Level density and gamma strength functions

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University of Oslo

20th Meeting of the Nuclear Structure and Decay Data (NSDD) Network
Kuwait, 28 January 2013

Outline of Talk:

- Our group
- Experimental setup
- The “Oslo method”
- Experimental results for γ-strength functions:
  - Small resonances
  - Low energy enhancement
- Effects on (n,γ) cross section calculations.
- Conclusions and ideas for a database of gamma strength functions

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Centre for accelerator-based research and energy (SAFE):

includes:

Nuclear Chemistry
PET Chemistry
Nuclear Physics
Solar Energy

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The nuclear physics group in Oslo:

Permanent staff:

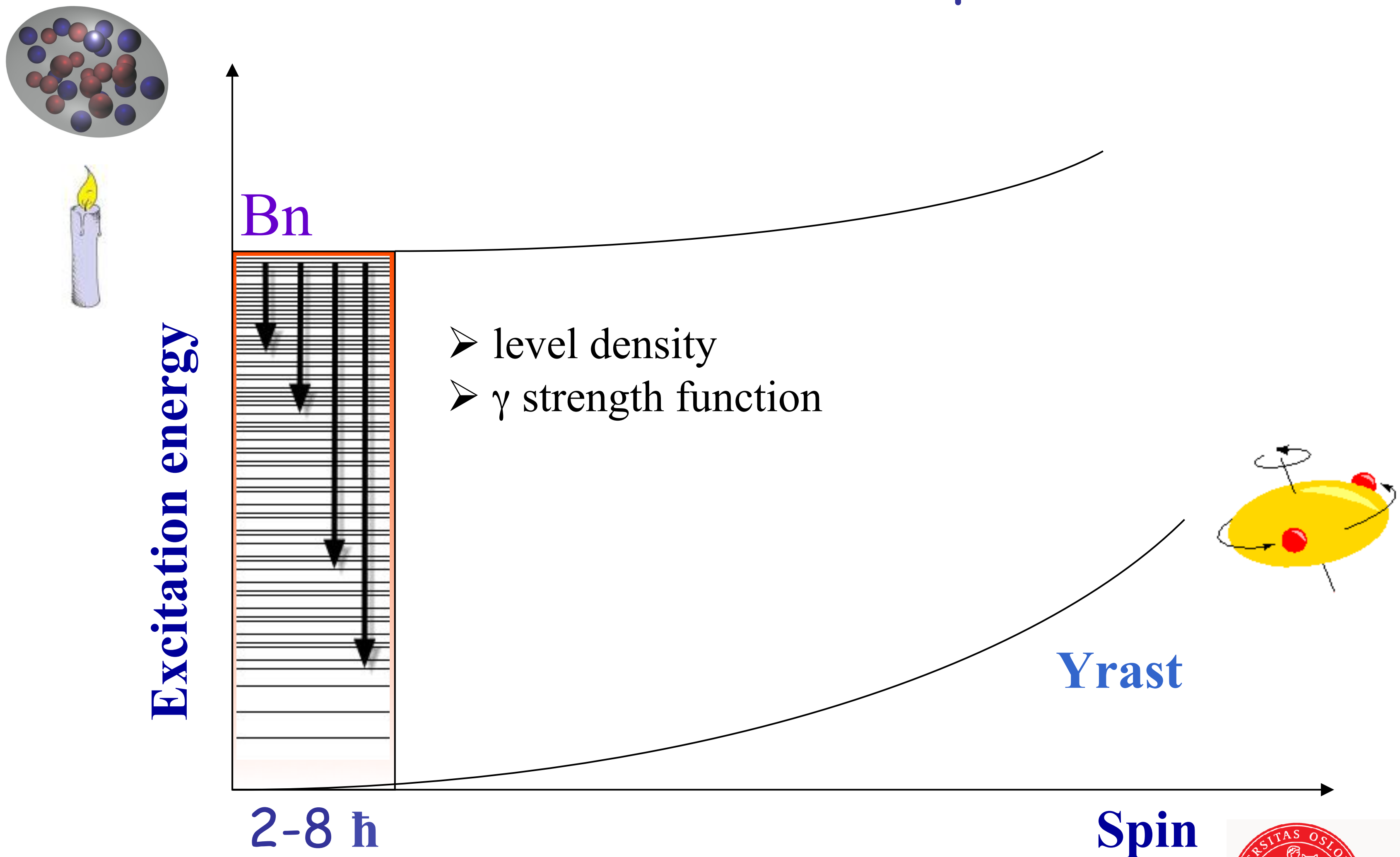
- John Rekstad (retires 2013)
- Magne Guttormsen
- Andreas Görgen
- Sunniva Siem

Postdocs:
Michaela Meir
Ann-Cecilie Larsen
Francesca Giacoppo
Eda Sahin
Gry M. Tveten(from 1/8-2013)

7 PhD students (+1 from Hungary)

Guest researchers:
Paul Koehler
Geirr Sletten

Statistical properties of warm nuclei at low spin



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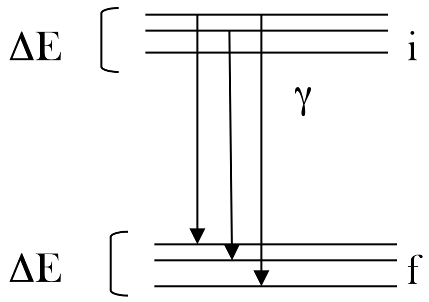
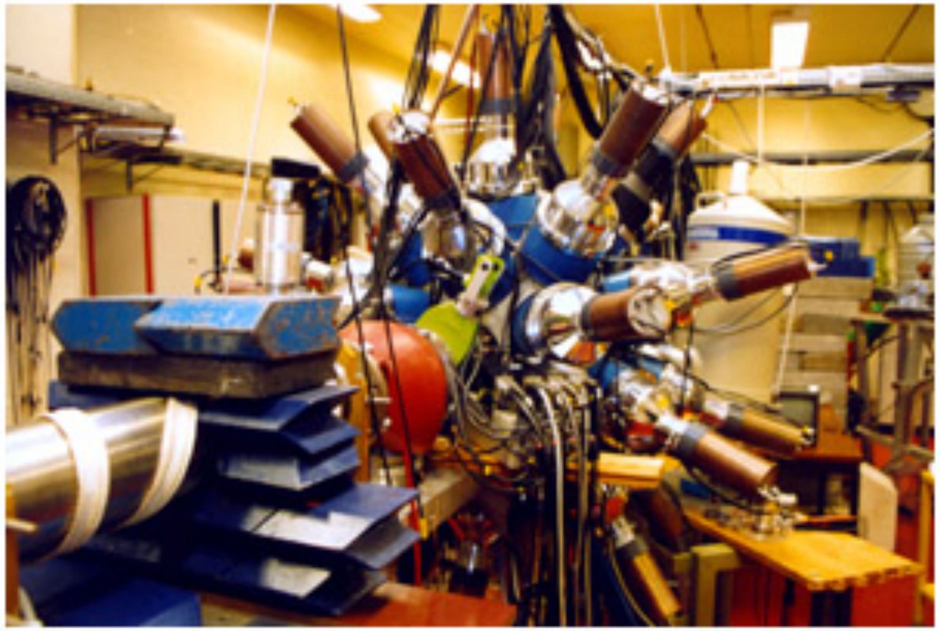
What is γ-ray strength functions?

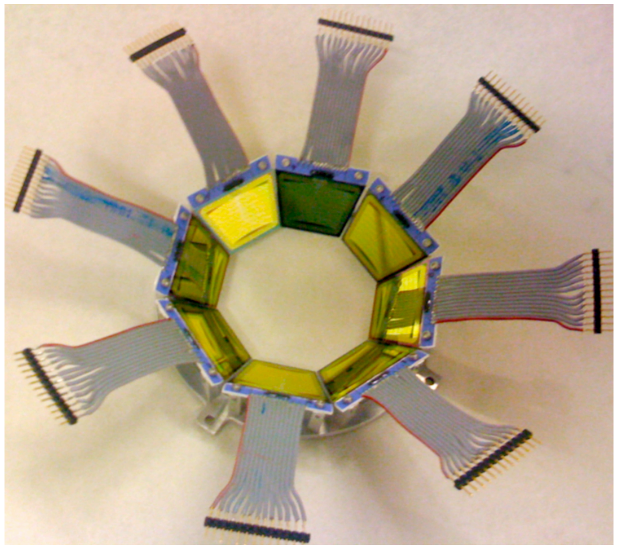
- A measure of the average, nuclear electromagnetic response determined by the nuclear structure and the available degrees of freedom
- Directly related to partial decay widths and reduced transition probabilities
- Fruitful concept in the quasi-continuum/continuum region



Experimental setup @ OCL

- Beam: p, d, 3He, α with energies up to 30-45 MeV
- Reactions: (^{3}He,αγ), (^{3}He,^{3}He'γ), (p,p´γ), (d,pγ) and (p,tγ)
- CACTUS: 28 5" x 5" NaI(Tl), $\varepsilon \approx 15\%$ @ E_γ=1.33 MeV
- SiRi: 64 Si ΔE-E particle telescopes, $\Delta\theta \approx 2^o$
- Spin 2-6 ħ





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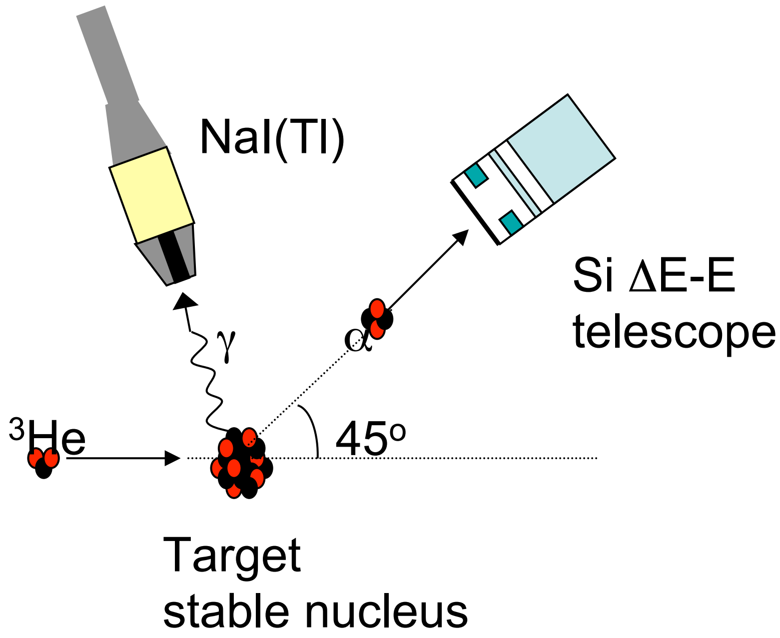
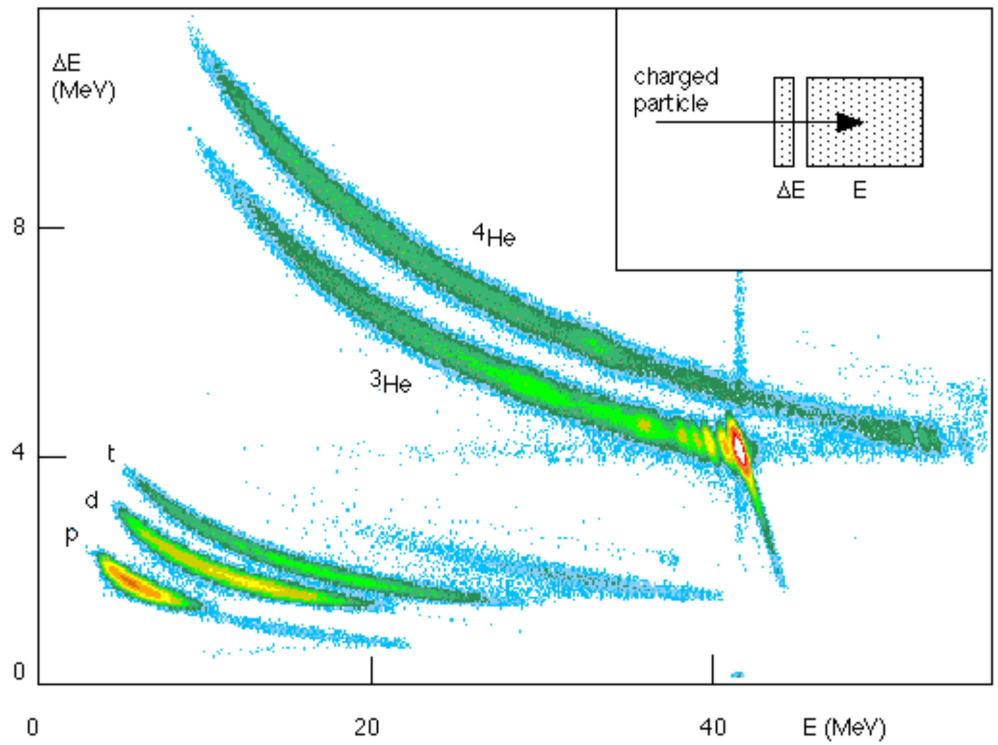
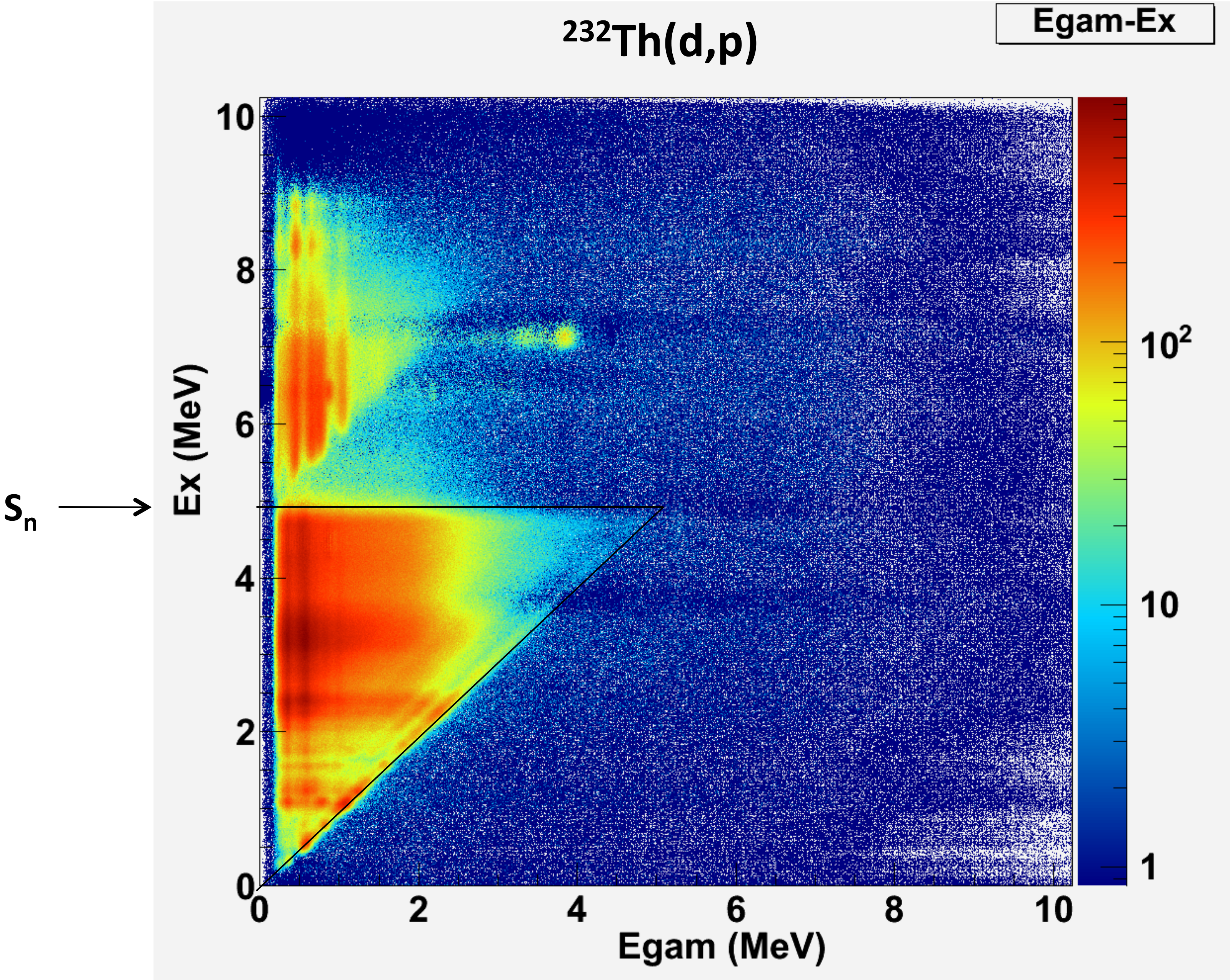


Particle gamma coincidences

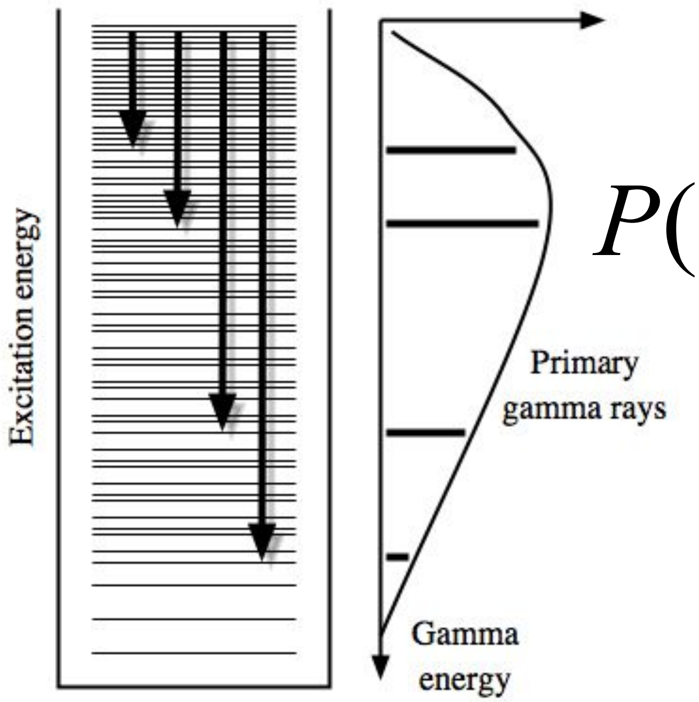
Particle identification,
Typical ΔE-E bananas:





^{232}Th(d,p)
Egam-Ex
Ex (MeV)
Egam (MeV)
S_n
0
2
4
6
8
10
1
10
10^2

The "Oslo-method" :
Isolating the primary γ-rays as a function of Ex



Brink-Axel

$$P(E_i, E_\gamma) \propto \rho(E_f) \cdot T(E_\gamma)$$

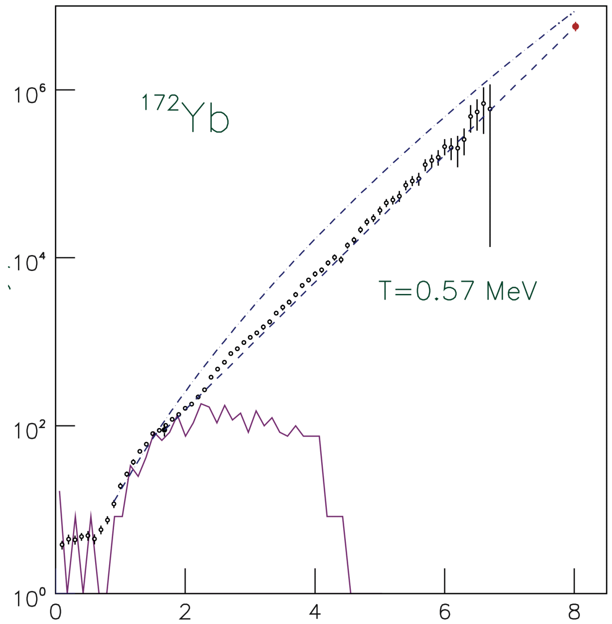
$$\mathcal{T}(E_\gamma) = 2\pi \sum_{XL} E_\gamma^{2L+1} f_{XL}(E_\gamma)$$

Assuming dominance of dipole radiation (*E1 and M1*)

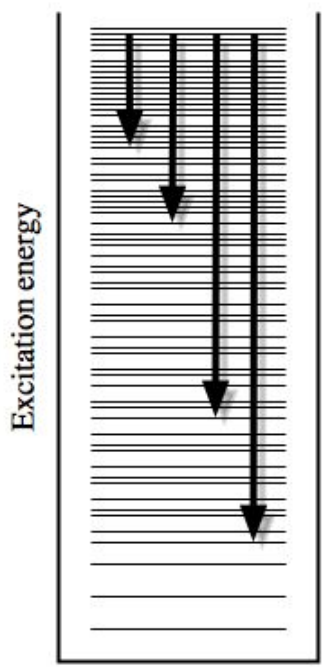
$$f(E_\gamma) \simeq \frac{1}{2\pi} \frac{\mathcal{T}(E_\gamma)}{E_\gamma^3}$$

From the primary gamma spectra: functional form of level densities and γ strength functions

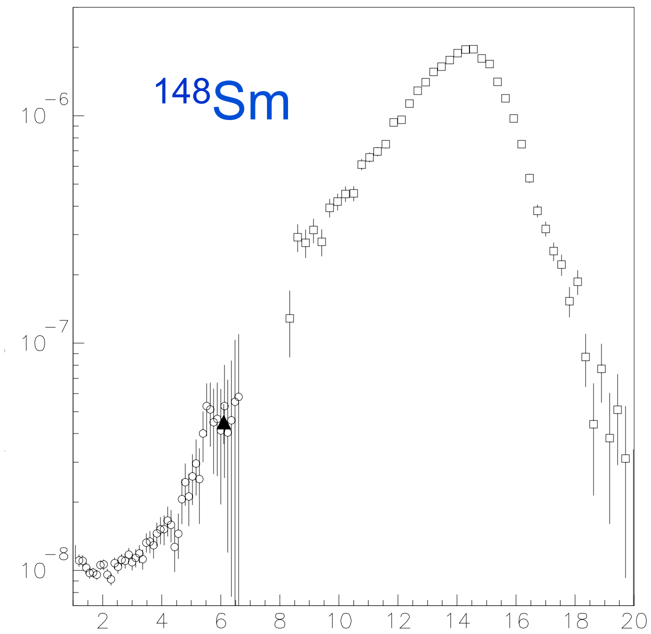
Level density MeV-1



Excitation energy MeV



γ-strength function MeV-3



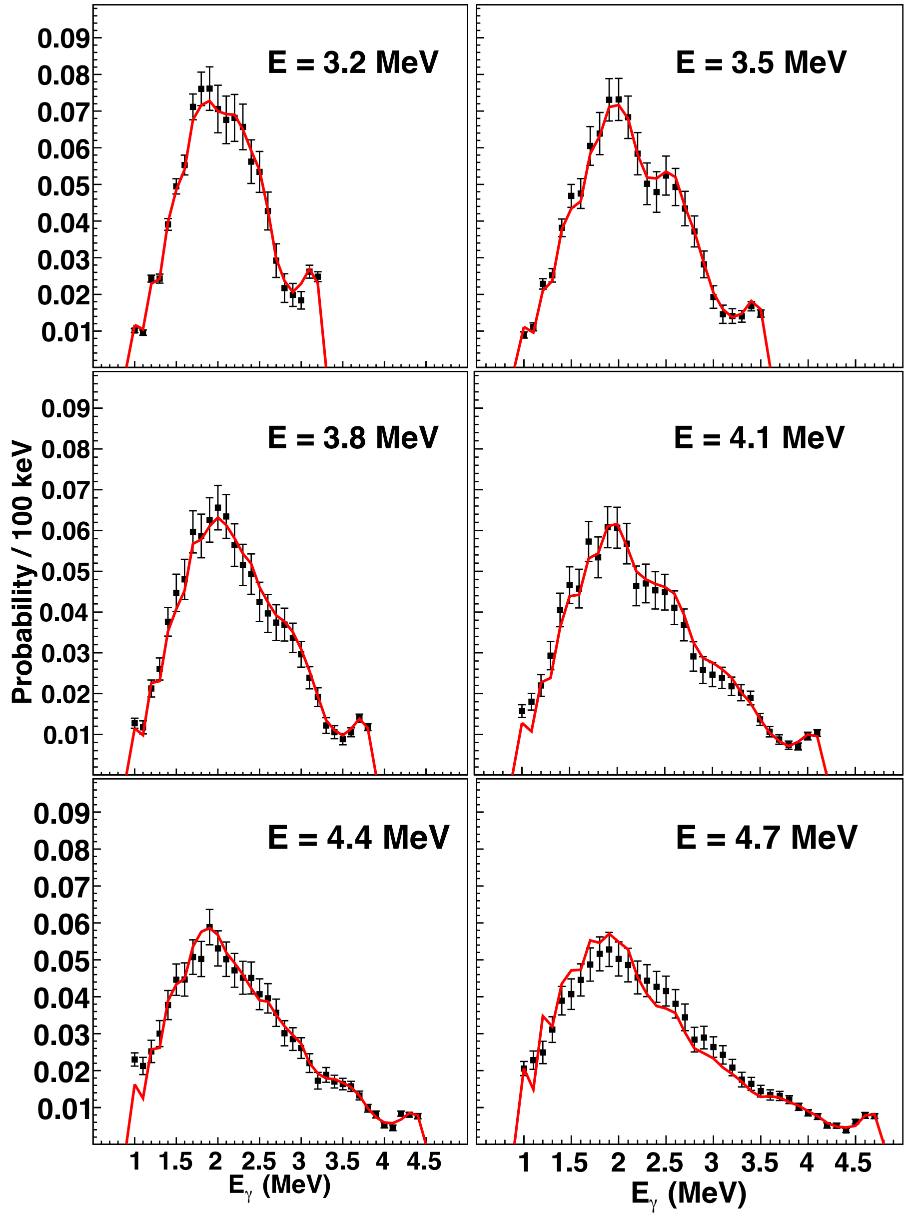
γ-ray energy MeV

We rely on other nuclear data for normalization!

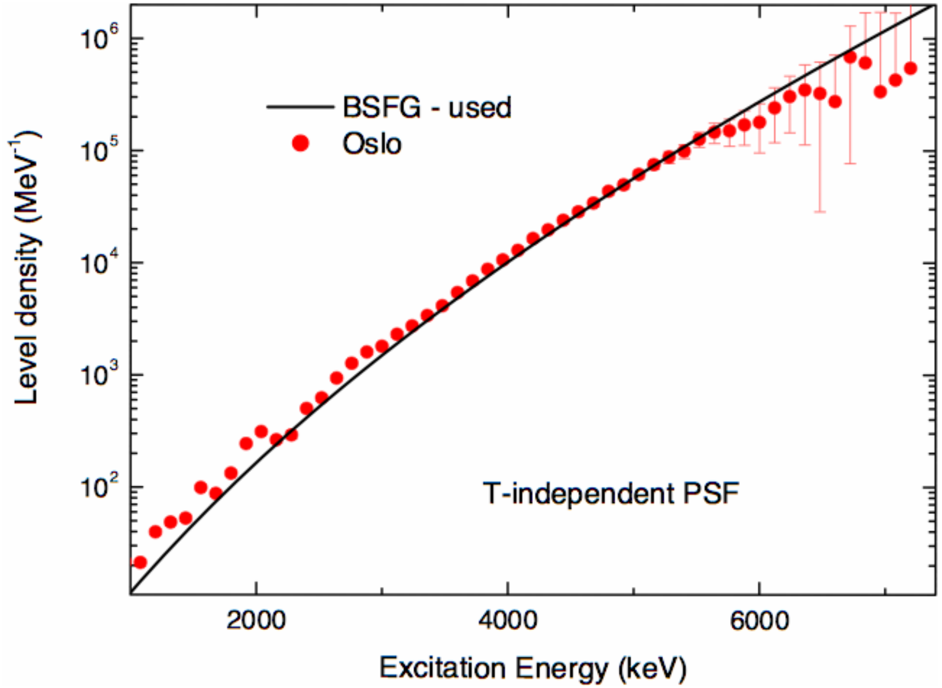
How well does it really work?

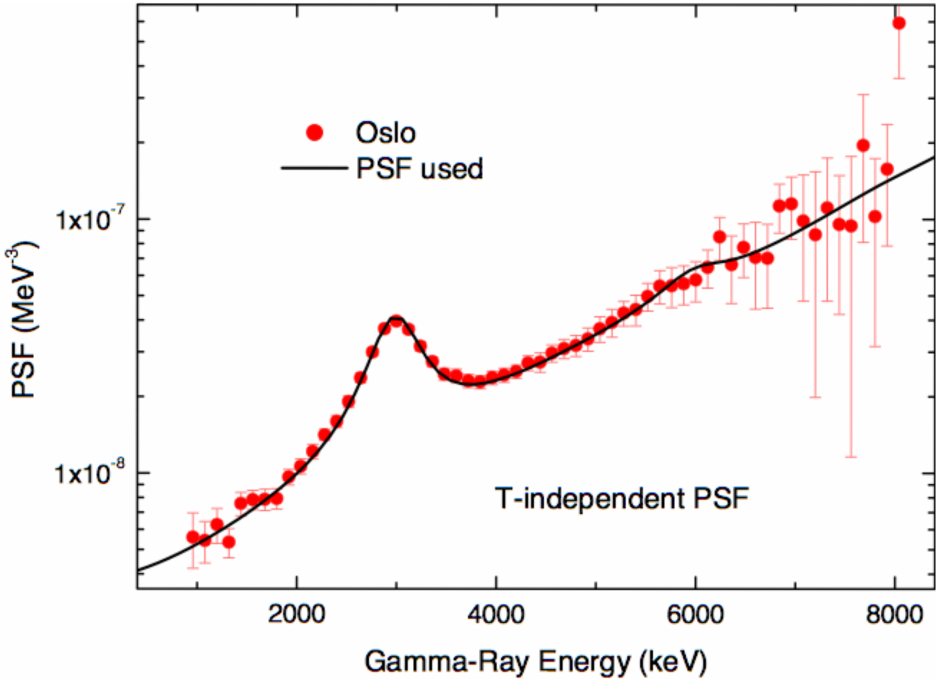
$$P \sim \rho(E_f) \cdot f(E_\gamma) \cdot E_\gamma^{3}$$

^{233}Th-data



Blind test of method





Collaboration with Milan Krticka

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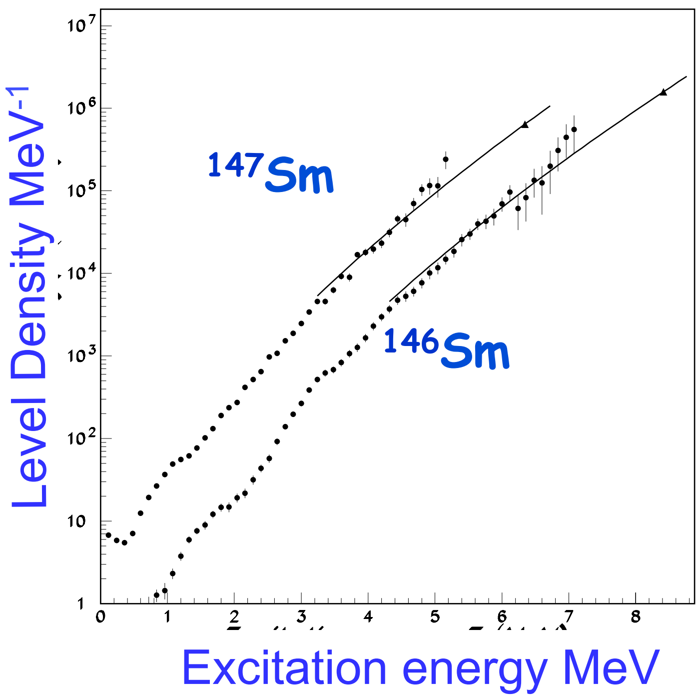
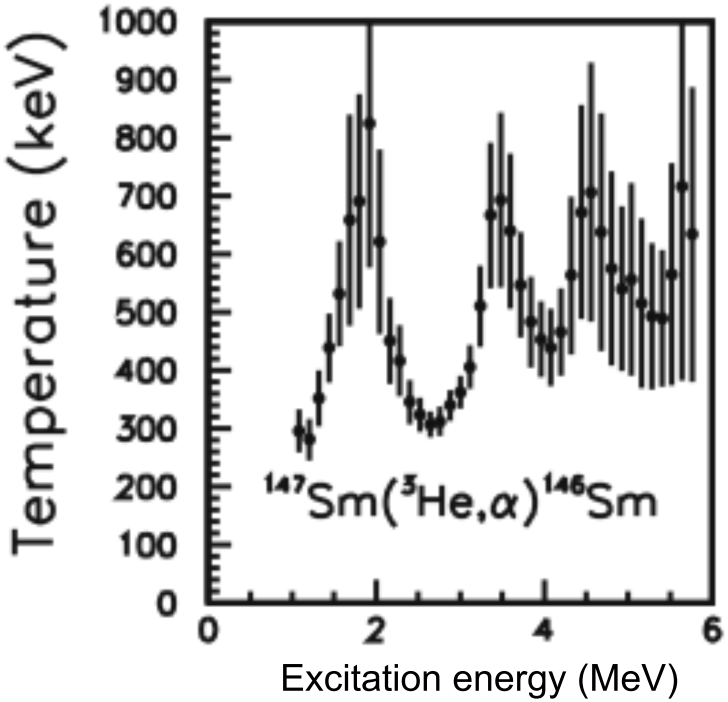
Thermodynamic properties of atomic nuclei

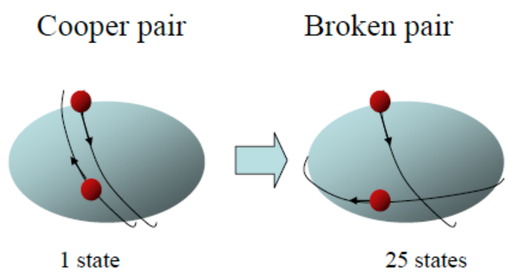




Level density ⇒ entropy ⇒ temperature

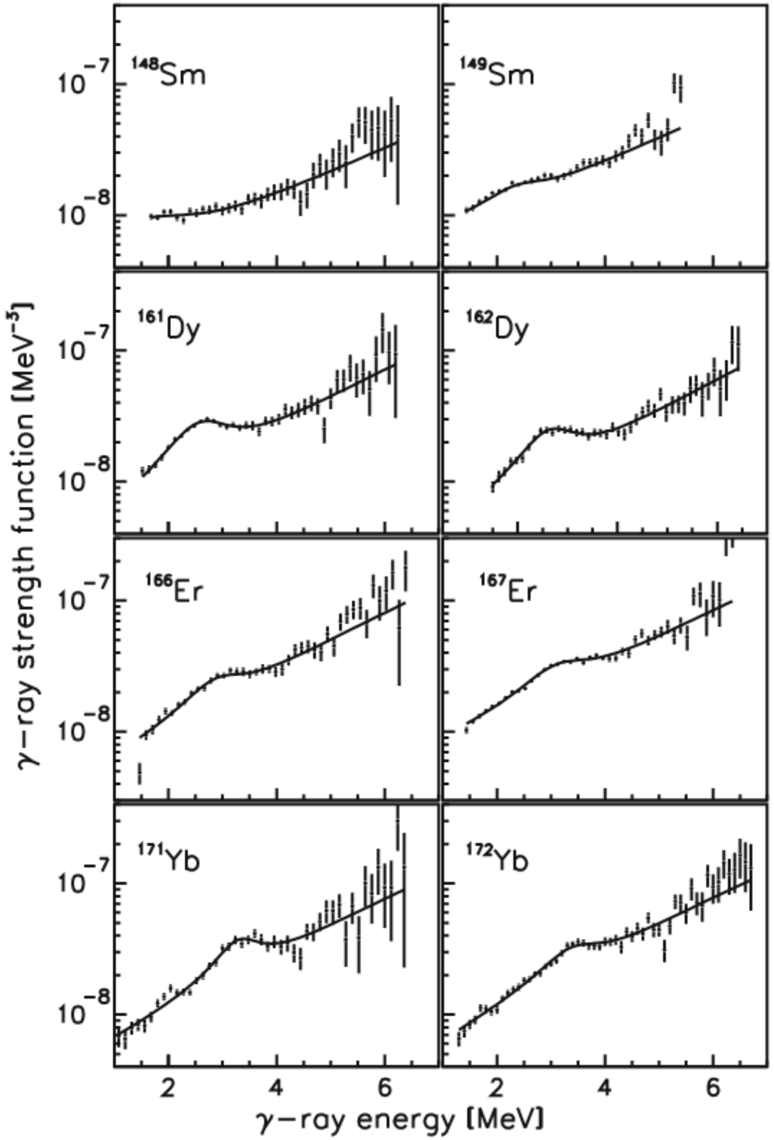
$$S(E) = k_B \ln\left[\rho(E)/\rho_0\right]$$

$$T(E) = \left(\frac{\partial S(E)}{\partial E}\right)_V^{-1}$$

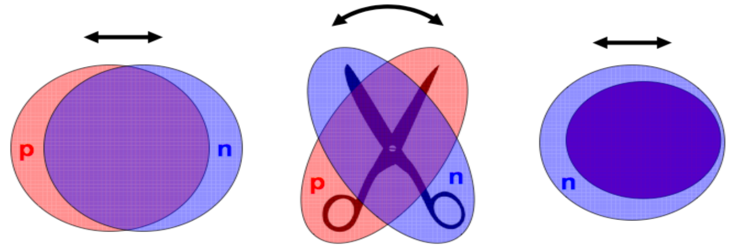


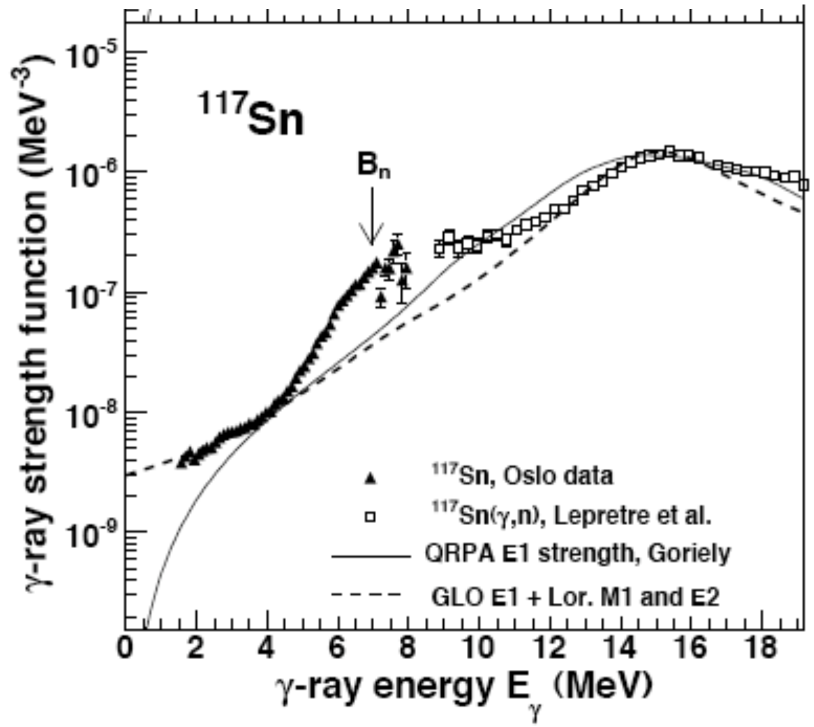
pairing phase transition

Small (Pygmy) resonances on the tail of the Giant Dipole Resonance



S.Siem et al. PRC(2002)



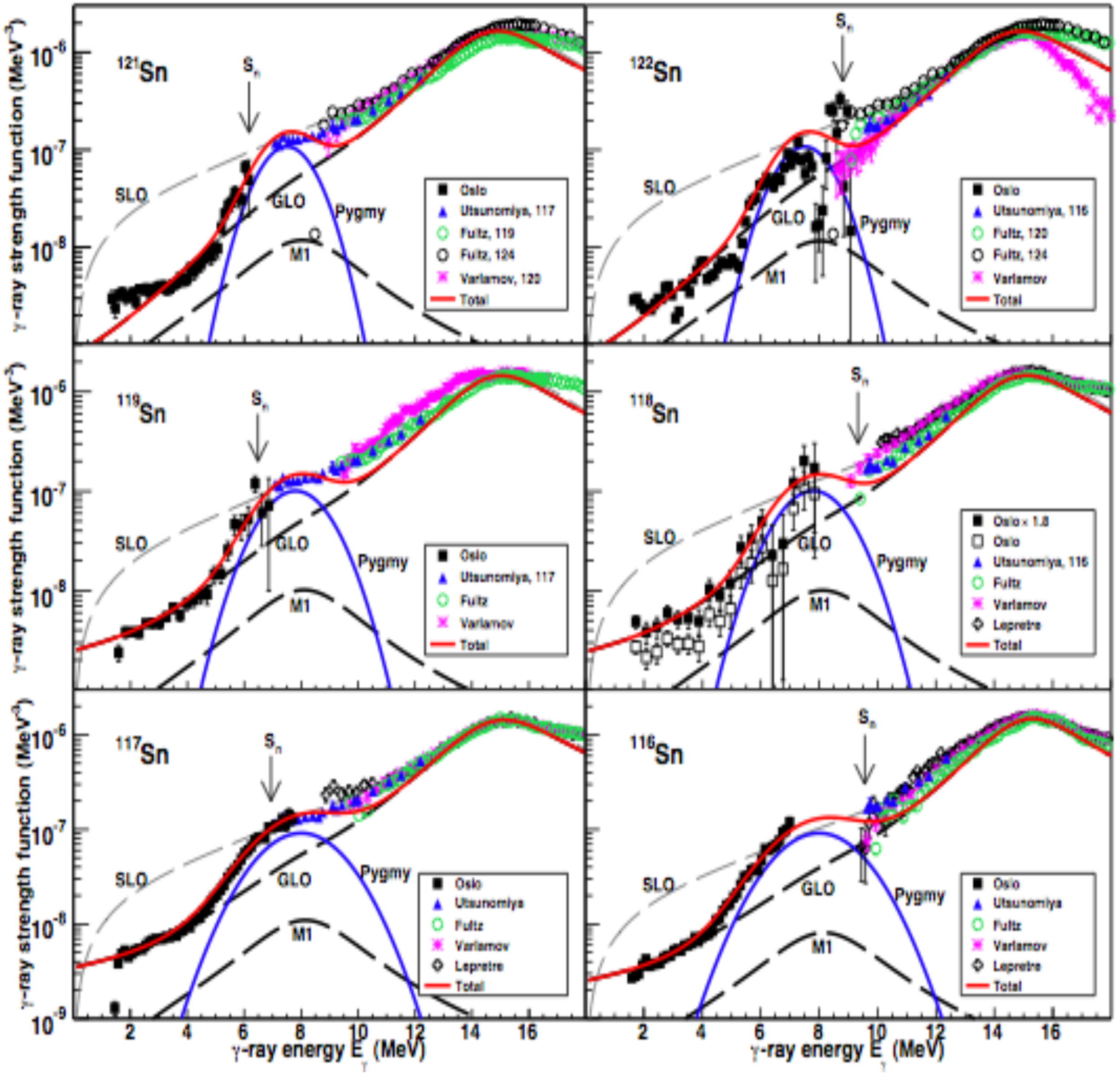


U.Agvaanluvsan et al. PRL(2009)

Strength of pygmy:
1.8 % of the TRK sum rule

no, increase with neutron number as expected

H.Toft et al. PRC 83, 044320 (2011).



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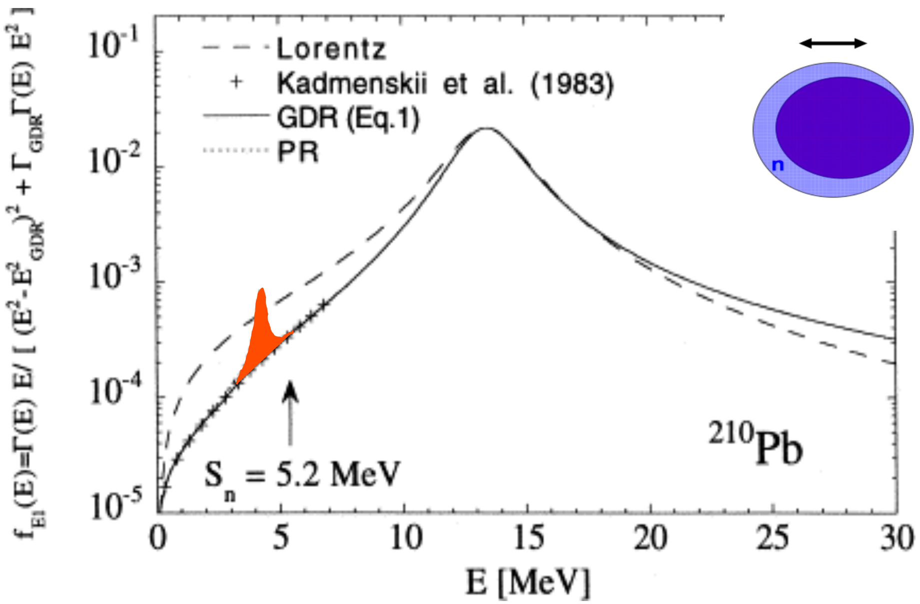
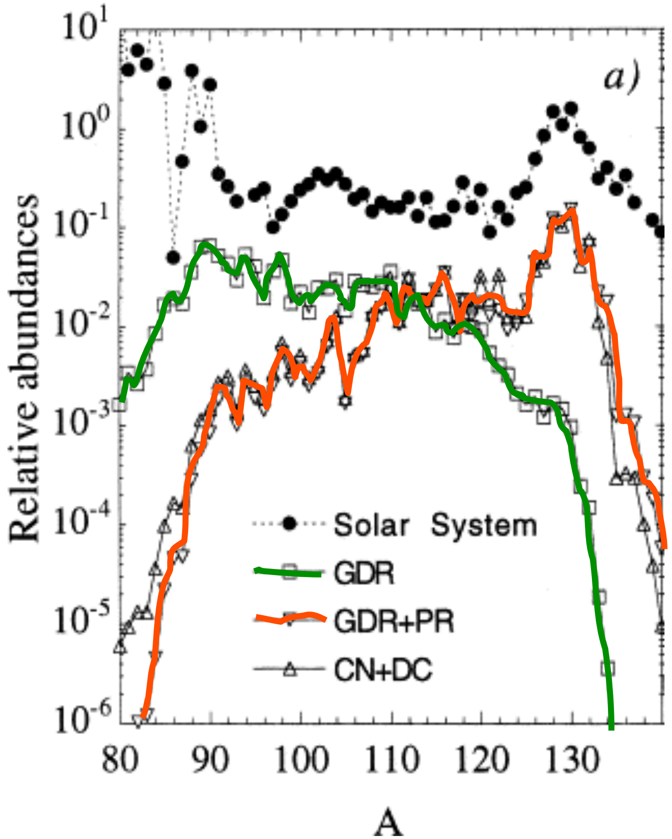
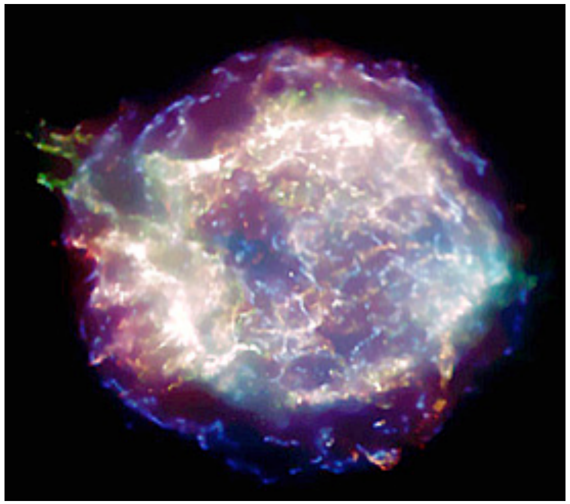


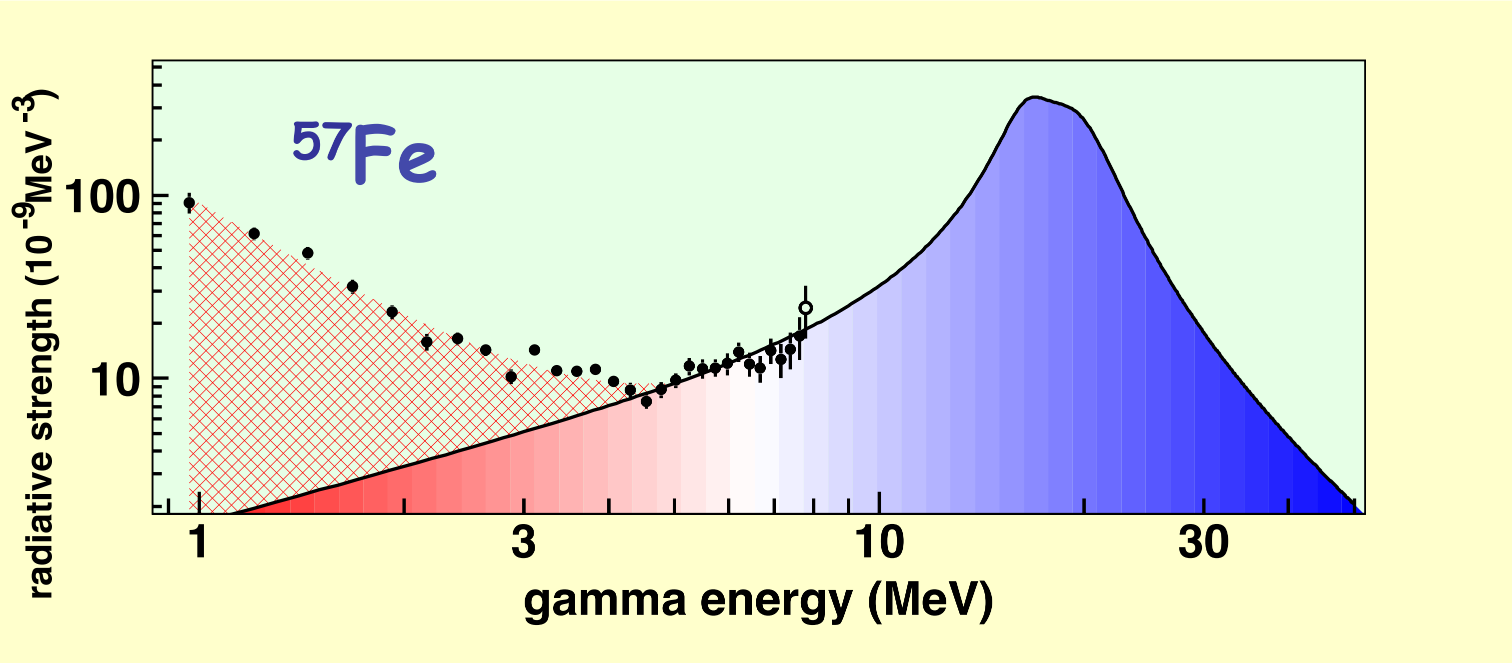
S. Goriely Phys. Lett. B 436 (1998)





Small resonances in the strength function can effect the results of abundance calculations

Low energy enhancement of the strength function



Unexpected and so far the physics behind
is unexplained

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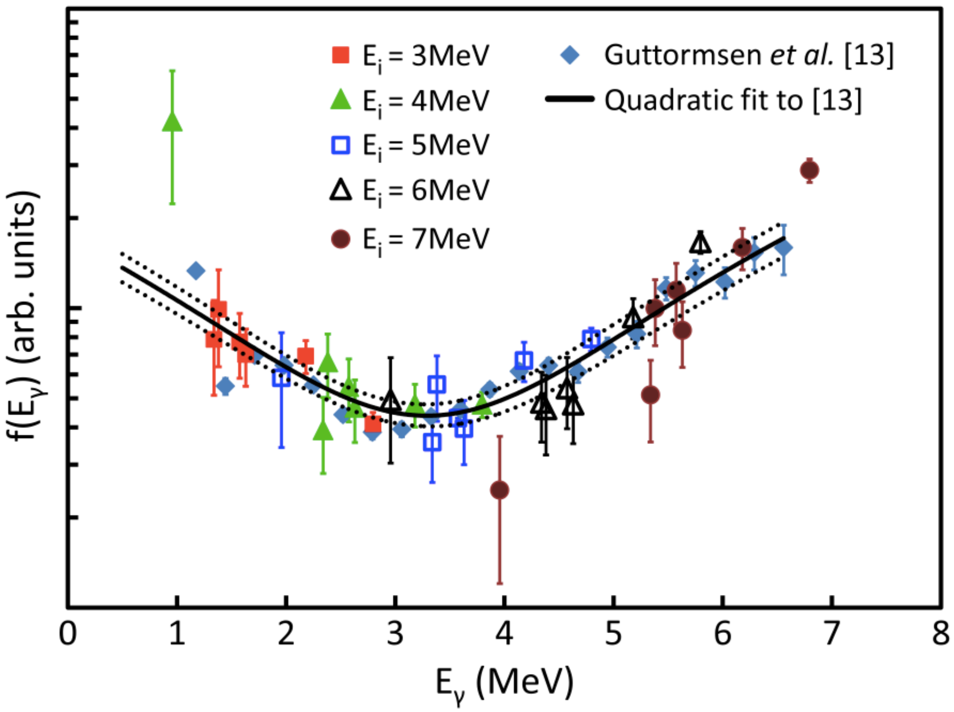
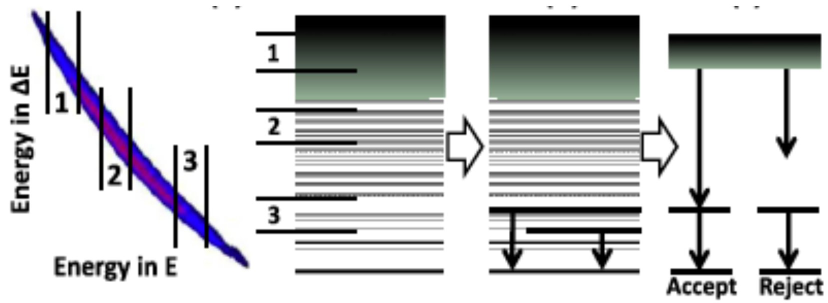
The low energy enhancement was recently confirmed in ^{95}Mo

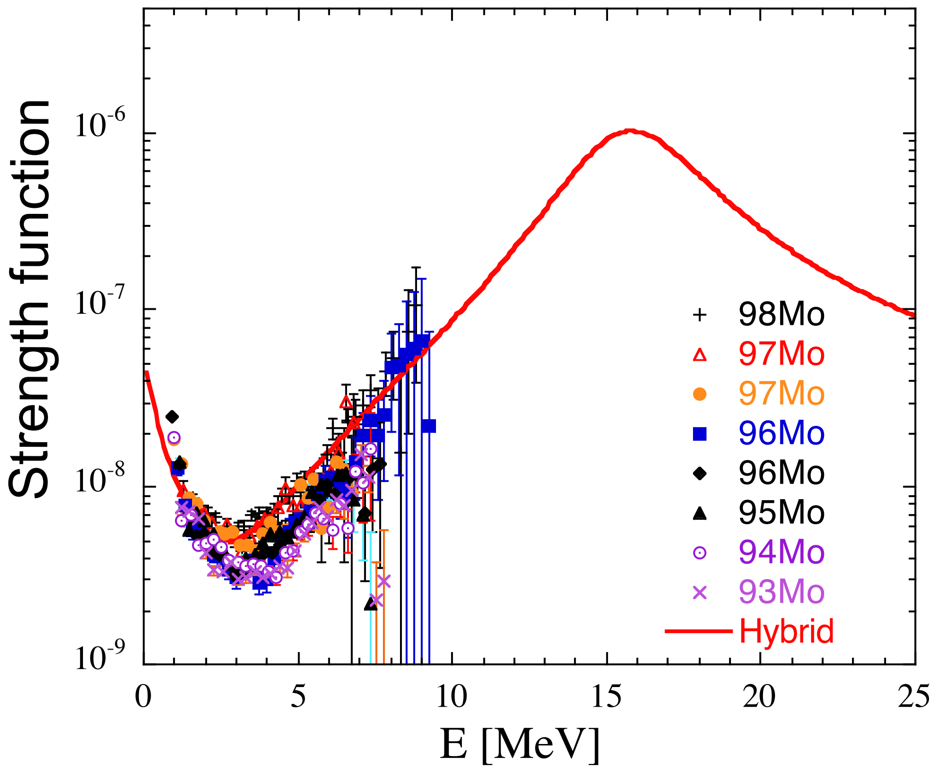
M. Wiedeking, L. A. Bernstein *et al.,* PRL 108, 162503 (2012)



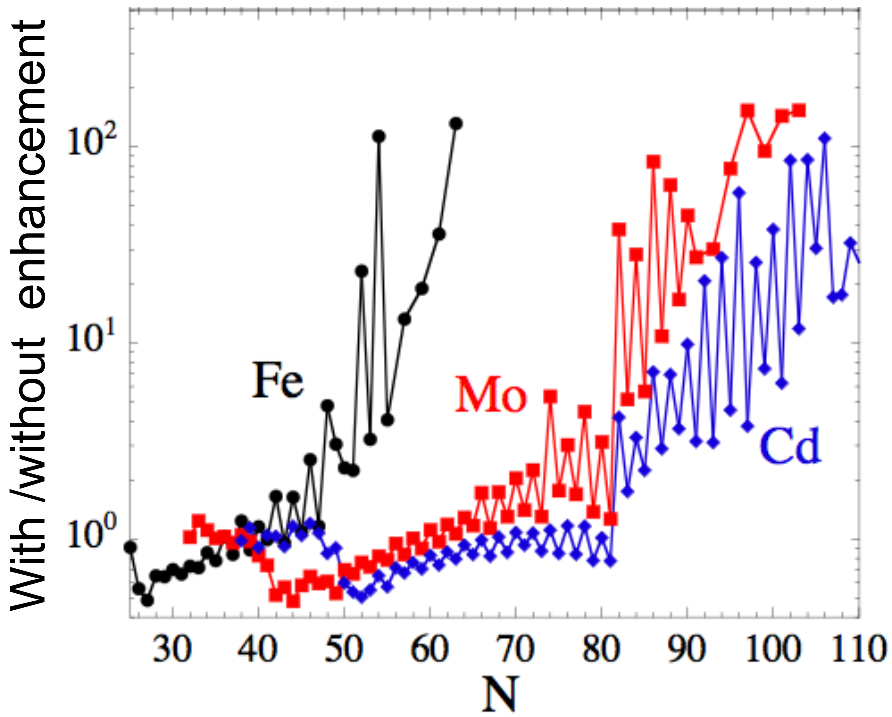


Proton-γ-γ correlations from the ^{94}Mo(d,p)^{95}Mo reaction (experiment at Berkeley National Lab).
Ge detectors. **Completely model-independent!**

How does the enhancement affect neutron capture cross sections?



Assuming the strength functions of Mo isotopes all have the same energy trend



A.C.Larsen et al. PRC (2010)

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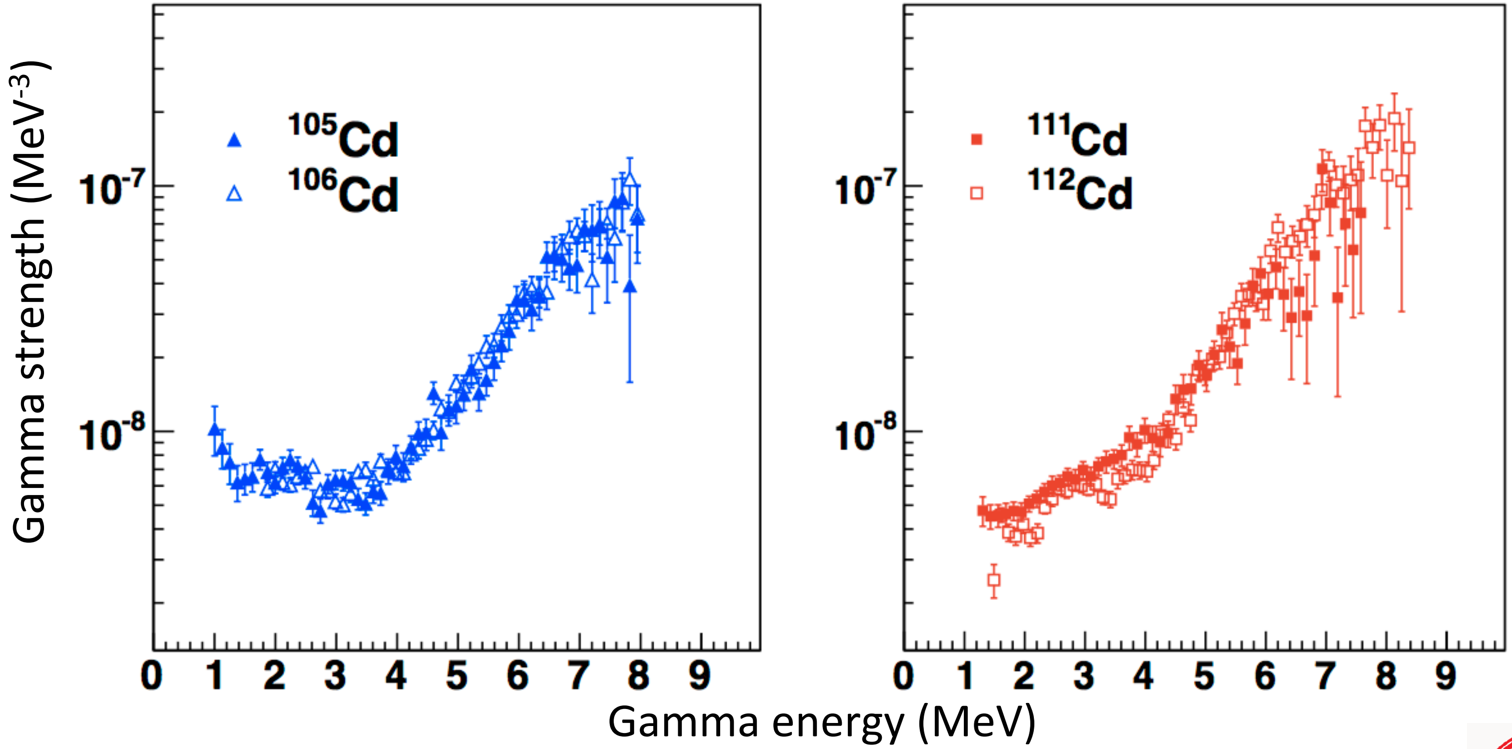
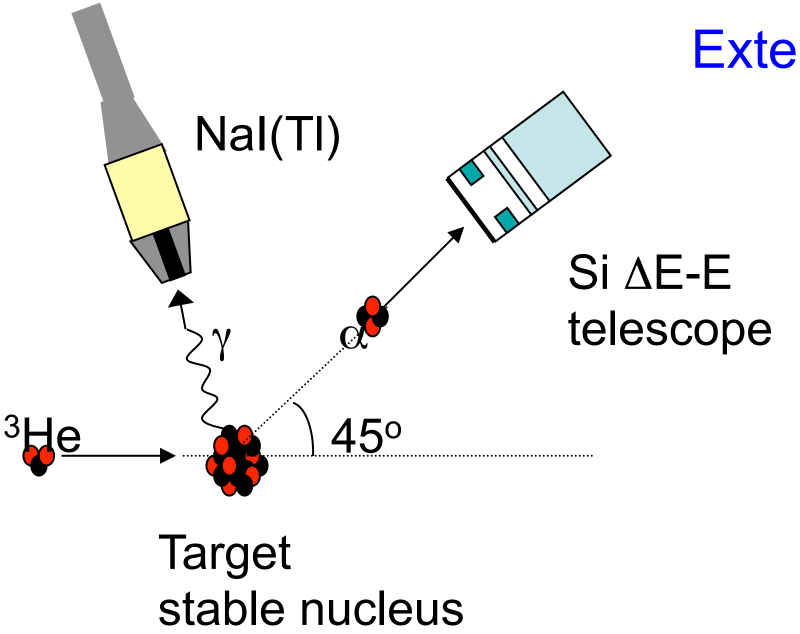
New data on Cd isotopes

A.C.Larsen et al. Phys. Rev. C 87, 014319 (2013)

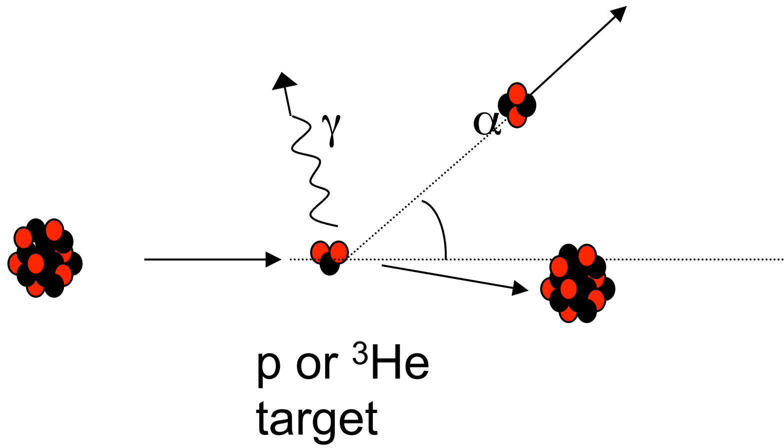


Many thanks to Cath Scholey @ JYFL for lending us the ^{106,112}Cd targets!

Extension of Oslo method to exotic nuclei



Oslo Method today:
only stable nuclei

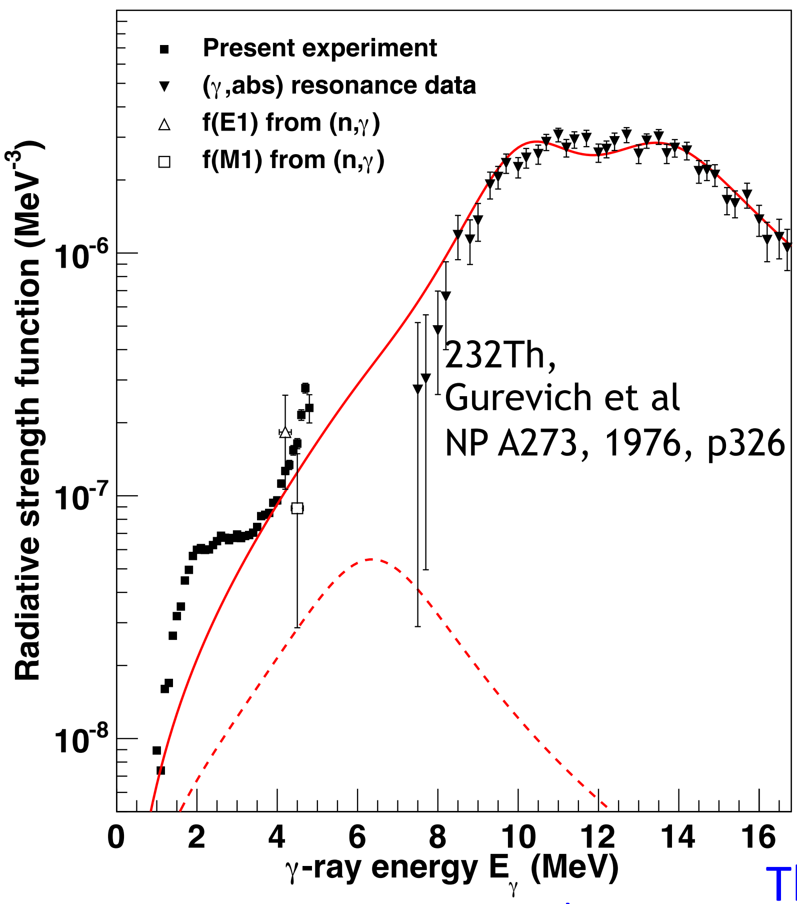


Exotic nuclei:
Inverse kinematics
with radioactive beams

We have an accepted proposal at HIE-ISOLDE

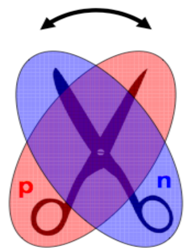
Nuclear data for reactor physics: Level density and strength functions in the actinide region

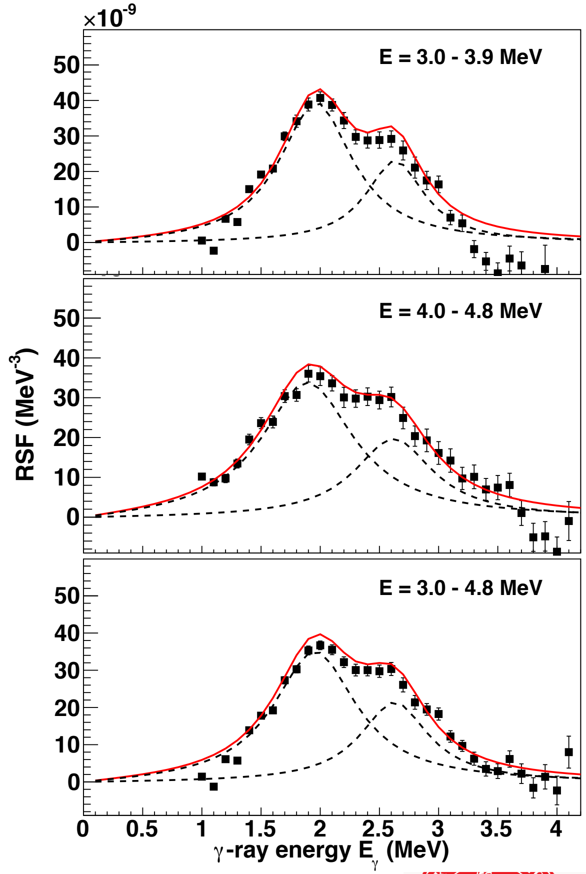
$^{232}Th(d,p)^{233}Th$



M. Guttormsen et al PRL (2012)

Scissors mode?

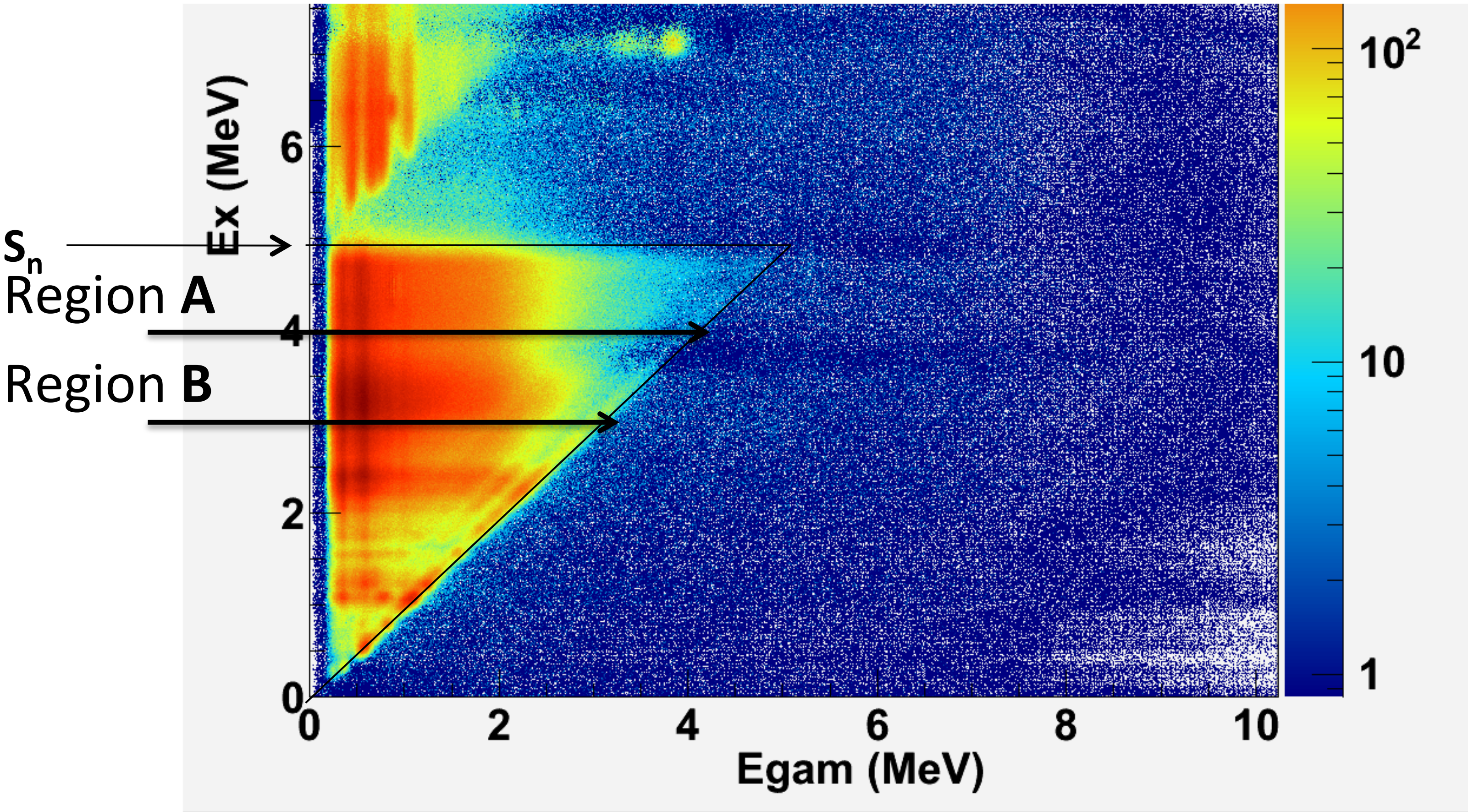




Thanks to Livermore for providing the target!

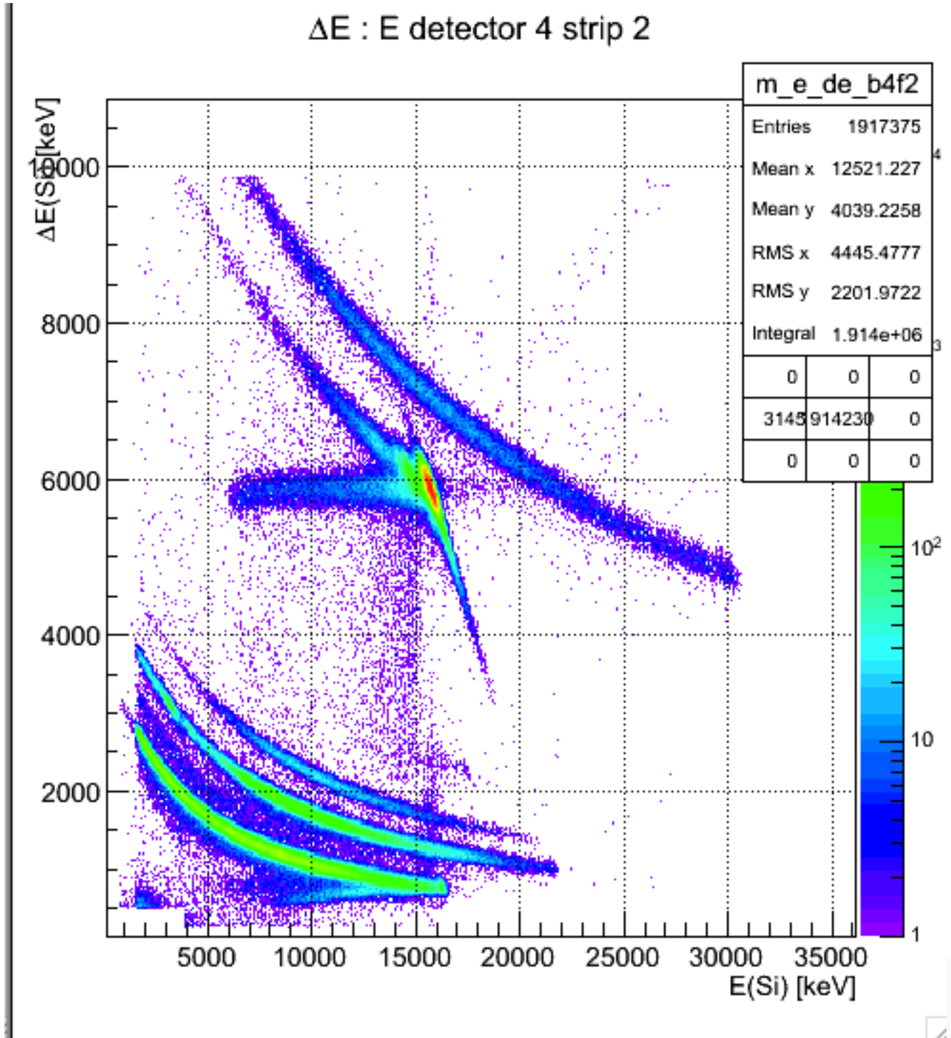
Test of Brink-Axel:
Two statistical independent data sets

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

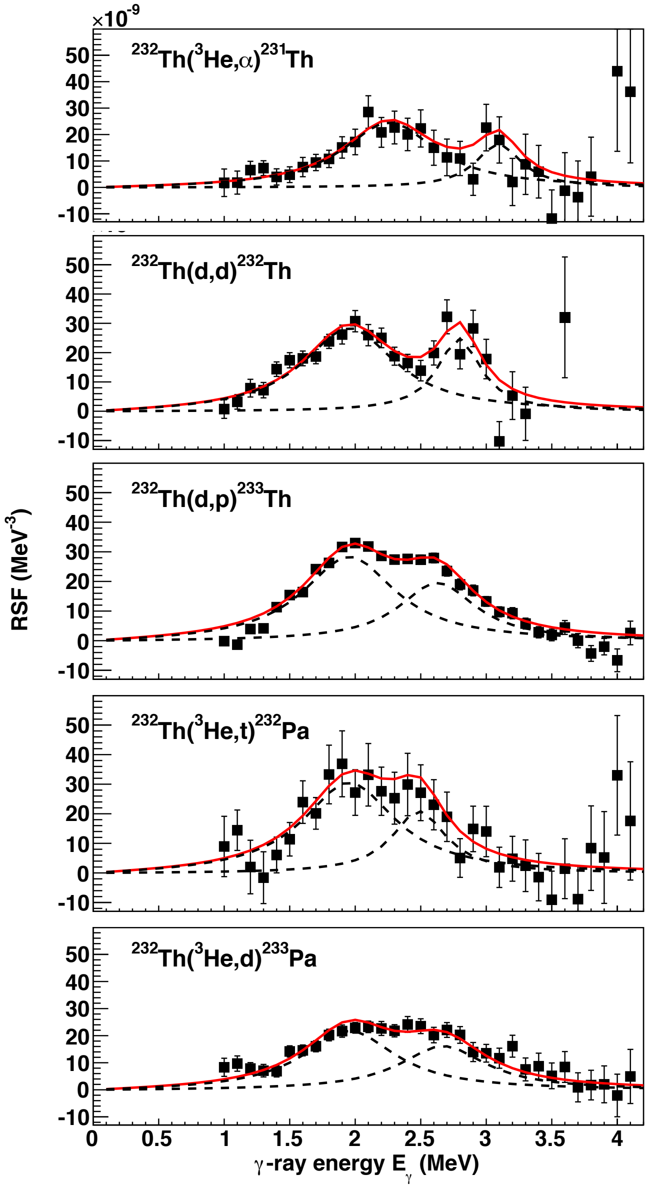


ΔE-E bananas

Several data setts from one experiment ;-)
$^{232}Th(^{3}He,x)$



M. Guttormsen et al.



M. Guttormsen et al PRL (2012)

- The scissor mode in actinides has huge strength of ~18 μ^2
- The resonance is located at Eγ ~2–2.5 MeV lower than for rare earth nuclei 2.5–3 MeV, indicating more softness

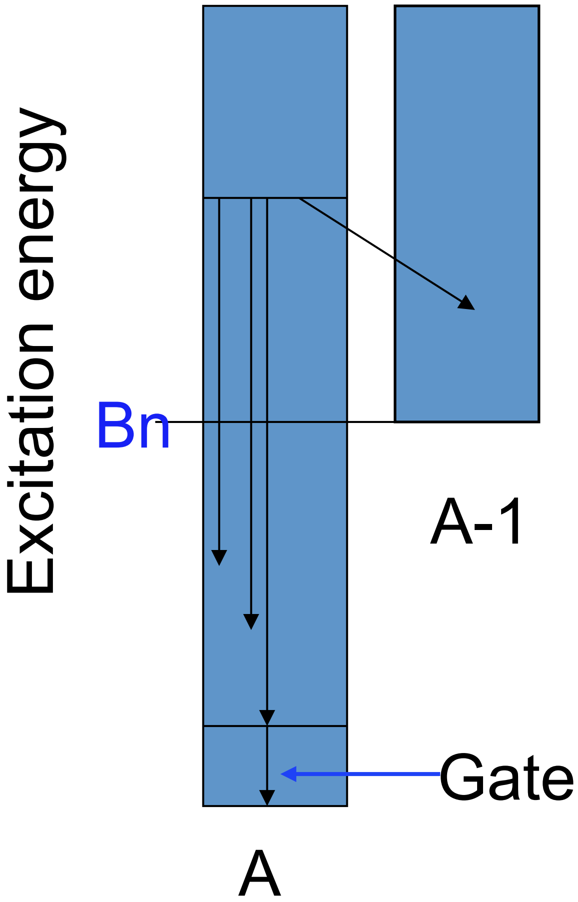
TABLE II: Scissors mode parameters (see text).

Nuclide	δ	ω_{M1} MeV	B_{M1} μ_N^2	$\omega_{M1}S_{-1}$ μ_N^2
^{231}Th	0.183	2.49(20)	11.2(30)	17.4
^{232}Th	0.192	2.23(20)	13.8(40)	15.8
^{233}Th	0.200	2.24(10)	15.3(20)	16.0
^{232}Pa	0.192	2.14(20)	14.7(40)	15.1
^{233}Pa	0.192	2.29(20)	12.7(30)	16.3

$$B_{M1} = \frac{9\hbar c}{32\pi^2}\left(\frac{\sigma\Gamma}{\omega_{M1}}\right),$$

Future plans:

Replace CACTUS detectors with LaBr3 detectors



- Better time and energy resolution
- high efficiency for high energy gamma rays.
- Extend Oslo method to Ex above Bn.
- Study competition between γ and particle decay.
- Study spin dependence of level density
- March 2012 exp in Oslo with 6 LaBr3 (3.5"x8") barrowed from the Milano group.
- We recieved funding for first 2 LaBr3 in 2012 ;-)

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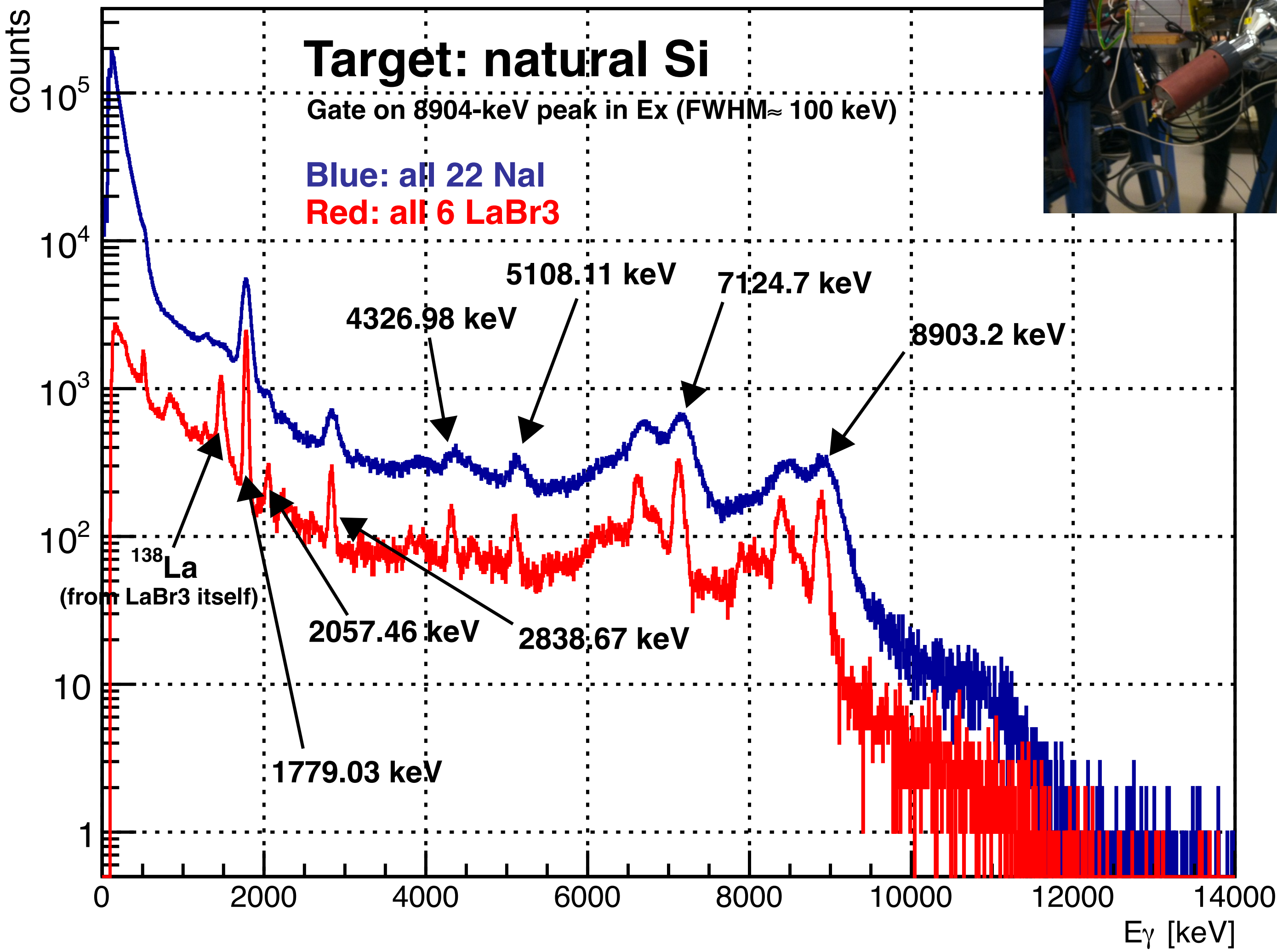
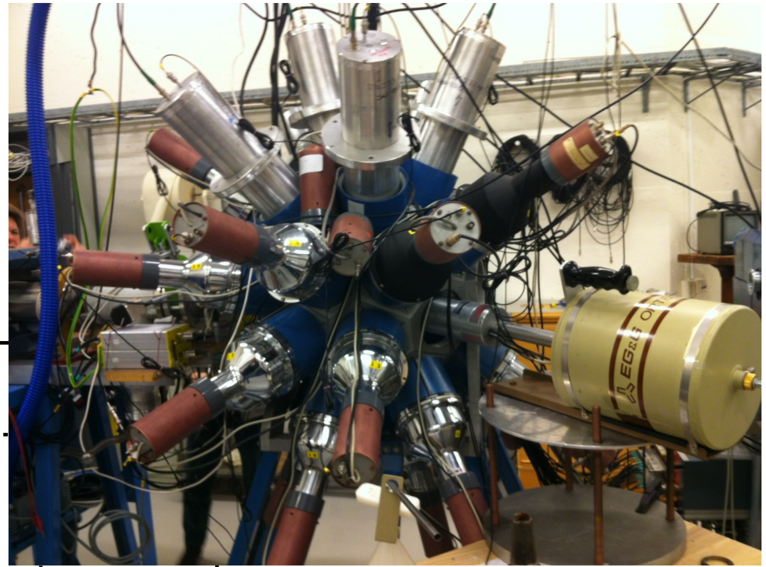
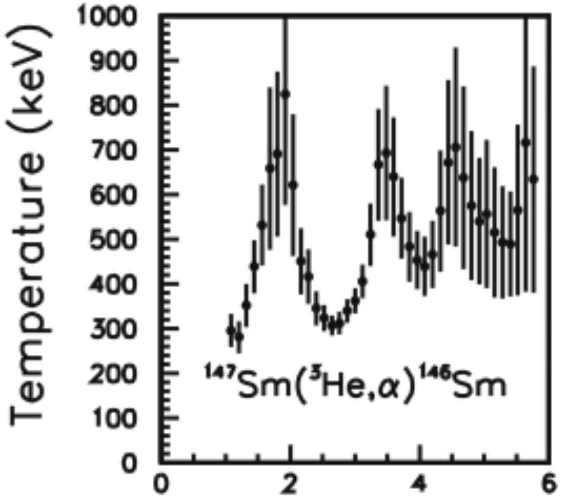
Example of difference in energy resolution:

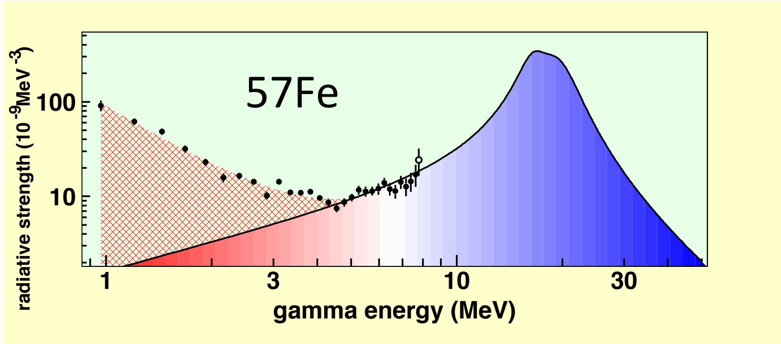




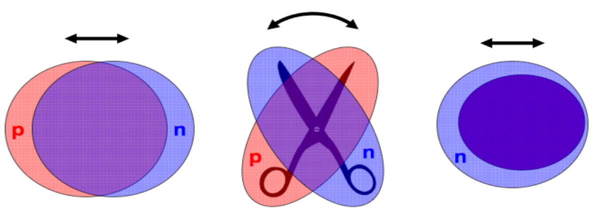
Summary



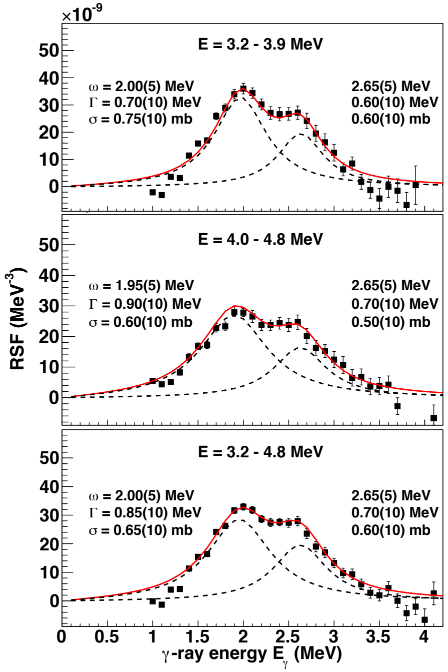
Temperature (keV)
1000
900
800
700
600
500
400
300
200
100
0
0
2
4
6
$^{147}Sm(^{3}He,\alpha)^{146}Sm$



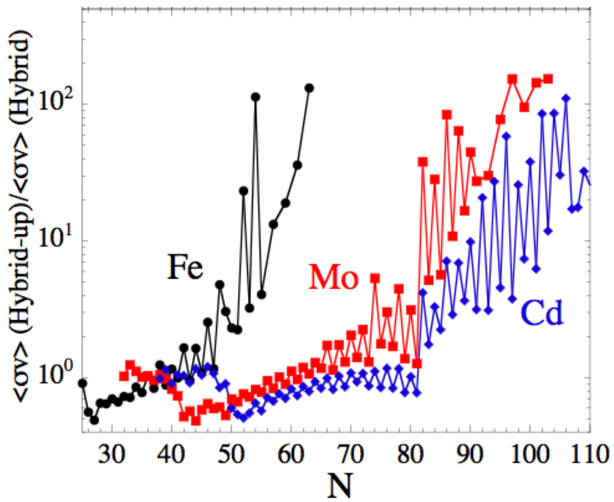
57Fe
radiative strength (10^{-9}MeV^{-3})
100
10
1
3
10
30
gamma energy (MeV)



p
n
p
n
n



$\times10^{-9}$
RSF (MeV^{-3})
E = 3.2 - 3.9 MeV
ω = 2.00(5) MeV
Γ = 0.70(10) MeV
σ = 0.75(10) mb
2.65(5) MeV
0.60(10) MeV
0.60(10) mb
E = 4.0 - 4.8 MeV
ω = 1.95(5) MeV
Γ = 0.90(10) MeV
σ = 0.60(10) mb
2.65(5) MeV
0.70(10) MeV
0.50(10) mb
E = 3.2 - 4.8 MeV
ω = 2.00(5) MeV
Γ = 0.85(10) MeV
σ = 0.65(10) mb
2.65(5) MeV
0.70(10) MeV
0.60(10) mb
0
0.5
1
1.5
2
2.5
3
3.5
4
γ-ray energy E_γ (MeV)



<σv> (Hybrid-up)/<σv> (Hybrid)
10^2
10^1
10^0
Fe
Mo
Cd
30
40
50
60
70
80
90
100
110
N

SAINT-GOBAIN
CRYSTALS

Future outlook and challenges:

- Ongoing analysis: $^{105\text{-}108}Pd$, $^{59,60}Ni$, $^{90\text{-}92}Zr$, $^{105,106,111,112}Cd$, $^{233,234,235}U$, $^{237,238}Np$, and ^{74}Ge
- $^{197}Au(d,p)$ and $^{197}Au(^{3}He, x)$ Nov/Dec. 2012 (F. Giacoppo)
- What is the origin of the enhancement of low energy γ emission of exited nuclei.
- Impact of this enhancement/pygmy resonances on large network calculations of formation of elements in stars.
- Go to higher spin, investigate the level density as a function of both spin and temperature.
- Accepted proposal: Oslo method in inverse kinematics to study neutron rich nuclei at HIE-ISOLDE, CERN

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Initiative to
Evaluate of Reaction γ-ray Data

R.B. Firestone, Lawrence Berkeley National Laboratory
S. Siem, Oslo University

Result of Rick spending sabbatical in Oslo fall 2012

Motivations

Measurements of particle/γ-ray data has become a major activity of the nuclear structure community.

- **Statistical properties** of the nucleus at high level densities – level density, photon strength, spin/parity
- **Surrogate reaction** measurements of nuclear cross sections
- **Nuclear transport** calculations – RIPL
- **Nuclear astrophysics** calculations – nucleosynthesis

These data are not evaluated in ENSDF or other data files

- These data would **complete ENSDF** coverage
- ENSDF would be the **natural repository** for this data
- The **Oslo Cyclotron group** is interested in leading this effort

OCL data compilation

Published level density and γ-strength data:

^{43,44,45}Sc, ^{44,45,46}Ti, ^{50,51}V, ^{56,57}Fe, $^{93\text{-}98}$Mo, $^{116\text{-}119,121,122}$Sn, ^{148,149}Sm, $^{160\text{-}164}$Dy, ^{166,167}Er, $^{170\text{-}172}$Yb, $^{205\text{-}208}$Pb, $^{231\text{-}233}$Th, ^{232,233}Pa,

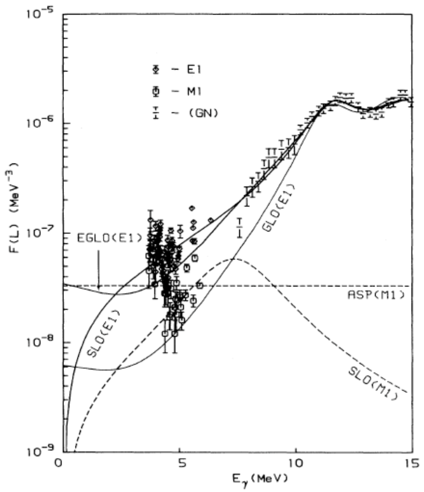
In analysis or under peer review:

^{56,57}Fe, ^{59,60}Ni, ^{73,74}Ge, $^{90\text{-}92}$Zr, ^{105,106,111,112}Cd, $^{105\text{-}108}$Pd, ^{143,144,146,147}Sm, $^{195\text{-}197}$Pt, ^{197}Au, ^{233,235,238}U, ^{238}Np

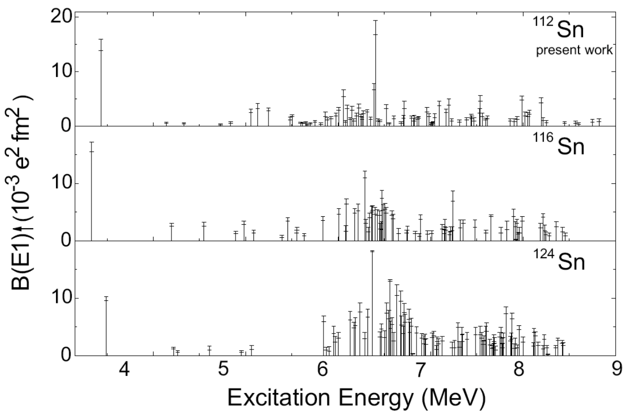
For references and to download the published data, see
http://www.mn.uio.no/fysikk/english/research/about/infrastructure/OCL/compilation/

Different gamma strength - experiments

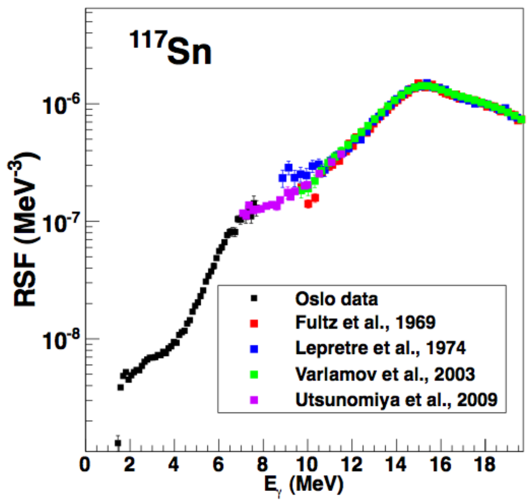
- Photonuclear reactions (above B_n)
- Primary transitions following neutron capture (around B_n)
- Nuclear resonance fluorescence (γ,γ'), electron scattering, proton scattering, ... (below B_n)
- Two-step cascade spectra following neutron/proton capture (below B_n)
- Primary γ spectra (below B_n)



[Kopecky et al, PRC 47, 312 (1993)]

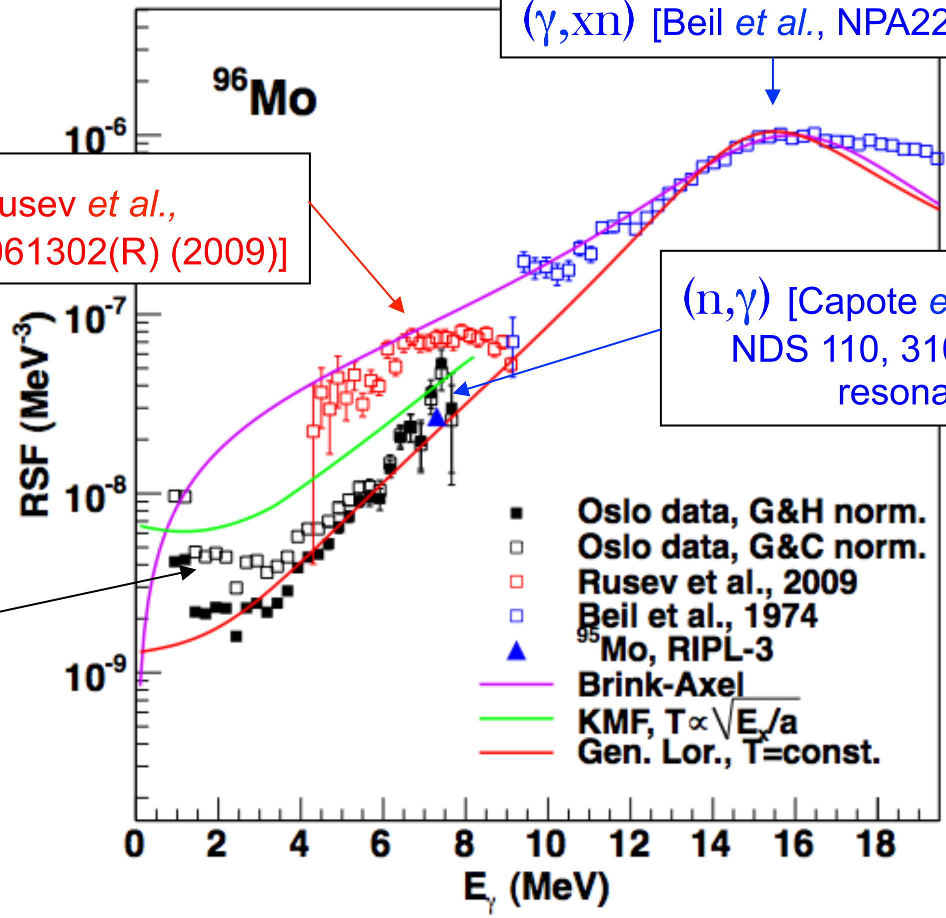


[Ôzel et al., NP A788, 385c (2007); Govaert et al, PRC 57, 2229 (1998)]



[Utsunomiya et al., PRC 80, 055806 (2009); Agvaanluvsan et al, PRL 102, 162504 (2009)]

Gamma strength – some experiments disagree, why?



(γ,xn) [Beil *et al.*, NPA227, 427 (1974)]

(γ,γ') [Rusev *et al.*, PRC 79, 061302(R) (2009)]

(n,γ) [Capote *et al.*, RIPL-3 compilation, NDS 110, 3107 (2009); coordinator resonances: Ignatyuk]

(^{3}He,^{3}He' γ) [Guttormsen *et al.*, PRC 71, 044307 (2005); Larsen & Goriely, PRC 82, 014318 (2010)]

Next Steps

- **Workshop in Oslo in May (2013)**
  Discussions/ establish a working group
- **IAEA Consultants Meeting (2013)**
  Scope the need and feasibility of this evaluation effort
- **IAEA CRP on the Evaluation of Continuum Particle/γ-ray data**
  Develop formats and procedures for these evaluations
- **Seek independent funding**
  Establish a lead evaluator position at UiO
- **Integration into the IAEA/NSDD evaluation effort**
  Coordination with RIPL, ENSDF, EGAF, …..

Collaboration: The γ-ray strength function of ^{74}Ge is being measured in several complementary experiments.

- Berkeley: ^{74}Ge(p,p´) STARS-LIBERACE (July 2011)
- Oslo: ^{74}Ge(^{3}He,α´,), (^{3}He,^{3}He´) (February 2012)
- iThemba: ^{73}Ge(α,α´) (November 2012)
- ELBE: (γ,γ´) (July 2012, + again 2013)
- FRM II (Promt gamma) in 2013

4th Workshop on Nuclear Level Density and Gamma Strength

Oslo, May 27 - 31, 2013

Navigation:

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*left for industry

Thank you for your attention!