Low-energy enhancement in the γ strength with impact on astrophysical reaction rates

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UiO : University of Oslo

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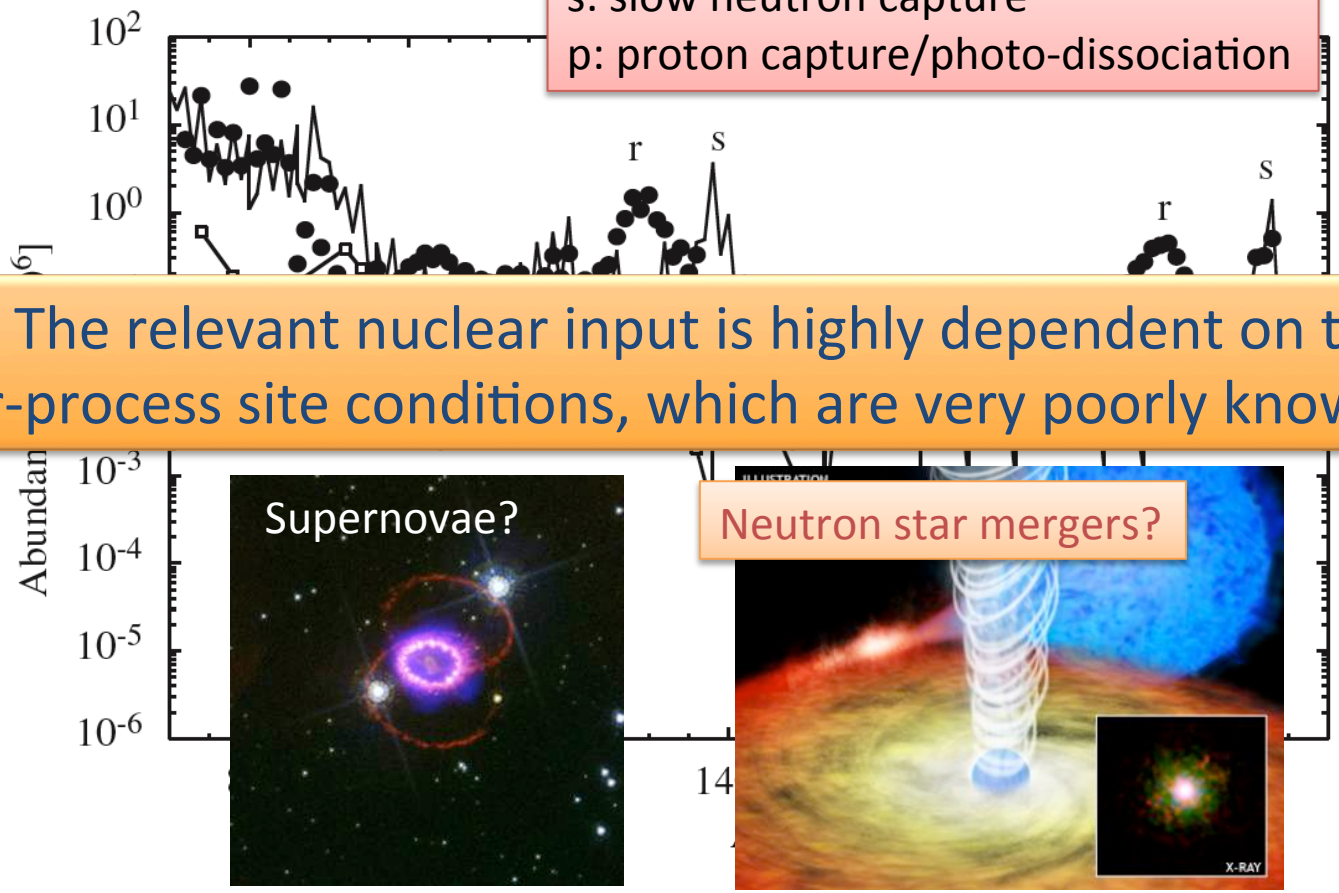
Outline

- Introduction
- Experiments @ OCL
- Low-energy enhancement in γ strength
- Astrophysical reaction-rate calculations
- New data on Cd isotopes
- Iron revisited – with $LaBr_3$(Ce) detectors
- Summary and outlook

Cassiopeia A, a 300-year-old supernova remnant. Credit: NASA/CXC/SAO

A tough nut to crack

r: rapid neutron capture
s: slow neutron capture
p: proton capture/photo-dissociation



The relevant nuclear input is highly dependent on the r-process site conditions, which are very poorly known…

[M. Arnould, S. Goriely, and K. Takahashi, Phys. Rep. **450**, 97 (2007)]

Maxwellian-averaged reaction rates

In large network calculations for the r-process:
≈ 5000 nuclei, ≈50 000 cross sections

$$N_A \langle \sigma v \rangle (T) = \left(\frac{8}{\pi m}\right)^{1/2} \frac{N_A}{(kT)^{3/2} G(T)} \int_0^\infty \sum_\mu \frac{(2I^\mu + 1)}{(2I^0 + 1)} \sigma^\mu(E) E \exp\left[-\frac{(E + E_x^\mu)}{kT}\right] dE$$

$$G(T) = \sum_\mu (2I^\mu + 1)/(2I^0 + 1) \exp(-E_x^\mu / kT)$$

Level density

Gamma strength function

OMP

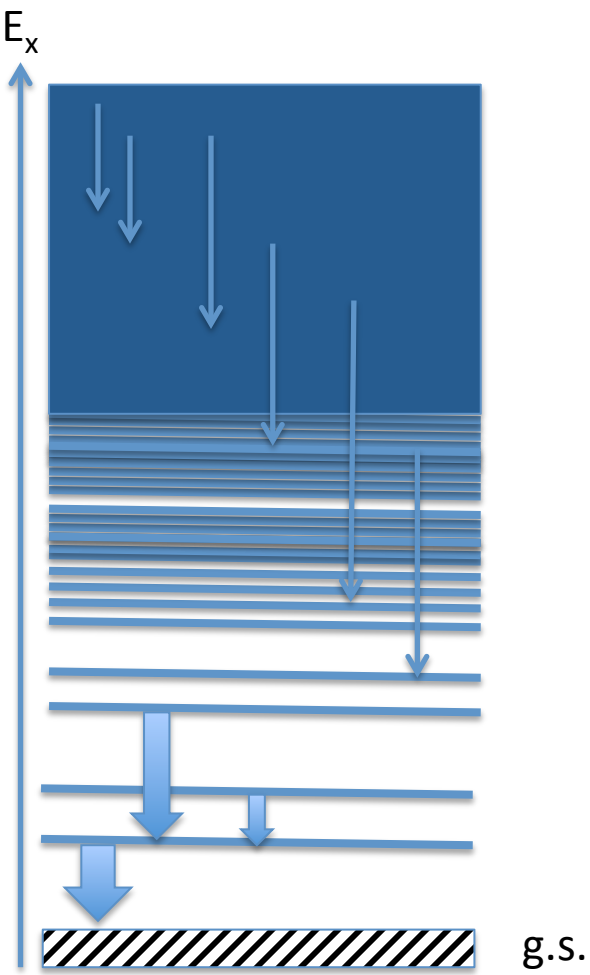
N_A: Avogadro's number; m: reduced mass of initial system; E: relative energy of projectile/target; I^μ,E_x^μ: spin/excitation energy of excited states μ; σ^μ: reaction cross section.

A quick reminder

Discrete => quasicontinuum:
Discrete levels => level density
Reduced transition probabilities => γ-strength function

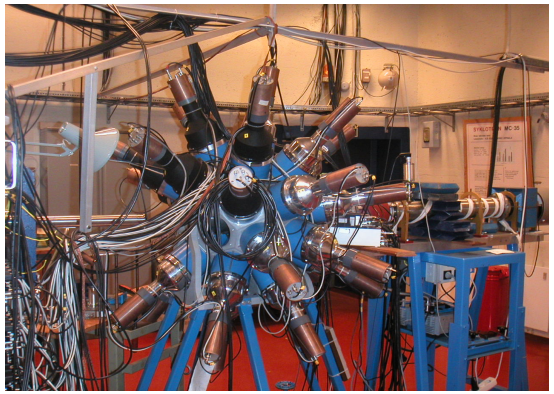
Level density:
number of nuclear energy levels per energy unit

Gamma-strength function:
average, nuclear electromagnetic response, directly related to partial decay widths

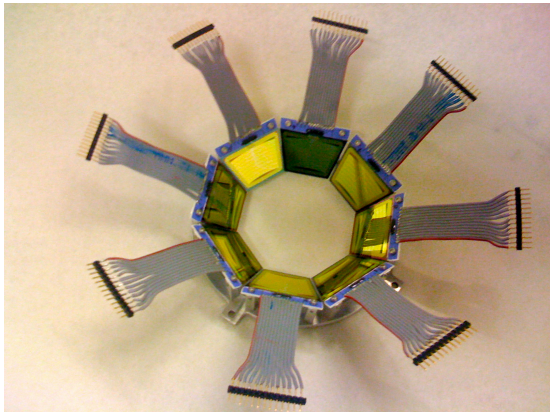


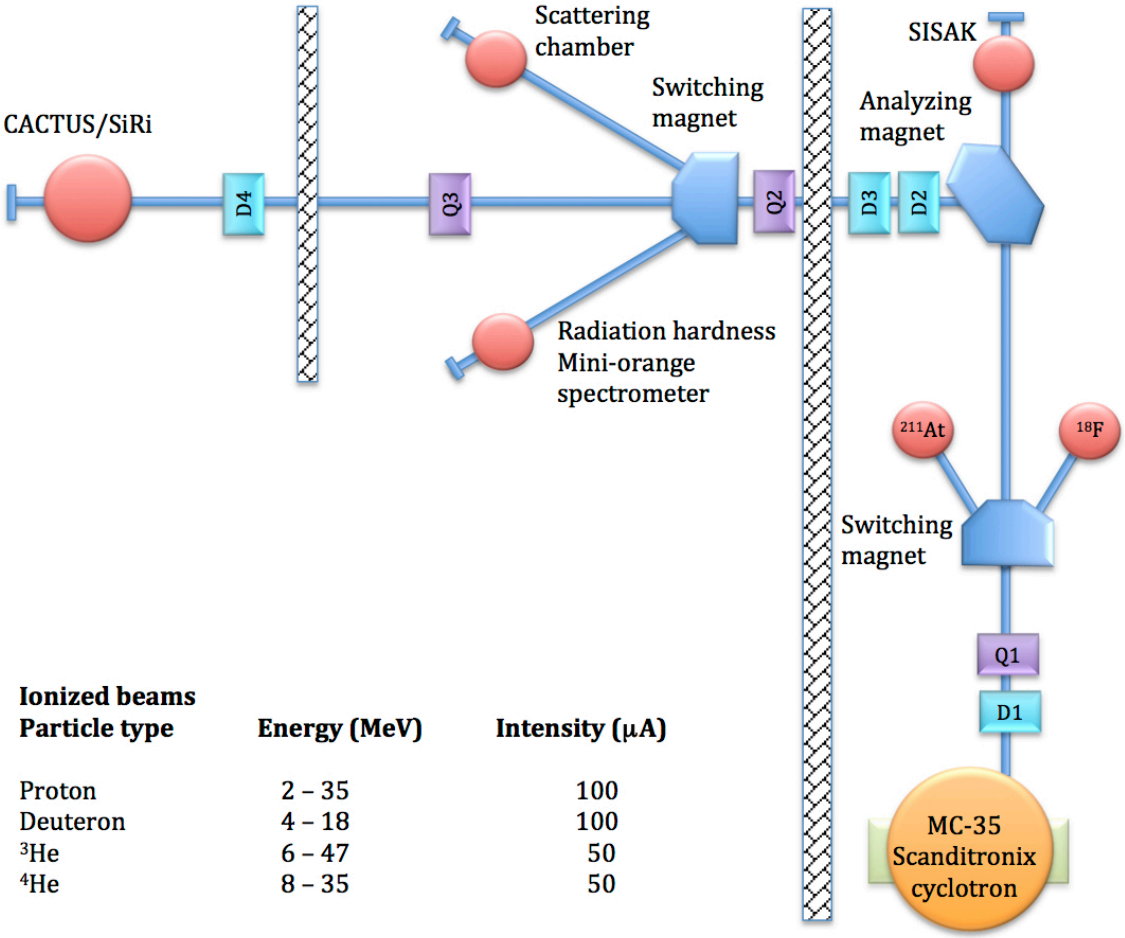
Experiments @ OCL

CACTUS: 28 collimated NaI(Tl) gamma detectors (efficiency 15.2%)



SiRi: 8x8 Si ΔE-E particle detectors (≈9% of 4π)





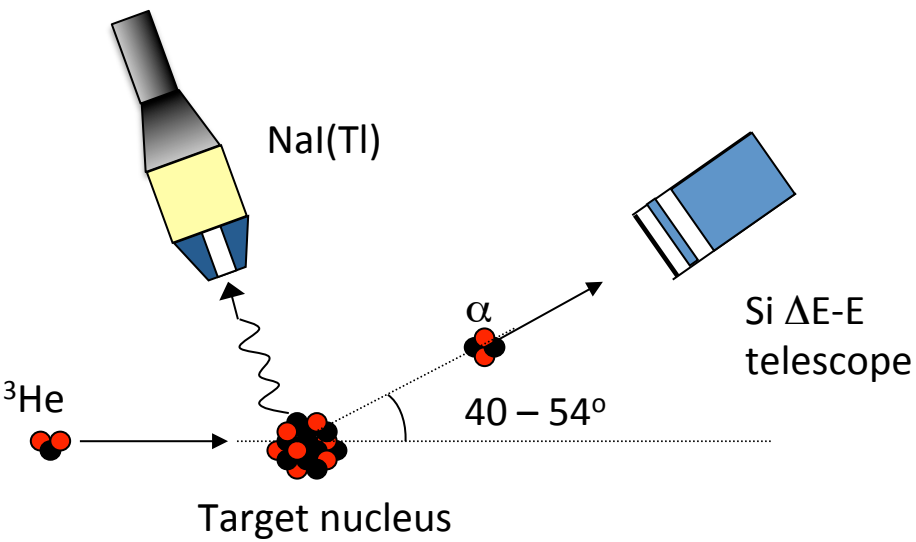
Ionized beams

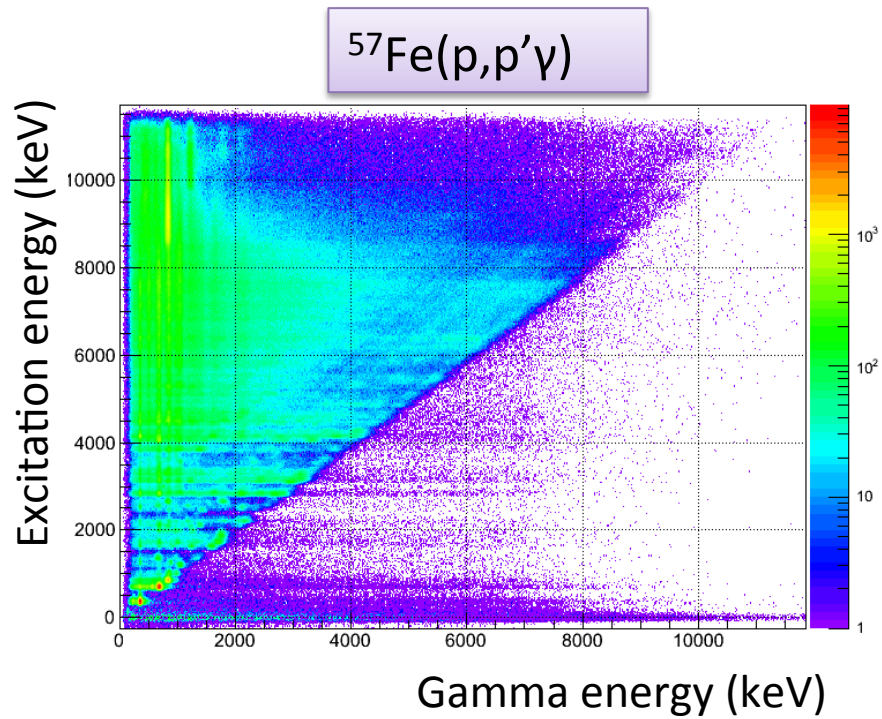
Particle type	Energy (MeV)	Intensity (μA)
Proton	2 – 35	100
Deuteron	4 – 18	100
^{3}He	6 – 47	50
^{4}He	8 – 35	50

Experimental technique

Particle-gamma coincidence measurements
(Signal in E detector is master gate)

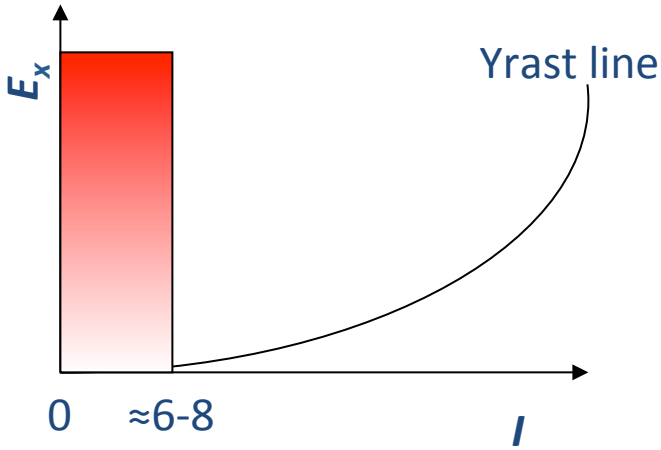
Excitation-energy tagged gamma spectra

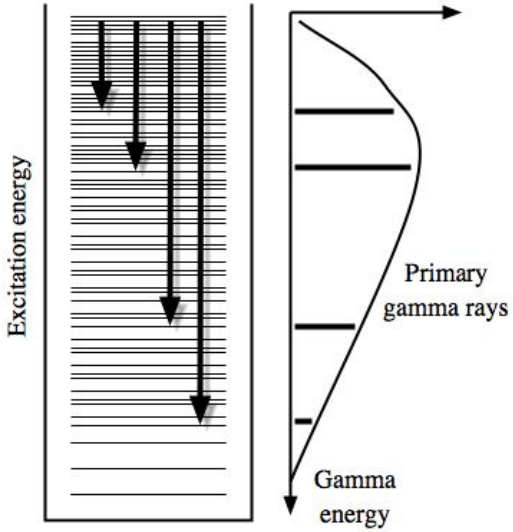




The Oslo method in a

1. Correct gamma spectra for detector response
   [M. Guttormsen *et al.*, NIM A **374**, 371 (1996)]
2. Extract primary gammas from the total gamma spectra
   [M. Guttormsen *et al.,* NIM A **255**, 518 (1987)]
3. Get level density and gamma strength from the matrix of primary gammas [A. Schiller *et al.,* NIM A **447**, 498 (2000)]





$$P(E_x,E_\gamma) \propto \rho(E_x-E_\gamma)\mathscr{T}(E_\gamma)$$

Evaluation of possible systematic errors: A.C. Larsen *et al.*, PRC 83, 034315 (2011)

OCL data

Published level density and γ-strength data:

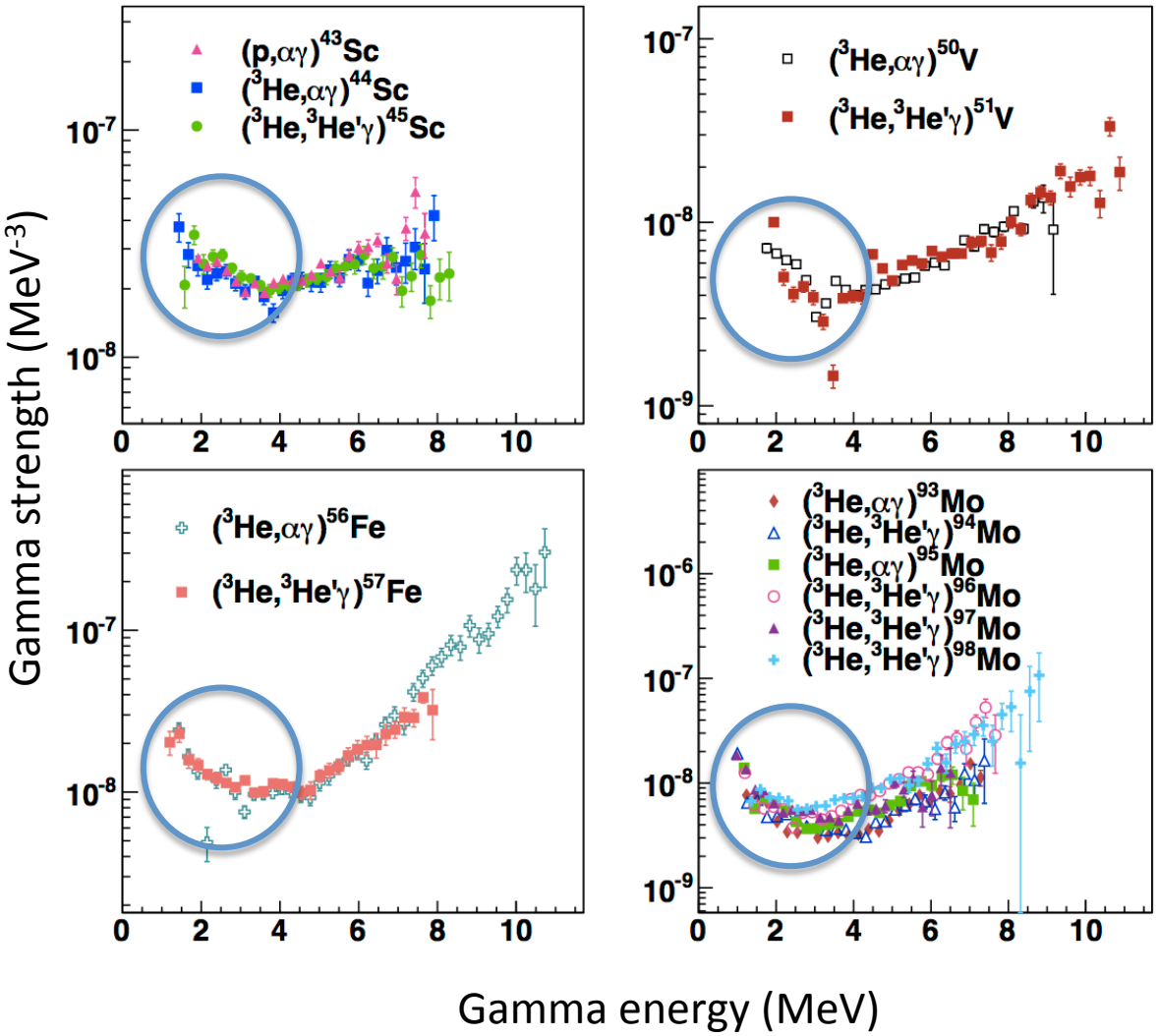
^{43,44,45}Sc, ^{44,45,46}Ti, ^{50,51}V, ^{56,57}Fe, $^{93-98}$Mo, $^{116-119,121,122}$Sn, ^{148,149}Sm, $^{160-164}$Dy, ^{166,167}Er, $^{170-172}$Yb, $^{205-208}$Pb

In analysis or under peer review:

^{56,57}Fe, ^{59,60}Ni, ^{73,74}Ge, $^{90-92}$Zr, ^{105,106,111,112}Cd, $^{105-108}$Pd, ^{143,144,146,147}Sm, $^{195-197}$Pt, $^{231-233}$Th, ^{232,233}Pa, ^{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/

Low-energy enhancement, γ strength



^{56,57}Fe:

Voinov *et al.*, PRL 93, 142504 (2004);
Renorm.:
Algin *et al.*, PRC 78, 054321 (2008)

$^{93\text{-}98}$Mo:

Guttormsen *et al.*,
PRC 71, 044307 (2005)

^{50,51}V:

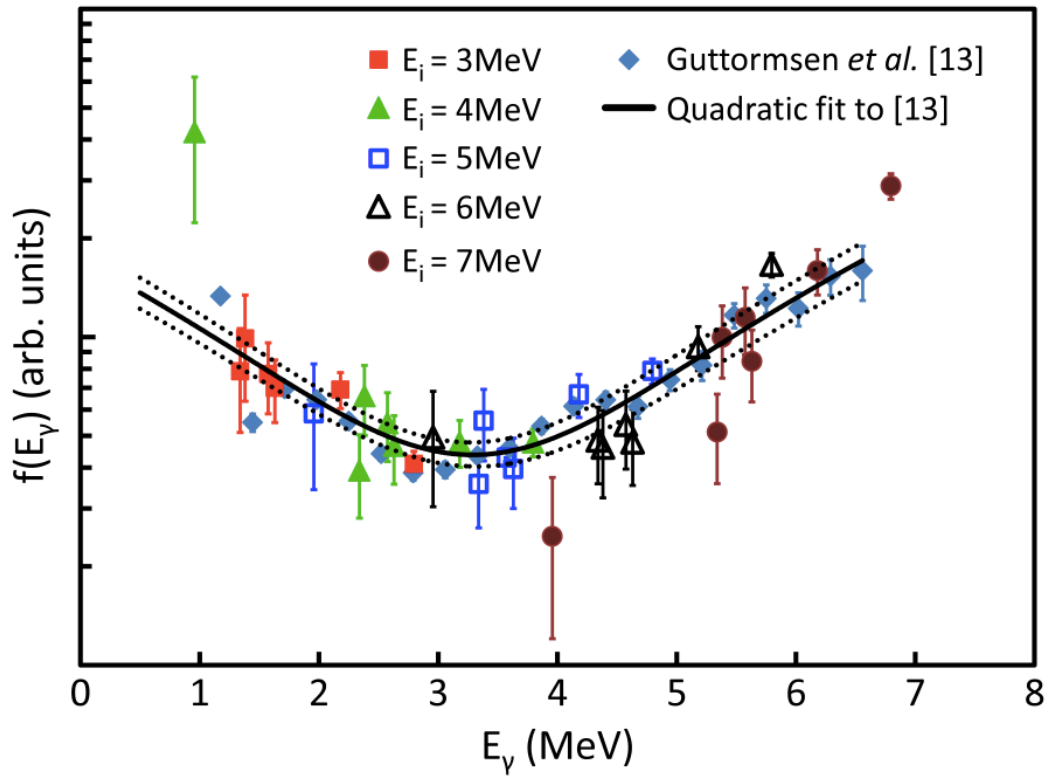
Larsen *et al.*, PRC 73, 064301 (2006)

^{43,44,45}Sc:

Larsen *et al.*, PRC 76, 044303 (2007);
Bürger *et al.*, PRC 85, 064328 (2012)

Recently confirmed in ^{95}Mo

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



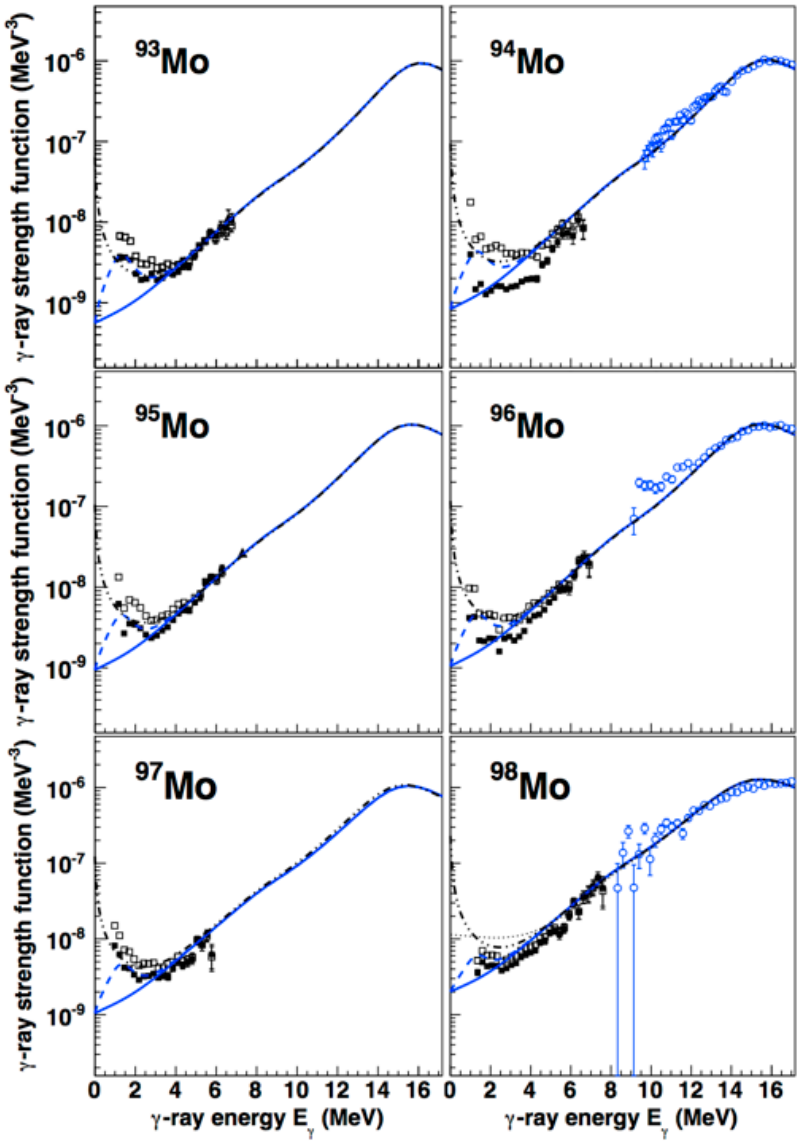
Proton-γ-γ correlations from the ^{94}Mo(d,p)^{95}Mo reaction (experiment at Berkeley National Lab).
Ge detectors. **Completely model-independent!**

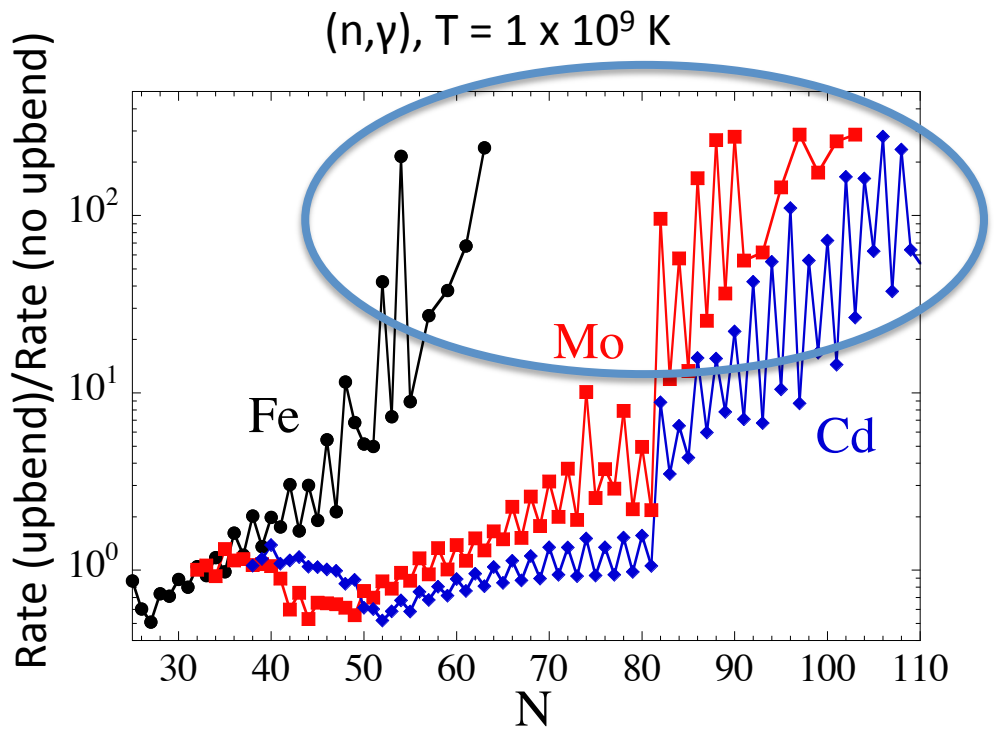
Status, low-energy enhancement

What we know:
- Seen in many nuclei below A = 116
- Seen in different types of experiments: Oslo, (p,2γ), (d,pγγ)
- Not dependent on deformation (Mo isotopic chain)
- Not dependent on excitation energy

What we don't know:
- What is the underlying physics?
- What is the multipolarity?
- What is the electromagnetic character?
- Does it depend on the spin of the initial levels?
- For which nuclei does it exist?

Impact on neutron-capture reaction rates

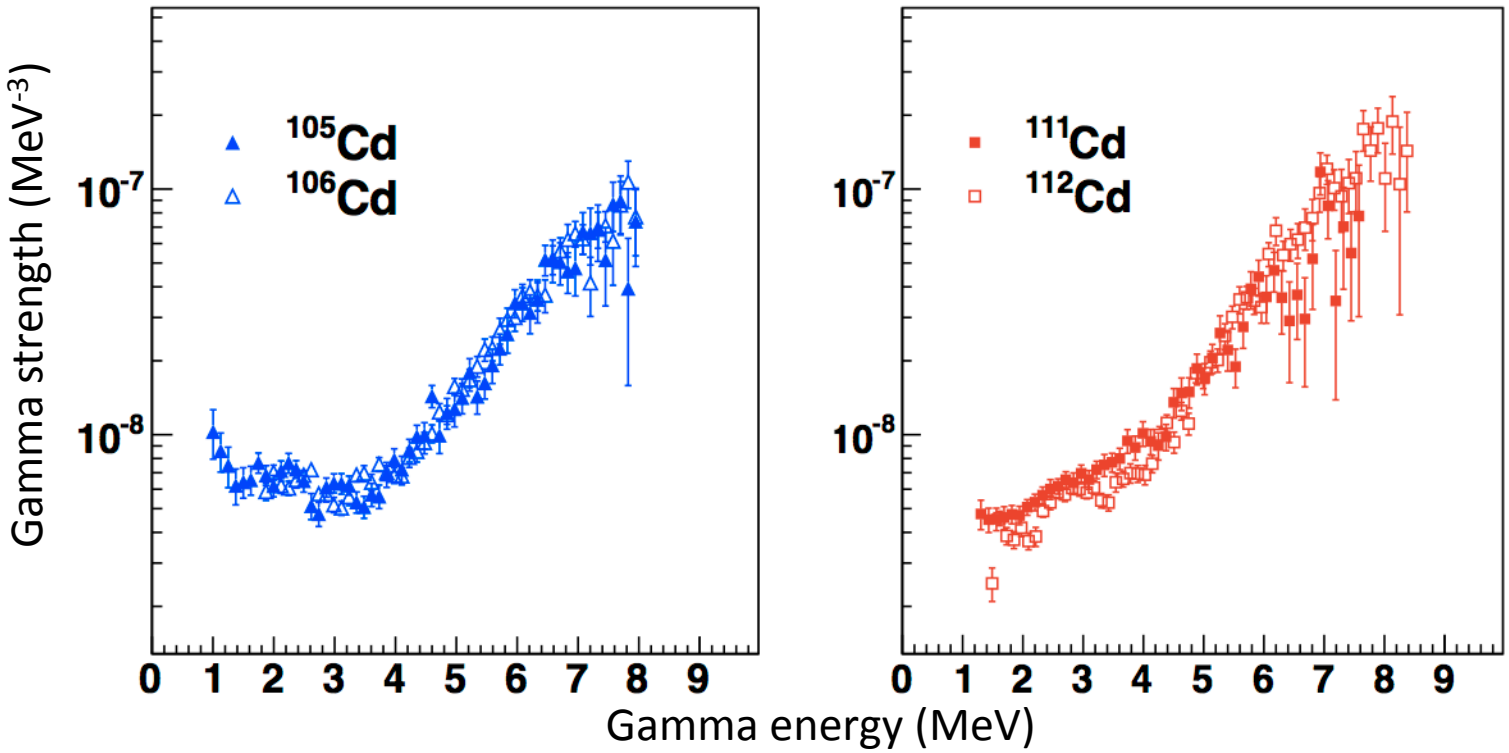




Assuming E1 character of enhancement.
A.C. Larsen and S. Goriely, Phys. Rev. C **82**, 014318 (2010)

New data on Cd isotopes

PRELIMINARY!

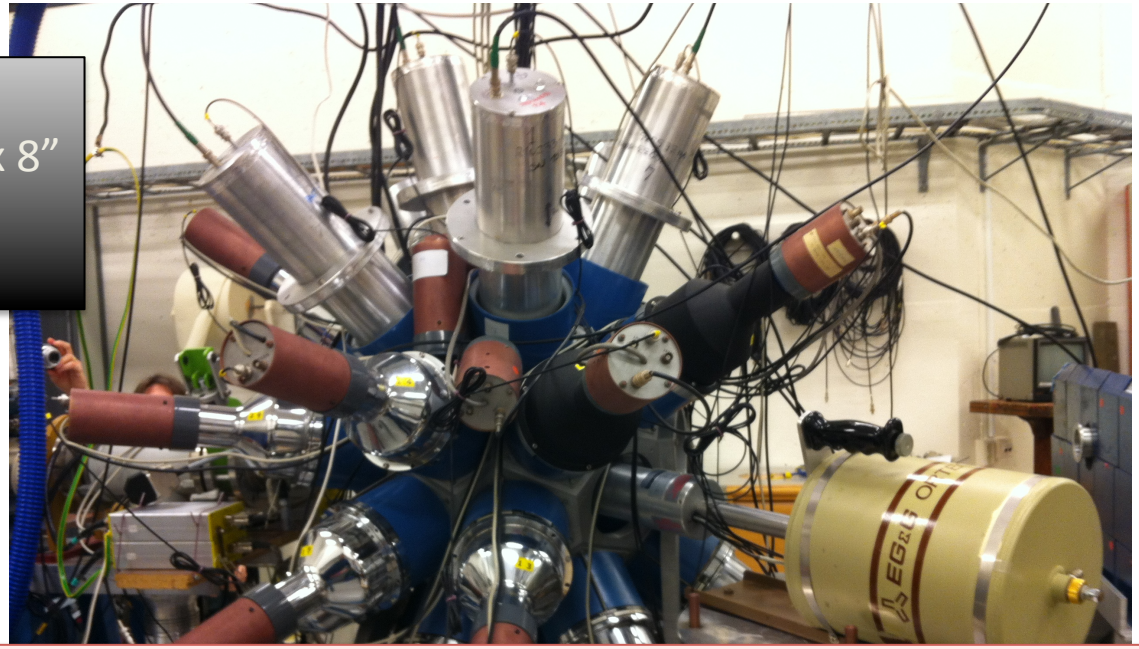


Many thanks to Cath Scholey @ JYFL for lending us the ^{106,112}Cd targets!

Iron revisited – $LaBr_3$(Ce) campaign

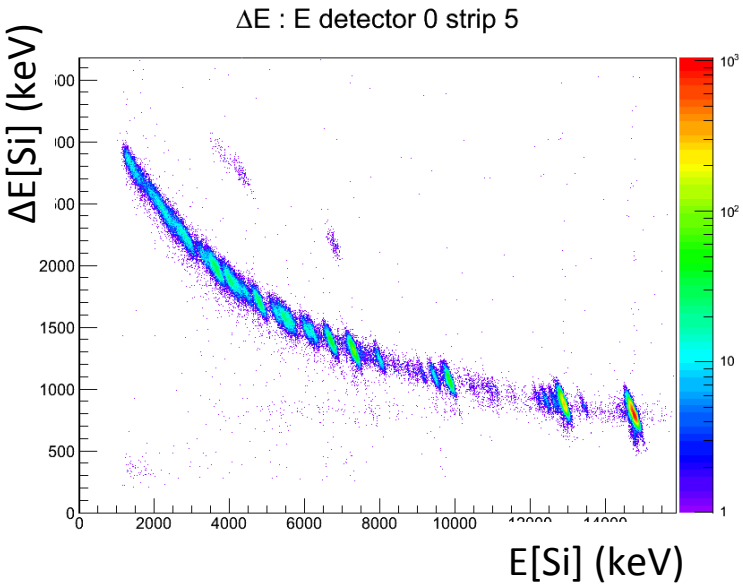
March 2 – 12, 2012: $^{56,57}Fe(p,p')$, E_p = 16 MeV

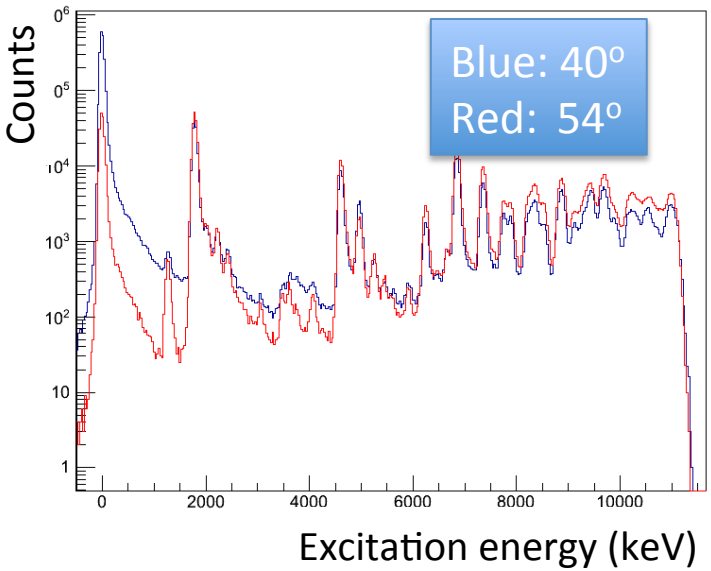
CACTUS:
6 $LaBr_3$(Ce), 3.5” x 8”
22 NaI(Tl), 5” x 5”
[collimated]

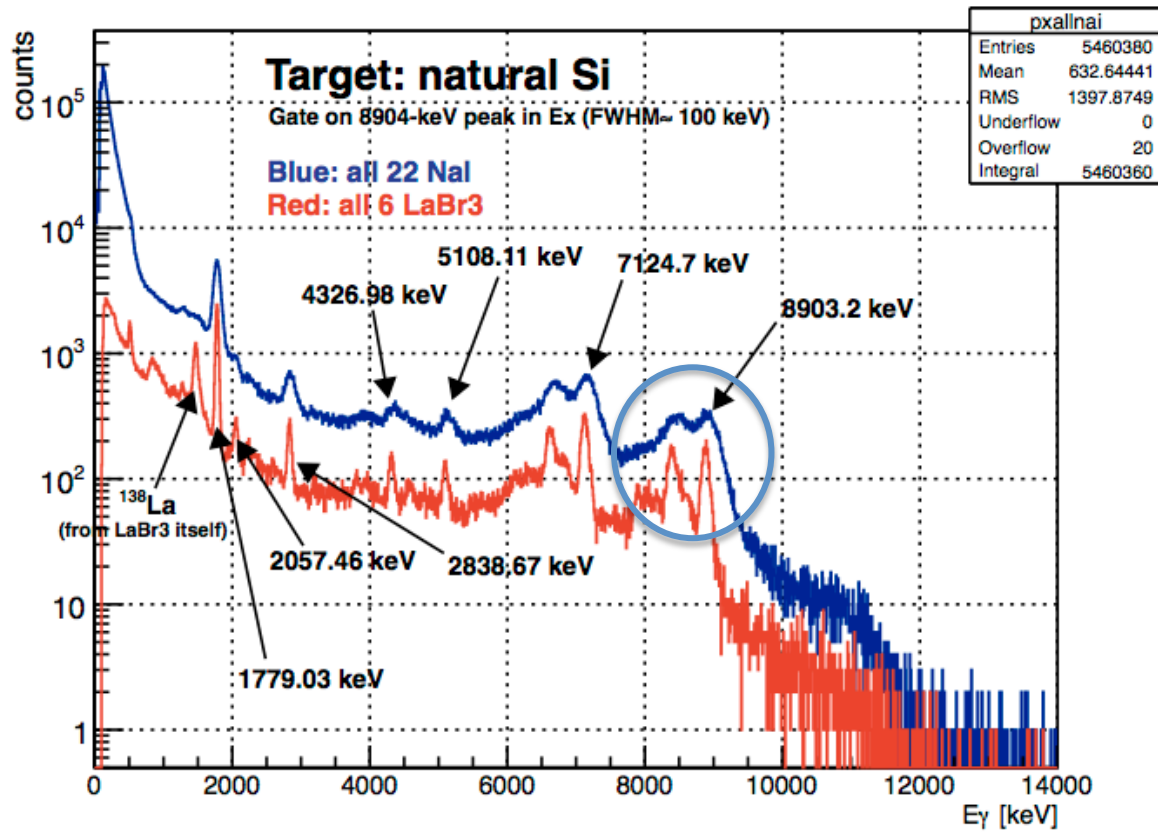


Special thanks to the INFN Milan group:
Angela Bracco, Franco Camera, Silvia Leoni,
Nives Blasi, and Benedicte Million

Particle and γ spectra – ^{28}Si calibration run

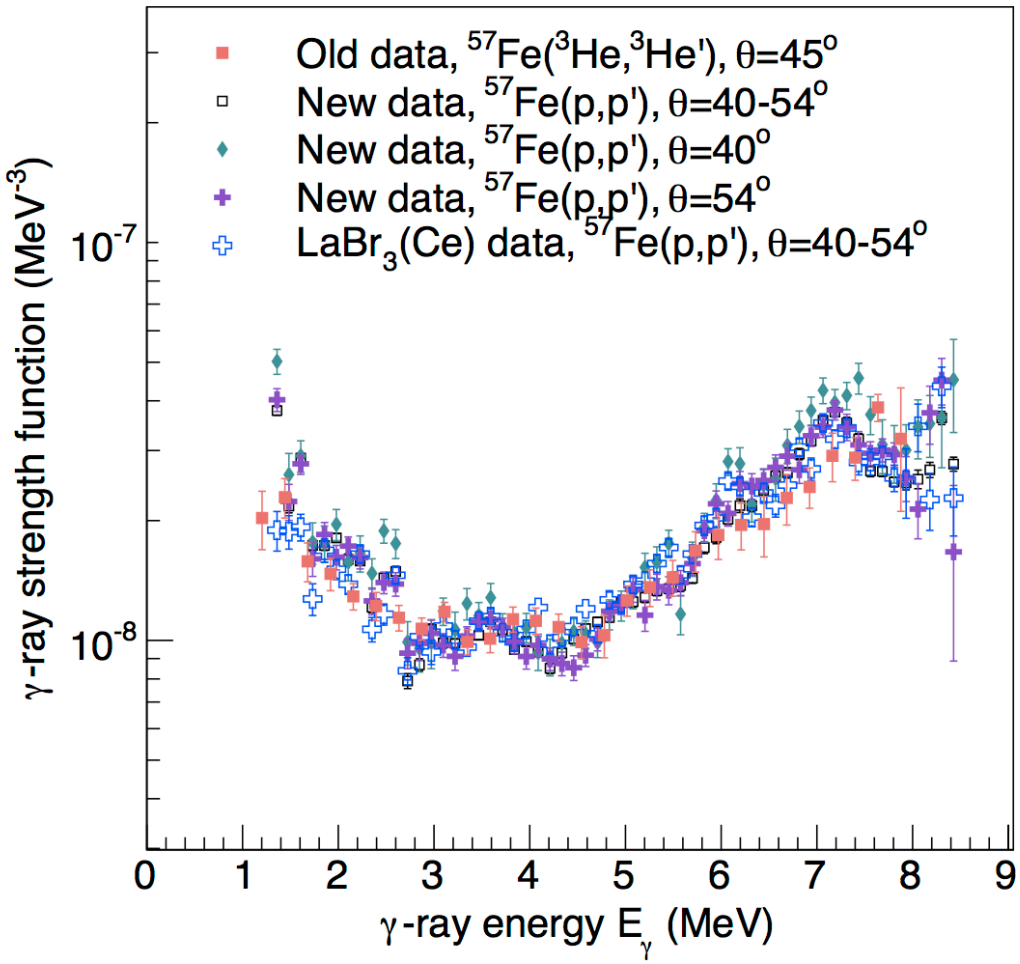






First results – ^{57}Fe

SUPER-PRELIMINARY!!!



To-do list:

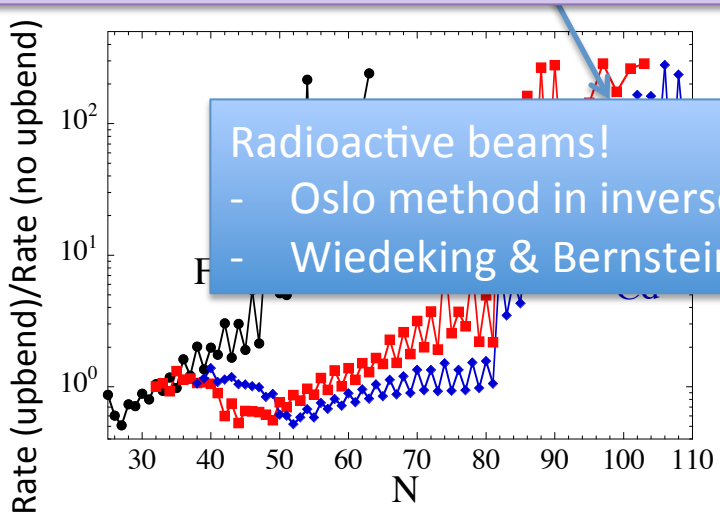
- Angular distributions, NaI
- Proper LaBr$_3$(Ce) response functions
- Look for strength 2-3 MeV above S_n
- ... And do ^{56}Fe too!

Summary & outlook

- Low-energy enhancement in γ strength
- Influence on reaction rates
- New data on Cd and Fe (with $LaBr_3$(Ce) det.)
- Future exp.: ^{89,90}Y, ^{197,198}Au, ^{233}U, … , ^{88}Sr???
- ^{57}Fe(^{3}He,α) with SiRi @ backward angles

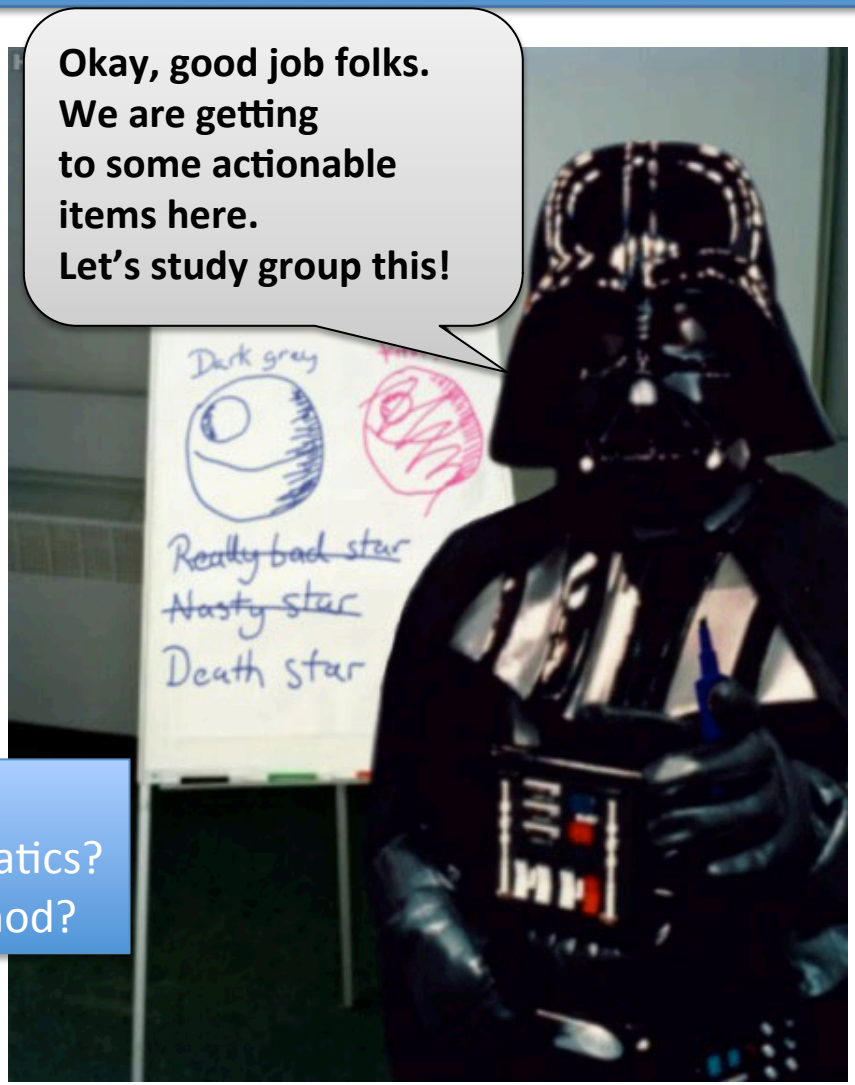
Open questions:

- What is the reason behind the enhancement?
- Electromagnetic character and multipolarity?
- For which nuclei is it present?
- **Does it exist for neutron-rich nuclei?**



Radioactive beams!

- Oslo method in inverse kinematics?
- Wiedeking & Bernstein's method?



Maybe the answers will be given in the…

4th Workshop on
Level Density and Gamma Strength
Oslo, May 27 – 31, 2013

http://tid.uio.no/workshop2013 [operational soon!]

Previous conferences:
http://tid.uio.no/workshop07/
http://tid.uio.no/workshop09/
http://tid.uio.no/workshop2011/

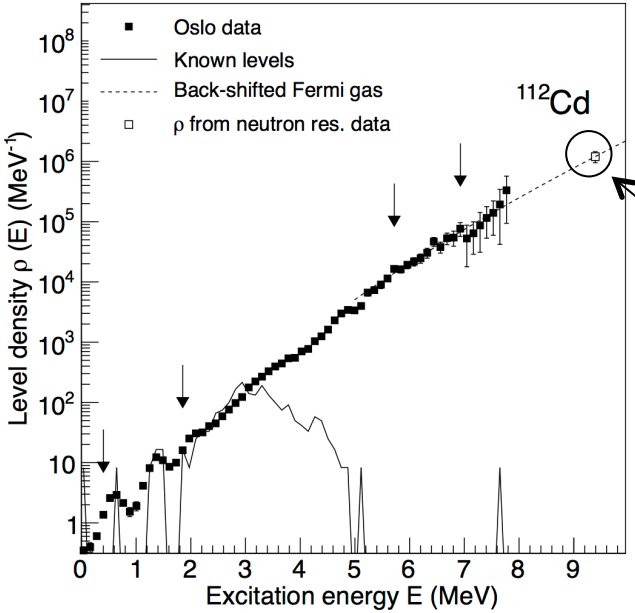
Many thanks for your attention!

Normalization of level density and γ-transmission coefficient

$$\rho(E_x\text{-}E_\gamma) = A\rho'(E_x\text{-}E_\gamma)\exp[\alpha(E_x\text{-}E_\gamma)]$$

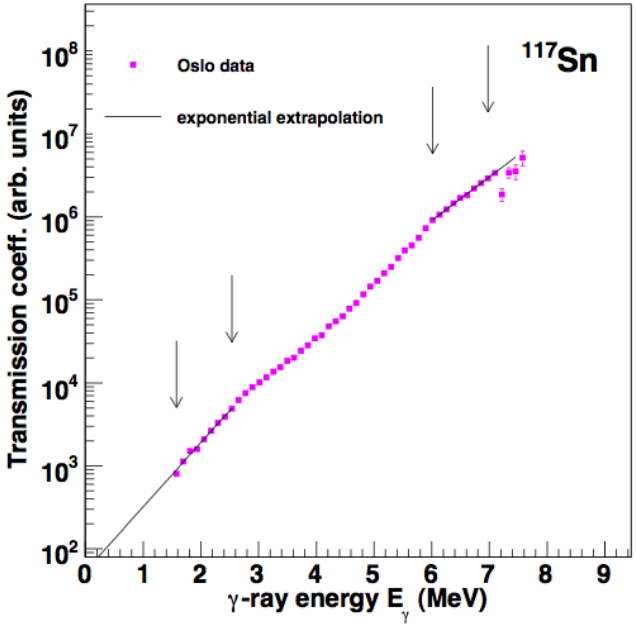
$$\mathscr{T}(E_\gamma) = B\,\mathscr{T}'(E_\gamma)\exp[\alpha(E_\gamma)]$$

A, α: discrete levels + *D*



Assuming $g(E_x,I)$ and $\rho_+ = \rho_-$

B: average, total rad. width $\langle\Gamma_\gamma\rangle$



[See A.C. Larsen *et al.*, Phys. Rev. C **83**, 034315 (2011)]