Level Densities and γ-ray Strength Functions: The case for some TLC

Jutta E. Escher
Nuclear Data & Theory Group
Lawrence Livermore National Laboratory

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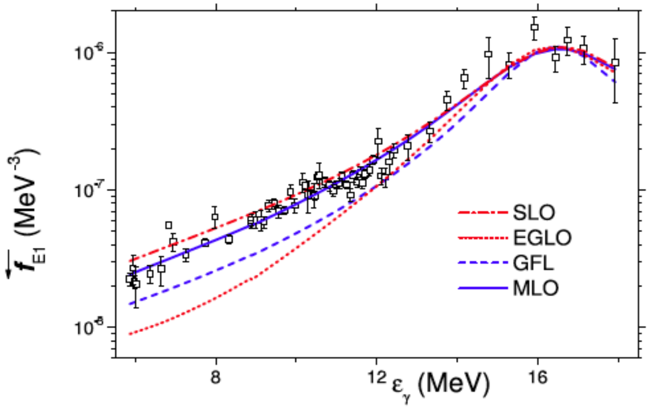
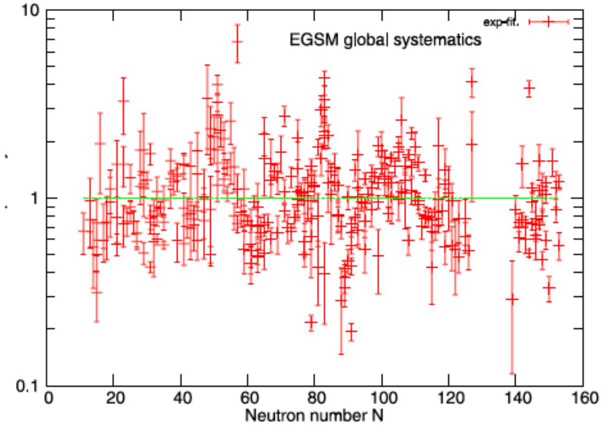
Applications do not use level densities and gamma strength functions! Evaluators do!

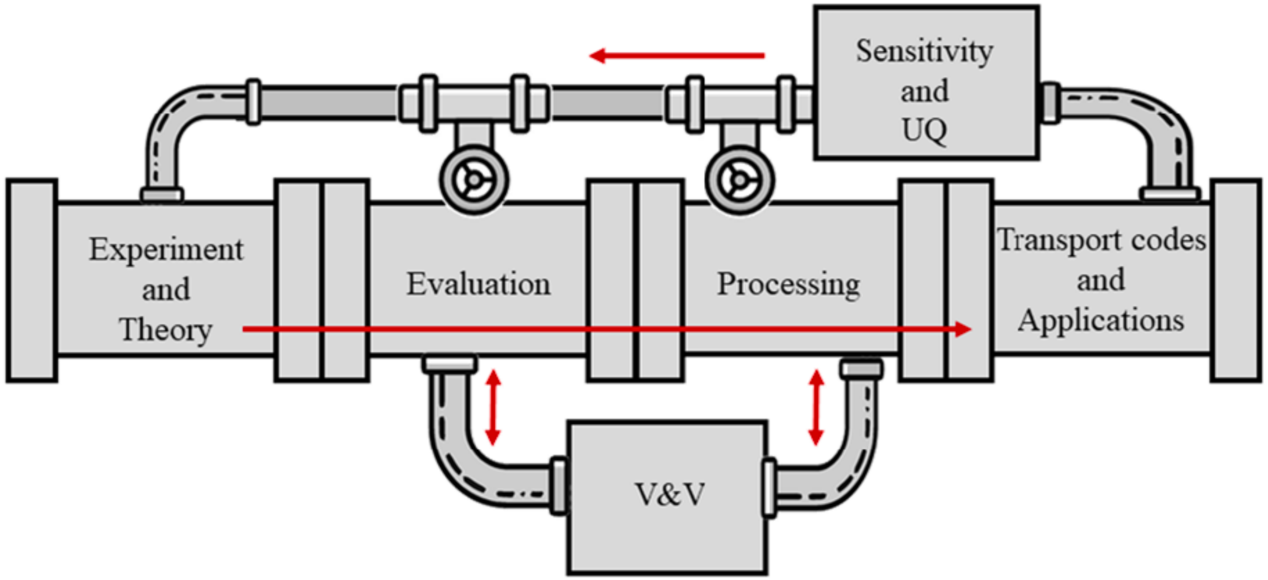
Data + Phenomenological E1 γSF

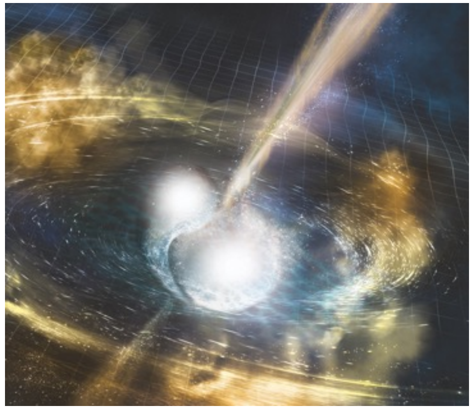


S-wave resonance spacings for LD



Capote *et al*, NDS 110(2009)3107

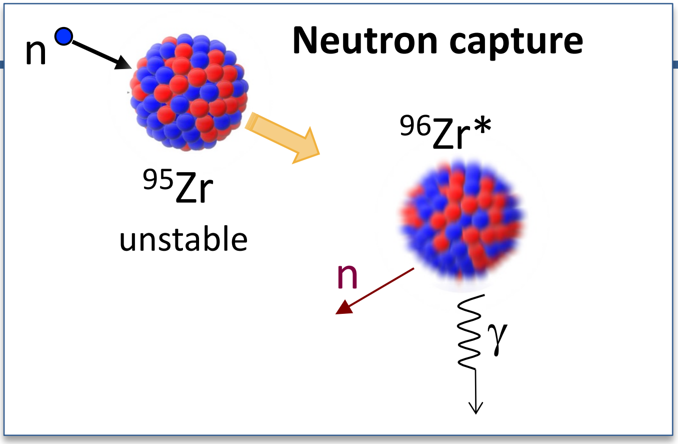


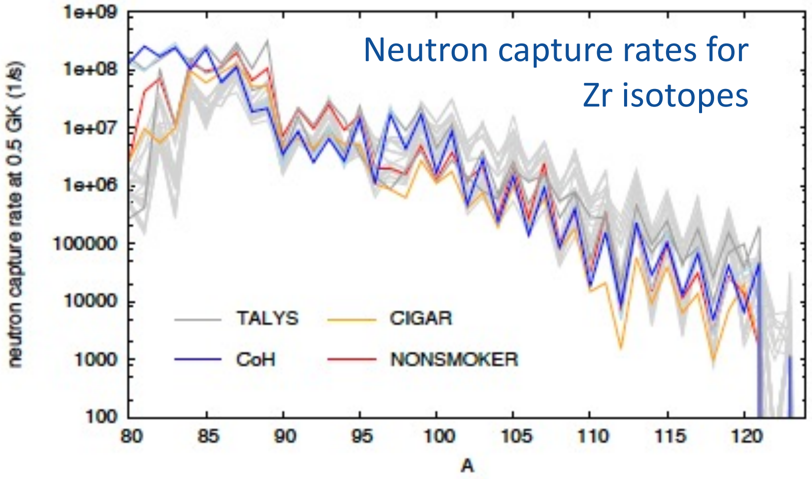


Evaluators use experimental inputs and theory tools to calculate cross sections and produce evaluations

Providing accurate cross section calculations requires a careful assessment of the level densities and gamma strength functions inputs

- Neutron capture is the prime example: (n,γ) cross sections are important for astrophysics, stockpile stewardship, nuclear energy, etc.
- Hauser-Feshbach calculations rely on optical model, LD, γSF inputs
- Optical model near stability is well-studied; new UQ-versions of popular models exist now (Pruitt et al, PRC 107, 014602), microscopic versions under development
- Cross sections are highly-sensitive to LD and γSF, become unreliable without constraints

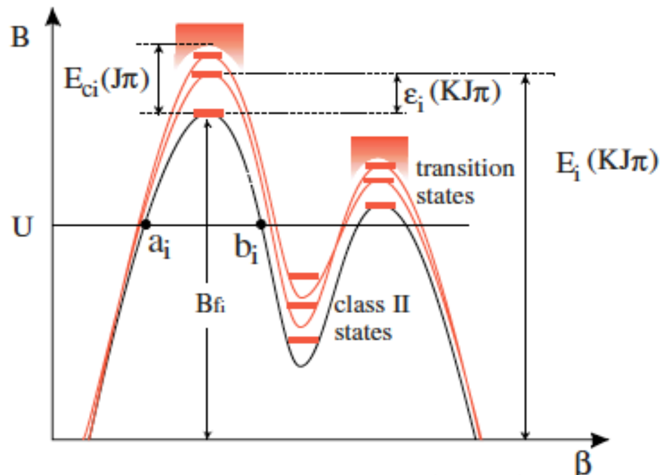




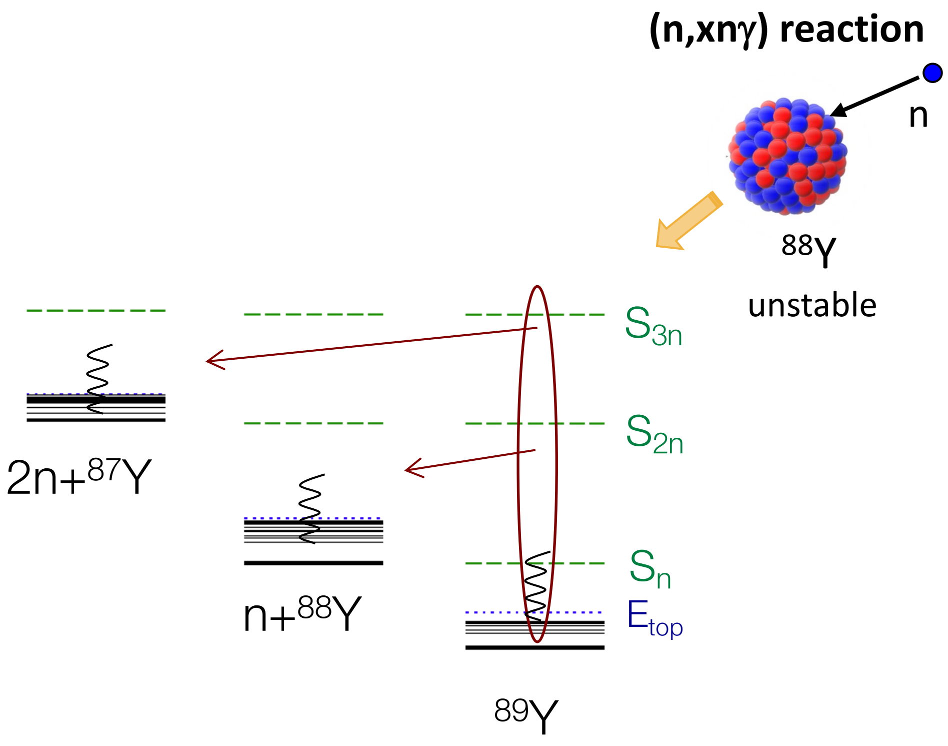
Nikas *et al*, arXiv:2010.01698

Providing accurate cross section calculations requires a careful assessment of the level densities and gamma strength functions inputs

- Many applications require cross sections for (n,n') and (n,2n) or γ-production (n,n'γ) and (n,2nγ)
- Calculation require LDs and γSF for multiple isotopes
- Calculations of (n,f) cross sections bring additional challenges: LDs for fission barriers



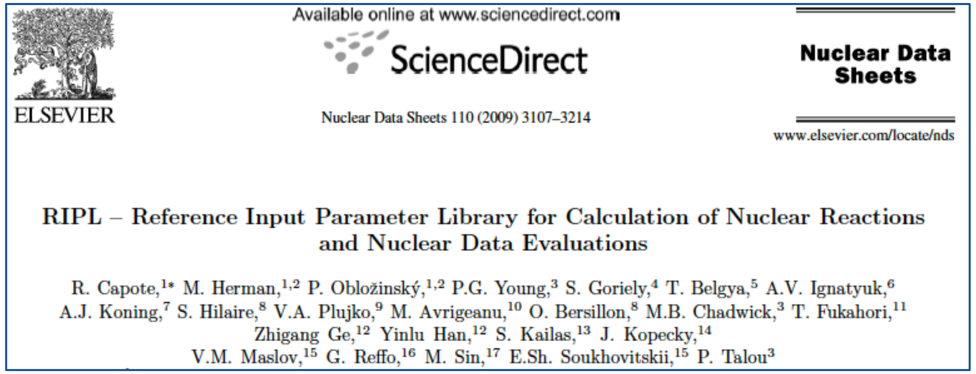
Capote *et al*, NDS 110 (2009) 3107



Evaluators make use of compilations, databases, direct and indirect constraints

- Starting points are RIPL-3 and other 'prior knowledge'
- Adjustments are made to reproduce observables - cross sections, auxiliary quantities
- Useful constraints:
  - low-E number of levels
  - Resonance spacing D_0
  - Radiative width $<\Gamma_\gamma>$
  - Measurements of D_0 and $<\Gamma_\gamma>$ for stable isotopes only!

Provide strong constraints for (n,γ) cross sections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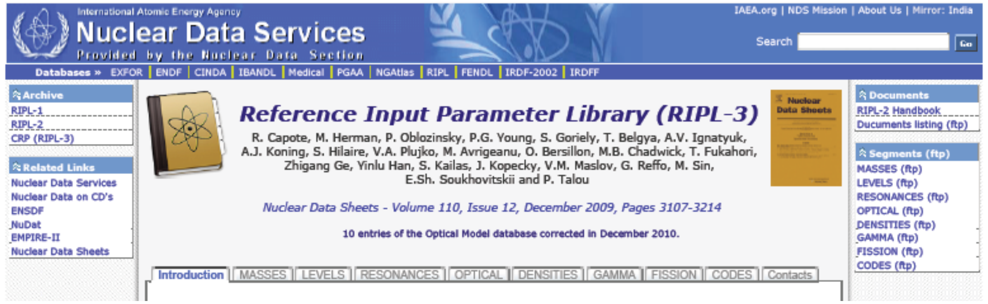
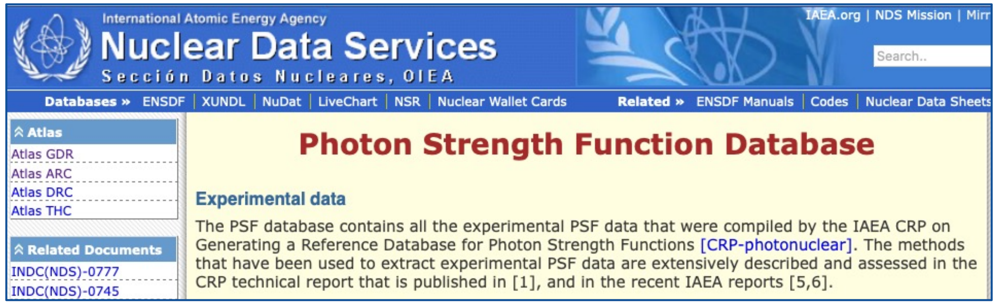
RIPL – Reference Input Parameter Library for Calculation of Nuclear Reactions and Nuclear Data Evaluations

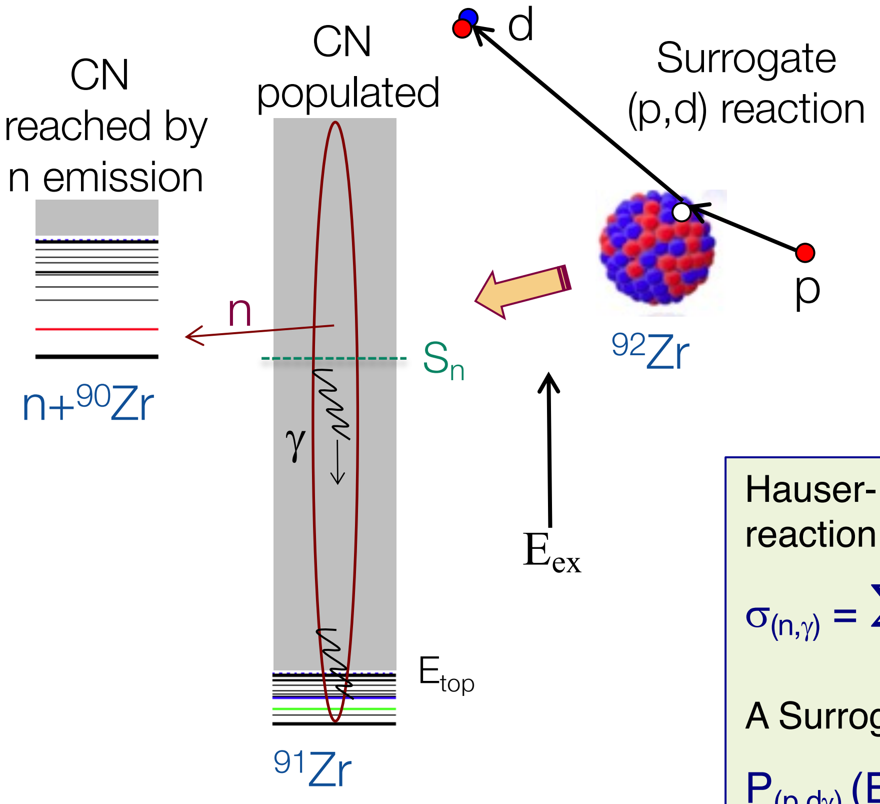
R. Capote,[1*] M. Herman,[1,2] P. Obložinský,[1,2] P.G. Young,[3] S. Goriely,[4] T. Belgya,[5] A.V. Ignatyuk,[6] A.J. Koning,[7] S. Hilaire,[8] V.A. Plujko,[9] M. Avrigeanu,[10] O. Bersillon,[8] M.B. Chadwick,[3] T. Fukahori,[11] Zhigang Ge,[12] Yinlu Han,[12] S. Kailas,[13] J. Kopecky,[14] V.M. Maslov,[15] G. Reffo,[16] M. Sin,[17] E.Sh. Soukhovitskii,[15] P. Talou[3]

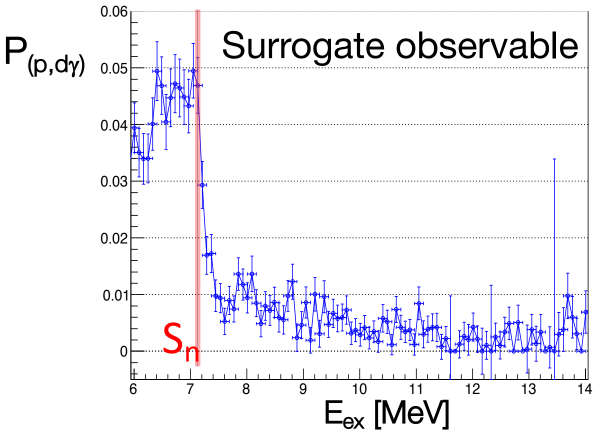


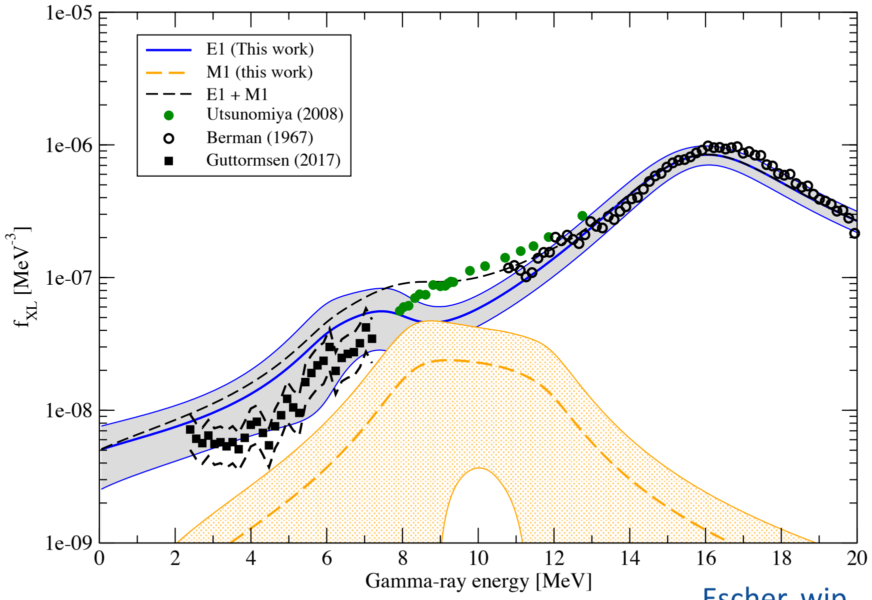


Evaluators make use of compilations, databases, direct and indirect constraints

Surrogate reaction measurements can be used when no direct constraints are available - gives (n,γ) cross section + LDs and γSF







Escher, wip

Hauser-Feshbach description of "desired" CN reaction

$$\sigma_{(n,\gamma)} = \sum_{J,\pi} \sigma_{n+target}^{CN}(E,J,\pi) \cdot G^{CN}_{\gamma}(E,J,\pi)$$

A Surrogate experiment gives

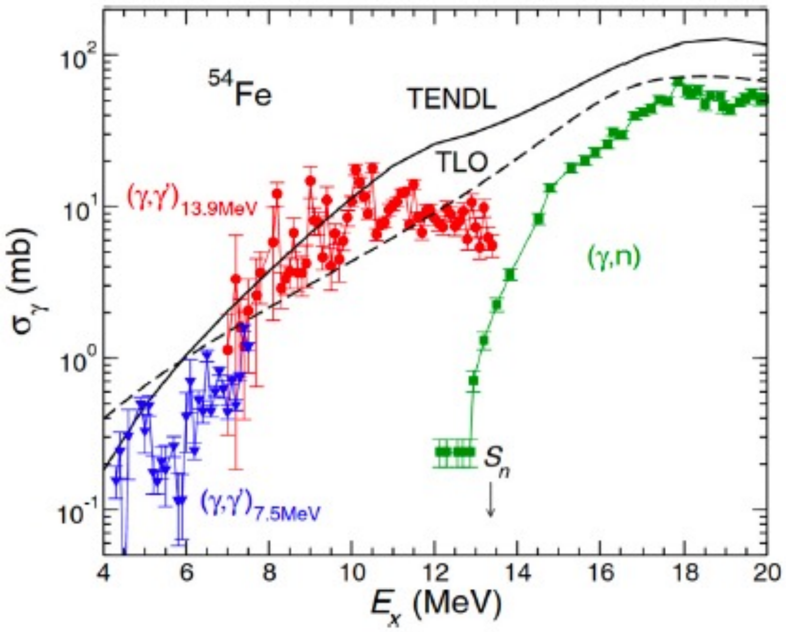
$$P_{(p,d\gamma)}(E) = \sum_{J,\pi} F_{(p,d)}^{CN}(E,J,\pi) \cdot G^{CN}_{\gamma}(E,J,\pi)$$

For cross section, see Escher *et al*, PRL 121 (2018) 052501

Concept: Escher *et al*, RMP 84 (2012) 353; EPJConf 122 (2016) 12001

Getting sufficient experimental constraints for all isotopes is a daunting task

- Measuring D_0 and $<\Gamma_\gamma>$ requires stable targets
- Convolution of LDs and γSF causes ambiguities when extracting components
- Partial level densities are often needed or measured
- Brink-Axel hypothesis is liberally used
- Conflicting results from different methods
- Too many nuclei to measure them all!



Zilges *et al*, PPNP 122 (2022) 103903

We need a deeper understanding of the underlying nuclear structure (and keep the reaction calculations in mind)

γSF

- Microscopic explanation of γSF features?
- Dependence on deformation, mass, N?
- Limits of Brink-Axel assumption(s)?

LD

- Correlations in LDs? Impact of deformation?
- Spin-dependence?
- Non-equal parities?

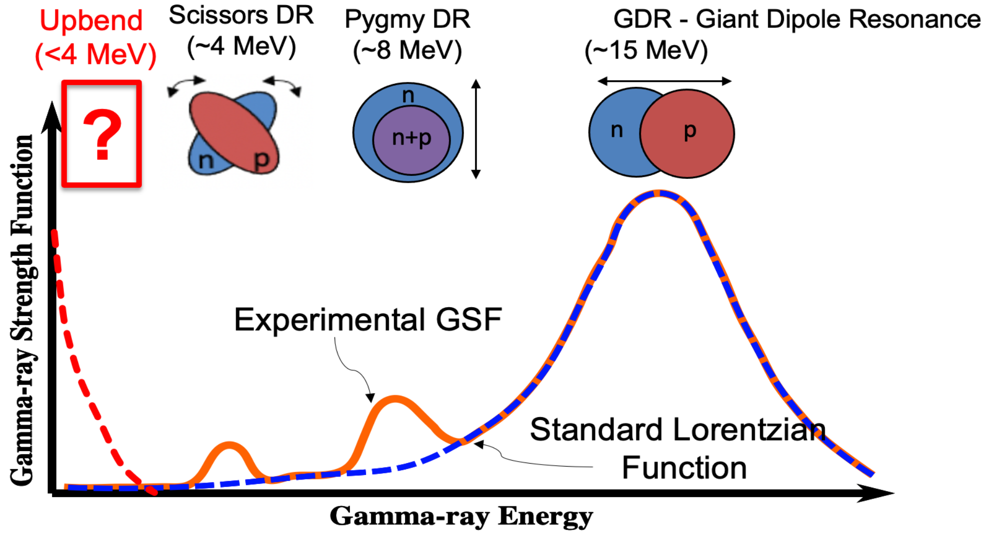
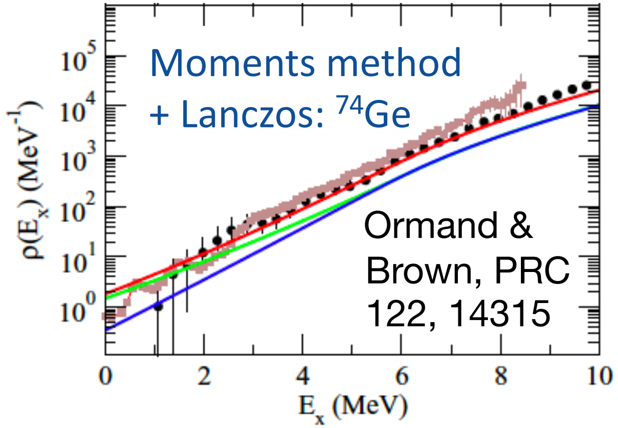


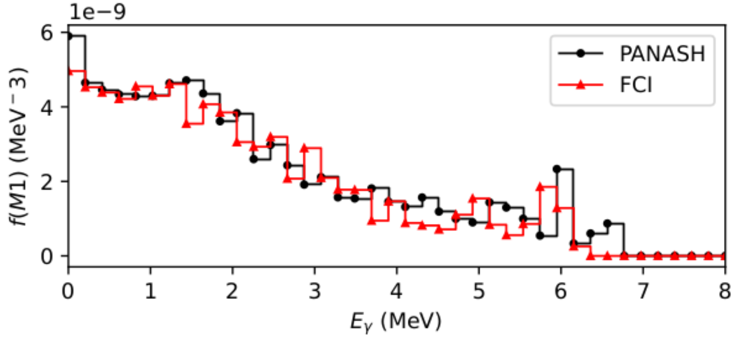
Figure courtesy A. Ramirez

Advances in nuclear theory enable us to tackle these challenges

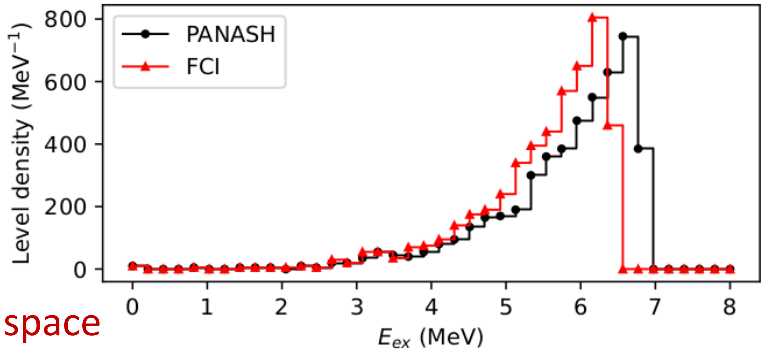
- The shell model provides a microscopic predictions for LDs and γSFs
- Smart truncations and modern computers increase reach of shell model
- Innovative combination of moments method with Lanczos algorithm enable new LD calculations
- Shell-model advantages:
  - Includes important correlations
  - Yields total and partial level densities
  - Gives low-energy γSF
  - Provides insights into structure
- Challenges:
  - Model space sizes for very heavy nuclei
  - Interactions needed



Gamma-ray strength function (γSF, M1) well-reproduced in truncated basis: ^{70}Ge

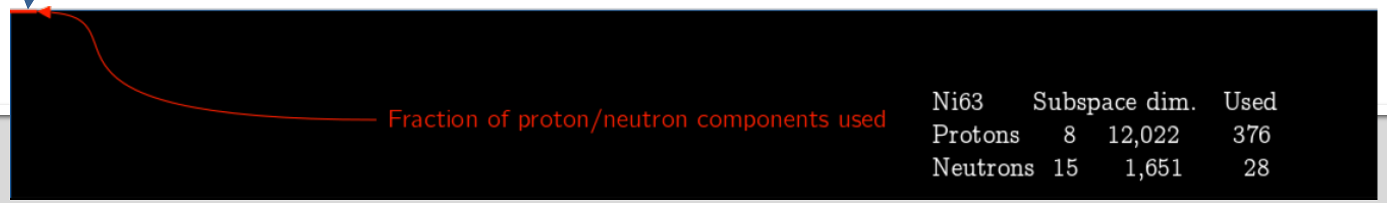


Level density (LD) is approximated in same truncated basis : ^{70}Ge



Smart truncation
to small fraction of FCI model space

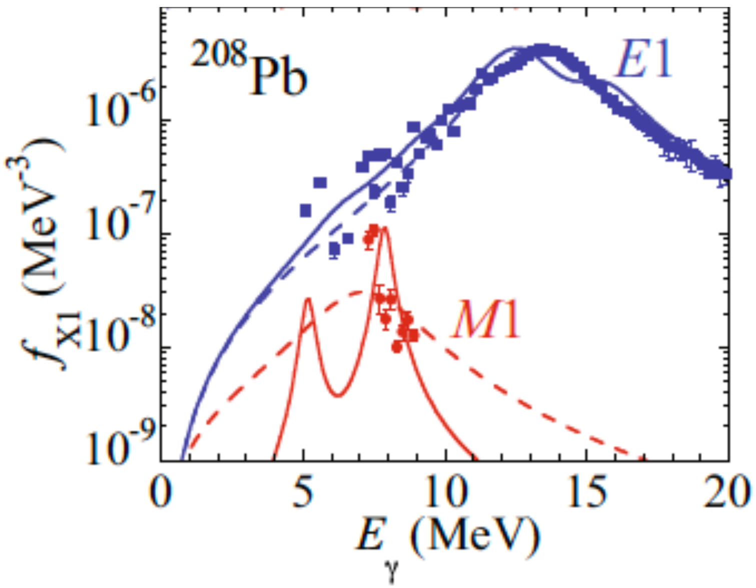
Gorton *et al*, arxiv:2210.05904



Advances in nuclear theory enable us to tackle these challenges

- DFT-based methods complement the shell model
- HFB/QRPA provides microscopic predictions
- Active theory community pushes developments
- Modern computational facilities enable large calculations
- Advantages:
  — Modern implementations cover most of isotopic chart, include deformation
  — Description of structure at low and high excitation energies
  — Provides insights into structure
- Challenges
  — Some correlations are not included (LD)
  — Transitions between excited states (γSF)

QRPA γSF compared to data



Goriely *et al*, EJPA 55 (2019) 172

DFT = Density Functional Theory
HFB = Hartree-Fock Boguliubov
QRPA = Quasiparticle Random-Phase Approximation

Targeted experiments can provide breakthrough insights: Monoenergetic and polarized photons as sensitive probe of structure

High Intensity Gamma-ray (HIGS) Facility

- Photon flux of 1×10^9 γ/s
- 100% linearly polarized photon beam
- Quasi-monoenergetic beam, tunable from 1-120 MeV with fine energy steps
- Highly segmented and efficient γ-ray clover detector array

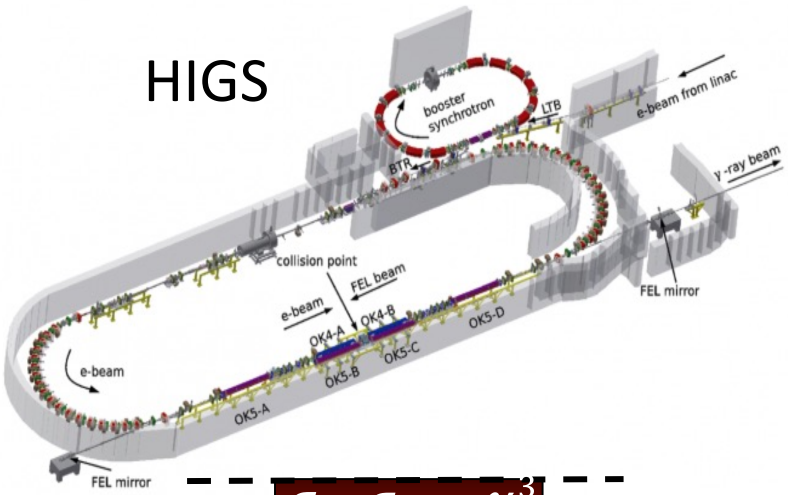
Experimental observables

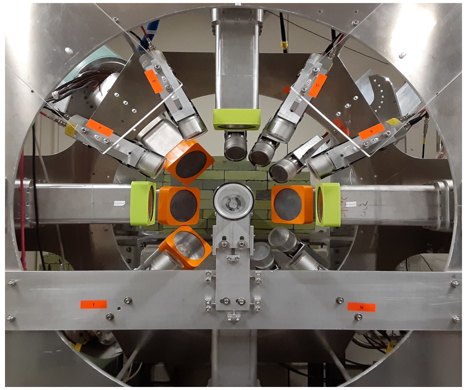
- Photoabsorption cross-section

$$\sigma_{abs} = \sigma_{el} + \sigma_{inel} \propto gSF \uparrow$$

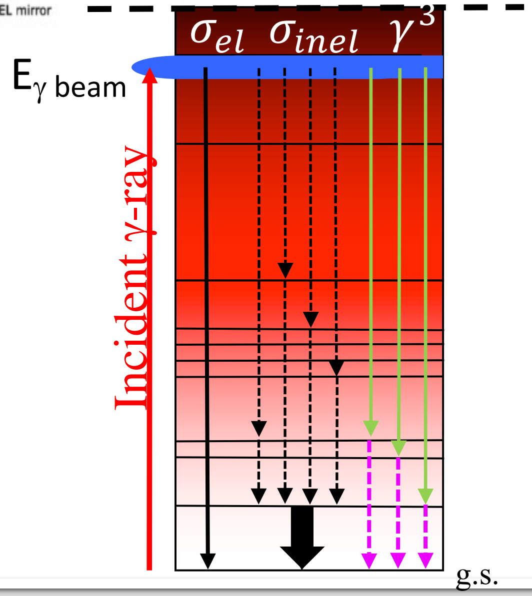
- Number of dipole state $\propto$ dipole LDs
- Ratio method

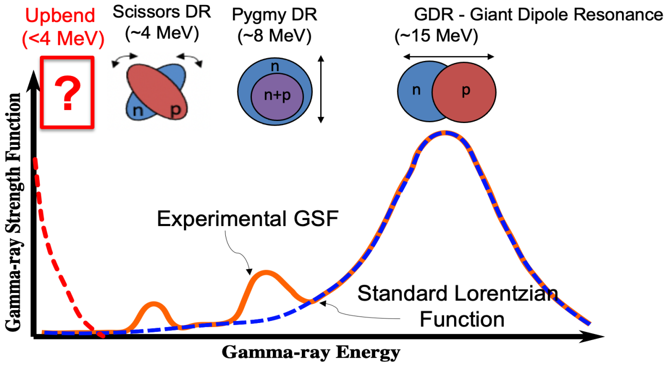
γ^3 or $(\vec{\gamma}, \gamma'\gamma'')$ technique

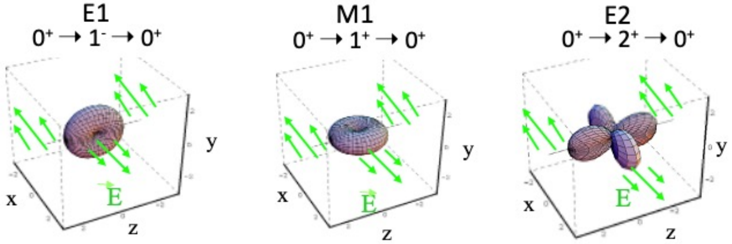




Clover array







Slide courtesy A. Ramirez

Summary
We need some TLC!

Targeted Experiments

- Probe specific properties relevant to resolving existing ambiguities, elucidating underlying structure
- Specify (and reduce number of) assumptions made in analysis

Lots of Theory

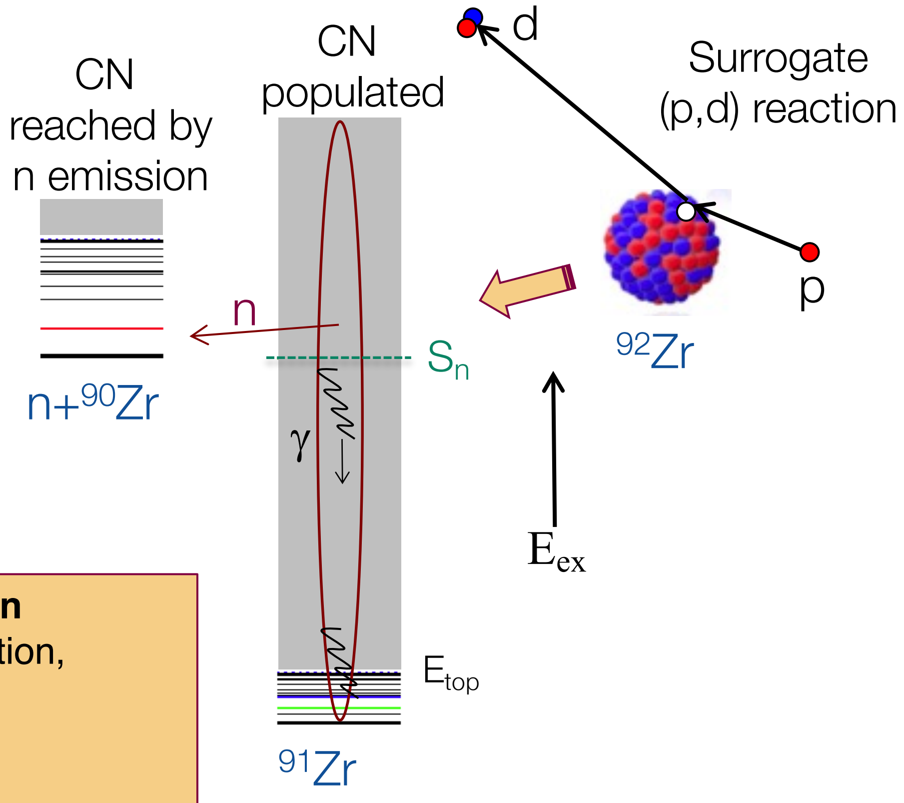
- Focus on understanding the structure effects responsible for the features observed
- Specify assumptions/approximations used
- Develop systematics that can be tested
- Predict inputs for reaction calculations

Considered interactions

- Between theory and experiment
- To advance our understanding of LDs and γSF

Thank you!

Capture cross sections from surrogate (p,d) reactions



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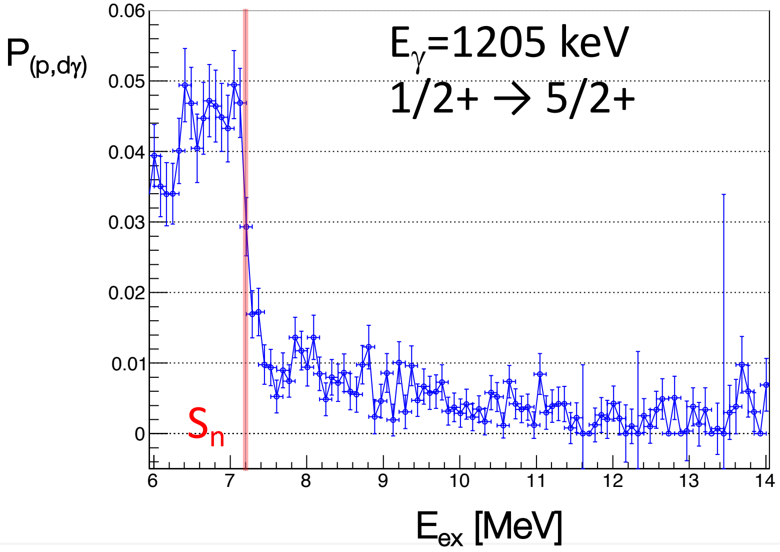


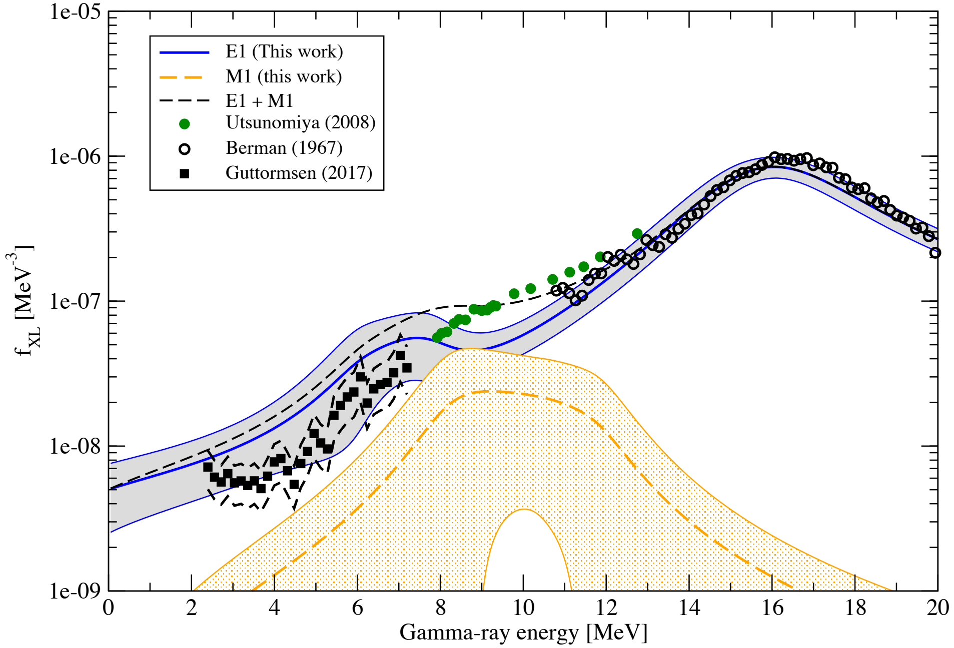
Turning measurement into cross section

1. Use theory to describe Surrogate reaction, predict $F_{(p,d)}^{CN}$
2. Develop rough decay model G^{CN}_{γ}
3. Fit uncertain parameters in G^{CN}_{γ} to reproduce $P_{(p,d\gamma)}$
4. Use best-fit parameters to calculate desired $\sigma_{(n,\gamma)}$

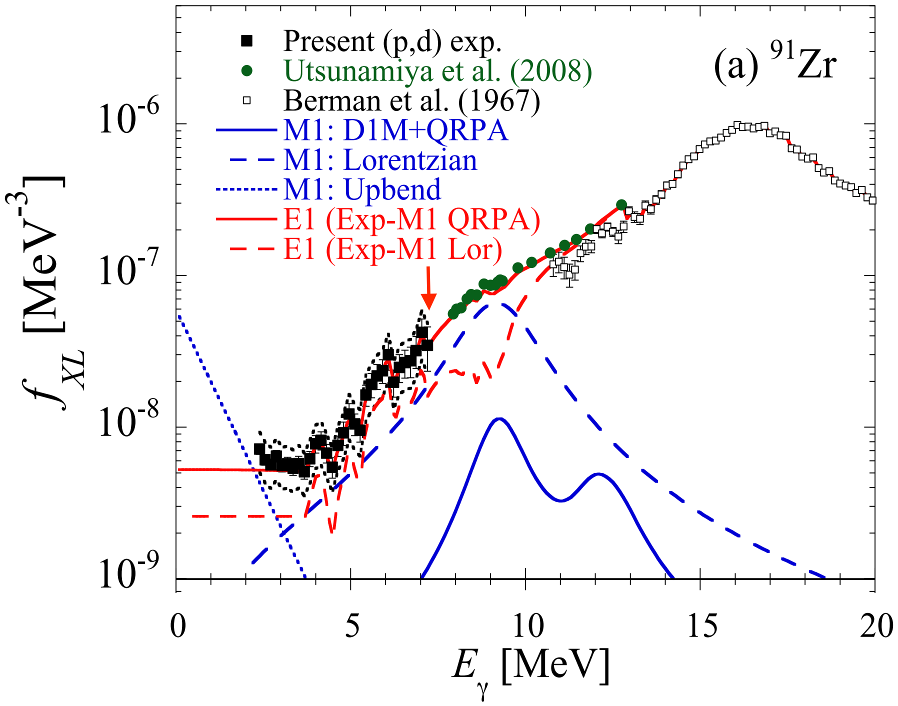
Result: Experimentally constrained cross section calculation.

Level density and γ strength function for ^{91}Zr from surrogate (p,d) data

Extracted E1, M1 strengths



Escher (wip)



Guttormsen et al, PRC 96, 024313 (2017)