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A little bit of many things…

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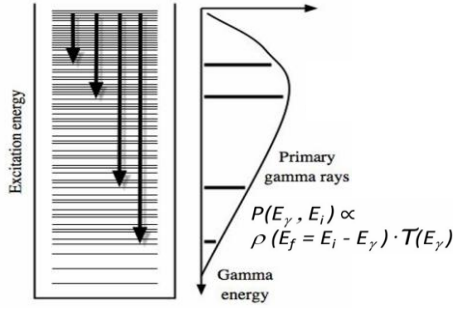
This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Contracts No. DE-AC02-05CH11231 and the US Nuclear Data Program.

Outline

- Shape Method
  - Nd, ^{63}Ni and ^{56}Fe
- Low-energy enhancement and Scissors Mode
- Inverse-Oslo
  - ^{85}Kr, ^{87}Kr, ^{67}Ni and ^{133}Xe
- (p,γ) reactions
  - ^{51}Mn, ^{61}Cu and ^{90}Zr
- UHECR and the GDR
- PSF and NLD databases
  - PSF outlier analysis

Oslo Methods

"Traditional" Oslo method



Beta-Oslo method

First for NLDs and PSFs to be measured away from stability.



Picture from: https://groups.nscl.msu.edu/SuN/SuN_photos.php

PRL 113, 232502 (2014) PHYSICAL REVIEW LETTERS week en 5 DECEMB

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]

CE-Oslo method

NLDs and PSFs from charge-exchange reactions.



PHYSICAL REVIEW C **113**, 015801 (2026)

Extraction of neutron-capture cross sections on ^{92}Zr using the charge-exchange Oslo method

N. D. Pathirana,[1,2,*] R. G. T. Zegers,[1,2,†] B. Gao,[3] A. Spyrou,[1,2] A. C. Larsen,[4] H. Berg,[1,2] D. Bazin,[1,2] H. L. Crawford,[5] A. Gade,[1,2] P. Gastis,[6] T. Ginter,[1] C. J. Guess,[7] M. Guttormsen,[4] S. Noji,[1] B. Longfellow,[1,2] J. Pereira,[1] L. A. Riley,[8] D. Weisshaar,[1] and J. C. Zamora[1]

Inverse-Oslo method

NLDs and PSFs from inverse-kinematic reactions.





Eur. Phys. J. A (2020) 56:68
https://doi.org/10.1140/epja/s10050-020-00070-7

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

First application of the Oslo method in inverse kinematics

Nuclear level densities and γ-ray strength functions of ^{87}Kr

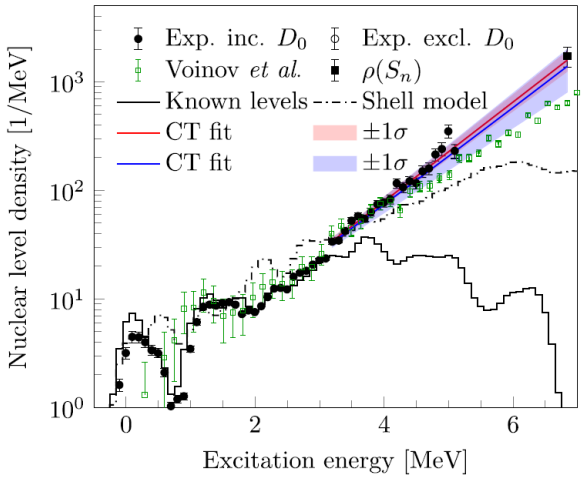
V. W. Ingeberg[1,a], S. Siem[1], M. Wiedeking[2], K. Sieja[3,4], D. L. Bleuel[5], C. P. Brits[2,6], T. D. Bucher[2], T. S. Dinoko[2], J. L. Easton[2,7], A. Görgen[1], M. Guttormsen[1], P. Jones[2], B. V. Kheswa[2,8], N. A. Khumalo[2], A. C. Larsen[1], E. A. Lawrie[2], J. J. Lawrie[2], S. N. T. Majola[2,8,9], K. L. Malatji[2,6], L. Makhathini[2,6], B. Maqabuka[2,7], D. Negi[2], S. P. Noncolela[2,7], P. Papka[2,6], E. Sahin[1], R. Schwengner[10], G. M. Tveten[1], F. Zeiser[1], B. R. Zikhali[2,9]

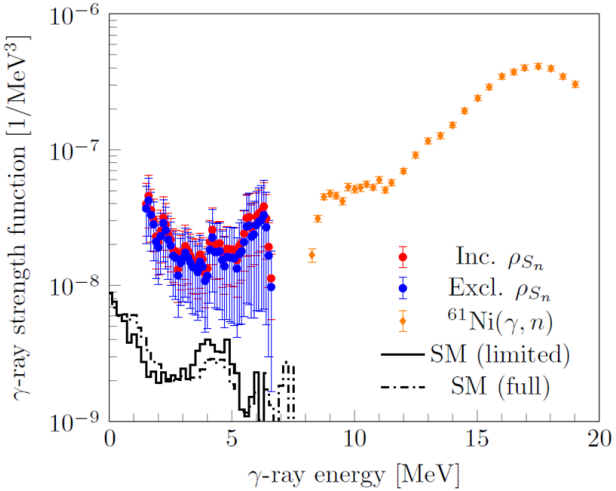
Oslo method: Normalization

- Slope:
  - NLD at low E_x: known discrete levels (from NNDC).
  - NLD at S_n: External data from neutron resonance spacing (D_0) assuming a specific spin distribution.
  - PSF: inferred from slope of NLD.

- PSF absolute value
  - average radiative width (Γ_γ) of neutron resonances.

Problem: neutron resonance data only available for A+1n from nearest stable nucleus.





Ingeberg, Jones, Msebi *et al.*, Phys. Rev. C 106 054315 (2022).

Shape Method

- D_0 is not known.
- No standardized approach in absence of D_0 .
- Unambiguous identification of origin and destination of primaries.
- Functional form is retained between primaries from same excitation energy bin.
- Concepts from Average Resonance Capture, Ratio, and χ^2 methods.

PHYSICAL REVIEW C **104**, 014311 (2021)

Independent normalization for γ-ray strength functions: The shape method

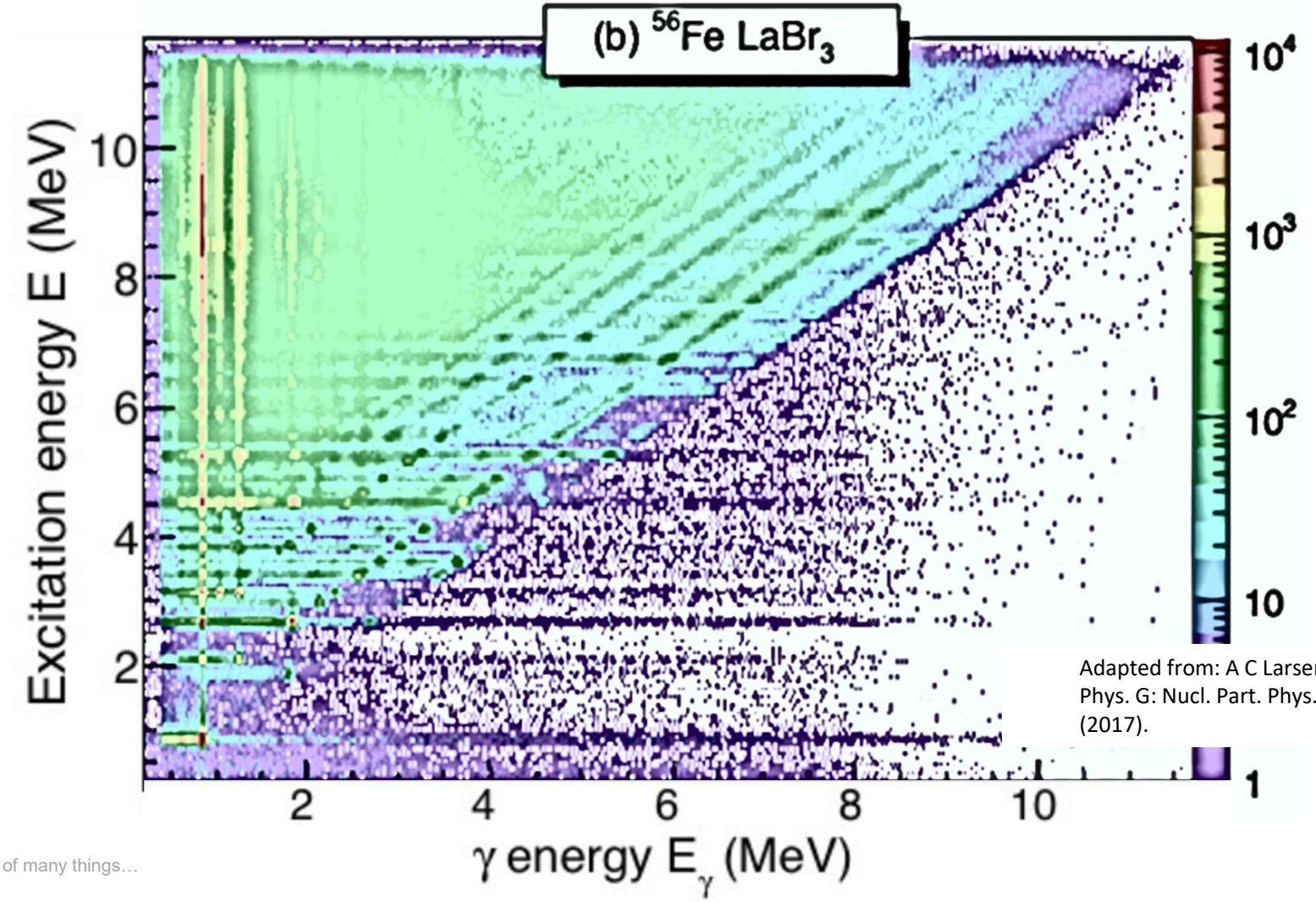
M. Wiedeking,[1,2,*] M. Guttormsen,[3] A. C. Larsen,[3] F. Zeiser,[3] A. Görgen,[3] S. N. Liddick,[4,5] D. Mücher,[6,7] S. Siem,[3] and A. Spyrou[4,8]

PHYSICAL REVIEW C **107**, L011602 (2023)

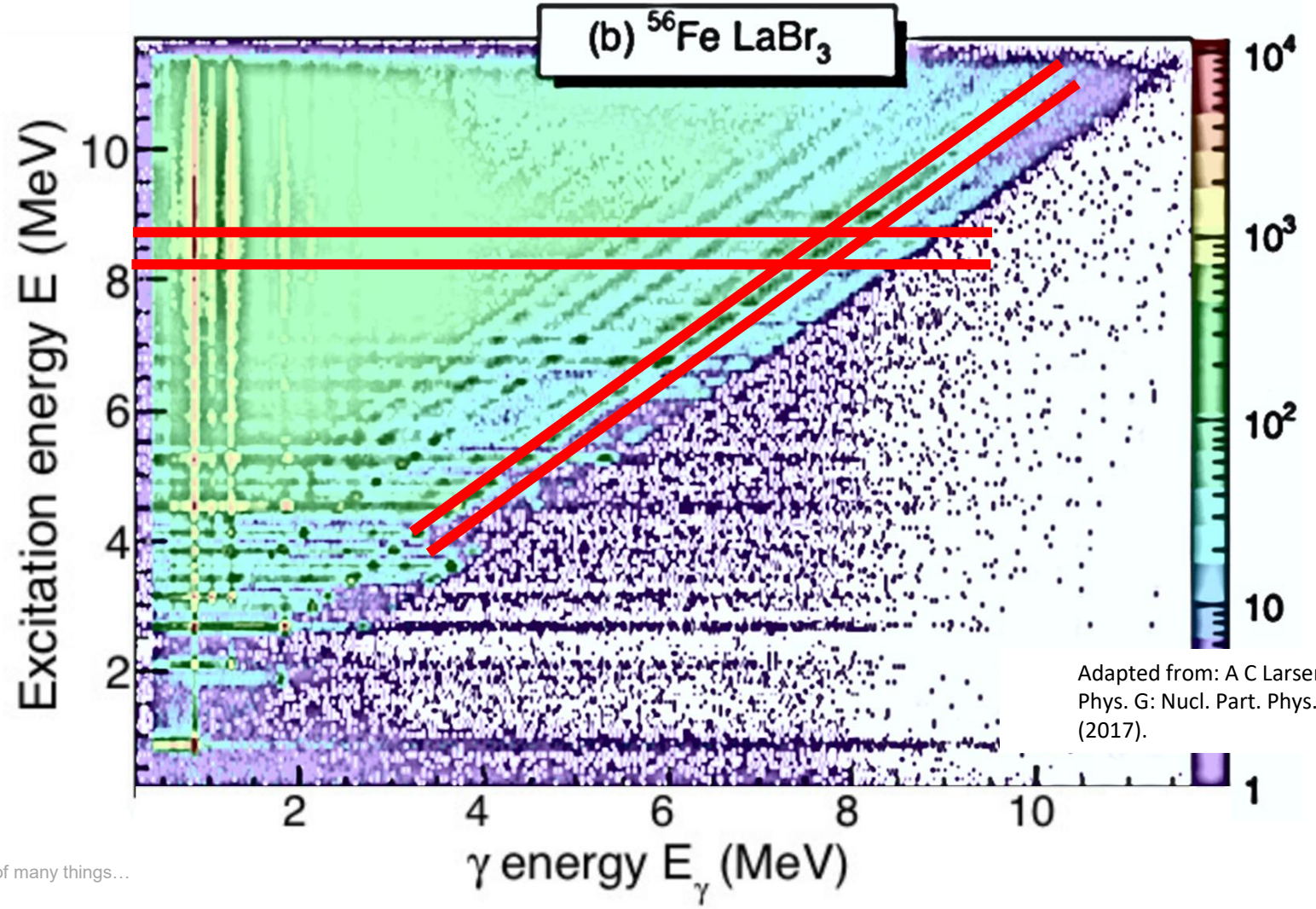
Letter

Extracting model-independent nuclear level densities away from stability

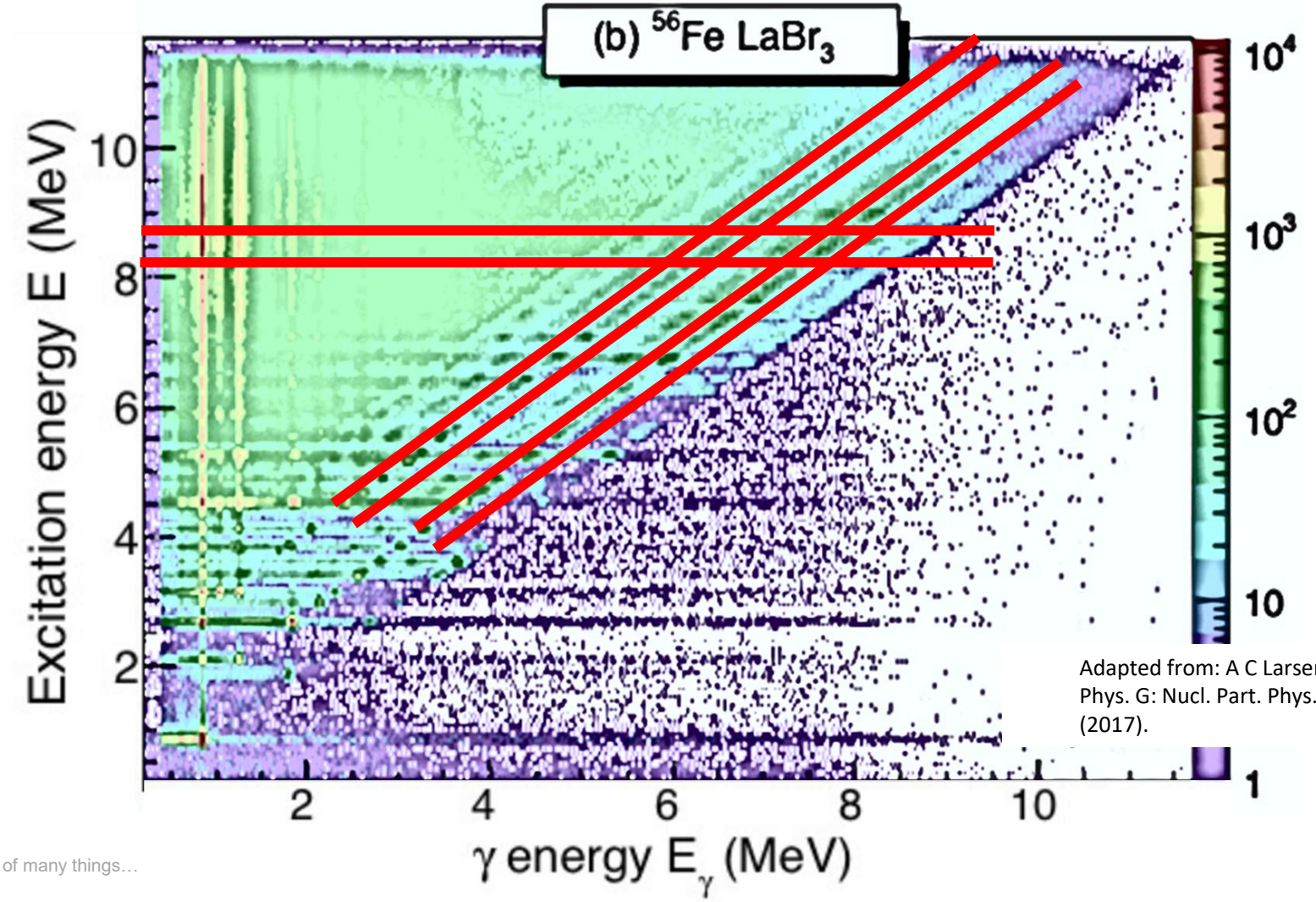
D. Mücher,[1,2,3,*] A. Spyrou,[4,5,6,†] M. Wiedeking,[7,8] M. Guttormsen,[9] A. C. Larsen,[9] F. Zeiser,[9] C. Harris,[10,5] A. L. Richard,[10,6] M. K. Smith,[10] A. Görgen,[9] S. N. Liddick,[10,11] S. Siem,[9] H. C. Berg,[10,5] J. A. Clark,[12] P. A. DeYoung,[13] A. C. Dombos,[14] B. Greaves,[1] L. Hicks,[10,5] R. Kelmar,[14] S. Lyons,[15] J. Owens-Fryar,[10,5] A. Palmisano,[10,5] D. Santiago-Gonzalez,[12] G. Savard,[12] and W. W. von Seeger[13]



Adapted from: A C Larsen et al., J. Phys. G: Nucl. Part. Phys. 44, 064005 (2017).



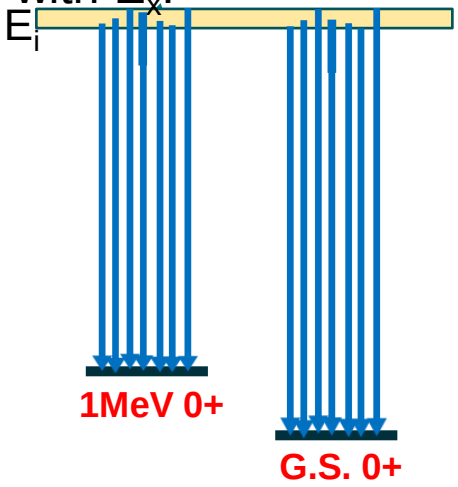
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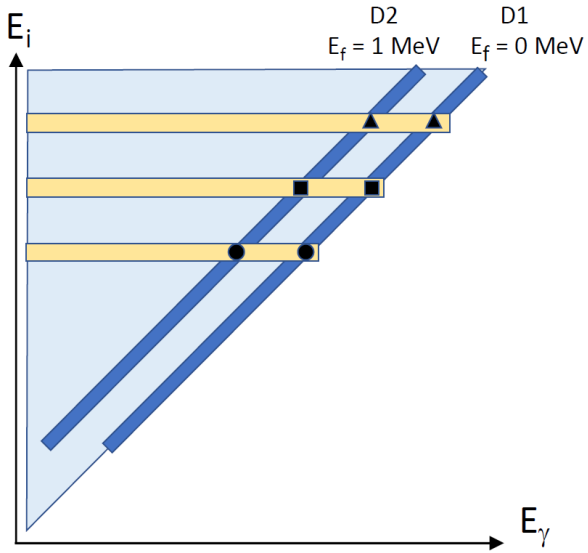


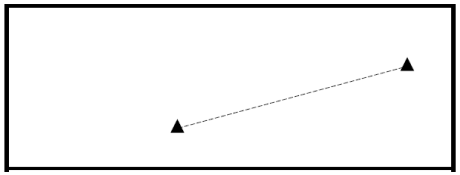
Adapted from: A C Larsen et al., J. Phys. G: Nucl. Part. Phys. 44, 064005 (2017).

Shape Method

Primaries from intercepts of diagonals with E_x.



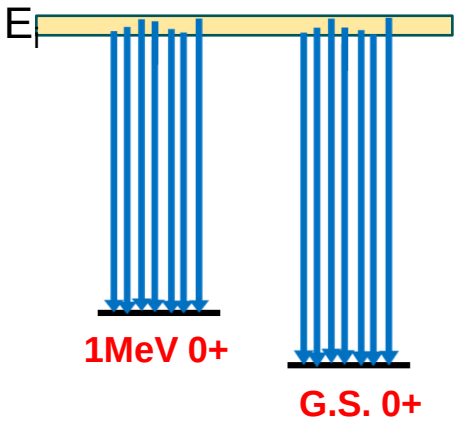


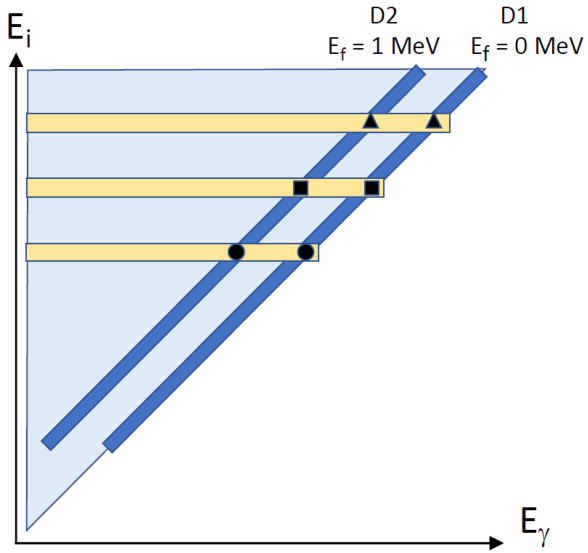


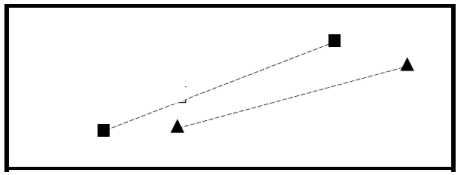
Pair of data points internally normalized and proportional to PSF.

Shape Method

Primaries from intercepts of diagonals with E_x.



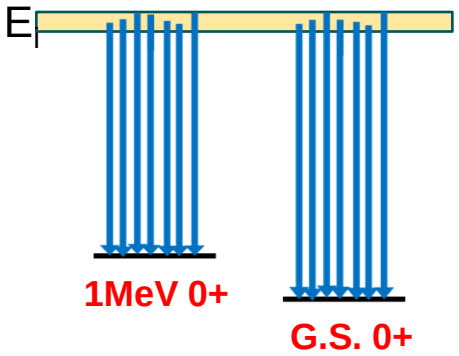


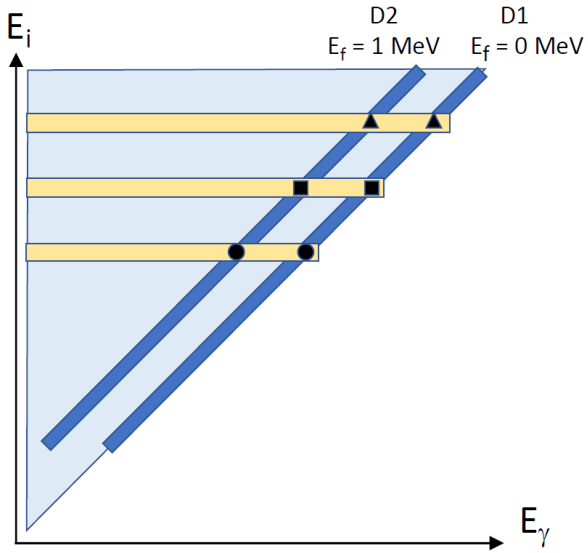


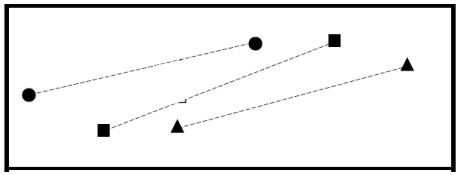
Pair of data points internally normalized and proportional to PSF.

Shape Method

Primaries from intercepts of diagonals with E_x.

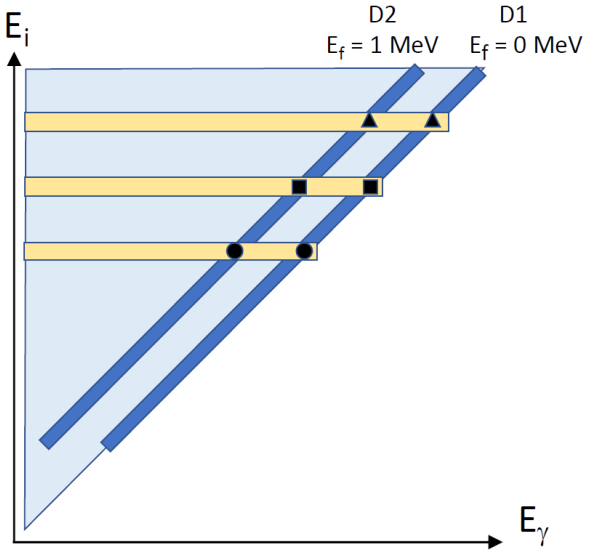




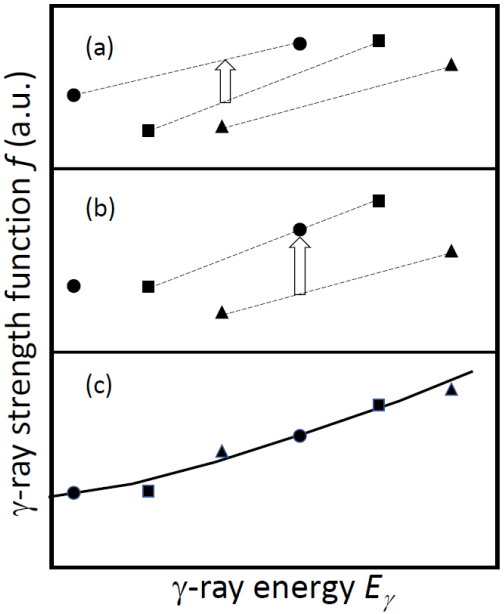


Pair of data points internally normalized and proportional to PSF.

Shape and Sewing Method

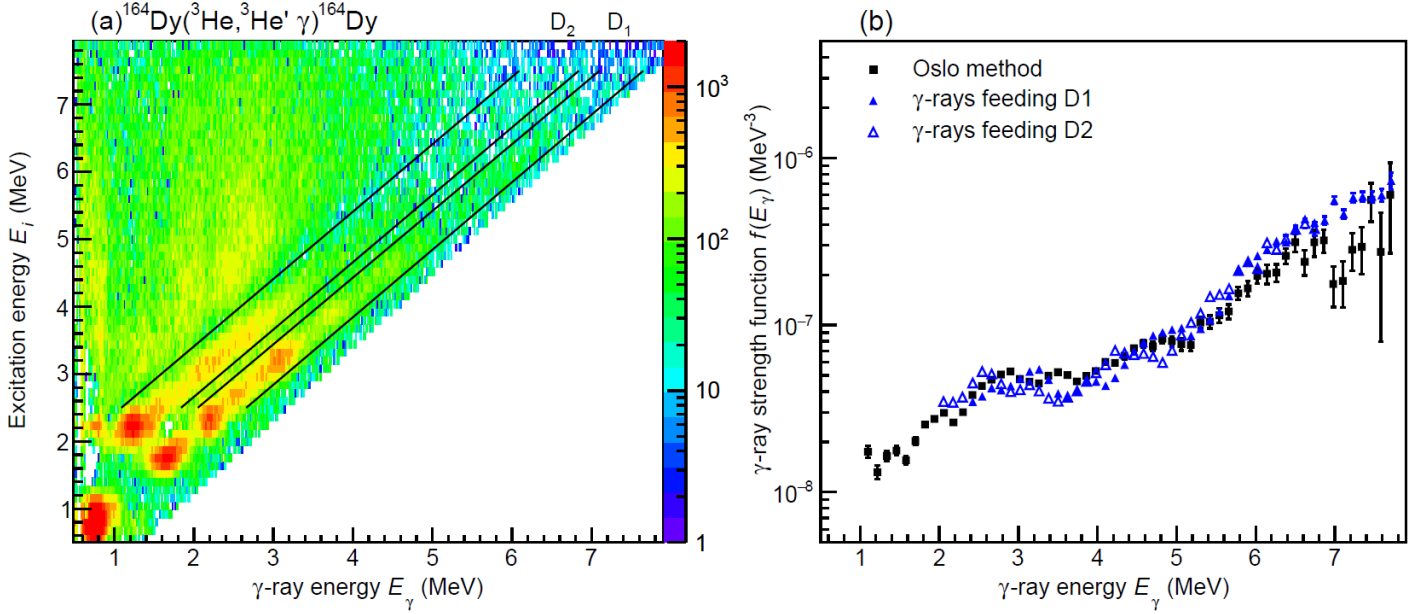


- Primary gamma-rays from intercepts of diagonals with E_x gate.



- Pair of data points internally normalized and proportional to PSF.
- Average γ energy of the extremes of 2 neighboring pairs.
- 2nd pair scaled by a factor to match 1st pair.
- Logarithmic interpolation.
- Results in functional form of PSF.

Shape Method in practice: ^{164}Dy

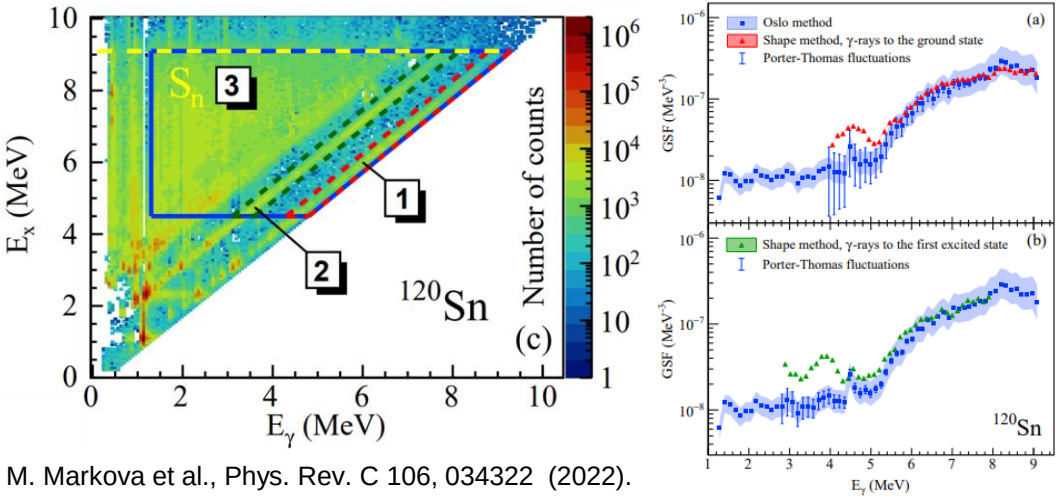


$D_1 = 0^+, 2^+, 4^+, 6^+, 0 – 0.5$ MeV

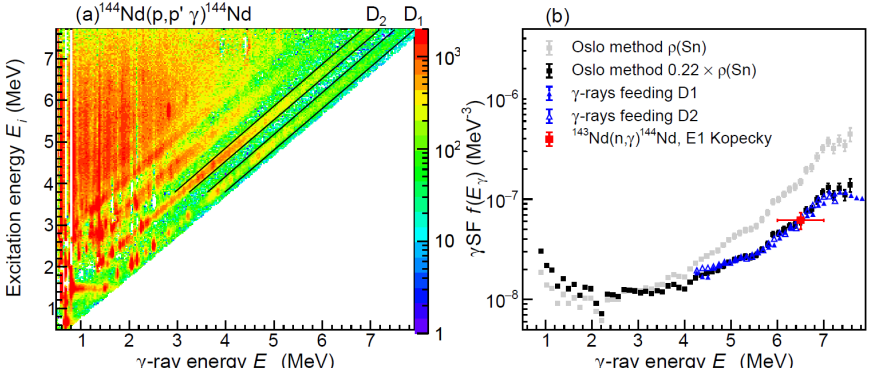
$D_2 = 14$ levels 0.76 – 1.39 MeV

MW, Guttormsen, Larsen *et al.*, Phys. Rev. C 104 014311 (2021).

Use of Shape Method



M. Markova et al., Phys. Rev. C 106, 034322 (2022).



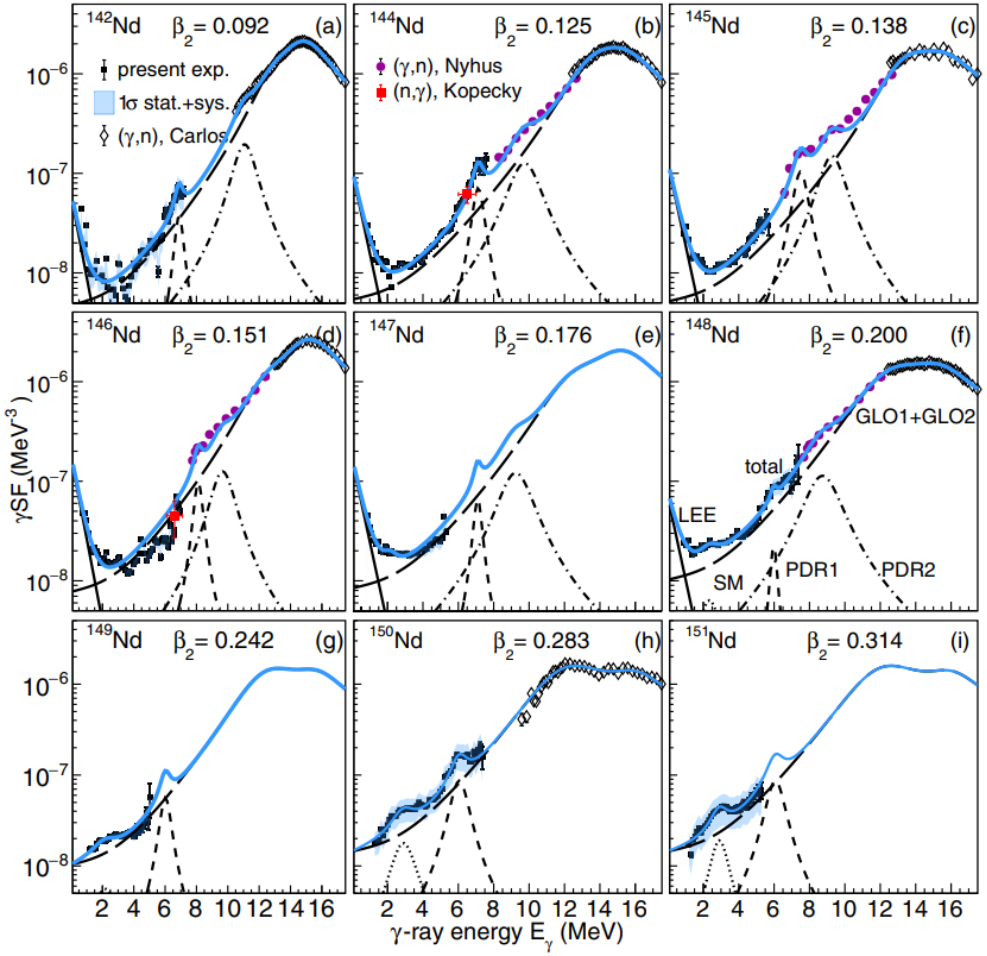
Guttormsen, Ay, Ozgur et al., Phys. Rev. C 106, 034314 (2022).

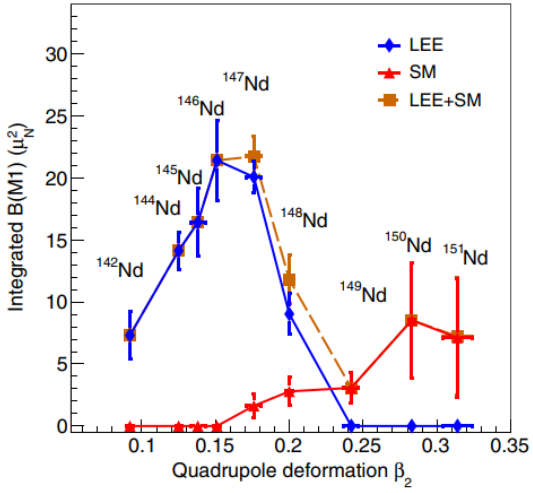
Shape method applied (probably more):

^{93}Sr: Sweet et al., Phys. Rev. C 109, 054305 (2024).
^{144,145,150}Nd: Guttormsen et al., Phys. Rev. C 106, 034314 (2022).
^{120,124}Sn: Markova et al., Phys. Rev. C 106, 034322 (2022).
^{112}Cd: Goriely et al., Phys Rev C 106, 044315 (2022).
^{96,100}Mo: Larsson, Ph.D. thesis, University Osof lo (2023).
^{164}Dy, ^{56}Fe, ^{92}Zr: Wiedeking et al., Phys Rev C 104, 014311 (2021).
^{106}Cd: Tsewu, ongoing, Ph.D. University of Johannesburg (2025).
^{76}Ge, ^{88}Kr: Mücher et al. Phys Rev C 107, L011602 (2023).
^{63}Ni, ^{85}Kr: Nkalanga, ongoing, PhD, University of Johannesburg (2025)
^{140}Ba: Spyrou et al. Phys. Rev. Lett. 132, 202701 (2024).
^{58}Fe: Abbott et al., Phys. Rev. C 111, 034322 (2025).
Zr: Larsen et al., ongoing
Ce: Spyrou et al., ongoing
^{70}Cu: Ronning et al, in preparation.
^{128}Te: P-A. Söderström, ongoing

….

Interplay of low-energy modes: experimental





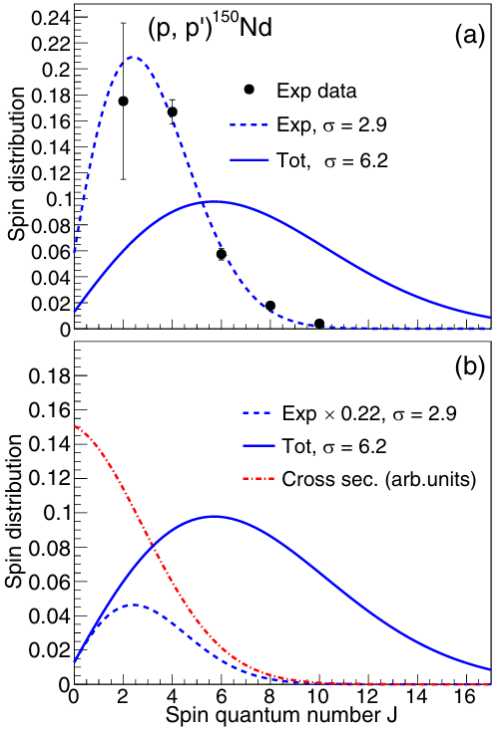
PHYSICAL REVIEW C **106**, 034314 (2022)

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,†] 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]

Nd isotopic chain

Comprehensive study on PSF evolution for 9 Nd isotopes with (p,p) and (d,p) reactions.
Oslo method, Shape Method, Side Feeding
Insight into spin distribution populated in these light-ion reactions compared to the intrinsic spin distribution.



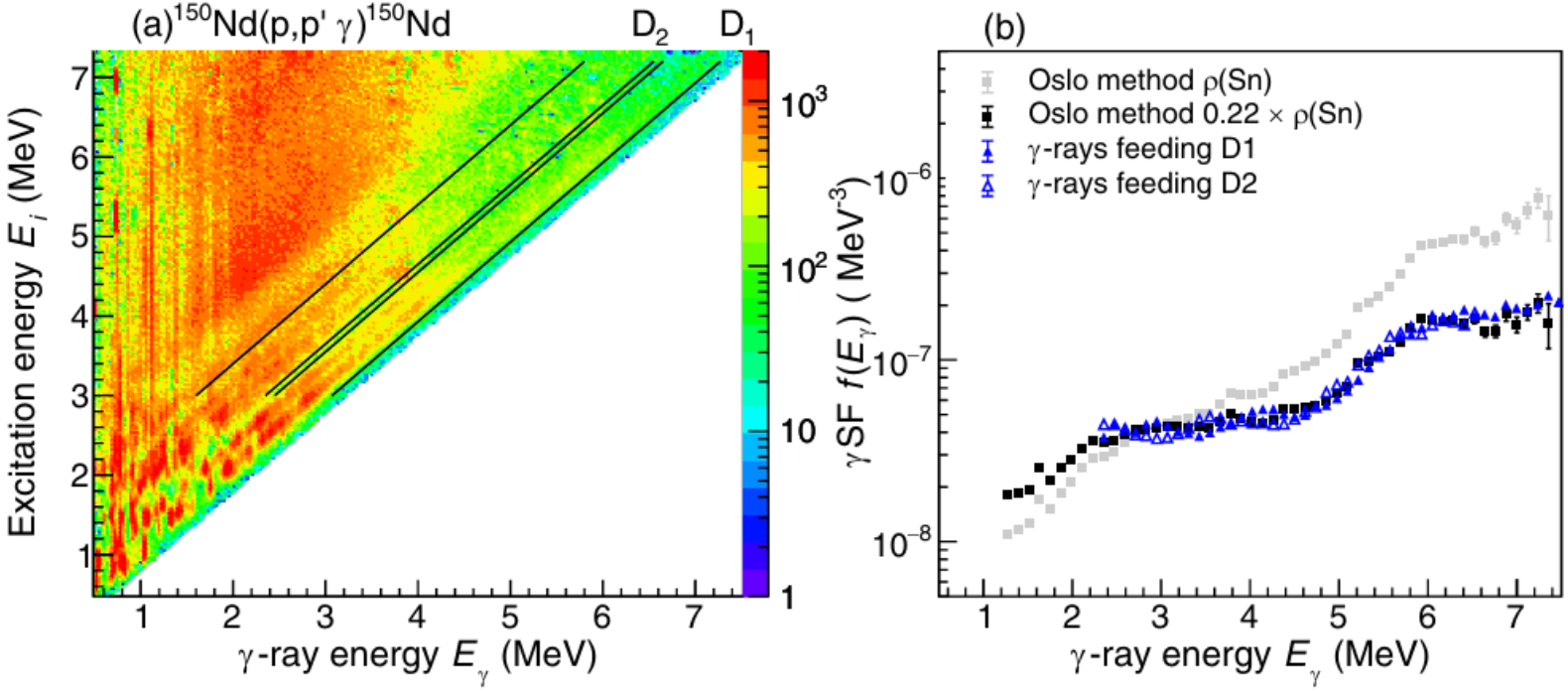
Side feeding analysis into rotational gs band up to 10^+ state

NLD reduction factor for (p,p')

$$\eta = \frac{g(S_n, J=0)_{\text{tot}}}{g(S_n, J=0)_{\text{exp}}} = 0.22(2)$$

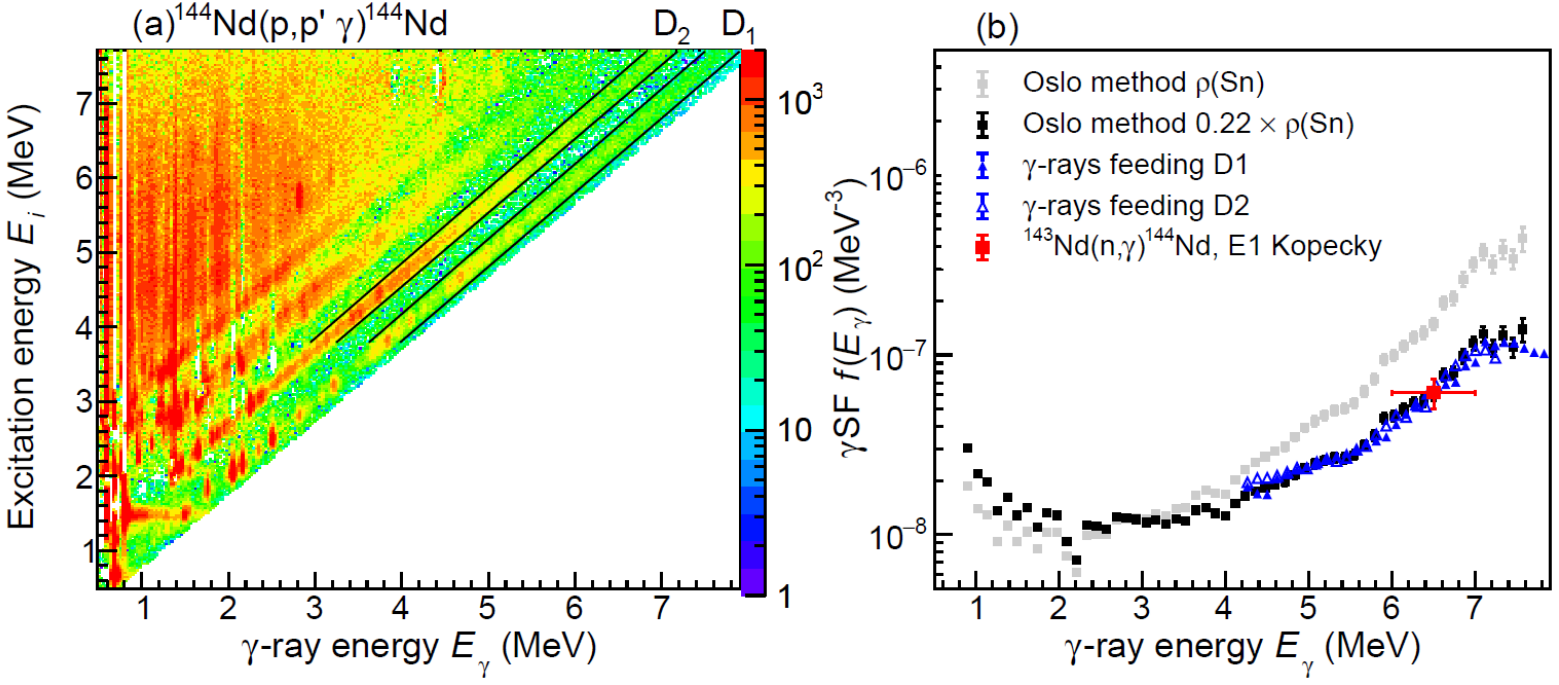
Guttormsen, Ay, Ozgur et al., Phys. Rev. C 106, 034314 (2022).

Shape Method: ^{150}Nd



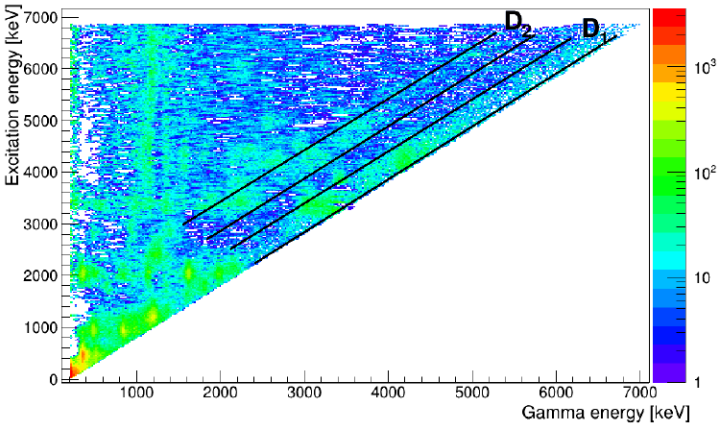
Guttormsen, Ay, Ozgur et al., Phys. Rev. C 106, 034314 (2022).

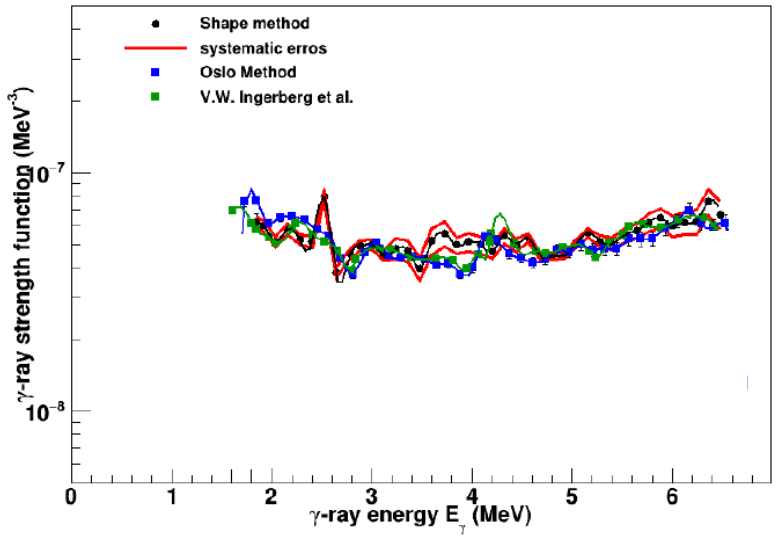
Shape Method: ^{144}Nd

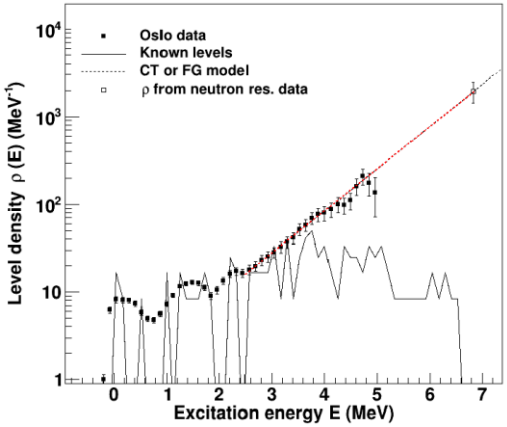


Guttormsen, Ay, Ozgur et al., Phys. Rev. C 106, 034314 (2022).

^{64}Ni(p,d)^{63}Ni - 27 MeV: Shape Method









PhD
Nkalanga
Mhlangano

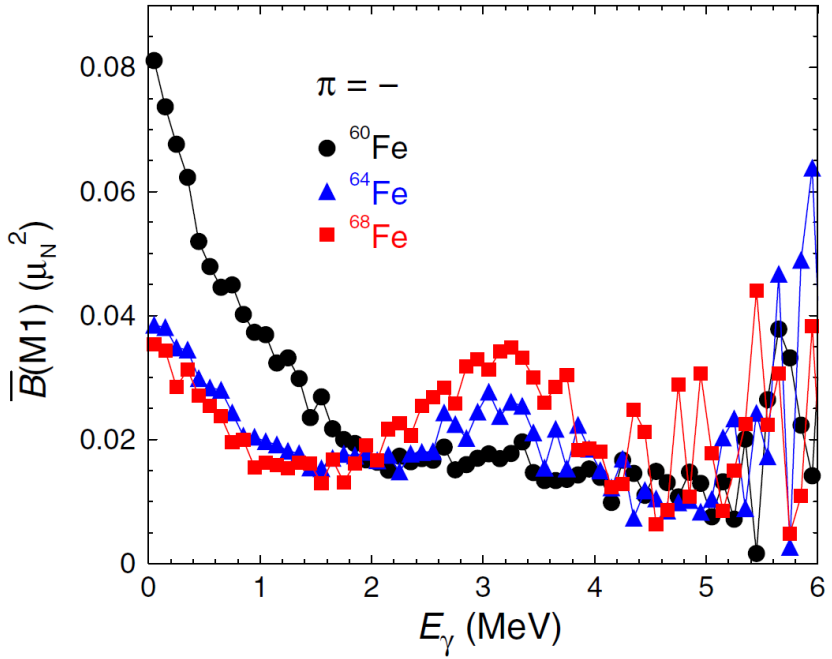
D_0 value of 15500 eV ± 4000 eV is obtained using the Shape method, consistent value of 16000 eV ± 3000 eV in RIPL3.

PHYSICAL REVIEW C **106**, 054315 (2022)

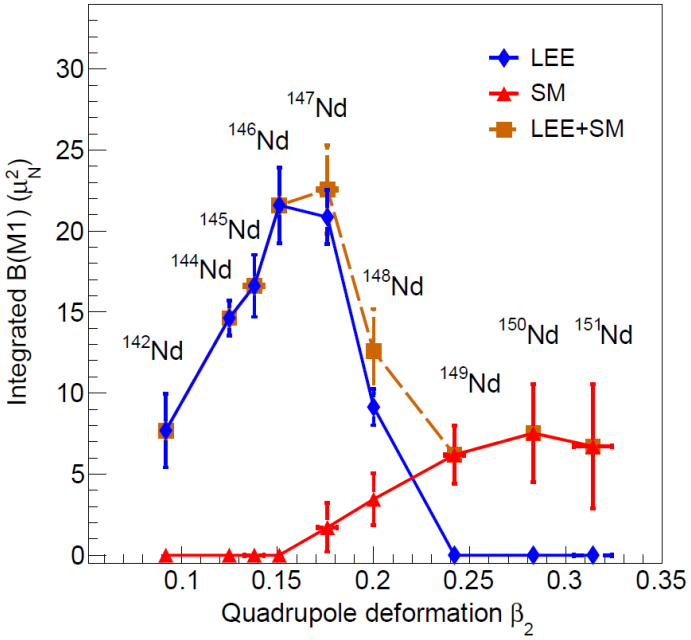
Nuclear level density and γ-ray strength function of ^{63}Ni

V. W. Ingeberg,[1] P. Jones,[2] L. Msebi,[2,3] S. Siem,[1] M. Wiedeking,[2,4] A. A. Avaa,[2,4] M. V. Chisapi,[2,5] E. A. Lawrie,[2,3] K. L. Malatji,[2,5] L. Makhathini,[2] S. P. Noncolela,[2,3] and O. Shirinda[6]

Scissor's Resonance versus Low Energy Enhancement



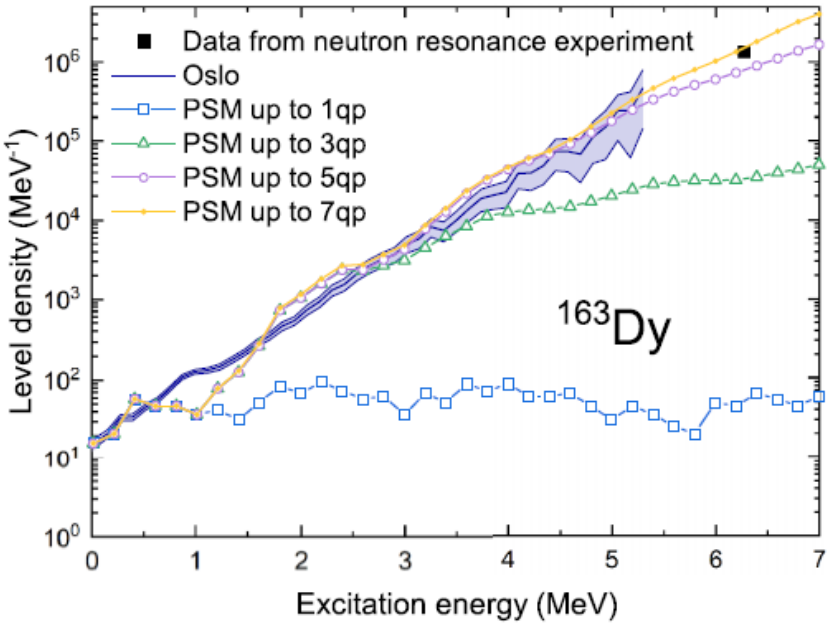
Schwengner, Frauendorf, Brown, Phys. Rev. Lett. 118, 092502 (2017).



Guttormsen, Ay, Ozgur et al., Phys. Rev. C 106, 034314 (2022).

Projected Shell Model: NLD

Projected Shell Model: A “complete” shell-model basis constructed by pair-breaking configurations. It adopts a large single-particle space and physically selects many-body configurations in terms of broken pairs. It is possible to solve the many-body eigenvalue problem and obtain all eigenvalues and eigenstates for arbitrarily heavy and deformed nuclei



In Ref. [45], Guttormsen *et al.* made an interesting observation from the ^{162}Dy and ^{172}Yb level densities obtained in the Oslo experiment using (^{3}He, $\alpha\gamma$) reaction. By deducing entropy within the microcanonical ensemble from the extracted Oslo NLD data for the two pairs of adjacent odd-A and even-even deformed heavy nuclei in the rare-earth sector, the authors made a comparative analysis and gave an interesting conclusion in terms of quasiparticle excitations [45]. They extracted the number of excited quasiparticles created over the energy range to indicate the phenomena of successive orders of qp state formation due to the breaking of the nucleon pairs. They concluded that at an excitation energy of ≈5.5 MeV in these two isotopes, the maximum number of excited quasiparticles is about six, corresponding to the breaking of three nucleon pairs. This experimental finding from the even-even isotopes is consistent with our present results in

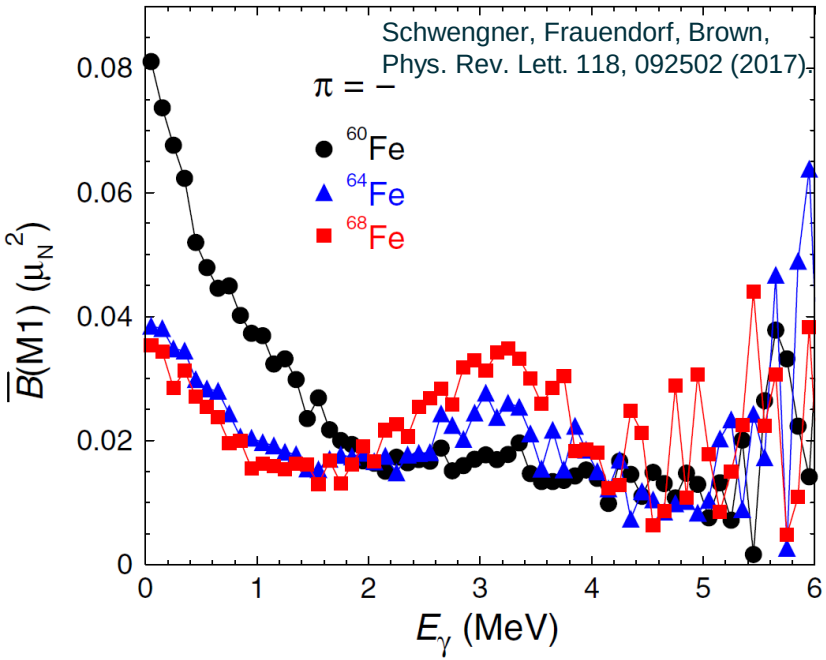
PHYSICAL REVIEW C **111**, 034324 (2025)

Nuclear level density studied in odd-mass nuclei in the framework of the projected shell model

Jiaqi Wang,[1] Saumi Dutta,[1] Cui-Juan Lv,[1] Long-Jun Wang,[2] and Yang Sun[1,*]
[1]*School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*
[2]*School of Physical Science and Technology, Southwest University, Chongqing 400715, China*

Theory: Scissors Mode and Low Energy Enhancement

Shell Model

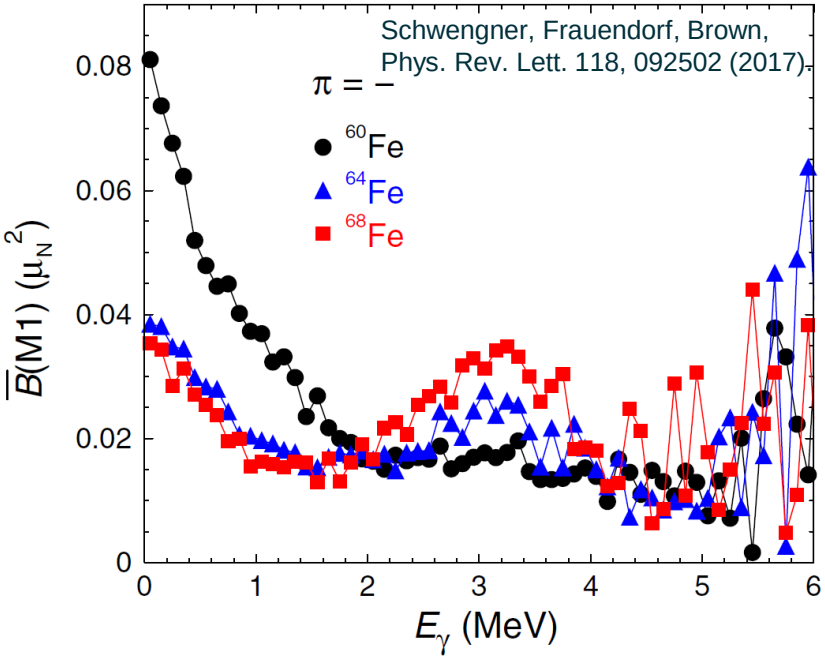


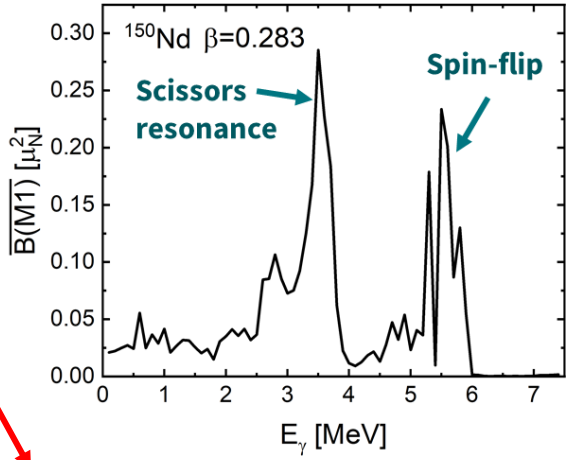
Theory: Scissors Mode and Low Energy Enhancement

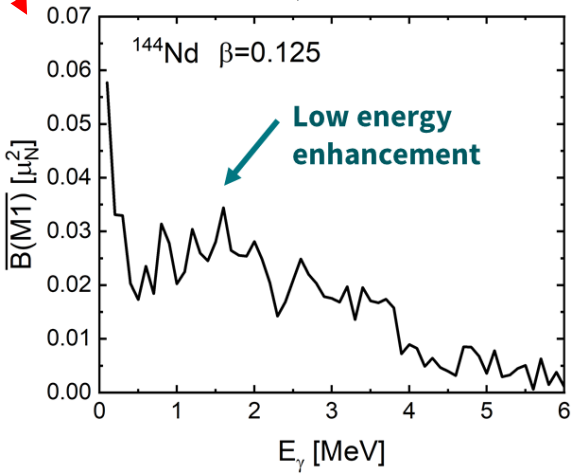
Projected Shell Model

Chen et al, Phys. Rev. Lett. 134, 082502 (2025).

Shell Model

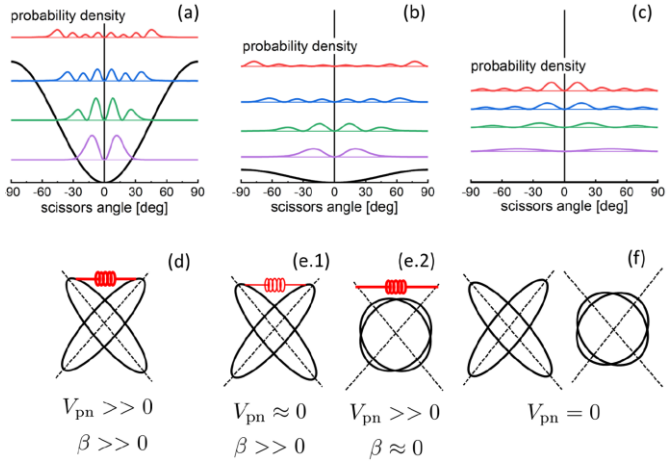


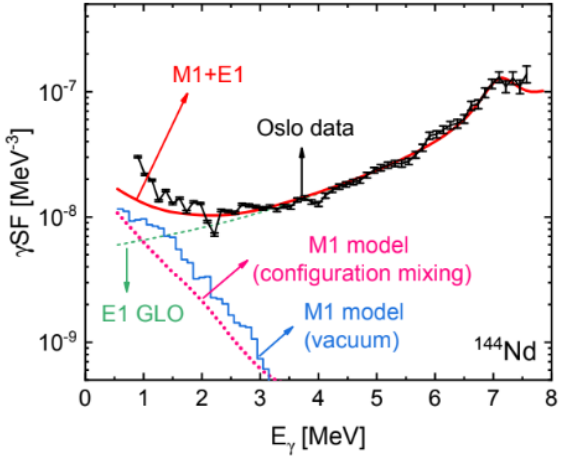




LEE: Scissors rotation, a new collective mode

- The LEE is the manifestation of a previously unknown type of collective motion: Scissors Rotation
- Scissors rotation refers to the relative rotation between proton and neutron systems, in the space spanned by the scissors angle.
- Scissors rotation consists of coherent contribution from many excited bands, with near-degenerate states connected by strong M1.
- The LEE is a universal effect.





PHYSICAL REVIEW LETTERS 134, 082502 (2025)

Origin of the Low-Energy Enhancement of the γ-Ray Strength Function

Fang-Qi Chen (陈芳祁)
School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China and MOE Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, China

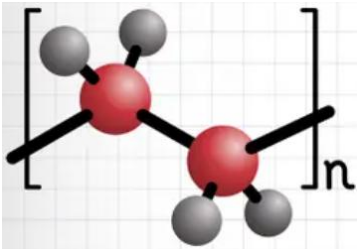
Y. F. Niu (牛一斐)*
School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China; MOE Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, China; Department of Nuclear Physics, China Institute of Atomic Energy, P.O. Box 275(7), Beijing 102413, China; and Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China

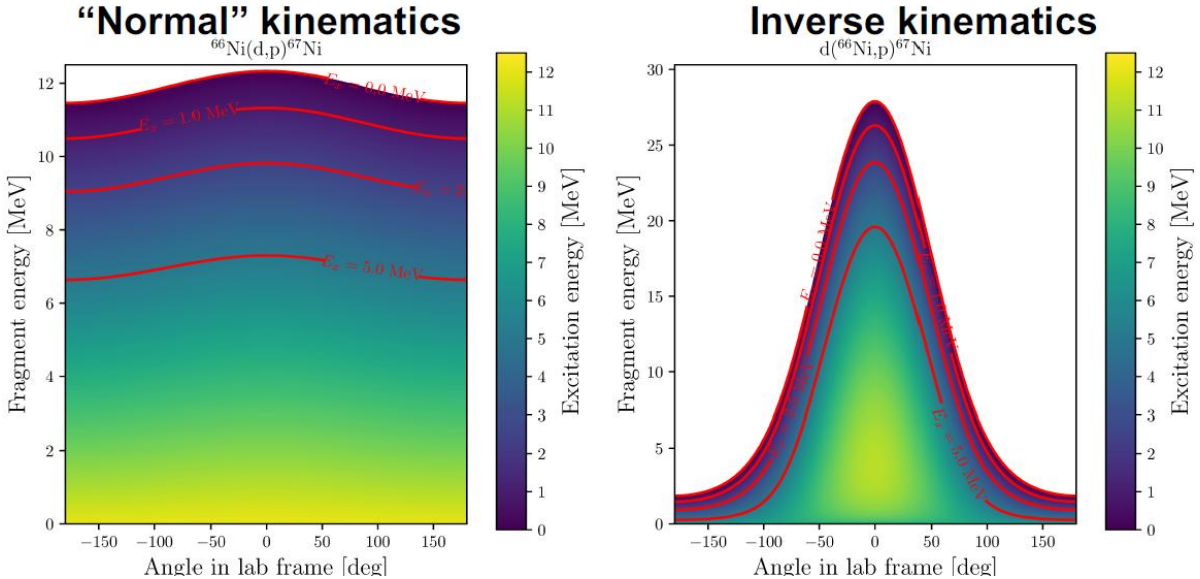
Yang Sun (孙扬)†
School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China

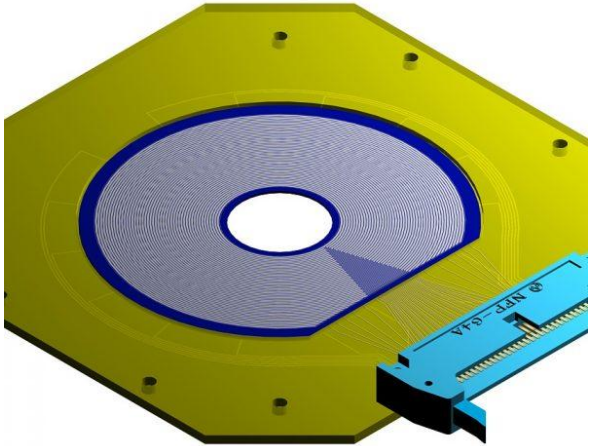
Mathis Wiedeking
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA;

Inverse Kinematics

- Interchange beam and target particle
- Deuterated polyethylene (C2D4)
- Large kinematic boost
- Large Doppler shifts

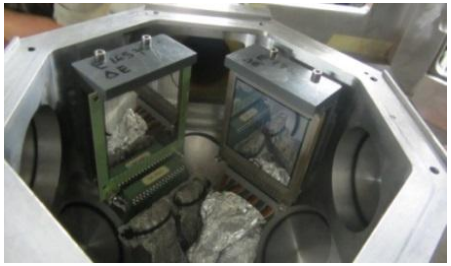




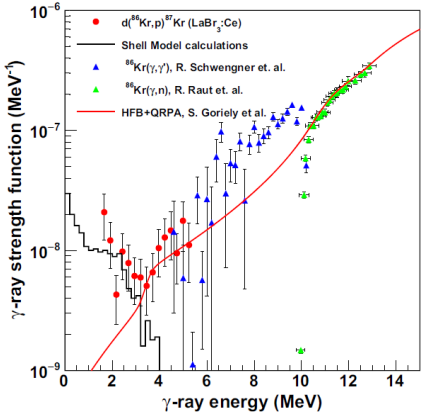


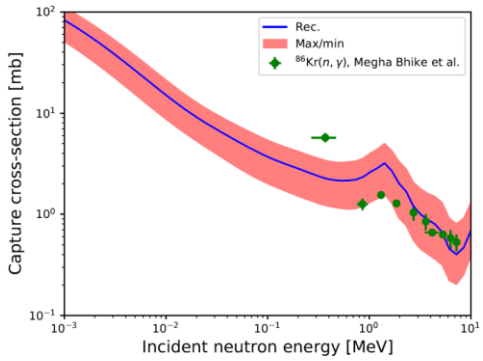
D(^{86}Kr,p)^{87}Kr - 300 MeV: Inverse-Oslo





300MeV ^{86}Kr, CD targets. HPGe + $LaBr_3$(Ce) + Silicon





- First: NLD and PSF from inverse kinematics.
- Complementary to Oslo & Beta-Oslo Methods.
- Applicable to **stable & radioactive** beam facilities.
- iThemba LABS: ^{133}Xe, ^{85}Kr, ^{87}Kr
- Texas A&M: ^{58}Fe
- HIE-ISOLDE CERN: ^{67}Ni

Eur. Phys. J. A (2020) 56:68
https://doi.org/10.1140/epja/s10050-020-00070-7

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

First application of the Oslo method in inverse kinematics

Nuclear level densities and γ-ray strength functions of ^{87}Kr

V. W. Ingeberg[1,a], S. Siem[1], M. Wiedeking[2], K. Sieja[3,4], D. L. Bleuel[5], C. P. Brits[2,6], J. L. Easton[2,7], A. Görgen[1], M. Guttormsen[1], P. Jones[2], B. V. Kheswa[2,8], N. A. Khum, E. A. Lawrie[2], J. J. Lawrie[2], S. N. T. Majola[2,8,9], K. L. Malatji[2,6], L. Makhathini[2,6], S. P. Noncolela[2,7], P. Papka[2,6], E. Sahin[1], R. Schwengner[10], G. M. Tveten[1], F. Zeiser[1],

MSc project
Vetle Ingeberg



D(^{66}Ni,p)^{67}Ni - 302 MeV: Inverse Oslo

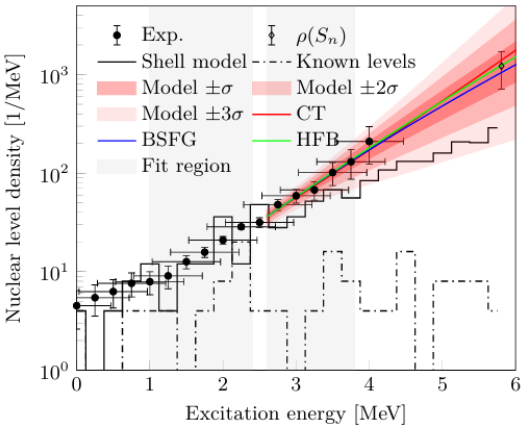
PhD project
Vetle Ingeberg

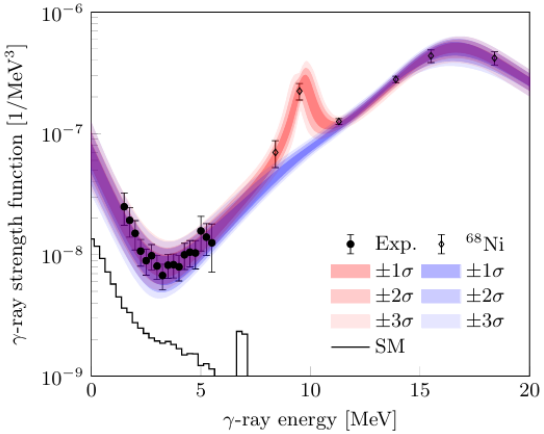






- d(^{66}Ni,p)^{67}Ni with 4.5 MeV/u
- CD target 0.7mg/cm^2
- 3.5x10^6 pps for 140 hours
- Miniball + LaBr$_3$(Ce) + C-REX
- LaBr: ~320k p-γ, Miniball: ~1.1m p-γ





PHYSICAL REVIEW C **111**, 015803 (2025)

Nuclear level density and γ-ray strength function of ^{67}Ni and the impact on the *i* process

V. W. Ingeberg,[1,2,*] S. Siem,[1,2,†] M. Wiedeking,[3,4,5] A. Choplin,[6] S. Goriely,[6] L. Siess,[6] K. J. Abrahams,[7] K. Arnswald,[8] F. Bello Garrote,[1] D. L. Bleuel,[9] J. Cederkäll,[10,11] T. L. Christoffersen,[1] D. M. Cox,[12,13] H. De Witte,[14] L. P. Gaffney,[11,‡] A. Görgen,[1,2] C. Henrich,[15] A. Illana,[14,§] P. Jones,[4] B. V. Kheswa,[1,‖] T. Kröll,[15] S. N. T. Majola,[4,‖] K. L. Malatji,[4,16] J. Ojala,[12,13] J. Pakarinen,[12,13] G. Rainovski,[17] P. Reiter,[8] M. von Schmid,[15] M. Seidlitz,[8] G. M. Tveten,[1] N. Warr,[8] and F. Zeiser[1]
(The ISOLDE Collaboration)

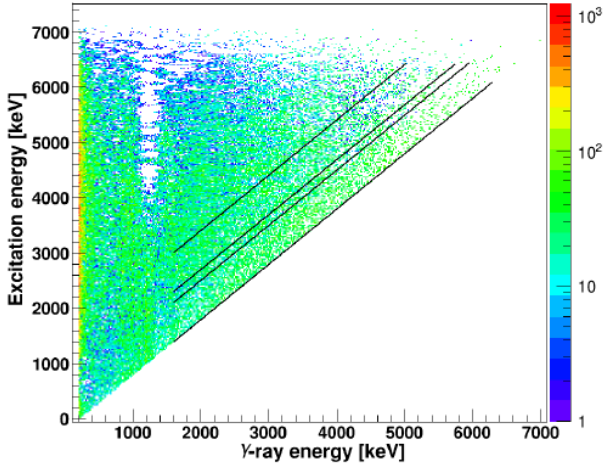
D(^{84}Kr,p)^{85}Kr - 428 MeV: Inverse Oslo & Shape Method

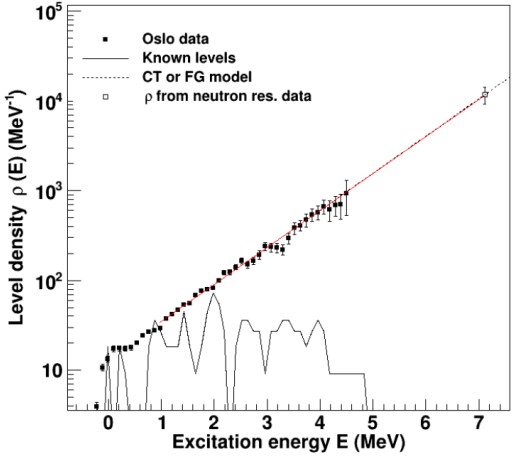
MSc Trine Olafsen

PhD Nkalanga Mhlangano





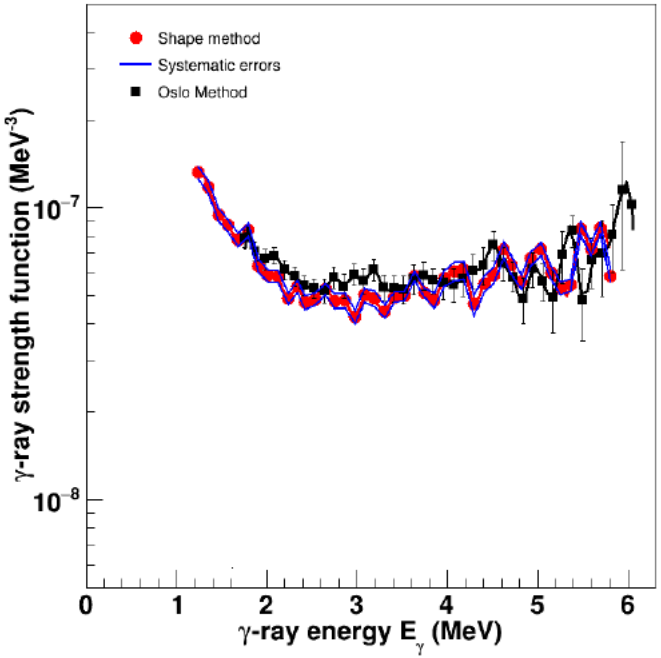




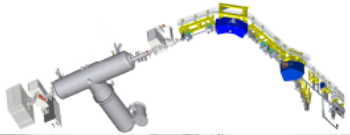
E(level) (keV)	XREF	J^{π}(level)
0.0	ABCD FGHI	9/2+
304.871 *20*	ABC FGHI	1/2-
1107.32 *7*	A C FGHI	1/2-,3/2-
1140.73 *7*	ABC F I	5/2+
1166.69 *6*	A C G I	(1/2,3/2,5/2-)
1223.98 *7*	A C G	(5/2-)
1342.61 *5*	A C F	(3/2+)
1416.57 *9*	A C GH	(5/2+)
1430.6 *10*	C FGH	1/2+

Singh & Chen, Nucl. Data Sheets 116, 1 (2014)

D0 of 3 ± 0.5 keV from the Shape method compares to the value of 4 ± 0.4 keV from RIPL3

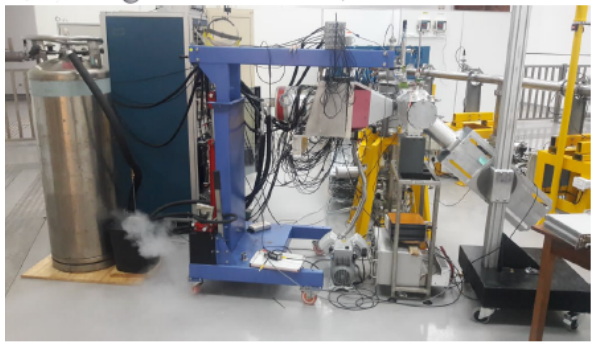


$^{50}Cr(p, \gamma)^{51}Mn^*$

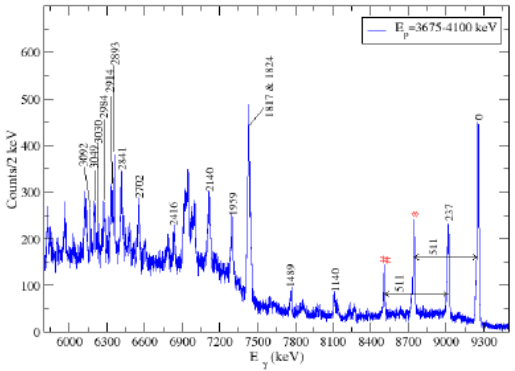




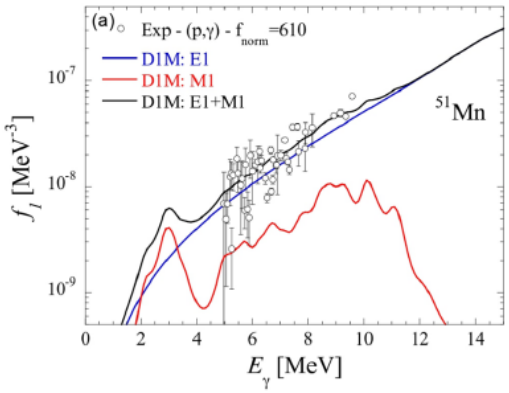
Adivhaho Netshiya PhD 2026 (WITS)

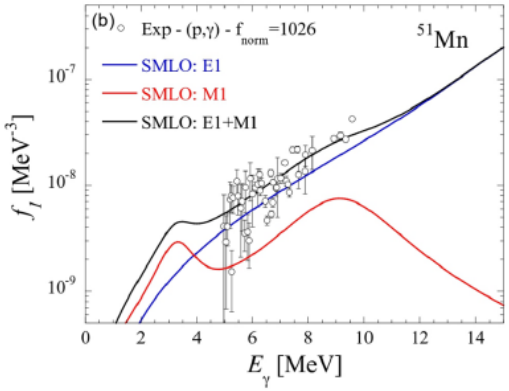


Measurements with **1 clover detector!**

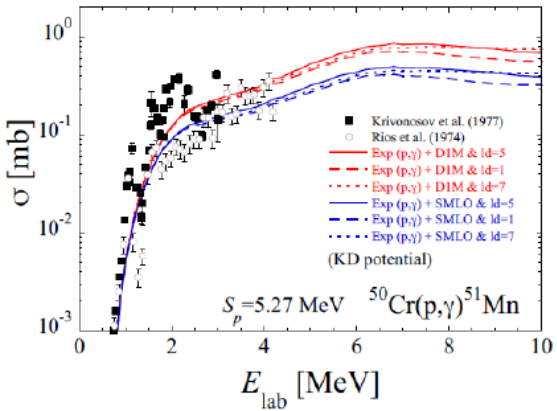


Netshiya et al., in preparation (2026)





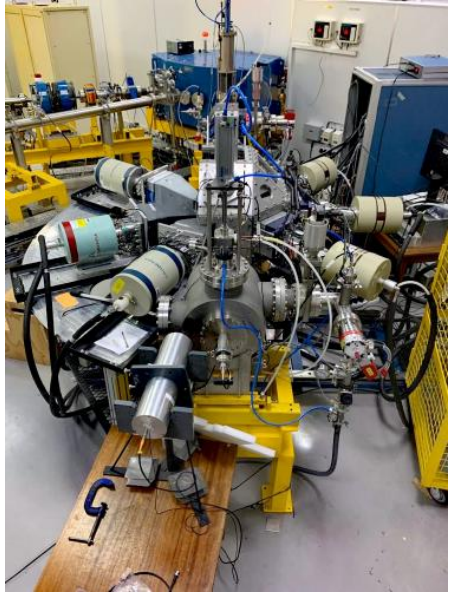
- ✓ 200-350 $\mu g/cm^2$ ^{50}Cr targets.
- ✓ **1 Compton-suppressed HPGe Clover detector.**
- ✓ 3 MV Tandetron: E_p = 2.5 - 4.5 MeV in 20-25 keV intervals.
- ✓ **A total of 64 γ-ray spectra collected (E_p change every 1-2 hours)**
- ✓ **71 γ-rays and 37 energy levels were observed for the first time**
- ✓ **Relative intensities of all 171 γ-rays were measured for the first time.**
- ✓ **Possible multipolarities were assigned to 17 γ-ray transitions.**
- ✓ Apply Average Resonance Proton Capture [1], to minimize statistical fluctuations.
- ✓ Apply Shape Method [2]

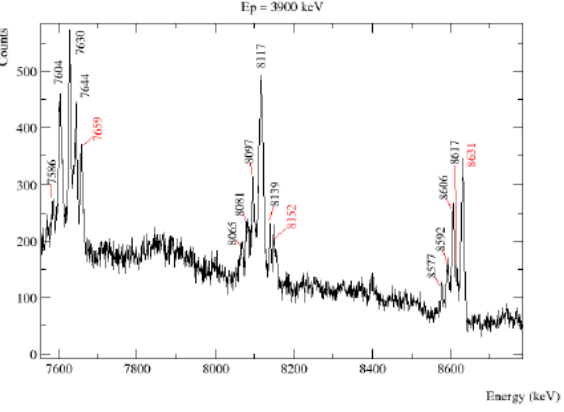


*Disclaimer: First time measurement of 51Mn using radiative (p,γ) above S(p)+3266.2. Present exp. S(p)+3266.2 + **1230** keV

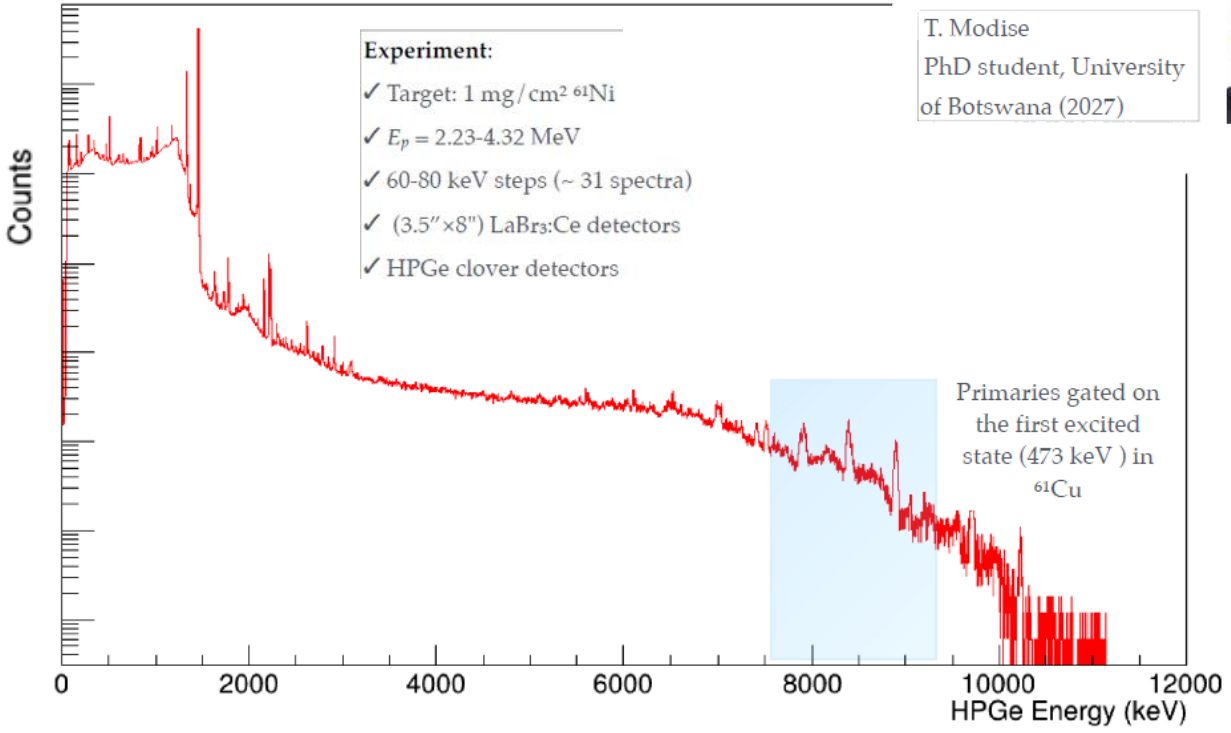
[1] Goriely, et al., Eur. Phys. J. A 55, 172 (2019)
[2] Wiedeking et al., Phys. Rev. C., 104 014311 (2021), Phys. Rev. Lett., 108 162503 (2012).
[3] Netshiya, et al., J. Phys. Conf. Ser. 2586, 012111 (2023)

$^{60}Ni(p,\gamma)^{61}Cu$





Testing the validity of the Brink-Axel Hypothesis



T. Modise
PhD student, University of Botswana (2027)



$^{89}Y(p,\gamma)^{90}Zr$ Experiment



Kgashane Malatji
UCB/LBNL

GRETINA: Gamma-Ray Energy Tracking In-beam Nuclear Array

Targets: natural ^{89}Y, 2.05 mg/cm², energy Loss ~150 keV
Proton energies (E_p): 3.15, 3.3, 3.45 and 3.6 MeV,
Beam current: ~ 0.1 – 0.2 eμA

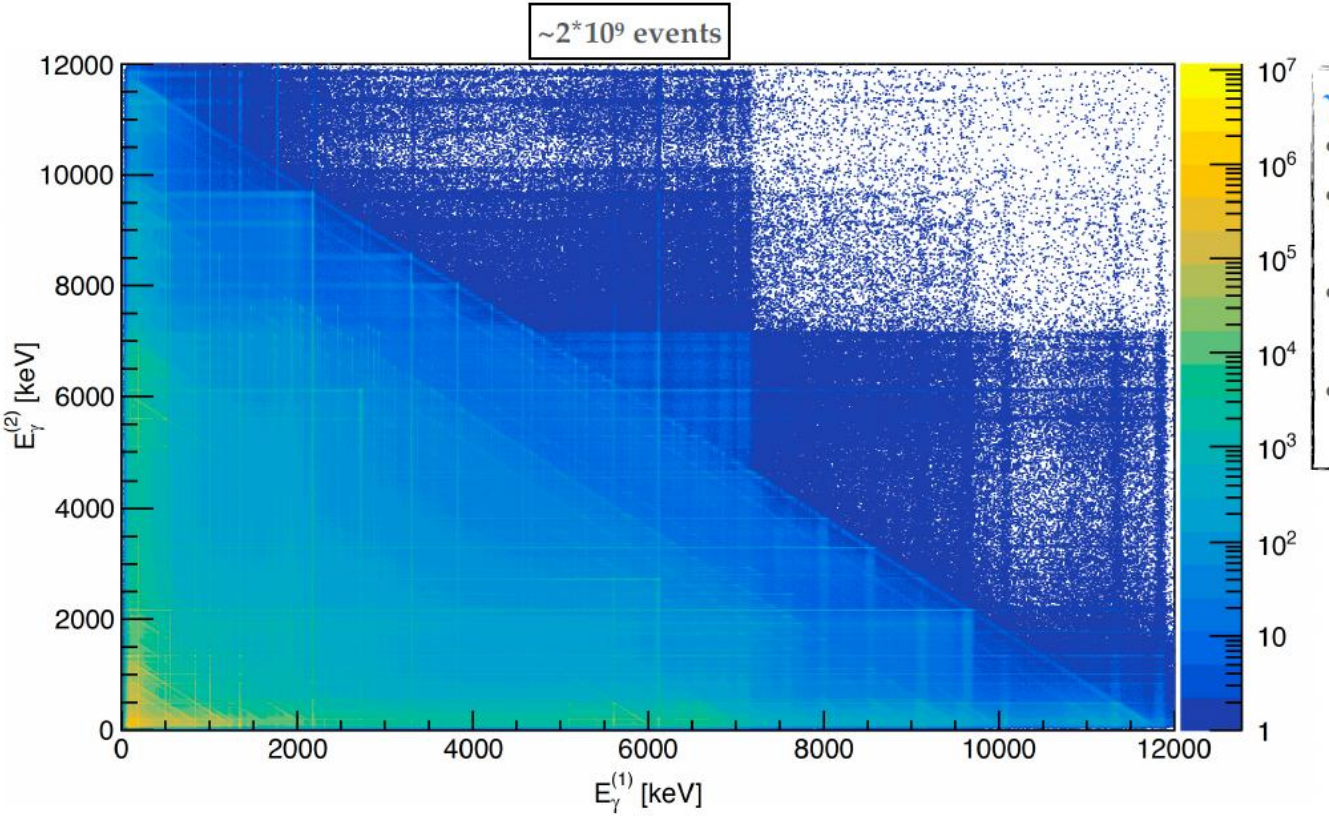
GRETINA configuration during (30/10 - 8/11, 2024):

- 11 quads (42 HPGe crystals used in the experiment), in stand-alone mode
- Photo peak efficiency of 8.7 % at 1.332 MeV and 1.6 % at 11.8 MeV
- Energy resolution ≈ 2-3 keV @ 1.332 MeV
- Angular coverage ~ 65° - 172°



Figure Credit: G. Savard, Workshop for Applied Nuclear Data Activities (WANDA) 2026

Primary γ-ray intensities from γγ coincidences (E_p = 3.6 MeV)



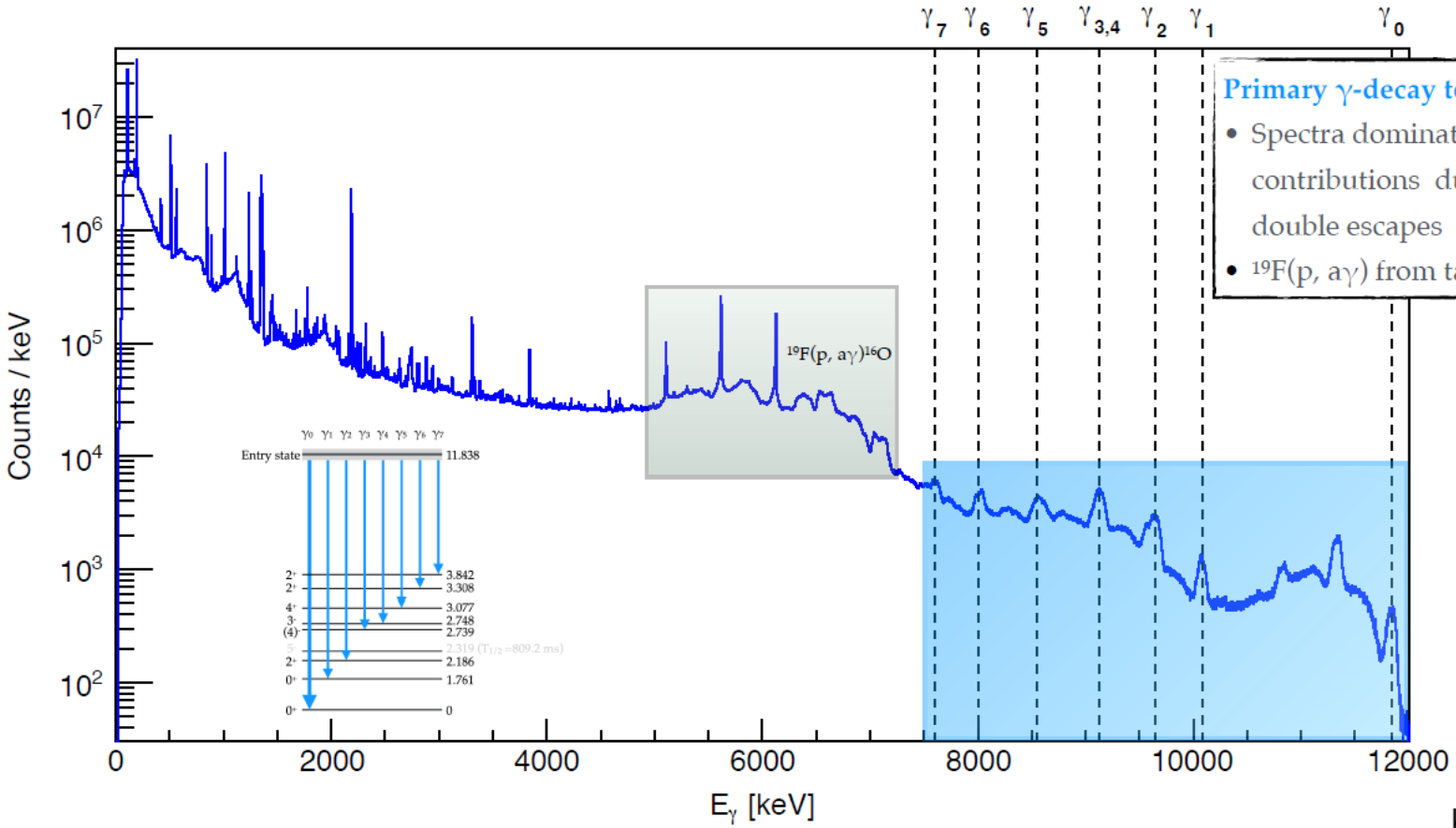
γγ coincidences

- **Multiplicity = 2 events only**
- **Coincidences within 90 ns time window**
- Competing reaction dominantly (p,pγ) and ^{19}F(p, aγ)
- Increased selectivity and sensitivity through γγ coincidences



Kgashane Malatji
UCB/LBNL

$^{89}Y(p,\gamma)^{90}Zr$ for $E_p = 3.6$ MeV

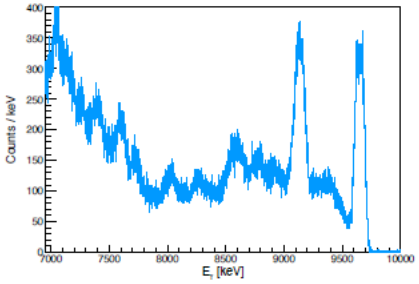




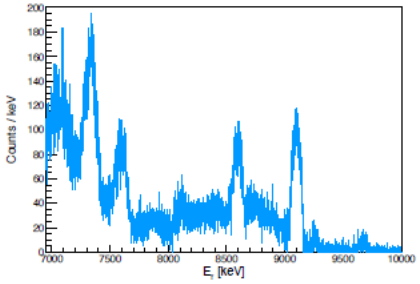
Kgashane Malatji
UCB/LBNL

Primary γ-ray intensities gated on secondary γ-rays ($E_p = 3.6$ MeV)

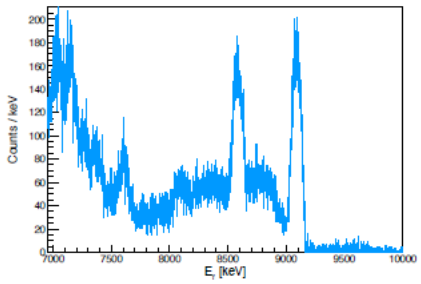
$J^\pi \rightarrow 2_1^+$



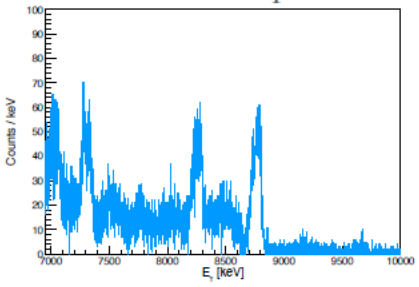
$J^\pi \rightarrow (4_1)^-$



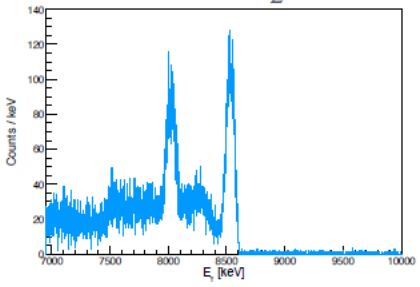
$J^\pi \rightarrow 3_1^-$



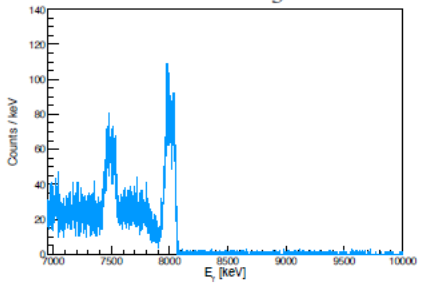
$J^\pi \rightarrow 4_1^+$

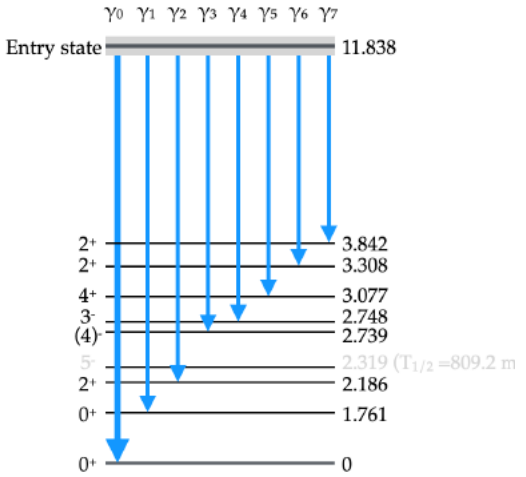


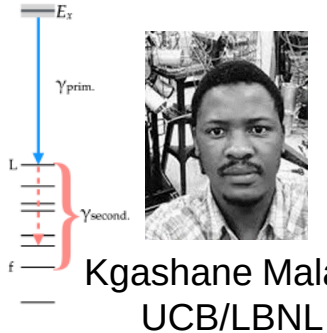
$J^\pi \rightarrow 2_2^+$



$J^\pi \rightarrow 2_3^+$

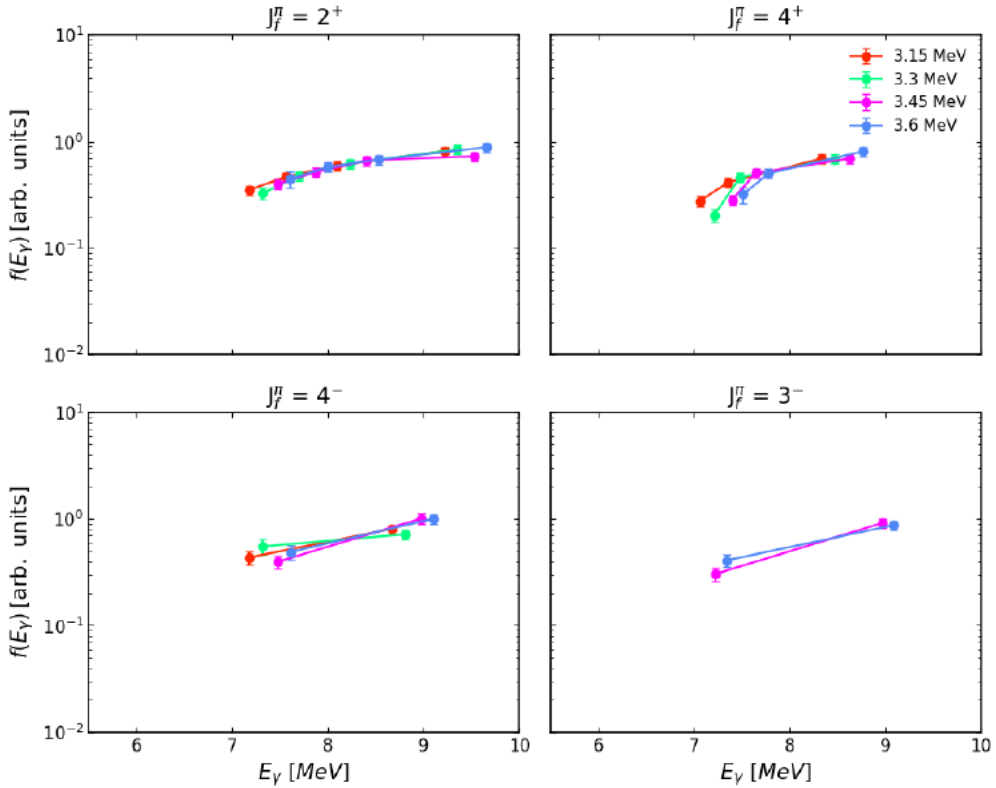




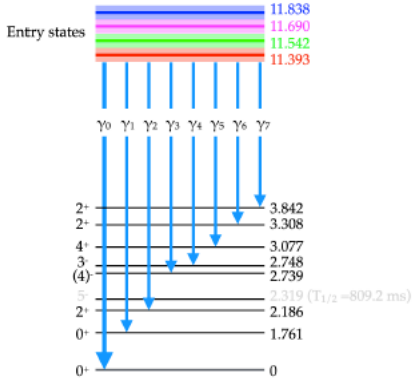


Kgashane Malatji
UCB/LBNL

Primary γ-ray intensities gated on secondary γ-rays



- Primary γ-ray intensities to final states with identical spin and parity
- Intensities from different initial E_x normalized relative to each other
- PSF (slope) is **consistent across different initial excitation energies**, supporting the **Brink–Axel hypothesis**.



Wiedeking et al., Phys. Rev. Lett., 108 162503 (2012), Phys. Rev. C., 104 014311 (2021)

$(p,\gamma\gamma)^{90}Zr$ vs $(p,p')^{90}Zr$

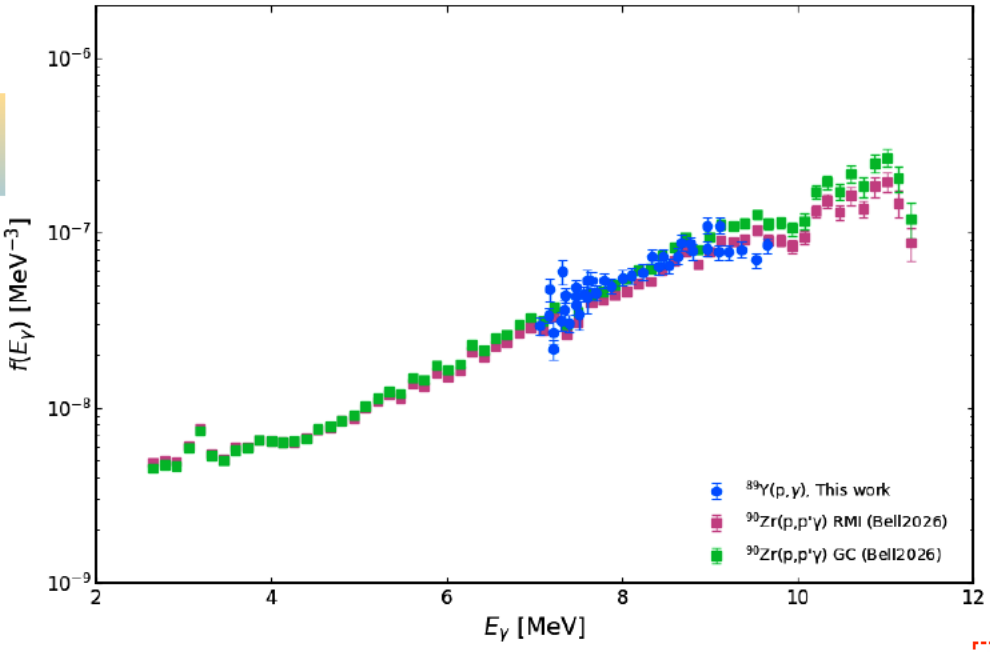
Preliminary



$^{90}Zr(p,p\gamma)^{90}Zr$ OM data courtesy of L.T. Bell (PhD student, UiO)

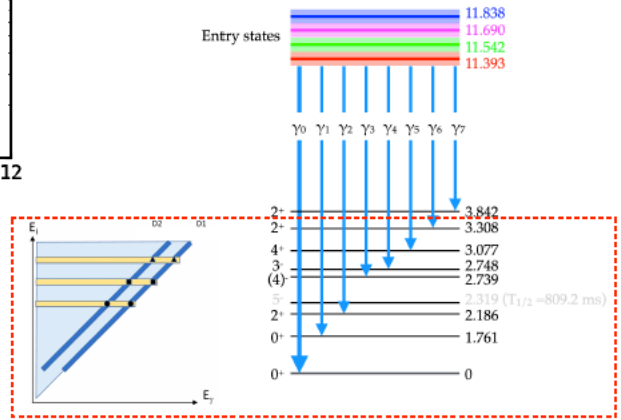


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UCB/LBNL



- PSF (slope) is **consistent across different initial excitation energies**, supporting the **Brink–Axel hypothesis**.
- gBA: γ-decay is dependent only on γ-energy E_γ and not J^π and E_x
- Good agreement between (p,γ) and **(p,p′) data from OM (constrained with the Shape Method)**

- Different reactions yield similar results
- PSF independent of beam particle & energy



PANDORA Project: UHECR

iThemba LABS
Cape Town



L. Pellegri

RCNP
Osaka



A. Tamii

ELI-NP
Bucharest



P.-A. Söderström

Eur. Phys. J. A (2023) 59:208
https://doi.org/10.1140/epja/s10050-023-01081-w

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

PANDORA Project for the study of photonuclear reactions below $A = 60$

PANDORA Collaboration

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The origin of the majority of nuclei can be explained by stellar nucleosynthesis processes except 6Li, 9Be, 10B and 11B.

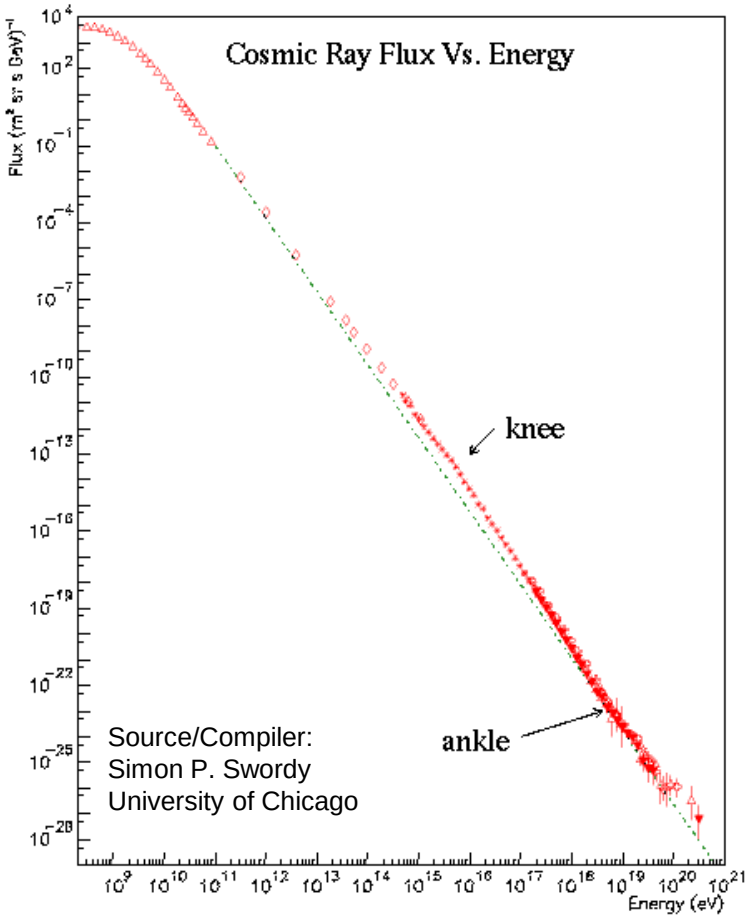
Their cross sections for proton induced reactions are very large because of the small Coulomb barrier and they are destroyed at H burning temperatures.

Yet, they are present and are associated with spallation reactions of cosmic rays.

Ultra High-Energy Cosmic Rays

Cosmic rays have been observed with energies from 10^9 eV to over 10^{20} eV. Over this range, the ***"flux"*** of cosmic rays (the number of arriving particles per unit area, per solid angle, per unit time) appears to follow a single ***power law*** ~E^{-3}.

Cosmic rays consist of energetic p, a, and heavier nuclide up to ^{56}Fe with kinetic energies up to several 100s TeV per nucleon and beyond.



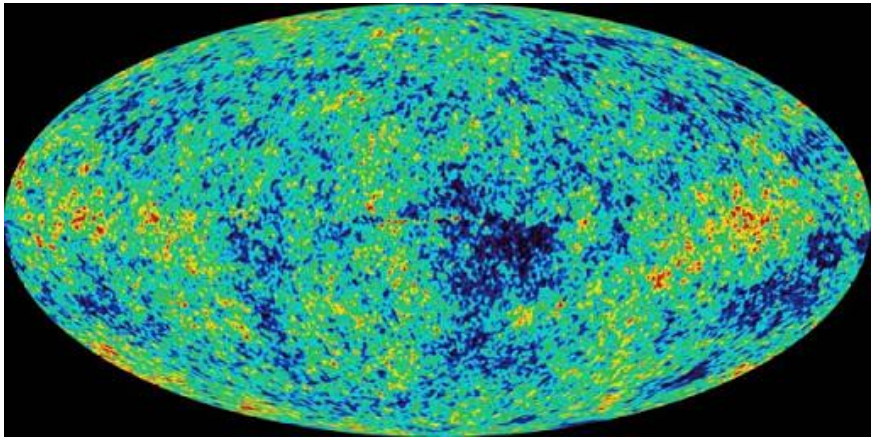
Interactions of UHE Cosmic Rays

Several possibilities exist for interactions of GCR:

1) Undergo high-energy collision (spallation) with interstellar nuclei.
2) Energetic cosmic ray particle may collide with interstellar electrons
3) Reactions with the Cosmic Microwave Background

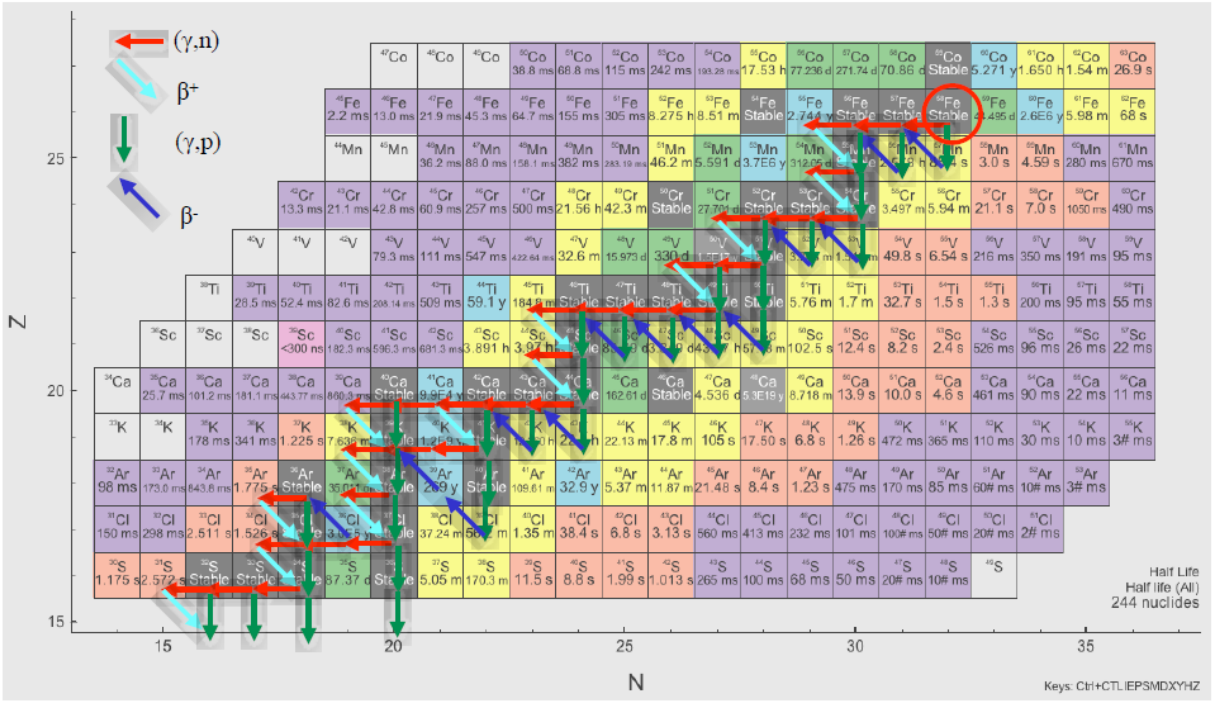
Nuclei and electrons have very low density in interstellar space except the Cosmic Microwave Background

High energy cosmic ray particles can undergo reactions with CMB through the gamma-induced (γ,x) reactions.
The actual temperature of the CMB microwave is 2.725 Kelvin (0.66 meV).
Bombarding with high-energy particles will effectively reach several 10s - 100s MeV due to Lorentz factor (>10^{10}).



Captured by NASA's Wilkinson Microwave Anisotropy Probe

Photodisintegration path of UHECRs



- Photodisintegration takes primary particles on a path through the nuclear chart before arriving to earth
- Around 200 nuclei involved. Photoabsorption, decay, and disintegration

P-A. Soderstrom, ELI-NP

Complementary GDR experiments

iThemba LABS
Cape Town



RCNP
Osaka



ELI-NP
Bucharest



- E1 response widely studied above A ~90 with smooth bulk properties
- E1 response of low-mass nuclei shows fragmented components in contrast to heavy nuclei
- Both experimental data and theoretical predictions have serious issues in the mass region.
- Experimental works often treat the (γ,xn) reaction cross section as a good approximation of the total photo-absorption cross section
- However, proton decay channel is equally important as the neutron decay channel.
- The decay channel is predicted to have a significant contribution in the decay of several light nuclei.
- Few experimental data especially for the decay channels other than the neutron decay.
- Existing data often show a large inconsistency by a factor of two or more.

- Pandora Project aims to address experimental data issues of the GDR (also theoretical issues).

Photon Strength Function Database

2013: Consultant's meeting at IAEA with recommendation on PSF database.
2016-2019: IAEA Coordinated Research Project
Photonuclear Data and Photon Strength Functions F41032.

https://www-nds.iaea.org/PSFdatabase/

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Review

Reference database for photon strength functions

S. Goriely[1], P. Dimitriou[2,a], M. Wiedeking[3], T. Belgya[4], R. Firestone[5], J. Kopecky[6], M. Krtička[7], V. Plujko[8], R. Schwengner[9], S. Siem[10], H. Utsunomiya[11], S. Hilaire[12], S. Péru[12], Y.S. Cho[13], D.M. Filipescu[14], N. Iwamoto[15], T. Kawano[16], V. Varlamov[17], and R. Xu[18]

Since 2024 update annually

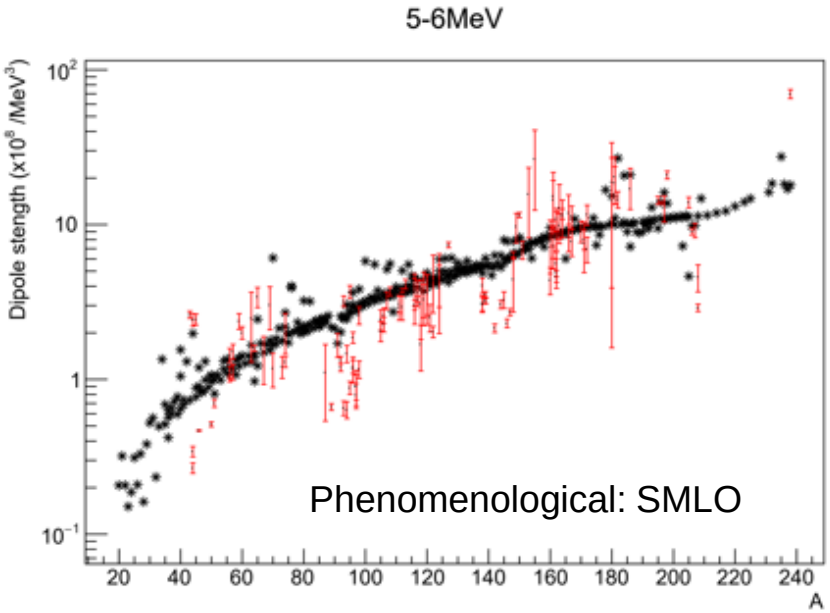
Data in the PSF database update 2025

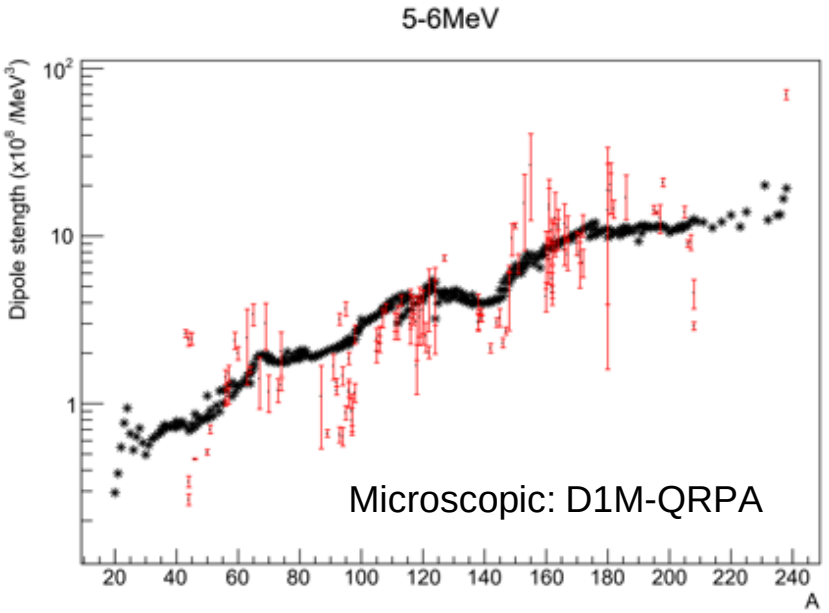
Experimental
338 unique nuclides (1123 datafiles) for all experimental methods

58 nuclides (137 files)	Thermal neutron capture
13 nuclides (34 files)	Ratio and Shape Method
113 nuclides (222 files)	Oslo Methods
9 nuclides (55 files)	Proton scattering
29 nuclides (47 files)	Nuclear Resonance Fluorescence
54 nuclides (123 files)	Average Resonance Capture
52 nuclides (99 files)	Discrete Resonance Capture
154 nuclides (337 files)	Photonuclear
63 nuclides (115 files)	Absolute Photonuclear
22 nuclides (37 files)	Proton capture

Theoretical
Two models validated and recommended to perform global calculations of
E1 and M1 PSFs for all nuclides across the nuclear chart: D1M-QRPA and SMLO.

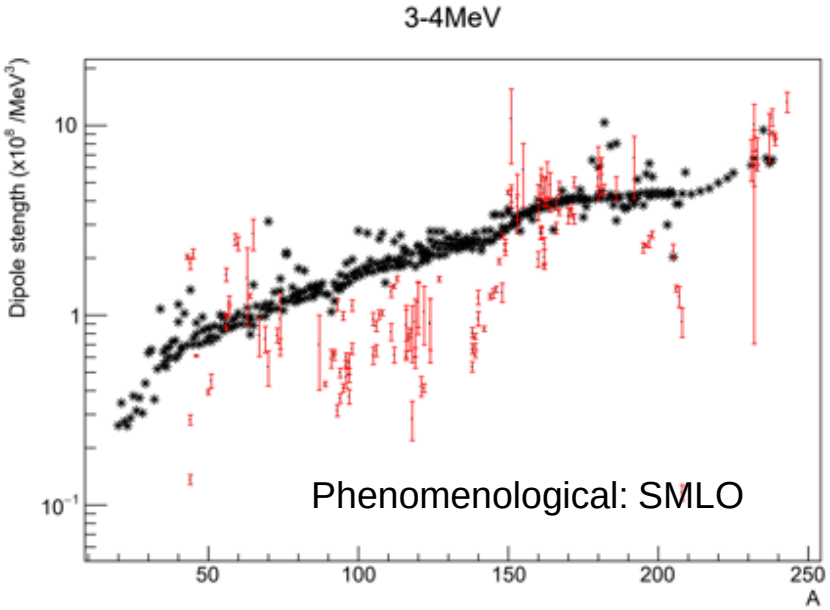
PSF Outliers: Guide where to focus attention

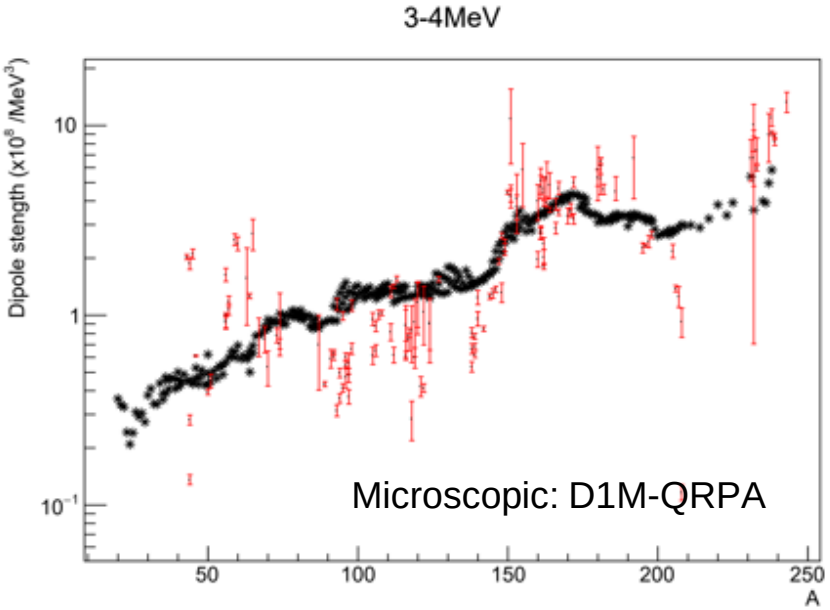




Individual data point outliers: focus on experiment or data analysis, e.g. A~44, A=240
Cluster of outliers: focus on model/theory: e.g. A~90, A=240

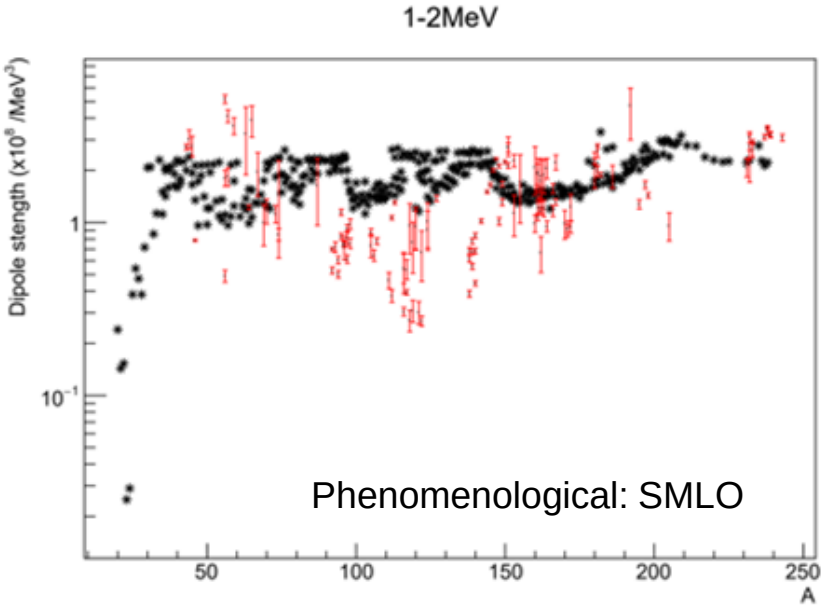
PSF Outliers: Guide where to focus attention

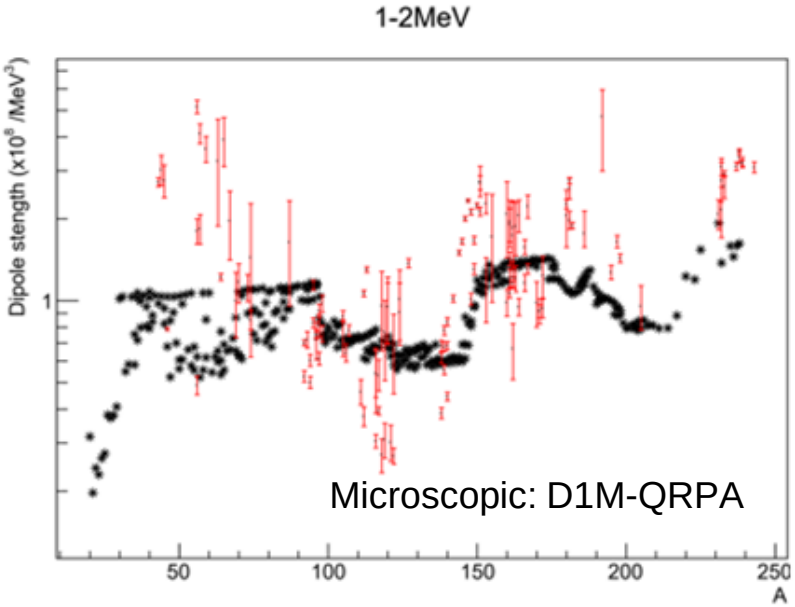




Individual data point outliers: focus on experiment or data analysis, e.g. A~44, A=240
Cluster of outliers: focus on model/theory: e.g. A~90, A~ 50 – 70, A~80 – 150,

PSF Outliers: Guide where to focus attention





Individual data point outliers: focus on experiment or data analysis, e.g. A~44, A=240, A=181
Cluster of outliers: focus on model/theory: e.g. A~90, A~ 50 – 70, A~80 – 150

Publication on outlier analysis in preparation.

Updating/Improving Nuclear Level Densities for Applications

- Since 2008: important developments and new information available
- Wealth of new experimental information obtained also with new methods
- New advanced modelling capabilities for global calculations
- Improved fundamental theories to guide the models
- New measurements to validate the models
- Enhanced dissemination tools: interactive retrieval interfaces, web-based APIs
- IAEA CRP started 2025.
- Estimated dissemination 2028.

Summary

- Tools available to obtain (n,γ) cross sections away from stability.
- Inverse Oslo Method
  - complementary and potential option when other methods cannot be used.
- Shape Method
  - normalization when neutron resonance spacing is not available.
- Many measurements/analyses underway
- Database developments
  - PSF annual updates, NLD started

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Office of Science

Thank you!

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