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U.S. DEPARTMENT OF ENERGY
Office of Science

Constraining Nuclear Level Densities Using the Shape Method and Related CRP Research Activities

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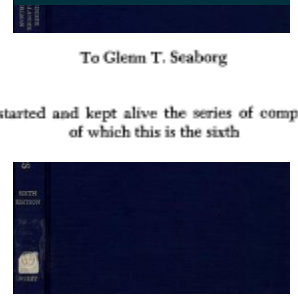
Brief history of the LBNL/UCB Nuclear Data Group

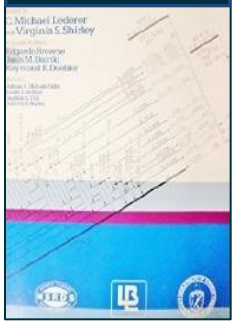
Pu (1951 Nobel)

Our roots go back to Seaborg & Isotope Production

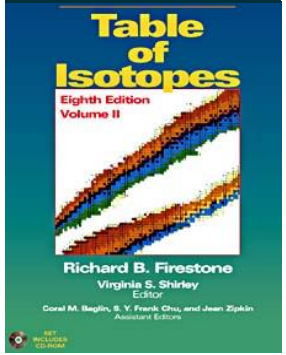
Table of Isotopes (ToI) 6th Edition (1967)



ToI 7th Edition (1978)



ToI 8th Edition (1999)



^{99}Tc for Medical Imaging

Next 50 years: group specialized in decay and neutron capture data.

Past 10 years: help develop a national plan to address nuclear data needs for applications.

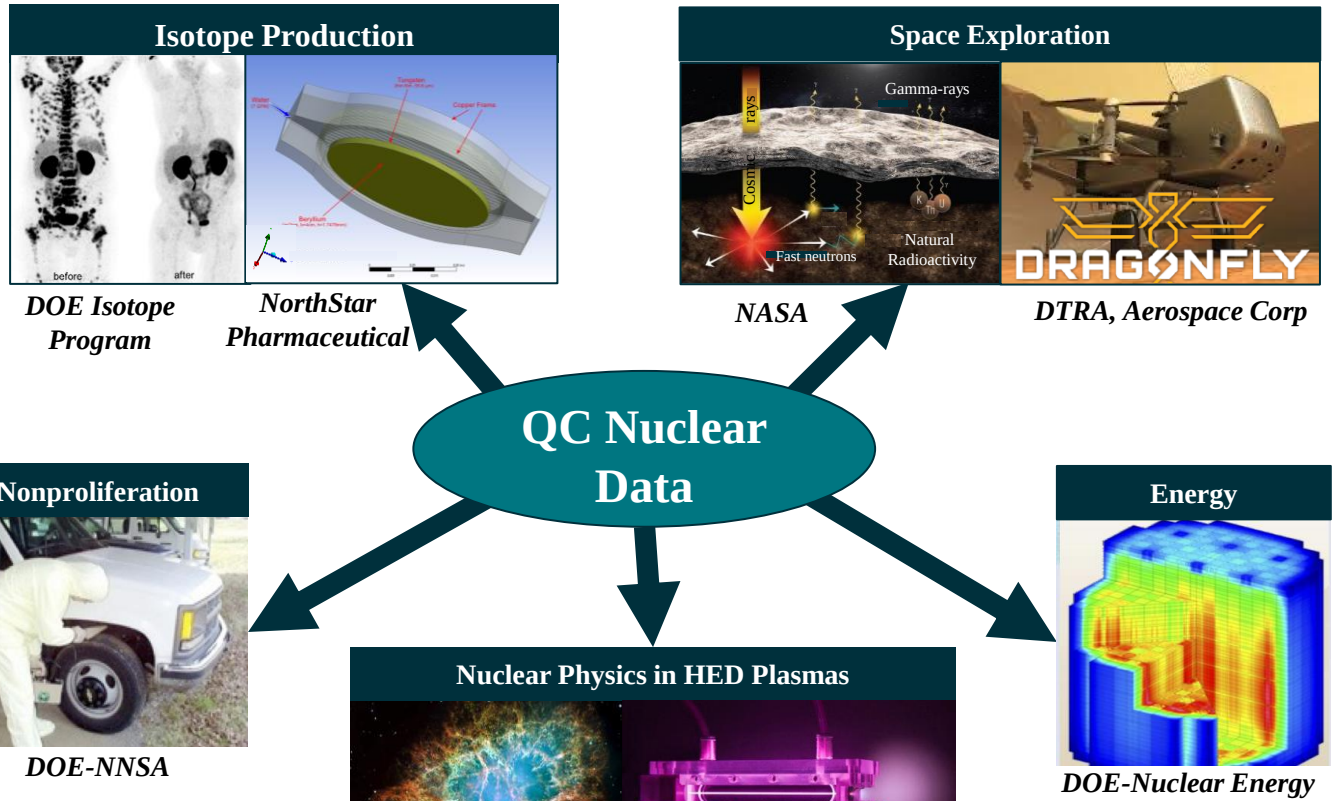
Filling in the Nuclear Data Gaps

Berkeley Lab researcher tackling common questions that cut across the field of nuclear science

Feature Story Glenn Roberts Jr. 510-486-5582 • DECEMBER 21, 2016

Measurements at the 88-Inch Cyclotron (2016+)

Nuclear data for applications at LBNL/UCB



DOE Isotope Program

NorthStar Pharmaceutical

NASA

DTRA, Aerospace Corp

DOE-NNSA

DOE-Nuclear Energy

DOE Nuclear Physics

DARPA

Google Project X

Nuclear Data Program

Current Funding sources

- DoE Nuclear Data Program
- DoE Isotope Program
- DoE Nuclear Energy
- NIF-STARFIRE
- SSAA
- Nuclear Technology Innovation Laboratory
- Berkeley Atlas
- Nuclear Data Interagency Working Group
  - NA-22 and USNDP
- DARPA
- MIND
  - NA-241 and USNDP
- North Star
- Google Project X

Where we do our measurements

Traineeship funded by US Nuclear Data Program

- Funding (over 4 years)
- 50% for post-doc and 25% Research Engineer

- Goals:
  - Ensure a comprehensive development of two emerging researchers, fostering a robust foundation for future contributions to nuclear data evaluation and management.

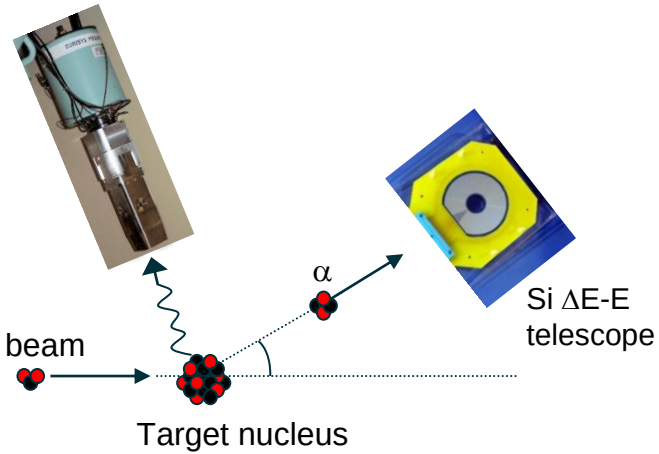
Measuring the NLD and PSF

Primaries from charged particle reactions (<S_n)

- Oslo, beta-Oslo, inverse Oslo Methods
- Shape Method

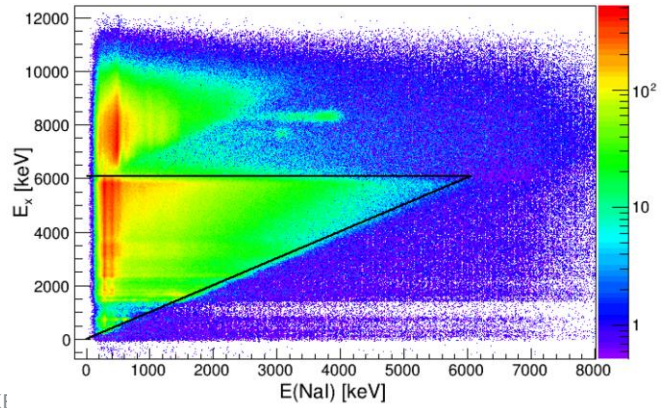
$$\rho'(E_x - E_\gamma) = Ae^{\tilde{\alpha}(E_x - E_\gamma)}\rho(E_x - E_\gamma)$$

$$T'(E_\gamma) = Be^{\tilde{\alpha}(E_\gamma)}T(E_\gamma),$$



A and B are constants and α is a common slope parameter.

The transformation parameters, A and B correspond to physical solutions and are deduced from external experimental data to get the solution.

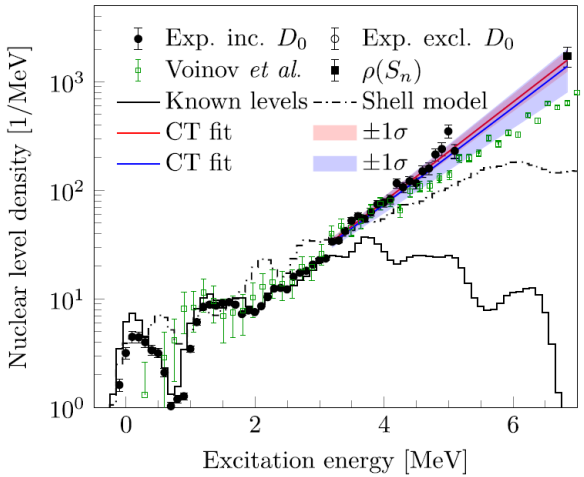


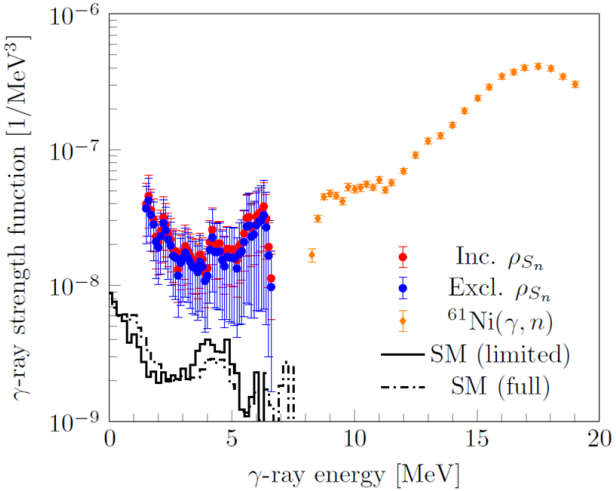
Oslo method: Normalization

- 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

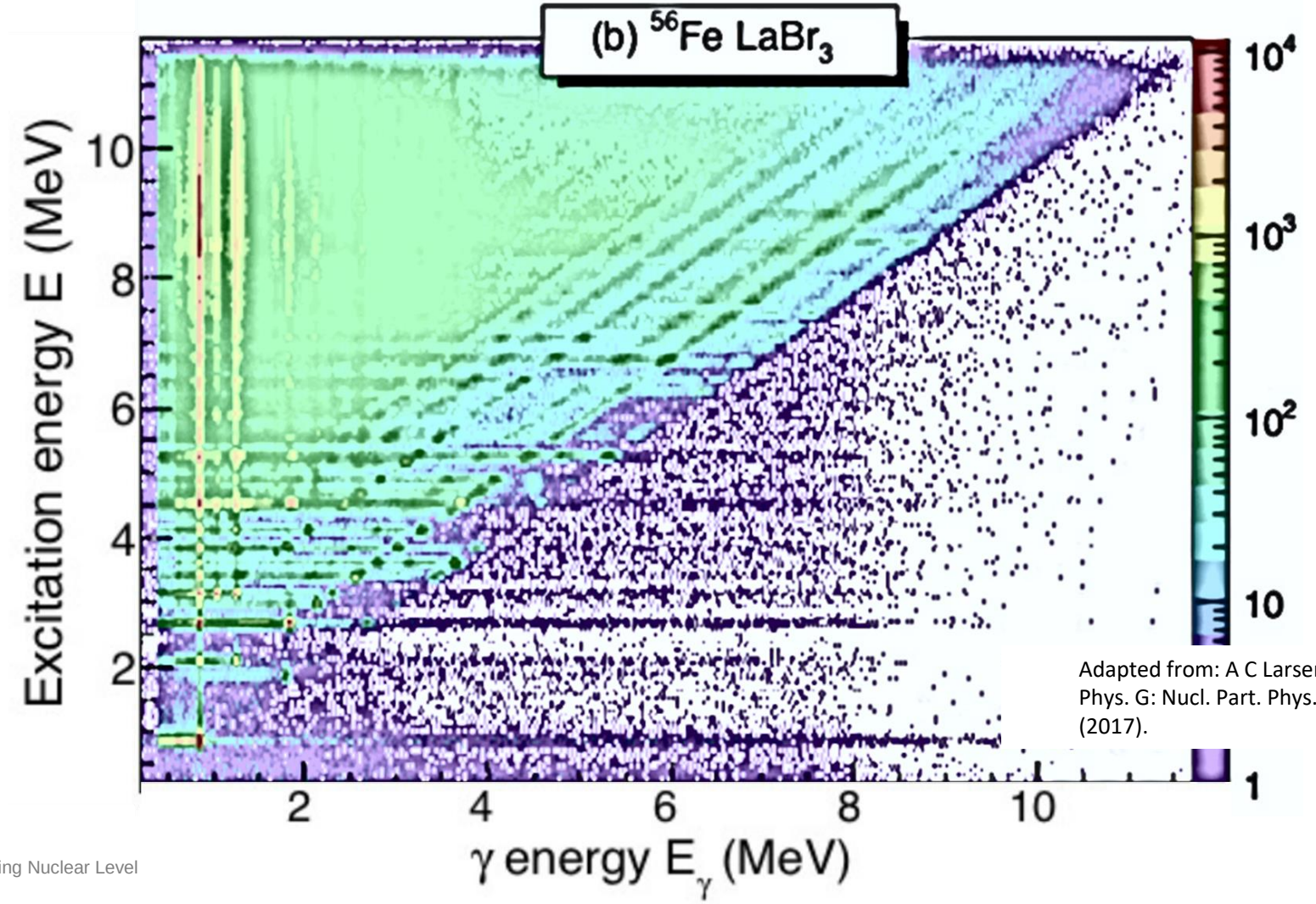
M. Wiedeking,[1,2,*] M. Guttormsen,[3] A. C. Larsen,[3] F. Zeiser,[3] A. Görgen,[3] S. N. Liddick,[4,5] D. Mücher,[6,7] S. Siem,[3] and A. Spyrou[4,8]

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

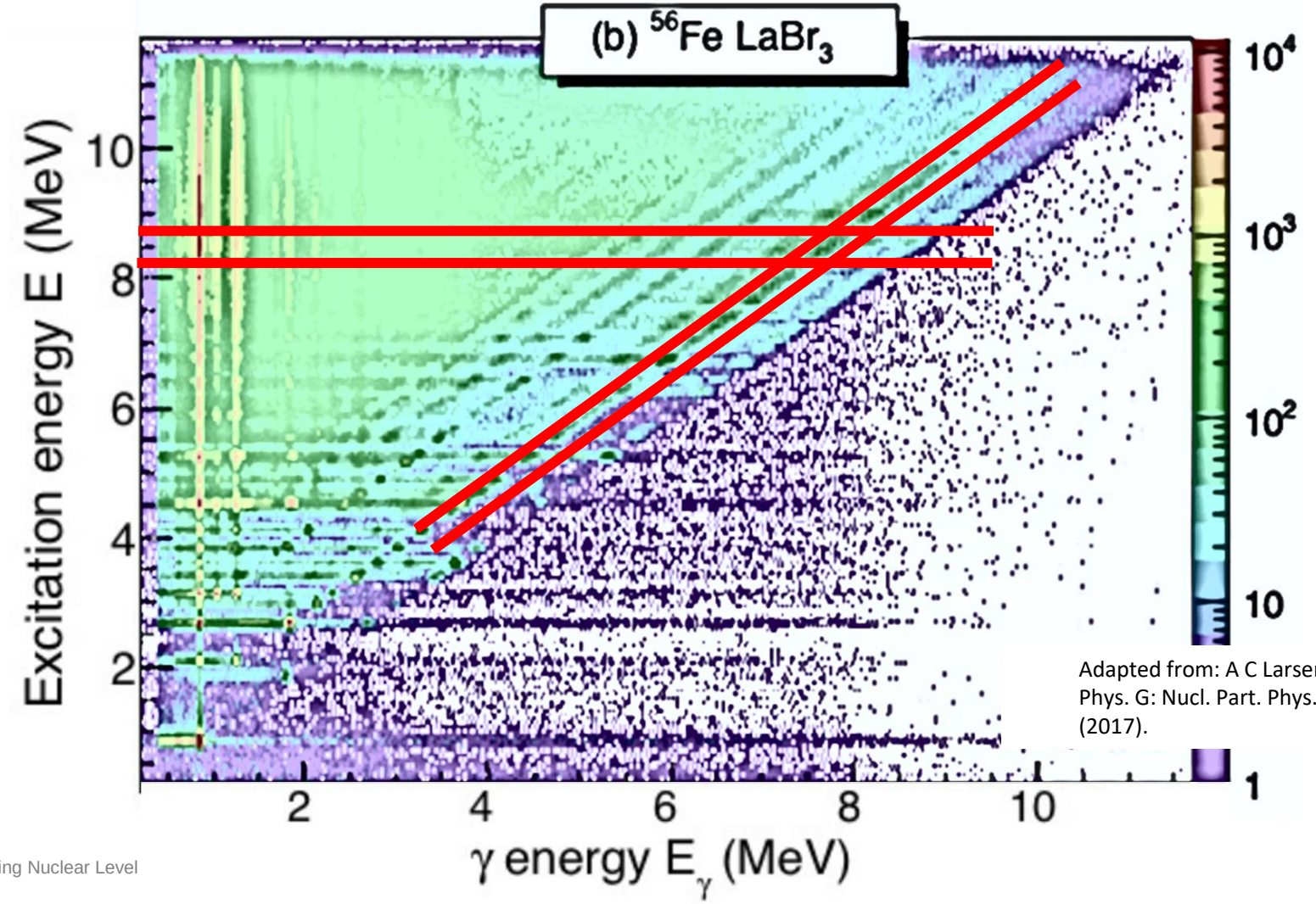
Letter

Extracting model-independent nuclear level densities away from stability

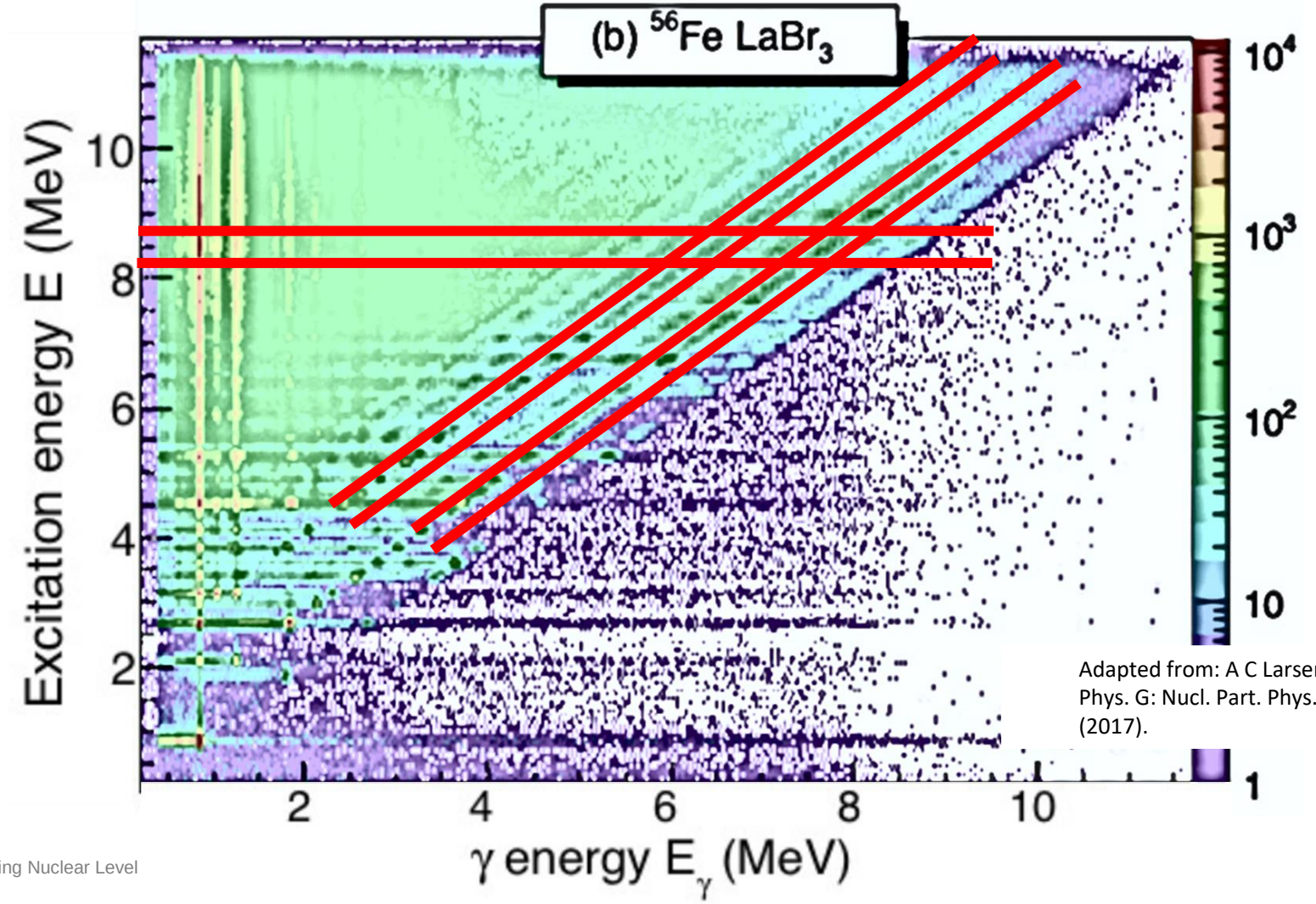
D. Mücher,[1,2,3,*] A. Spyrou,[4,5,6,†] M. Wiedeking,[7,8] M. Guttormsen,[9] A. C. Larsen,[9] F. Zeiser,[9] C. Harris,[10,5] A. L. Richard,[10,6] M. K. Smith,[10] A. Görgen,[9] S. N. Liddick,[10,11] S. Siem,[9] H. C. Berg,[10,5] J. A. Clark,[12] P. A. DeYoung,[13] A. C. Dombos,[14] B. Greaves,[1] L. 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).



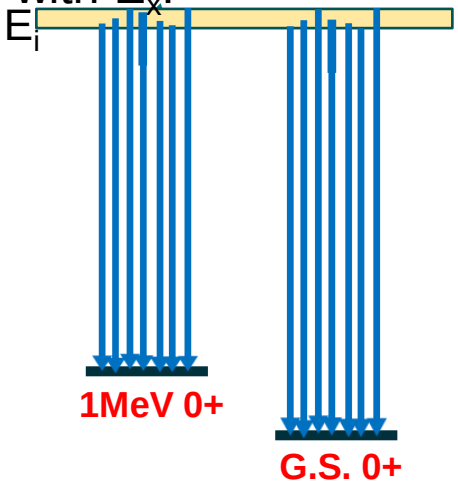
Adapted from: A C Larsen et al., J. Phys. G: Nucl. Part. Phys. 44, 064005 (2017).

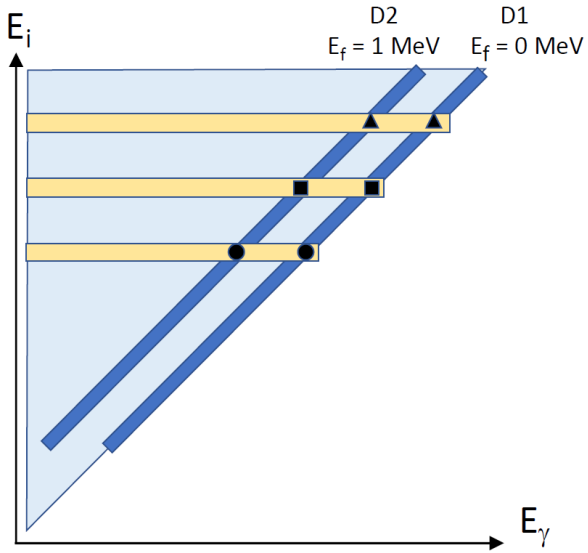


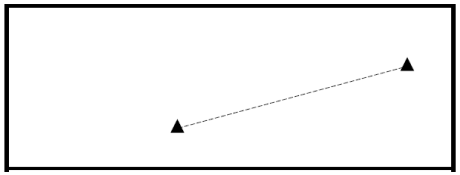
Adapted from: A C Larsen et al., J. Phys. G: Nucl. Part. Phys. 44, 064005 (2017).

Shape Method

Primaries from intercepts of diagonals with E_x.



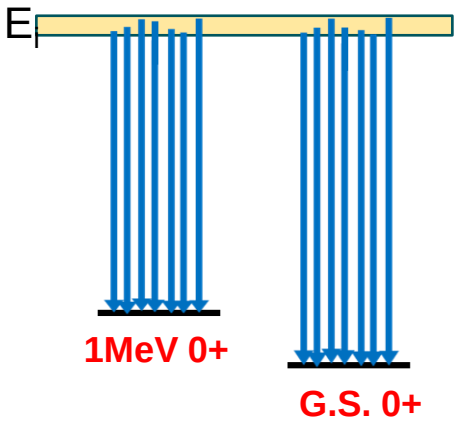


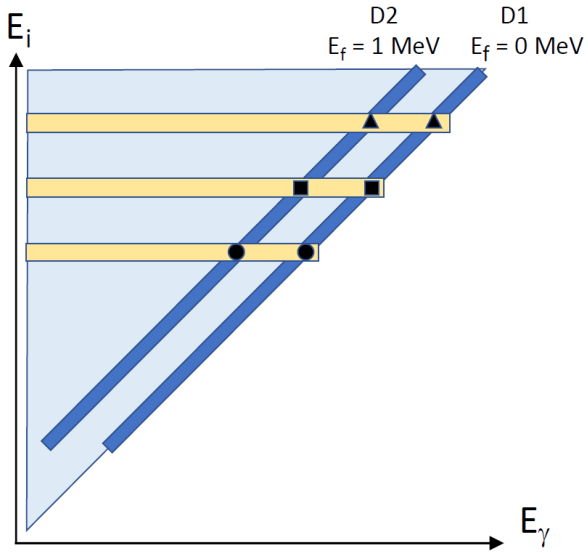


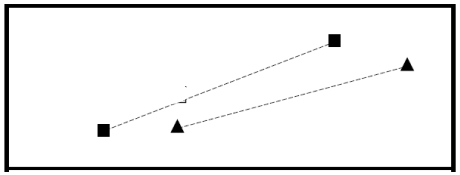
Pair of data points internally normalized and proportional to PSF.

Shape Method

Primaries from intercepts of diagonals with E_x.



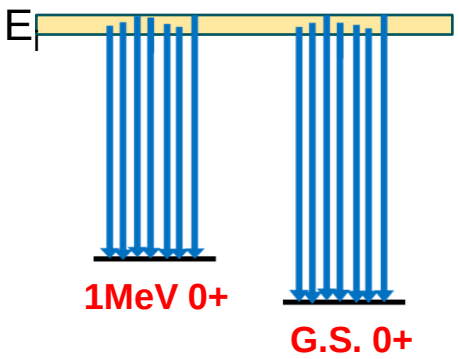


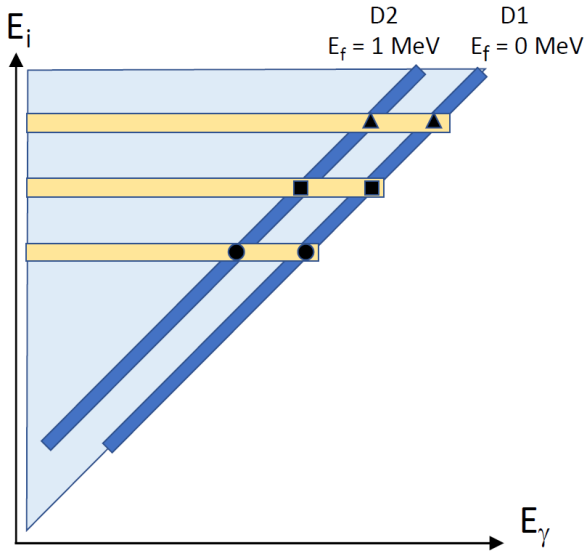


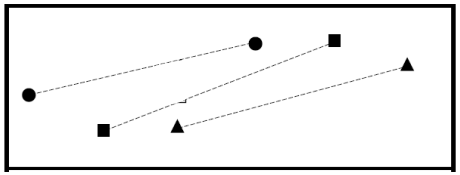
Pair of data points internally normalized and proportional to PSF.

Shape Method

Primaries from intercepts of diagonals with E_x.

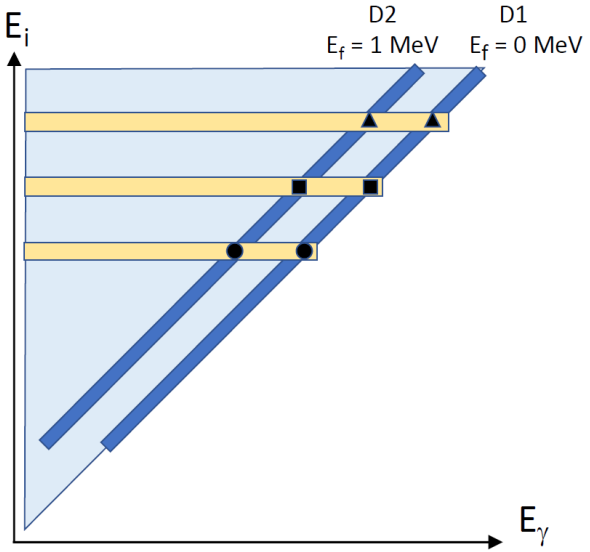




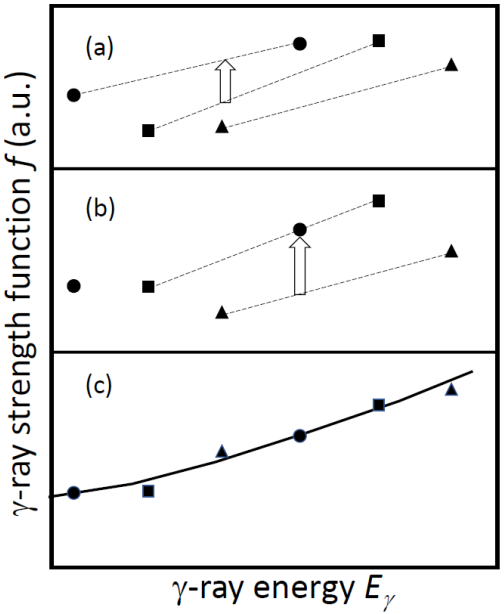


Pair of data points internally normalized and proportional to PSF.

Shape and Sewing Method

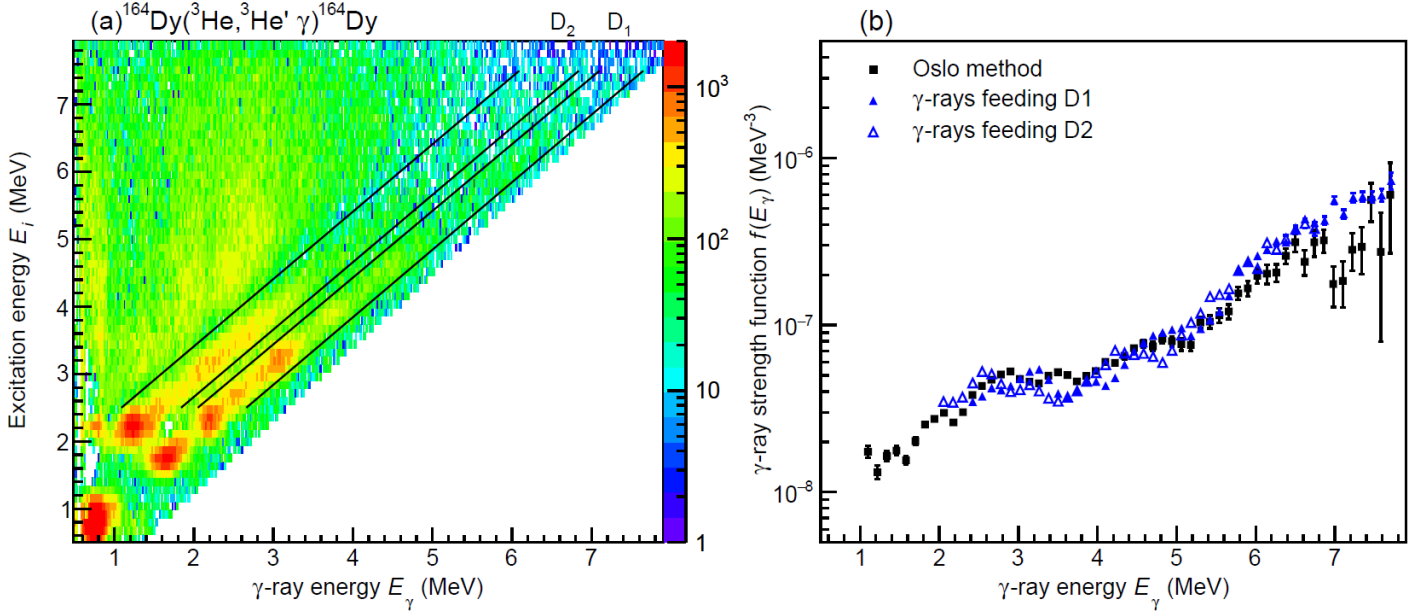


- Primary gamma-rays from intercepts of diagonals with E_x gate.



- 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

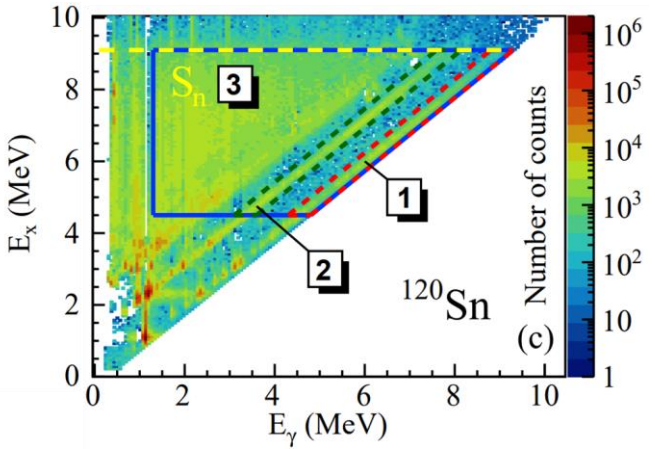


$D_1 = 0^+, 2^+, 4^+, 6^+, 0 – 0.5$ MeV

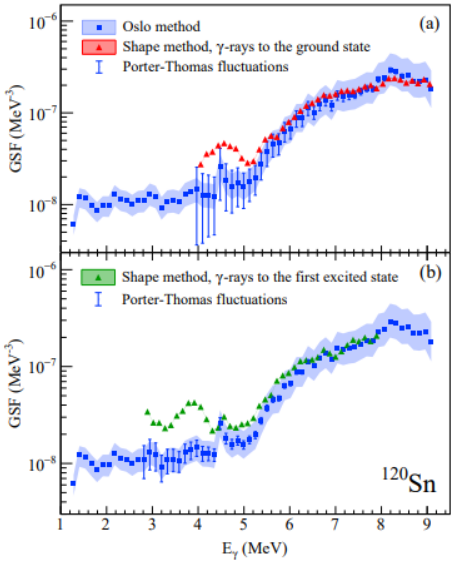
$D_2 = 14$ levels 0.76 – 1.39 MeV

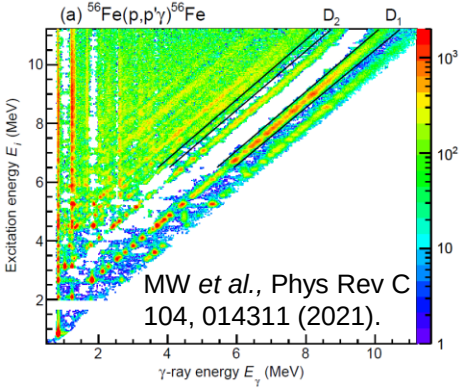
MW, Guttormsen, Larsen *et al.*, Phys. Rev. C 104 014311 (2021).

Limitations of the Shape Method

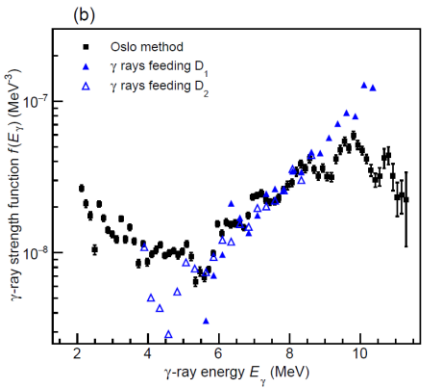


M. Markova et al., Phys. Rev. C 106, 034322 (2022).





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



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 of Oslo (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).

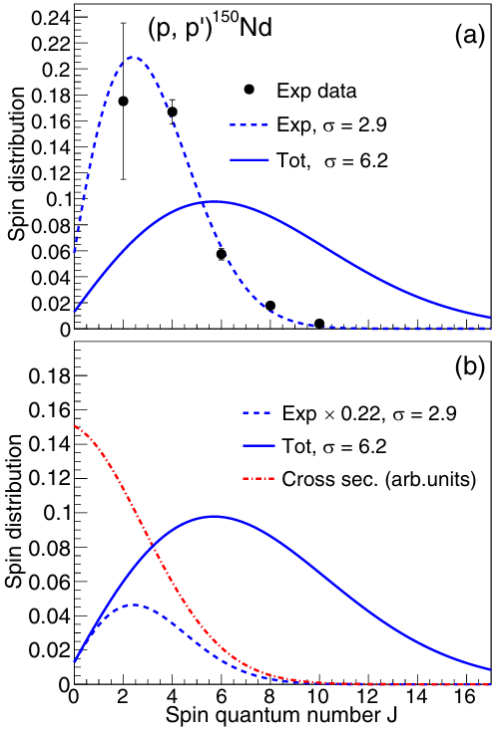
^{63}Ni: Nkalanga, ongoing, PhD, University of Johannesburg (2025)

^{140}Ba: Spyrou et al. Phys. Rev. Lett. 132, 202701 (2024).

^{58}Fe: Abbott et al., Phys. Rev. C 111, 034322 (2025).

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.



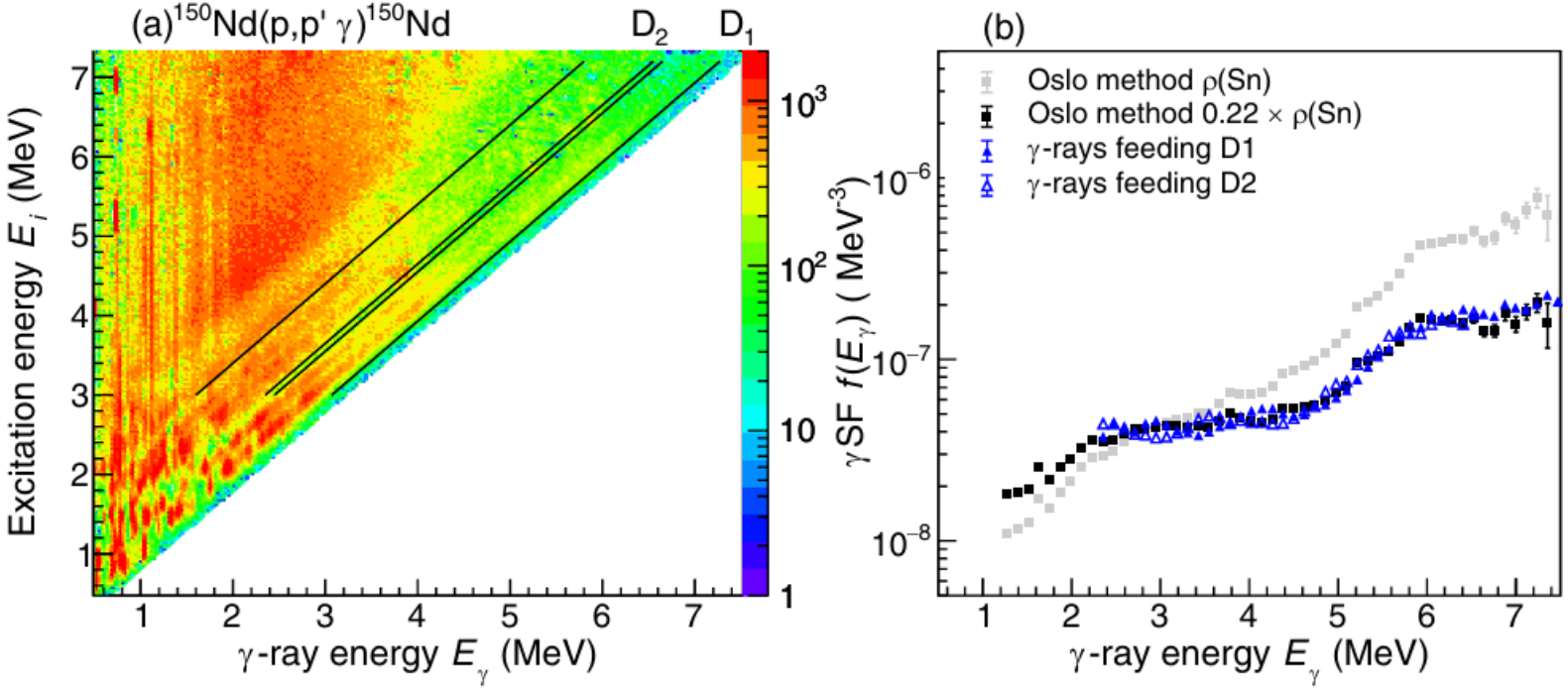
Side feeding analysis into rotational gs band up to 10^+ state

NLD reduction factor for (p,p')

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

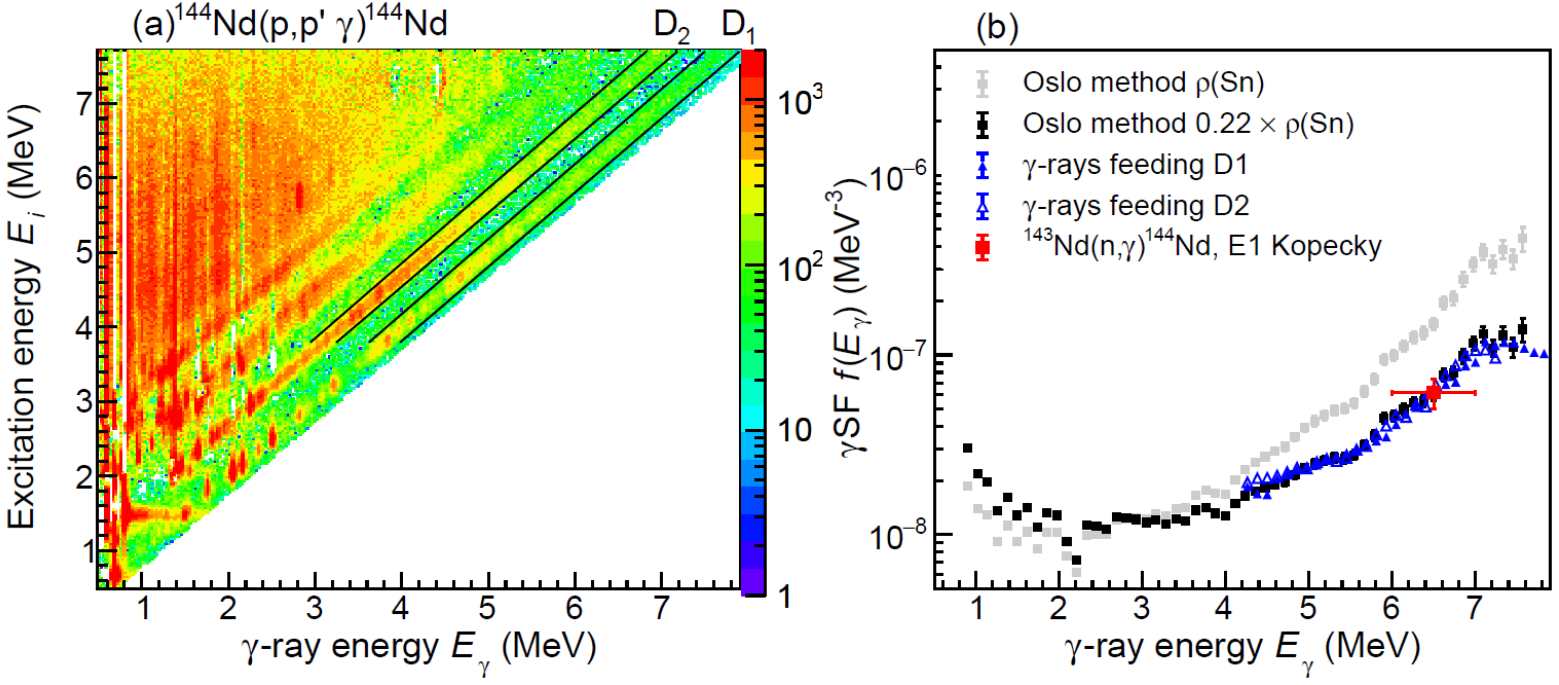
Guttormsen, Ay, Ozgur et al., Phys. Rev. C 106, 034314 (2022).

Shape Method: ^{150}Nd



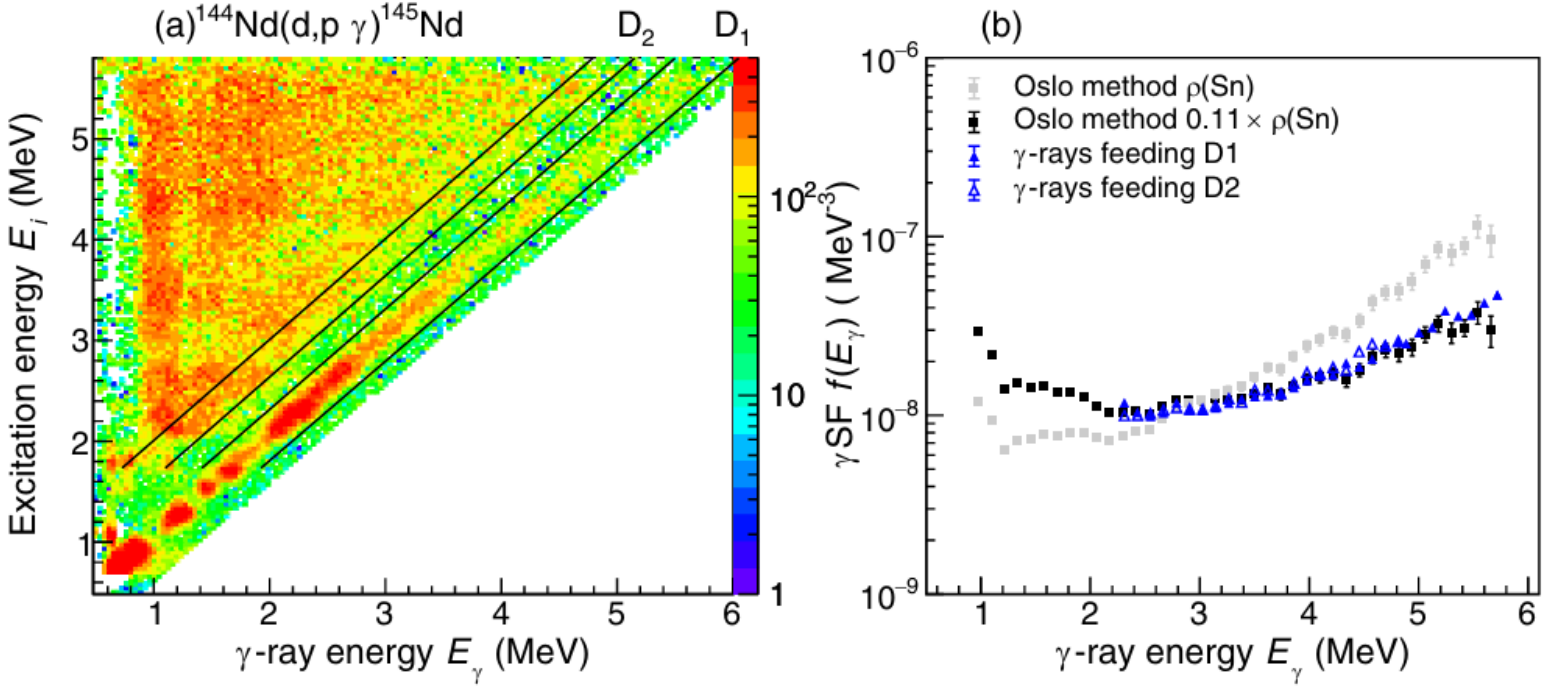
Guttormsen, Ay, Ozgur et al., Phys. Rev. C 106, 034314 (2022).

Shape Method: ^{144}Nd



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

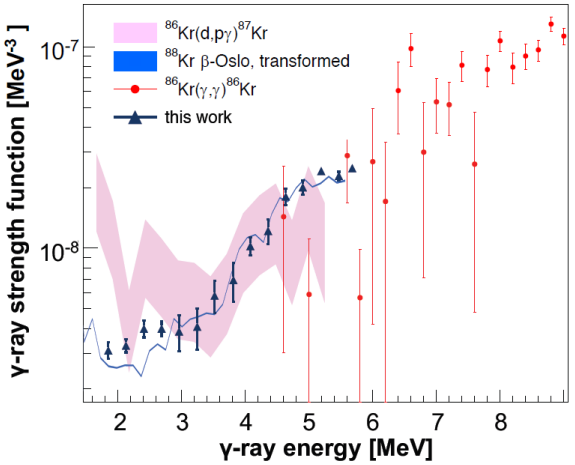
Shape Method: ^{145}Nd

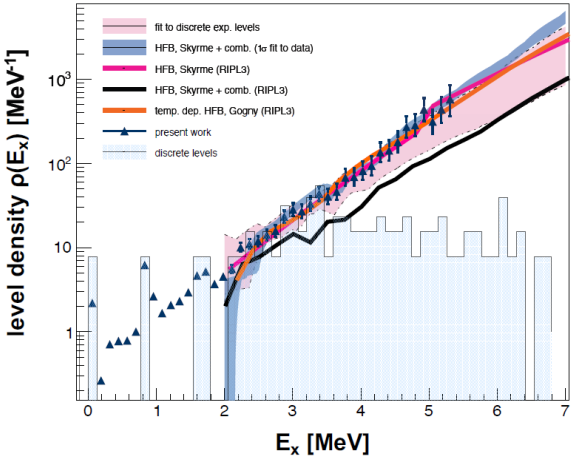


NLD reduction factor for (d,p') = 0.11(2)

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

Shape Method: PSF and NLD away from stability





$$\rho'(E_x - E_\gamma) = Ae^{\tilde{\alpha}(E_x - E_\gamma)}\rho(E_x - E_\gamma)$$
$$T'(E_\gamma) = Be^{\tilde{\alpha}(E_\gamma)}T(E_\gamma),$$

^{88}Kr

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

Letter

Extracting model-independent nuclear level densities away from stability

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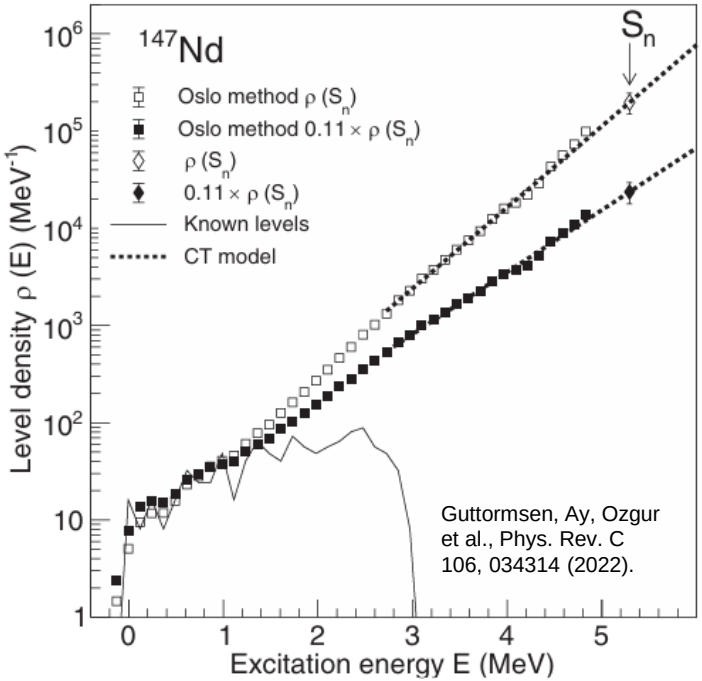
Reduction factor and NLD



NLD reduction factor for (d,p') = 0.11(2)

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

Evolution of the γ-ray strength function in neodymium isotopes

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

PHYSICAL REVIEW C **93**, 014323 (2016)

Statistical properties of ^{243}Pu, and ^{242}Pu(n,γ) cross section calculation

T. A. Laplace, F. Zeiser, M. Guttormsen, A. C. Larsen, D. L. Bleuel, L. A. Bernstein, B. L. Goldblum, S. Siem, F. L. Bello Garrote, J. A. Brown, L. Crespo Campo, T. K. Eriksen, F. Giacoppo, A. Görgen, K. Hadyńska-Klęk, .. A. Henderson, M. Klintefjord, M. Lebois, T. Renstrøm, S. J. Rose, E. Sahin, T. G. Tornyi, G. M. Tveten, A. Voinov, M. Wiedeking, J. N. Wilson, and W. Younes

PHYSICAL REVIEW C **100**, 024305 (2019)

Restricted spin-range correction in the Oslo method: The example of nuclear level density and γ-ray strength function from ^{239}Pu($d,p\gamma$)^{240}Pu

F. Zeiser, G. M. Tveten, G. Potel, A. C. Larsen, M. Guttormsen, T. A. Laplace, S. Siem, D. L. Bleuel, B. L. Goldblum, L. A. Bernstein, F. L. Bello Garrote, L. Crespo Campo, T. K. Eriksen, A. Görgen, K. Hadynska-Klek, V. W. Ingeberg, J. E. Midtbø, E. Sahin, T. Tornyi, A. Voinov, M. Wiedeking, and J. Wilson

What are the implications of published data (most) that have not investigated the reduction factors?

LBNL/UCB: NLD database actions year 1

Collection of experimental NLD:

- In coordination with other experimental CRP participants.
- This will be accomplished by sourcing publications and extracting data from tables.
- If not possible the author(s) will be contacted to request data.
- If unsuccessful digitize data from figures.

Assess collected data:

- Assessment of data on the basis of agreed constraints during the CRP meeting.

Assignment of quality indicators

- Full uncertainty budget, full model uncertainties, normalization, other constraints e.g. Shape Method, etc

Data and readme files:

- The data files will be accompanied by readme files which
- include pertinent experimental and analytical information.
- In format agreed on by CRP.

Submit compilation of experimental NLD to IAEA

- By ???

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Office of Science

Thank you!

Mathis Wiedeking
Nuclear Science Division
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http://nucleardata.berkeley.edu

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