Thermodynamic and electromagnetic properties of nuclei

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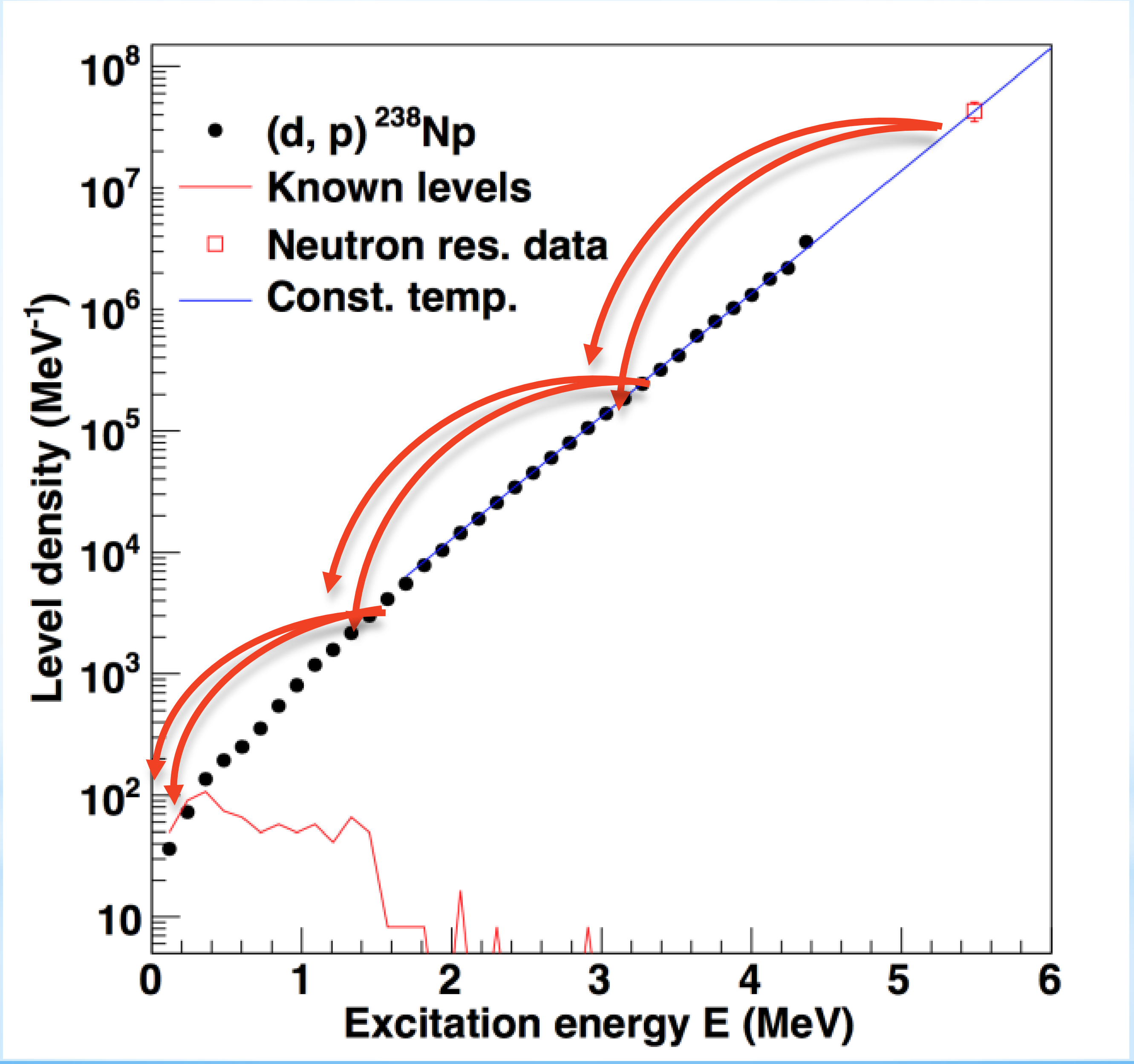
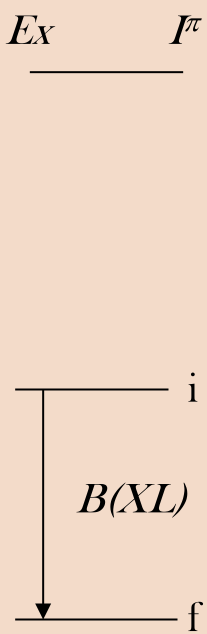
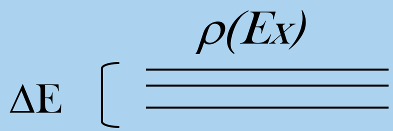


(d, p) ^{238}Np
Known levels
Neutron res. data
Const. temp.
Level density (MeV^{-1})
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
0
1
2
3
4
5
6
Excitation energy E (MeV)

Discrete

Quasi-continuum

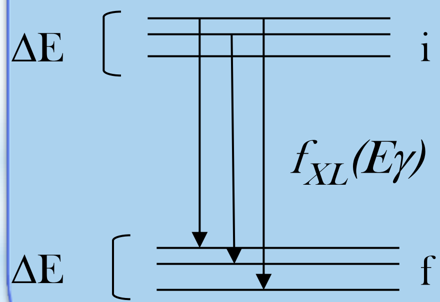




NUCLEAR LEVEL DENSITY (NLD)

Number of levels per MeV

- Nuclear entropy
- Nuclear temperature and heat capacity



γ-RAY STRENGTH FUNCTION (γSF)

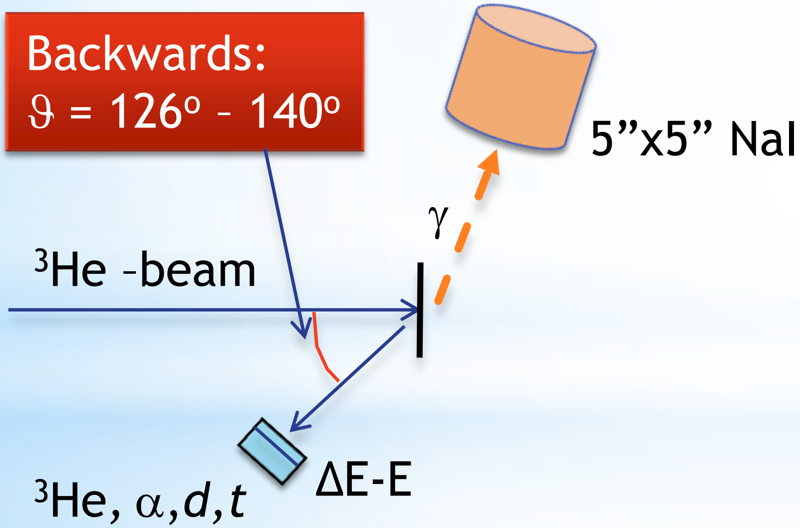
Average, nuclear electromagnetic response

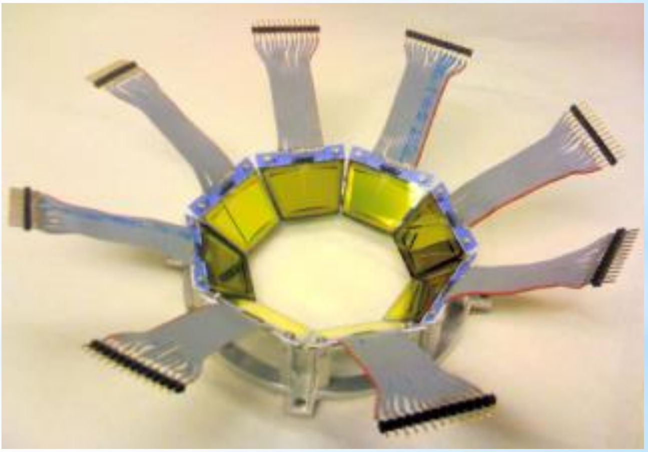
- Independent on the number of levels
- $f_{XL}(E_g) = E_g^{-(2L+1)} \langle G_{XL}(E_g) \rangle / D$

Th and U experiment at OCL

12 MeV d on ^{232}Th
24 MeV ^{3}He on ^{232}Th
15 MeV d on ^{238}U

Backwards:
$\vartheta = 126^{o} - 140^{o}$

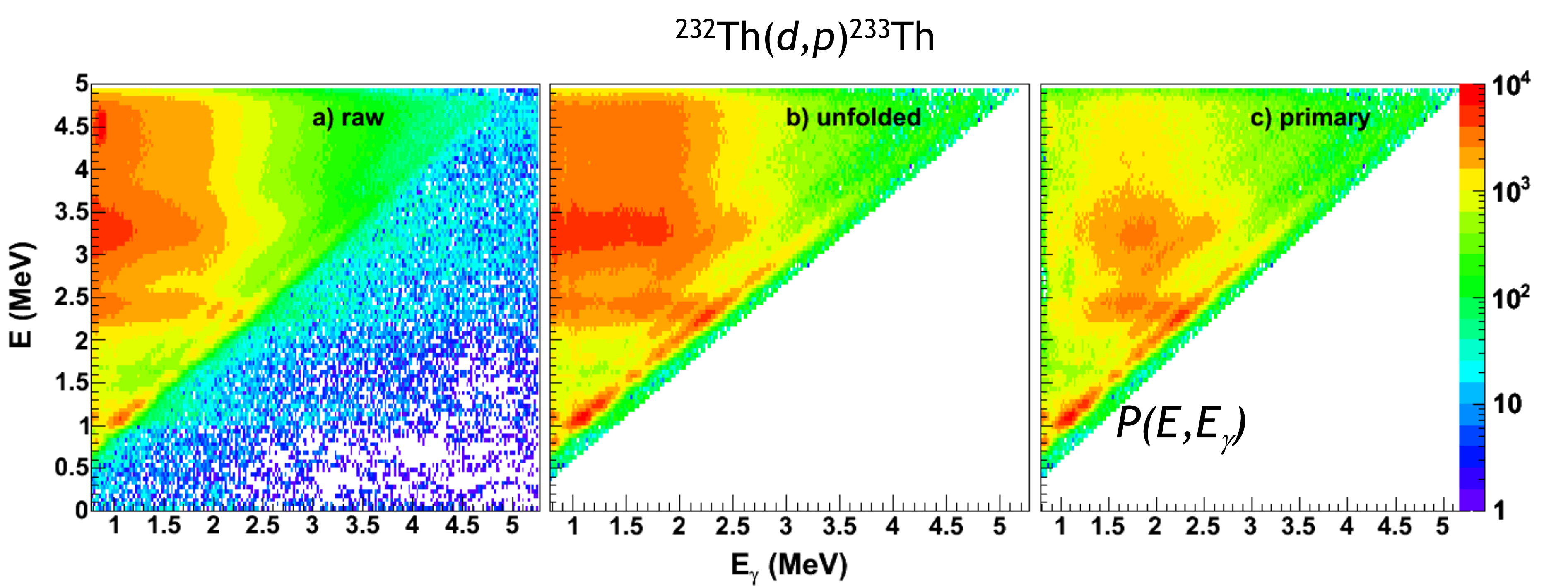




M.Guttormsen, A.Bürger, T.E.Hansen, N.Lietaer, NIM A648(2011)168

The Oslo method

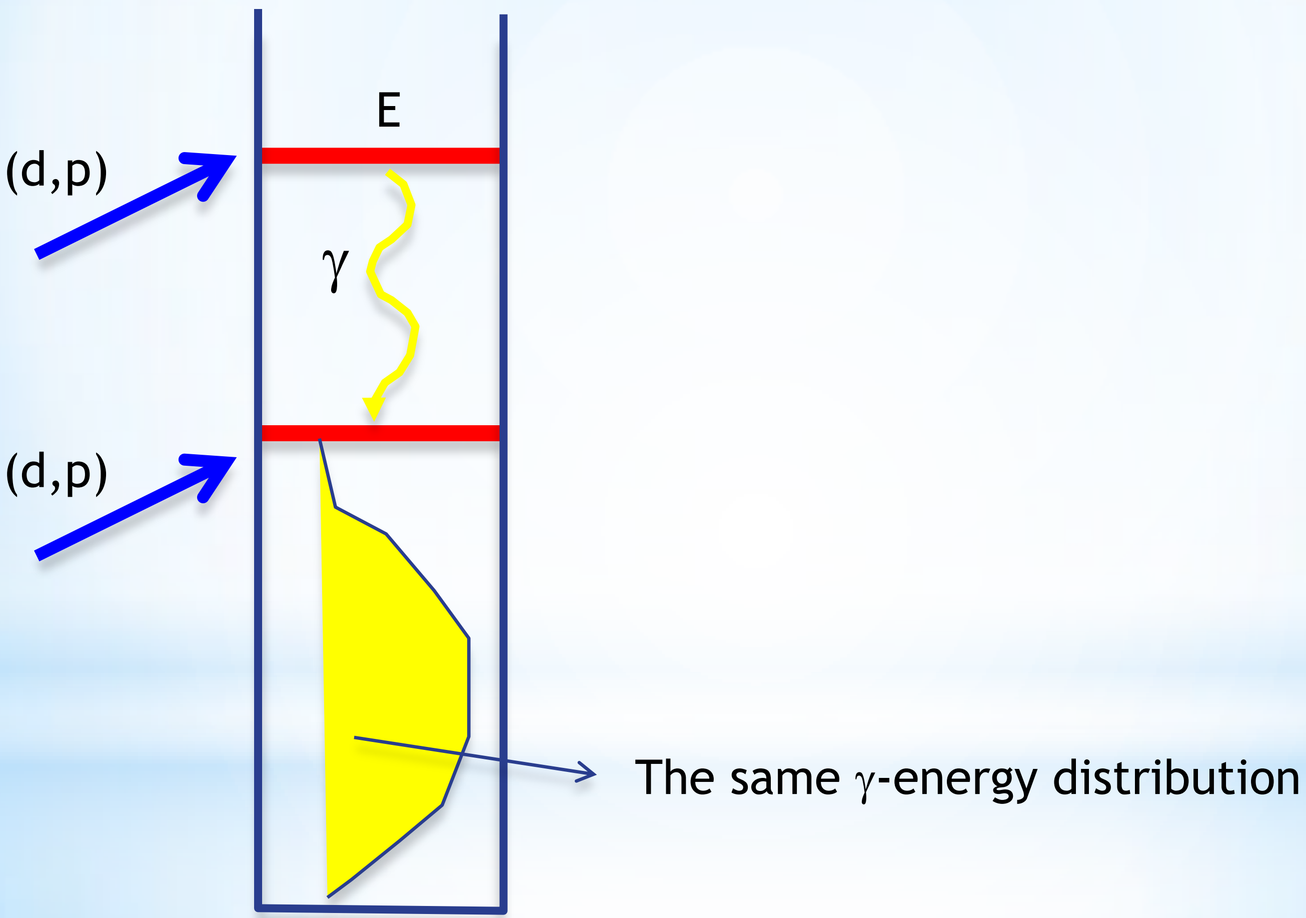
Simultaneous extraction of NLD and γSF



Oslo method:

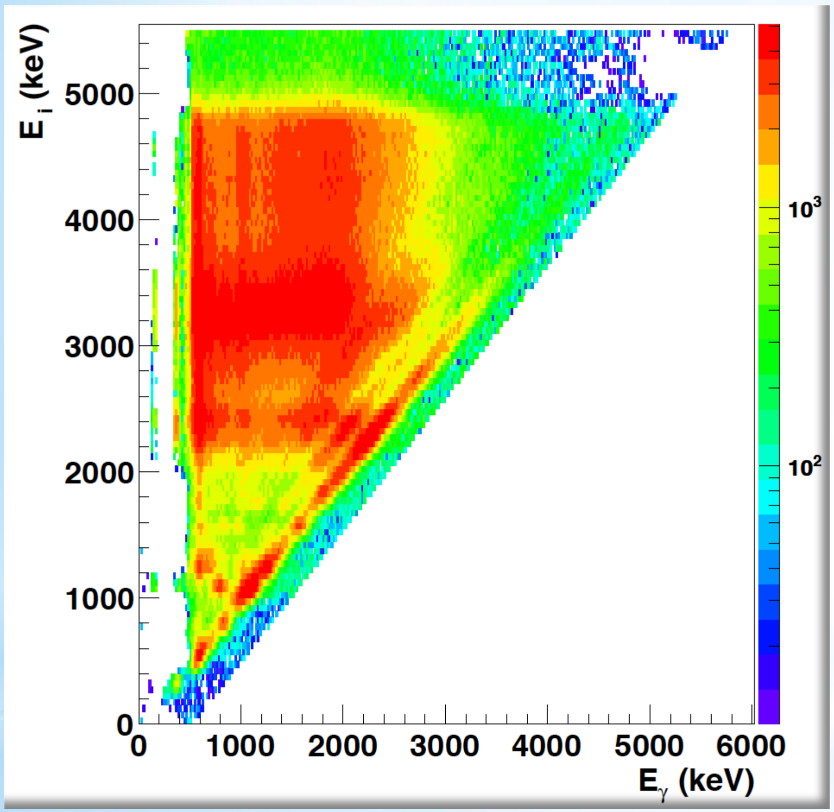
M. Guttormsen et al.,	NIM A374 (1996) 371
M. Guttormsen et al.,	NIM A255 (1987) 518
A. Schiller et al.,	NIM A447 (2000) 498
A.C. Larsen et al.,	Phys. Rev. C 83, 034315 (2011)

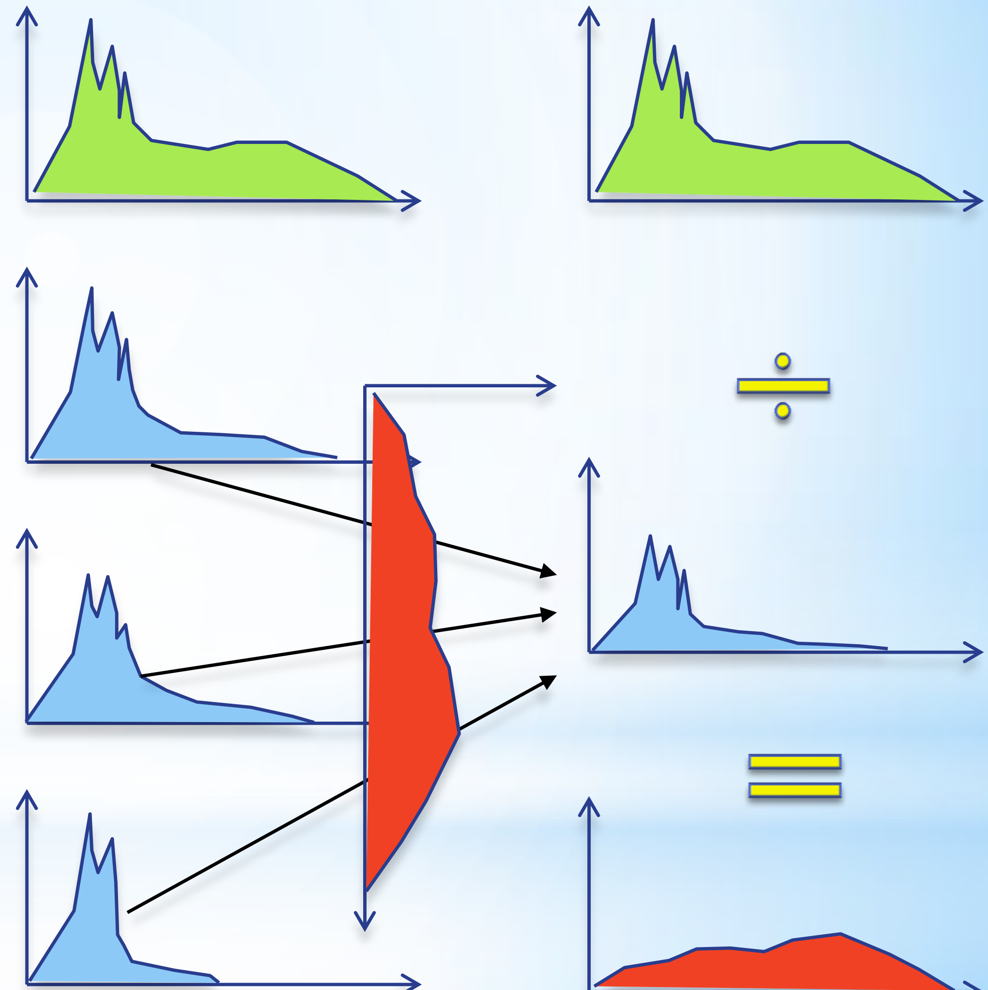
Assumption for the extraction of primary γ-spectra



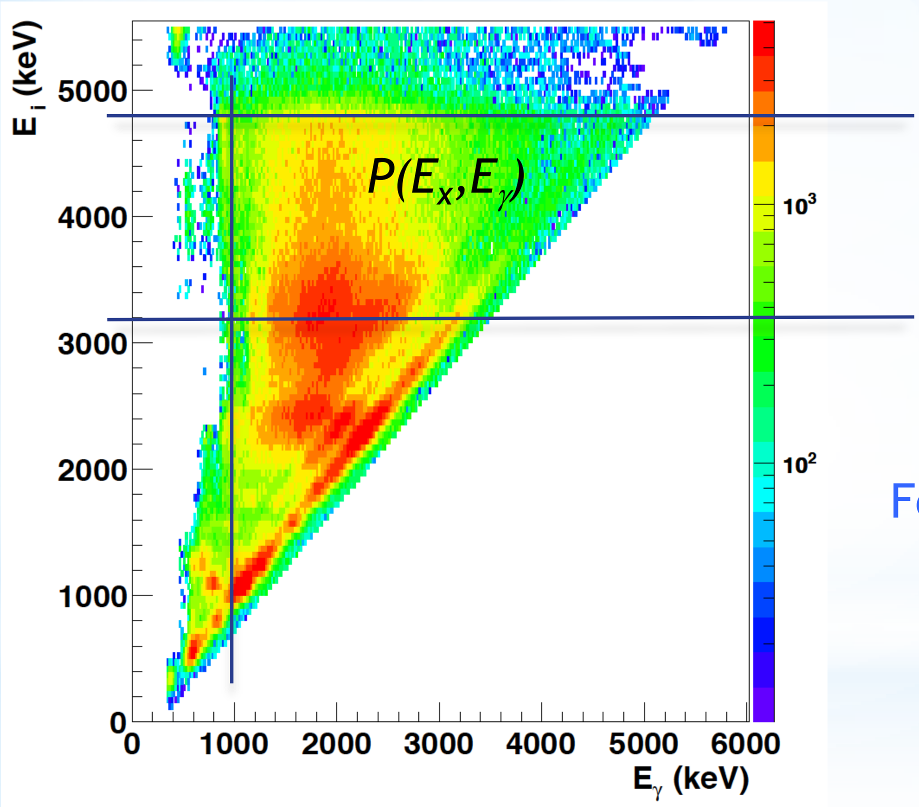
From total to primary γ-ray matrix

$^{232}Th(d,p)\,^{233}Th$





Primary γ-ray matrix

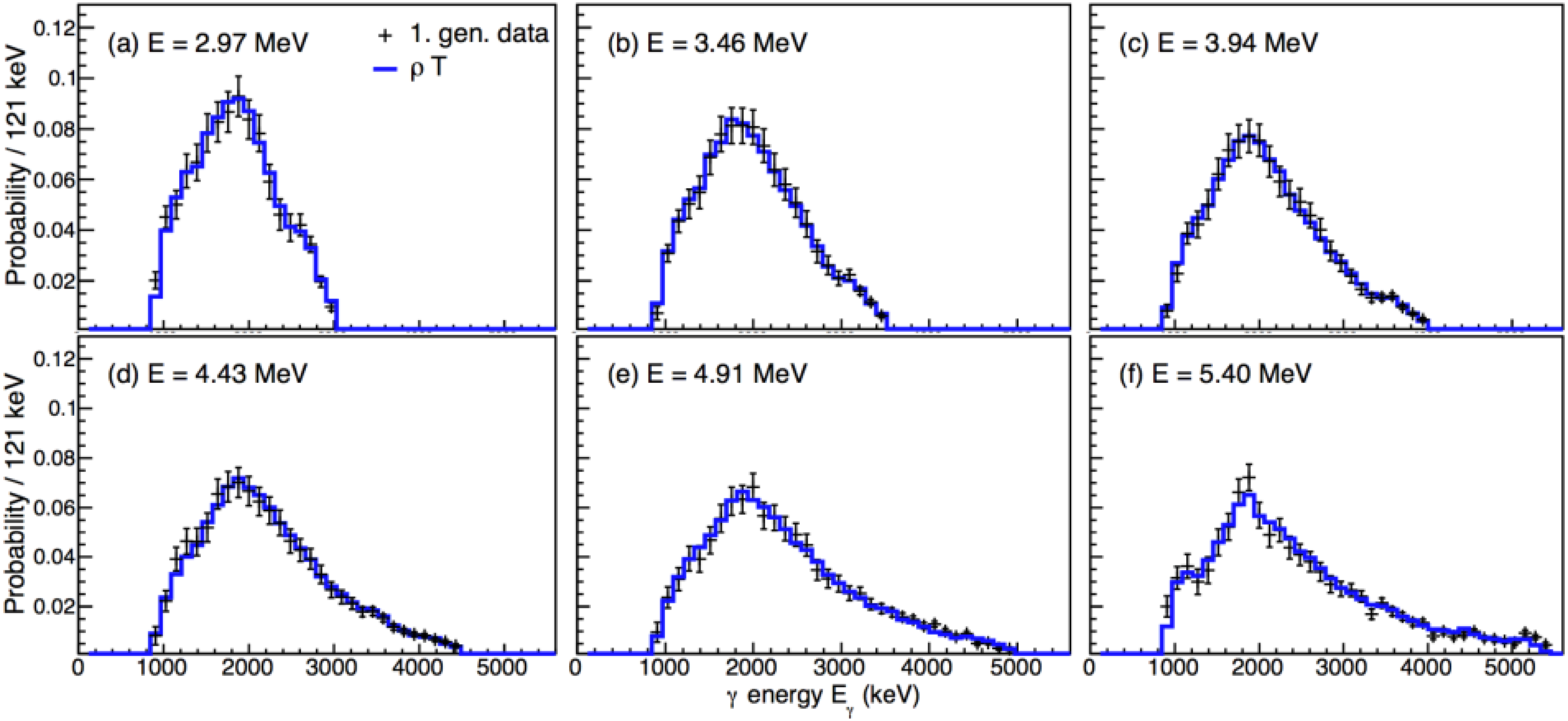


$P(E_x,E_\gamma)$

Level density
$\rho(E_f)$
Fermi's golden rule

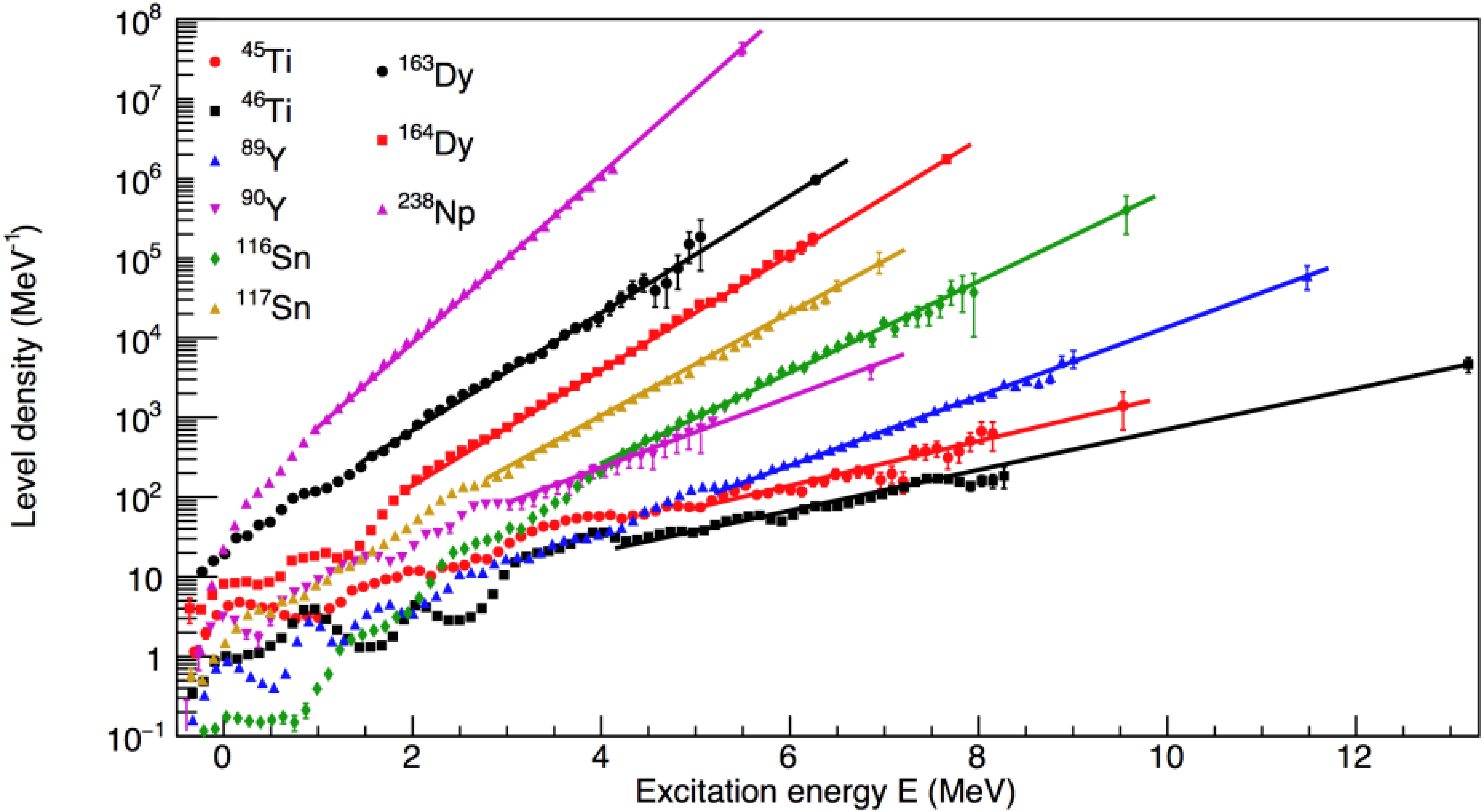
Trans. coeff.
$T(E_\gamma)$
Brink hypothesis

$P(E,E_\gamma) = \rho(E_f) \cdot T(E_\gamma)$?

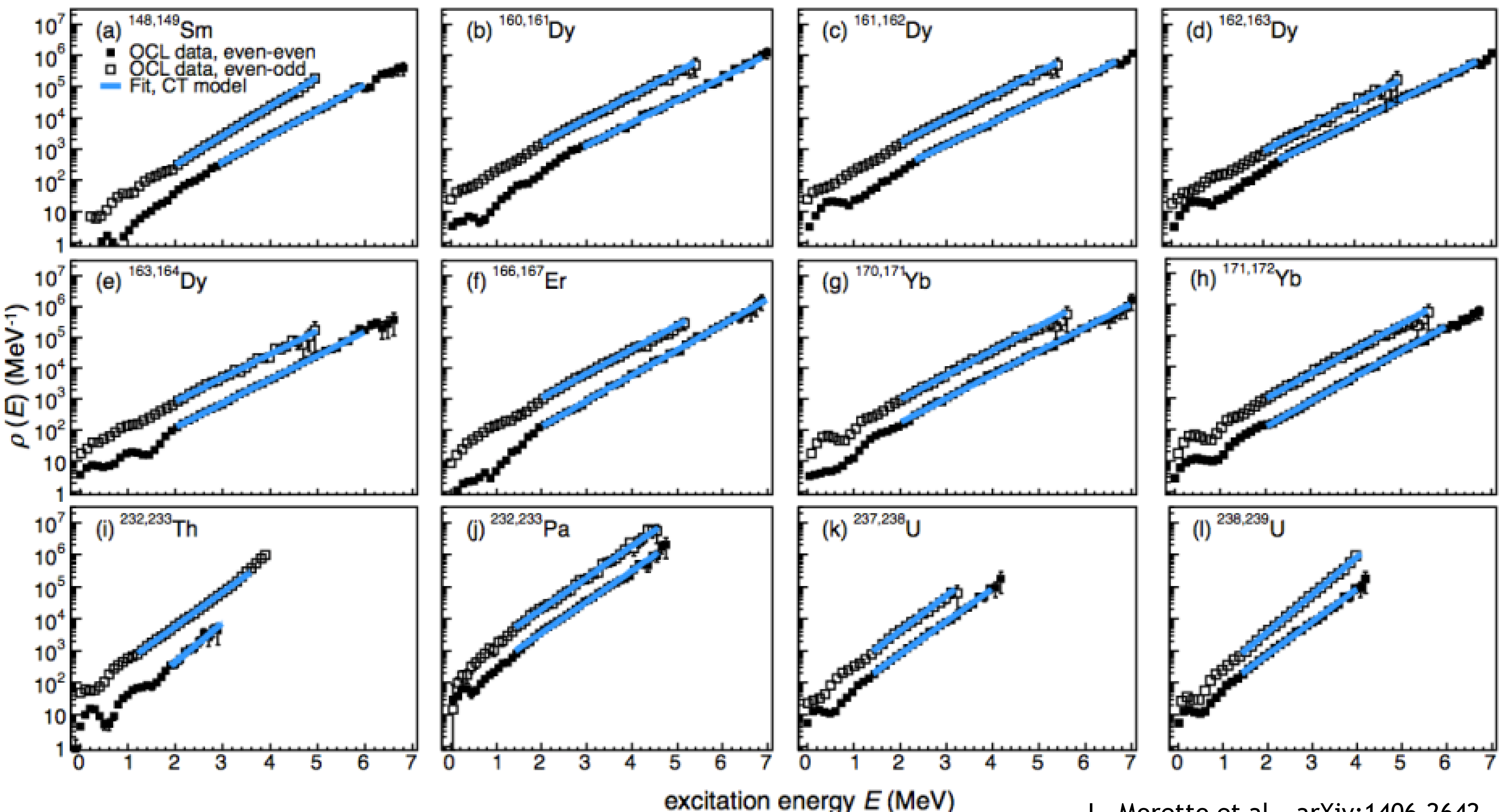


Thermodynamics

Constant-temperature level densities



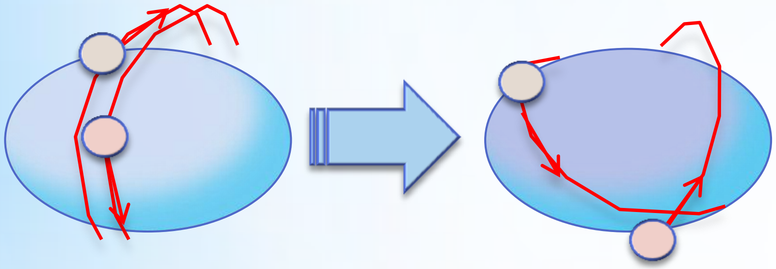
Constant-temperature level densities

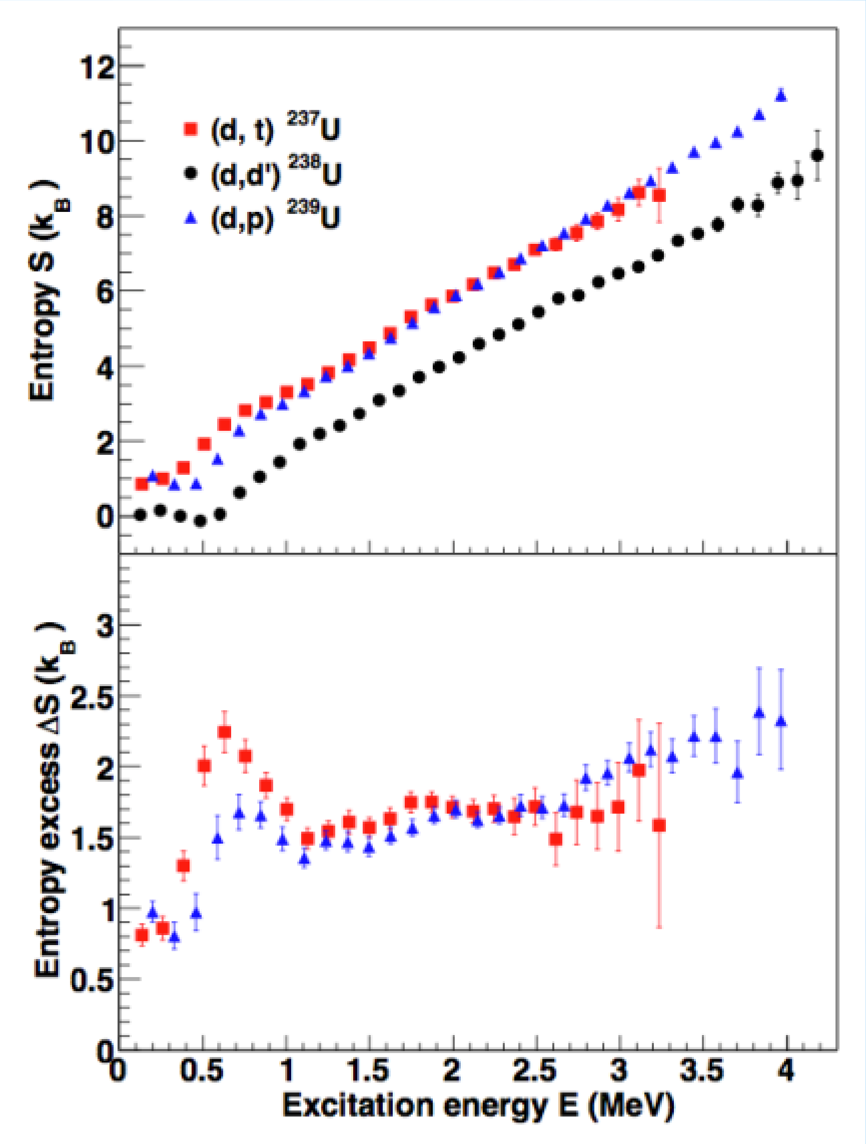


L. Moretto et al., arXiv:1406.2642

Level density and entropy

$$S(E) = k_B \ln W(E) \propto \ln \rho(E)$$



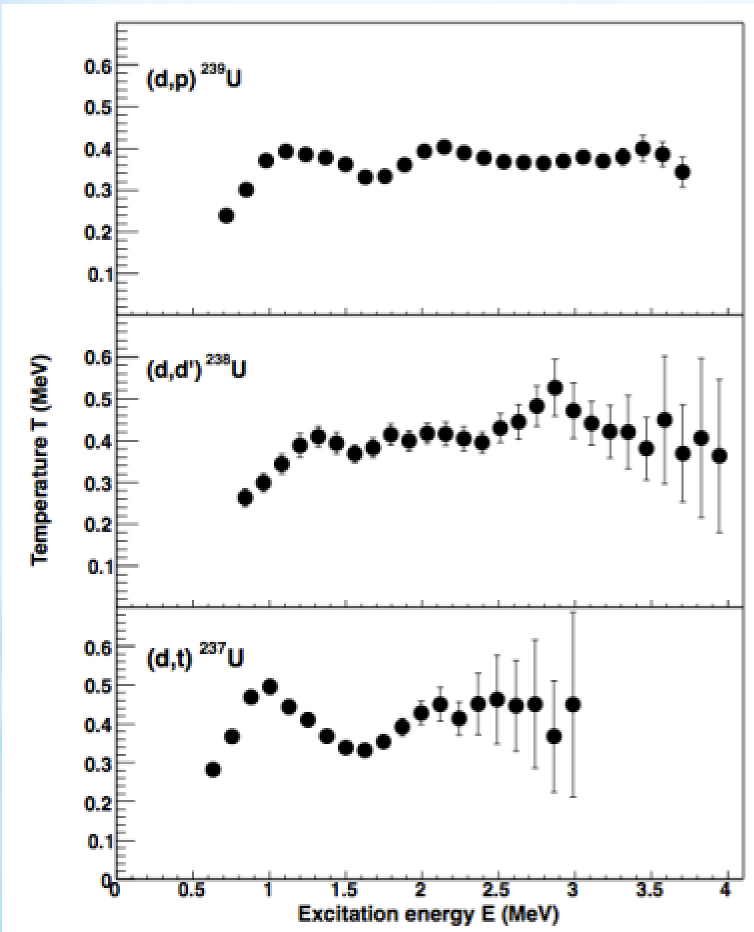


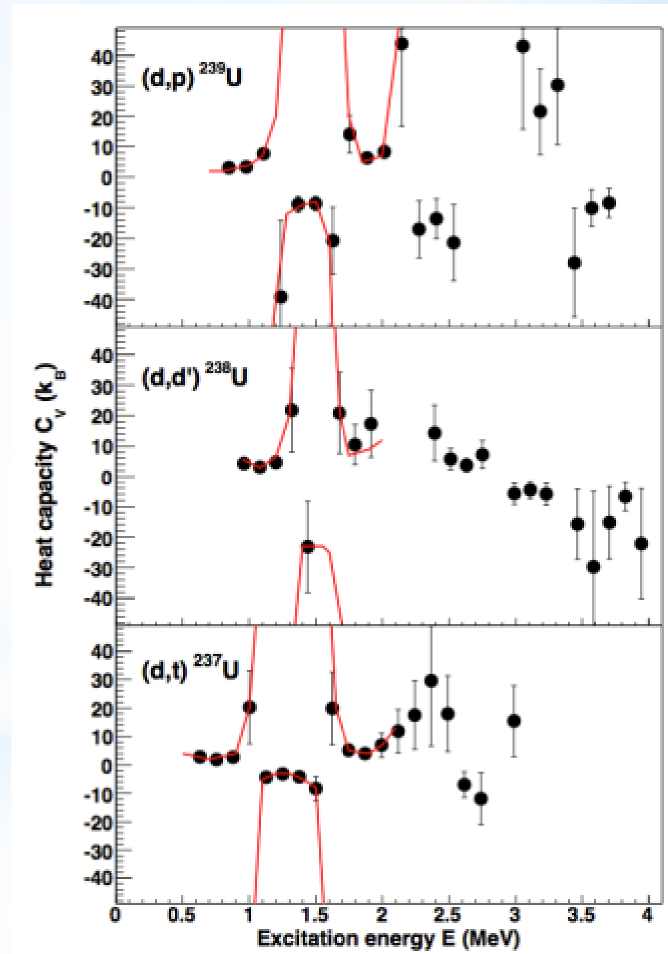
M. Guttormsen et al., PRC **88**, 024307 (2013)

Temperature and heat capacity

$$T(E) = (\partial S / \partial E)^{-1}$$

$$C_V(E) = (\partial T / \partial E)^{-1}$$



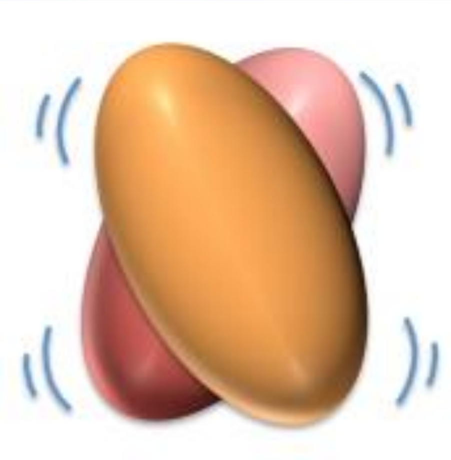


γ-ray strength functions

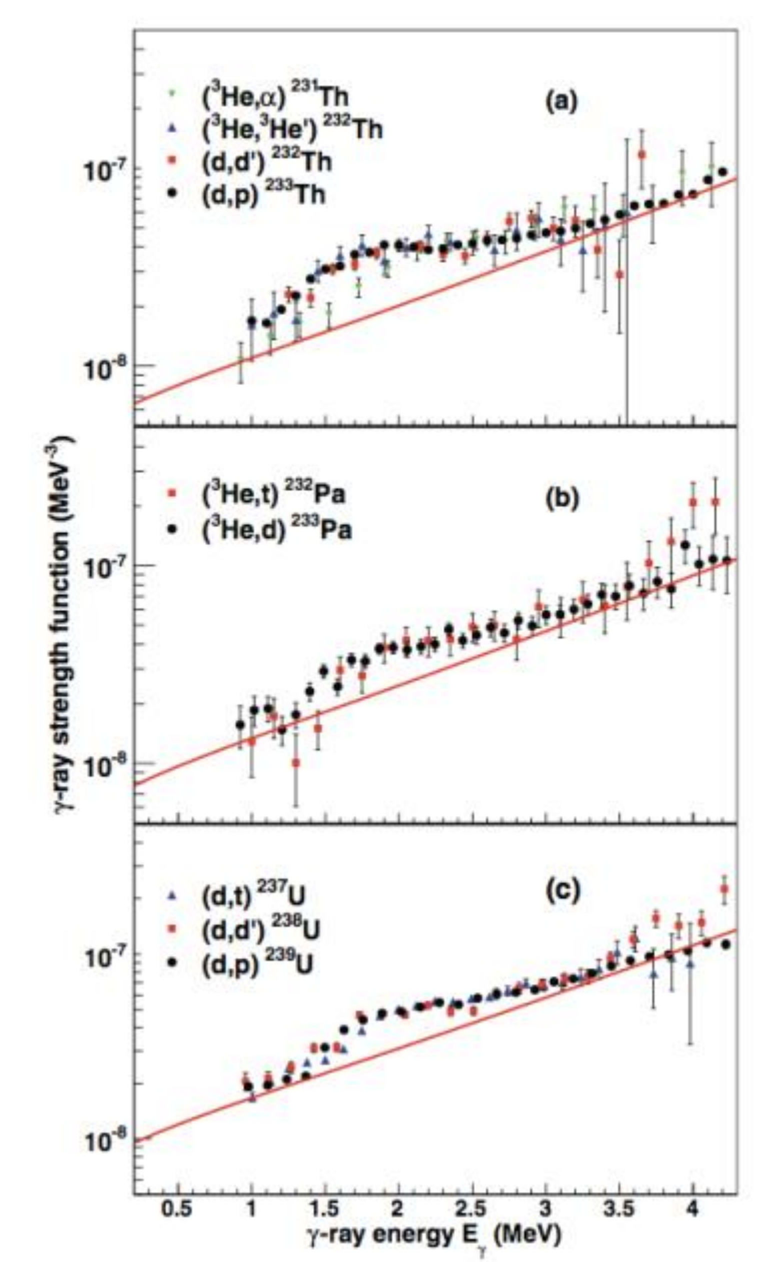
$$f(E_g) = \frac{1}{2p} \frac{T(E_g)}{E_g^3}$$

The scissors resonance

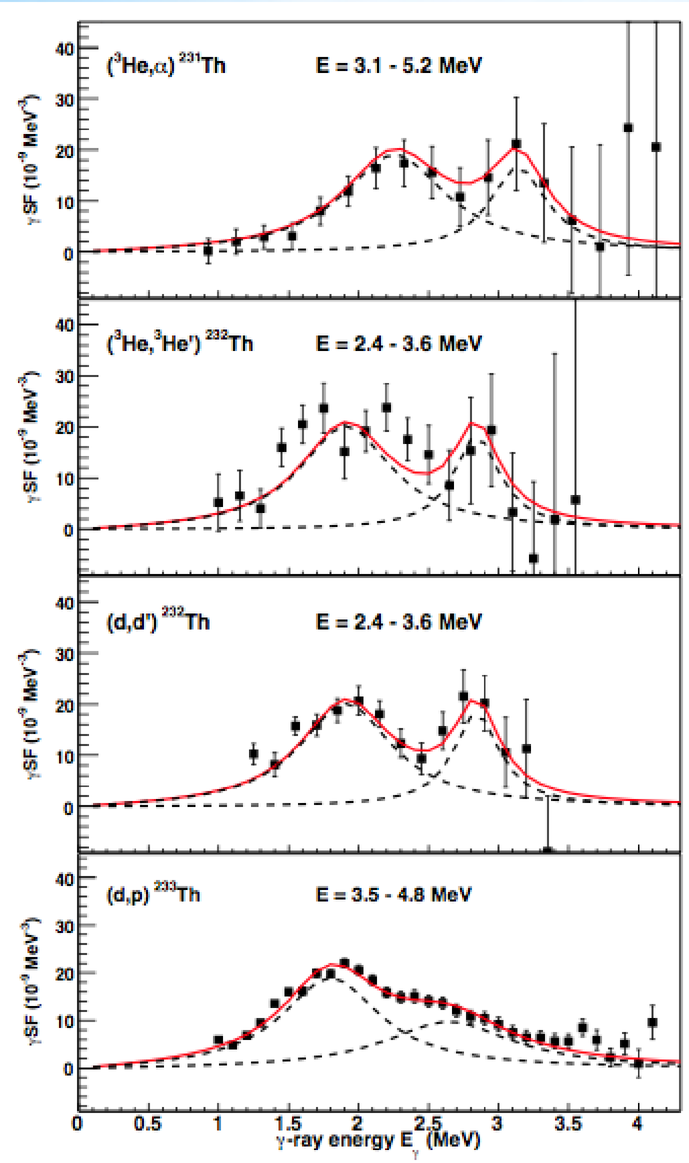
M1 scissors resonance mode
K. Heyde et al., Rev. Mod. Phys. **82**, 2365 (2010)
Sum rules: Enders et al., PRC **71**, 014316 (2005)
Strength and centroid depend on deformation

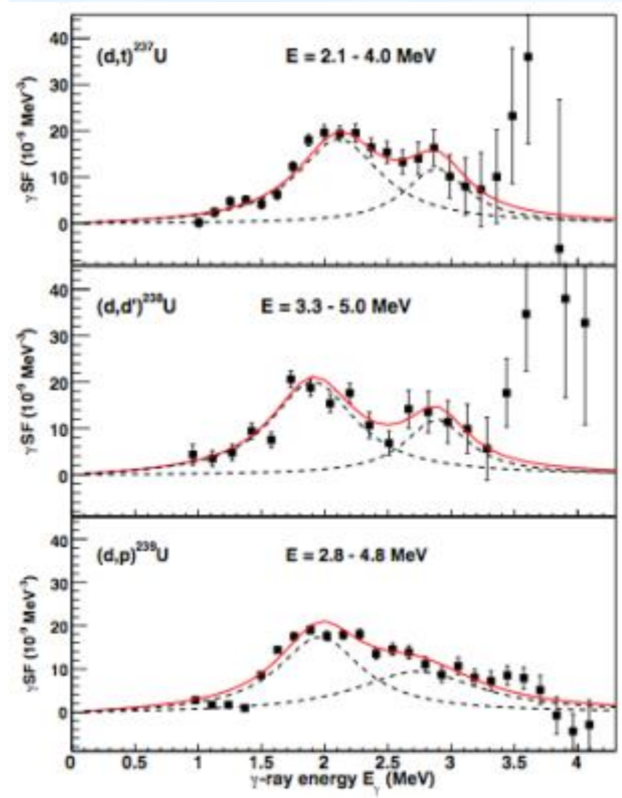


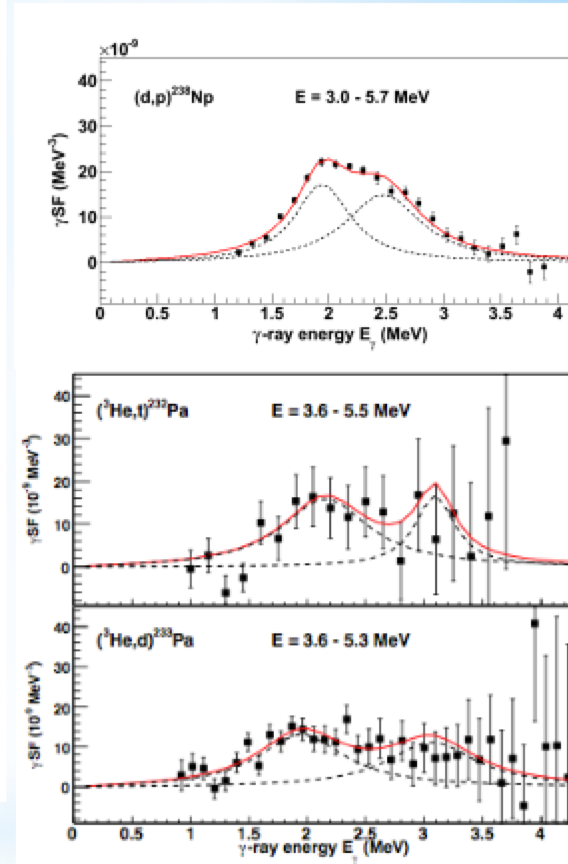
Guttormsen et al., PRC **89**, 014302 (2014)
Guttormsen et al., PRL 109, 162503 (2012)



Scissors resonance, $B(M1) = 8\text{-}11\mu_N^2$







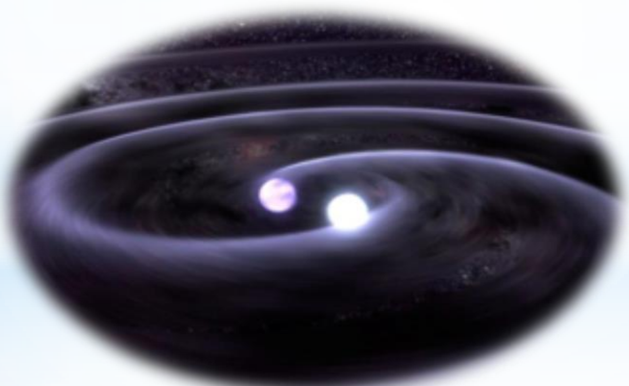
Theory: Orbital and spin scissors
E. B. Balbutsev, I.V. Molodtsova, and P. Schuck,

Phys. Rev. C **91**, 064312 (2015)

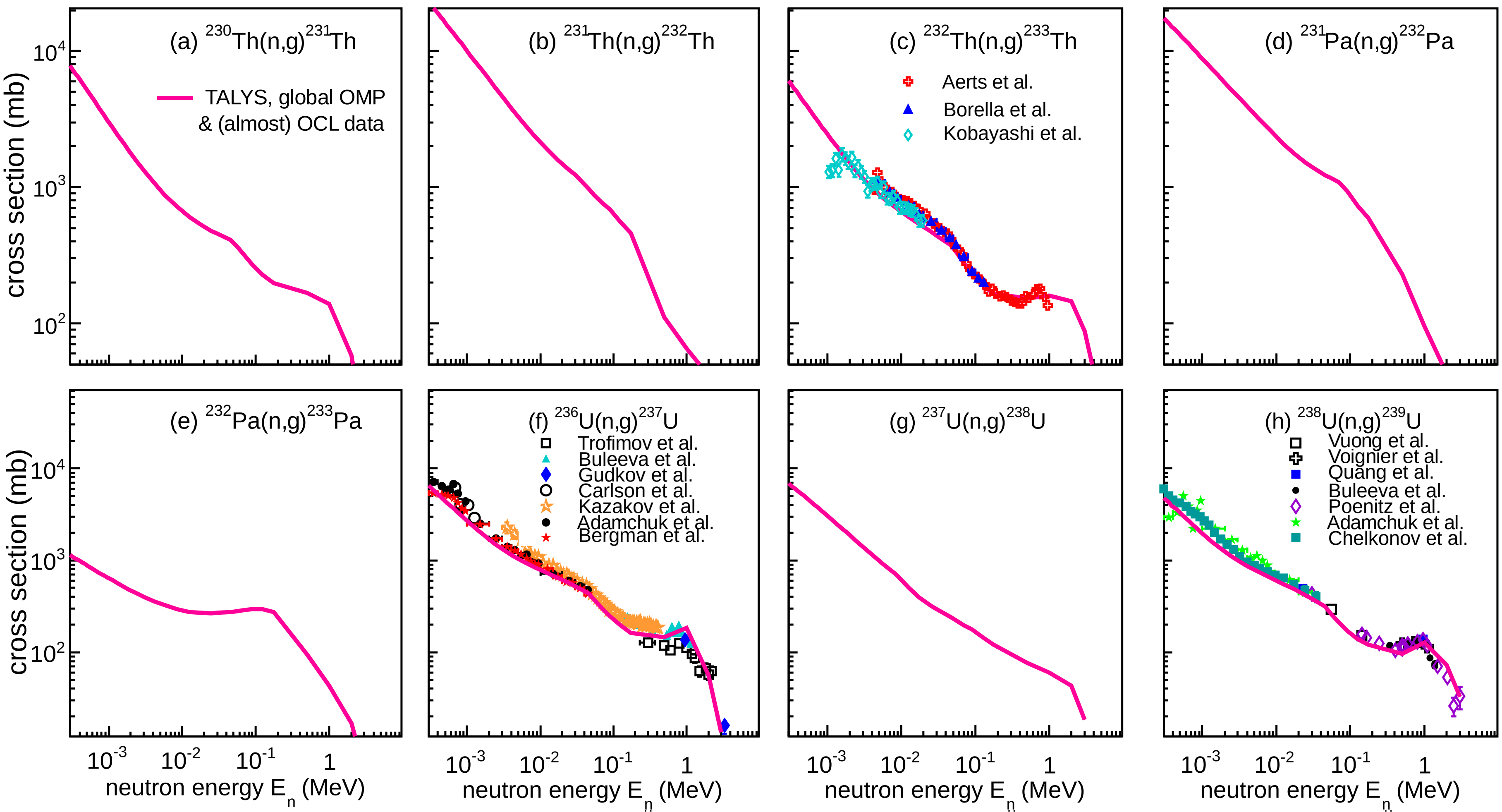
Applications

Astrophysics, nuclear energy and radioactive waste

Oslo NLD γSF → **TALYS with global OMP** → **(n, γ) cross sections**

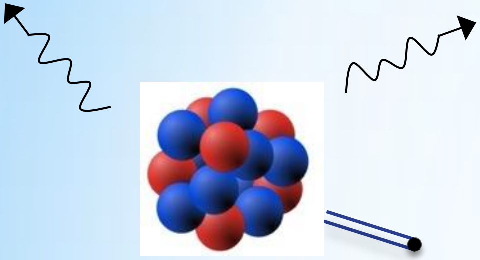


(*n*, γ) cross sections



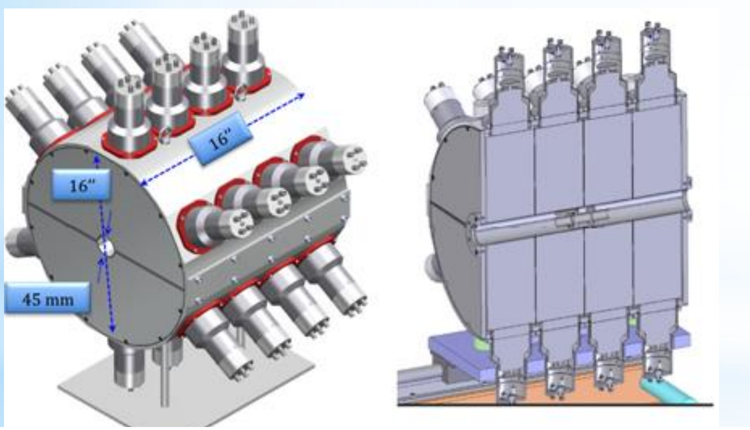
Recent achievement and outlook

The new β-Oslo method @ NSCL/MSU

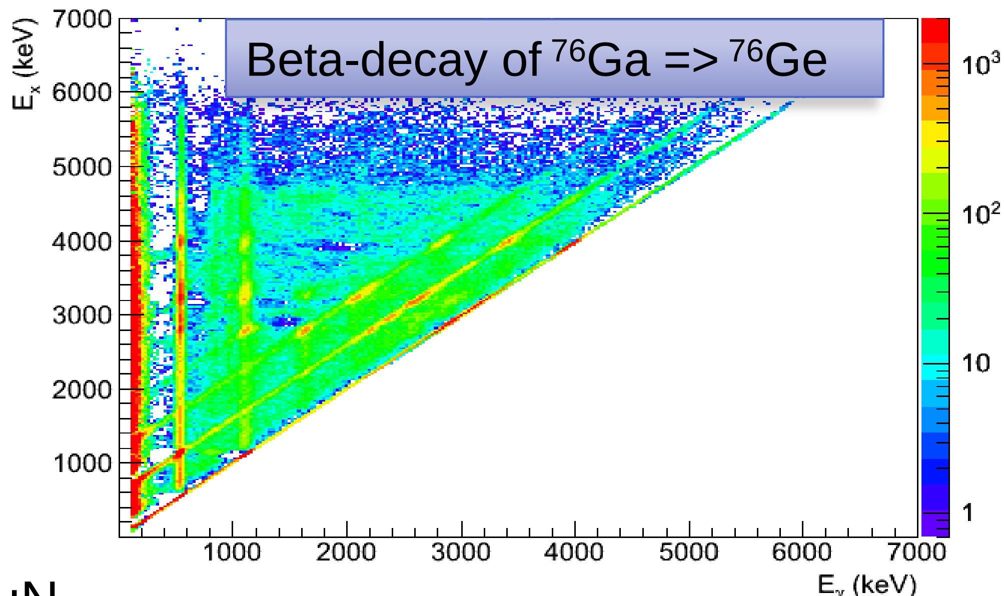


- Implant a neutron-rich nucleus in a total-absorption spectrometer
- Measure β in coincidence with γ's from the daughter nucleus

^{76}Ge primary beam, 130 MeV/nucleon on Be target
^{76}Ga: $T_{1/2}$ = 32.6s; Q_β = 6.916 MeV

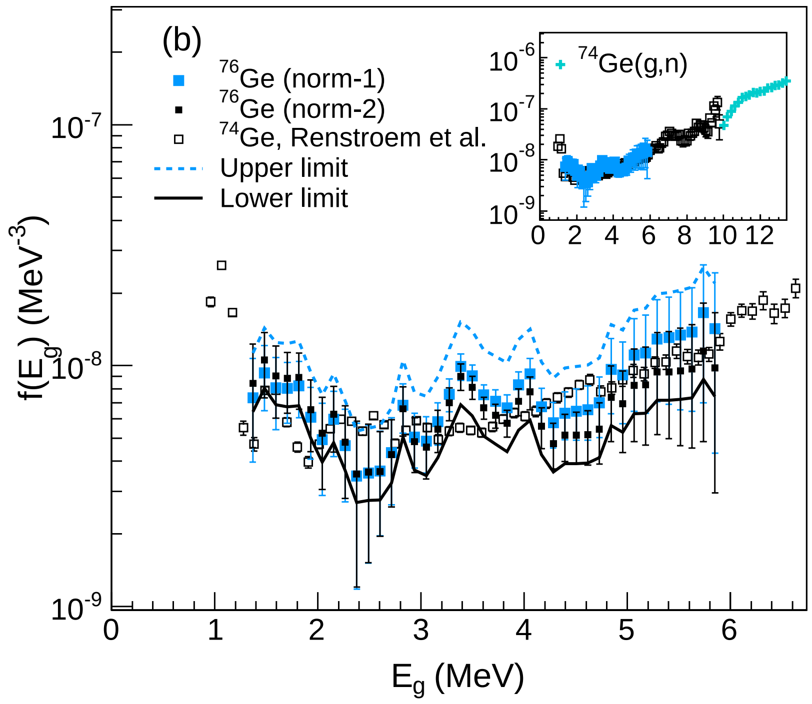


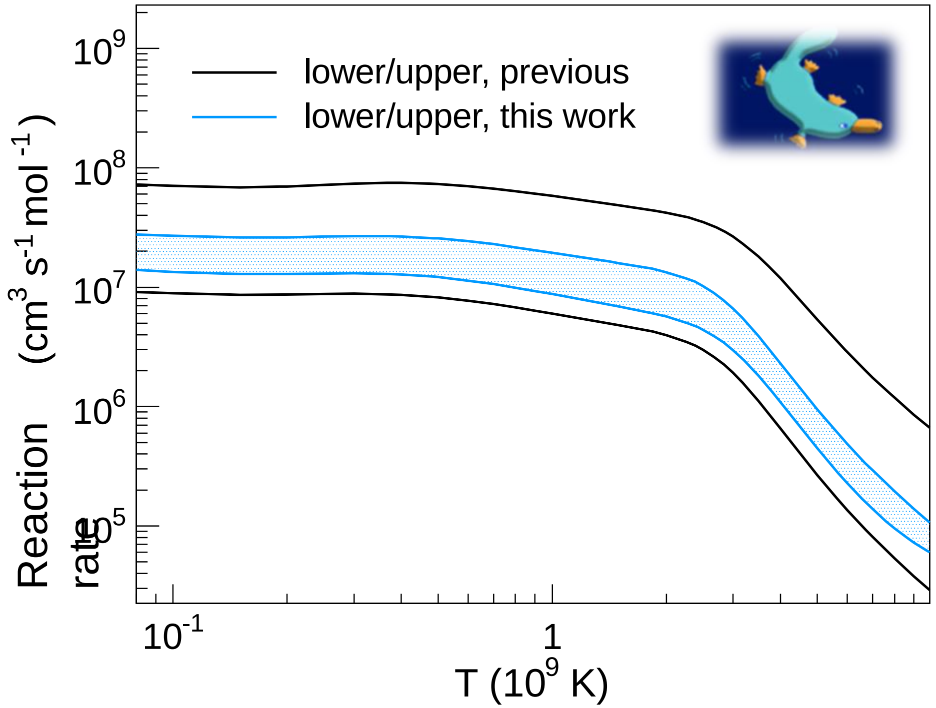
Total absorption spectrometer SuN
A. Simon et al, NIM A 703, 16 (2013)



A. Spyrou, et al.,
Phys. Rev. Lett. **113**, 232502 (2014)

(n, γ) reaction rates with β-Oslo method



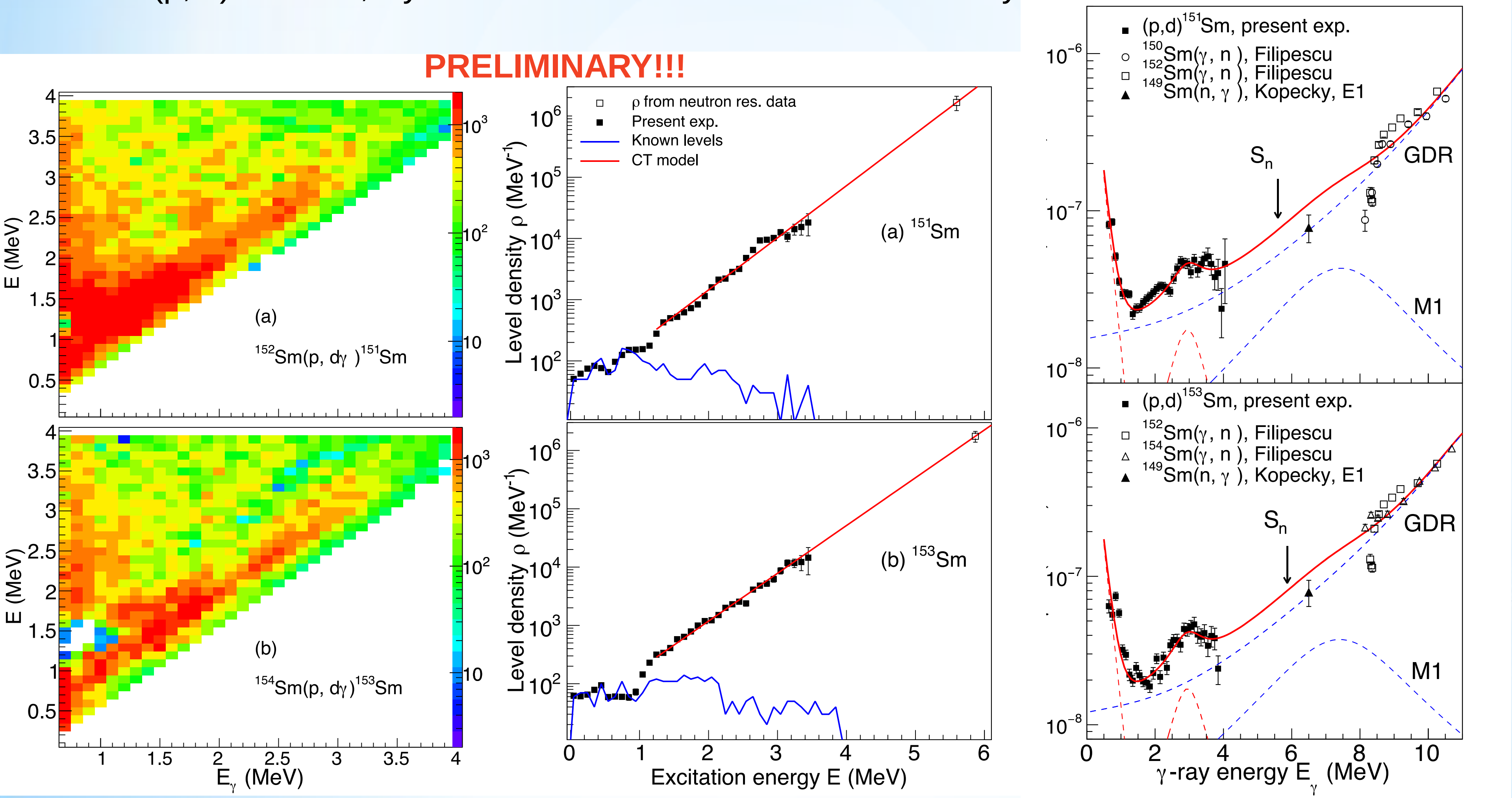


A. Spyrou et al., Phys. Rev. Lett. **113**, 232502 (2014)

Low-energy γ-enhancement in rare-earth nuclei

A. Simon et al.,
STARLiTER Clover detectors,
25 MeV (p, d) reaction, Cyclotron Institute of Texas A&M University

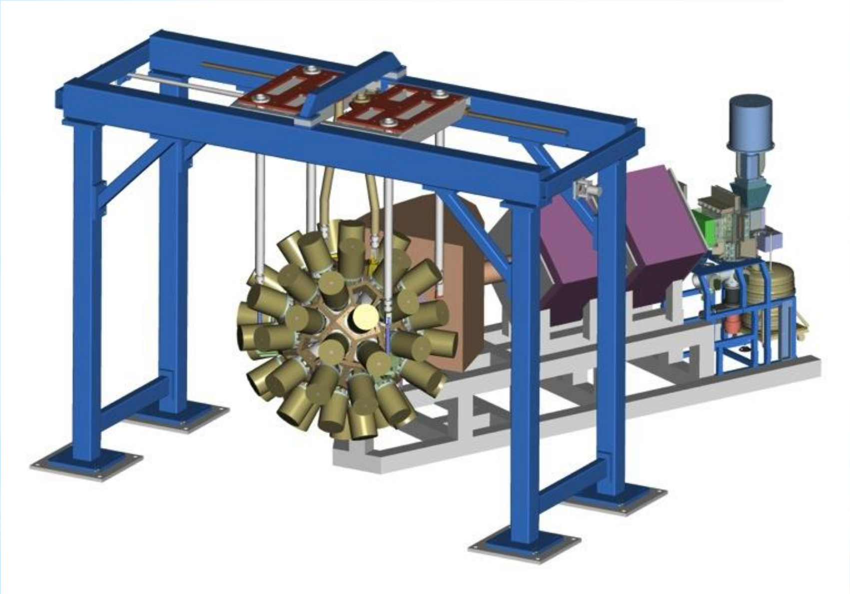
PRELIMINARY!!!



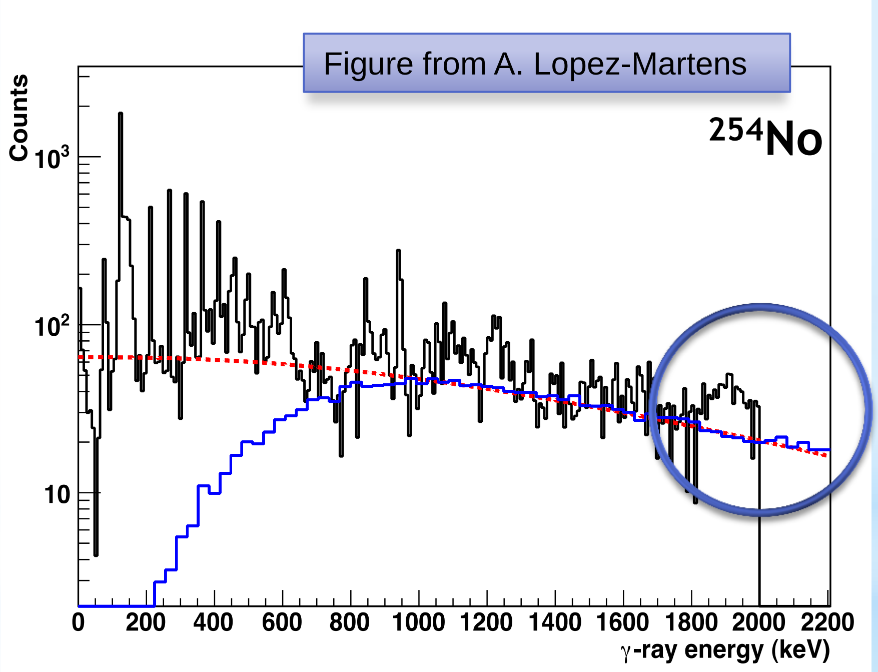
Scissors resonance in superheavy nuclei?

Proposal approved @ JYFL – JR137:
"Search for the M1 Scissors Mode in ^{254}No"

Fusion-evaporation reaction
^{208}Pb(^{48}Ca,2n)^{254}No $\Rightarrow$ Tag recoils (^{254}No), look for γ-rays in coincidence



JUROGAM2-RITU-GREAT
spectrometers @ JYFL



Blue: statistical E1, simulations [T. Lauritsen, private comm.]
Red: statistical E1, fit [S. Leoni et al., PLB **409**, 71 (1997)]

Summary

NLD	• Constant-temperature level densities • Total entropy *S* and single-particle entropy Δ*S* • Nuclear temperature *T* and heat capacity C_V
γSF	• Scissors strength of $B(M1) \approx 8$ -11 μ_N^2 at $E_\gamma \approx 2$ MeV • Splits into two components
Applications	• γSF + NLD predict accurate (*n*,γ) cross sections
Outlook	• Far from stability, new detectors and methods • Funding for 30 3.5x8" $LaBr_3$ in CACTUS

A great working team!

M. Aiche, F.L. Bello Garrote, L.A. Bernstein, D. Bleuel, Y. Byun, Q. Ducasse, T.K. Eriksen, F. Giacoppo, A. Görgen, F. Gunsing, T.W. Hagen, B. Jurado, S.N. Liddick, M. Klintefjord, A.C. Larsen, L. Lebois, F. Naqvi, H.T. Nyhus, G. Perdikakis, T. Renstrøm, S.J. Rose, E. Sahin, A. Simon, A. Spyrou, S. Siem, T.G. Tornyi, G.M. Tveten, A. Voinov, M. Wiedeking and J.N. Wilson

University of Oslo, CENBG Gradignan, LLNL, Ohio University, IPN Orsay, CEA Saclay, iThemba LABS, NSCL/MSU, University of Notre Dame