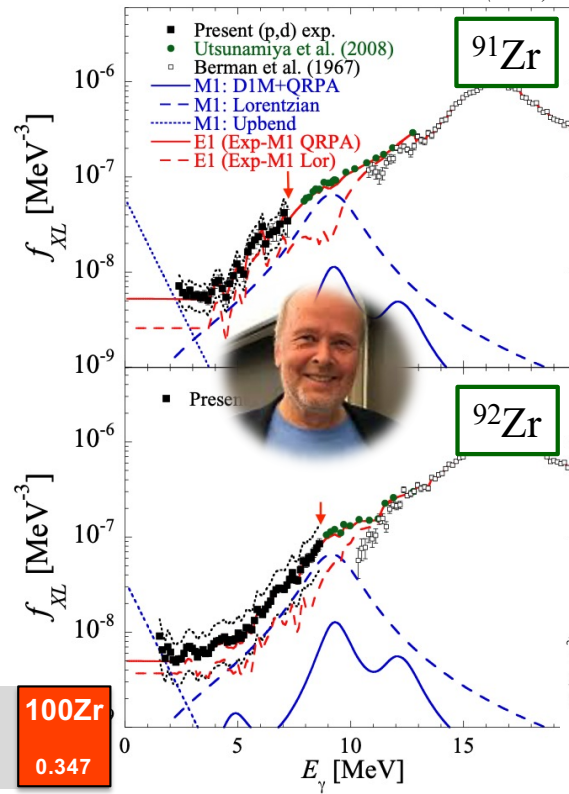


Facility for Rare Isotope Beams
National Science Foundation

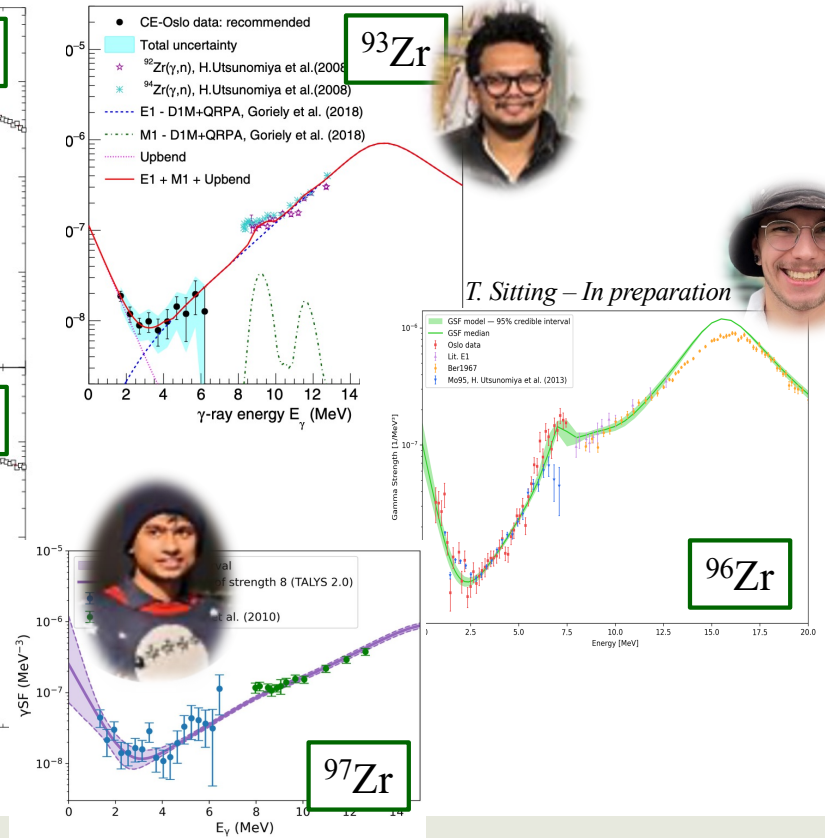
Existing measurements along the Zr isotopic chain



Guttormsen et al. PRC 96, 024313 (2017)



Pathirana et al. PRC 113, 015801 (2026)



T. Sitting – In preparation

A. Sebastian et al. PRC - Submitted

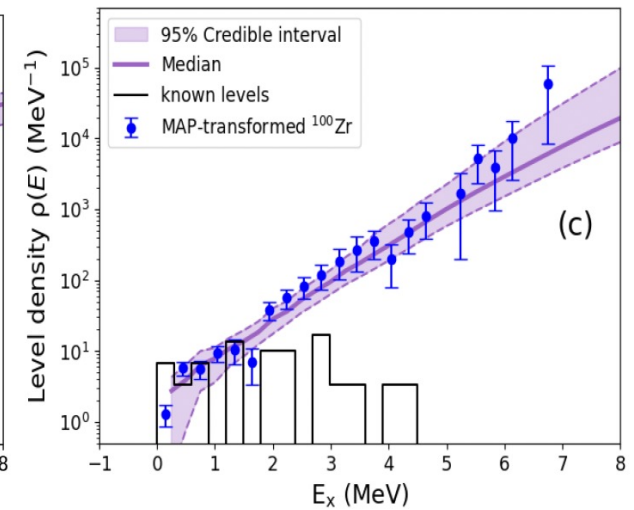
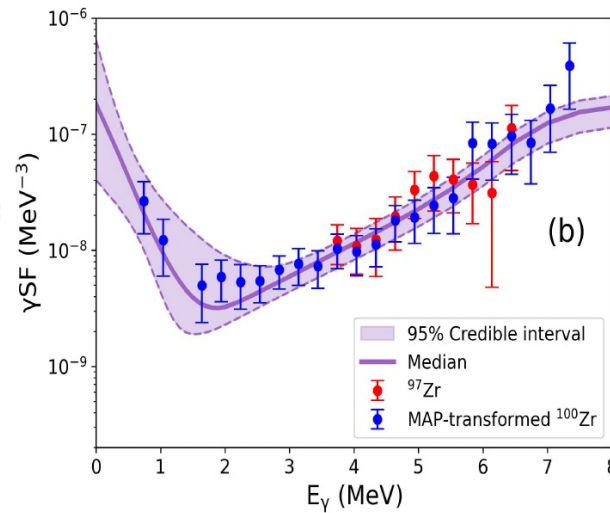
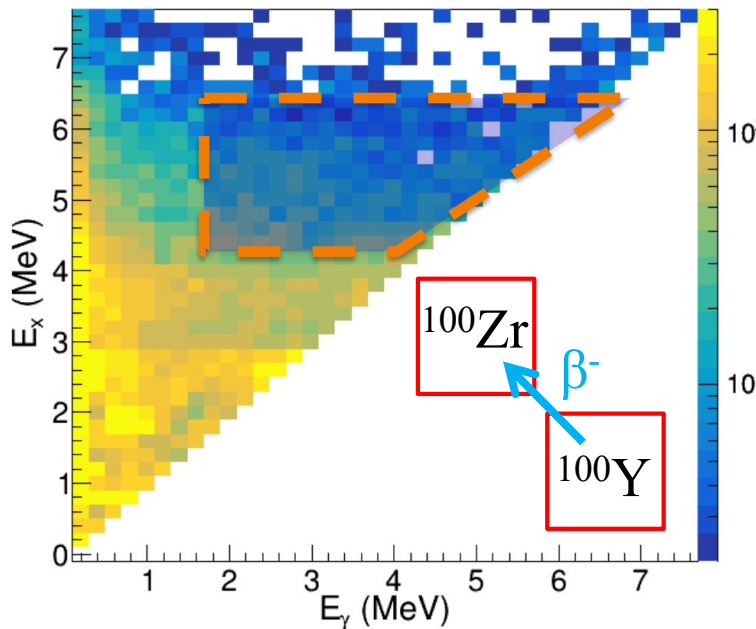
^{90}Zr	^{92}Zr	^{94}Zr	^{96}Zr	^{98}Zr	^{100}Zr
0.092	0.10	0.088	0.06	0.06	0.347



Facility for Rare Isotope Beams
National Science Foundation

β -Oslo Method on ^{100}Zr

Raw matrix

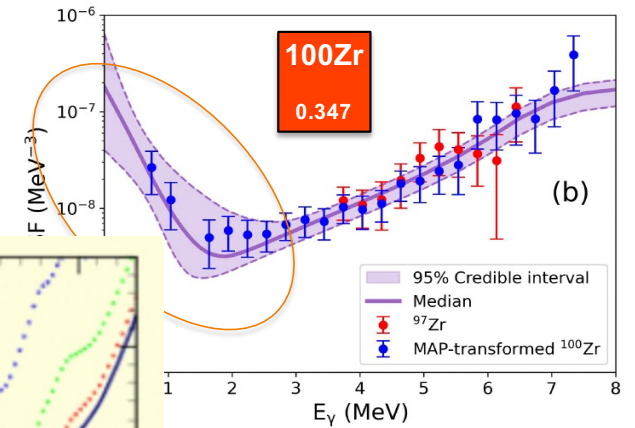
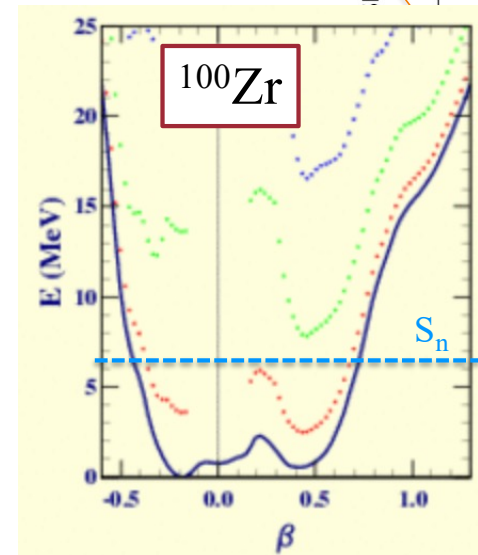
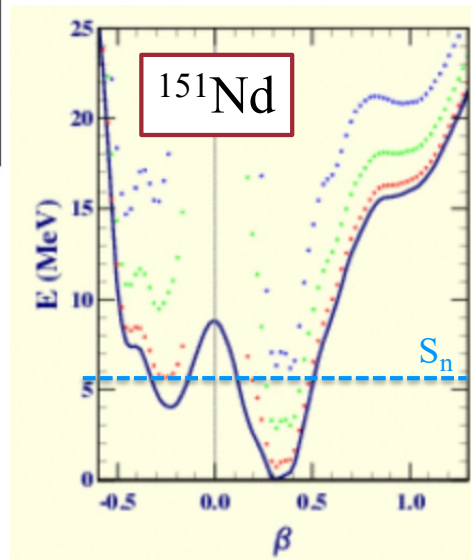
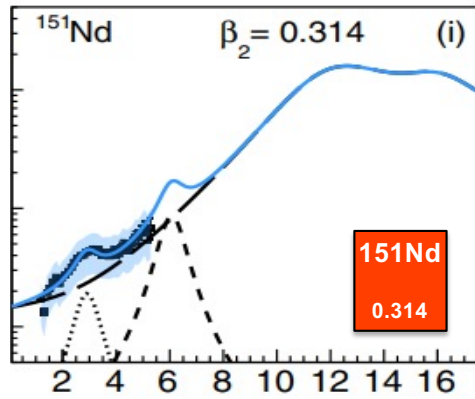


Normalization points:

- Low-lying discrete levels
- γSF fixed to the ^{97}Zr slope at $E_\gamma > 3$ MeV
 - Note: slope consistent with other Zr isotopes



Interpretation: Shape Coexistence in ^{100}Zr



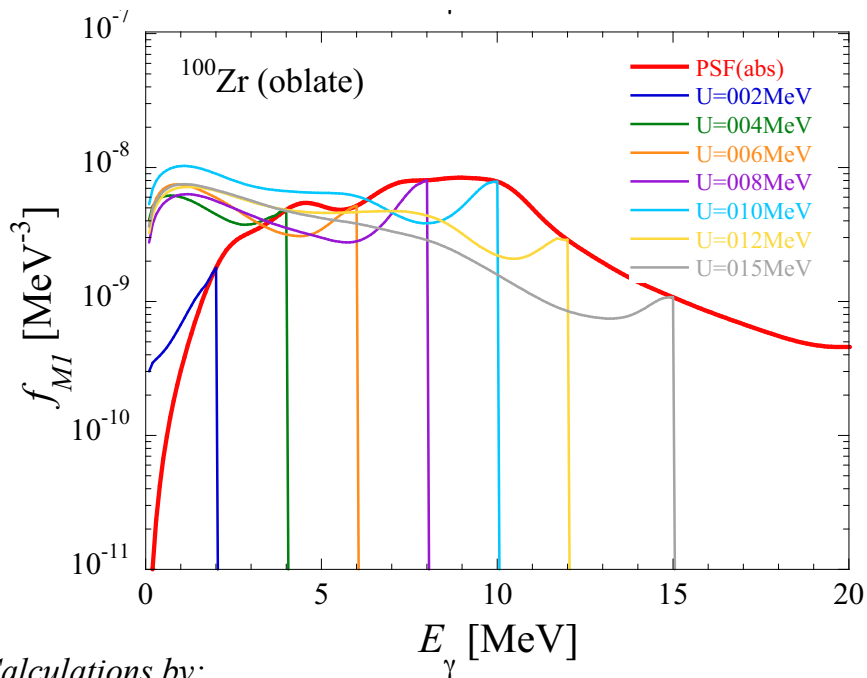
Calculations by:
Stephane Goriely
Stephane Hilaire
Sophie Peru

A. Sebastian et al. In Preparation



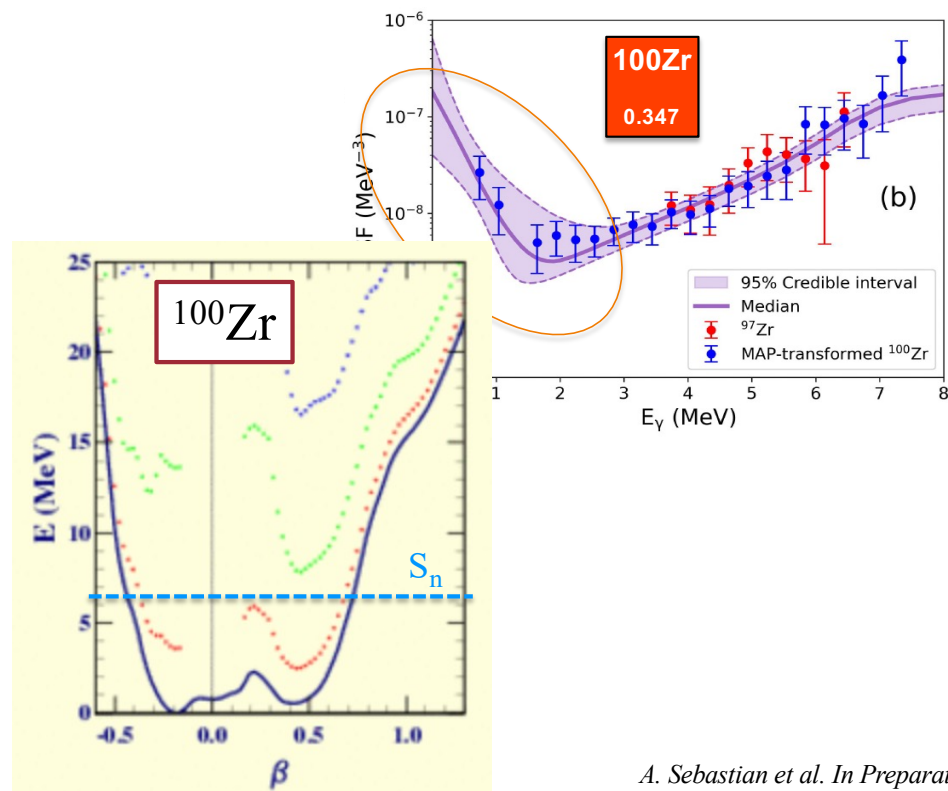
Facility for Rare Isotope Beams
National Science Foundation

Interpretation: Shape Coexistence in ^{100}Zr



Calculations by:
 Stephane Goriely
 Stephane Hilaire
 Sophie Peru

Goriely et al. *Physics Letters B* 868 (2025) 139677



A. Sebastian et al. *In Preparation*



Facility for Rare Isotope Beams
 National Science Foundation

Summary

- β -Oslo method applied to $^{97,100}\text{Zr}$
- The evolution of the low energy enhancement in the γ SF is not a simple dependence on the ground state deformation.
- Systematically investigate other nuclei with similar structures
- Identify cases where we can investigate the excitation energy dependence of the upbend

Collaboration

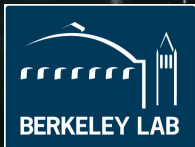
**MICHIGAN STATE
UNIVERSITY**

S.N. Liddick

A. Chester
A.C. Dombos
A. Hartley
P. Giuliani
M. Mogannam
T. Ogunbeku

Current SuN group

H. Berg
K. Bosmpotinis
S. Coil
C. Harris
H. Gadaria
J. Owens-Fryar
A. Sebastian
M. K. Smith
A. Tsantiri
S. Uthayakumaar



M. Wiedeking



A. Richard



C. Dembski



S. Goriely



S. Hilaire
S. Peru



P. DeYoung



J. Clark
D. Santiago-Gonzalez
G. Savard



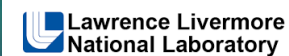
A.C. Larsen
M. Guttormsen



D. Muecher



S. Lyons
E. Good



A. Sweet
D. Bleuel