The beta-Oslo method

Experimentally constrained (n, γ) reaction rates relevant to the r-process

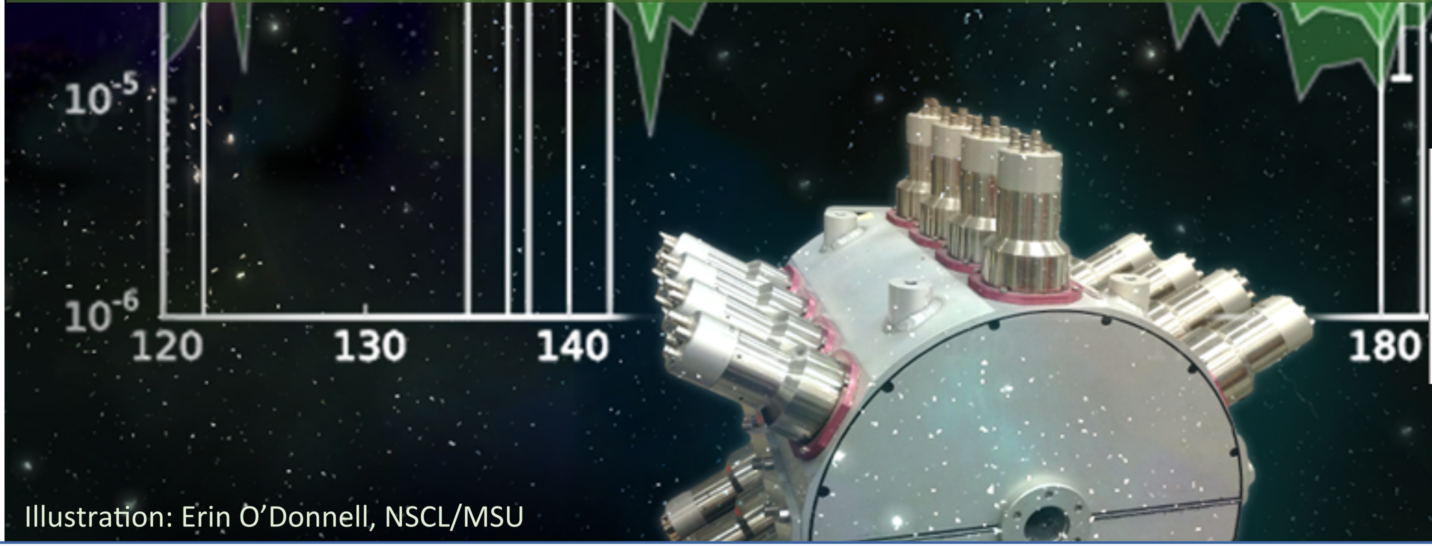


Illustration: Erin O'Donnell, NSCL/MSU

NSCL

JINA–CEE

ChETEC Action

Ann-Cecilie Larsen

UiO : Department of Physics
University of Oslo

ERC-STG-2014 G.A. No 637686
gRESONANT

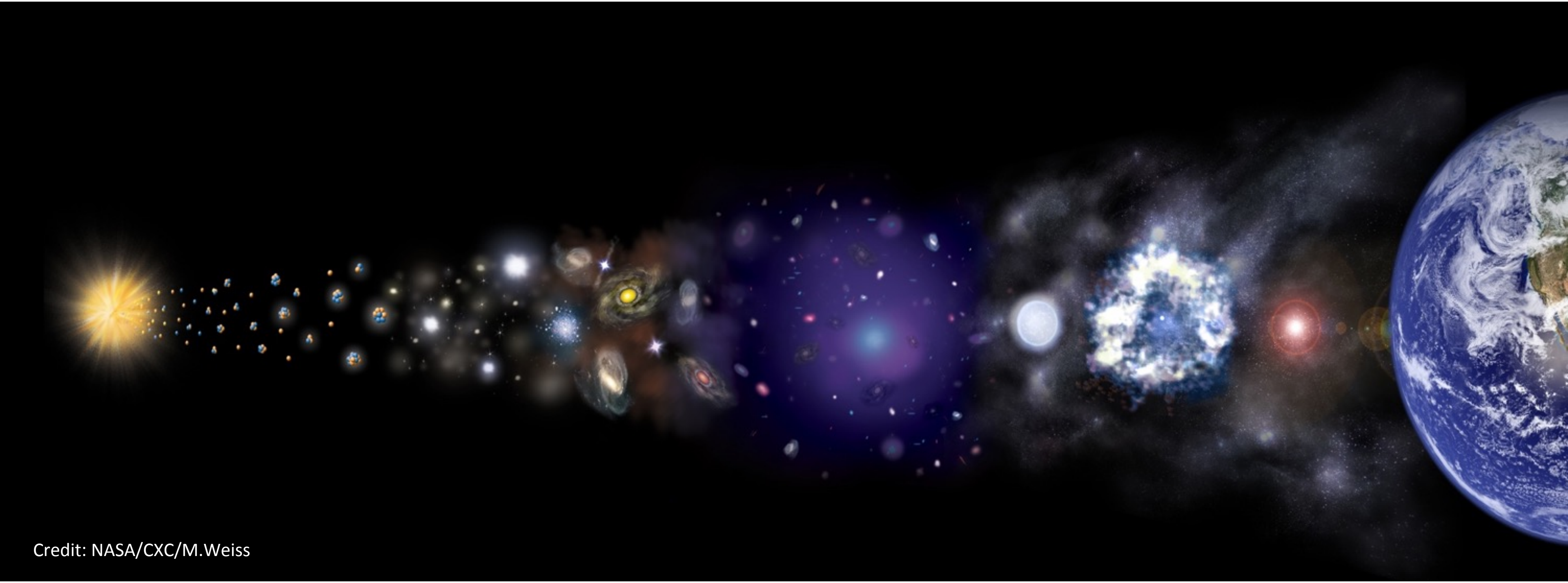
European Research Council
Established by the European Commission

Special thanks to

- **M. Guttormsen, J.E. Midtbø, T. Renstrøm, F. Bello Garrote** & the rest of the Oslo nuclear-physics group (University of Oslo)
- **A. Spyrou, S. Liddick**, K. Childers, B. Crider, F. Naqvi, **B. Alex Brown**, A.C. Dombos, R. Lewis, S. Lyons, D.J. Morrissey, C. Prokop, S.J. Quinn, A. Rodriquez, C.S. Sumithrarachchi, M.K. Smith, R.G.T. Zegers (NSCL/MSU)
- G. Perdikakis, S. Nikas (Central Michigan University)
- R. Surman, M. Mumpower, S. Frauendorf, A. Simon (Univ. of Notre Dame)
- **S. Goriely** (Université Libre de Bruxelles)
- M. Wiedeking (iThemba LABS)
- **R. Schwengner** (HZDR Dresden-Rossendorf)
- **S. Frauendorf** (University of Notre Dame)
- A. Bracco, F. Camera, S. Leoni, N. Blasi, B. Million (INFN Milano)
- A. V. Voinov (Ohio University)
- A. Couture, S.M. Mosby (Los Alamos National Lab)
- D.L. Bleuel (Lawrence Livermore National Lab)
- B. Rubio (CSIC-Universidad de Valencia)

From peanutsmovie.com

Where do the elements come from?



Credit: NASA/CXC/M.Weiss

Hydrogen and helium (some Li, …) from the Big-Bang, everything else from stellar processes

[Burbidge, Burbidge, Fowler & Hoyle, Rev. Mod. Phys. 29, 547 (1957); Cameron, Pub. Astron. Soc. Pac. 69, 201 (1957)]

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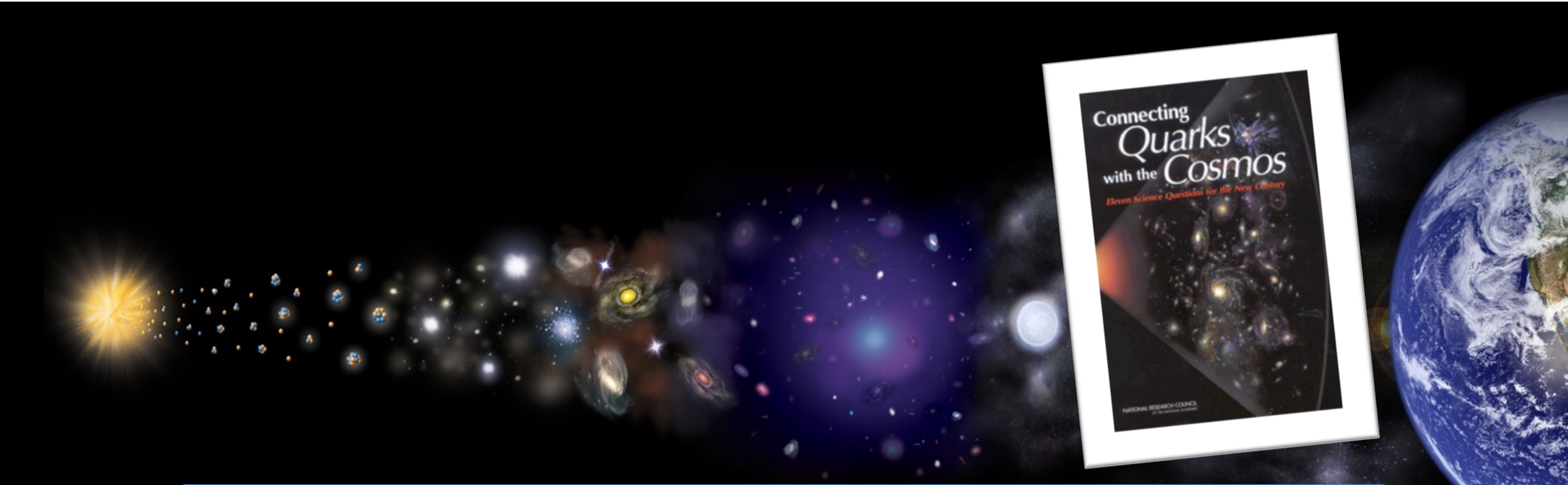

Credit: NASA/CXC/

"How Were the Elements from Iron to Uranium Made?"

[Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century; US National Research Council (2003)]

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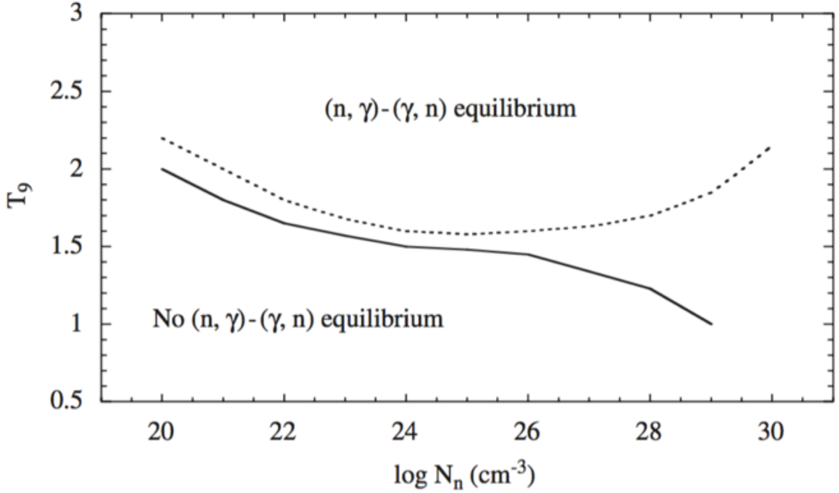
The r-process: do neutron-capture rates matter?



Solid line: pure Hauser-Feshbach; dashed line: also direct capture
[M. Arnould, S. Goriely and K. Takahashi, Phys. Rep. 450, 97 (2007)]

For "cold" conditions (<1 GK) and after freeze-out
[no (n,γ)- (γ,n) equilibrium]: (n,γ) rates are needed
[e.g. Mendoza-Temis et al., PRC 92, 055805 (2015);
Eichler et al., Astrophys. J. 808, 30 (2015)]

Detection of a neutron star collision 17 Aug 2017 by LIGO & Virgo

Finally one confirmed site for the r-process!

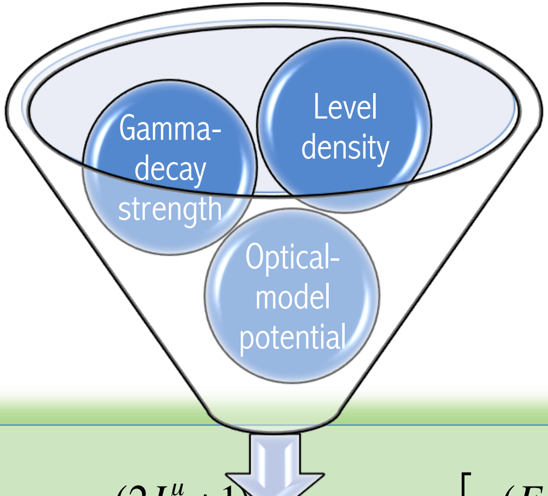
[B.P. Abbott et al., Phys. Rev. Lett. **119**, 161101 (2017)]
[D. Kasen et al., Nature **551**, 80 (2017)] +++

Theoretical estimates for the vast majority of the r-process (n,γ) reaction rates

The work horse:

Hauser-Feshbach theory

[W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952)]



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

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

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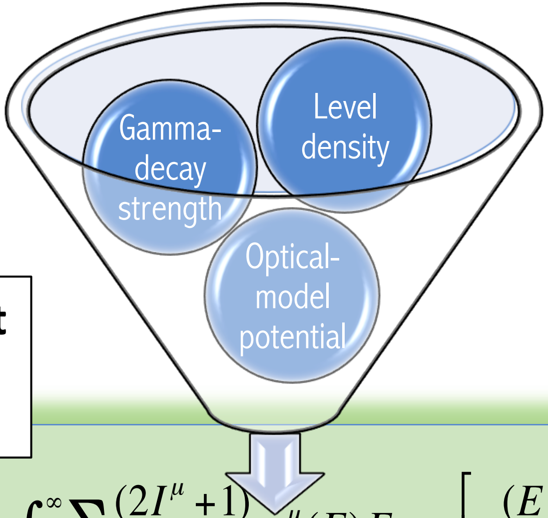

Uncertain input → Uncertain output (orders of magnitude!)

[Mumpower et al., PPNP 86, 86 (2016)]

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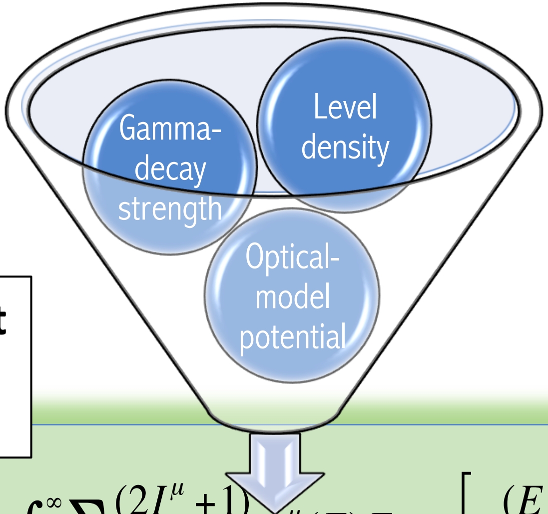

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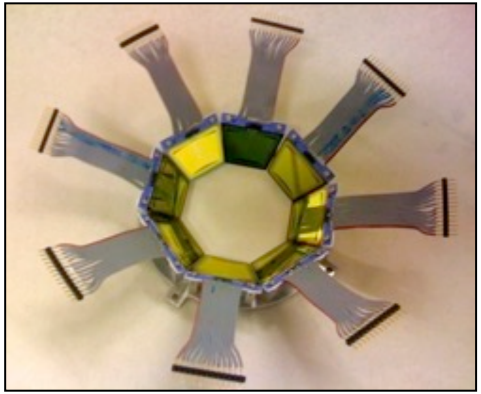
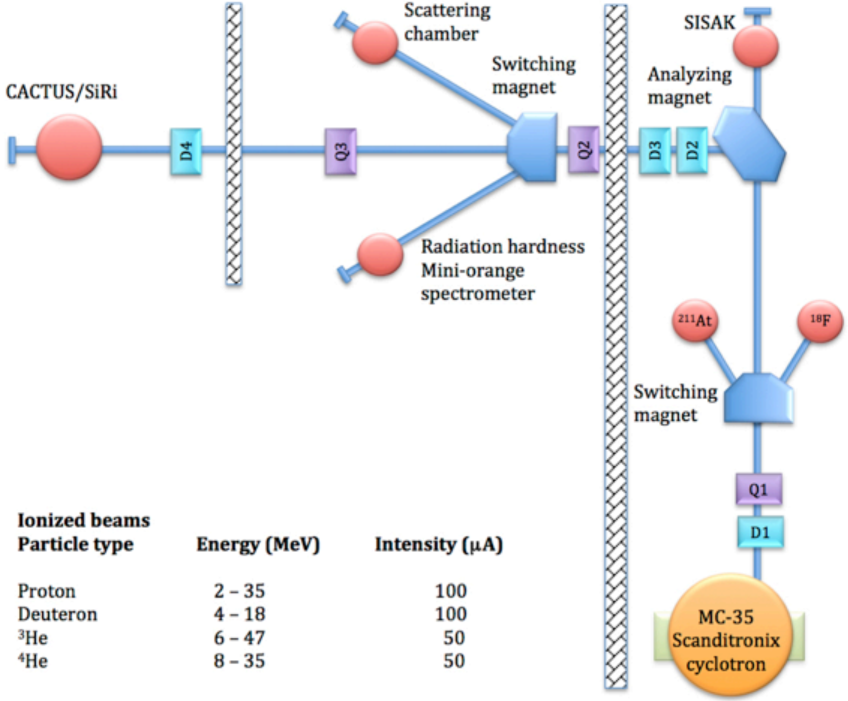
Indirect constraint: measure level density and γ-decay strength

Experiments at the Oslo Cyclotron Laboratory

CACTUS:
26 collimated NaI(Tl) crystals, 5’’ x 5’’



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

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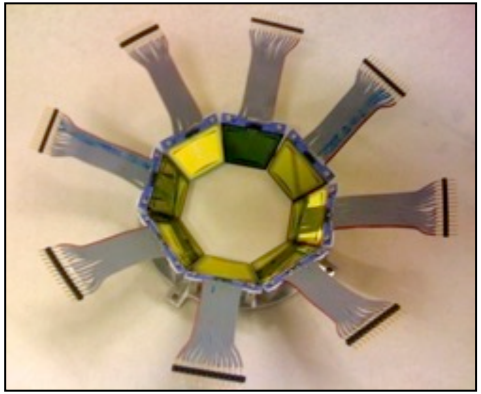

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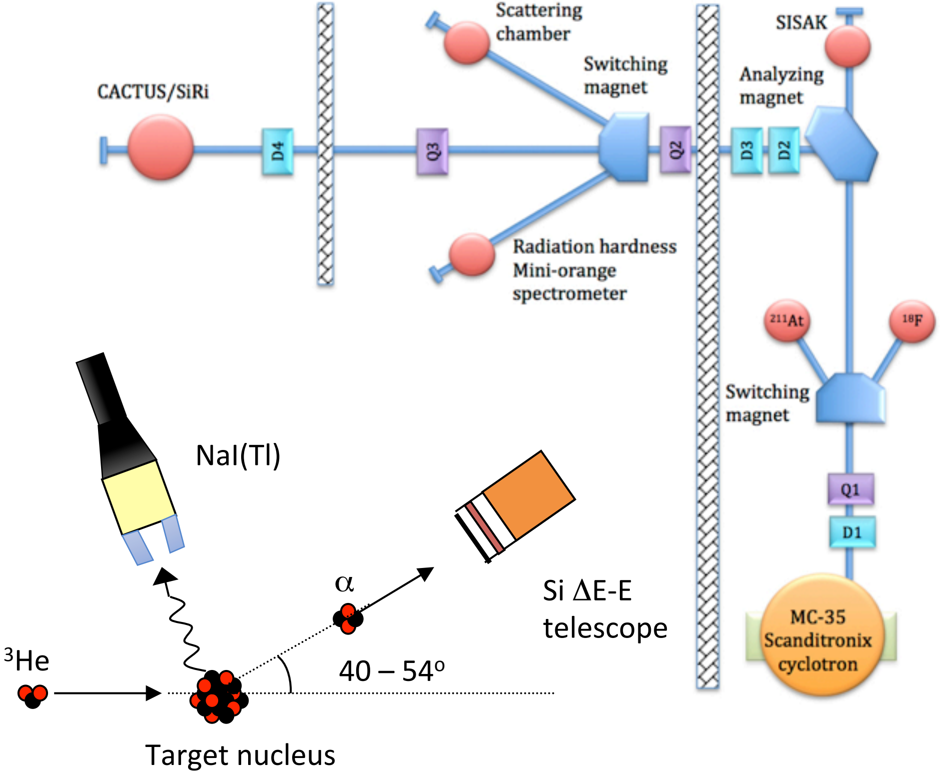

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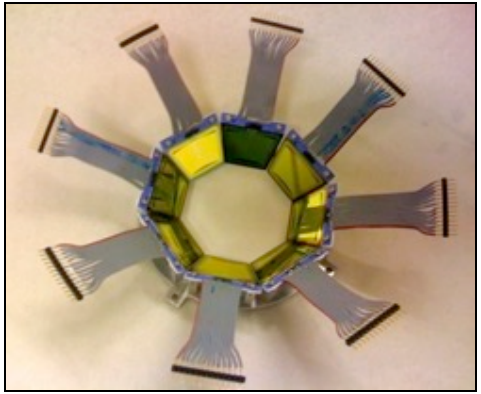

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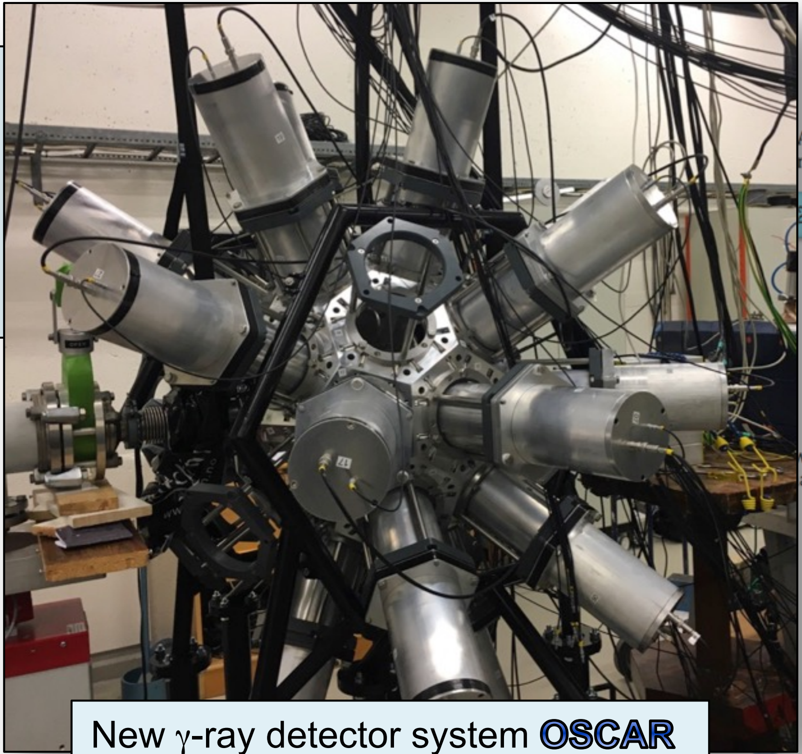
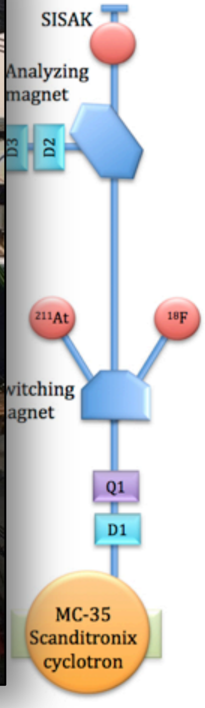


New γ-ray detector system **OSCAR**
(30 $LaBr_3$ 3.5’’ x 8’’ crystals)
[Funding from the Research Council of Norway]



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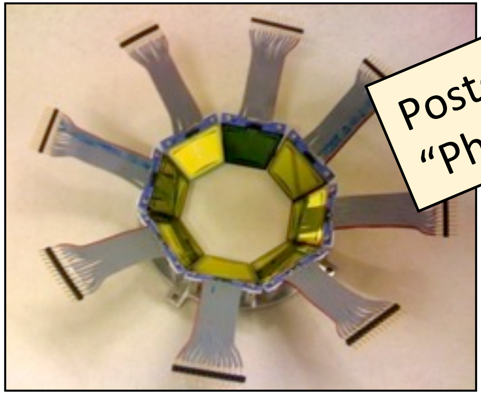

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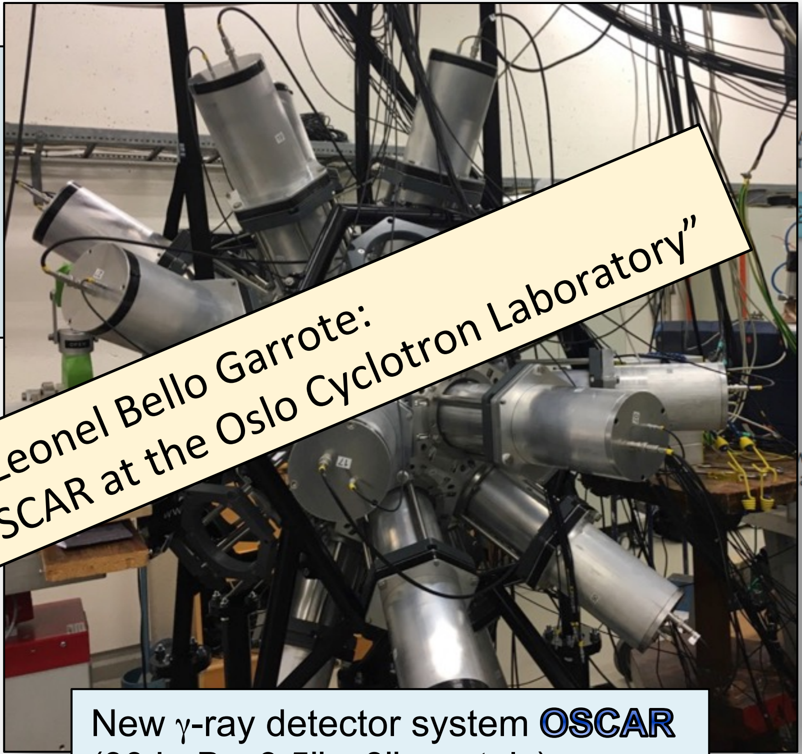

Poster by Frank Leonel Bello Garrote:
"Physics with OSCAR at the Oslo Cyclotron Laboratory"

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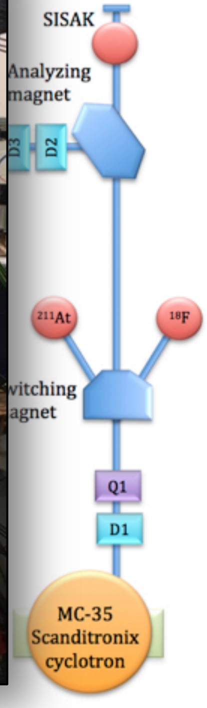
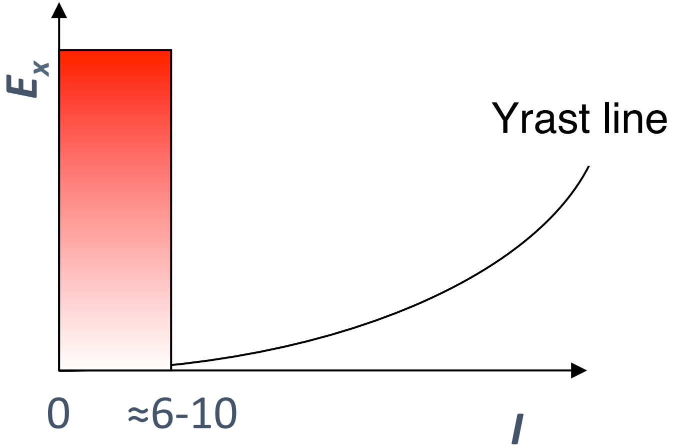
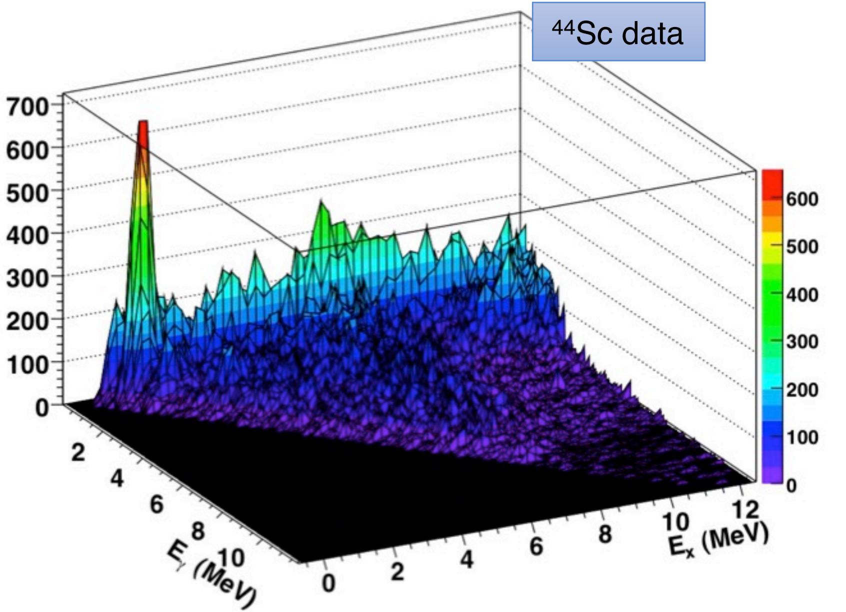


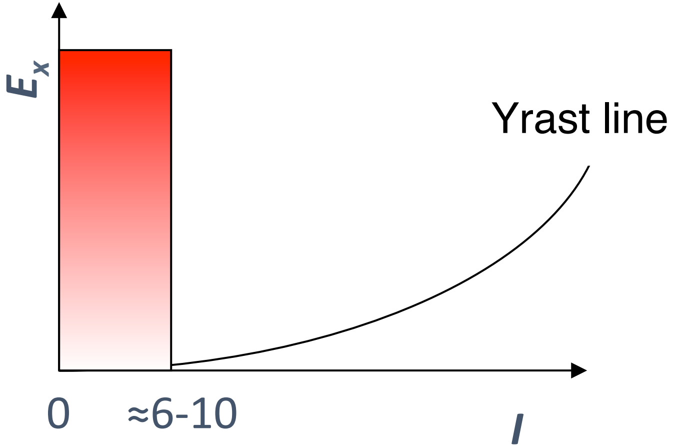
The Oslo method in a 

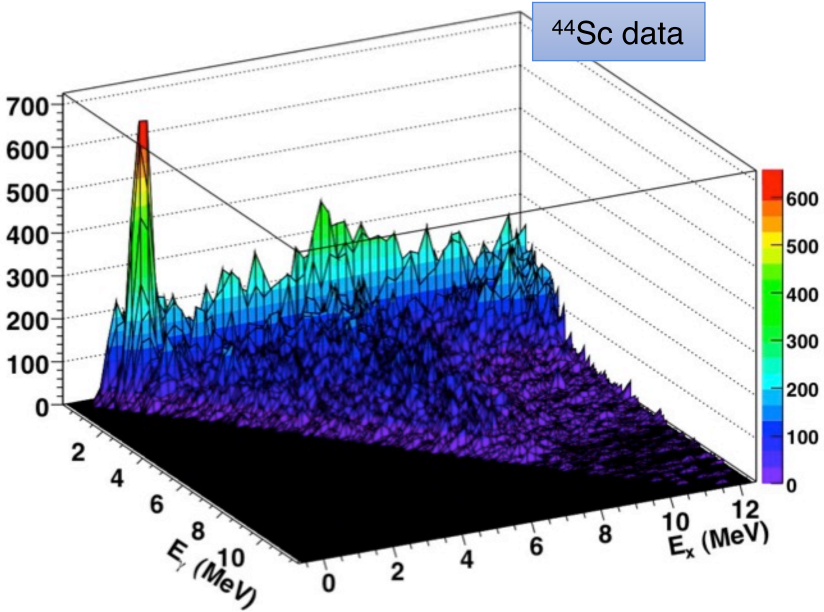




0. Get a hold of an ($E\gamma$,Ex) matrix (> 30-40 000 coincidences)
1. Correct for the NaI response [Guttormsen et al., NIM A 374, 371 (1996)]
2. Extract *distribution of* primary γs for each Ex [Guttormsen et al., NIM A 255, 518 (1987)]
3. Get level density and γ-strength from primary γ's [Schiller et al., NIM A 447, 498 (2000)]
4. Normalize & evaluate systematic errors [Schiller et al., NIM A 447, 498 (2000), Larsen *et al.*, PRC **83**, 034315 (2011)]

The Oslo method in a 





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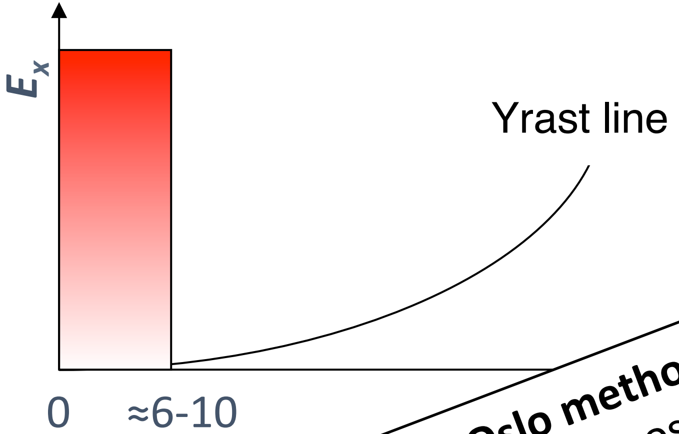
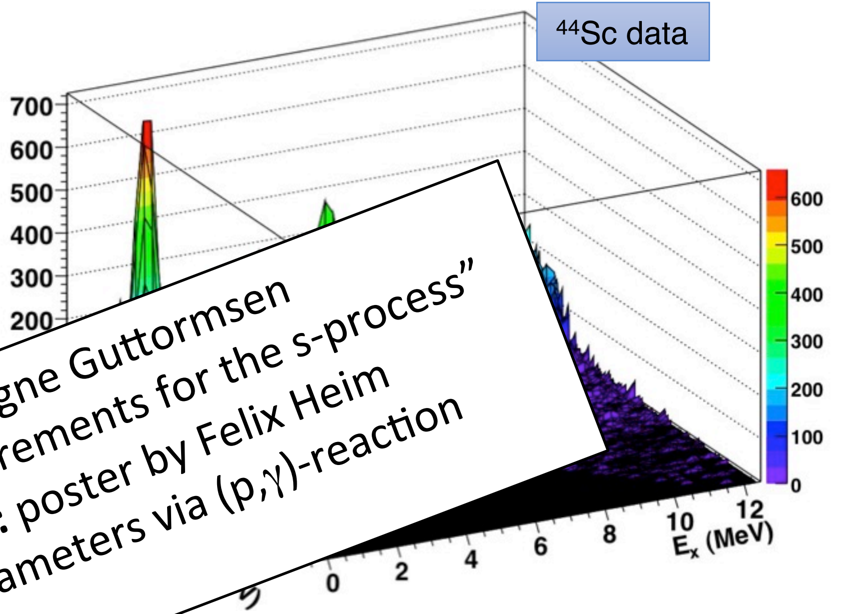
Data and references:
ocl.uio.no/compilation/
Analysis codes and tools:
github.com/oslocyclotronlab/oslo-method-software

The Oslo method in a





More on the Oslo method: poster by Magne Guttormsen
"Indirect (n,γ)^{91,92}Zr cross section measurements for the s-process"
A different way to measure γ-strength: poster by Felix Heim
"Detailed study of nuclear physics parameters via (p,γ)-reaction cross-section measurements"

0. Ge... coincidences)
1. Co... NIM A 374, 371 (1996)]
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Surprise! The low-energy *upbend*

VOLUME 93, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 1 OCTOBER 2004

Large Enhancement of Radiative Strength for Soft Transitions in the Quasicontinuum

A. Voinov,[1,2,*] E. Algin,[3,4,5,6] U. Agvaanluvsan,[3,4] T. Belgya,[7] R. Chankova,[8] M. Guttormsen,[8] G. E. Mitchell,[4,5] J. Rekstad,[8] A. Schiller,[3,†] and S. Siem[8]

[1]*Frank Laboratory of Neutron Physics, Joint Institute of Nuclear Research, 141980 Dubna, Moscow region, Russia*
[2]*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA*
[3]*Lawrence Livermore National Laboratory, L-414, 7000 East Avenue, Livermore, California 94551, USA*
[4]*North Carolina State University, Raleigh, North Carolina 27695, USA*
[5]*Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA*
[6]*Department of Physics, Osmangazi University, Meselik, Eskisehir, 26480 Turkey*
[7]*Institute of Isotope and Surface Chemistry, Chemical Research Centre HAS, P.O. Box 77, H-1525 Budapest, Hungary*
[8]*Department of Physics, University of Oslo, N-0316 Oslo, Norway*

(Received 26 April 2004; published 29 September 2004)

Radiative strength functions (RSFs) for the ^{56,57}Fe nuclei below the separation energy are obtained from the ^{57}Fe(^{3}He, $\alpha\gamma$)^{56}Fe and ^{57}Fe(^{3}He, ^{3}He$'\gamma$)^{57}Fe reactions, respectively. An enhancement of more than a factor of 10 over common theoretical models of the soft ($E_\gamma \lesssim 2$ MeV) RSF for transitions in the quasicontinuum (several MeV above the yrast line) is observed. Two-step cascade intensities with soft primary transitions from the ^{56}Fe(n, 2γ)^{57}Fe reaction confirm the enhancement.

DOI: 10.1103/PhysRevLett.93.142504 PACS numbers: 25.40.Lw, 25.20.Lj, 25.55.Hp, 27.40.+z

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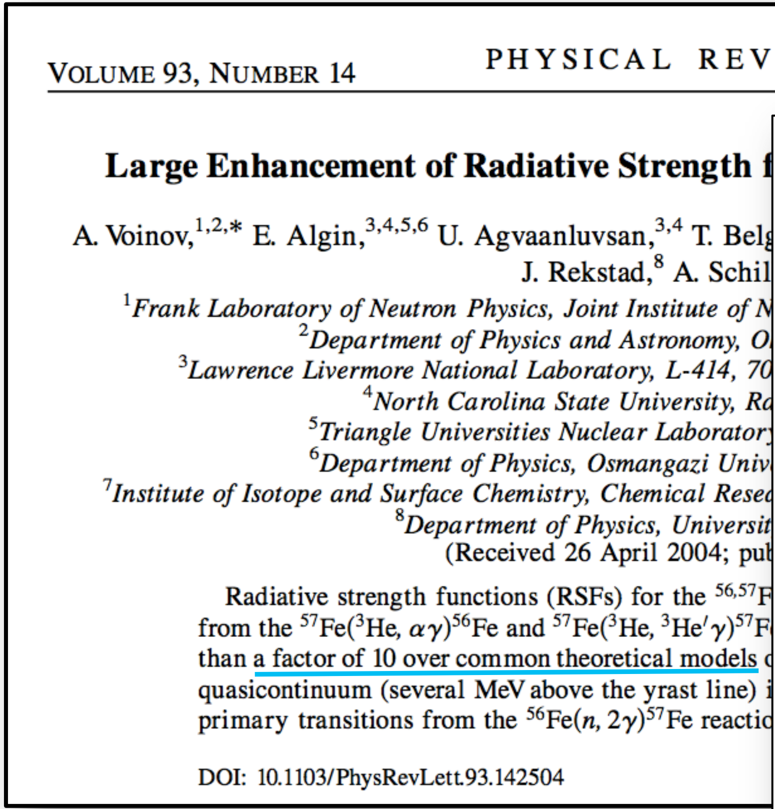

VOLUME 93, NUMBER 14 PHYSICAL REVIEW LETTERS week ending 1 OCTOBER 2004

Large Enhancement of Radiative Strength f

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J. Rekstad,[8] A. Schil
[1]*Frank Laboratory of Neutron Physics, Joint Institute of N*
[2]*Department of Physics and Astronomy, O*
[3]*Lawrence Livermore National Laboratory, L-414, 70*
[4]*North Carolina State University, Ra*
[5]*Triangle Universities Nuclear Laborator*
[6]*Department of Physics, Osmangazi Univ*
[7]*Institute of Isotope and Surface Chemistry, Chemical Rese*
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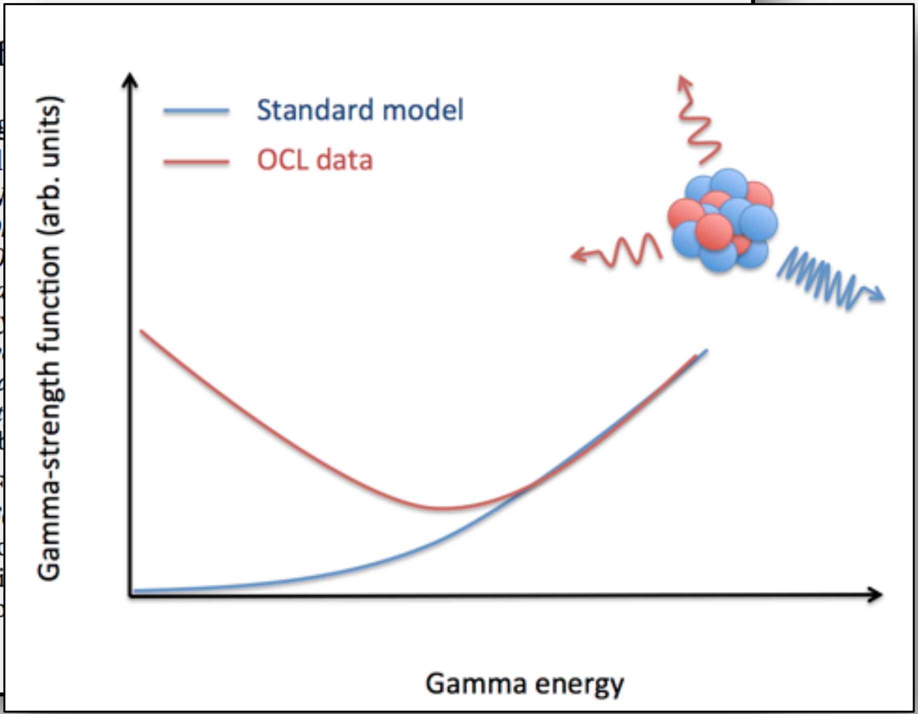
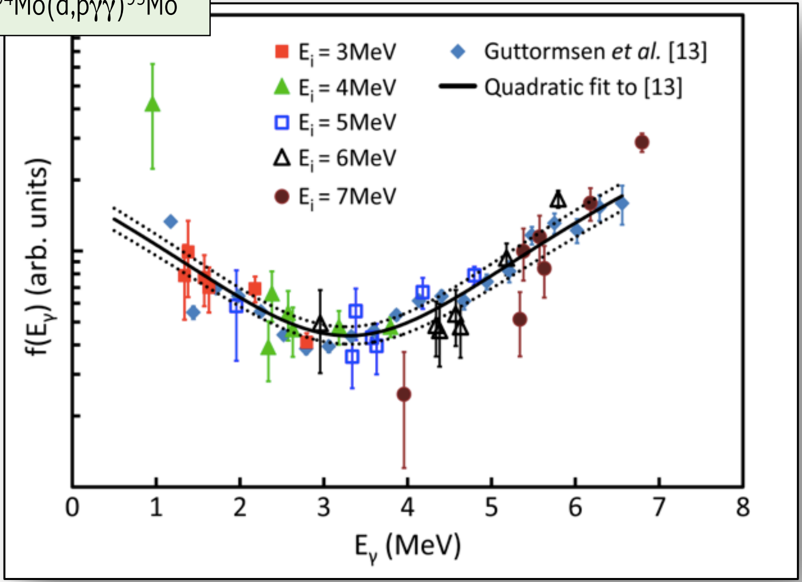
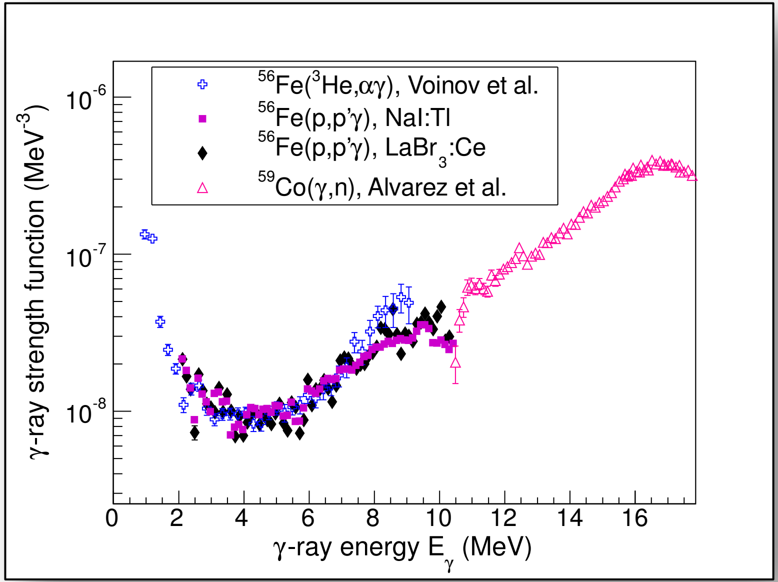


What do we know about the upbend?

$^{94}Mo(d,p\gamma\gamma)^{95}Mo$





Confirmed with an independent technique using (d,pγγ) coincidences
[M. Wiedeking et al., PRL **108**, 162503 (2012)]

6 3.5" x 8" $LaBr_3$(Ce) from the HECTOR$^+$ array
Dominated by **dipole transitions**
[A.C. Larsen et al., PRL **111**, 242504 (2013)]

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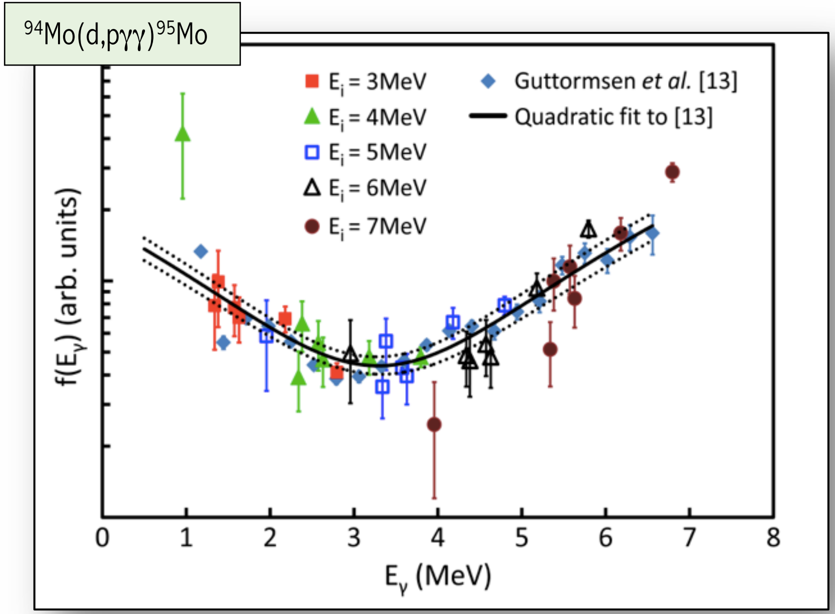

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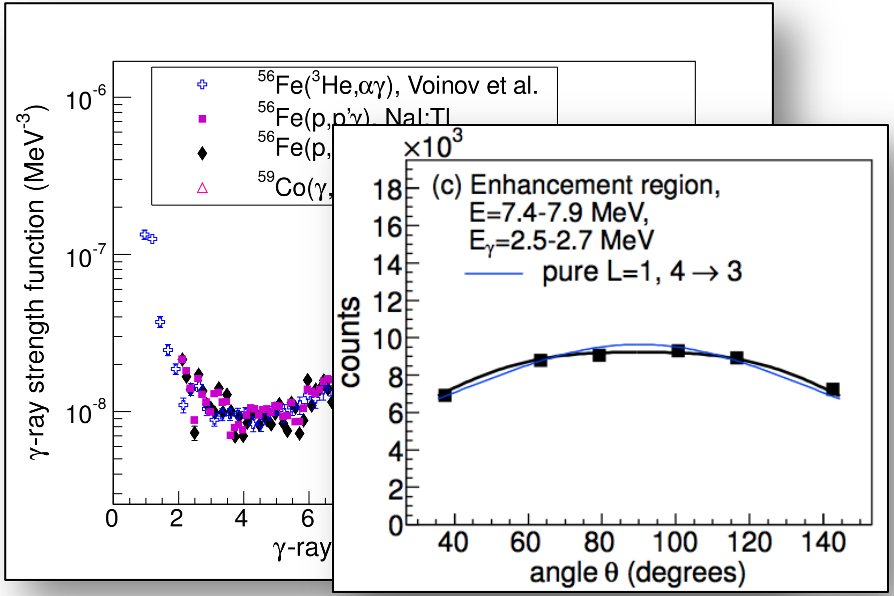

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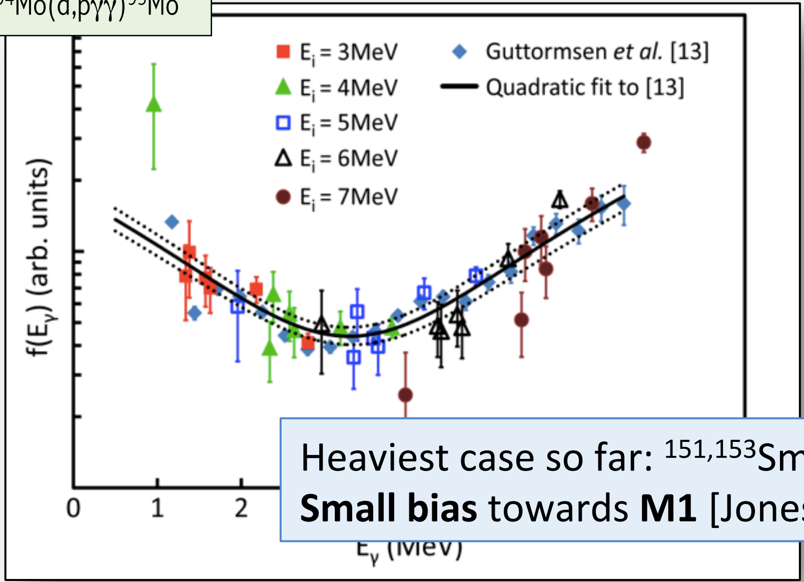

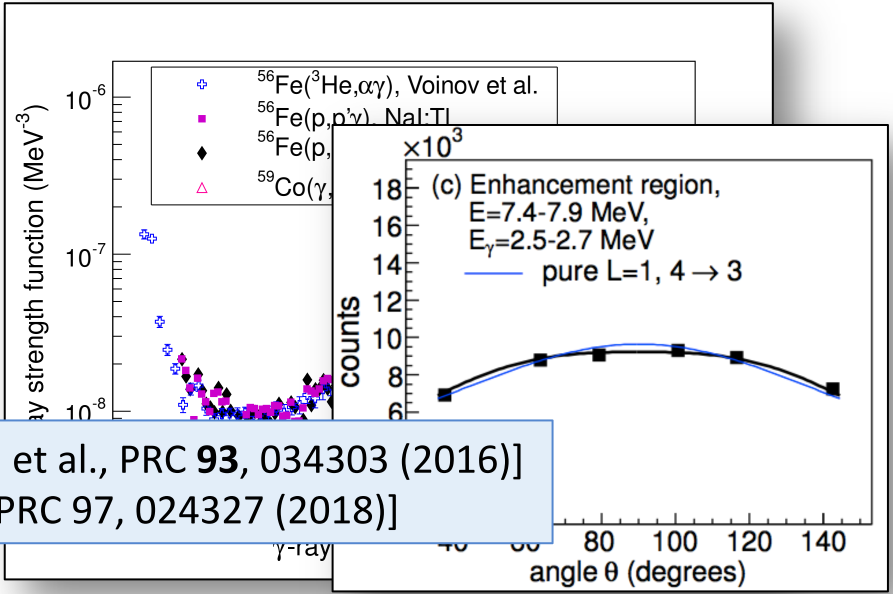

Heaviest case so far: $^{151,153}Sm$ [Simon et al., PRC **93**, 034303 (2016)]
Small bias towards **M1** [Jones et al., PRC 97, 024327 (2018)]

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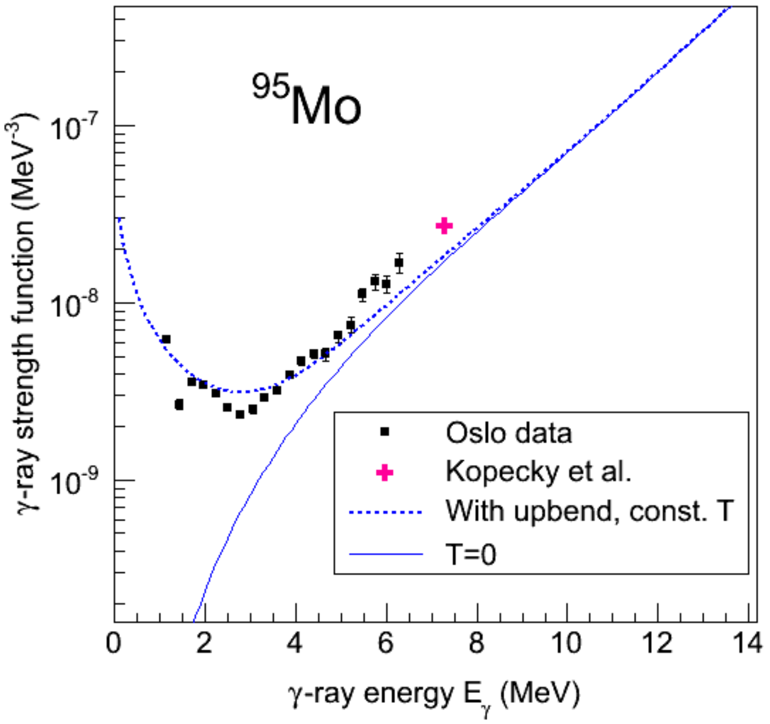
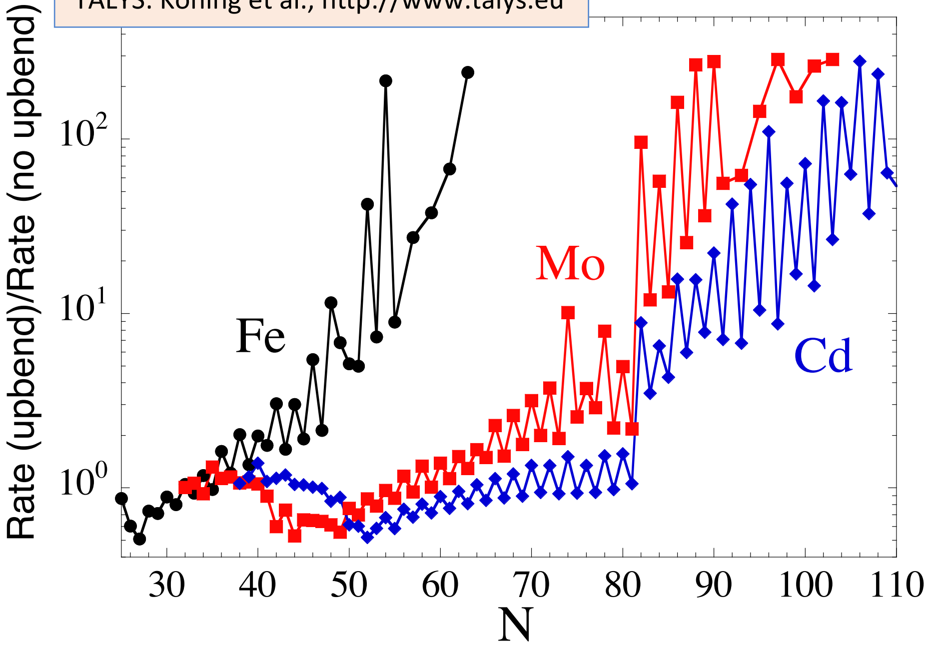
Impact on r-process reaction rates?



Reaction rates @T = 1 GK
TALYS: Koning et al., http://www.talys.eu



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

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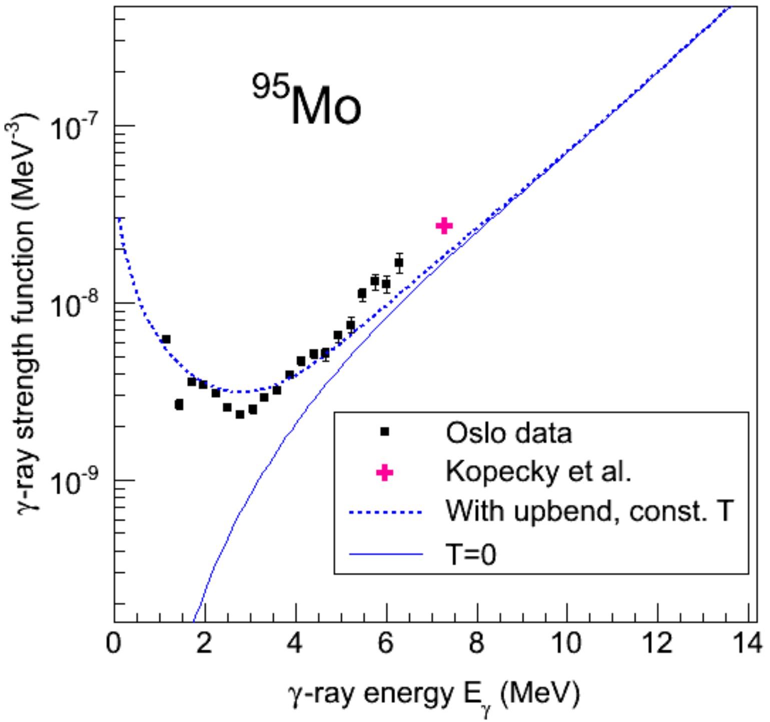

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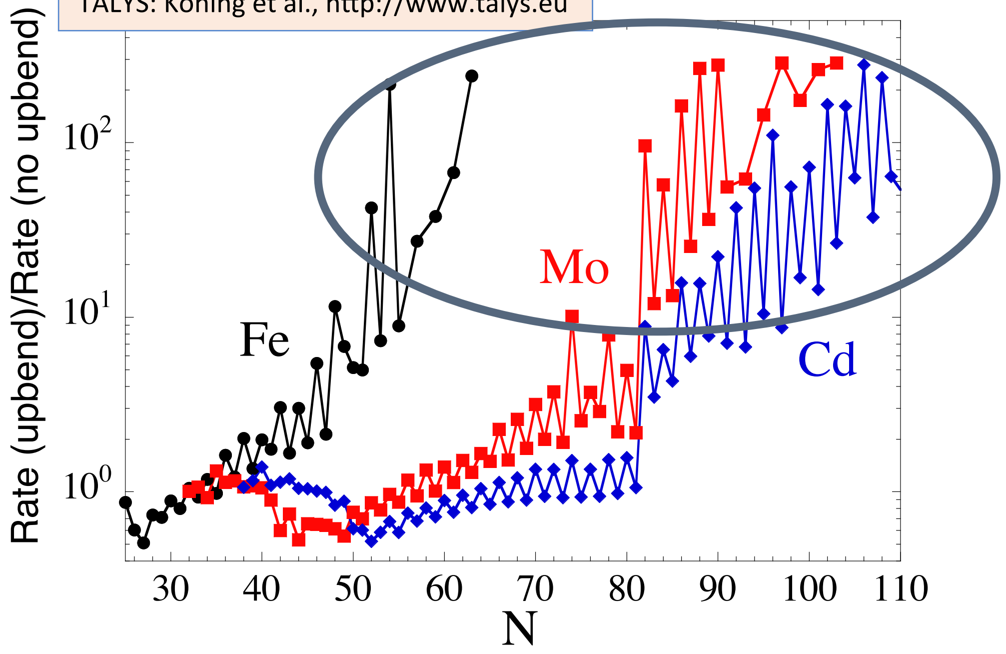

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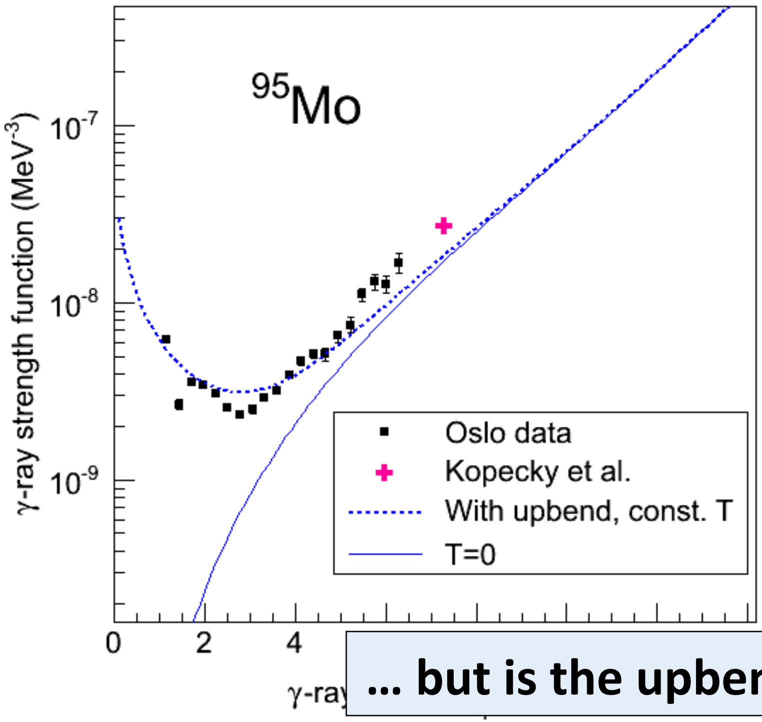

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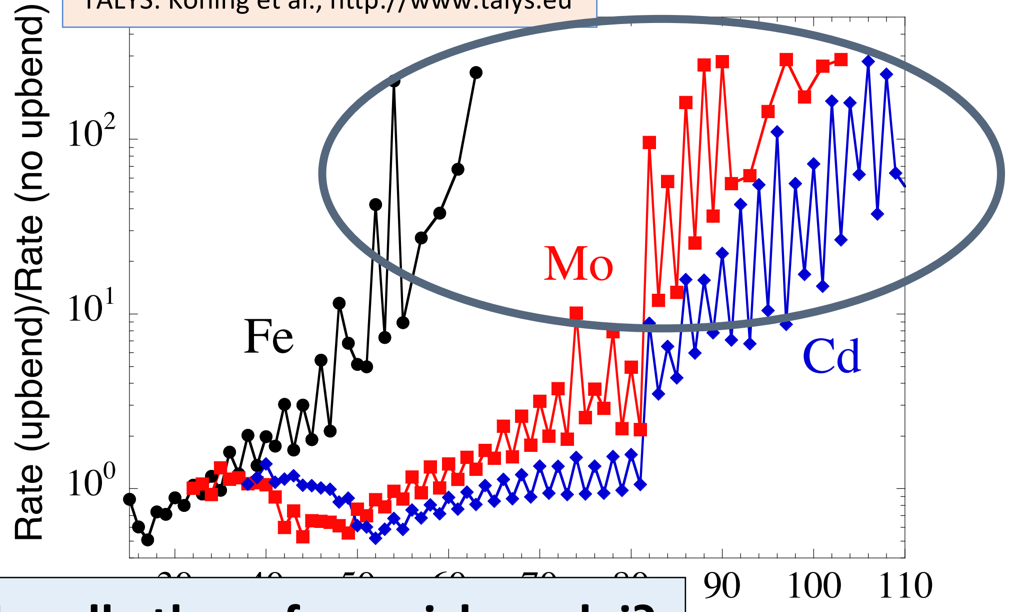


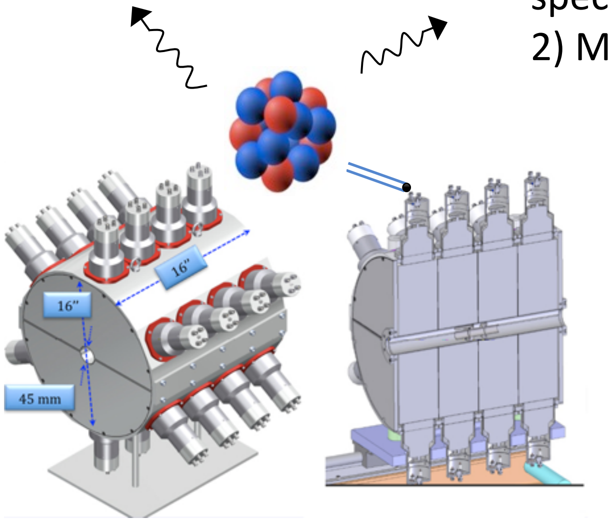
… but is the upbend really there for n-rich nuclei?

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

The beta-Oslo method

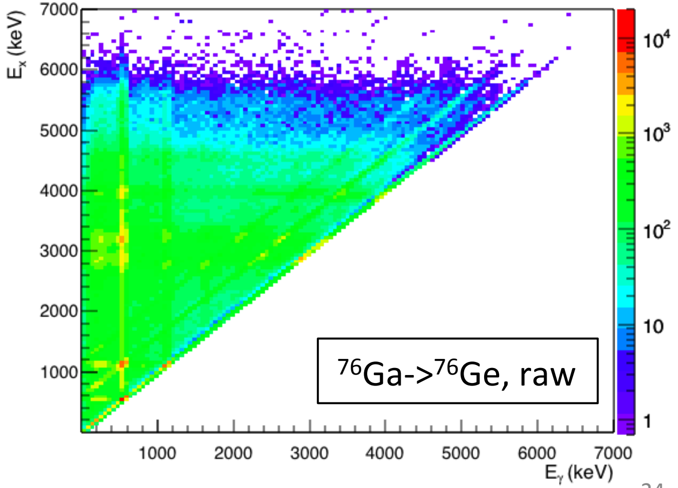
Special thanks to
Artemis Spyrou,
Sean Liddick,
Magne Guttormsen

Developed @ NSCL/Michigan State University summer 2014
Advantage: can go down to implantation rate of ≈**1 pps**
1) Implant a neutron-rich nucleus inside a *segmented* total-absorption spectrometer (preferably with $Q_\beta \approx S_n$)
2) Measure β^- in coincidence with *all* γ rays from the daughter nucleus



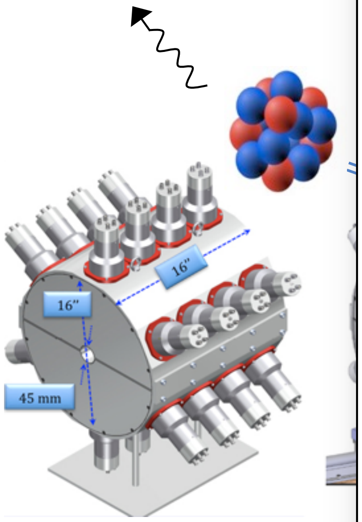
Segmented, total absorption spectrometer SuN
[A. Simon, S.J. Quinn, A. Spyrou et al, NIM A 703, 16 (2013)]

Segments give individual γ rays, the sum of all gives initial Ex



The beta-Oslo method

Special thanks to
Artemis Spyrou,
Sean Liddick,
Magne Guttormsen



PRL **113,** 232502 (2014) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2014

Novel technique for Constraining *r*-Process (*n*, *γ*) Reaction Rates

A. Spyrou,[1,2,3,*] S. N. Liddick,[1,4,†] A. C. Larsen,[5,‡] M. Guttormsen,[5] K. Cooper,[1,4] A. C. Dombos,[1,2,3]
D. J. Morrissey,[1,4] F. Naqvi,[1] G. Perdikakis,[6,1,3] S. J. Quinn,[1,7,3] T. Renstrøm,[5] J. A. Rodriguez,[1]
A. Simon,[1,8] C. S. Sumithrarachchi,[1] and R. G. T. Zegers[1,7,3]
[1]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
[5]*Department of Physics, University of Oslo, NO-0316 Oslo, Norway*
[6]*Central Michigan University, Mount Pleasant, Michigan, 48859, USA*
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[8]*Department of Physics and The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
(Received 25 August 2014; published 2 December 2014)

A novel technique has been developed, which will open exciting new opportunities for studying the very neutron-rich nuclei involved in the *r* process. As a proof of principle, the *γ* spectra from the *β* decay of ^{76}Ga have been measured with the SuN detector at the National Superconducting Cyclotron Laboratory. The nuclear level density and *γ*-ray strength function are extracted and used as input to Hauser-Feshbach calculations. The present technique is shown to strongly constrain the ^{75}Ge$(n,\gamma)^{76}$Ge cross section and reaction rate.

DOI: 10.1103/PhysRevLett.113.232502 PACS numbers: 26.30.Hj, 21.10.Ma, 27.50.+e

Segmented, total absorption
[A. Simon, S.J. Quinn, A. Spyrou et al, NIM A 703, 16 (2013)]

The beta-Oslo method

Special thanks to
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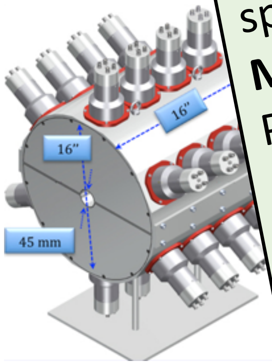
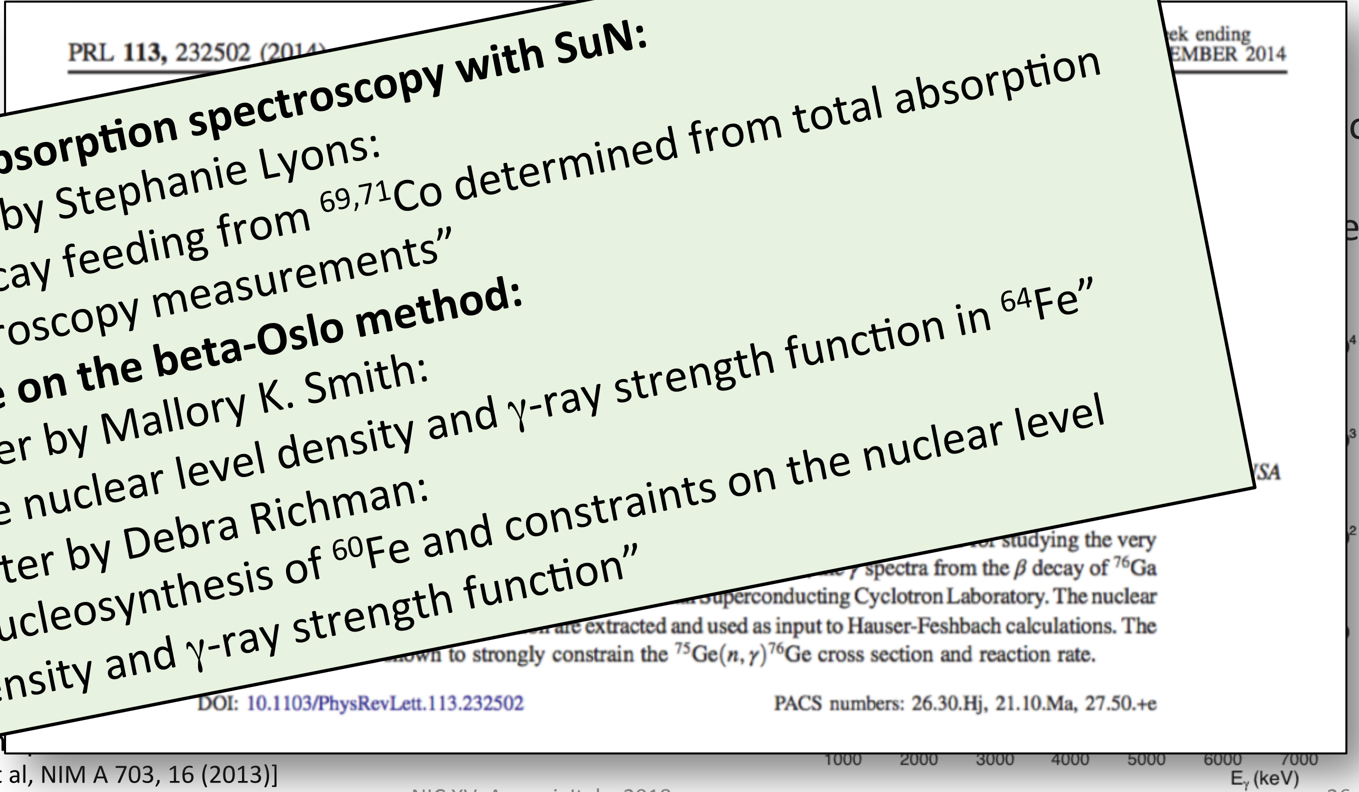


Segmented, total absorption ...
[A. Simon, S.J. Quinn, A. Spyrou et al, NIM A 703, 16 (2013)]


PRL **113,** 232502 (2014) ... ek ending ... EMBER 2014

... for studying the very ... γ spectra from the β decay of ^{76}Ga ... Superconducting Cyclotron Laboratory. The nuclear ... are extracted and used as input to Hauser-Feshbach calculations. The ... shown to strongly constrain the ^{75}Ge$(n,\gamma)^{76}$Ge cross section and reaction rate.

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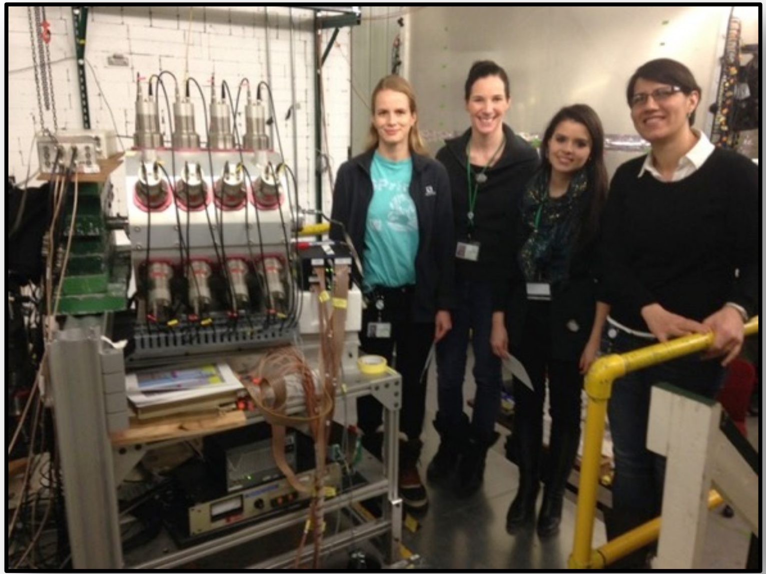
Total absorption spectroscopy with SuN:
Poster by Stephanie Lyons:
"β-decay feeding from ^{69,71}Co determined from total absorption spectroscopy measurements"

More on the beta-Oslo method:
Poster by Mallory K. Smith:
"The nuclear level density and γ-ray strength function in ^{64}Fe"
Poster by Debra Richman:
"Nucleosynthesis of ^{60}Fe and constraints on the nuclear level density and γ-ray strength function"

The beta-Oslo method: ^{70}Ni

Discretionary beam time @ NSCL/MSU, February 2015; ^{70}Co beta-decaying into ^{70}Ni
(Spokespersons: Sean Liddick, Artemis Spyrou, ACL & Magne Guttormsen)

^{86}Kr primary beam, 140 MeV/nucleon on thick Be target
^{70}Co implanted on DSSD detector in SuN



^{70}Co $T_{1/2}$: 105 ms, $I^{\pi} = 6^{-}$, Q_{β} = 12.3 MeV
S_n of ^{70}Ni: 7.3 MeV
Initial spins, ^{70}Ni (Gamow-Teller): $5^{-}, 6^{-}, 7^{-}$

[S.N. Liddick A. Spyrou, B.P. Crider, F. Naqvi, A.C. Larsen, M. Guttormsen et al., Phys. Rev. Lett. **116**, 242502 (2016)]

The beta-Oslo method: ^{70}Ni

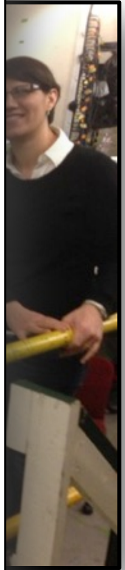
PRL **116,** 242502 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

Experimental Neutron Capture Rate Constraint Far from Stability

S. N. Liddick,[1,2] A. Spyrou,[1,3,4] B. P. Crider,[1] F. Naqvi,[1] A. C. Larsen,[5] M. Guttormsen,[5] M. Mumpower,[6,7] R. Surman,[6] G. Perdikakis,[8,1,4] D. L. Bleuel,[9] A. Couture,[10] L. Crespo Campo,[5] A. C. Dombos,[1,3,4] R. Lewis,[1,2] S. Mosby,[10] S. Nikas,[8,4] C. J. Prokop,[1,2] T. Renstrom,[5] B. Rubio,[11] S. Siem,[5] and S. J. Quinn[1,3,4]

[1]*National Superconducting Cyclotron Laboratory (NSCL), Michigan State University, East Lansing, Michigan 48824, USA*
[2]*Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[4]*Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA*
[5]*Department of Physics, University of Oslo, N-0316 Oslo, Norway*
[6]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[7]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87544, USA*
[8]*Central Michigan University, Mount Pleasant, Michigan 48859, USA*
[9]*Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, California 94550-9234, USA*
[10]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[11]*IFIC, CSIC-Universidad de Valencia, 46071 Valencia, Spain*

(Received 5 January 2016; published 16 June 2016)



The beta-Oslo method: ^{70}Ni

PRL **116**, 242502 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

Experimental Ne

S. N. Liddick,[1,2] A. Spyrou,[1,3,4] ... ower,[6,7]
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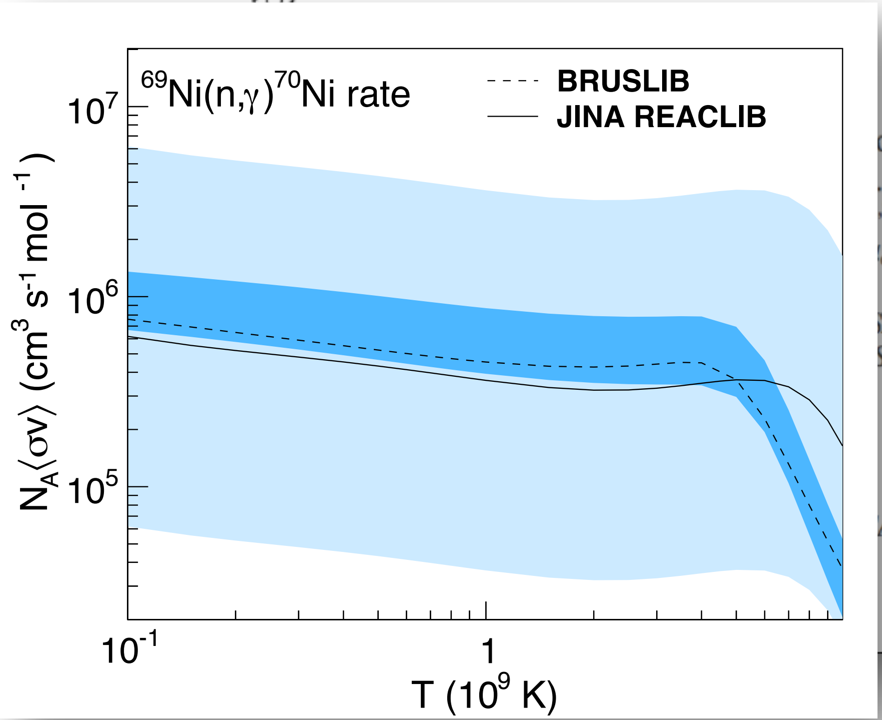
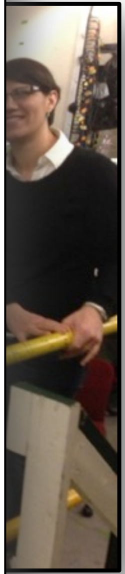
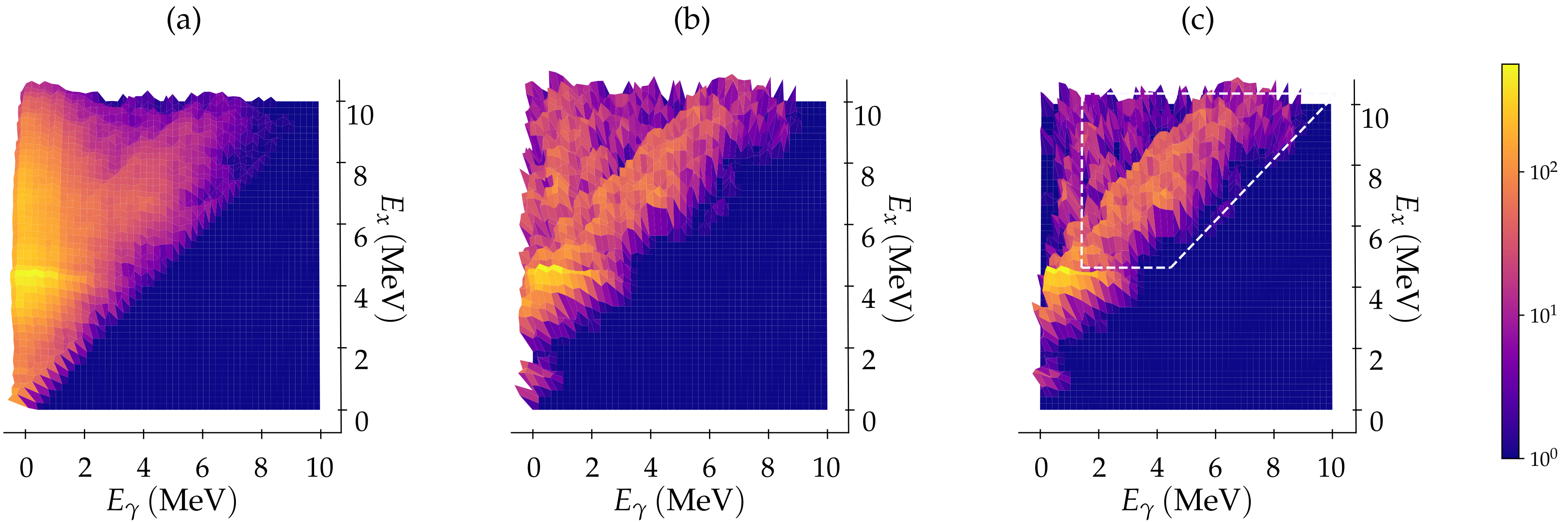




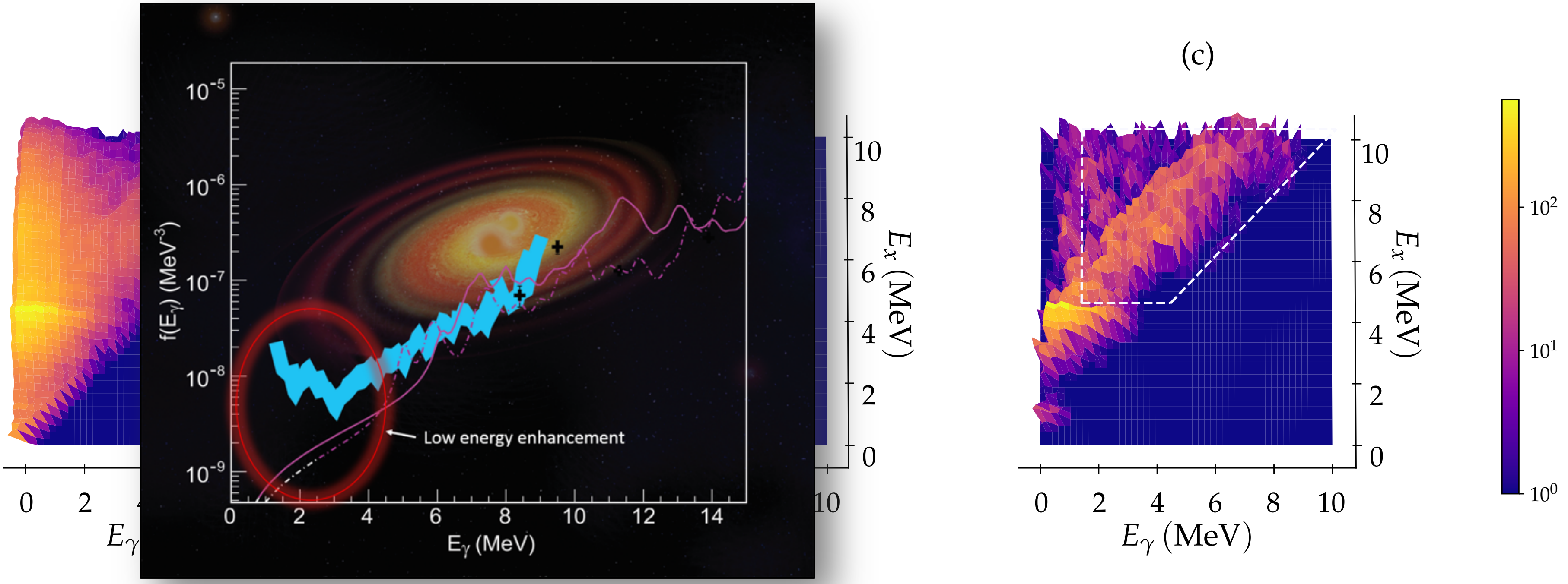
The beta-Oslo method: ^{70}Ni upbend



Improved data analysis: deconvolution of the E_x axis as well [M. Guttormsen et al., in preparation]

[Larsen, Midtbø, Guttormsen, Renstrøm et al., PRC 97, 054329 (2018)]

The beta-Oslo method: ^{70}Ni upbend



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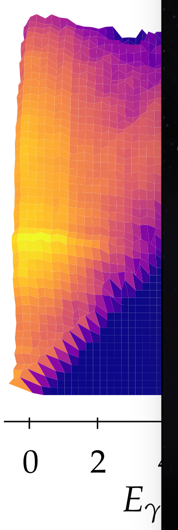
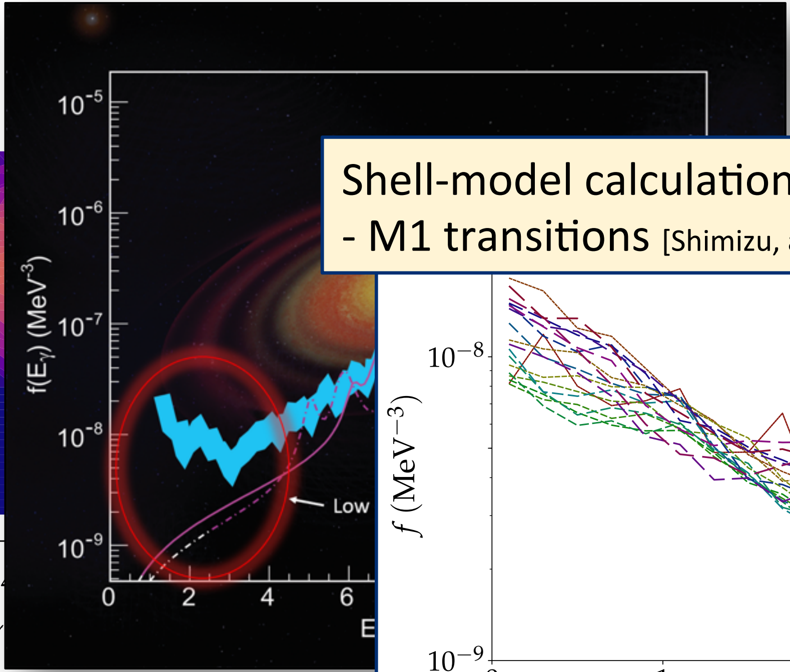
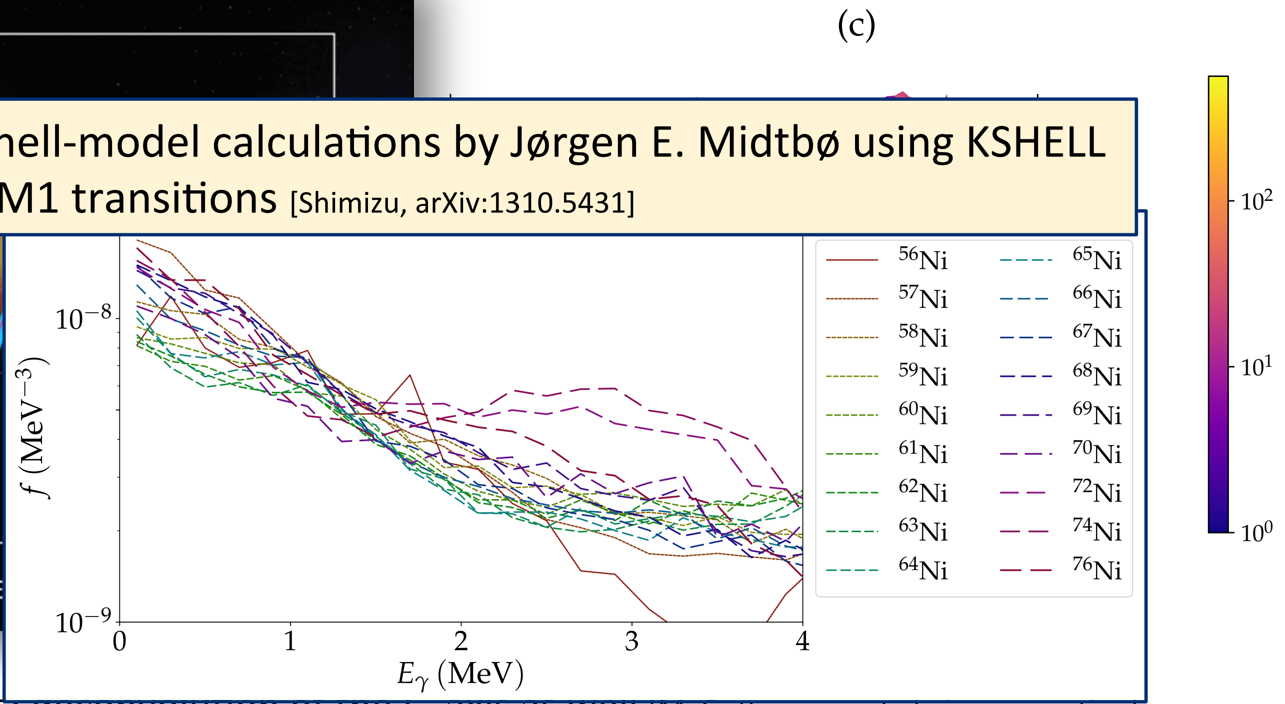




Shell-model calculations by Jørgen E. Midtbø using KSHELL - M1 transitions [Shimizu, arXiv:1310.5431]



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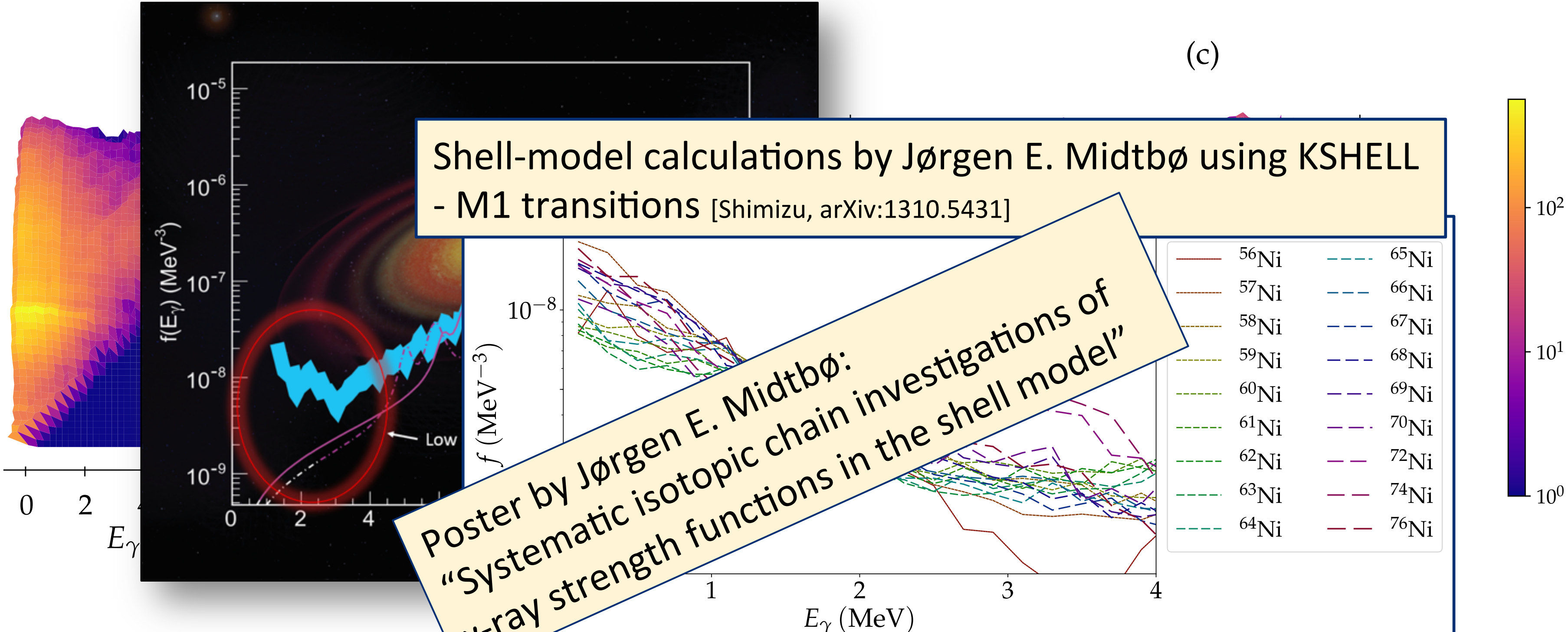


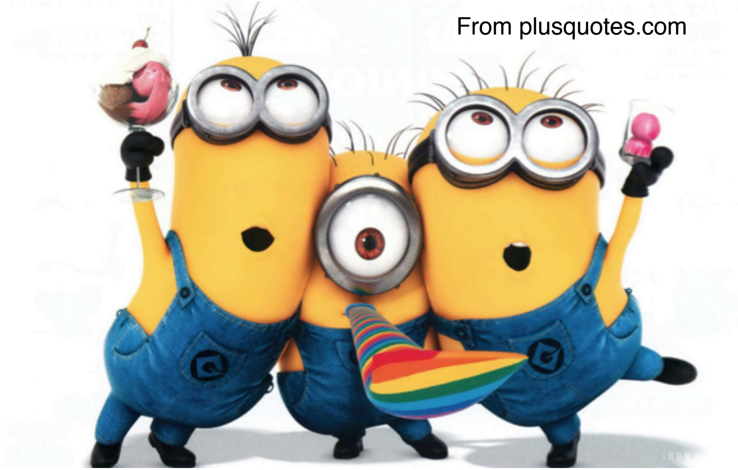
Shell-model calculations by Jørgen E. Midtbø using KSHELL - M1 transitions [Shimizu, arXiv:1310.5431]

Poster by Jørgen E. Midtbø: "Systematic isotopic chain investigations of γ-ray strength functions in the shell model"

Improved data analysi[...]econvolution of the E_x axis as well [M. Guttormsen et al., in preparation]

[Larsen, Midtbø, Guttormsen, Renstrøm et al., PRC 97, 054329 (2018)]

Summary & outlook



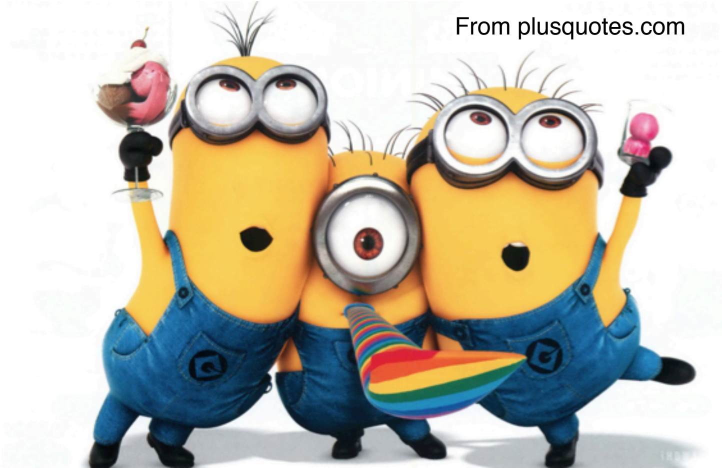
The beta-Oslo method provides level densities and γ-decay strengths of n-rich nuclei -> experimental constraint on (n,γ) rates

To-do list:

(i) Extend beta-Oslo to more neutron-rich nuclei
(ii) Work on new methods for normalization
(iii) Thorough investigation of systematic errors
…

What about the neutron OMP? Direct capture? Neutron resonances? +++

Summary & outlook



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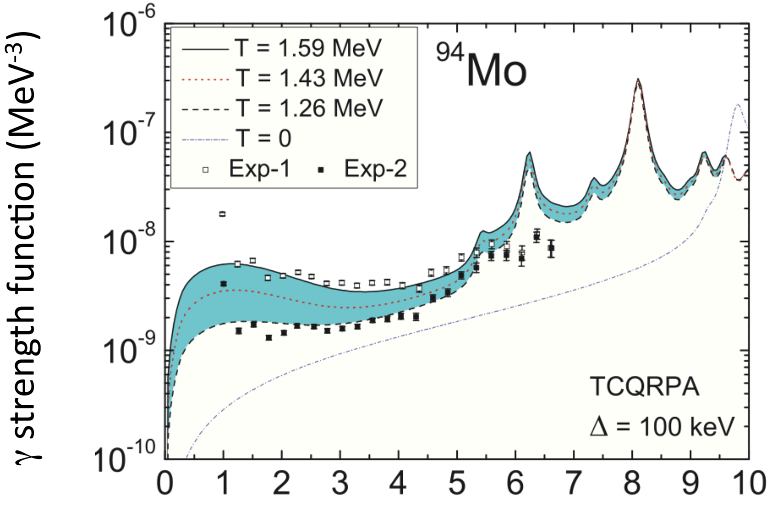
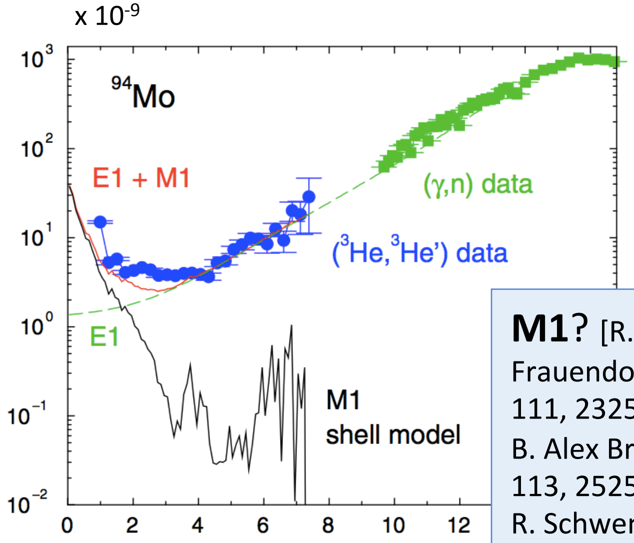
Many thanks for listening!

Extra slides

What does theory tell us about the upbend now?

Recent theoretical predictions seem to disagree…





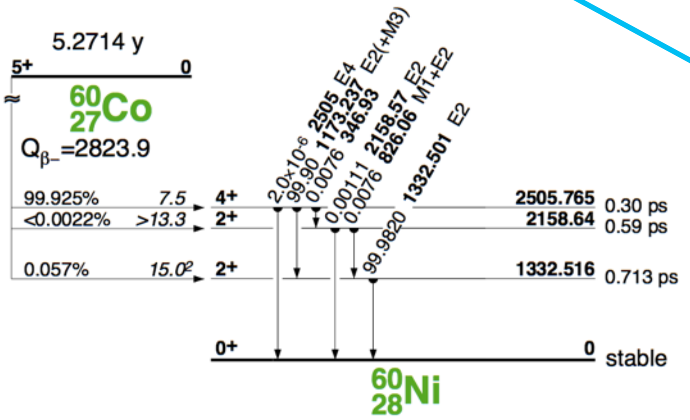
γ energy E_γ (MeV)

E1? [E. Litvinova and N. Belov, PRC **88**, 031302(R) (2013)]

M1? [R. Schwengner, S. Frauendorf, and A. C. Larsen, PRL 111, 232504 (2013);
B. Alex Brown and A.C. Larsen, PRL 113, 252502 (2014);
R. Schwengner, S. Frauendorf, B. Alex Brown, PRL 118, 092502 (2017);
K. Sieja, PRL 119, 052502 (2017);
A.C. Larsen, J.E. Midtbø et al., PRC 97, 054329 (2018)]

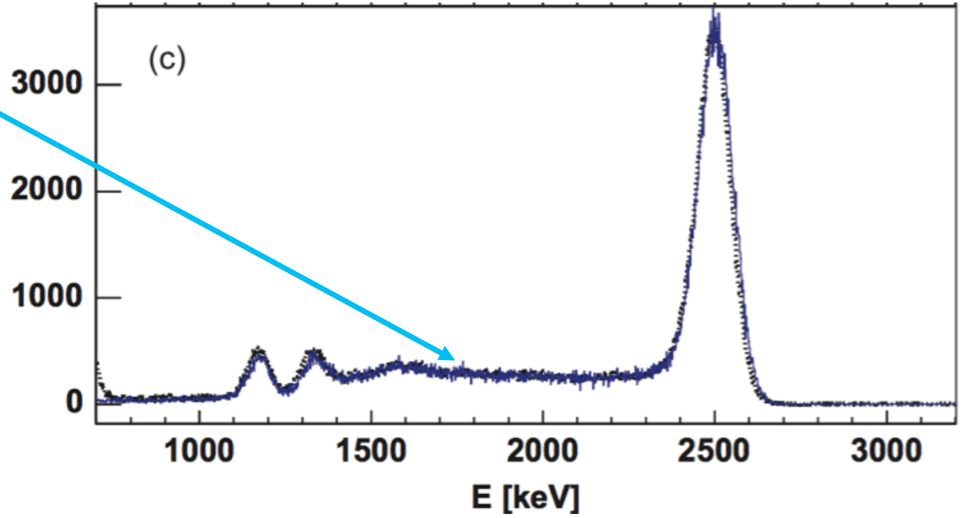
Challenge: incomplete summing

Note the "tail" towards low E_x!



[From Table of isotopes, R.B. Firestone]

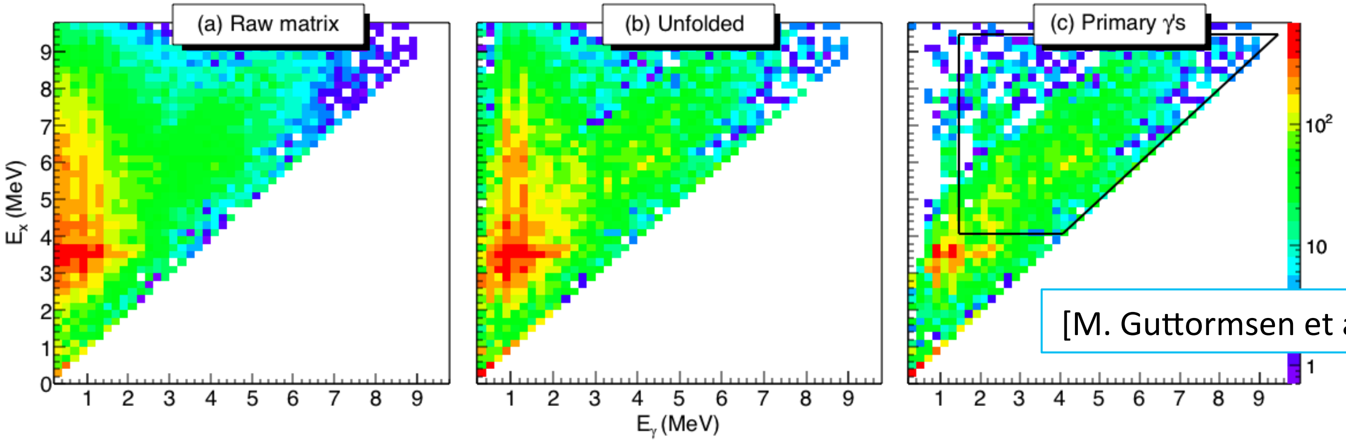
Sum of all segments, ^{60}Co source (1173keV+1332keV)



[A. Simon, S.J. Quinn, A. Spyrou et al, NIM A 703, 16 (2013)]

Solution: unfolding also on the E_x axis

Old, 70Ni:



[M. Guttormsen et al., in preparation]

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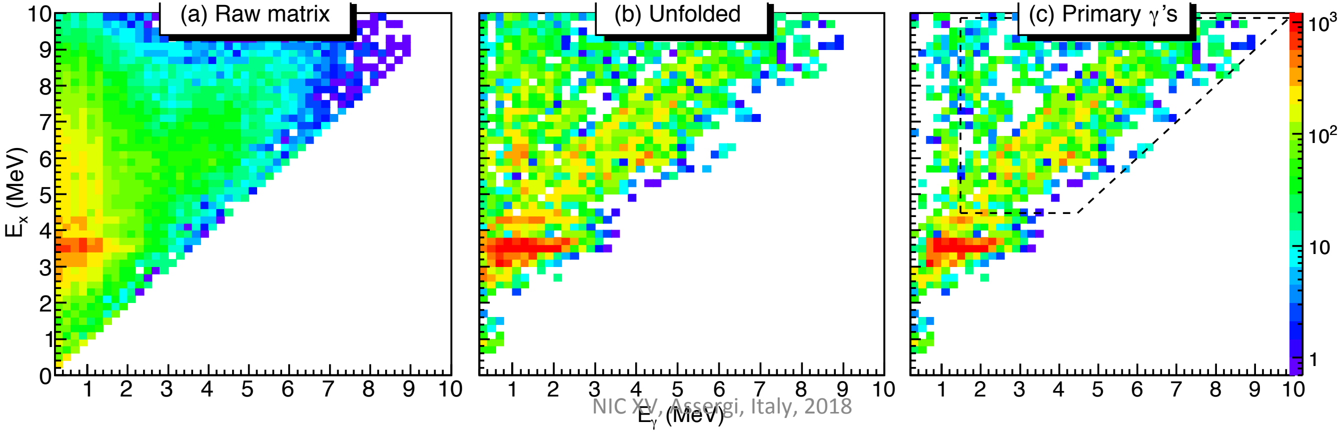
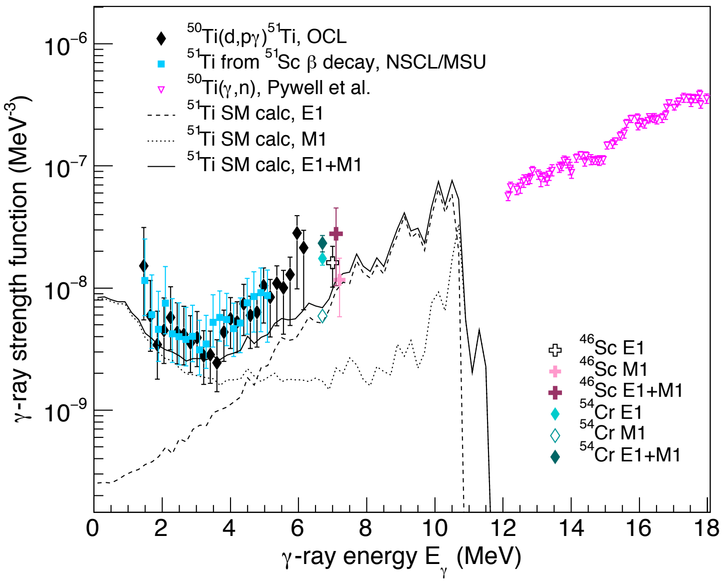
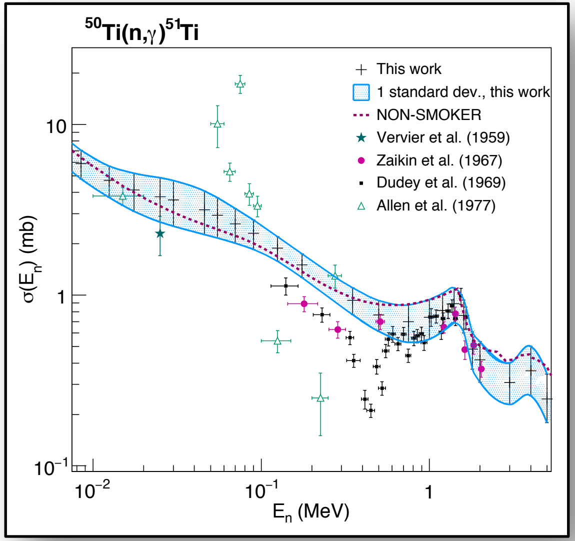


The ^{51}Ti case: beta-Oslo and Oslo method

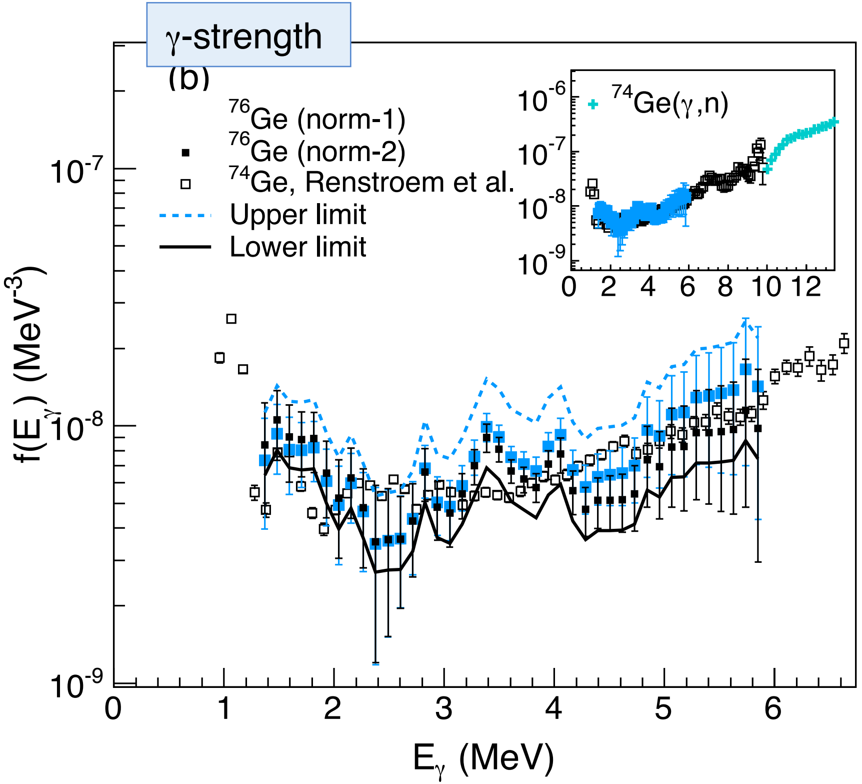
Beta decay (g.s. ^{51}Sc: $7/2^-$): initial $5/2^-$, $7/2^-$, $9/2^-$ (after dipole: 3/2, 5/2, 7/2, 9/2, 11/2)
(d,p): 1/2, 3/2, 5/2, 7/2, 9/2 (after dipole: 1/2, 3/2, 5/2, 7/2, 9/2, 11/2)

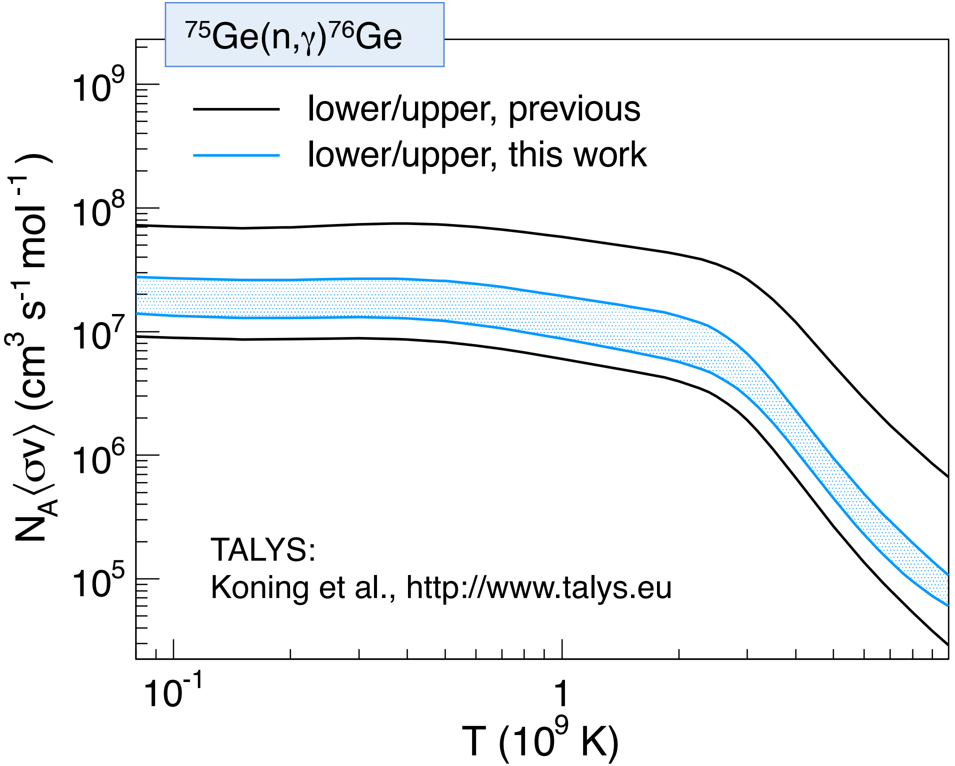




[S.N. Liddick, A.C. Larsen, M. Guttormsen et al., in preparation]

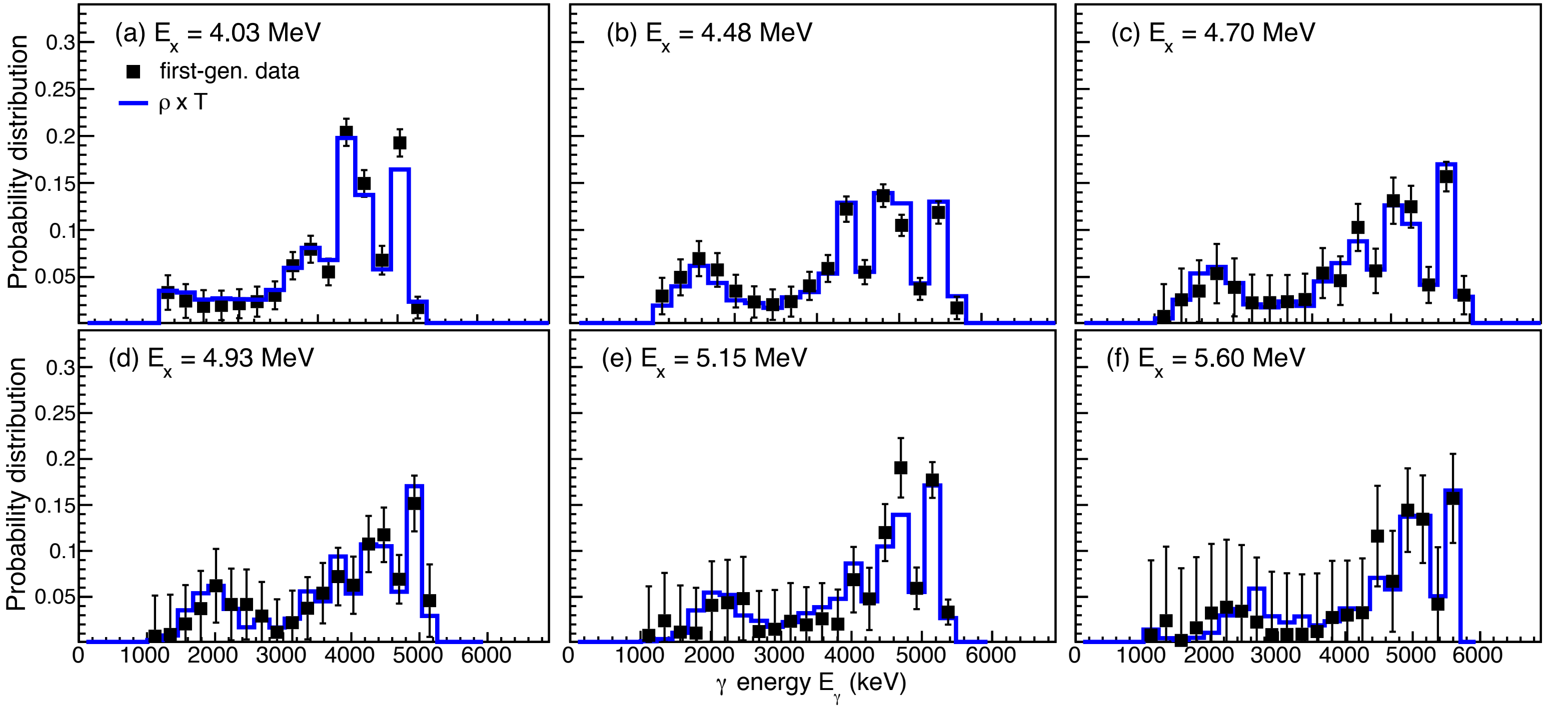
The beta-Oslo method – results, ^{76}Ge





[A. Spyrou, S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRL **113**, 232502 (2014)]

The beta-Oslo method, ^{76}Ge: does it work?



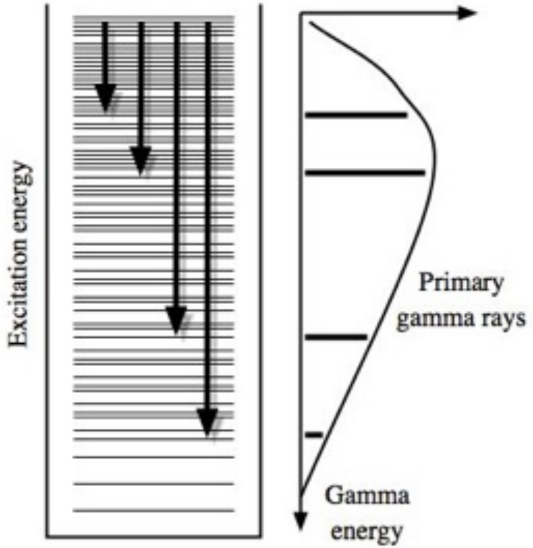
[A. Spyrou, S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRL **113**, 232502 (2014)]

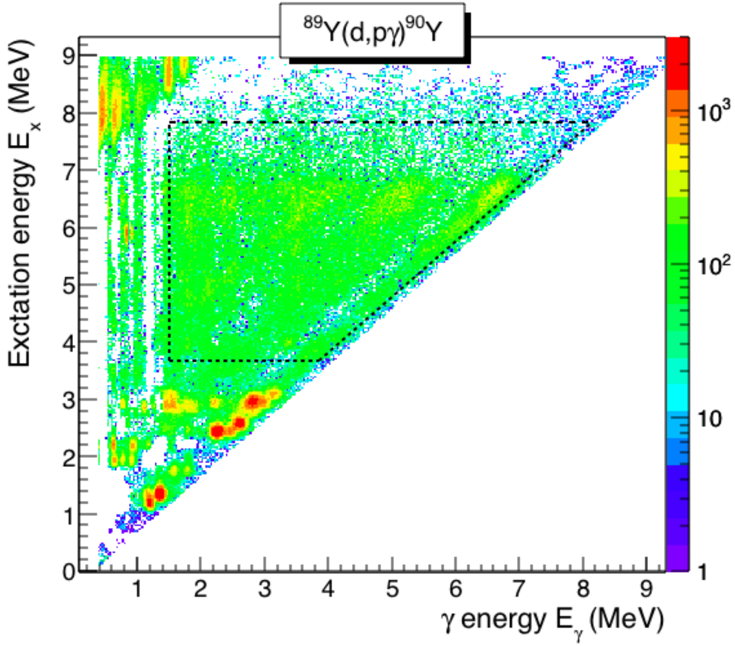
Extraction of level density and γ-decay strength

Ansatz: primary γ matrix can be factorized into two independent functions (vectors)

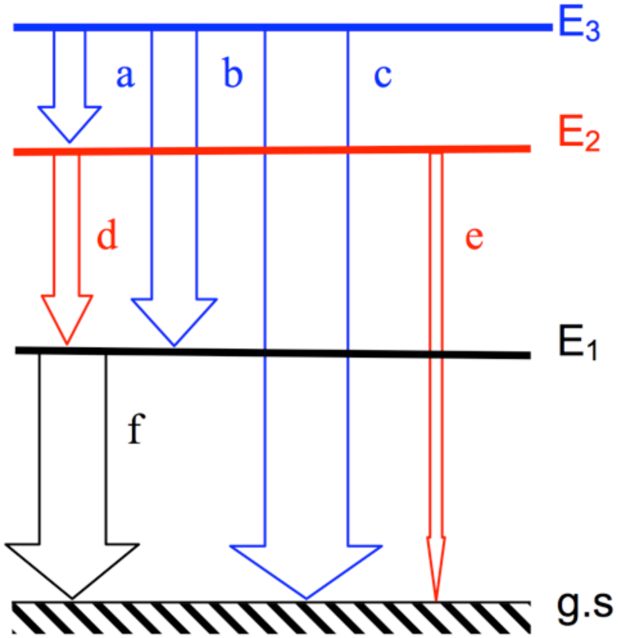
$$P(E_i, E_\gamma) \propto \rho(E_i - E_\gamma)\tau(E_\gamma)$$

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





Distribution of primary γ rays



[M. Guttormsen et al., NIM A 255, 518 (1987);
A.C. Larsen et al., PRC 83, 034315 (2011)]