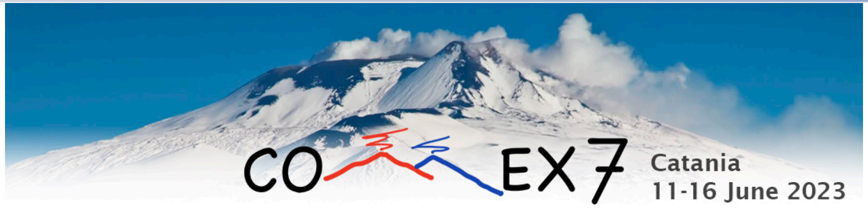
Statistical properties of well-deformed ^{153,155}Sm and the M1 scissors mode

Kgashane L. Malatji
kl.malatji@ilabs.nrf.ac.za

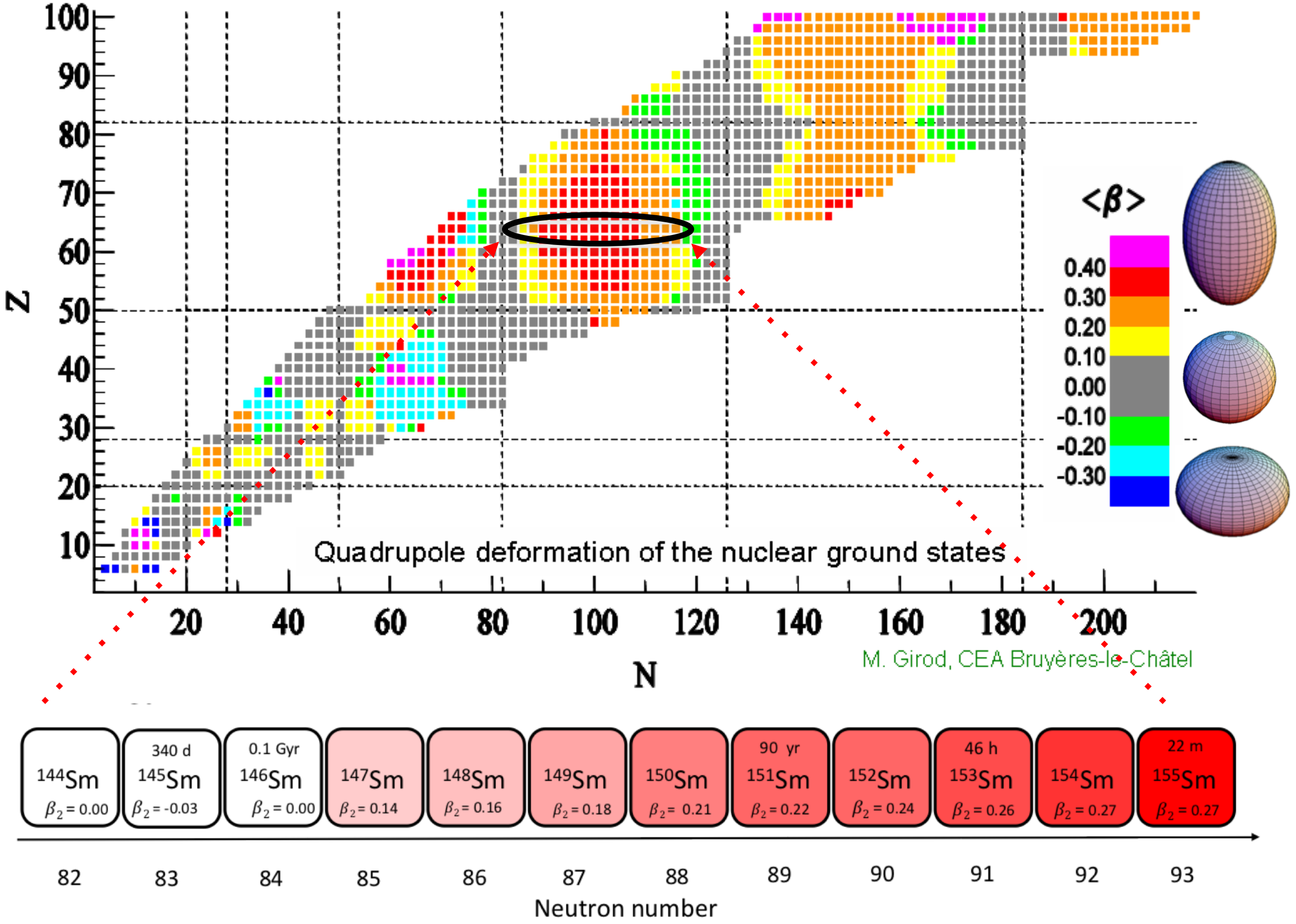
Research supported in part by the National Research Foundation of South Africa, the IAEA, and Norwegian Research Council (INTPART).

science & innovation
Department:
Science and Innovation
REPUBLIC OF SOUTH AFRICA



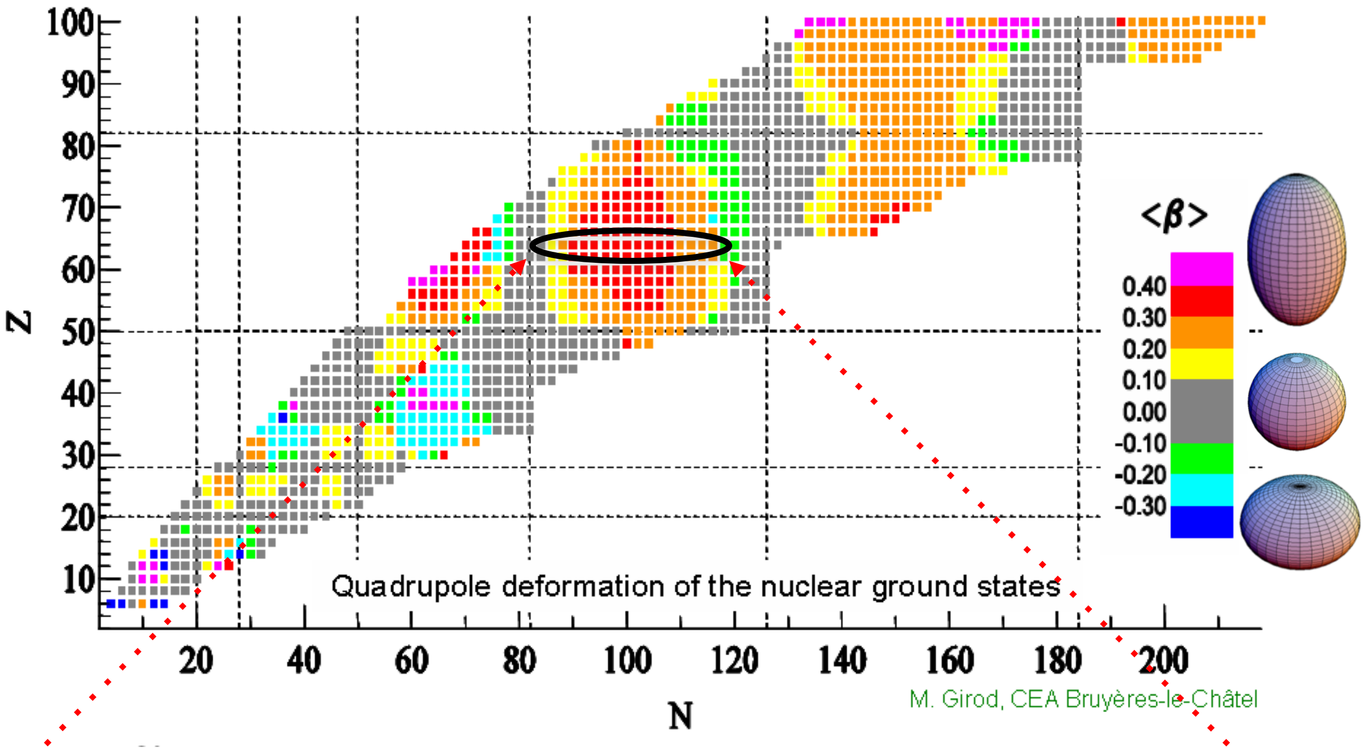
NRF
National Research Foundation
iThemba LABS
Laboratory for Accelerator Based Sciences

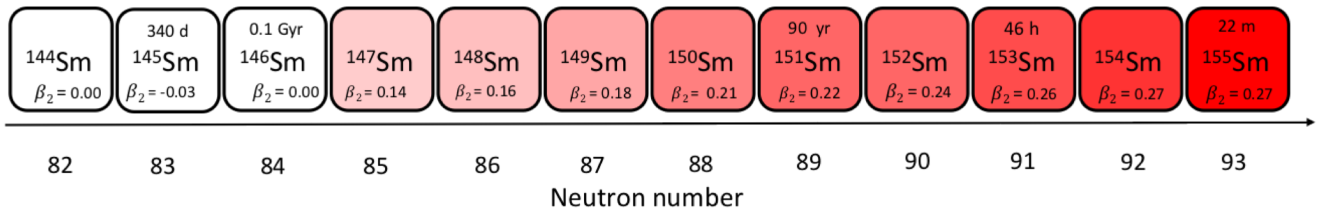
Samarium Isotopic Chain

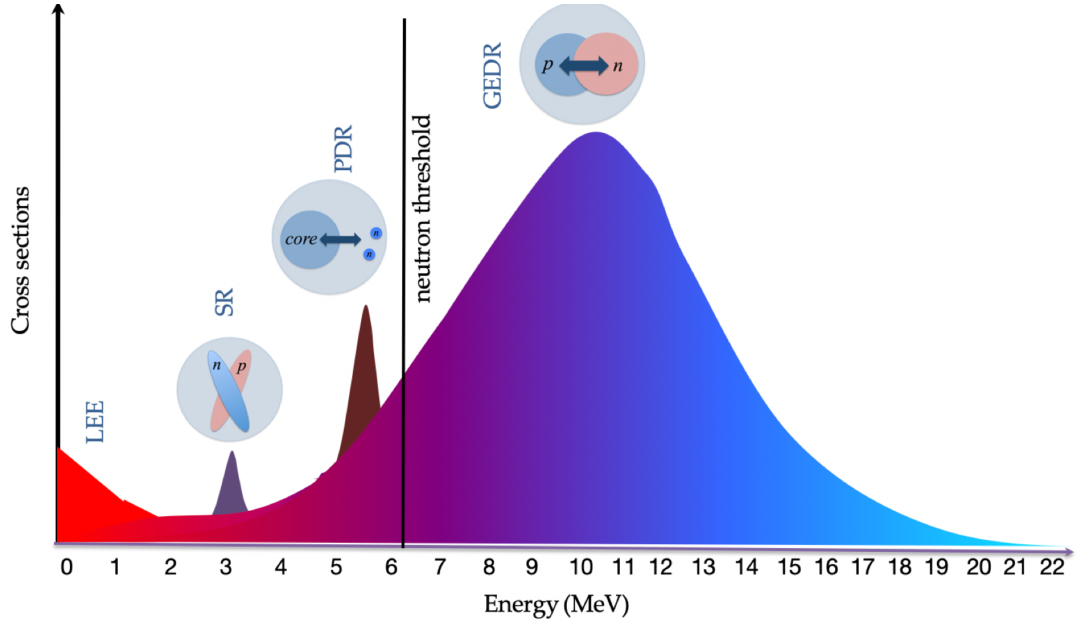


- Systematically investigate the evolution of nuclear structure effects from ^{144}Sm (β_2~0.00) to ^{155}Sm (β_2~0.27)
- As the nuclear shape changes, γ-ray strength function (γSF) will be affected
- In particular, nuclei response modes such as the Pygmy dipole (PDR) , Scissors Resonance (SR) and Low-Energy Enhancement (LEE) may reveal interesting features

Electromagnetic Dipole Response in Nuclei







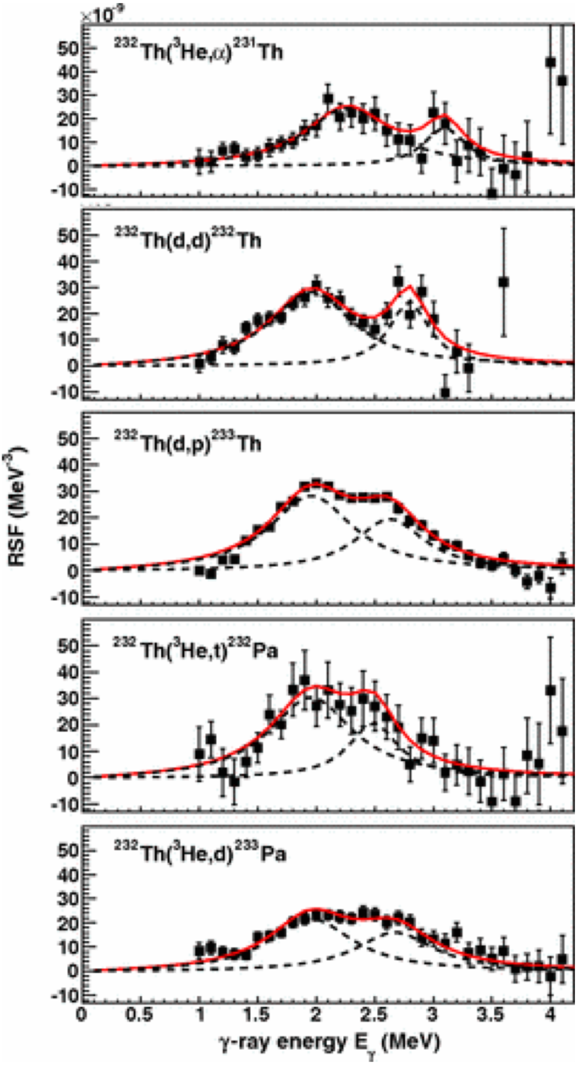
<u>Open Questions…</u>

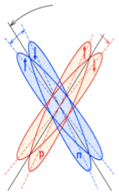
- Are the LEE and SR interconnected?
- How are the excitation modes affected as deformation changes?
- Do different probes yield similar results?
- Validity of the GBA hypothesis and many more …

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*



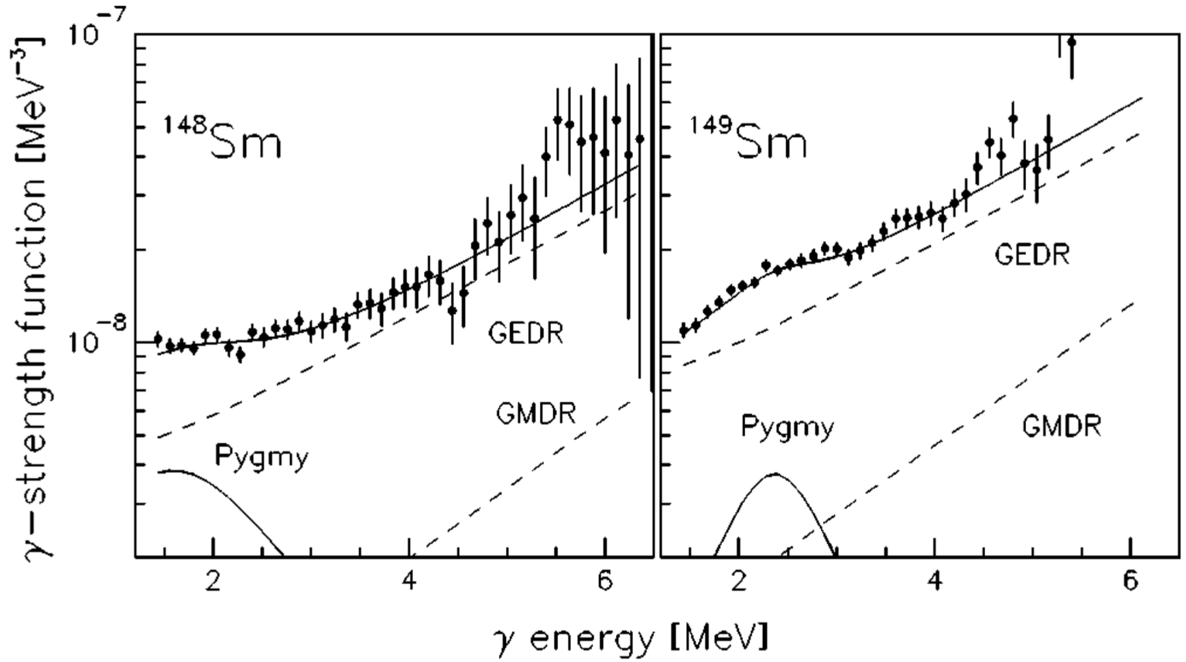


E. B. Balbutsev et al., Phys. Rev. C 97, 044316 (2018)

PHYSICAL REVIEW C, VOLUME 65, 044318

Level densities and γ-strength functions in ^{148,149}Sm

S. Siem,* M. Guttormsen, K. Ingeberg, E. Melby, J. Rekstad, and A. Schiller[†]
Department of Physics, University of Oslo, P.O. Box 1048, Blindern, N-0316 Oslo, Norway
A. Voinov
Frank Laboratory of Neutron Physics, Joint Institute of Nuclear Research, RU-141980 Dubna, Moscow region, Russia
(Received 16 November 2001; published 26 March 2002)

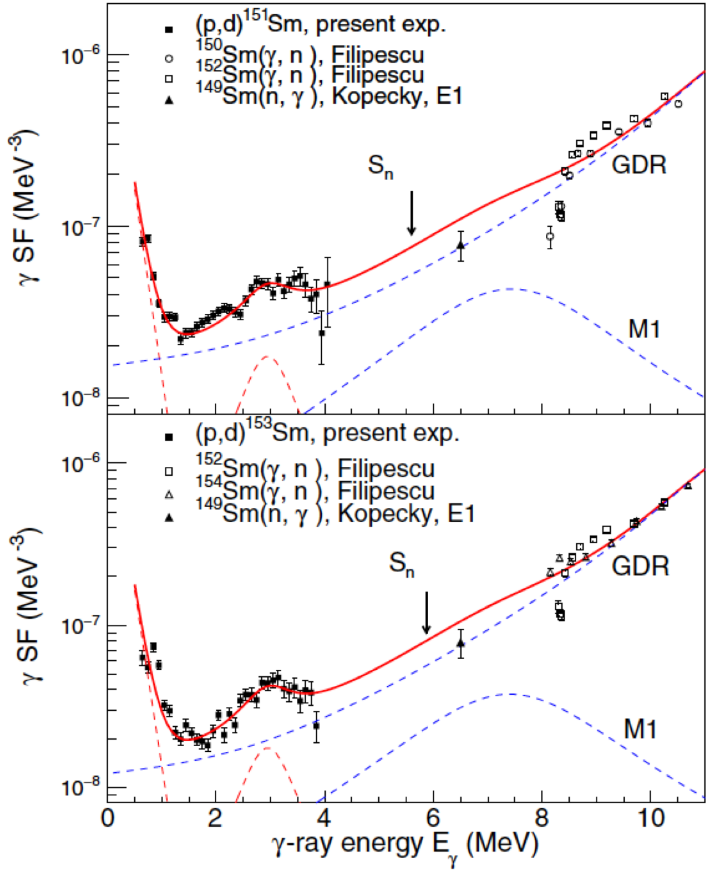


- Data analyzed using the Oslo Method

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, Indiana 46556-5670, USA*
[2]*Department of Physics, University of Oslo, N-0316 Oslo, Norway*

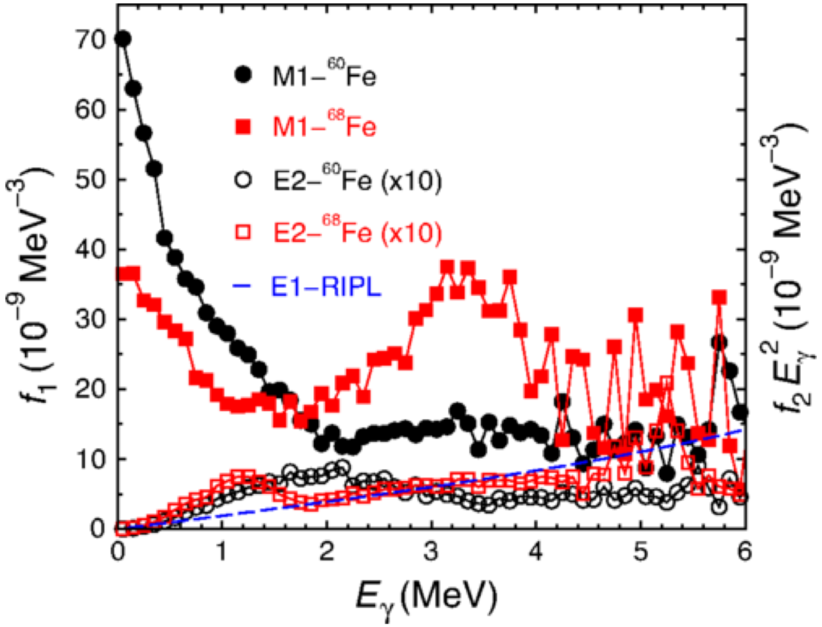


Both the LEE and the scissors mode have been observed simultaneously in the same nucleus.

PRL 118, 092502 (2017) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2017

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*



- Large-scale shell-model calculations for $^{60,64,68}Fe$.
- The strength of the SM increases by a factor of 2 when going from ^{60}Fe to ^{68}Fe.
- LEE strength decreases correspondingly and thereby **conserves the total strength of B(M1) ≈ 9.8μ_N^2.**
- The conservation of the summed SM and LEE strengths has been experimentally tested for $^{147,149,151,153}Sm$ [1], but large uncertainties prohibit a firm conclusion.

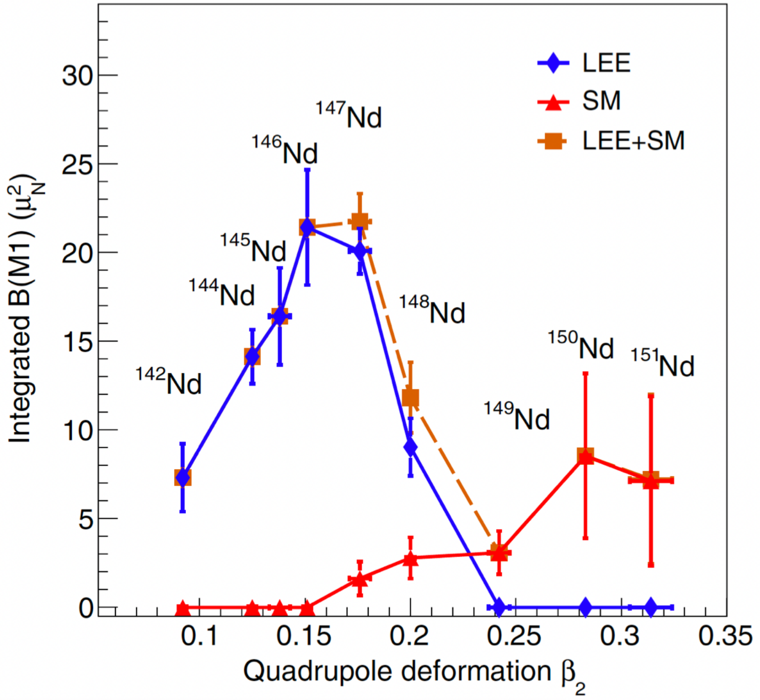
[1] F. Naqvi et al., Phys. Rev. C 99, 054331 (2019)

PHYSICAL REVIEW C 106, 034314 (2022)

Evolution of the γ-ray strength function in neodymium isotopes

M. Guttormsen,[1,*] K. O. Ay,[2] M. Ozgur,[2] E. Algin,[2,3] A. C. Larsen,[1] F. L. Bello Garrote,[1] H. C. Berg,[1,†] L. Crespo Campo,[1] T. Dahl-Jacobsen,[1] F. W. Furmyr,[1] D. Gjestvang,[1] A. Görgen,[1] T. W. Hagen,[1] V. W. Ingeberg,[1] B. V. Kheswa,[1,4] I. K. B. Kullmann,[5] M. Klintefjord,[1] M. Markova,[1] J. E. Midtbø,[1] V. Modamio,[1] W. Paulsen,[1] L. G. Pedersen,[1] T. Renstrøm,[1] E. Sahin,[1] S. Siem,[1] G. M. Tveten,[1] and M. Wiedeking[6,7]

Data analyzed using the Oslo Method



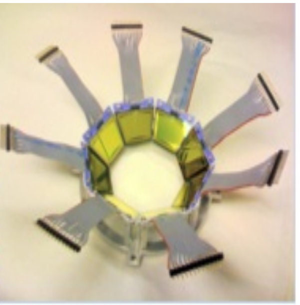
"The data reveal how the low-energy enhancement, the scissors mode, and the pygmy dipole resonance evolve with nuclear deformation and mass number. This indicates that the mechanisms behind the **low-energy enhancement and the scissors mode are decoupled from each other**."-Guttormsen *et al*.

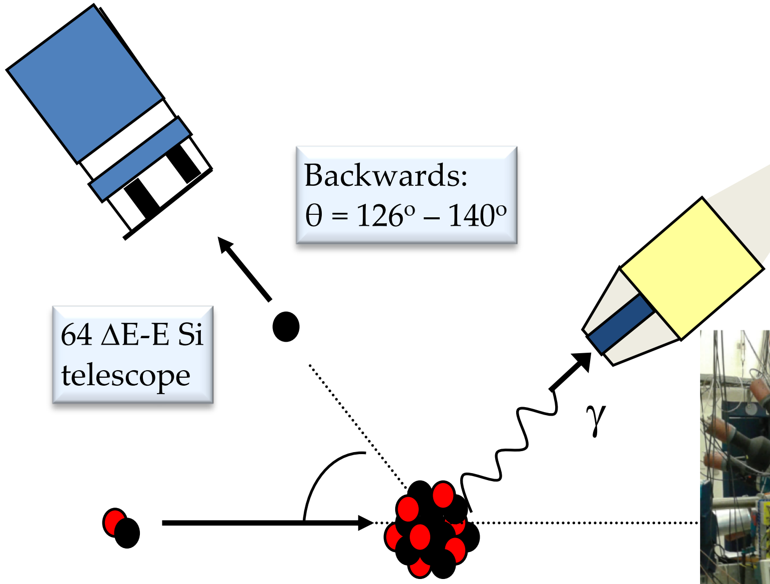
OCL
Oslo Cyclotron Laboratory

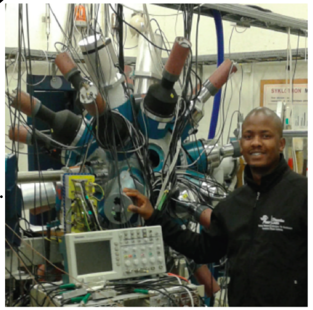
Experimental Details

Oslo Cyclotron Laboratory

- 2.9 & 3.2 mg/cm^2 thick ^{152,154}Sm
- ^{152,154}Sm(d,pγ)^{153,155}Sm 13.5 & 13 MeV



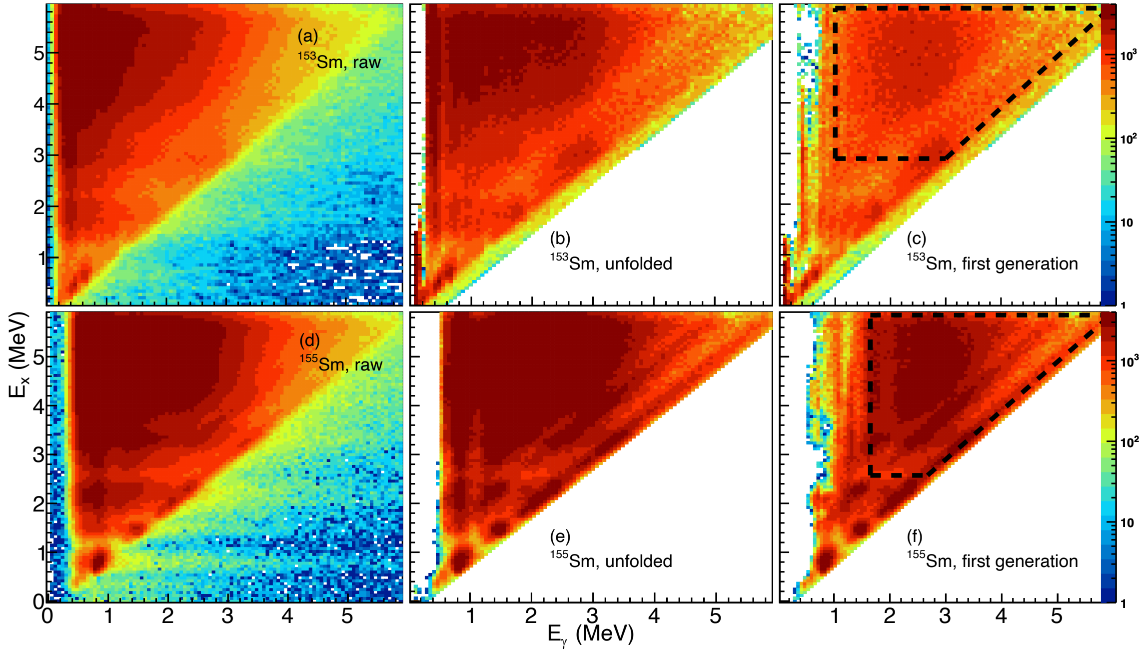




- SiRi Array, ΔE, E and Al foil thicknesses (130, 1550 and 10.5 μm)
- CACTUS Array: 24 collimated 5″ × 5″ NaI(Tl) (~22 cm)
- + 6 $LaBr_3$(Ce) (3.5″x8″)

M. Guttormsen *et al*., NIM A 648, 168 (2011)

$$P(E_i, E_\gamma) \propto \rho(E_f).\mathcal{T}\ (E_\gamma)$$

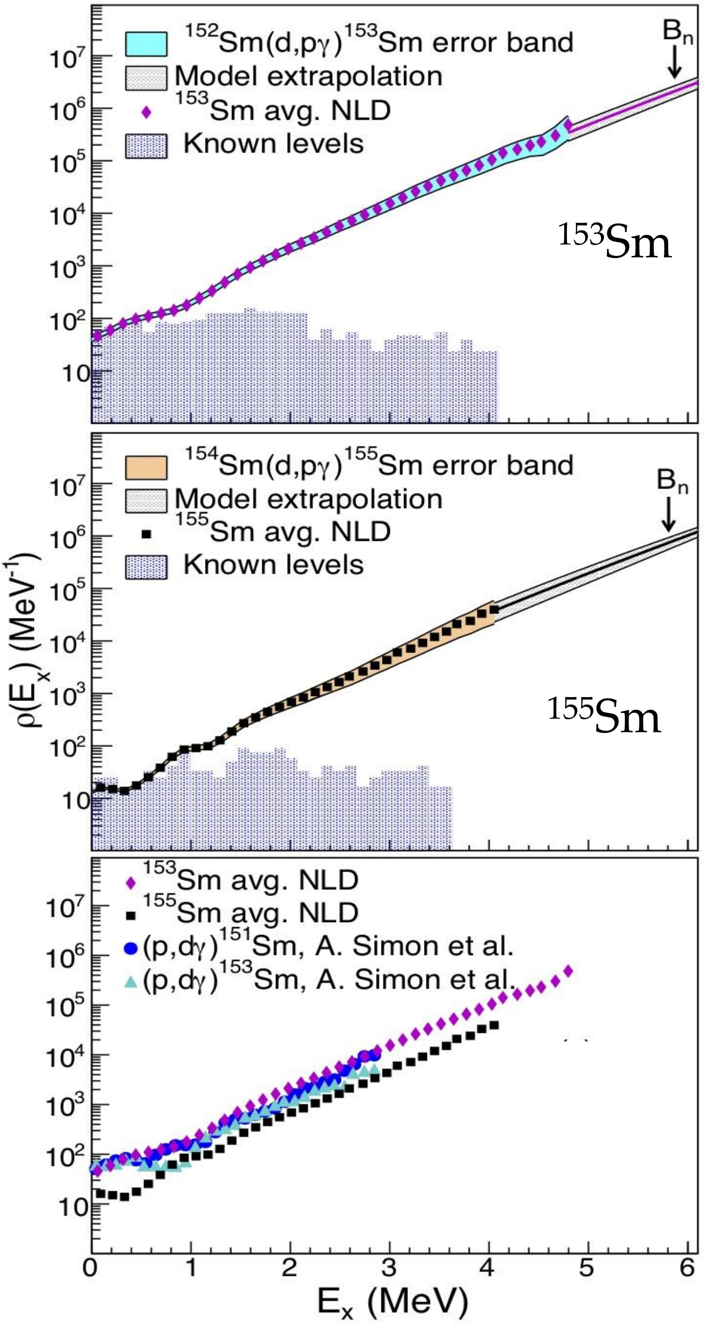


The Oslo Method in a 

1. Unfolding the continuum γ-ray spectra [1]
2. Extraction of primary γ-rays [2]
3. Simultaneous extraction of NLD and γSF [3]
4. Normalization [4, 5]

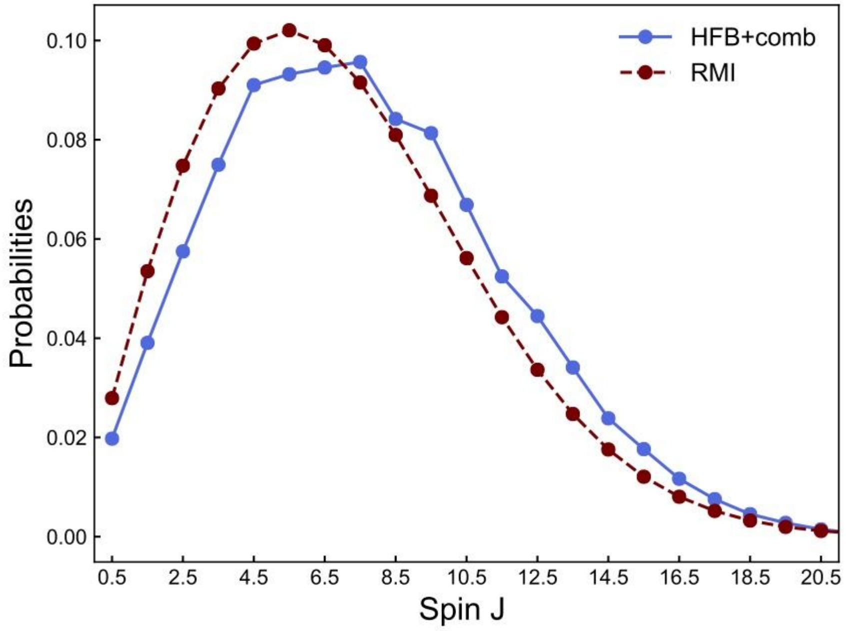
[1] Guttormsen et al., NIM A 374, 371 (1996), [2] Guttormsen et al., NIM A 255, 518 (1987)
[3] Schiller et al., NIM A 447, 498 (2000), [4] Larsen et al., PRC 83, 034 315 (2011)
[5] Midtbø et al., Comput. Phys. Commun. 262, 107795 (2021)

Normalized ^{153,155}Sm NLDs



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

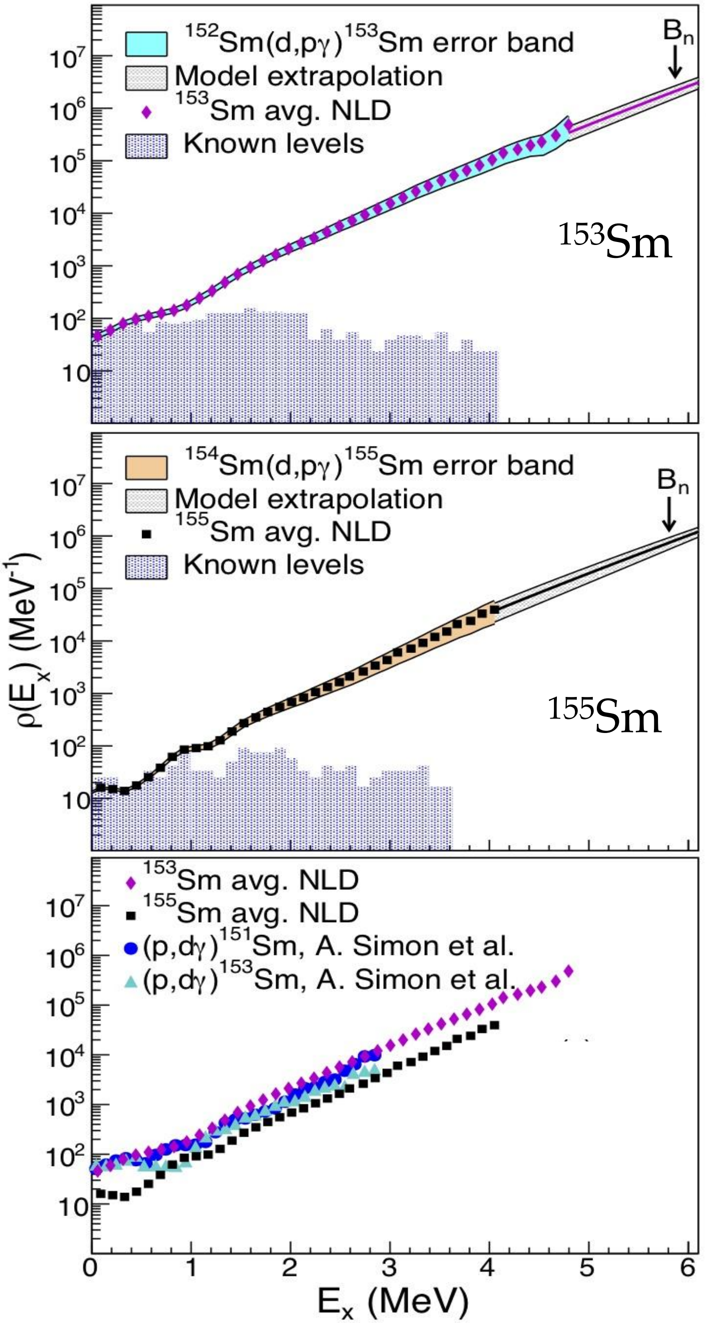
Due to the unavailability of experimental J^π data at B_n, RMI [2] and HFB+comb. [3] utilized to model the spin distributions.



Malatji, et al., PRC 103, 014309 (2021)

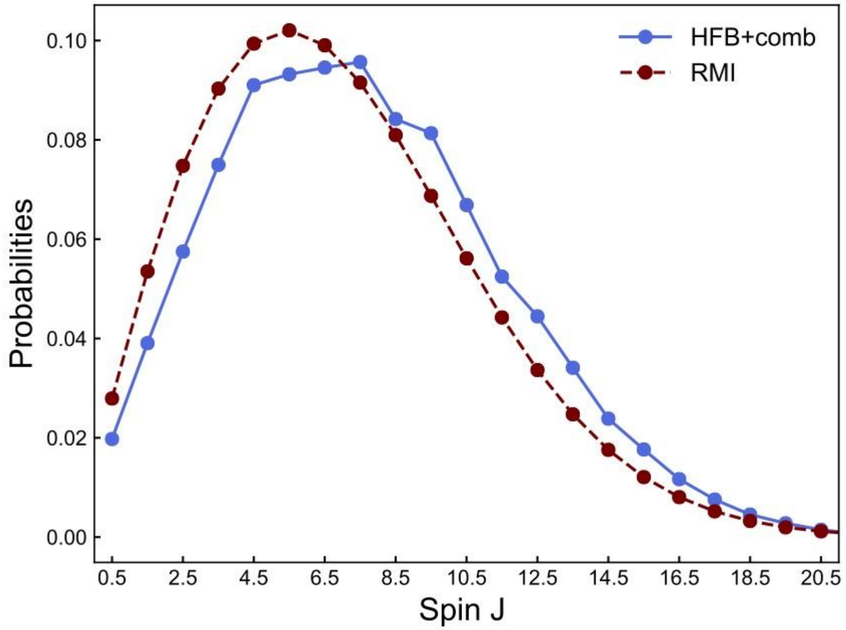
[1] Capote et al., Nucl. Data Sheets 110, 3107 (2009)
[2] von Egidy and Bucurescu, PRC 73, 049901(E) (2006)
[3] Goriely, Hilaire, and Koning, PRC 78, 064307 (2008)

Normalized ^{153,155}Sm NLDs



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

Due to the unavailability of experimental J^π data at B_n, RMI [2] and HFB+comb. [3] utilized to model the spin distributions.

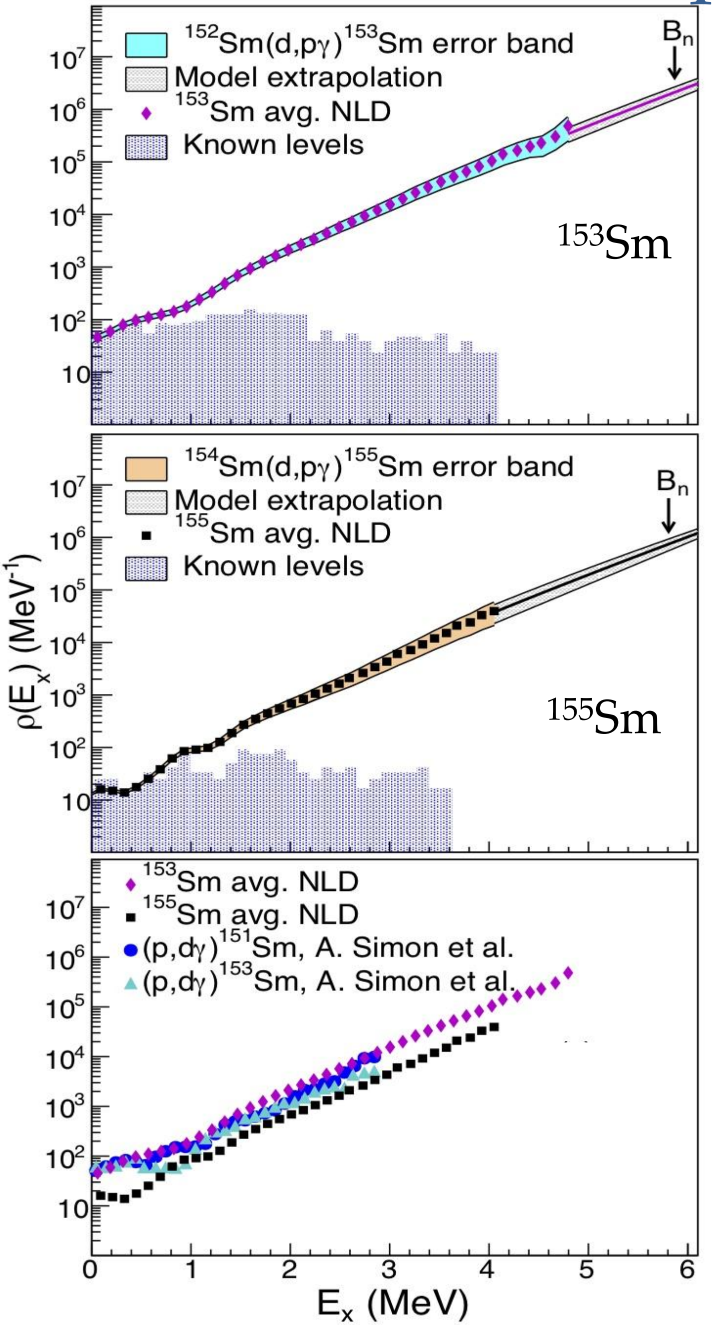


- Error bands - statistical and systematic uncertainties
- Upper limit - HFB+comb. + FG interpolation
- Lower limit - RMI + CT interpolation
- **^{153}Sm has a higher NLD than ^{155}Sm**, which is counterintuitive

Malatji, et al., PRC 103, 014309 (2021)

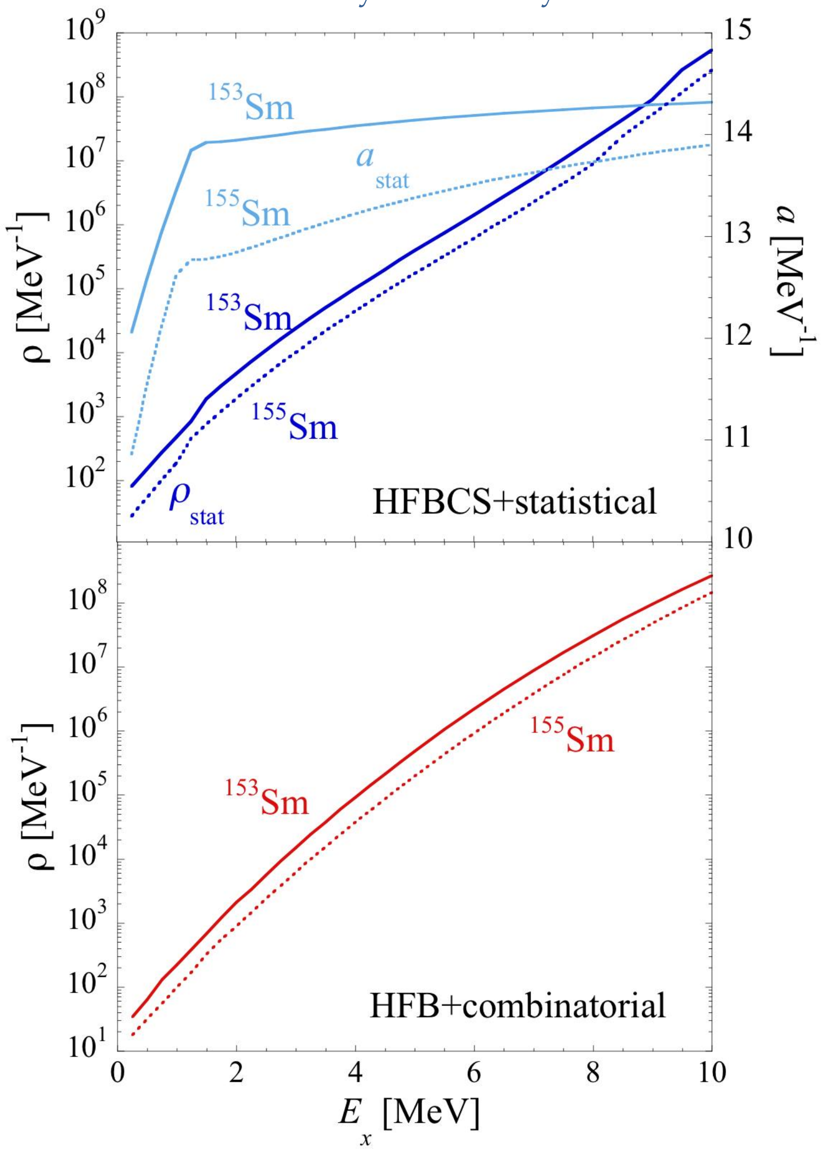
[1] Capote et al., Nucl. Data Sheets 110, 3107 (2009)
[2] von Egidy and Bucurescu, PRC 73, 049901(E) (2006)
[3] Goriely, Hilaire, and Koning, PRC 78, 064307 (2008)

Comparison to microscopic NLD models



Malatji, et al., PRC 103, 014309 (2021)

Courtesy of S. Goriely

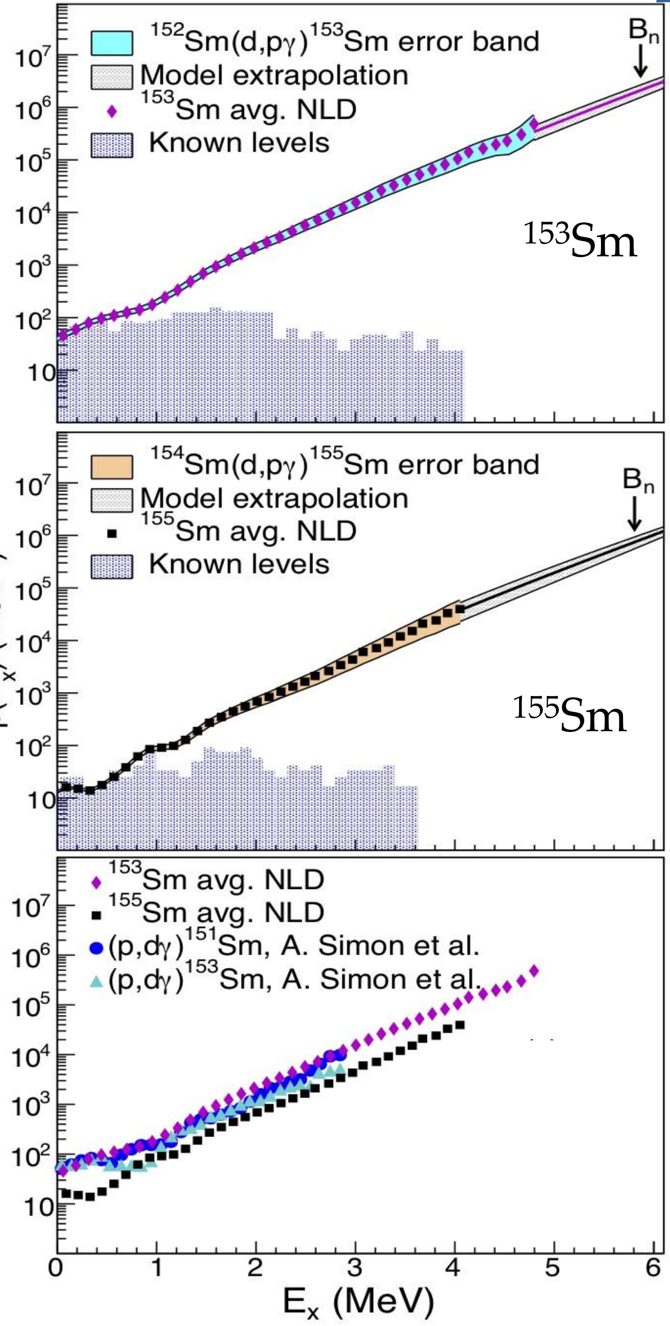


$$a(Ex) = \frac{\pi^2}{6}(g_\pi + g_v)$$

- Stronger shell + pairing effects in ^{155}Sm than in ^{153}Sm

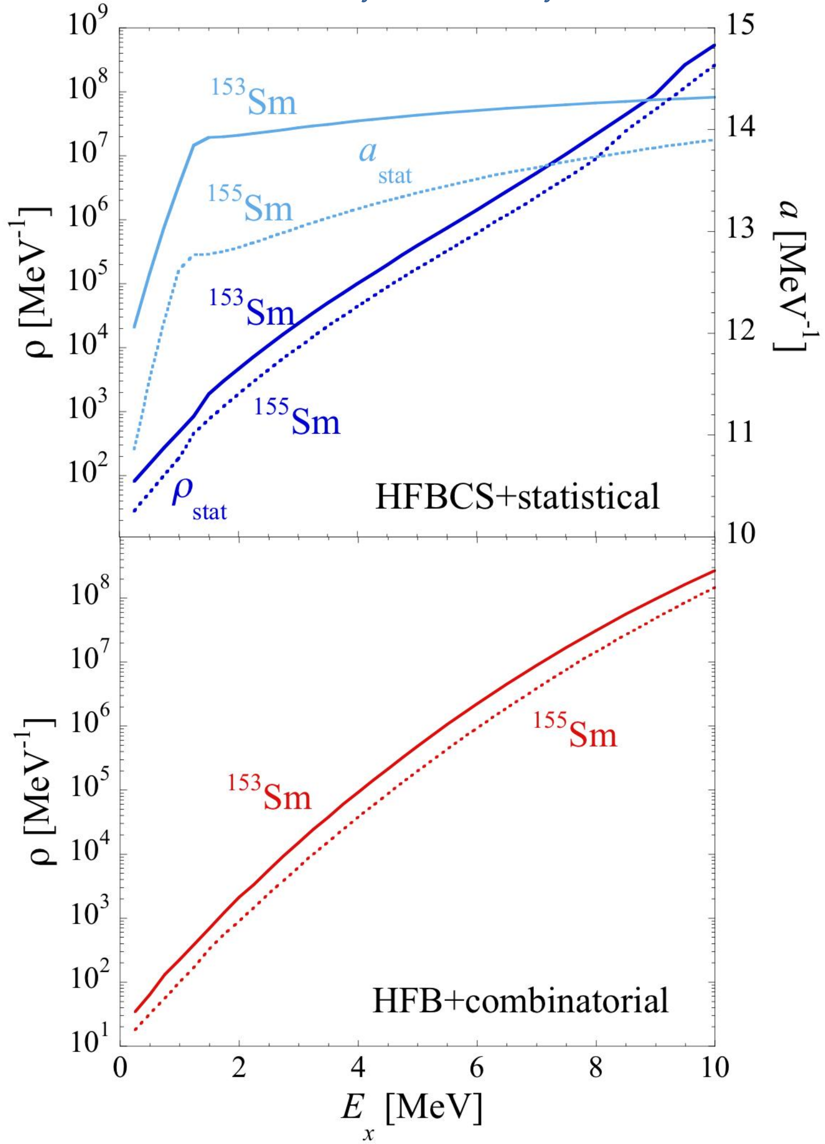
Demetriou and Goriely, Nucl. Phys. A 695, 95 (2001).
Goriely, Hilaire, and A. J. Koning, Phys. Rev. C 78, 064307 (2008)
Guttormsen, Alhassid, Ryssens, et al., Phys. Lett. B 816, 136206 (2021)

Comparison to microscopic NLD models



Malatji, et al., PRC 103, 014309 (2021)

Courtesy of S. Goriely

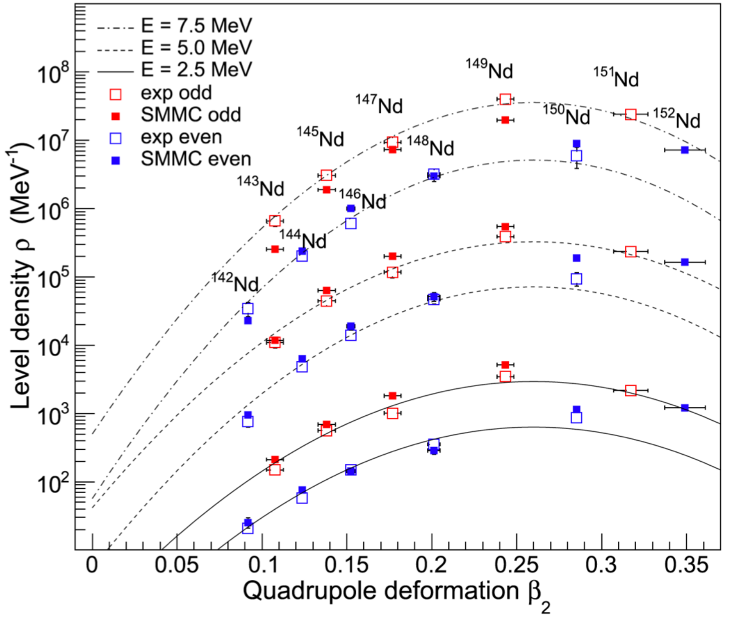


$a(Ex)$ measures singles particle LD at the E_f

$$a(Ex) = \frac{\pi^2}{6}(g_\pi + g_\nu)$$

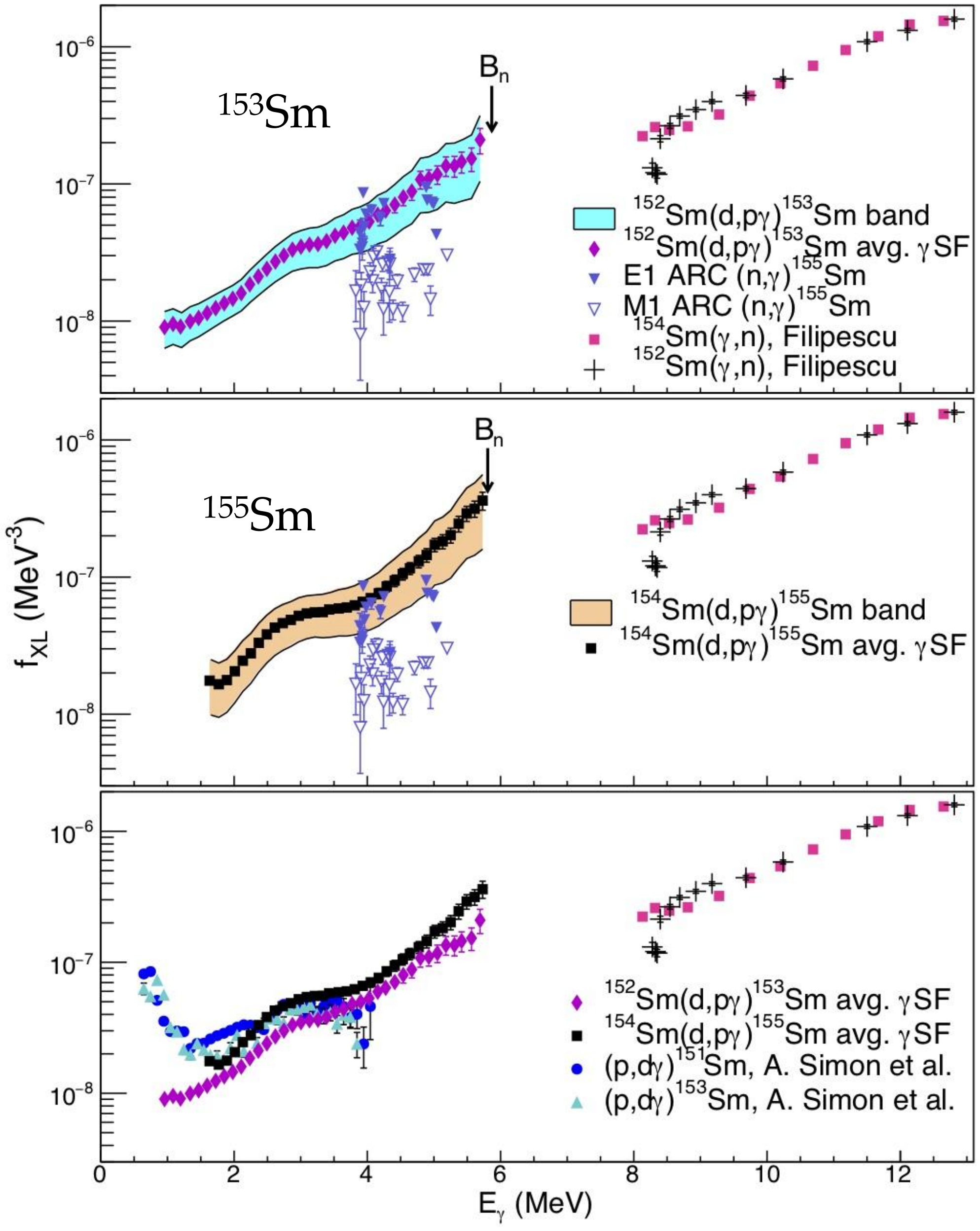
- Stronger shell + pairing effects in ^{155}Sm than in ^{153}Sm

$$\rho(\beta_2) = C\exp[-\eta(\beta_2 - \beta_2^{max})]$$



Demetriou and Goriely, Nucl. Phys. A 695, 95 (2001).
Goriely, Hilaire, and A. J. Koning, Phys. Rev. C 78, 064307 (2008)
Guttormsen, Alhassid, Ryssens, et al., Phys. Lett. B 816, 136206 (2021)

Normalized ^{153,155}Sm γSF



- Statistical decays are dominated by dipole transitions:

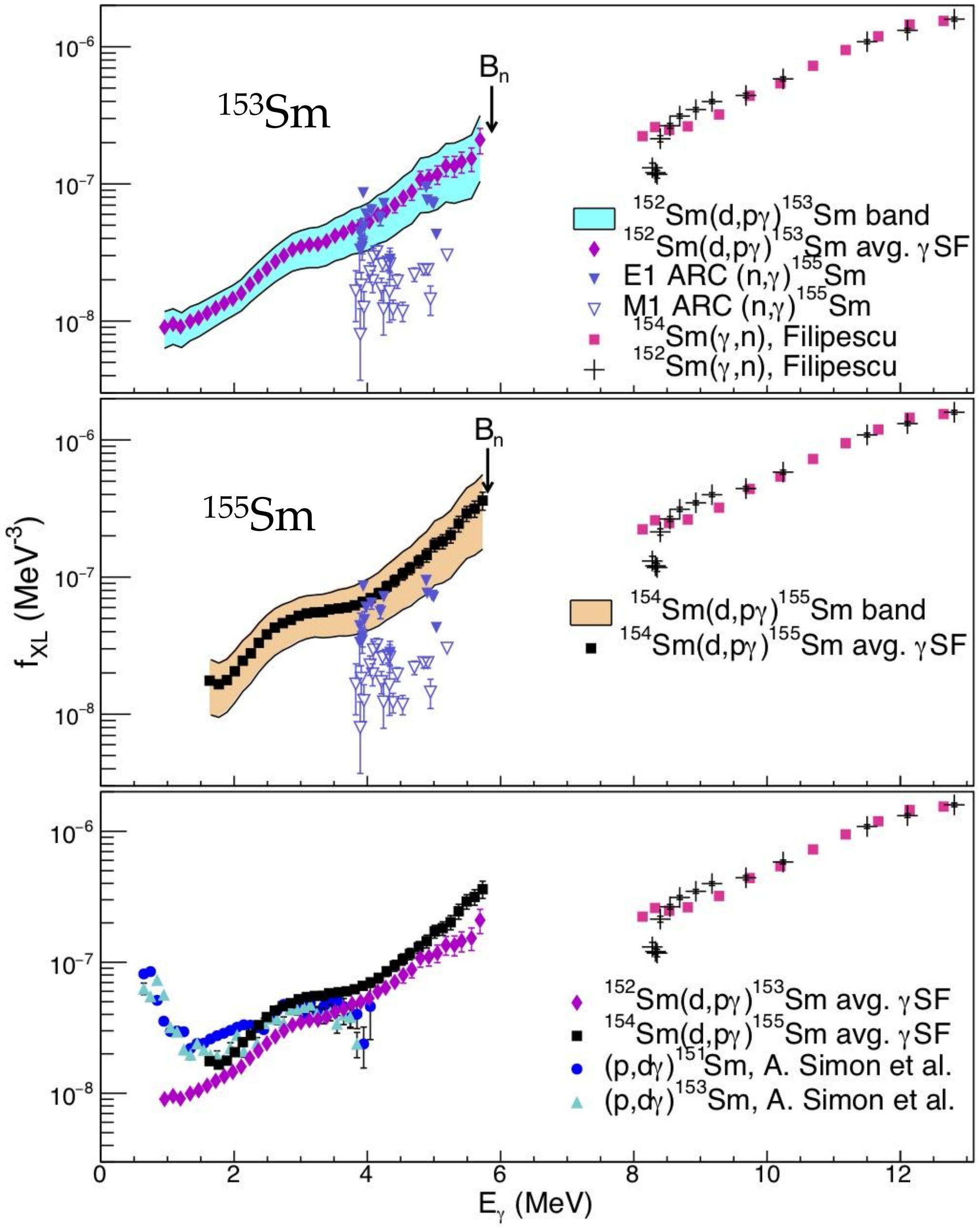
$$f(E_\gamma) = \frac{1}{2\pi E_\gamma{}^3} BT(E_\gamma)$$

- Photonuclear cross-section

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

Kopecky and Chrien, Nucl. Phys. A 468, 285 (1987)
Malatji, et al., PRC 103, 014309 (2021)

Normalized ^{153,155}Sm γSF



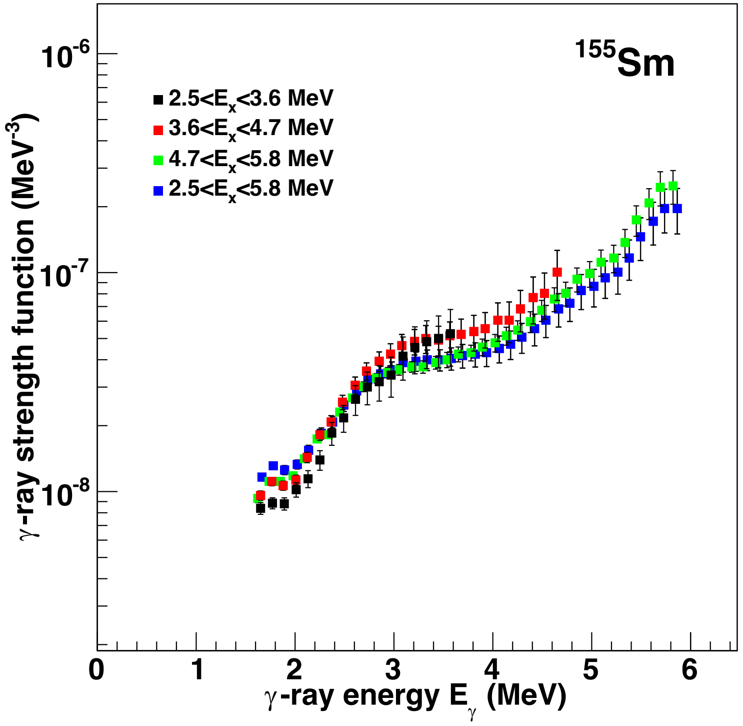
- Statistical decays are dominated by dipole transitions:

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

- Photonuclear cross-section

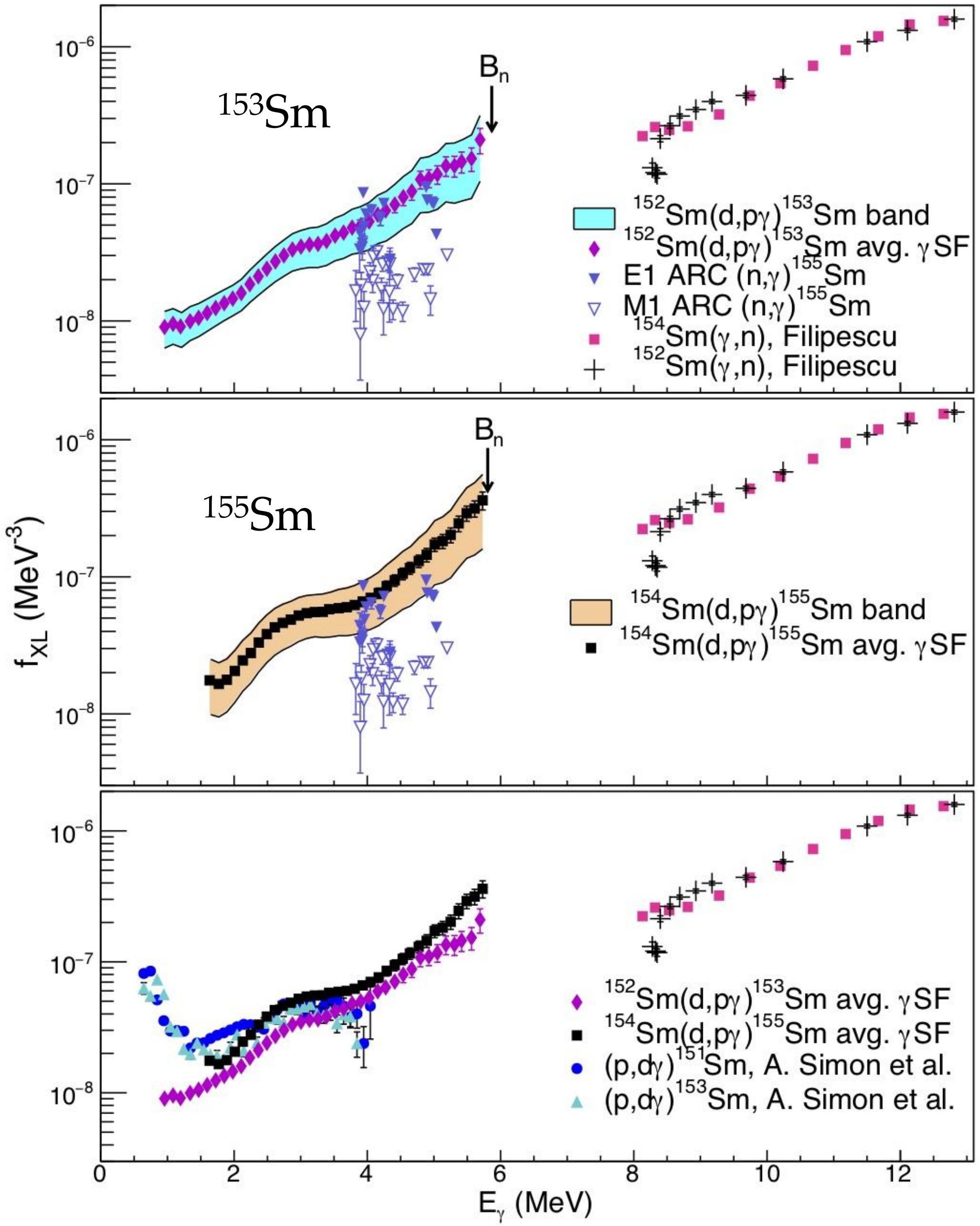
$$f(E_\gamma) = \frac{1}{3\pi^2\hbar^2c^2}\frac{\sigma_{abs}(E_\gamma)}{E_\gamma}$$

The PSF and even the SR is not excitation energy dependent



Kopecky and Chrien, Nucl. Phys. A 468, 285 (1987)
Malatji, et al., PRC 103, 014309 (2021)

Comparison to D1M+QRPA+0lim γSF



- Statistical decays are dominated by dipole transitions:

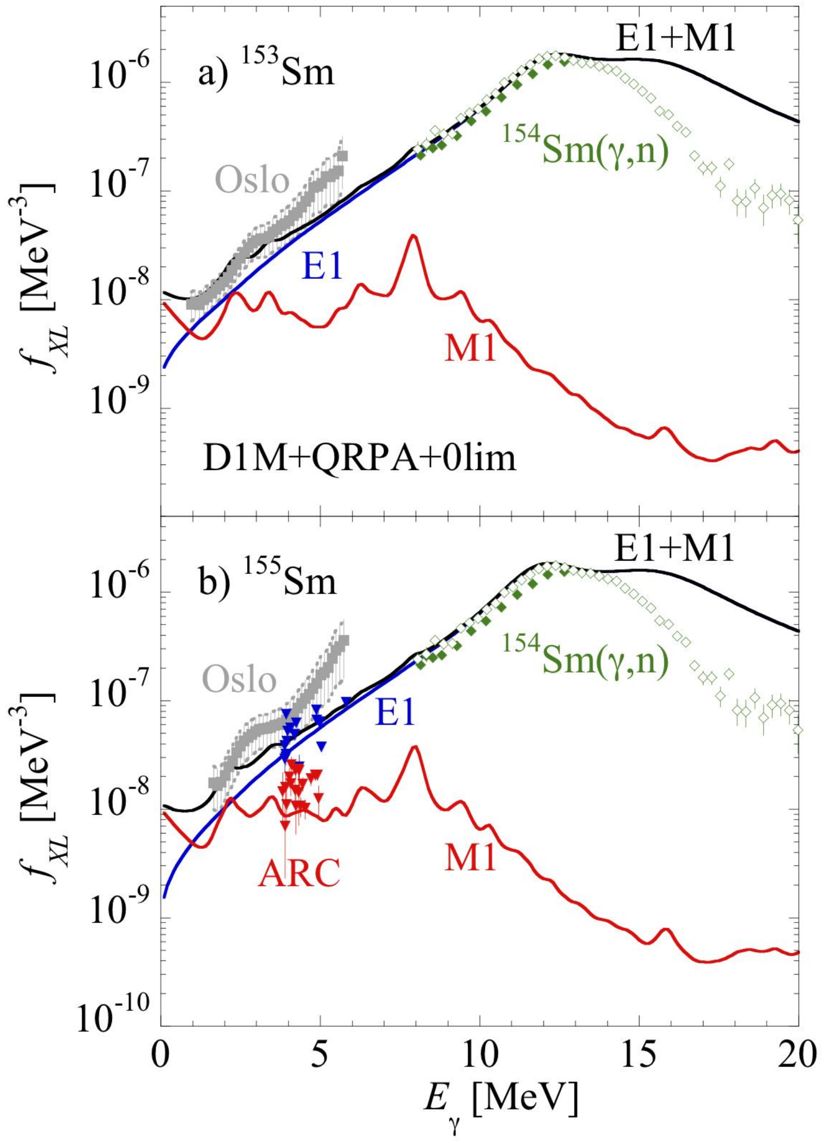
$$f(E_\gamma) = \frac{1}{2\pi E_\gamma{}^3} BT(E_\gamma)$$

- Photonuclear cross-section

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

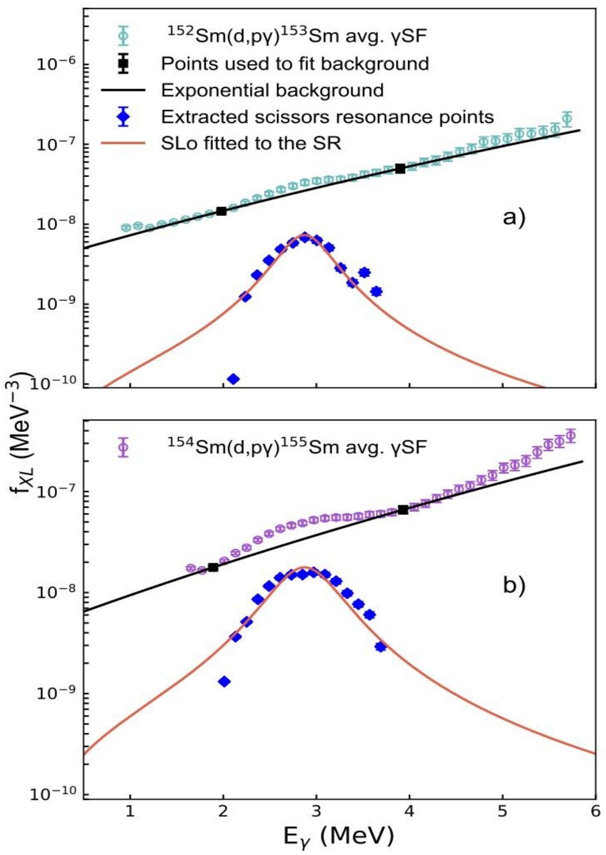
Kopecky and Chrien, Nucl. Phys. A 468, 285 (1987)
Malatji, et al., PRC 103, 014309 (2021)

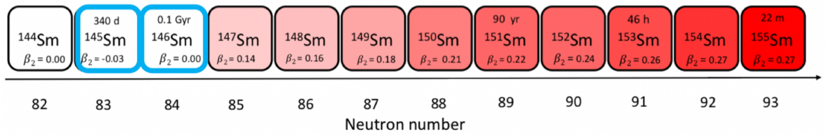
Courtesy of S. Goriely



^{153,155}Sm Scissors resonance

$$B_{SR} = \frac{(3\hbar c)^3}{16\pi} \int f_{SLo}^{SR}(E_\gamma)\, dE_\gamma$$



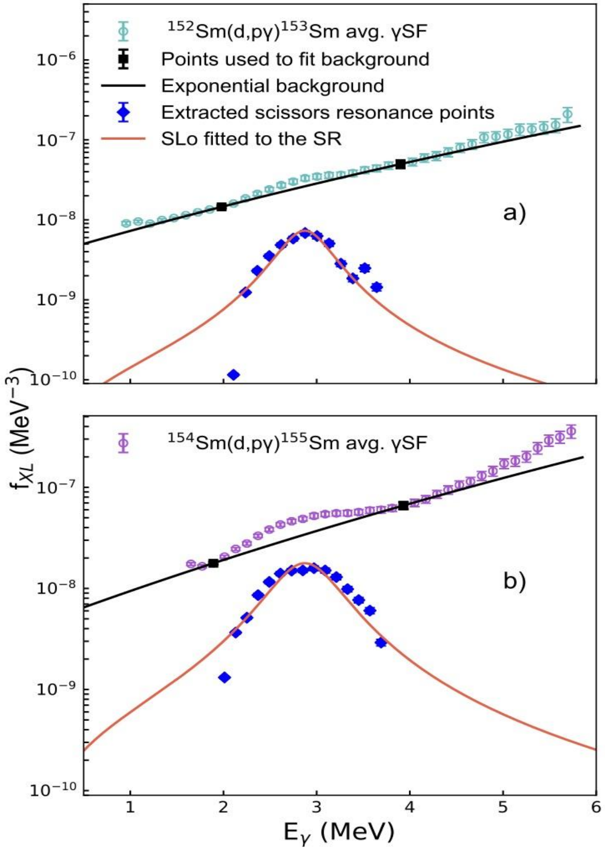


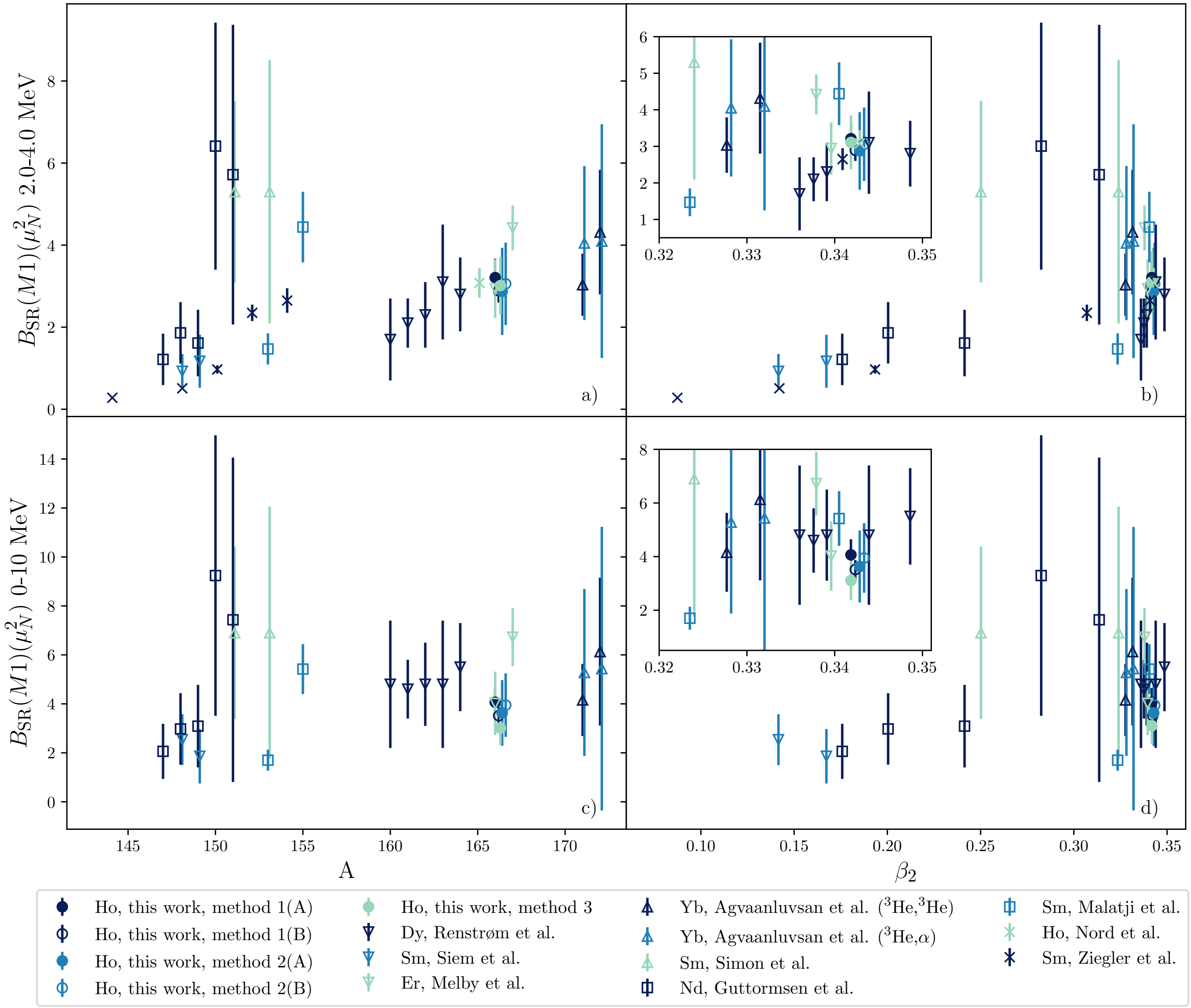
SR B(M1) strength not measured

^{153,155}Sm Scissors resonance

F. Pogliano, et al., Phys. Rev. C 107, 034605 (2023)

$$B_{SR} = \frac{(3\hbar c)^3}{16\pi} \int f_{SLo}^{SR}(E_\gamma)\, dE_\gamma$$

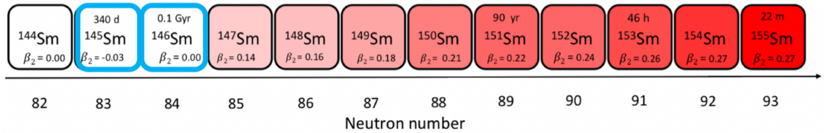




- ^{155}Sm B($M1$) in agreement with measurements of other rare-earth nuclei studied with the Oslo Method
- B($M1$) increases linearly with deformation squared

  $$\sum B_{exp}(M1) \uparrow \sim \delta^2$$

- Differences between the (p,d)^{153}Sm and (d,p) ^{153}Sm



SR B(M1) strength not measured

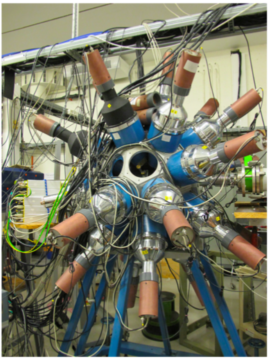
Lo Iudice, Riv. Nuovo Cim. 23, 1. (2000)

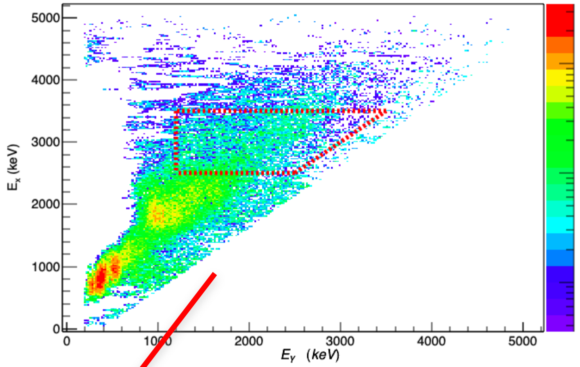
Ongoing Analysis

(d,tγ) ^{151}Sm

- 2.9 and 3.2 mg/cm^2 thick
- ^{152,154}Sm foil, 13.5 MeV d beam
- CACTUS [26 NaI(Tl)] + SiRi Array

MSc (Wits)

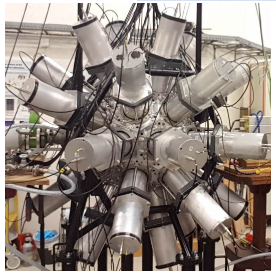


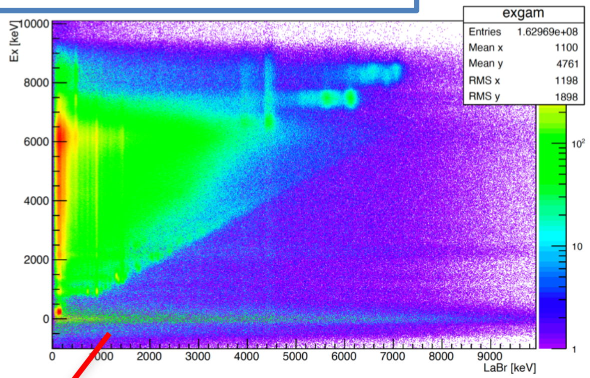


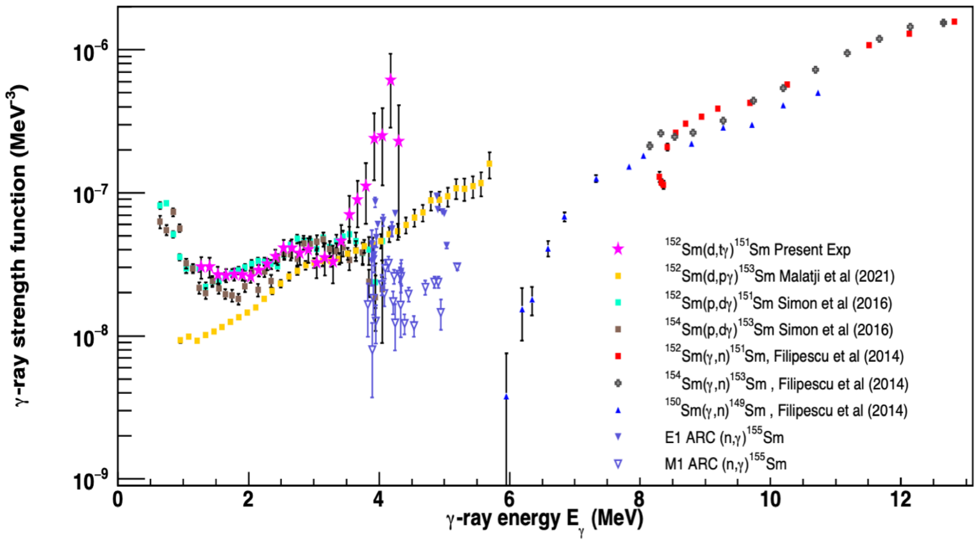
(p,p'γ) ^{152,154}Sm

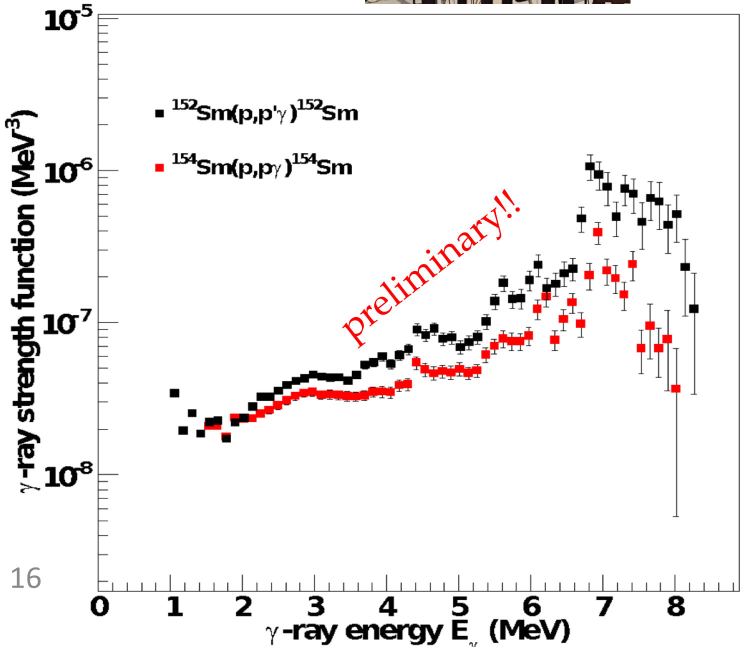
- 2.9 and 3.2 mg/cm^2 thick
- ^{152,154}Sm foil, 15 MeV proton beam
- OSCAR (30 LaBr$_3$:Ce +SiRi)
- ^{12}C and ^{16}O contamination

MSc (UiO)









OCL
Oslo Cyclotron Laboratory

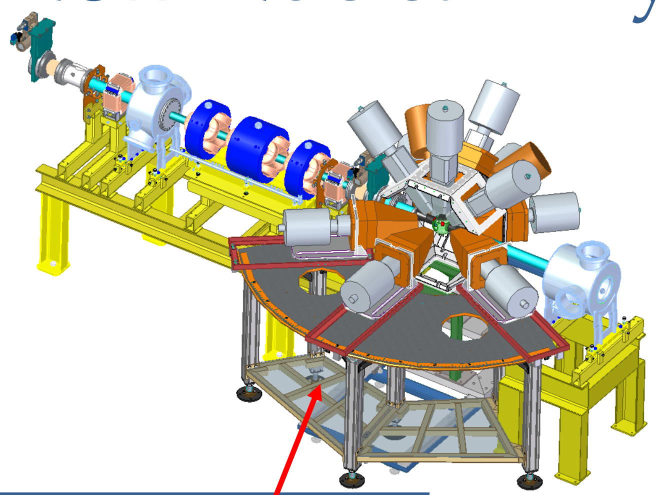
Summary

- ^{153,155}Sm NLDs and γSFs extracted from (d,pγ) coincidences, using the Oslo Method
- First time measurements of NLD and γSF below S_n in ^{155}Sm
- Unexpectedly, ^{153}Sm has higher NLD than ^{155}Sm but feature reproduced with combinatorial and statistical models
- **Lower ^{155}Sm NLD explained as a result of shell and strong pairing effects at the fermi surface**
- SR observed in ^{153,155}Sm, B(M1) extracted and that of **^{155}Sm in agreement with other deformed rare-earth isotopes**
- The ^{153,155}Sm γSF is in fairly good agreement with QRPA calculations

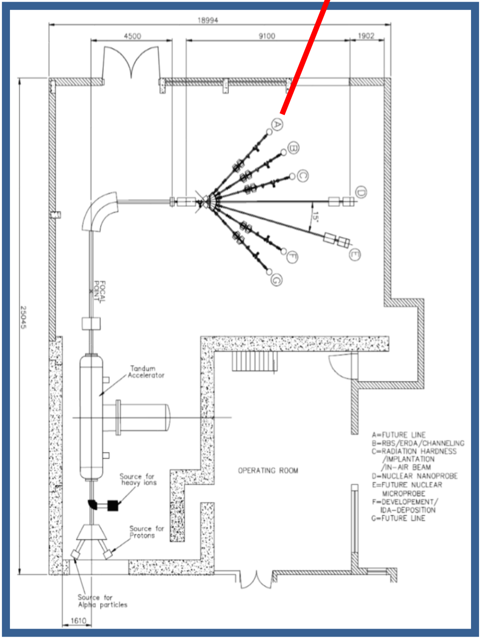
Outlook

- Analysis of **^{152,154}Sm(p,pγ)** experiment using OSCAR at OCL ongoing (Bell *et al.*)
- Preliminary results on **^{152}Sm(d,tγ) ^{151}Sm** experiment using CACTUS at OCL (Magagula *et al.*)
- **^{154}Sm(p,p')** [RCNP, von Neumann-Cosel *et al.*] and **^{154}Sm(α,α'γ)** [iThemba LABS, Pellegri *et al.*] on PDR and GDR
- Recent measurements: NLD and γSF of neutron rich **$^{156\text{-}159}$Sm**, scheduled at ANL (CARIBU, Larsen *et al.*) **Sept. 2022**

New Nuclear Physics Setup at iThemba LABS' Tandetron Facility



- **Beams**: Protons, Alphas & in the future 3He
- **Energies**: 1-6 MeV protons & 2-9 MeV Alphas
- **Intensities**: ~ 10 nA - 10 μA

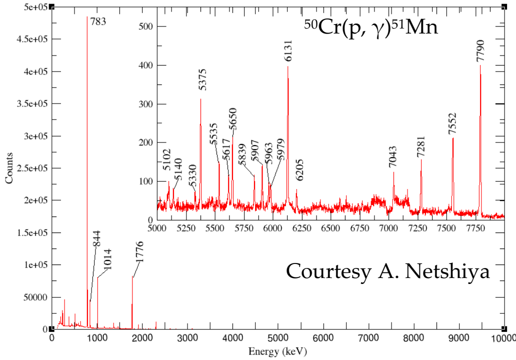


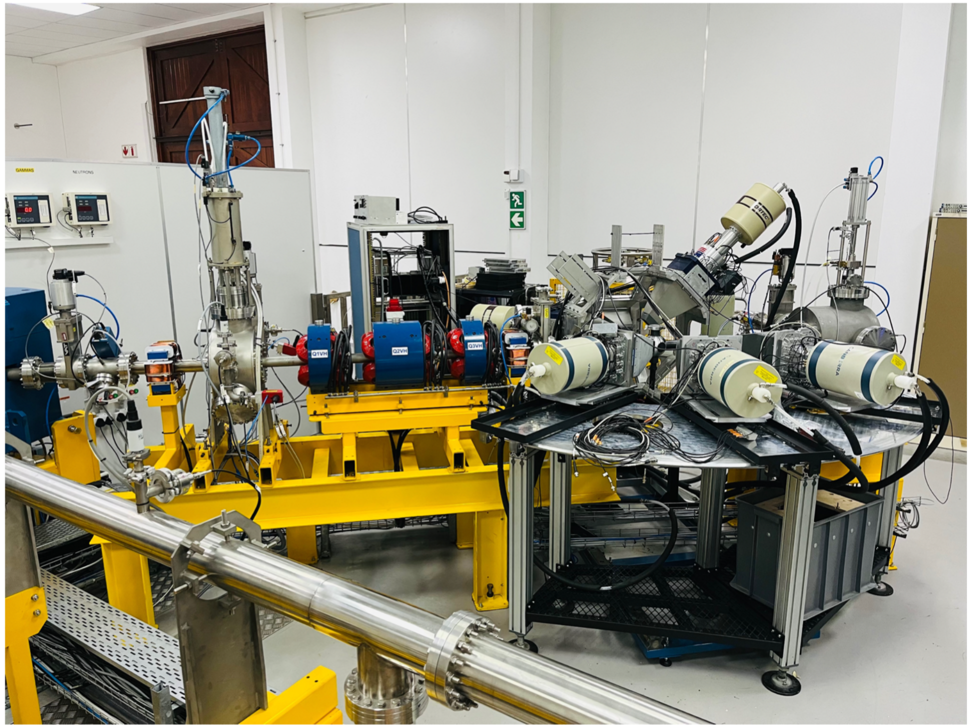
2017 : Replacement of the 52 year old Van de Graaff with 3MV Tandetron

Proton beam of various energies and intensities successfully commissioned in April 2023

Applications:

- Photon Strength Function measurements (neutron-deficient isotopes)



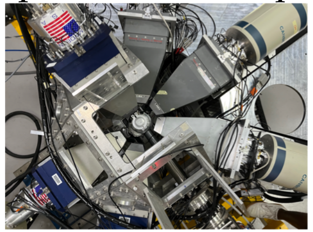


Beam Left: Half-AFRODITE frame, Slide ~1.3 meter outward

- +7 HPGe or large LaBr3:Ce
- +4 Small LaBr3:Ce detectors
- Angular range (45, 90, 135 deg.)

Beam Right: Angular Distribution Table, three detectors on carriages for multiple angles (~ 27-141 deg.)

Target Ladder, Frames and Chamber: Depends on user specifications



XIA cards (100 & 500MHz)

Statistical properties of the well deformed ^{153,155}Sm nuclei and the scissors resonance

K. L. Malatji,[1,2,*] K. S. Beckmann,[3,†] M. Wiedeking,[1,4,‡] S. Siem,[3] S. Goriely,[5] A. C. Larsen,[3] K. O. Ay,[6] F. L. Bello Garrote,[3] L. Crespo Campo,[3] A. Görgen,[3] M. Guttormsen,[3] V. W. Ingeberg,[3] P. Jones,[1] B. V. Kheswa,[1,7] P. von Neumann-Cosel,[8] M. Ozgur,[6] G. Potel,[9] L. Pellegri,[1,4] T. Renstrøm,[3] G. M. Tveten,[3] and F. Zeiser[3]

[1] *Department of Subatomic Physics, iThemba LABS, P.O. Box 722, Somerset West 7129, South Africa*
[2] *Physics Department, Stellenbosch University, Matieland 7602, South Africa*
[3] *Department of Physics, University of Oslo, N-0316 Oslo, Norway*
[4] *School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa*
[5] *Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, CP 226, B-1050 Brussels, Belgium*
[6] *Department of Physics, Faculty of Science and Letters, Eskisehir Osmangazi University, TR-26040 Eskisehir, Turkey*
[7] *Department of Applied Physics and Engineering Mathematics, University of Johannesburg, Doornfontein 2028, South Africa*
[8] *Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*
[9] *Lawrence Livermore National Laboratory, Livermore, California 94551, USA*

Universiteit Stellenbosch University

OCL Oslo Cyclotron Laboratory

University of the Witwatersrand Johannesburg

Universitas Osloensis MDCCCXI

Eskişehir Osmangazi Üniversitesi 1970

Phy. Rev. C
103, 014309
(2021)

Technische Universität Darmstadt

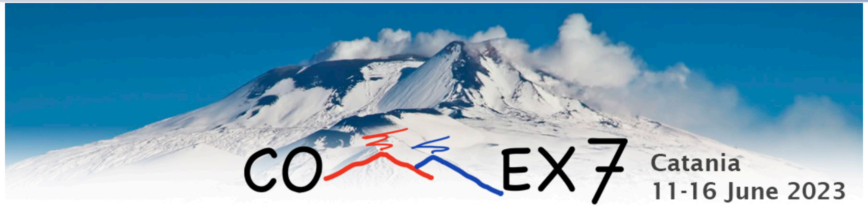
University of Johannesburg

Lawrence Livermore National Laboratory

Thank you all for you attention!

Université Libre de Bruxelles ULB

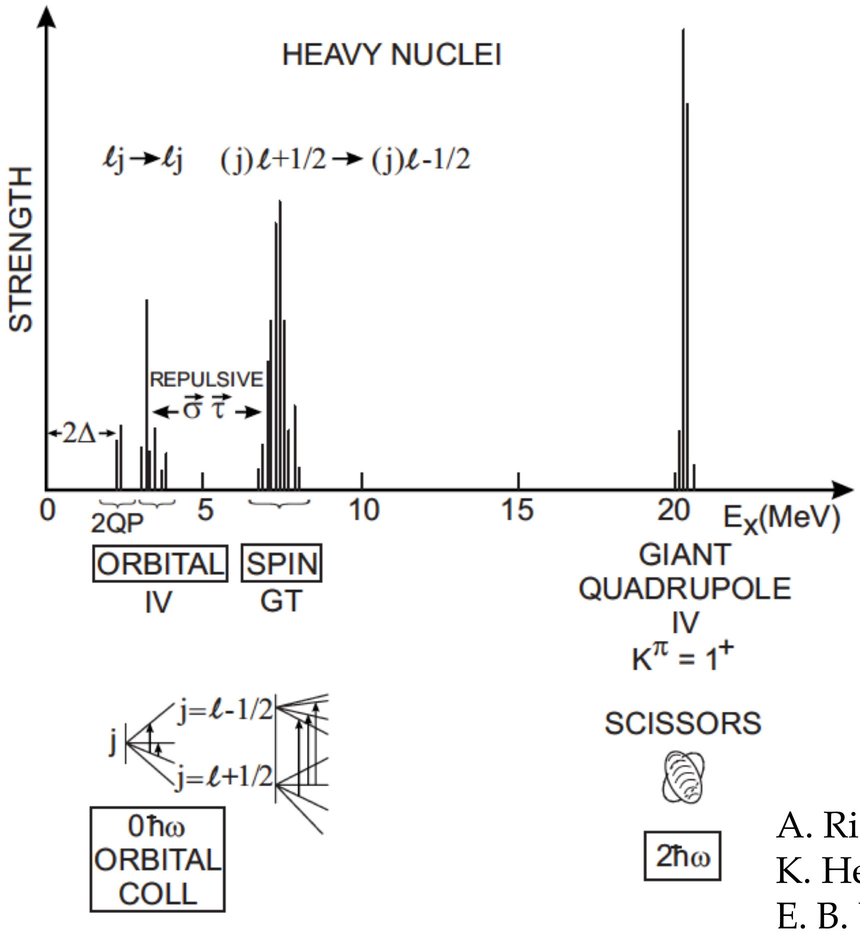
science & innovation
Department:
Science and Innovation
REPUBLIC OF SOUTH AFRICA

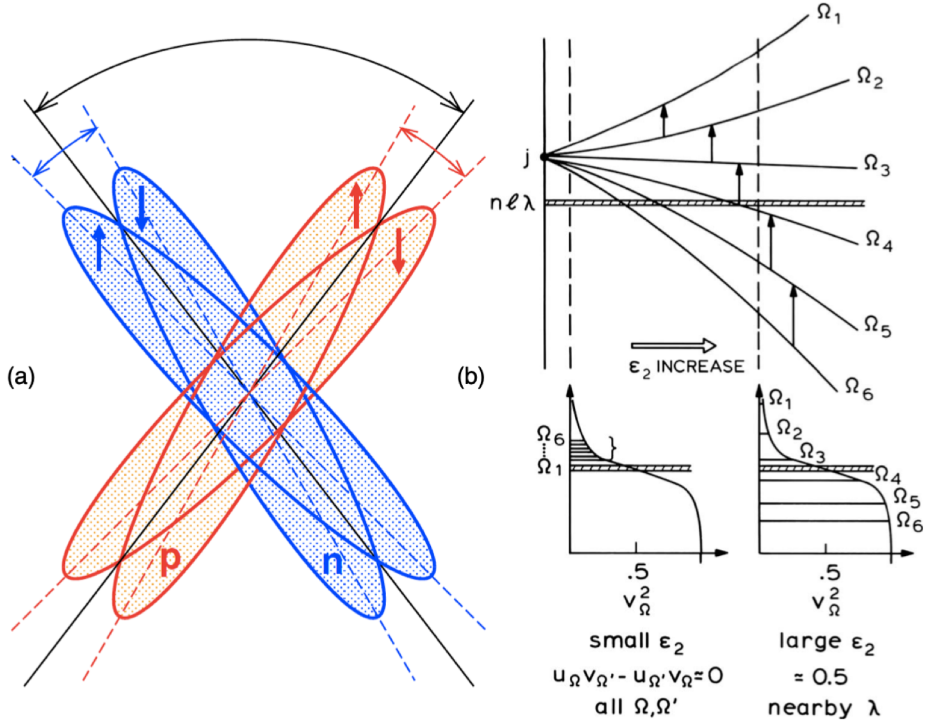


NRF National Research Foundation
iThemba LABS Laboratory for Accelerator Based Sciences

Thank you all for you attention!

Scissors Mode





A. Richter, Nucl. Phys. A 507, 99c. (1990)
K. Heyde et al., Rev. Mod. Phys. 82, 2365 (2010)
E. B. Balbutsev et al., Phys. Rev. C 97, 044316 (2018)