Experiments of reaction model inputs: level density and gamma strength

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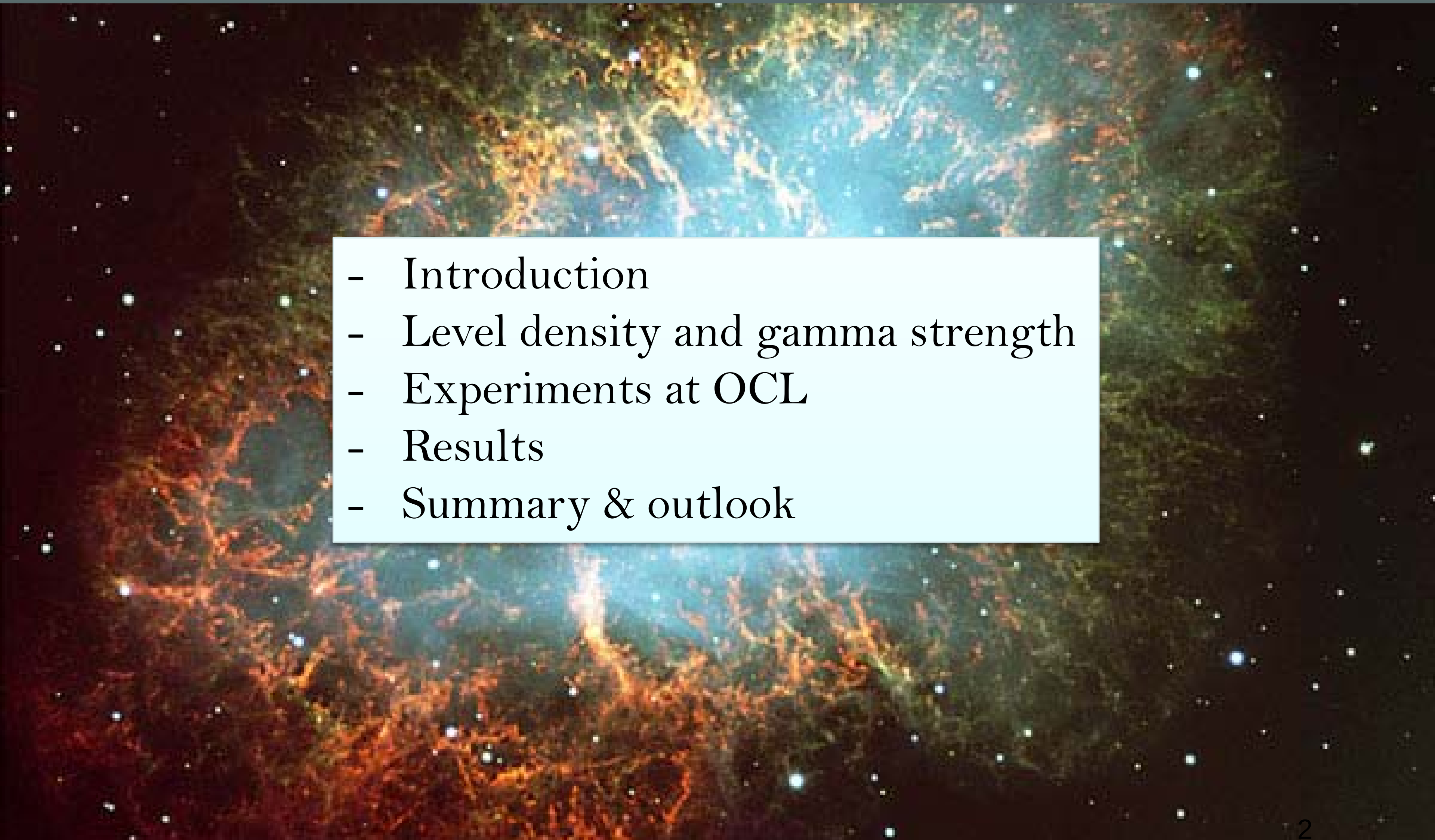
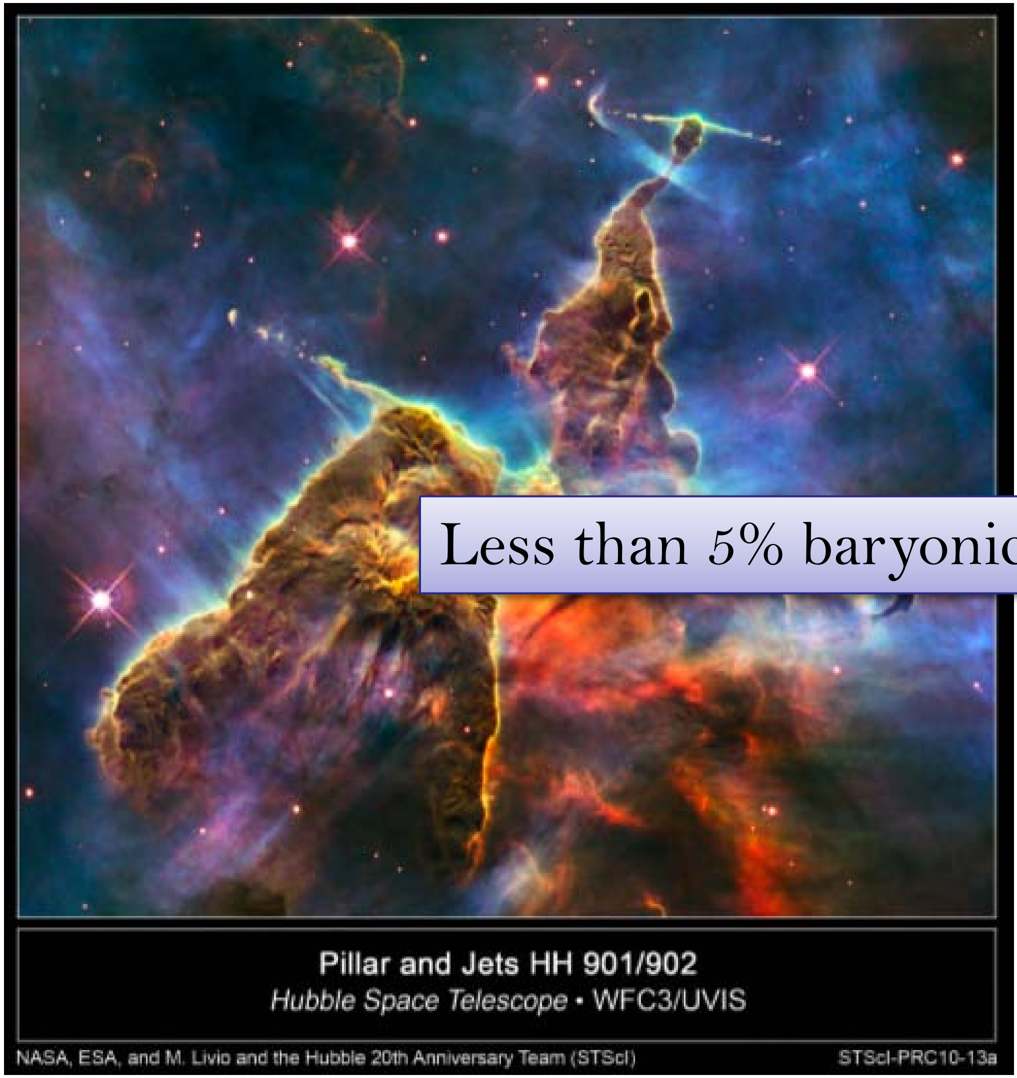
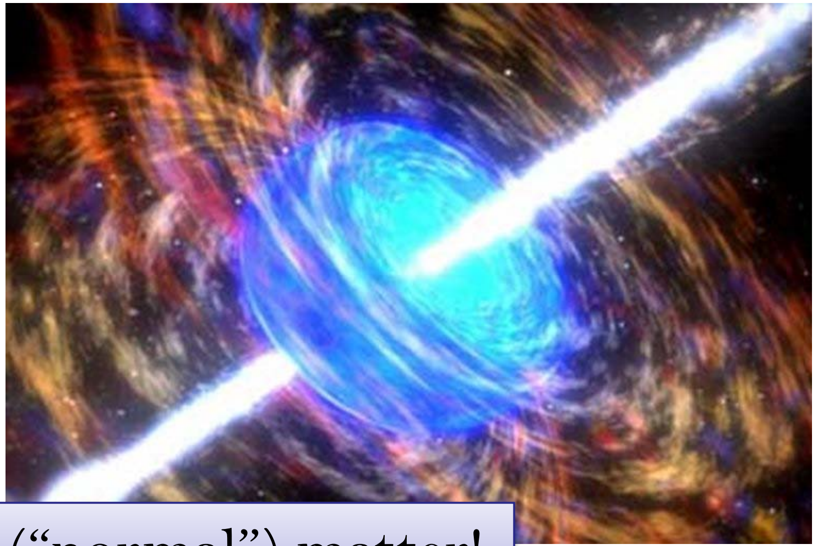
Outline



- Introduction
- Level density and gamma strength
- Experiments at OCL
- Results
- Summary & outlook

Our amazing Universe





Less than 5% baryonic ("normal") matter!

Main physical processes, heavy elements

REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

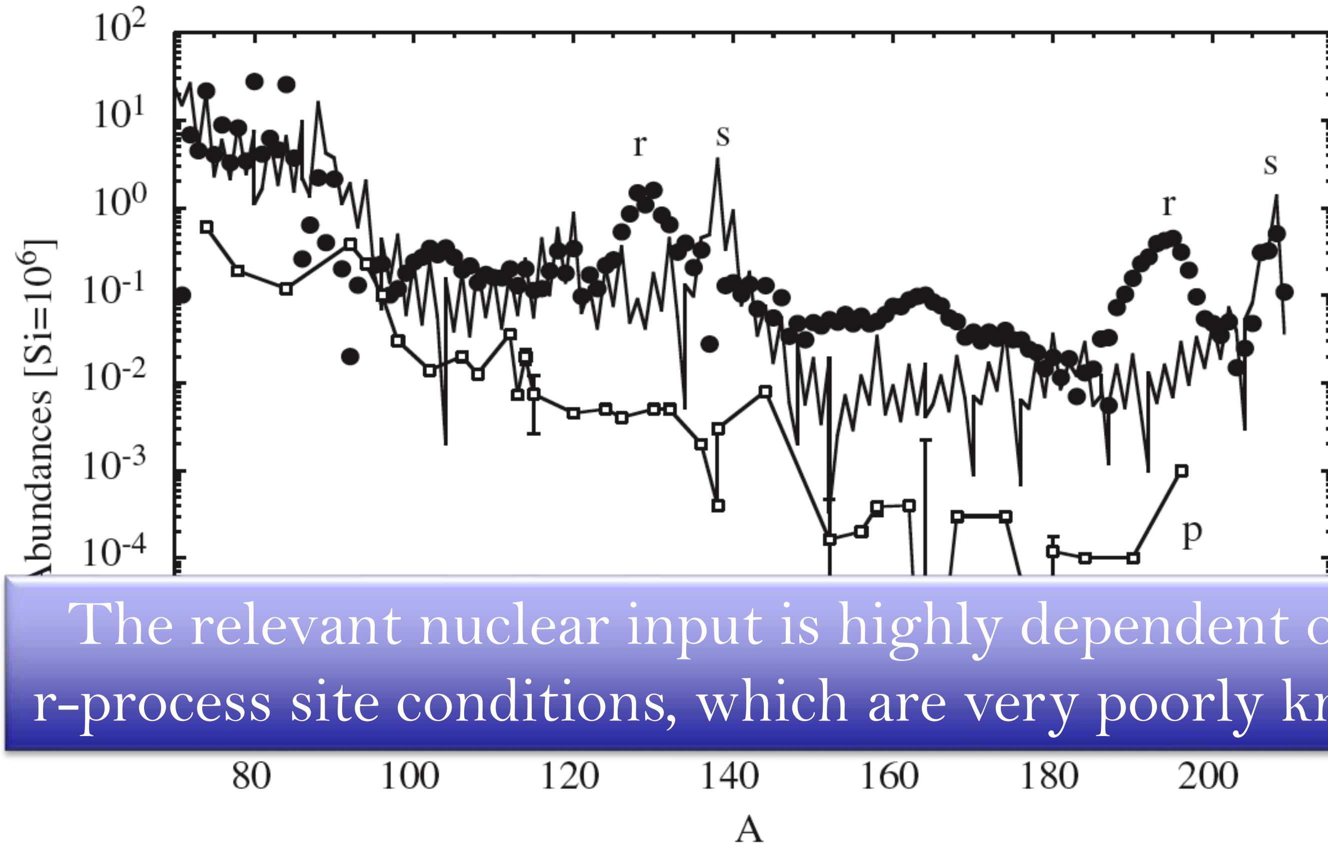
Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

Distribution of heavy elements



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:
≈ 2000 nuclei, ≈20 000 cross sections

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

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

$\sigma^\mu(E)$ ← 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.

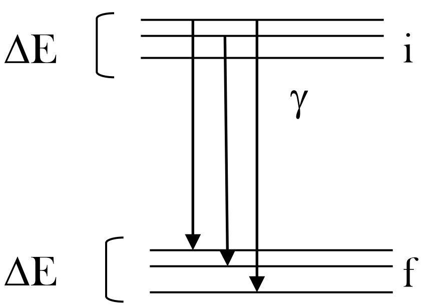
What are these guys?

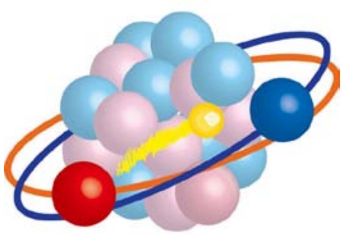
Level density:
number of nuclear energy levels per energy unit

Gamma strength function:
measure on average, nuclear electromagnetic response

For dipole radiation

$$f(E_\gamma) = \tau(E_\gamma)/(2\pi E_\gamma^3)$$

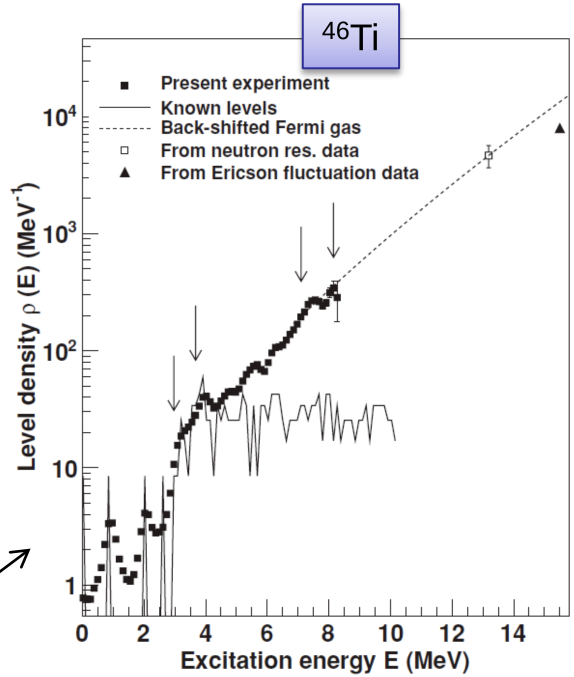




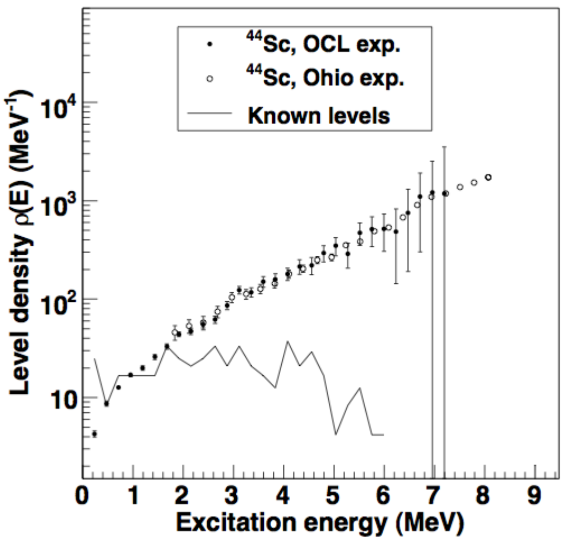
Experiments – level density

Level density:

- Discrete levels
- Neutron/proton resonances
- Particle evaporation spectra
- Ericsson fluctuations
- **Oslo method (primary gamma spectra)**



Guttormsen et al., PRC 83,014312 (2011)
Salas-Bacci et al., PRC 70, 024311 (2004)

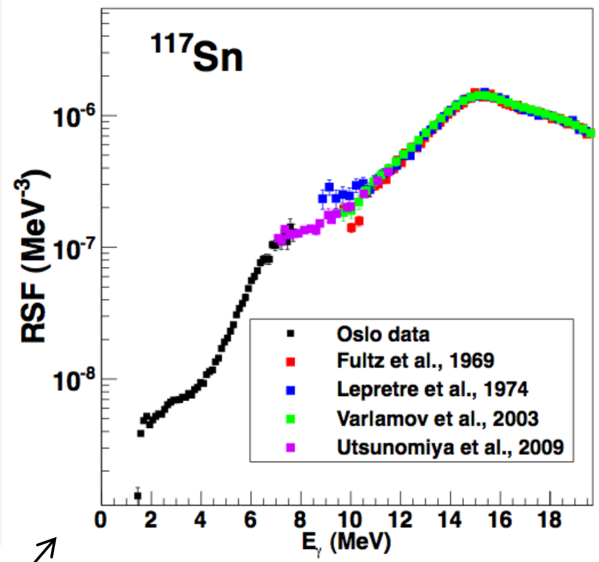


Larsen et al., PRC 76,044303 (2007)
Voinov et al., PRC 77, 034613 (2008)

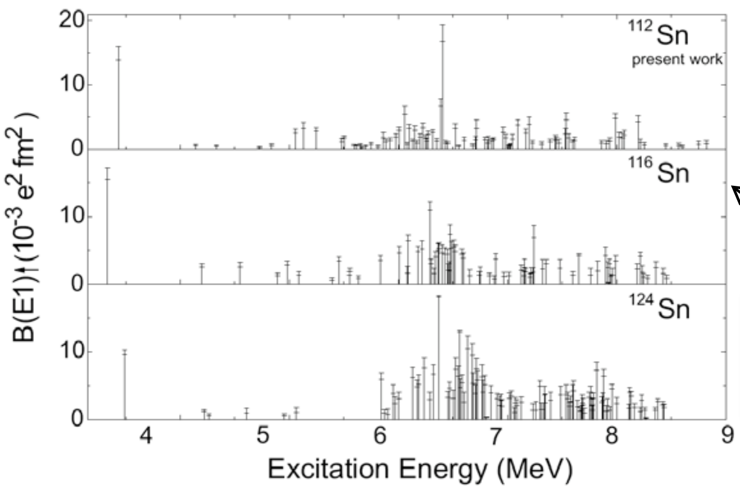
Experiments – gamma strength

Gamma strength function:

- Photonuclear reactions
- (n,gamma) primary transitions
- Nuclear resonance fluorescence
- Electron/proton/alpha scattering
- Fitting of two-step cascade spectra
- **Oslo method (primary gamma spectra)**

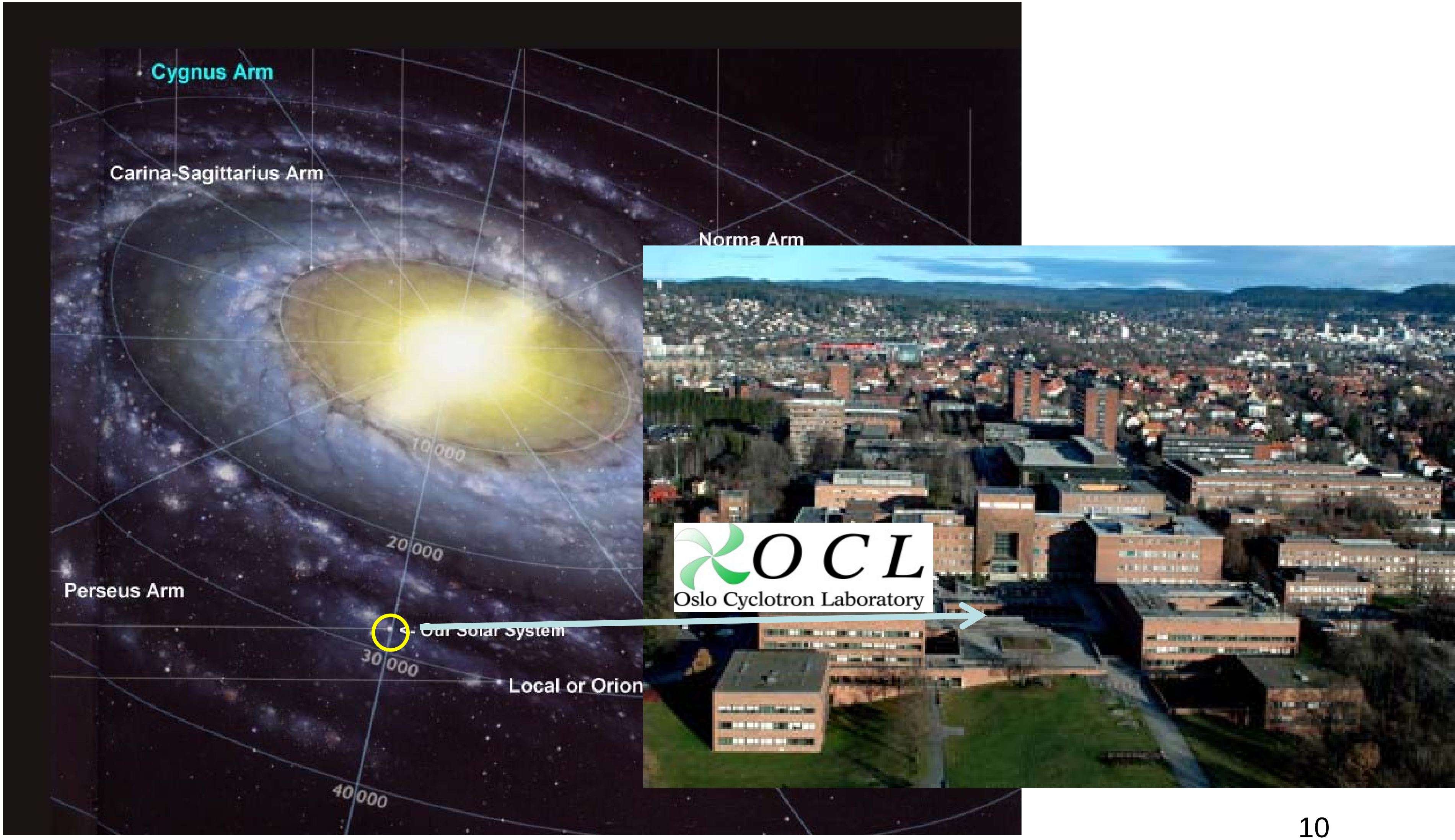


Utsunomiya et al., PRC 80, 055806 (2009);
Agvaanluvsan et al, PRL 102, 162504 (2009)



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

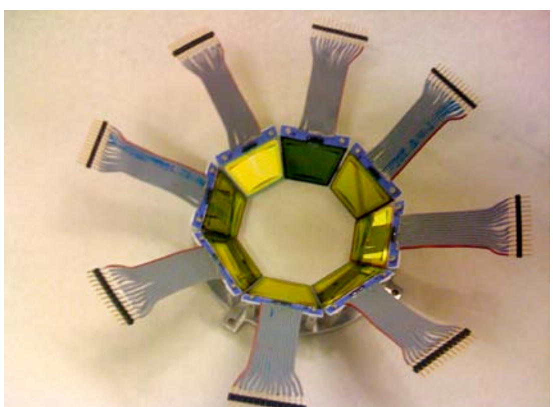
Oslo Cyclotron Laboratory

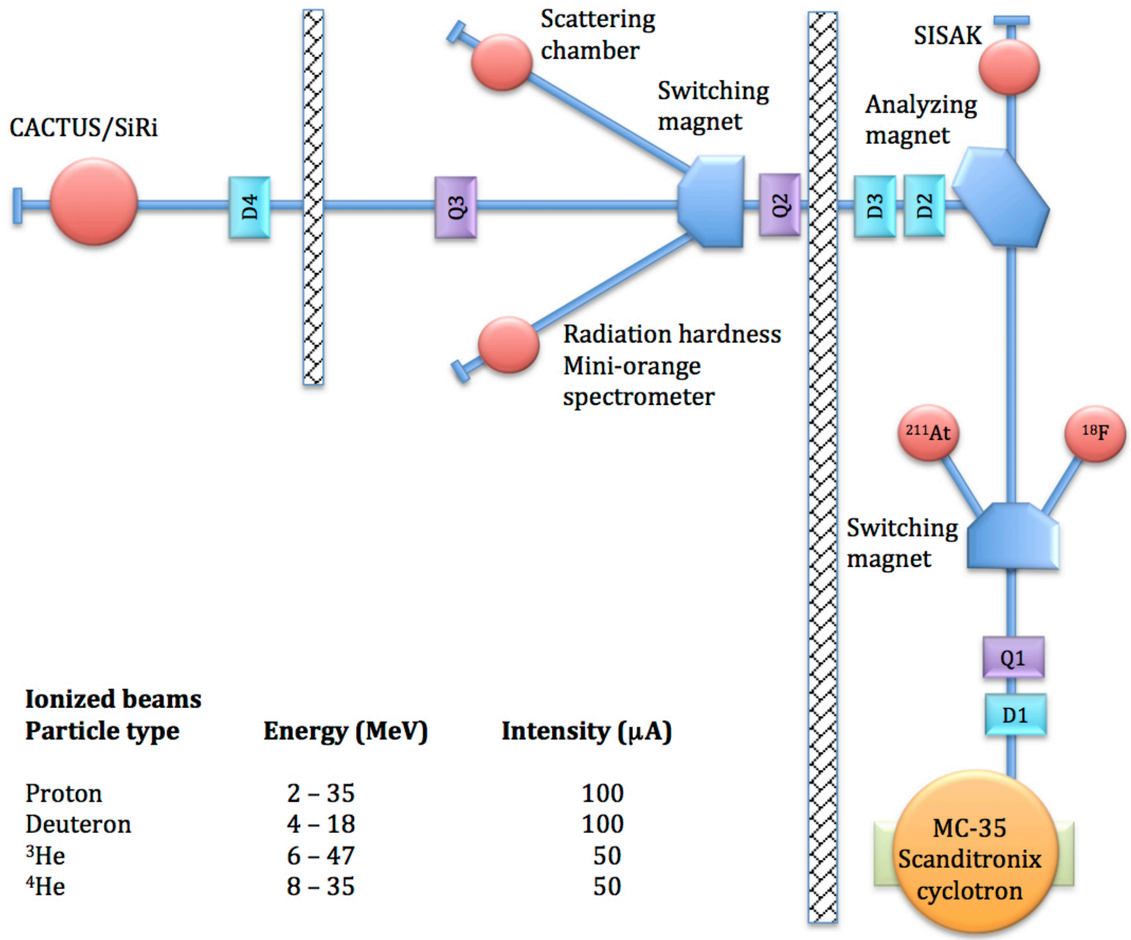


Overview of OCL

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

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





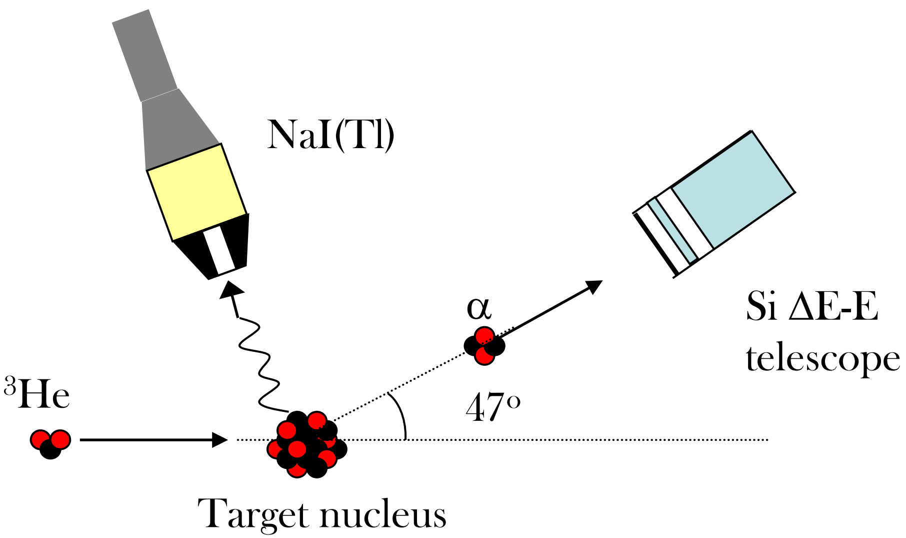
Ionized beams

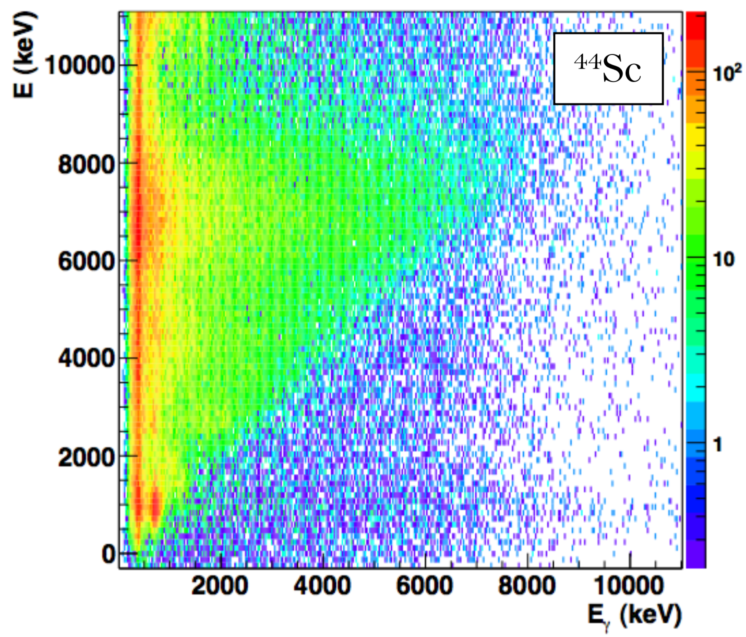
Particle type	**Energy (MeV)**	**Intensity (μA)**
Proton	2 – 35	100
Deuteron	4 – 18	100
^{3}He	6 – 47	50
^{4}He	8 – 35	50

Experimental technique

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

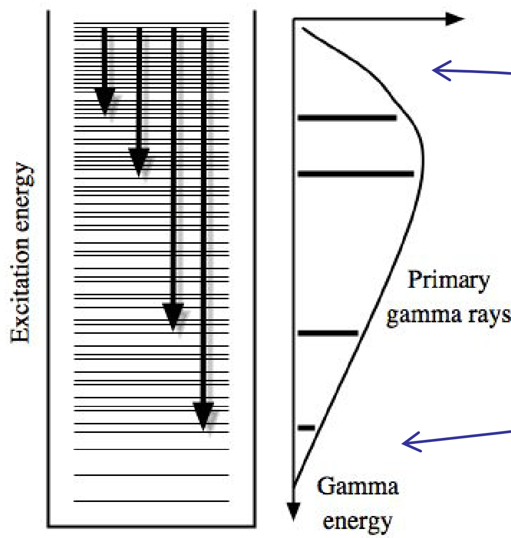
Excitation-energy tagged gamma spectra





Data analysis – the Oslo method

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)]



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

Nuclei under study

Published level density data:

^{44,45}Sc, ^{45,46}Ti, ^{50,51}V, ^{56,57}Fe, $^{93-98}$Mo, $^{116-119,121,122}$Sn, ^{148,149}Sm, $^{160-162}$Dy, ^{166,167}Er, $^{170-172}$Yb, $^{205-208}$Pb

In analysis or under peer review:

^{44}Ti, ^{59,60}Ni, $^{90-92}$Zr, ^{105,106,111,112}Cd, $^{105-108}$Pd, ^{143,144,146,147}Sm, ^{163,164}Dy, ^{233}Th, ^{235}U

Published gamma strength data:

^{44,45}Sc, ^{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

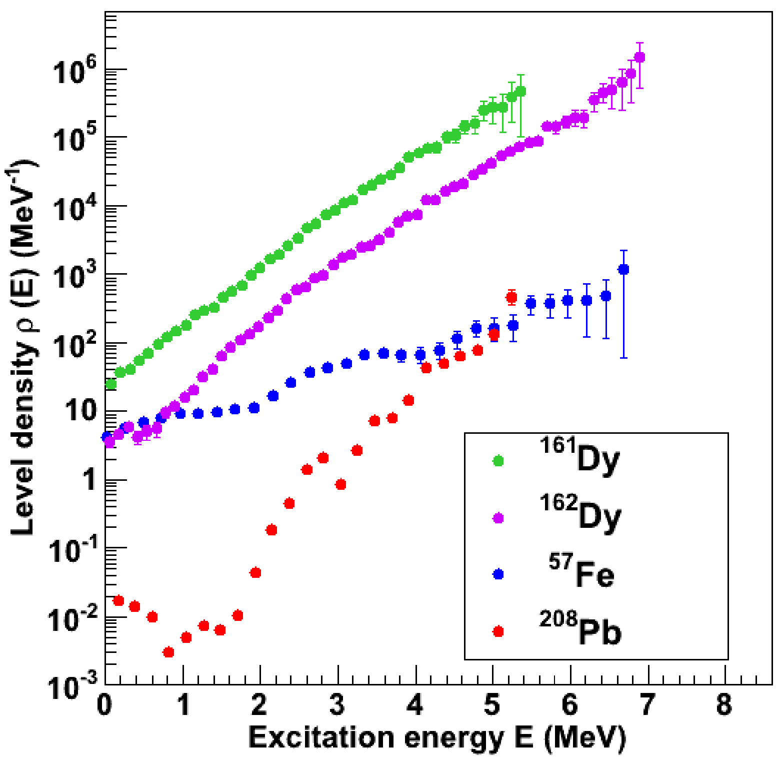
In analysis or under peer review:

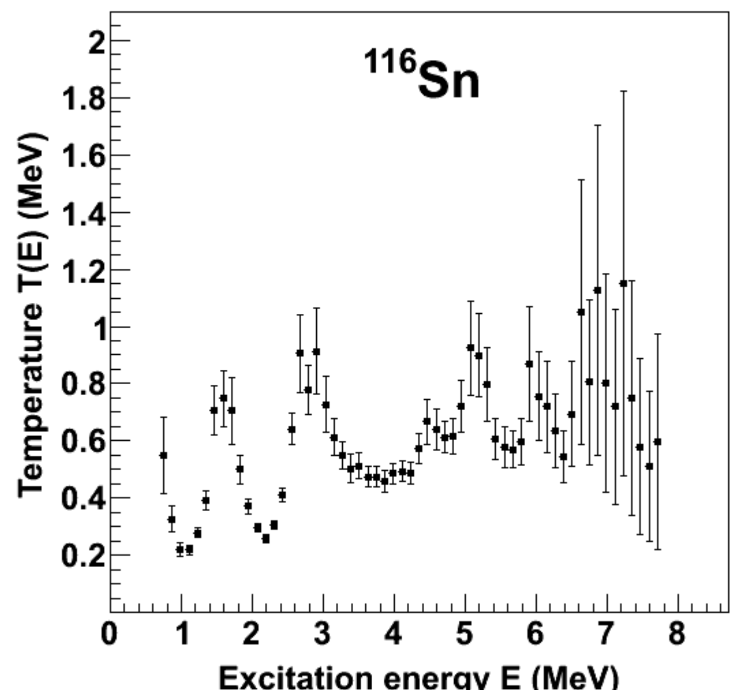
^{44}Ti, ^{59,60}Ni, $^{90-92}$Zr, ^{105,106,111,112}Cd, $^{105-108}$Pd, ^{143,144,146,147}Sm, ^{233}Th, ^{235}U

See
http://www.mn.uio.no/fysikk/english/research/about/infrastructure/OCL/compilation/
for all references and to download the published data

Highlights of results – level density

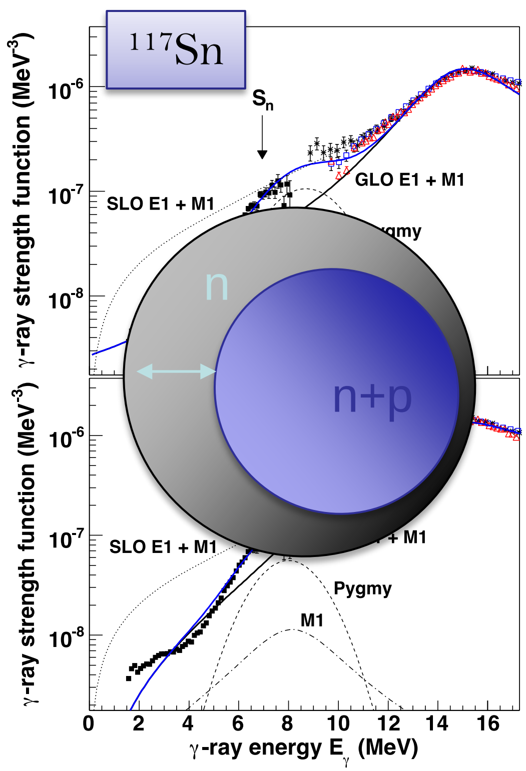
Significant shell effects for closed-shell nuclei, even at high E_x
Signatures of phase transitions:
- Sequential pair breaking
- Quenching of pairing force

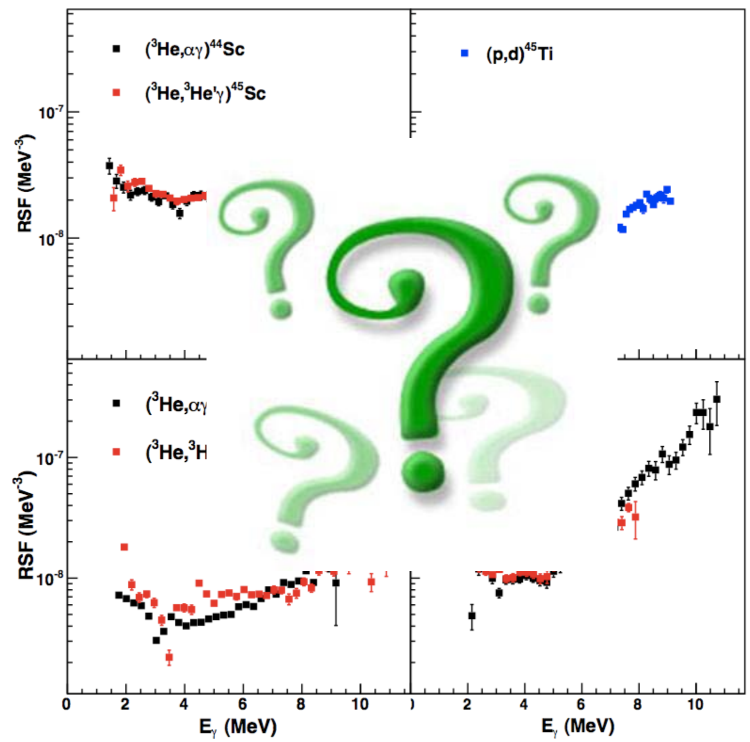




Highlights of results – gamma strength

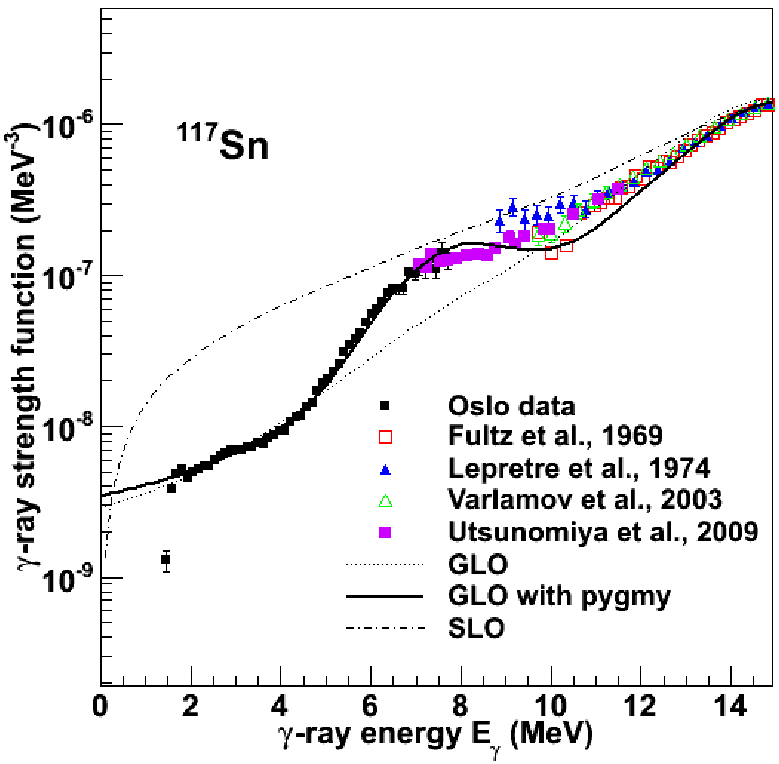
Structures in the gamma strength function:
- Scissors mode (rare-earth region)
- “Pygmy resonance” (Sn)
- Low-energy enhancement (medium-light nuclei)

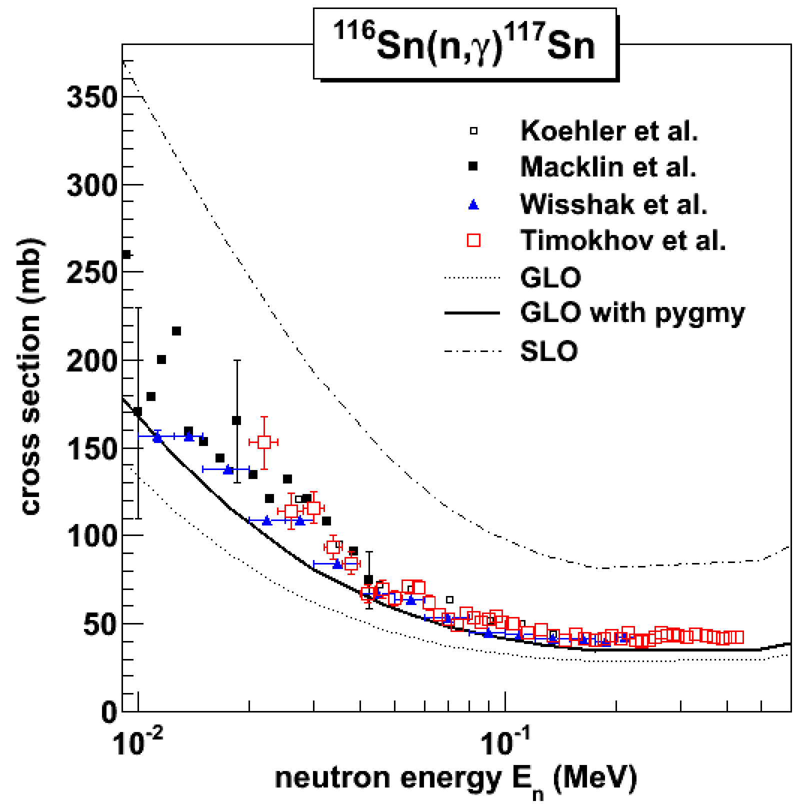




Cross-section calculations, Sn

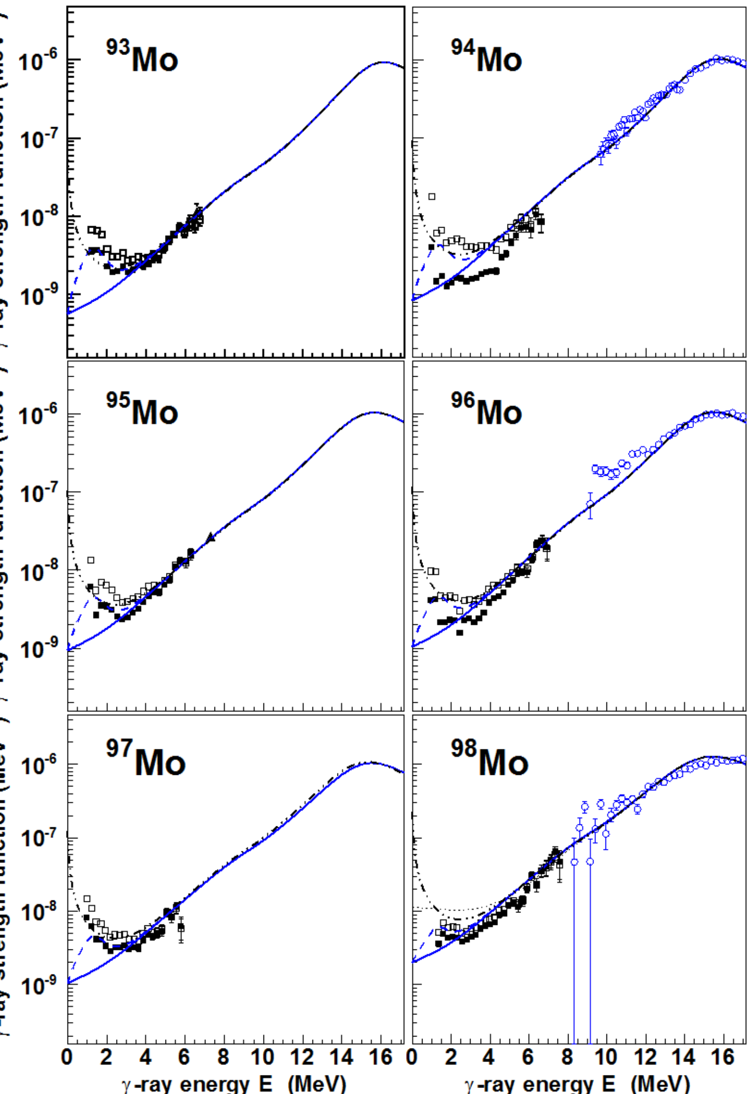
H. K. Toft *et al.*, Phys. Rev. C **83**, 044320 (2011)

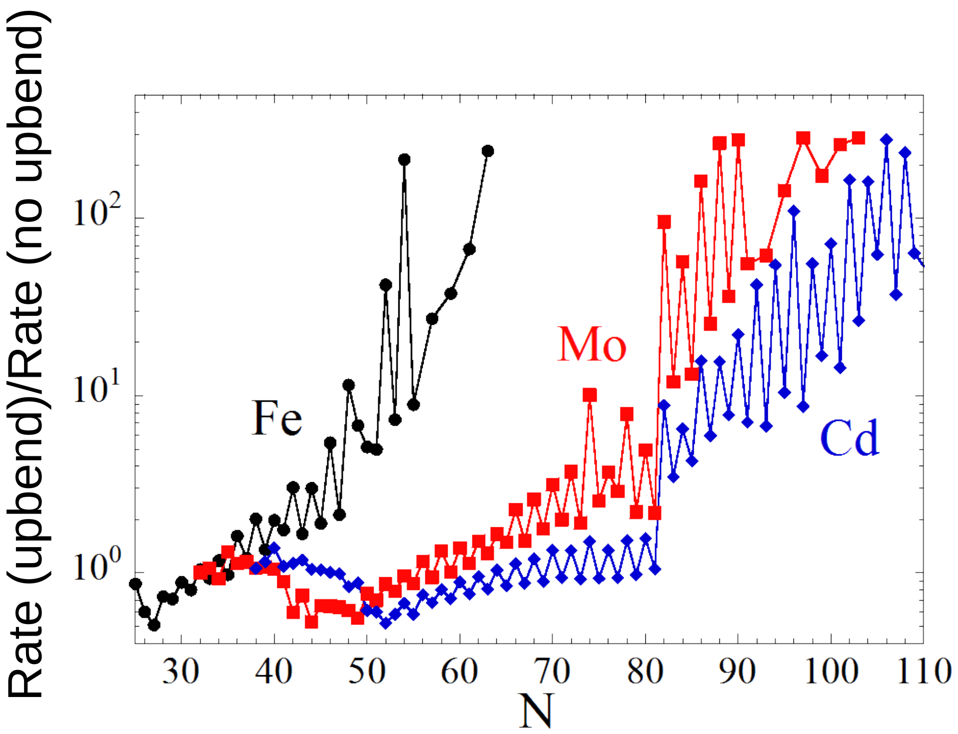




New photoneutron data : Utsunomiya *et al.*, Phys. Rev. C **80**, 055806 (2009)
TALYS code: A. J. Koning, S. Hilaire, and M. C. Duijvestijn, www.talys.eu

Low-energy enhancement, reaction rates

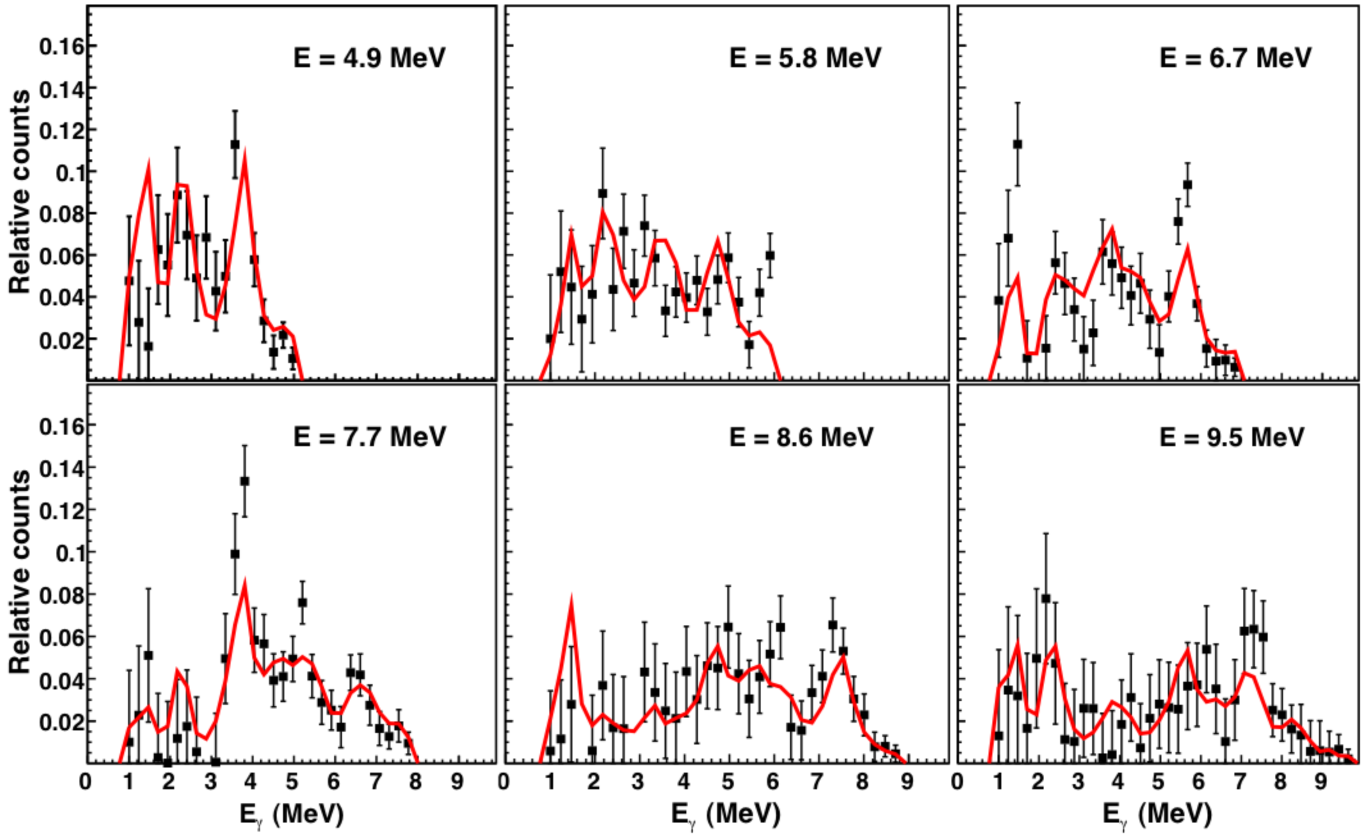




A.C. Larsen and S. Goriely, Phys. Rev. C **82**, 014318 (2010)

Gamma spectra of ^{44}Ti

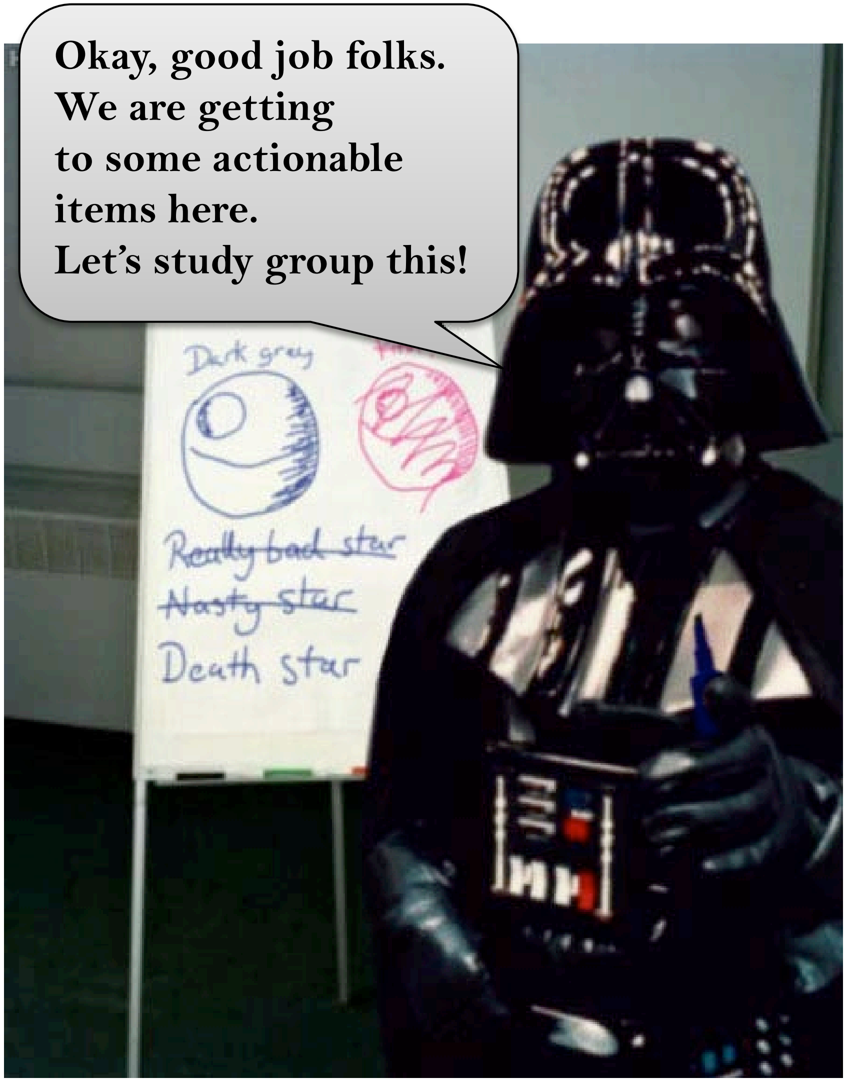
^{46}Ti(p,tγ)^{44}Ti



Red line: from extracted level density and gamma strength

Summary & outlook

- Relevant nuclear information?
- Level density and gamma strength on many nuclei, more to come…
- Influence on reaction rates
- Replace NaI with $LaBr_3$?
- ^{73,74}Ge (NIF), ^{233}U (Th cycle), ^{56,57}Fe revisited



Collaborators

- The Oslo group: A. Bürger, T. K. Eriksen, A. Görgen, M. Guttormsen, T. W. Hagen, H. T. Nyhus, J. Rekstad, T. Renstrøm, S. J. Rose, I. E. Ruud, S. Siem, and G. M. Tveten; technical staff: E. A. Olsen, A. Semchenkov and J. Wikne
- Stephane Goriely, Université Libre de Bruxelles
- Sotirios Harrisopulos, NCSR "Demokritos"
- Andreas Schiller and Alexander Voinov, Ohio University
- Jonathan Wilson and Baptist Leniau, IPN Orsay
- Frank Gunsing, CEA Saclay
- Milan Krticka, Charles University
- Emil Betak, Institute of Physics SAS
- Lee Bernstein and Darren Bleuel, Livermore National Lab
- Mathis Wiedeking, iThemba Lab
- Undraa Agvaanluvsan, Stanford University/MonAme Scientific Research Center
- Gary Mitchell, North Carolina State University/Triangle Universities Nuclear Laboratory
- Emel Algin, Eskisehir Osmangazi University
- Tom Lönnroth, Åbo Akademi

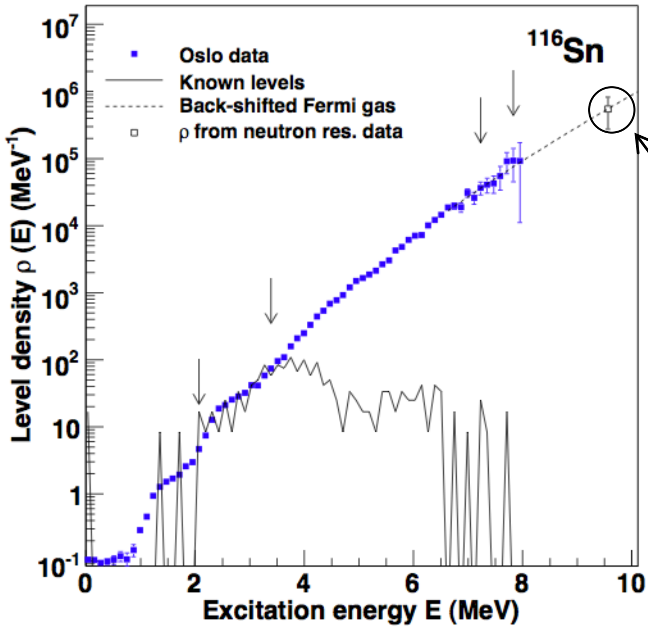
Many thanks!

Normalizations

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

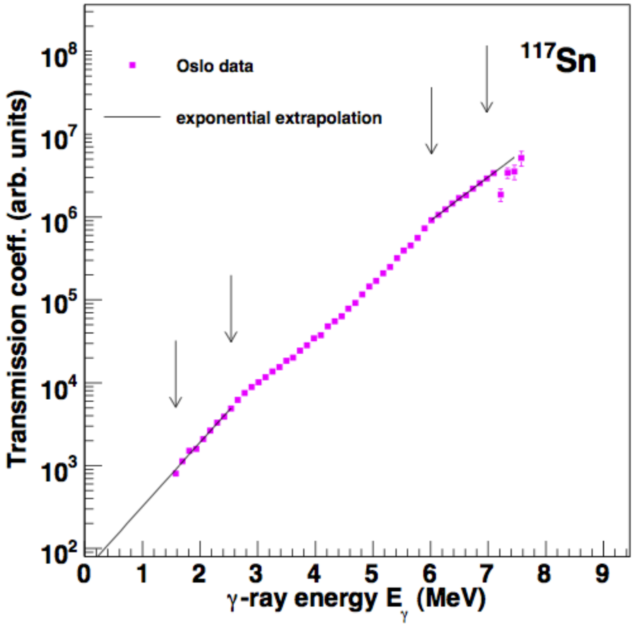
$$\mathscr{T}(E_\gamma) = B\,\mathscr{T}'\,(E_\gamma)\;\exp[\alpha(E_\gamma)]$$

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)]