UNIVERSITEIT STELLENBOSCH UNIVERSITY

# Statistical properties of well-deformed Samarium isotopes

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This work is based on the research supported in part by the NRF South Africa Grant No. 92600 and the IAEA Grant No. 20454.

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6th International Conference on Collective Motion in Nuclei under Extreme Conditions (COMEX6), Cape Town, Oct 29-Nov 2, 2018

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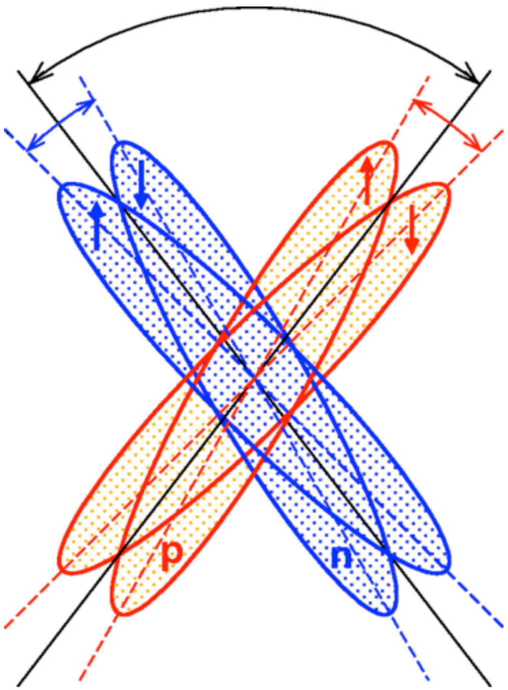
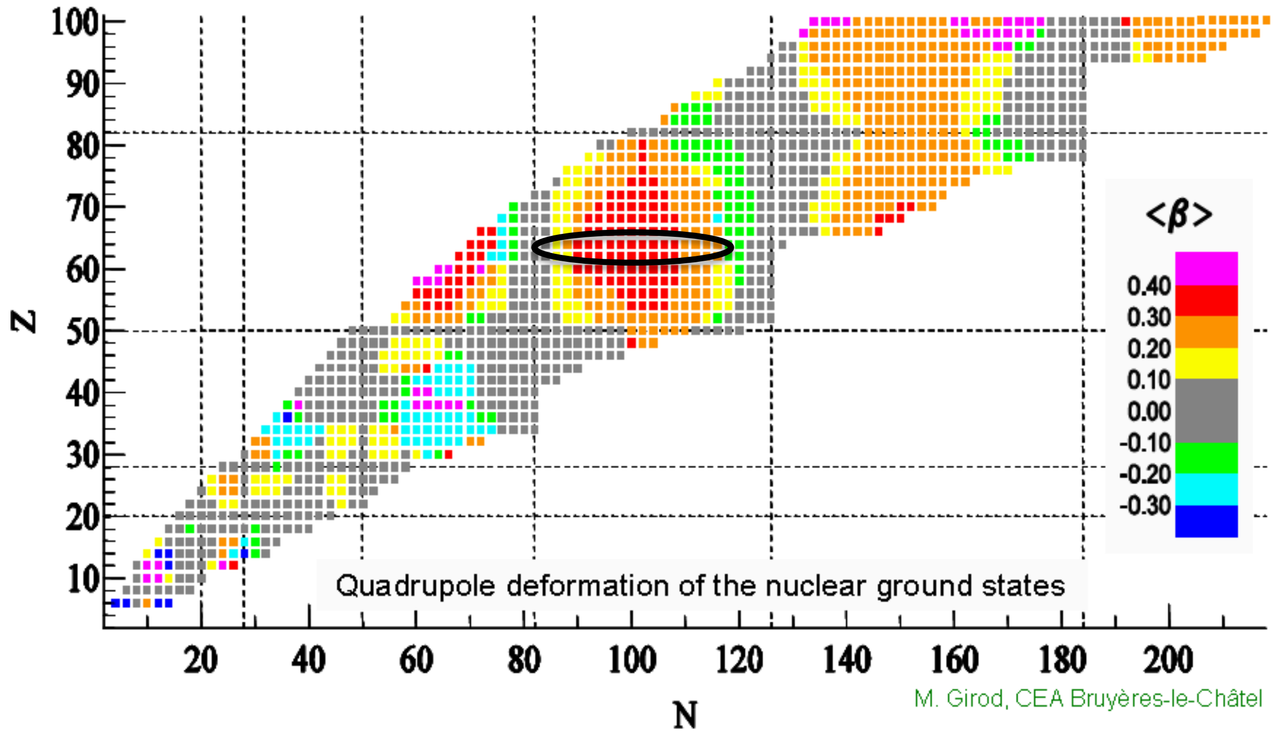
# Overview

- Physics Motivation for $^{154,155}Sm$
- Experimental Setup
- Nuclear Level Densities
- γ-ray Strength Functions
- Scissors Resonance
- Future Work



# Motivation for $^{154,155}$Sm

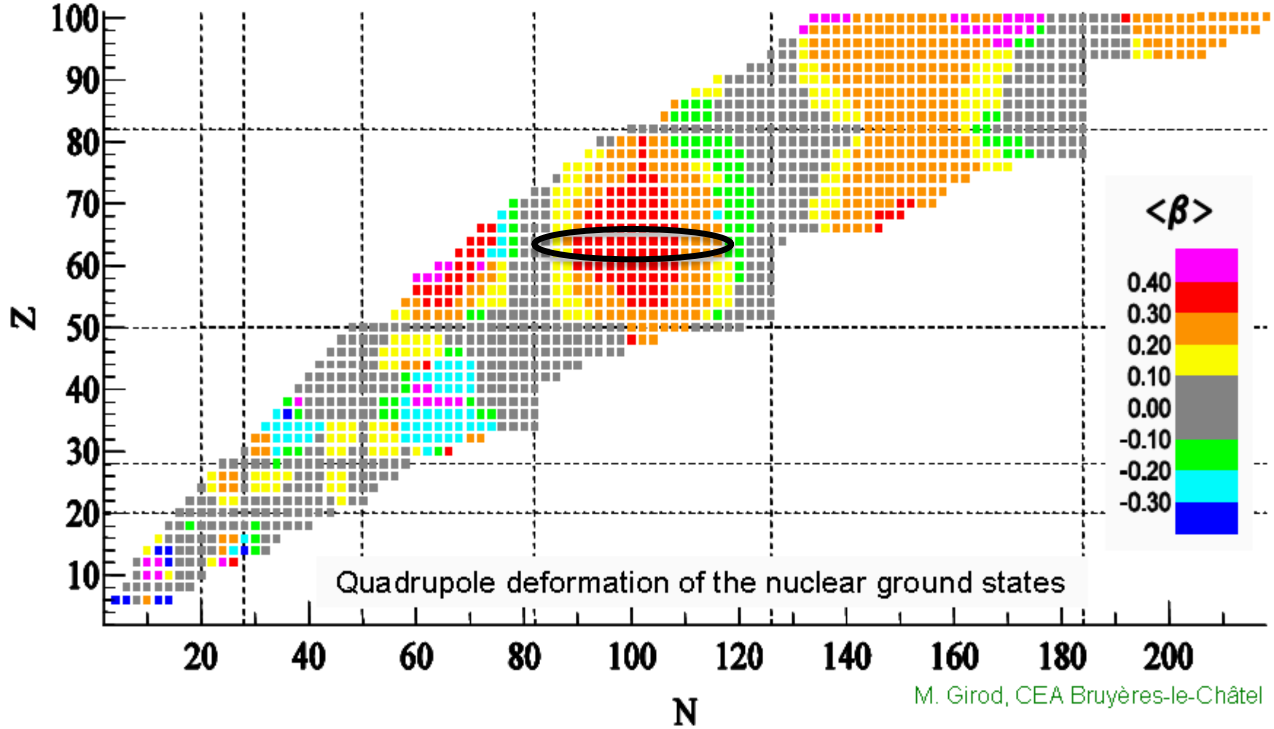



- Systematics of the evolution of nuclear structure effects from $^{144}$Sm ($\beta_2$=0.00) to $^{154}$Sm ($\beta_2$=0.27).

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 340 d | 0.1 Gyr | | | | | 90 yr | | 46 h | | 22 m |
| $^{144}$Sm | $^{145}$Sm | $^{146}$Sm | $^{147}$Sm | $^{148}$Sm | $^{149}$Sm | $^{150}$Sm | $^{151}$Sm | $^{152}$Sm | $^{153}$Sm | $^{154}$Sm | $^{155}$Sm |
| $\beta_2 = 0.00$ | $\beta_2 = -0.03$ | $\beta_2 = 0.00$ | $\beta_2 = 0.14$ | $\beta_2 = 0.16$ | $\beta_2 = 0.18$ | $\beta_2 = 0.21$ | $\beta_2 = 0.22$ | $\beta_2 = 0.24$ | $\beta_2 = 0.26$ | $\beta_2 = 0.27$ | $\beta_2 = 0.27$ |
| 82 | 83 | 84 | 85 | 86 | 87 | 88 | 89 | 90 | 91 | 92 | 93 |

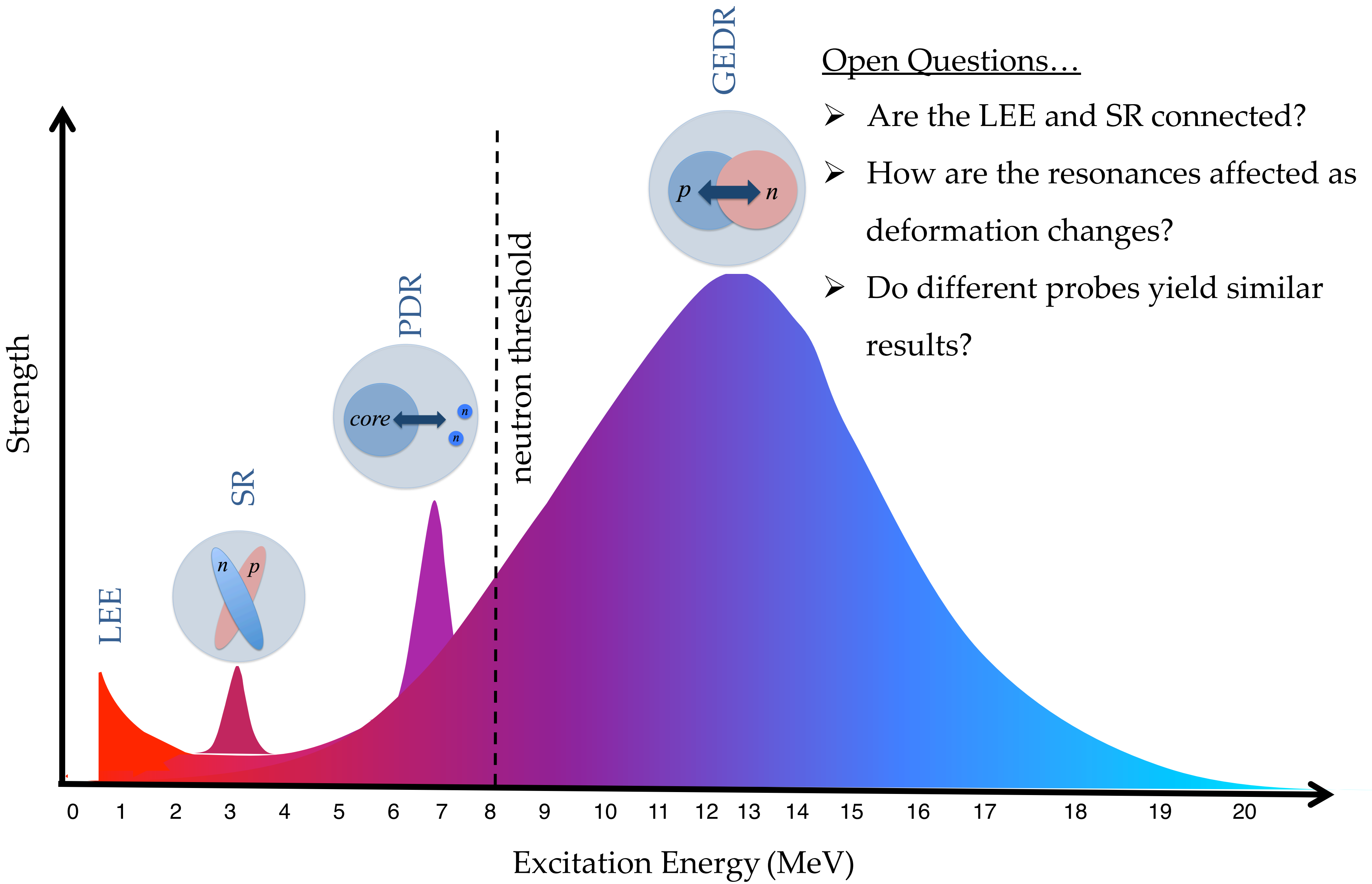
Neutron number

# Motivation for $^{154,155}$Sm




- Systematics of the evolution of nuclear structure effects from $^{144}$Sm ($\beta_2$=0.00) to $^{154}$Sm ($\beta_2$=0.27).
- As the nuclear shape changes, γ-ray strength functions (γSF) are expected to be affected.
- In particular, resonances such as the Pygmy dipole (PDR) , Scissors Resonance (SR) and Low-Energy Enhancement (LEE) may reveal interesting features.

# Electromagnetic dipole response in nuclei



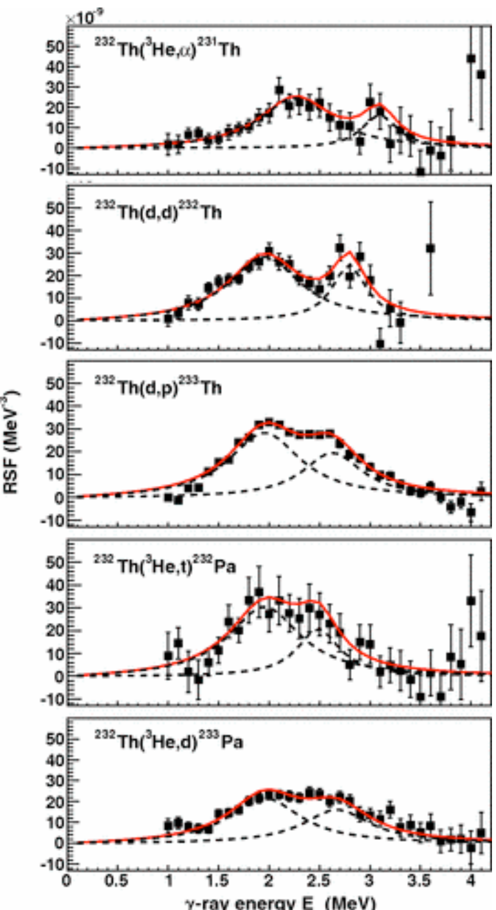

<u>Open Questions…</u>

- ➢ Are the LEE and SR connected?
- ➢ How are the resonances affected as deformation changes?
- ➢ Do different probes yield similar results?

PRL **109**, 162503 (2012) PHYSICAL REVIEW LETTERS week ending 19 OCTOBER 2012

### Observation of Large Scissors Resonance Strength in Actinides

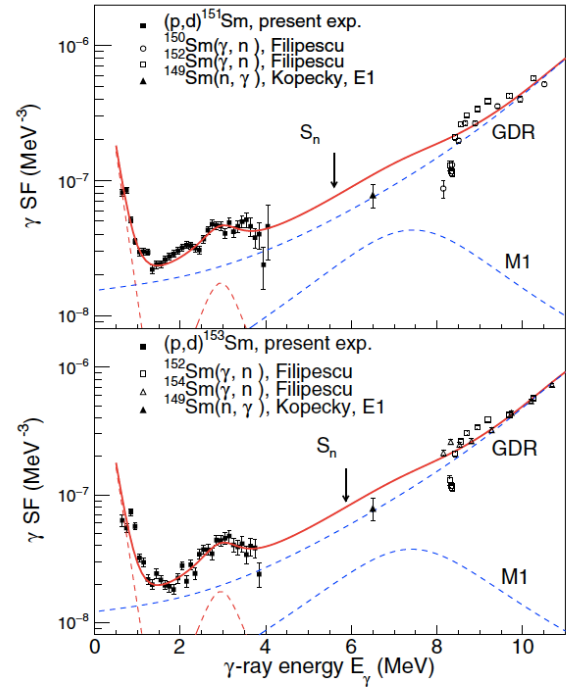
M. Guttormsen,[1,*] L. A. Bernstein,[2] A. Bürger,[1] A. Görgen,[1] F. Gunsing,[3] T. W. Hagen,[1] A. C. Larsen,[1] T. Renstrøm,[1] S. Siem,[1] M. Wiedeking,[4] and J. N. Wilson[5]
[1]*Department of Physics, University of Oslo, N-0316 Oslo, Norway*
[2]*Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, California 94550-9234, USA*




PHYSICAL REVIEW C **93**, 034303 (2016)

### First observation of low-energy γ-ray enhancement in the rare-earth region

A. Simon,[1,*] M. Guttormsen,[2,†] A. C. Larsen,[2,‡] C. W. Beausang,[2] P. Humby,[3,4] J. T. Burke,[5] R. J. Casperson,[5] R. O. Hughes,[5] T. J. Ross,[6] J. M. Allmond,[7] R. Chyzh,[8] M. Dag,[8] J. Koglin,[5] E. McCleskey,[8] M. McCleskey,[8] S. Ota,[5,9] and A. Saastamoinen[8]
[1]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556-5670, USA*
[2]*Department of Physics, University of Oslo, N-0316 Oslo, Norway*

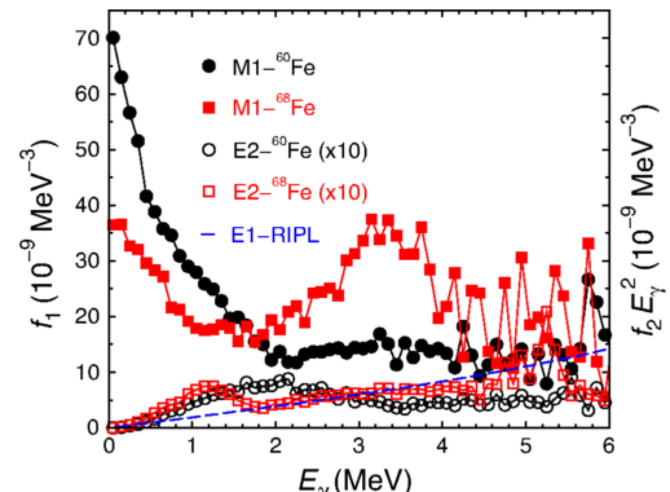



- Data analyzed using the Oslo Method.

PRL **118**, 092502 (2017) PHYSICAL REVIEW LETTERS

### Low-Energy Magnetic Dipole Radiation in Open-Shell Nuclei

R. Schwengner,[1,*] S. Frauendorf,[2] and B. A. Brown[3]
[1]*Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany*
[2]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[3]*National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

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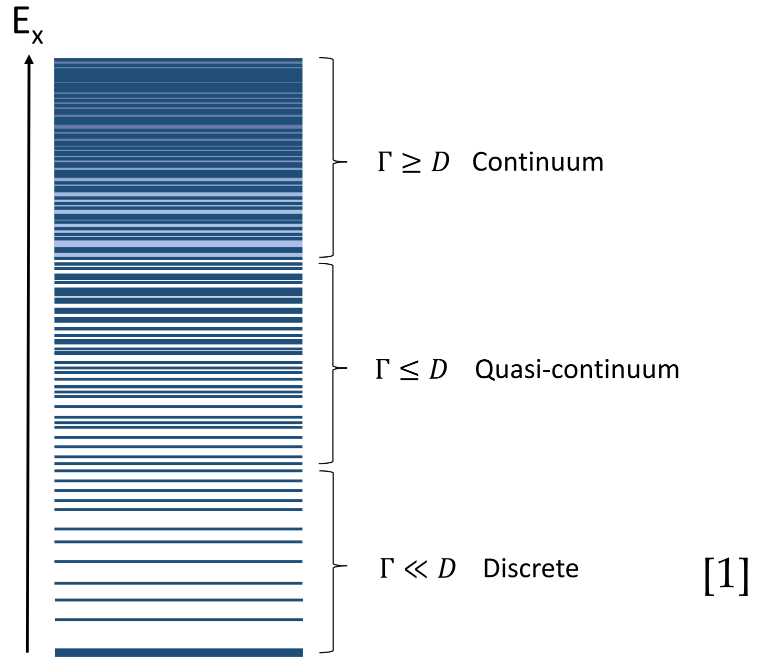
# Objectives

- Measure Nuclear Level Density (NLD) and $\gamma$-ray Strength Function ($\gamma$SF) below $S_n$ in $^{154,155}$Sm isotopes (Oslo Method).



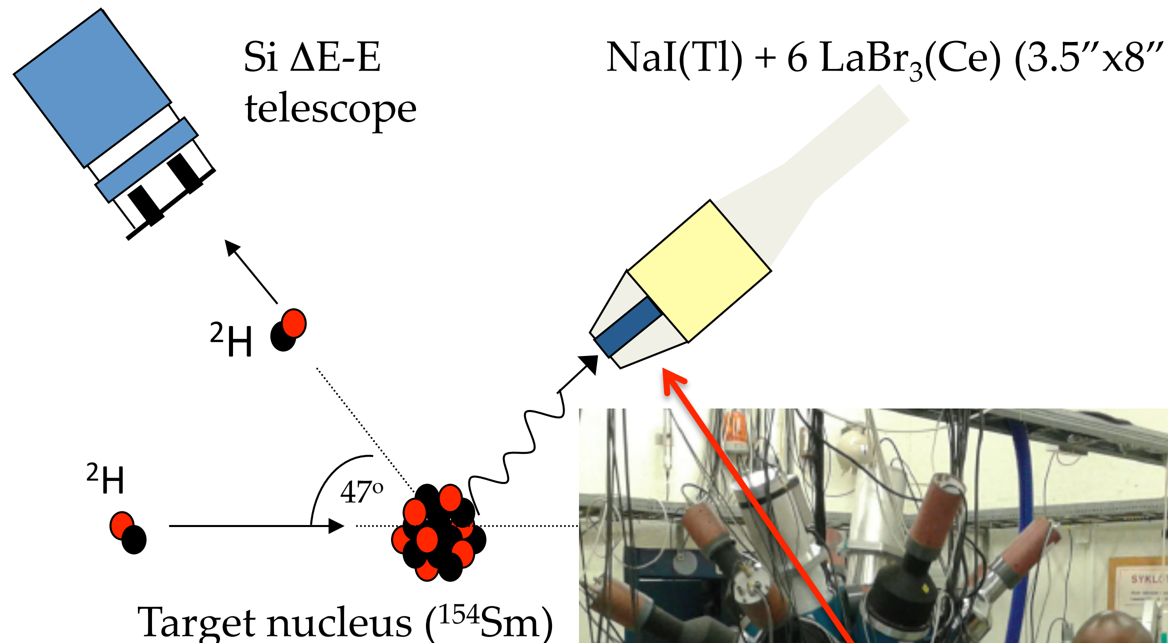

- Extract the $B(M1)$ of scissors resonance.
- Compare to other measurements and provide a near complete picture of systematics in Samarium isotopes ($^{144\text{-}159}$Sm).

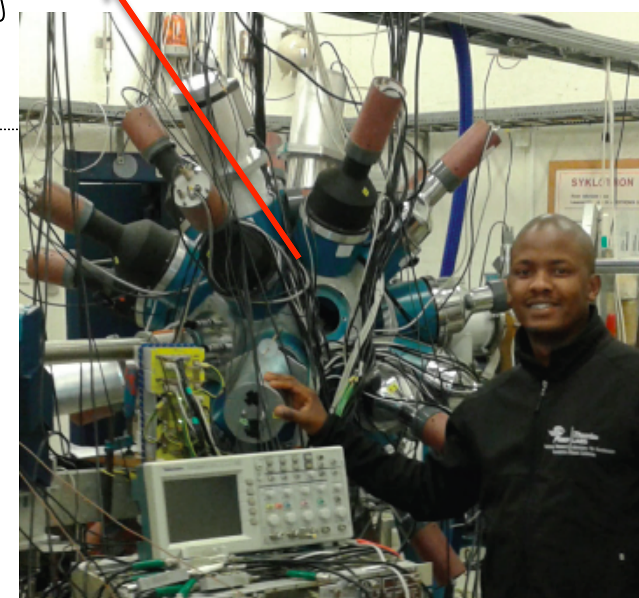
[1] M. Guttormsen et al., Eur. Phys. J. A 51 (12), 170 (2015)

# Experimental Setup

## Oslo Cyclotron Laboratory

- 3.2 mg/cm$^2$ thick $^{154}$Sm foil
- $^{154}$Sm(d,X)$^{154,155}$Sm 13 & 15 MeV

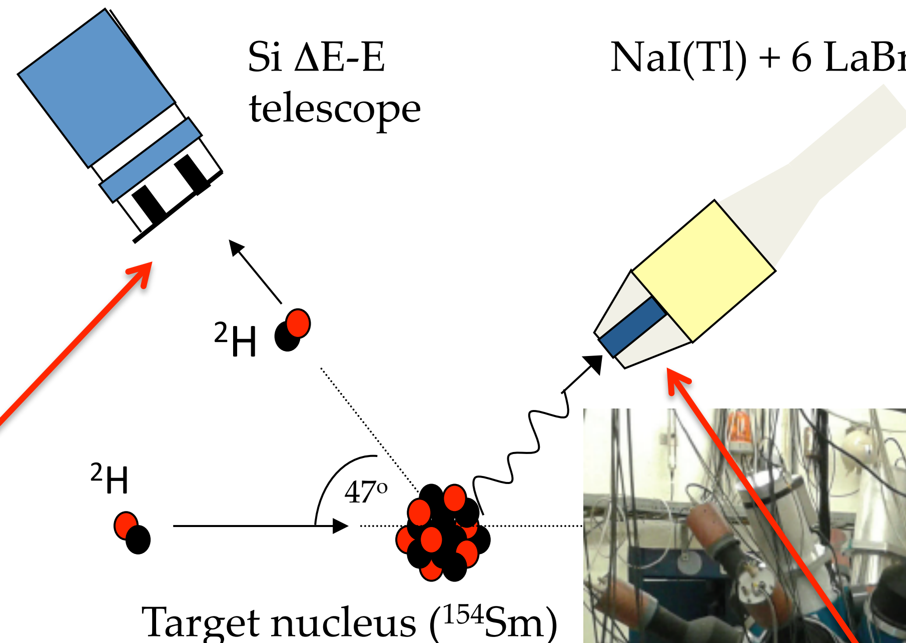


- CACTUS Array: 24 collimated 5″×5″ NaI(Tl) (~22 cm)
- 14.1% eff. at Eγ= 1332 keV

# Experimental Setup

## Oslo Cyclotron Laboratory

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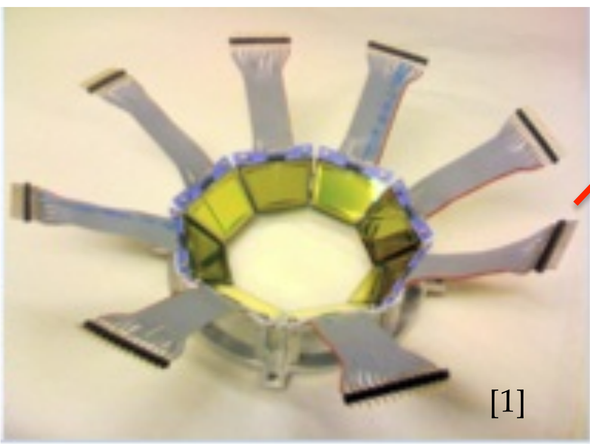
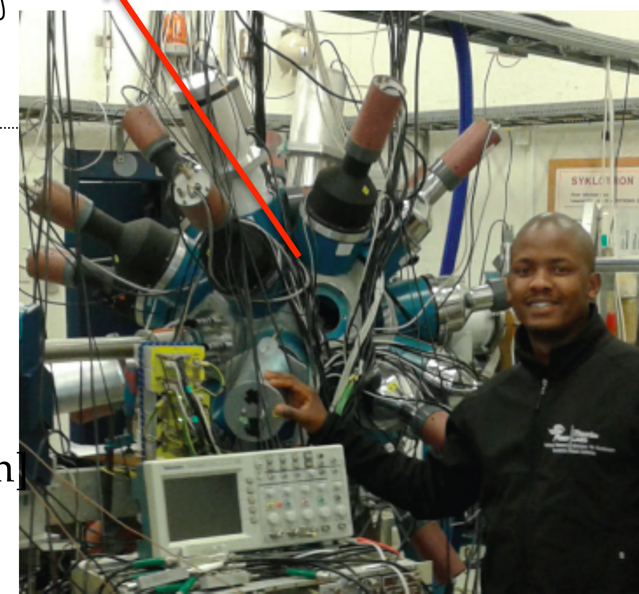
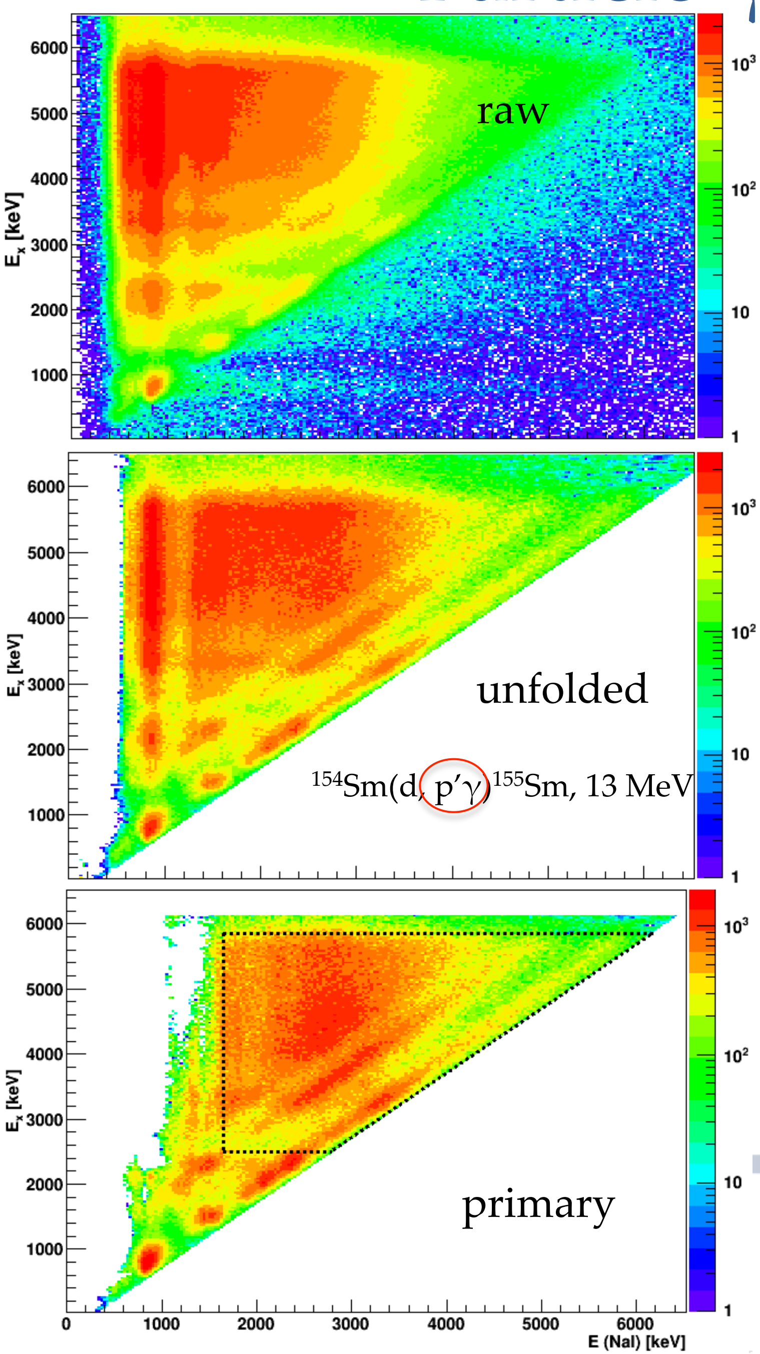


- SiRi Array, 64 ΔE-E Si particle telescopes [θ = 126° to 140°,~ 5 cm]
- ΔE, E and Al foil thicknesses (130, 1550 and 10.5 μm)


[1] M. Guttormsen et al., NIM Phys. Res. A 648, 168 (2011)

# Particle-$\gamma$ Coincidence Matrices




**The Oslo Method**

1. Unfolding the continuum $\gamma$-ray spectra [1]
   > Unfolding iterative procedure
2. Extraction of primary $\gamma$-rays [2]
   > first-generation method
3. Simultaneous extraction of level density and strength function [3]

$$\lambda_{if} = \frac{2\pi}{\hbar}\left|M_{if}\right|^2 \cdot \rho(E_f)$$ Fermi's golden rule

$$P(E_i, E_\gamma) \propto \rho(E_f).\mathcal{T}(E_\gamma)$$ Assumes Brink-Axel hypothesis

4. Normalization

[1] M. Guttormsen et al., NIM Phys. Res. A 374, 371 (1996)
[2] M. Guttormsen et al., NIM Phys. Res. A 255, 518 (1987)
[3] A. Schiller et al., NIM Phys. Res. A 447, 498 (2000)
[4] A. C. Larsen et al., Phys. Rev. C 83, 034 315 (2011)



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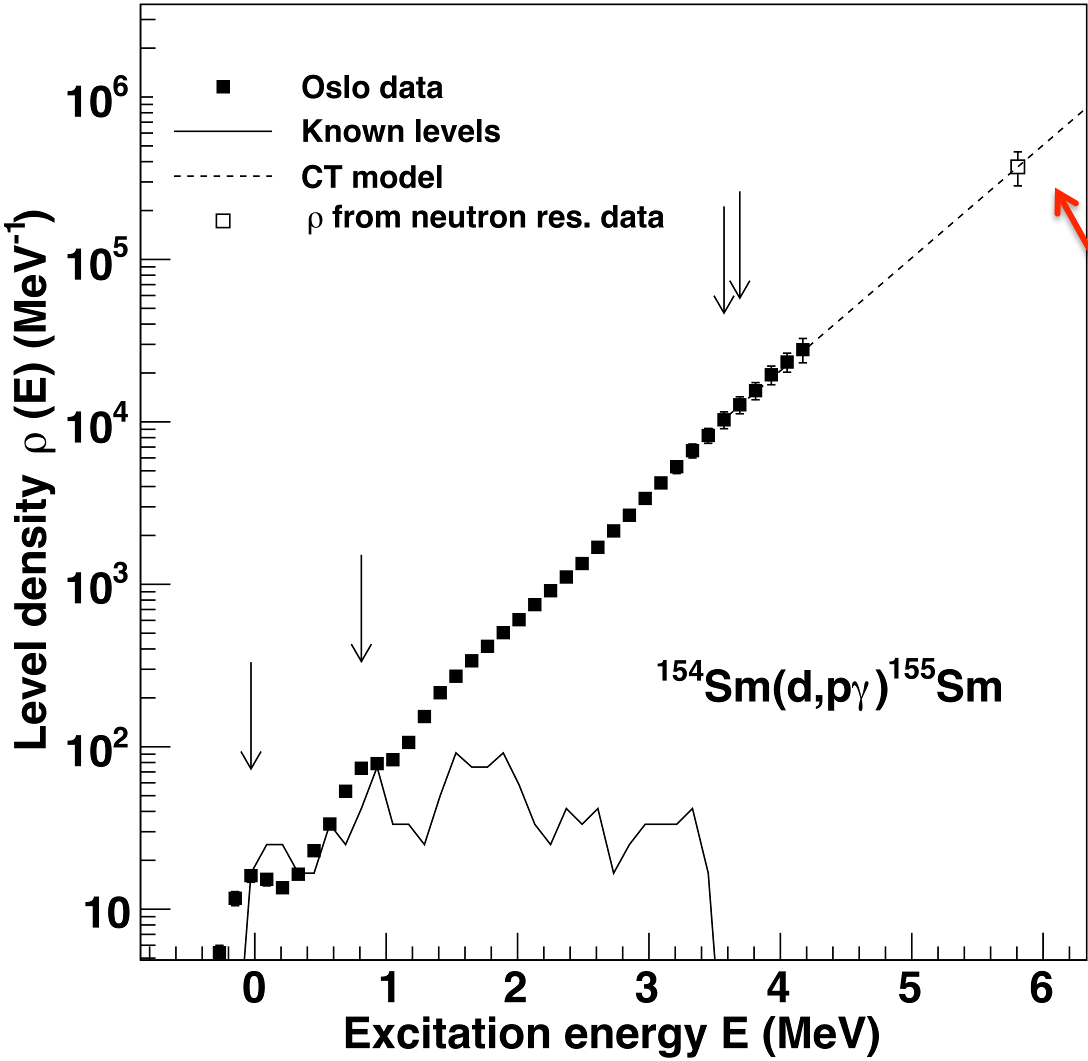
# Normalization of the Nuclear Level Density




$$\rho(S_n) = \frac{2\sigma^2}{D_0}\frac{1}{(J_T+1)e^{[-(J_T+1)^2/2\sigma^2]} + e^{[-J_T^2/2\sigma^2]}}$$

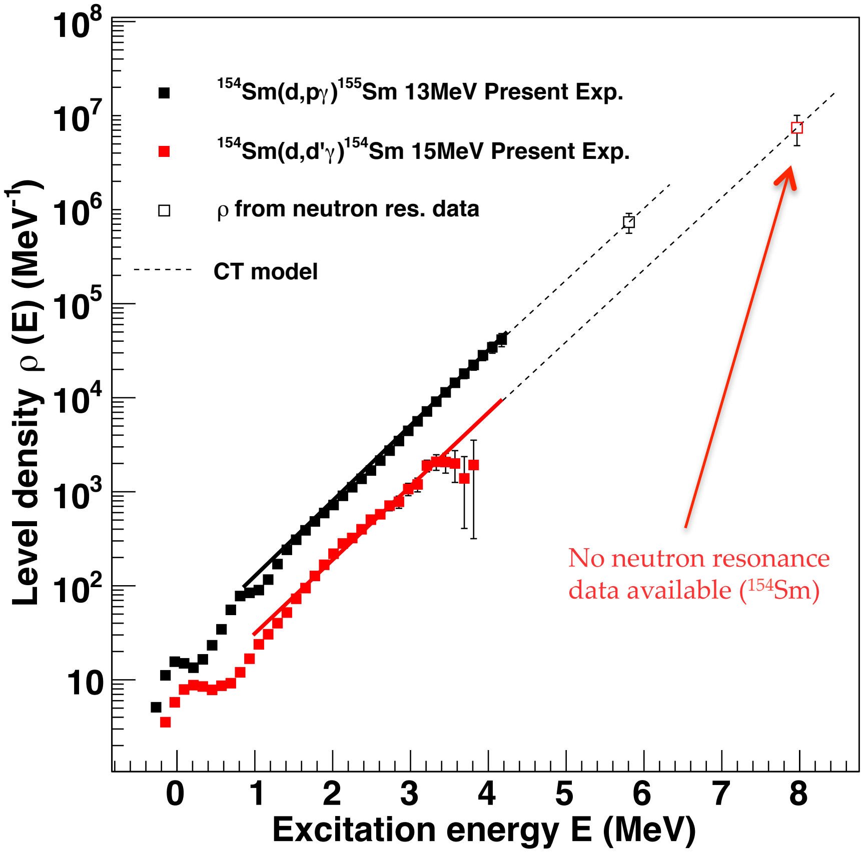
http://www.nndc.bnl.gov

S. F. Mughabghab, Atlas of Neutron Resonance, 5th ed. (Elsevier Science, Amsterdam) 2006.

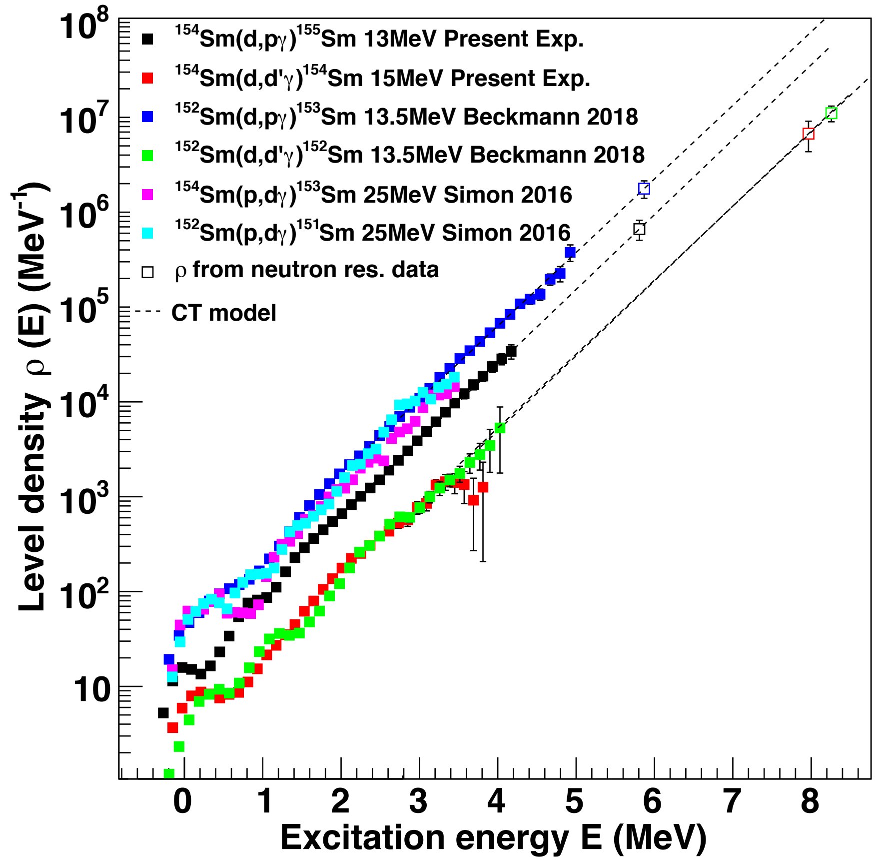
https://www-nds.iaea.org/RIPL-3/

# $^{151-155}$Sm Nuclear Level Densities

- NLDs of neighbouring isotopes




- NLDs of even-even vs. even-odd isotopes

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K. Sønstevold Beckmann ($^{152,153}$Sm), MSc thesis, UiO, (2018)
A. Simon et al., Phys. Rev. C 93, 034303 (2016)

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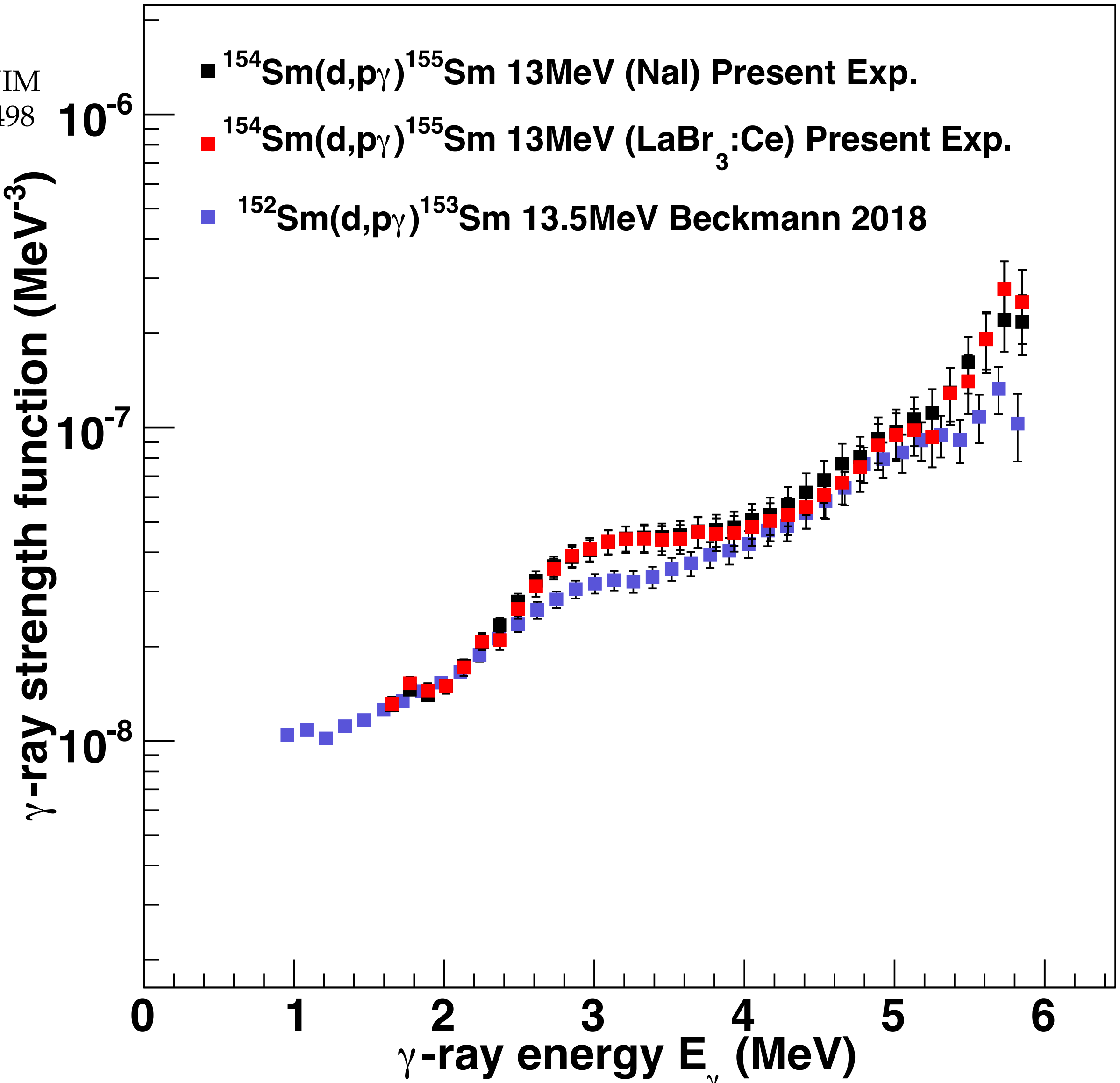
# Even-odd $^{153,155}$Sm γ-ray strength functions

$$f(E_\gamma) = \frac{1}{2\pi E_\gamma^3} B\mathcal{T}(E_\gamma)$$

A. Schiller et al., NIM Phys. Res. A 447, 498 (2000)

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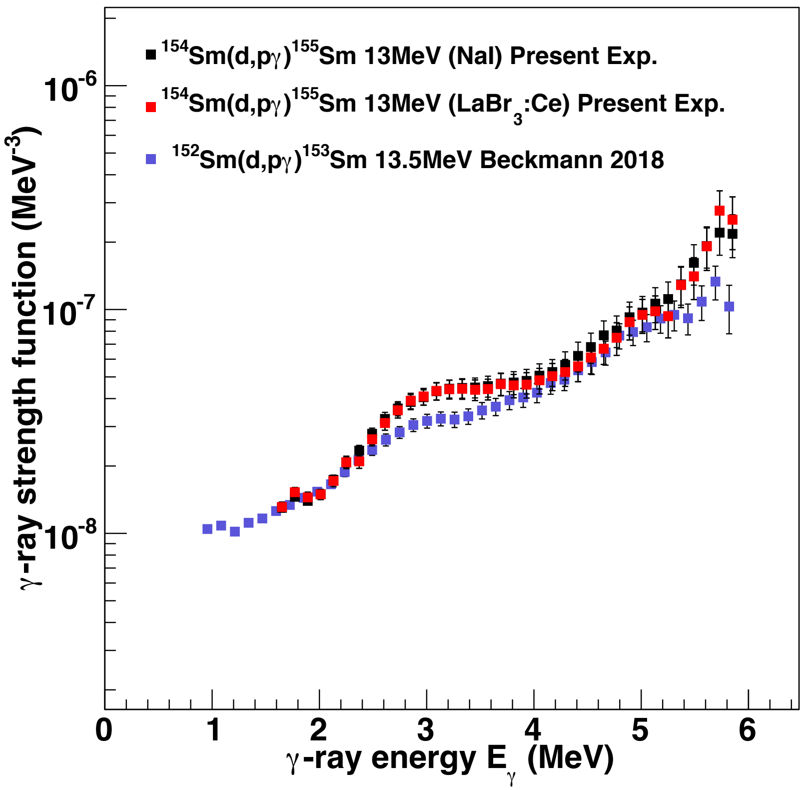
# Even-odd $^{153,155}$Sm vs. Even-even $^{152,154}$Sm

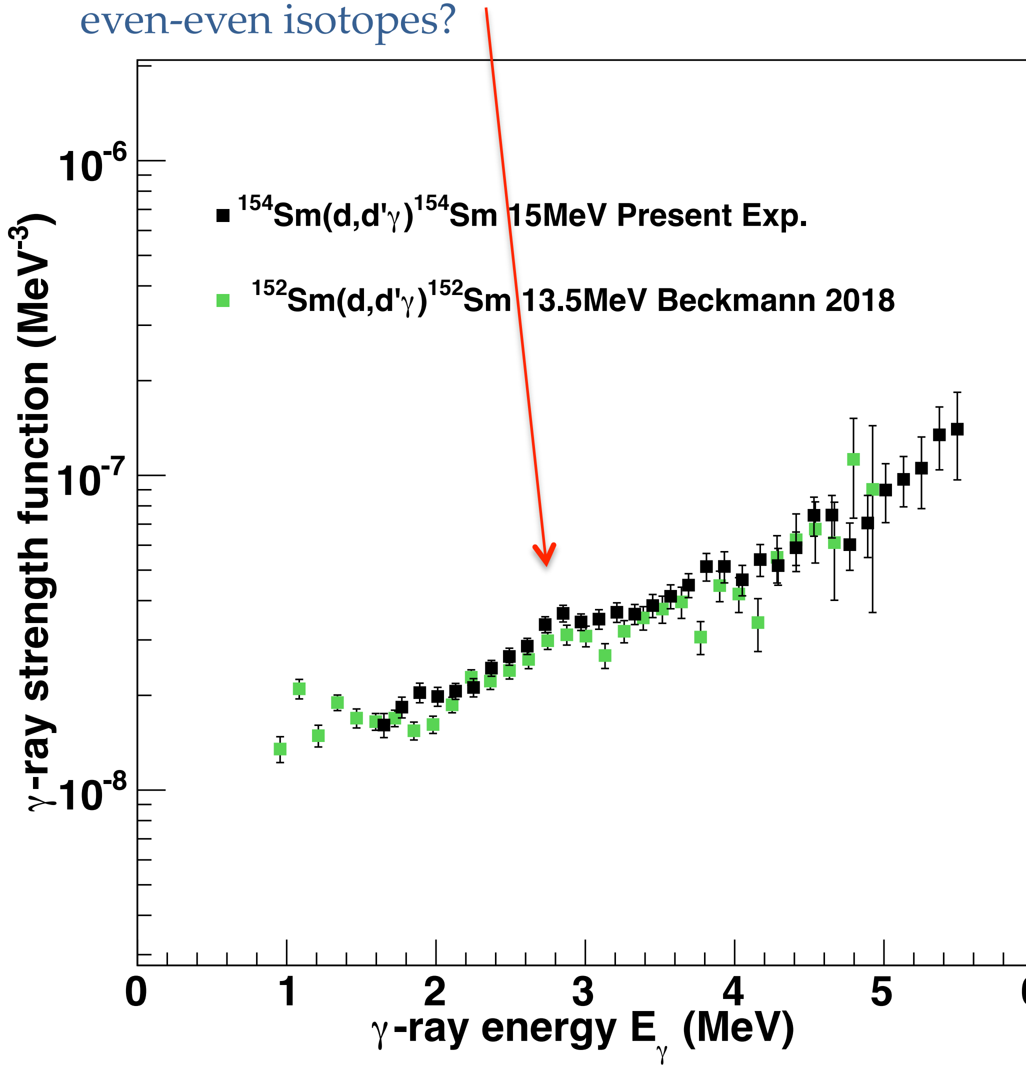
$$\sum B(M1)\uparrow \sim B(E2;0_1^+ \rightarrow 2_1^+) \sim \delta^2$$

K. Heyde, P. von Neumann-Cosel, and A. Richter, Rev. Mod. Phys. 82, 2365 (2010)

- $\gamma$SFs of neighbouring isotopes




- Where is the scissors resonance for well-deformed even-even isotopes?

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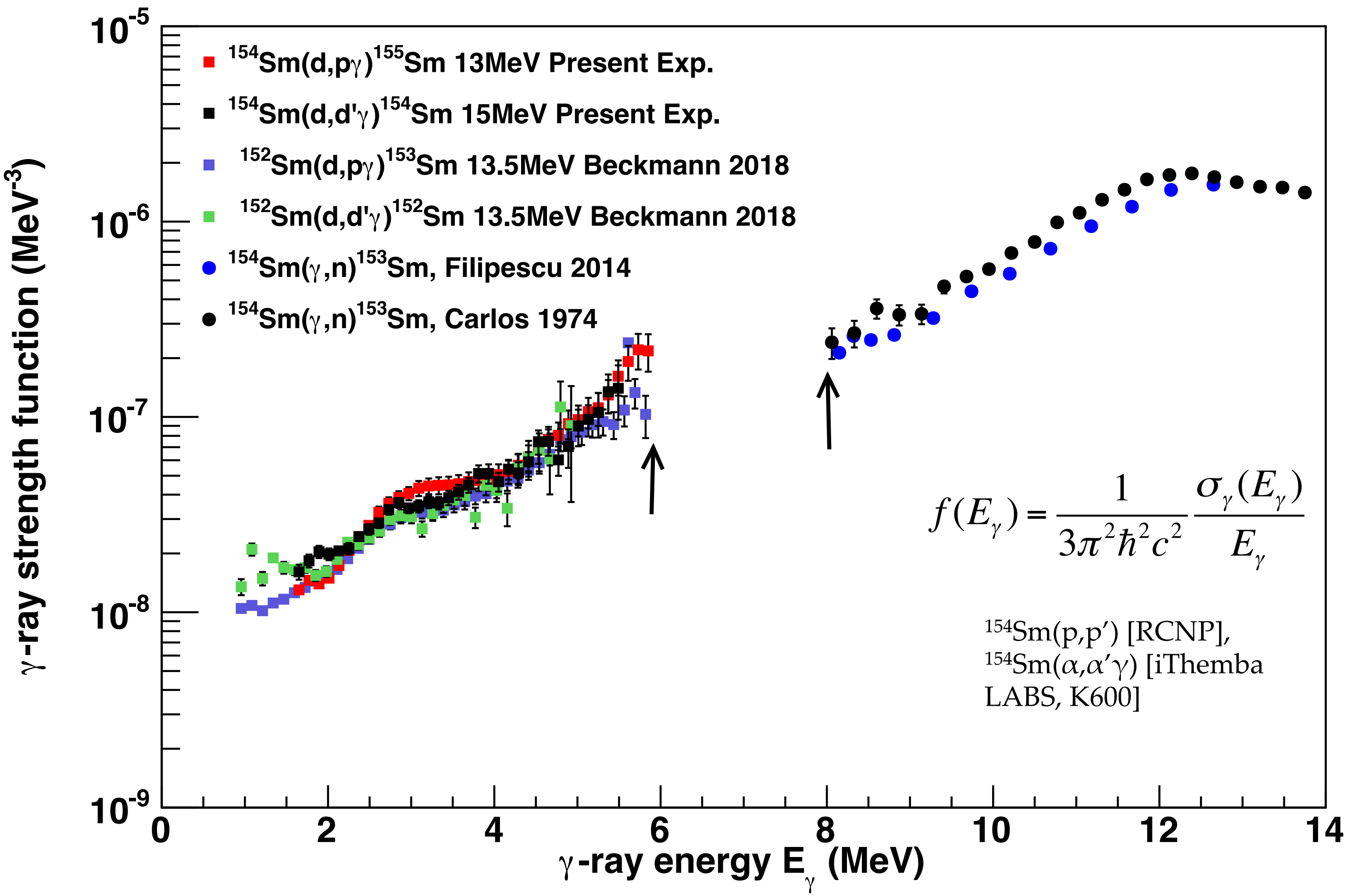
# $^{152-155}$Sm

## Comparison with photoabsorption data




$$f(E_\gamma) = \frac{1}{3\pi^2\hbar^2c^2}\frac{\sigma_\gamma(E_\gamma)}{E_\gamma}$$

$^{154}$Sm(p,p′) [RCNP], $^{154}$Sm($\alpha$,$\alpha'\gamma$) [iThemba LABS, K600]

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Nucl. Data Sheets 120, (2014) 272: Experimental Nuclear Reaction Data (EXFOR)
Nucl. Data Sheets 110, (2009) 3107: Reference Input Parameter Library (RIPL-3)
-available online at http://www-nds.iaea.org

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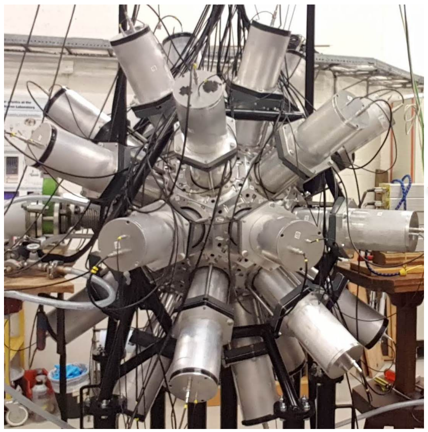
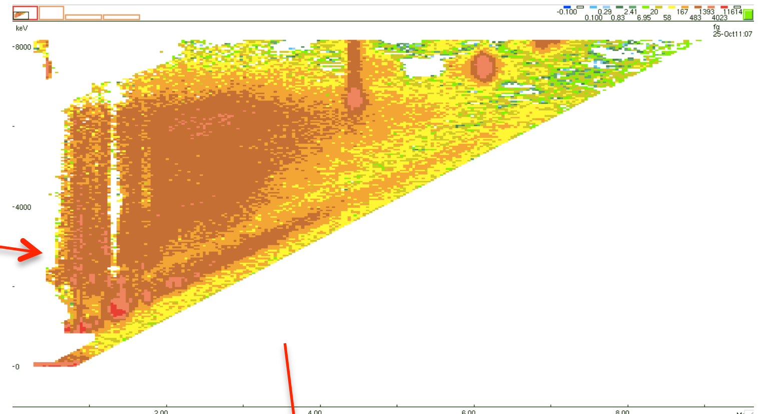
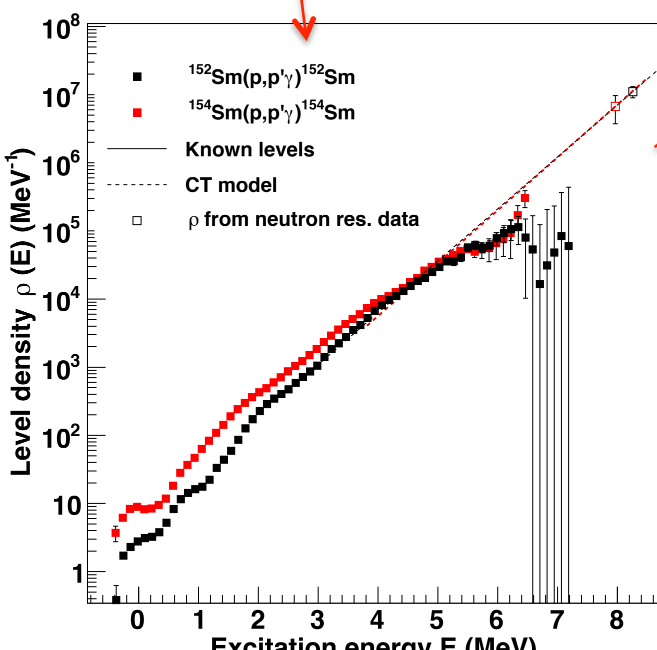
# $^{152,154}$Sm(p,p’γ) experiment

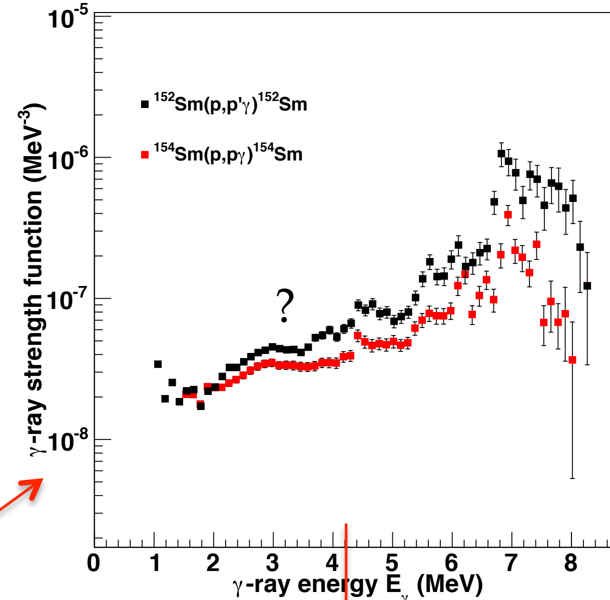
- 2.9 and 3.2 mg/cm$^2$ thick $^{152,154}$Sm foil, 15 MeV beam
- OSCAR (30 $LaBr_3$:Ce Array+SiRi)
- $^{12}$C and $^{16}$O contamination

Very very … preliminary!!



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# Future Work

- Finalize analysis and extraction of B(M1) values in $^{154,155}$Sm
- Test difference spin distribution models
- Compare resonances in the $\gamma$SF to those of $^{144,148,149,152,153}$Sm [Oslo Group], $^{154}$Sm(p,p') [RCNP], $^{154}$Sm($\alpha$,$\alpha'\gamma$) [K600, iThemba LABS]

- Analysis of $^{152,154}$Sm(p,p'$\gamma$) experiment using OSCAR at OCL, which took place September 2018.
- Other measurements: NLD and $\gamma$SF of neutron rich $^{156-159}$Sm, scheduled 2019 at ANL (CARIBU)

# Acknowledgements

K. L. Malatji (klmalatji@tlabs.ac.za)
P. Papka (Supervisor)

M. Wiedeking (Main supervisor)
P. Jones

B. V. Kheswa

L. Pellegri

A. Krugmann
P. Von Neumann-Cosel

A. Y. Kursad
M. Ozgur

F. L. Bello Garrote
L. Crespo Campo
A. Görgen
M. Guttormsen
K. Hadynska-Klek
T. W. Hagen
V. W. Ingeberg
M. Klintefjord
A.C. Larsen
T. Renstrøm
S. Rose
E. Sahin
S. Siem (Supervisor)
G. M. Tveten
F. Zeiser
K. Beckmann
J. Midtbø

# Thank you all!!