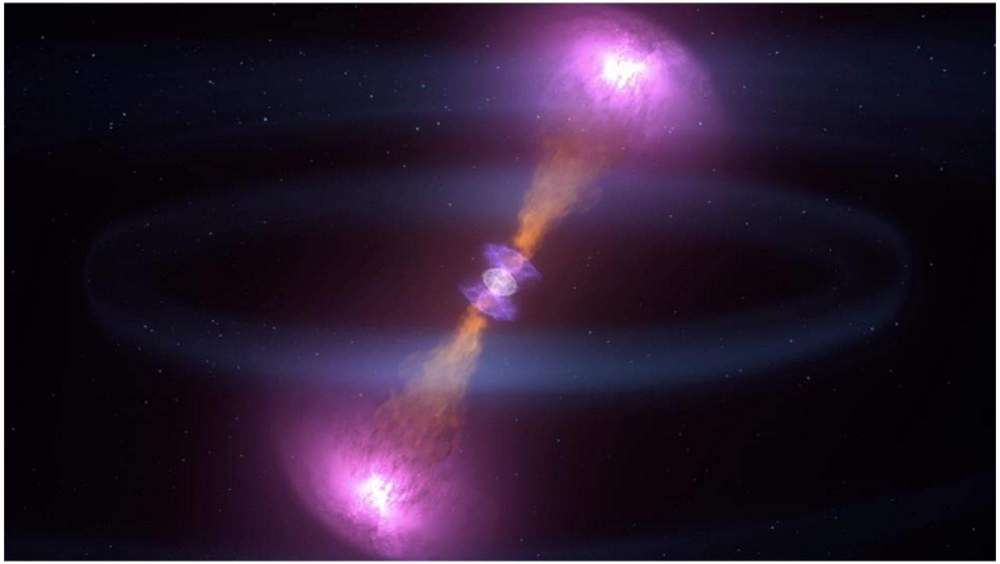
UiO : Department of Physics
University of Oslo

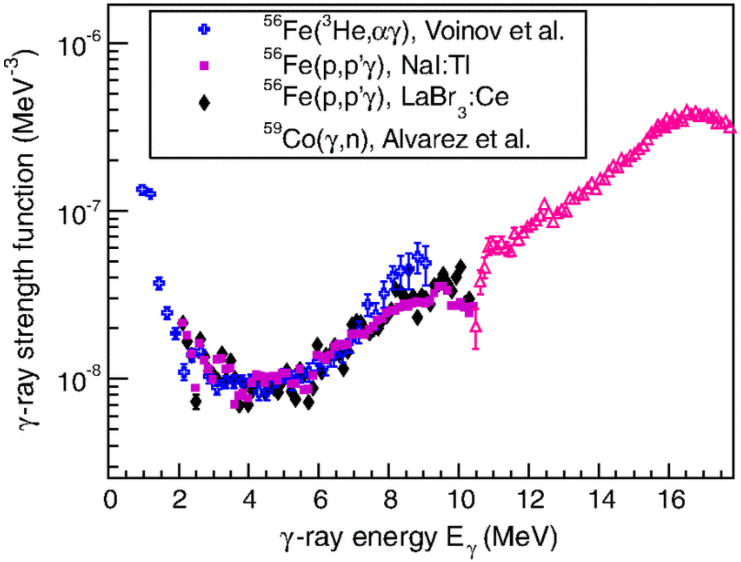
Vetle W. Ingeberg

The Inverse-Oslo method

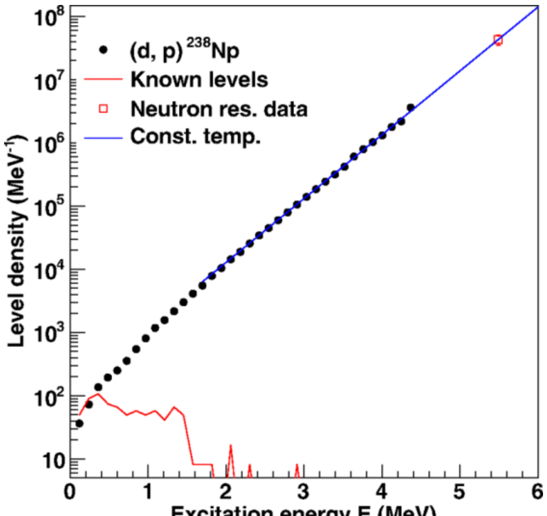
Motivation

- s- and r-process
- Understanding nuclei
- It is fun!





A. C. Larsen *et al.*, Phys. Rev. Lett. **111**, 242504 (2013)



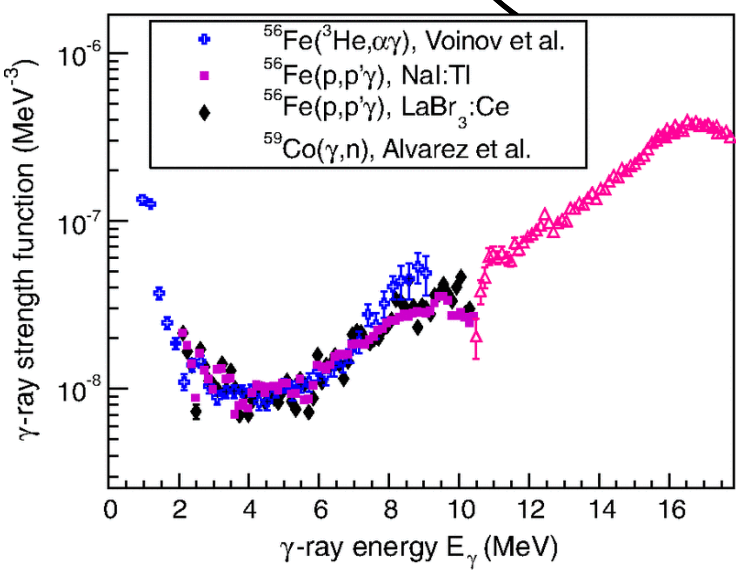
T. G. Tornyi *et al.*, Phys. Rev. C **89**, 044323 (2014)

γ-ray strength function

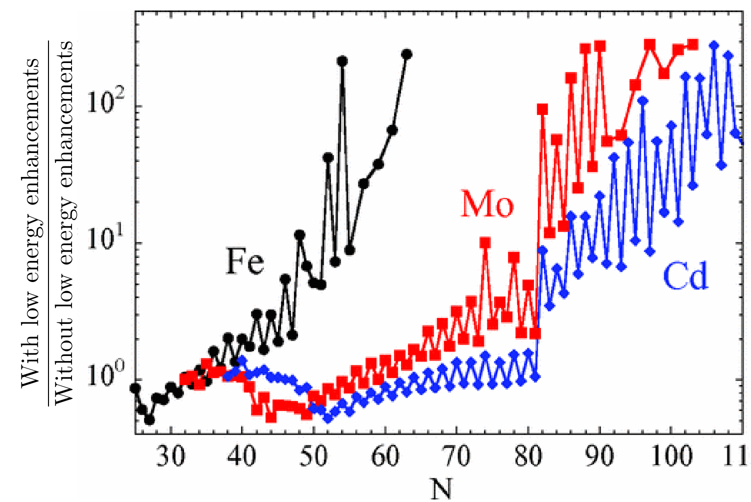
Level density

Hauser-Feshbach calculations
–
(n, γ) cross section

Optical model potential

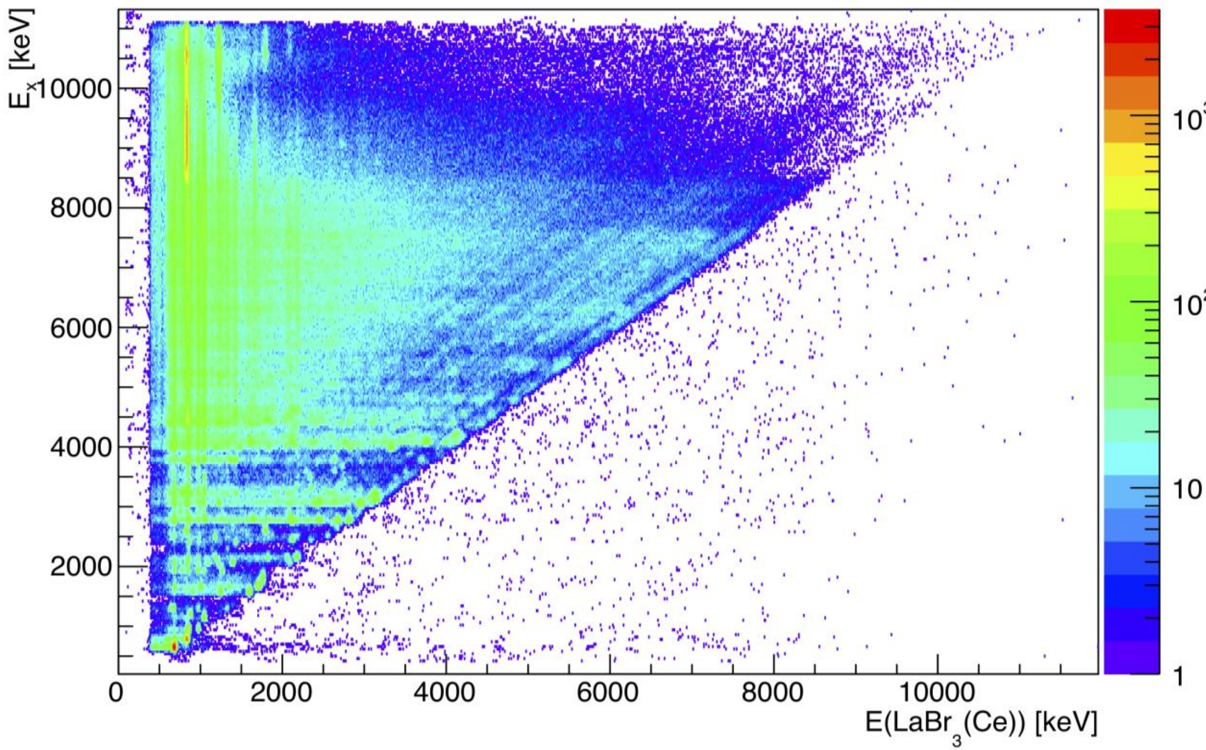


A. C. Larsen *et al.*, Phys. Rev. Lett. **111**, 242504 (2013)



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

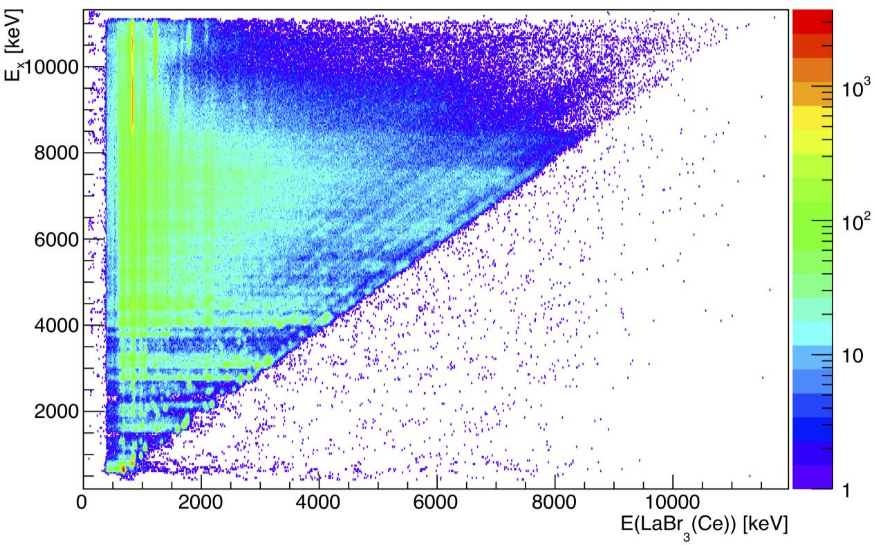
Oslo Method, how



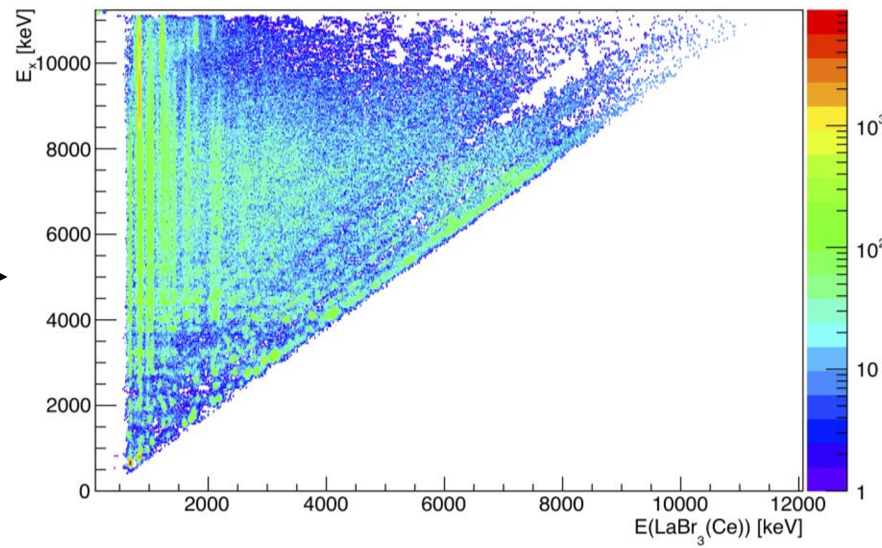
M. Guttormsen, Workshop on the Oslo Method (Des. 2016)

Oslo Method, how

Folded



Unfolded

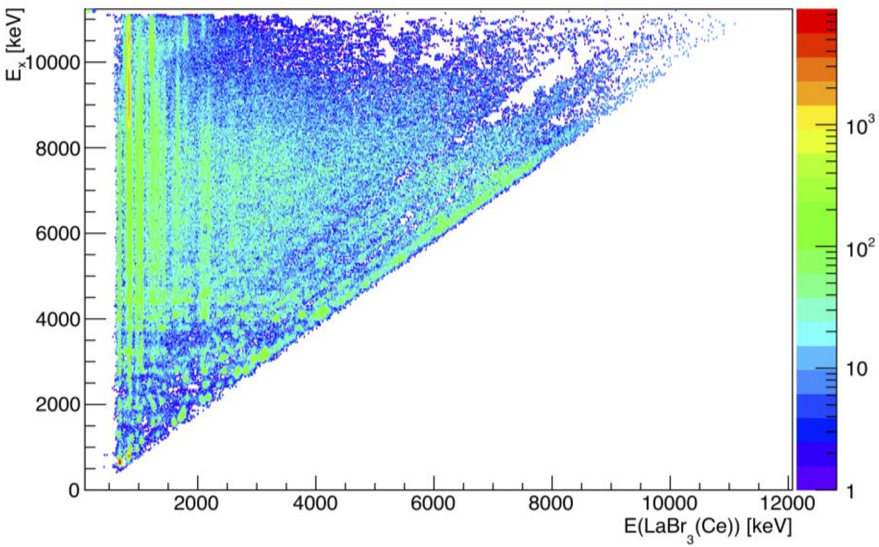


M. Guttormsen, Workshop on the Oslo Method (Des. 2016)

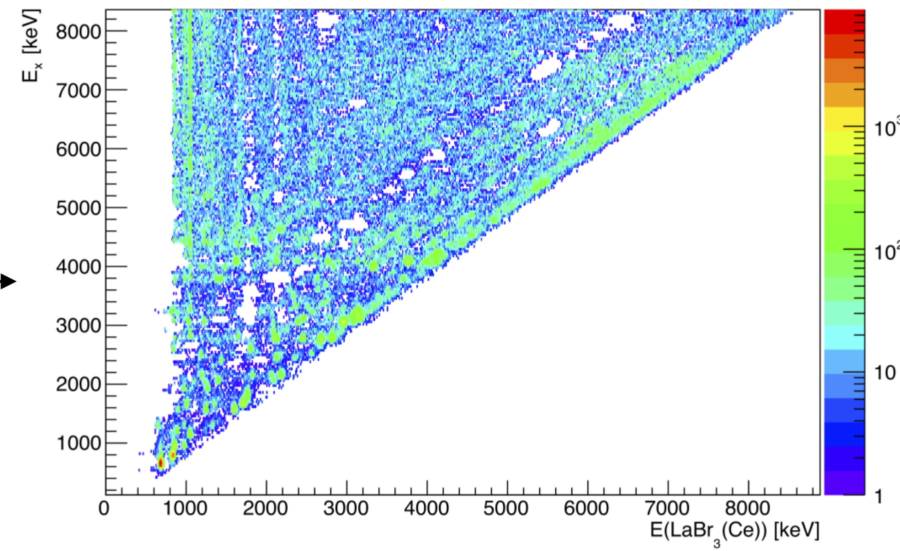
M. Guttormsen *et al.*, NIM A **374,** 371-376 (1996)

Oslo Method, how

Unfolded



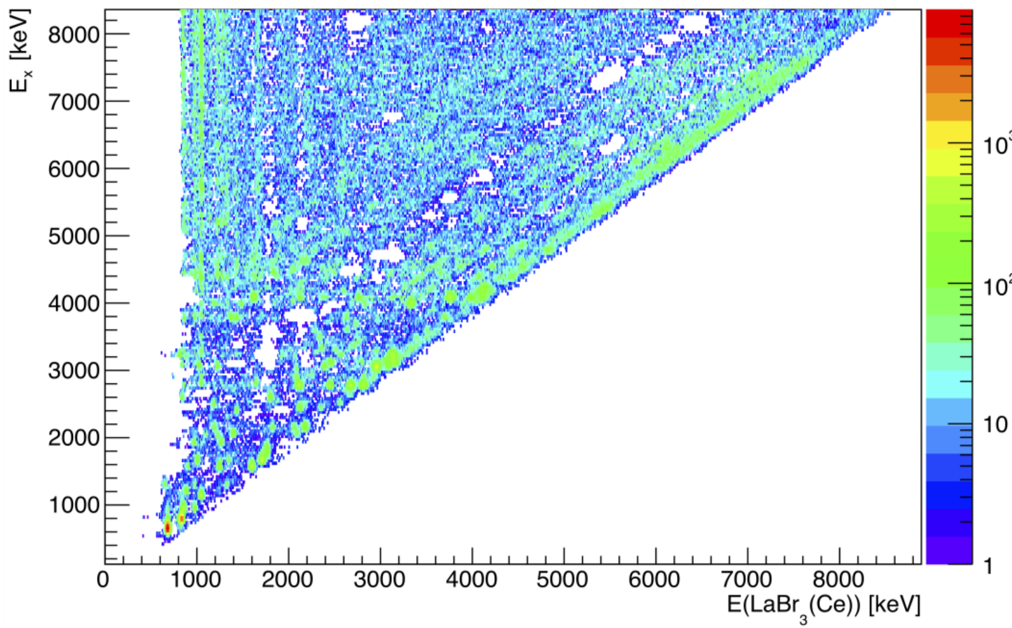
First generation



M. Guttormsen, Workshop on the Oslo Method (Des. 2016)

M. Guttormsen *et al.*, NIM A **255,** 518-523 (1987)

Oslo Method, how



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

$$\chi^2 = \frac{1}{N_{\mathrm{free}}} \sum_{E_x = E_x^{\min}}^{E_x^{\max}} \sum_{E_\gamma = E_\gamma^{\min}}^{E_x} \left(\frac{\Gamma_{\mathrm{th}}(E_x, E_\gamma) - \Gamma(E_x, E_\gamma)}{\Delta\Gamma(E_x, E_\gamma)} \right)^2$$

$$\Gamma_{\mathrm{th}}(E_x, E_\gamma) = \frac{\rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)}{\sum_{E_\gamma = E_\gamma^{\min}}^{E_x} \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)}$$

$$\tilde{\rho}(E_x - E_\gamma) = \rho(E_x - E_\gamma) A e^{\alpha(E_x - E_\gamma)}$$

$$\tilde{\mathcal{T}}(E_\gamma) = \mathcal{T}(E_\gamma) B e^{\alpha E_\gamma}$$

M. Guttormsen, Workshop on the Oslo Method (Des. 2016)

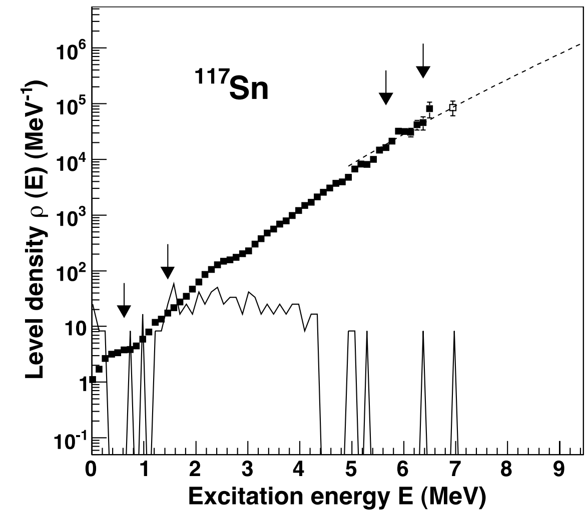
A. Schiller *et al.*, NIM A **447**, 494 (2000)

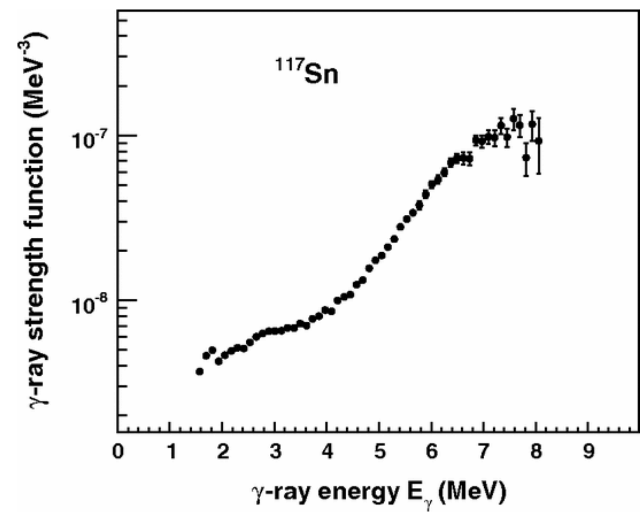
Oslo Method, how

$$\tilde{\rho}(E_x - E_\gamma) = \rho(E_x - E_\gamma) A e^{\alpha(E_x - E_\gamma)}$$

$$\tilde{\mathcal{T}}(E_\gamma) = \mathcal{T}(E_\gamma) B e^{\alpha E_\gamma}$$

- NLD normalized to
  - Known discrete states
  - Avg. neutron resonance spacing
- gSF normalized to
  - Total radiative width

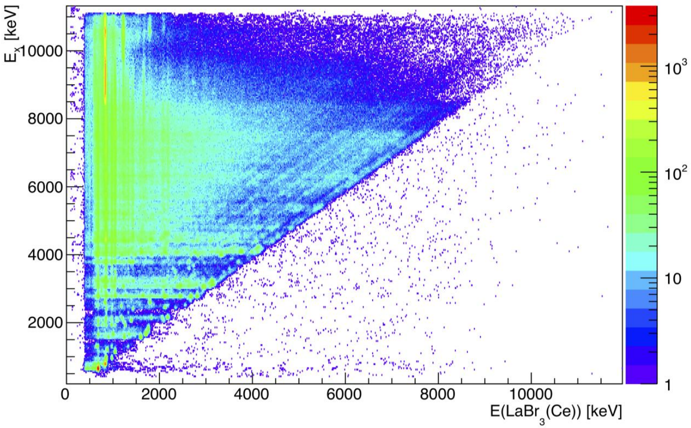


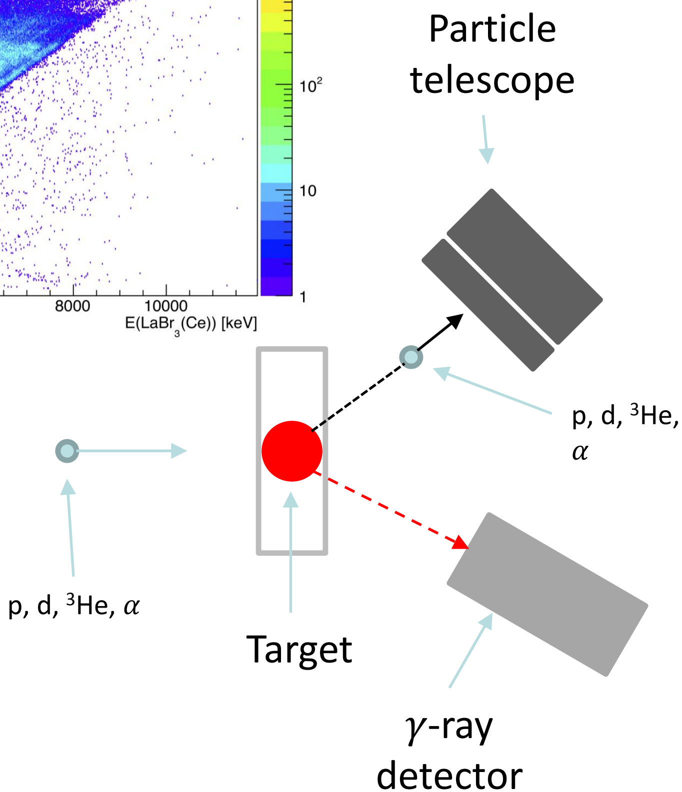


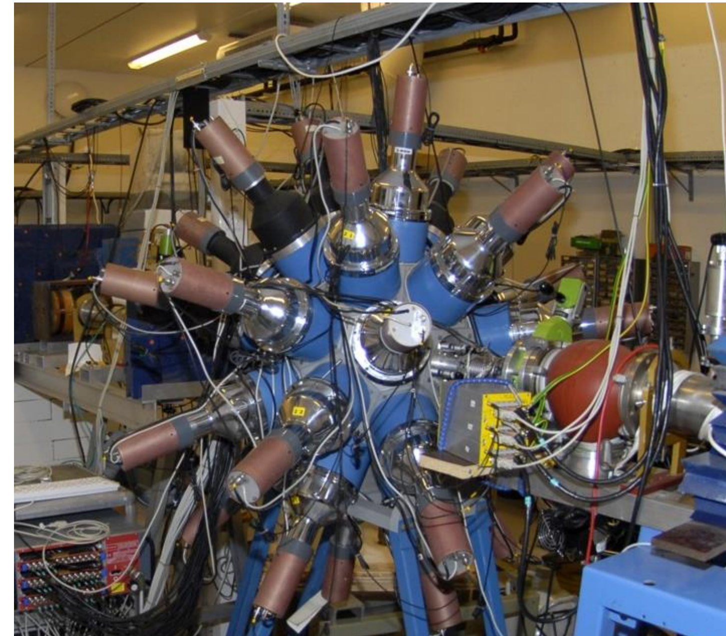
U. Agvaanluvsan *et al.*, Phys. Rev. C **79**, 014320 (2009)

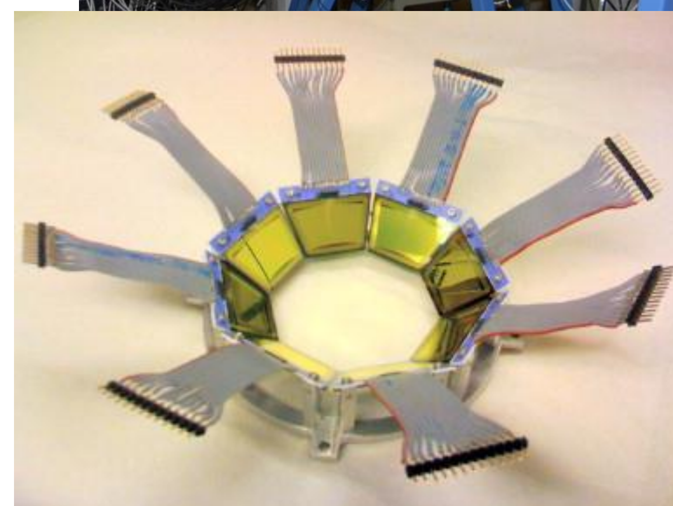
U. Agvaanluvsan *et al.*, Phys. Rev. Lett. **102**, 162504 (2009)

Oslo Method, how









M. Guttormsen *et al.*, NIM A **648**, 168-173 (2011)

OSCAR

- Approved in 2015
- Budget: 23 MNOK (≈ 2.4M €)
- Funded by The Research Council of Norway
- Part of the national research infrastructure program
- Replaces CACTUS with modern large volume $LaBr_3$(Ce) detectors

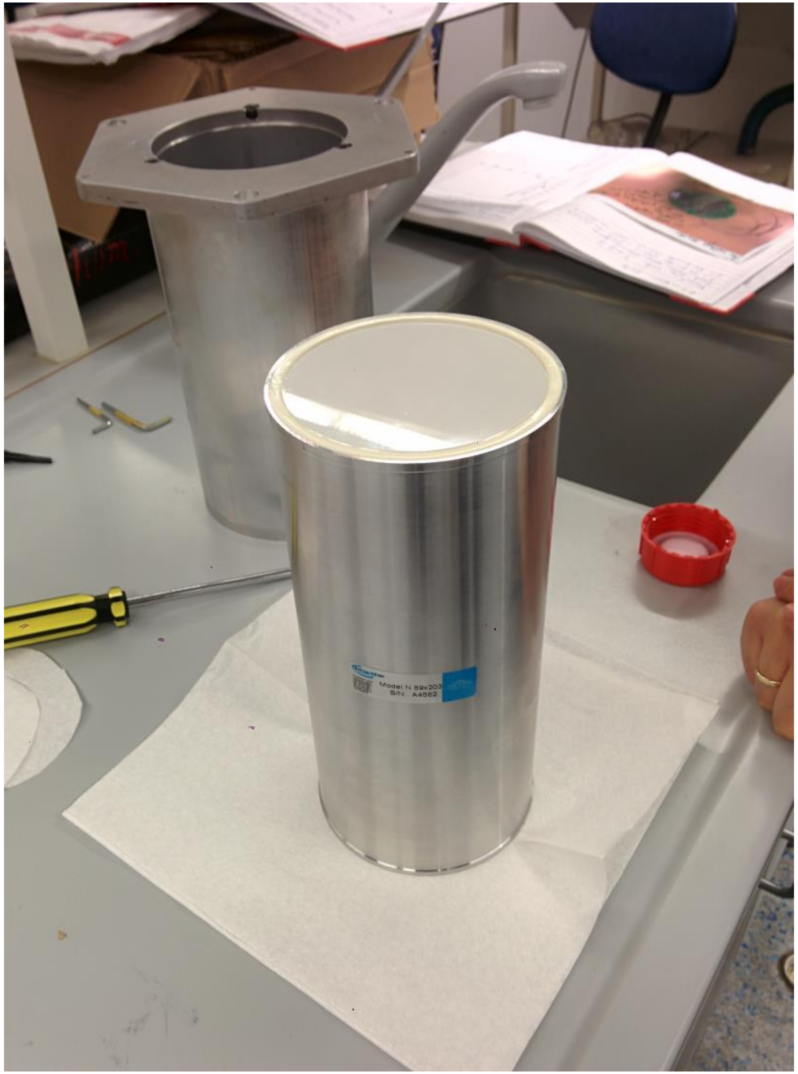
- 28 new $LaBr_3$(Ce) detectors
  - Plus two from a previous project for a total of 30 detectors!

- New frame & target chamber
- New digital electronics from XIA

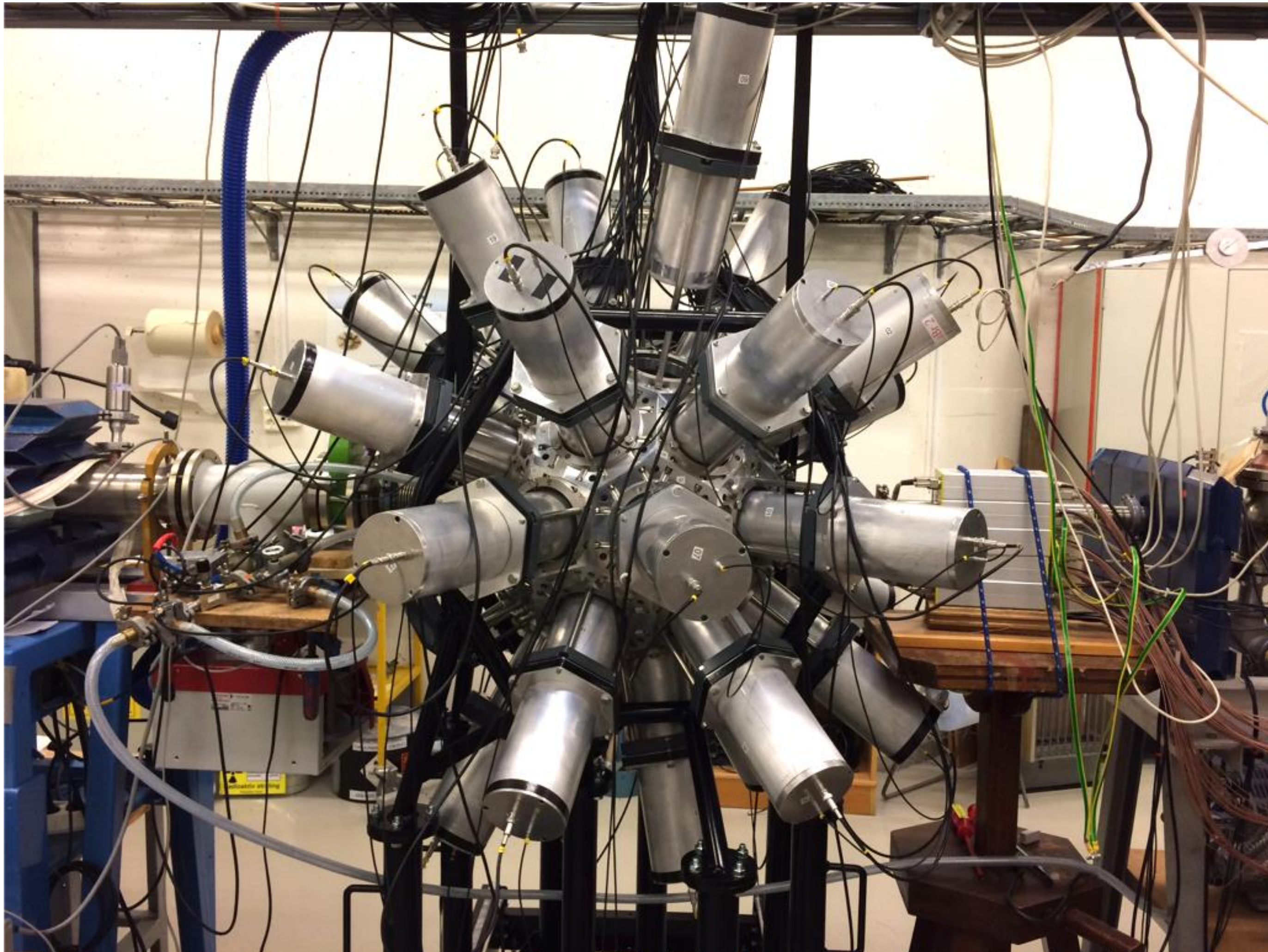
With funding from
The Research Council of Norway

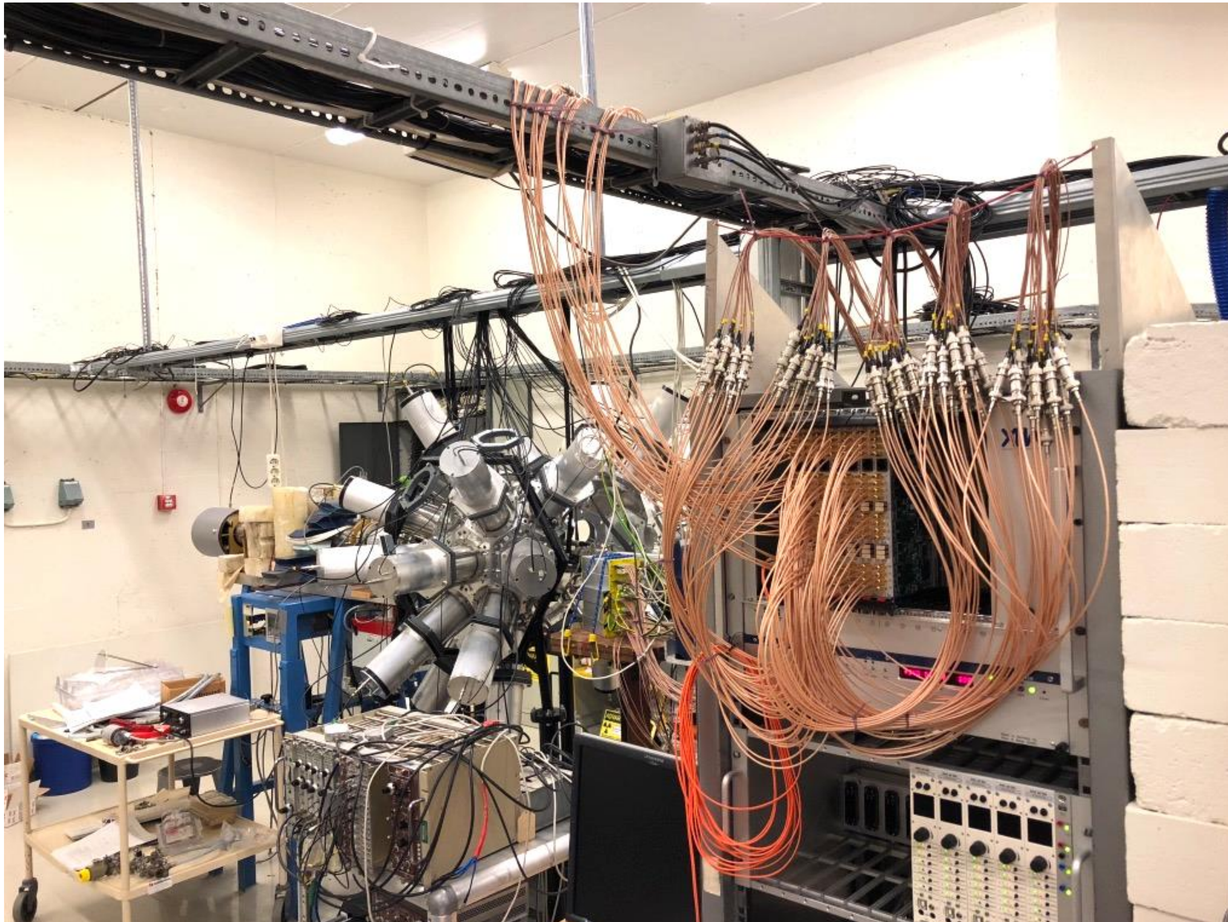
$LaBr_3$(Ce)

- Large volume crystal – 3.5x8 inch
- Hamatsu R10233-100 PMT
- Active voltage dividers, LABRVD*
- Housing designed and manufactured at UiO - based on design by the Milano group



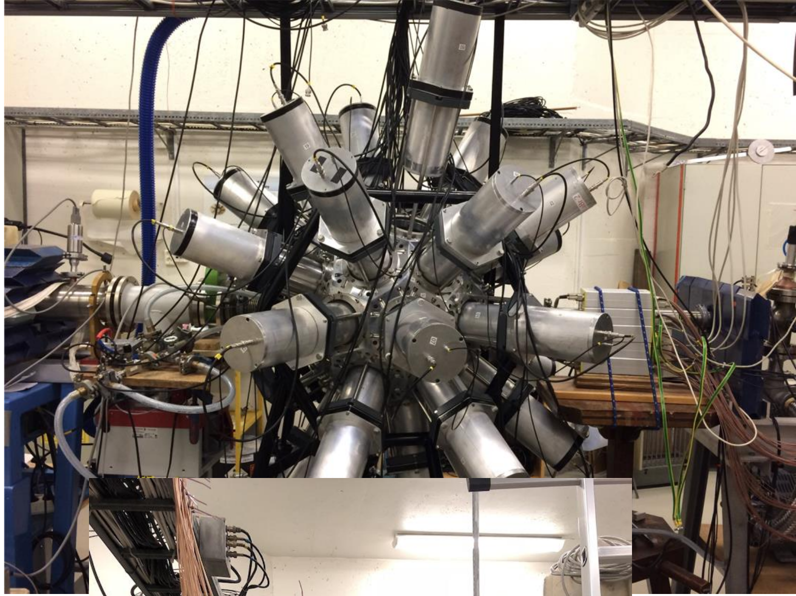
*A. Giaz *et al.*, NIM A 729, 910 (2013)

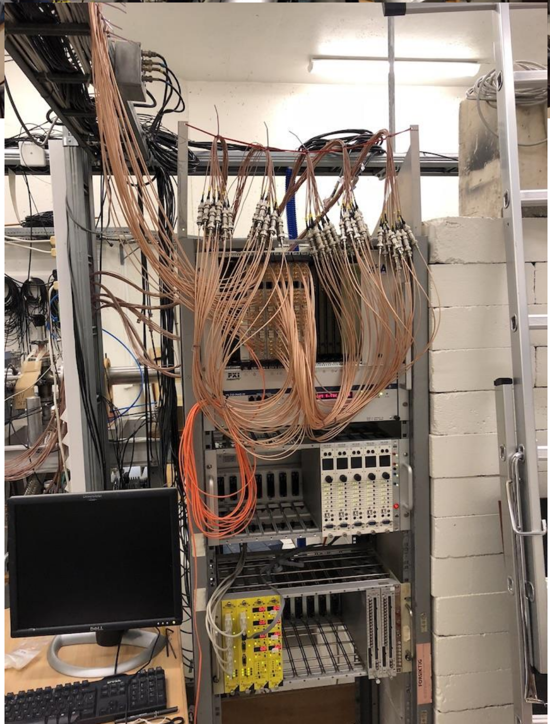


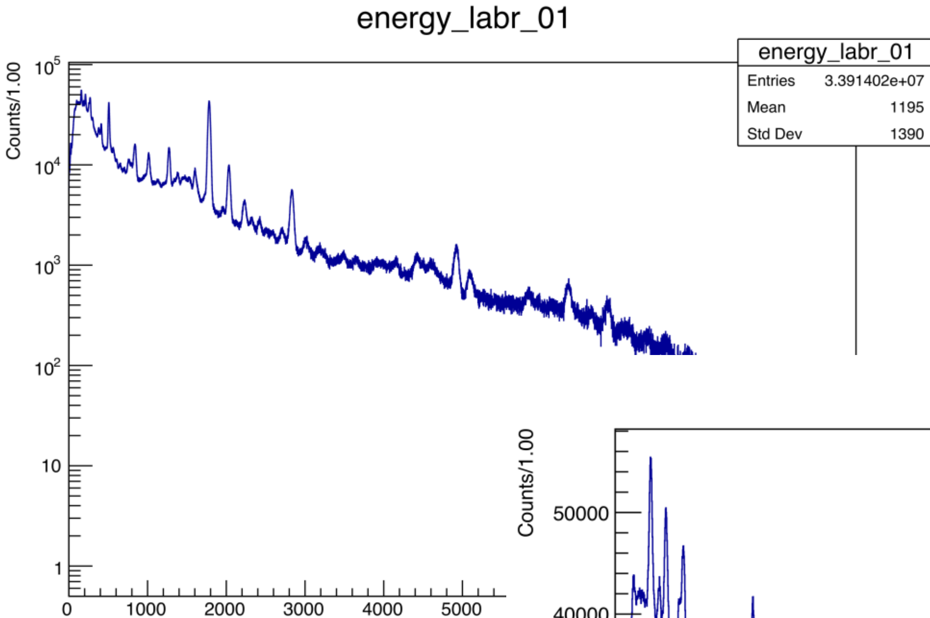


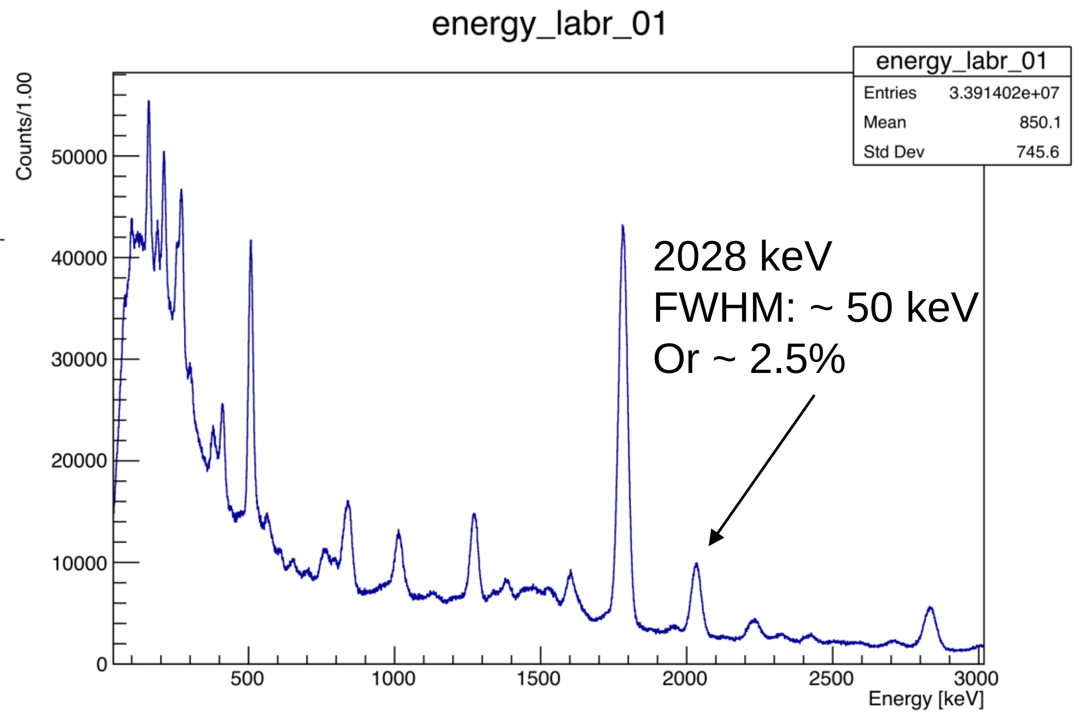
OSCAR – exp. setup

- Calibration run with $^{28}Si(d,p)^{29}Si$, $E_d = 13.5$ MeV
- Intensity of ≈ 0.9 nA
- Trigger rate (E pads) ≈ 3.5k x 8
- ≈ 1 hour with beam on target
- ≈ 10 GB/h

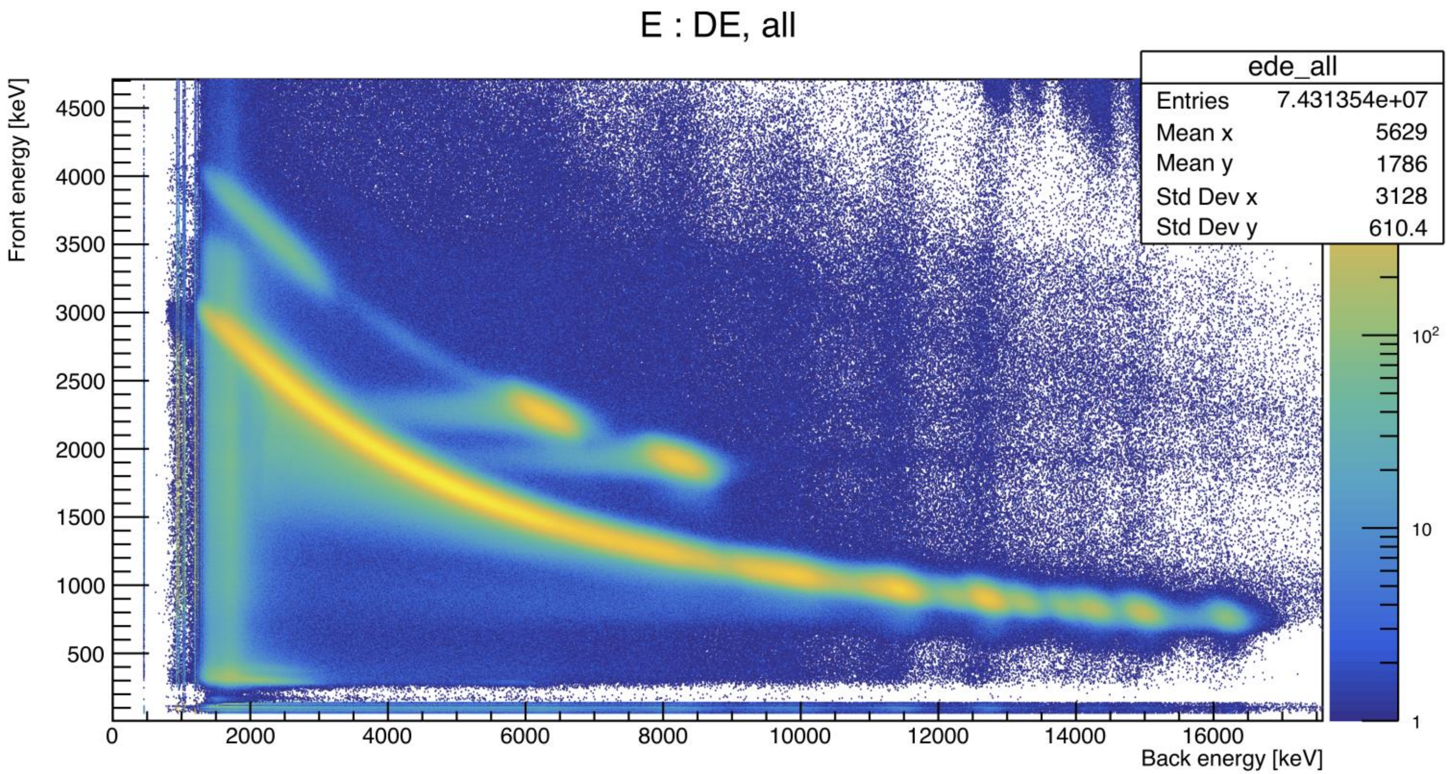




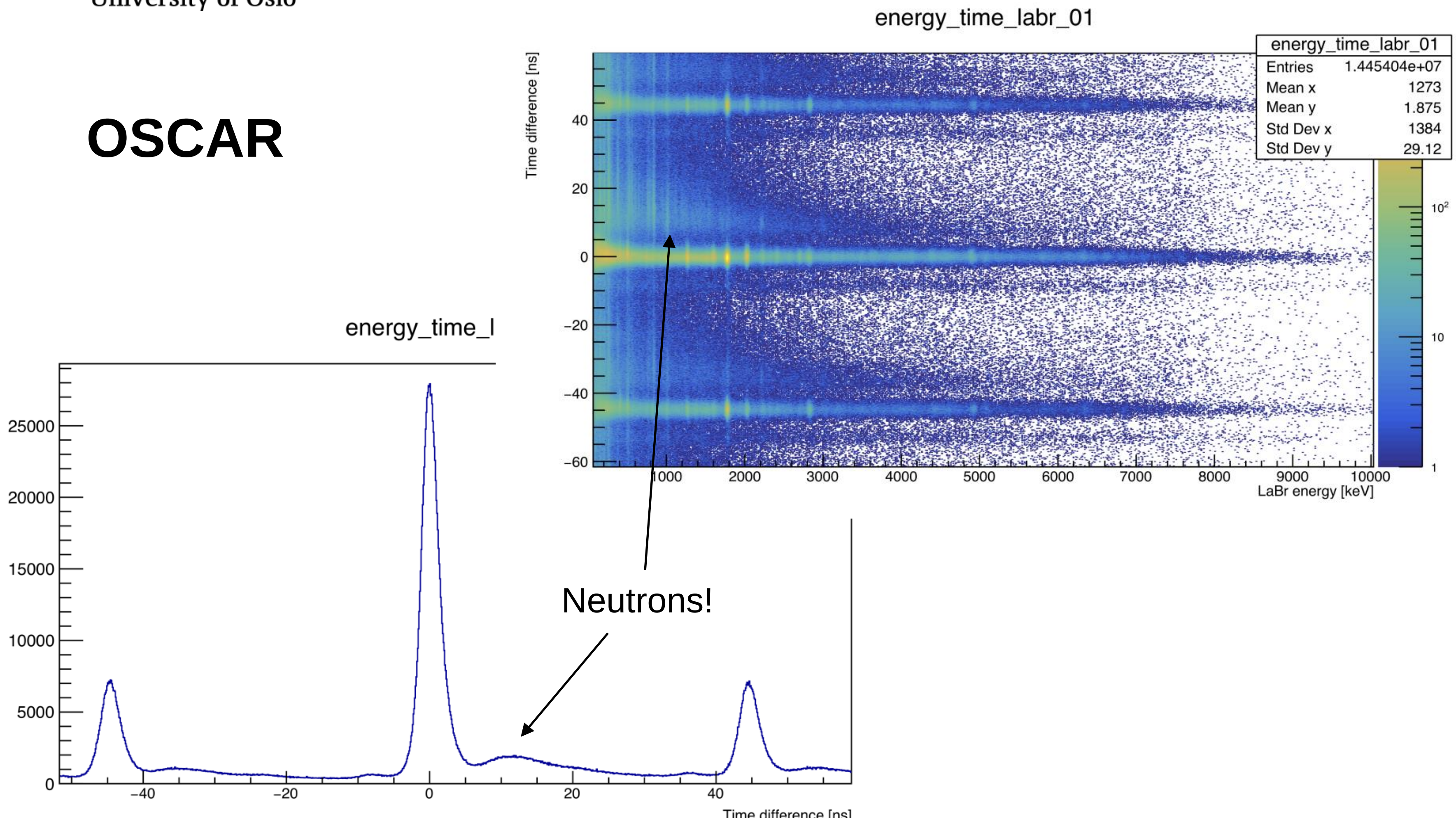

energy_labr_01
energy_labr_01
Entries 3.391402e+07
Mean 1195
Std Dev 1390
Counts/1.00
10^5
10^4
10^3
10^2
10
1
0
1000
2000
3000
4000
5000


energy_labr_01
energy_labr_01
Entries 3.391402e+07
Mean 850.1
Std Dev 745.6
Counts/1.00
50000
40000
30000
20000
10000
0
500
1000
1500
2000
2500
3000
Energy [keV]
2028 keV
FWHM: ~ 50 keV
Or ~ 2.5%

OSCAR

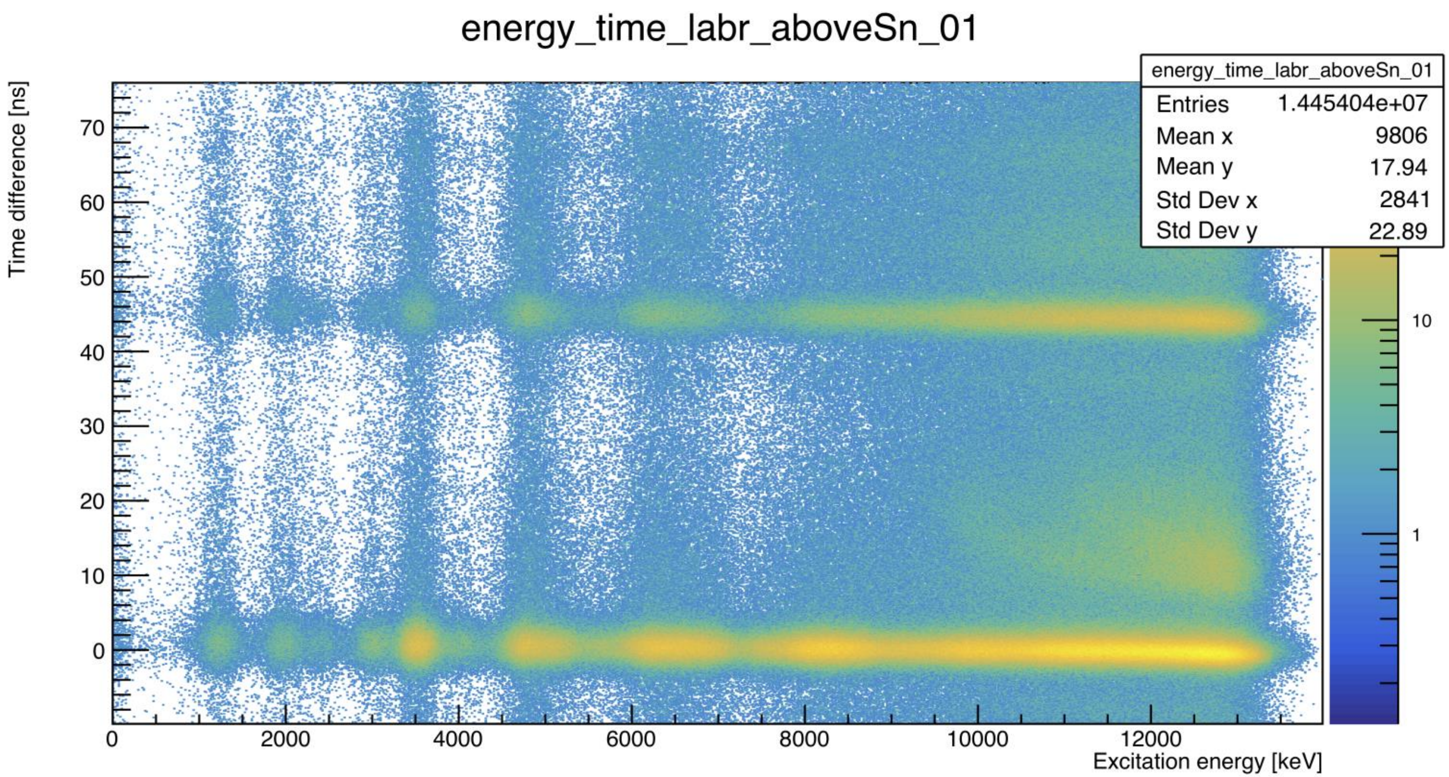

E : DE, all
ede_all
Entries 7.431354e+07
Mean x 5629
Mean y 1786
Std Dev x 3128
Std Dev y 610.4
Front energy [keV]
4500
4000
3500
3000
2500
2000
1500
1000
500
0
2000
4000
6000
8000
10000
12000
14000
16000
Back energy [keV]
10²
10
1

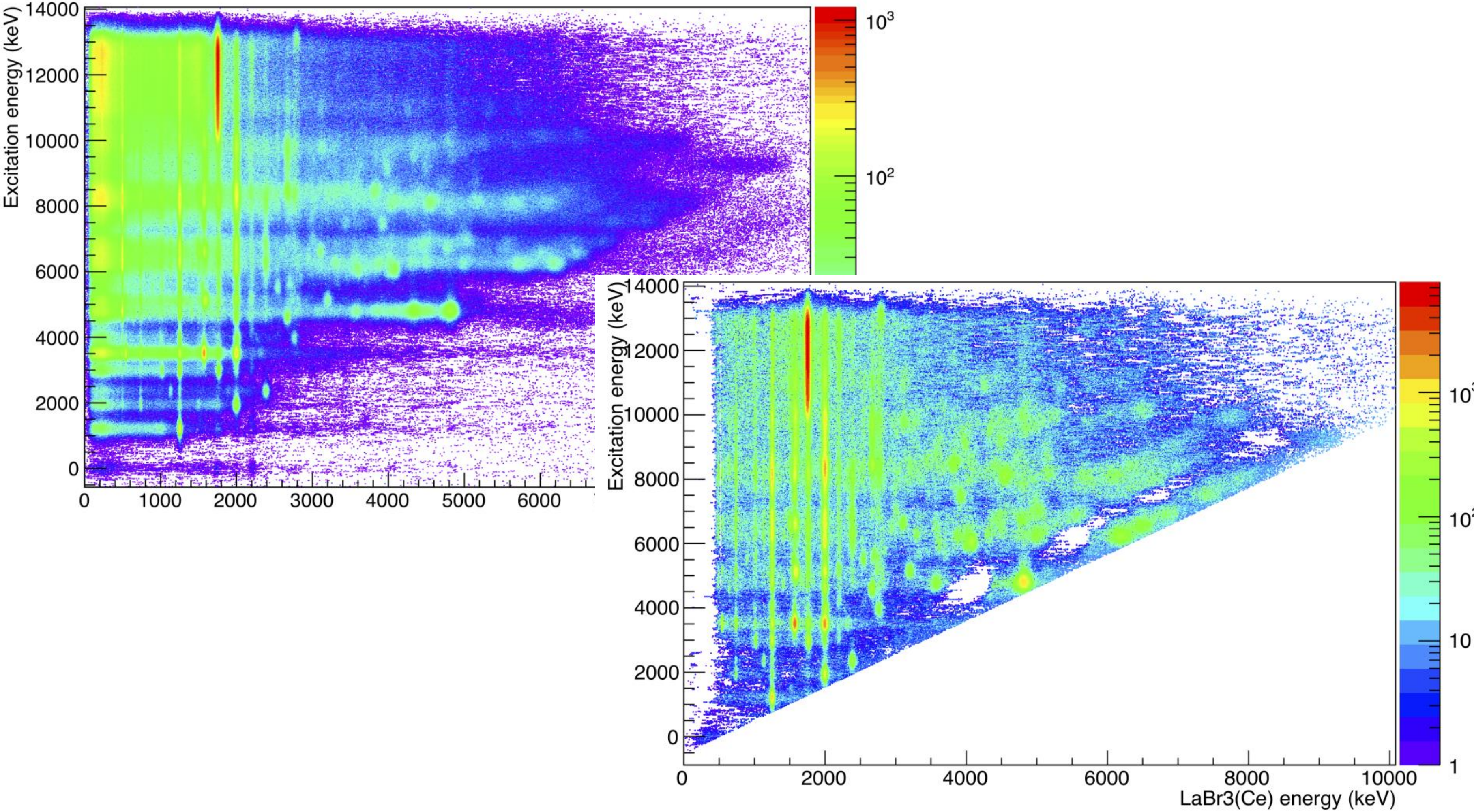
OSCAR



Proton-γ time FWHM: ~2.6 ns

OSCAR

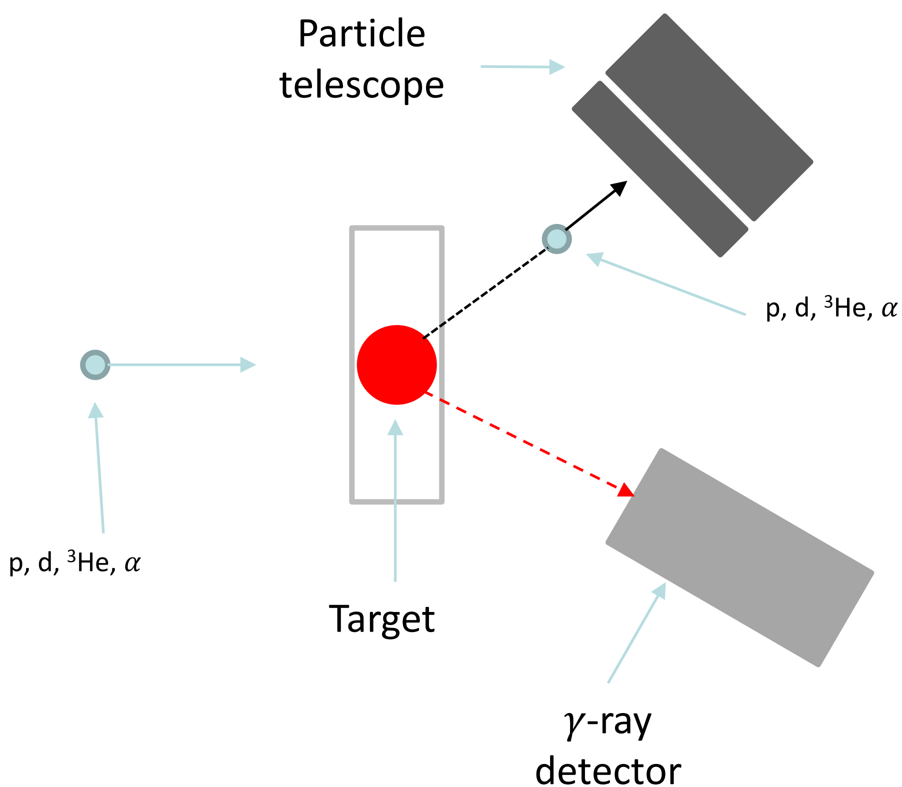

energy_time_labr_aboveSn_01
energy_time_labr_aboveSn_01
Entries 1.445404e+07
Mean x 9806
Mean y 17.94
Std Dev x 2841
Std Dev y 22.89
Time difference [ns]
70
60
50
40
30
20
10
0
0
2000
4000
6000
8000
10000
12000
Excitation energy [keV]
10
1

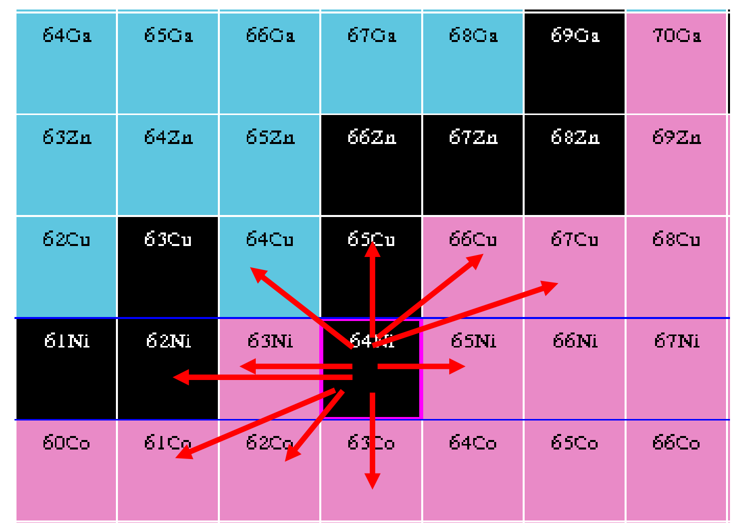

Excitation energy (keV)
14000
12000
10000
8000
6000
4000
2000
0
1000
3000
5000
10^3
10^2
10
1
LaBr3(Ce) energy (keV)

Oslo Method, how - Experiments

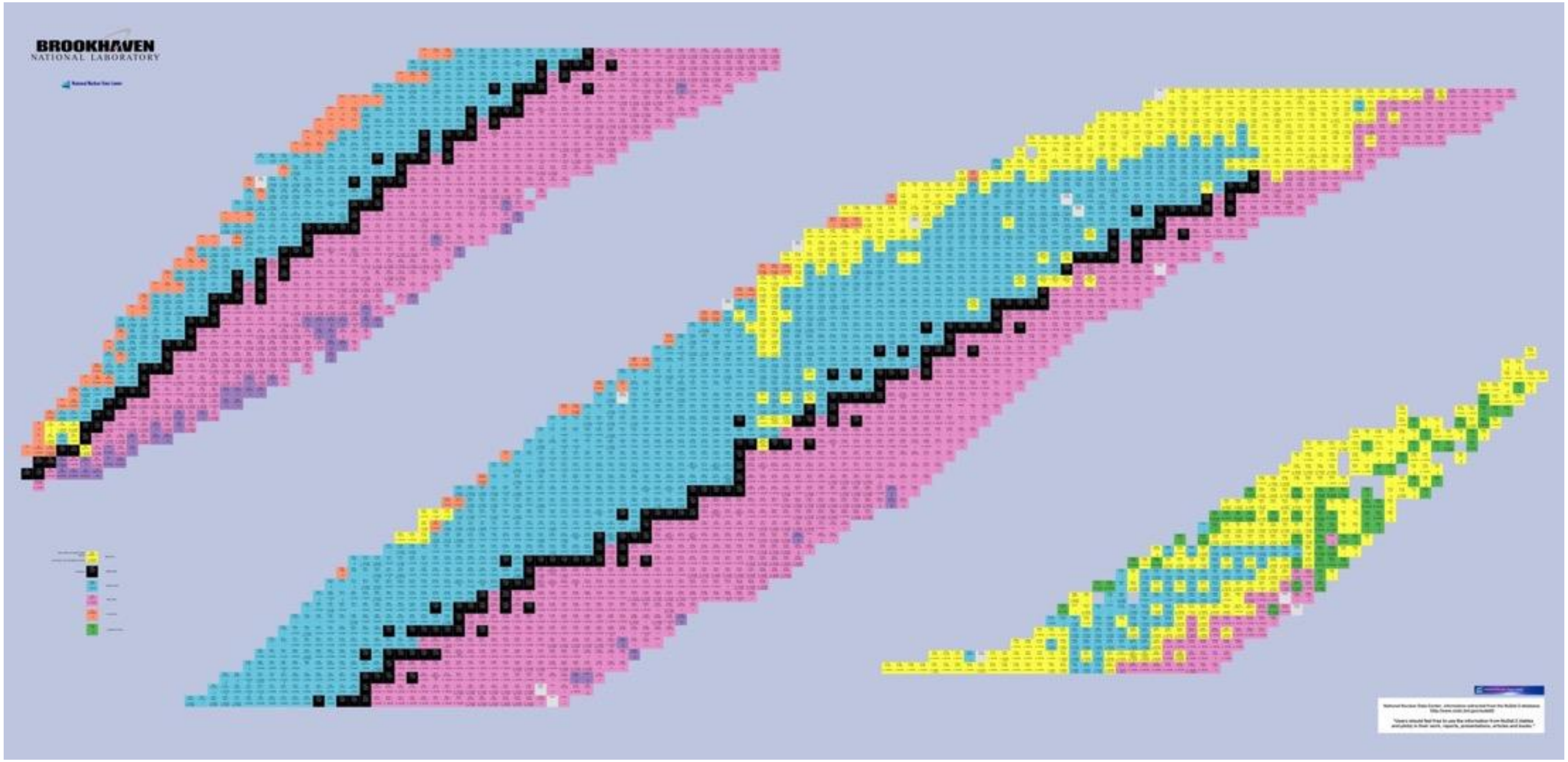
- Traditional kinematics
  - Light ion beam, typically (p,p'), (^{3}He, a), etc.
- β-Oslo
  - Isotope of interest is populated in β-decay (don't miss Magne's talk tomorrow)
- **Inverse-Oslo**
  - Heavy ion beam on target of light ions (e.g. deuterated plastic)

Why inverse kinematics?

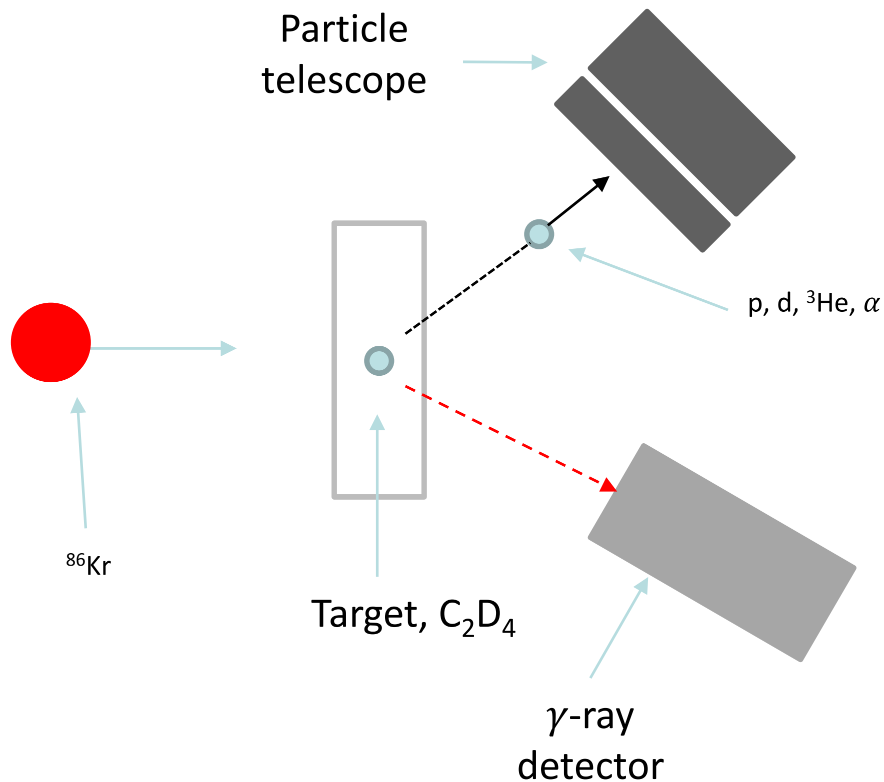




Why inverse kinematics?

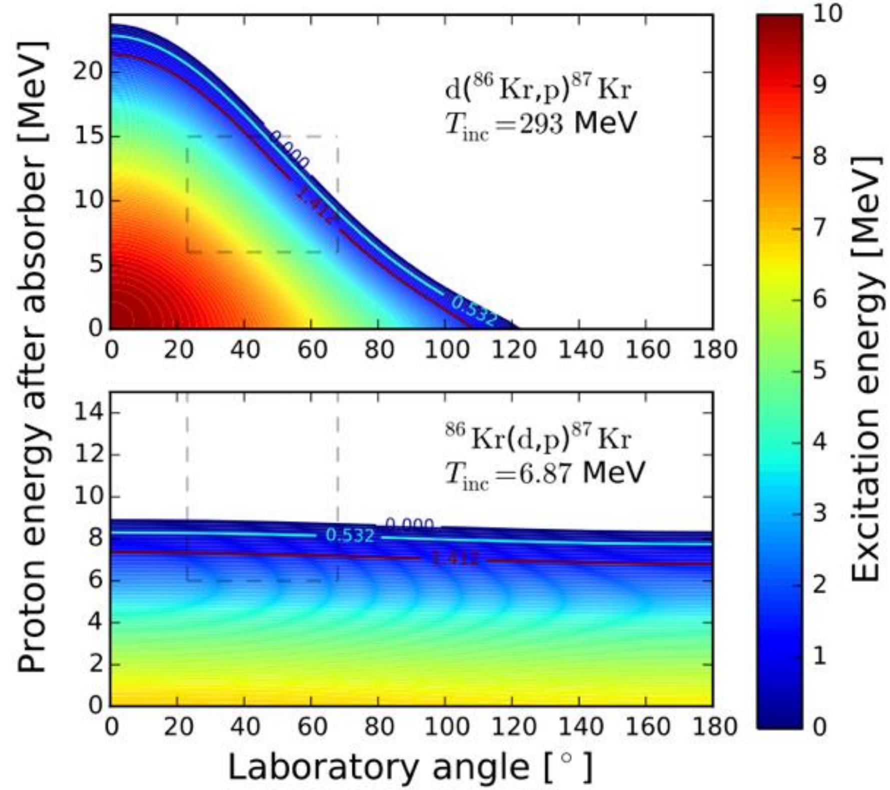


Why inverse kinematics?



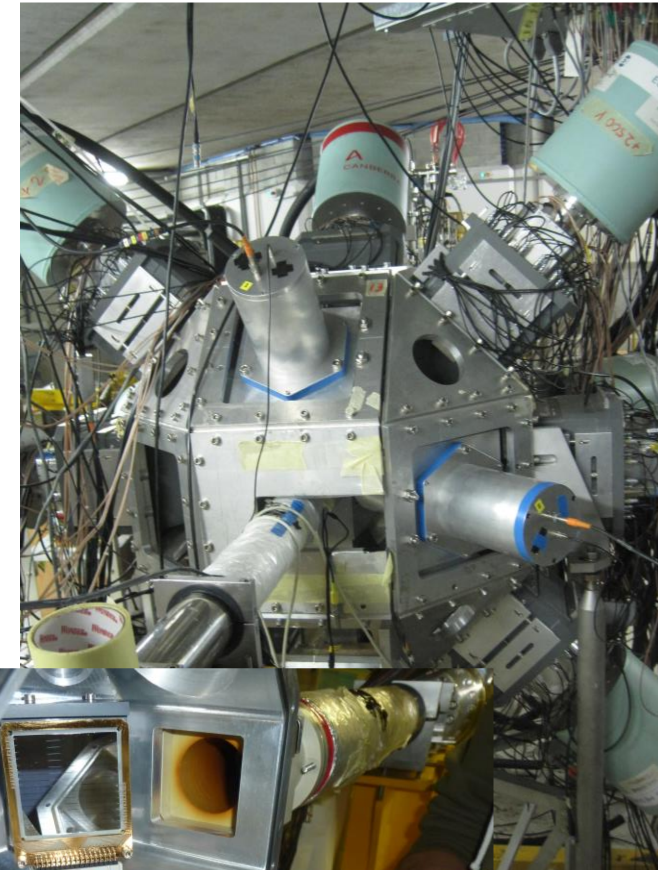
Why inverse kinematics?

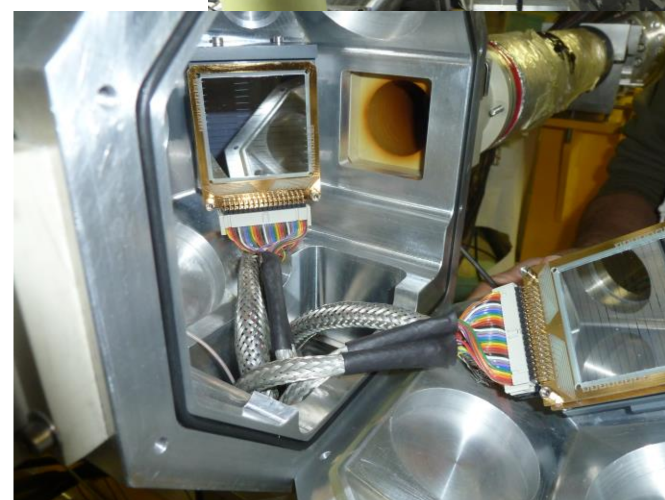
- Benefits
  - Not limited by chemistry
  - Radioactive beams
- Challenges
  - Doppler shift
  - Different kinematics
  - Deuteron breakup (in case of deuterated target)
  - Target burn



Experimental setup

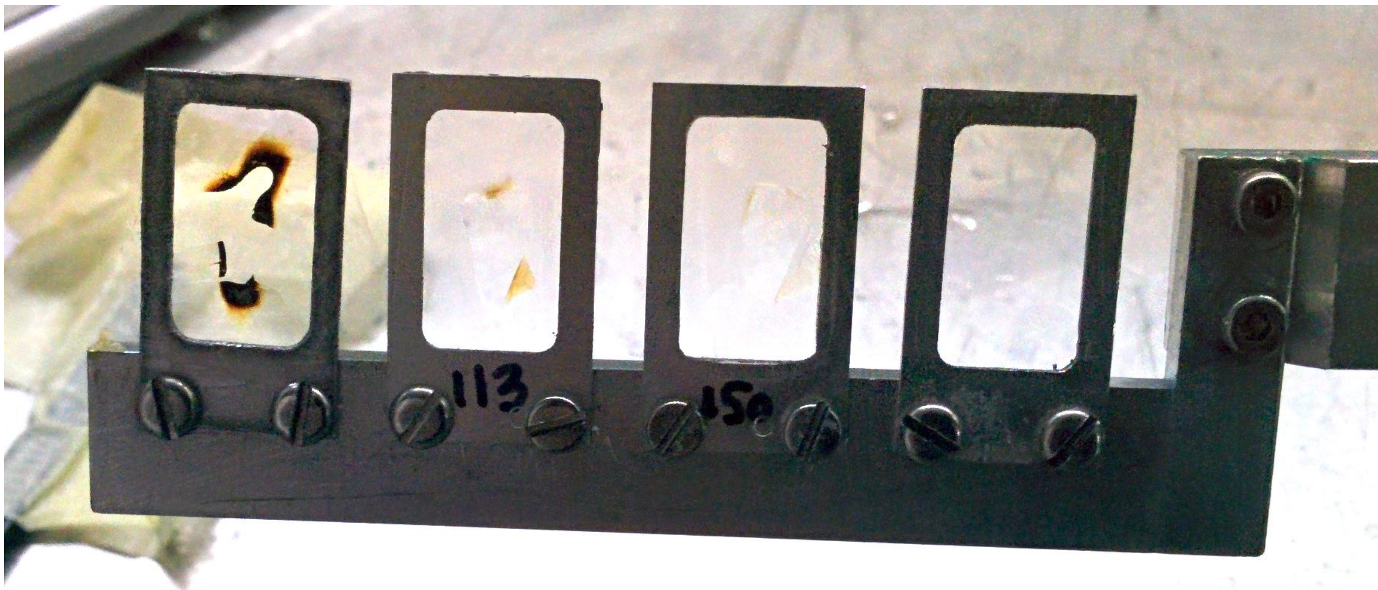
- Experiment at iThemba LABS in April/May 2015
- ^{86}Kr beam at 300 MeV
- ≈ 160 hours on target
- 8 Compton suppressed CLOVER detectors
- 2 Large volume (3.5x8”) $LaBr_3(Ce)$ from Oslo
- Two particle ΔE – E telescopes consisting of square DSSD





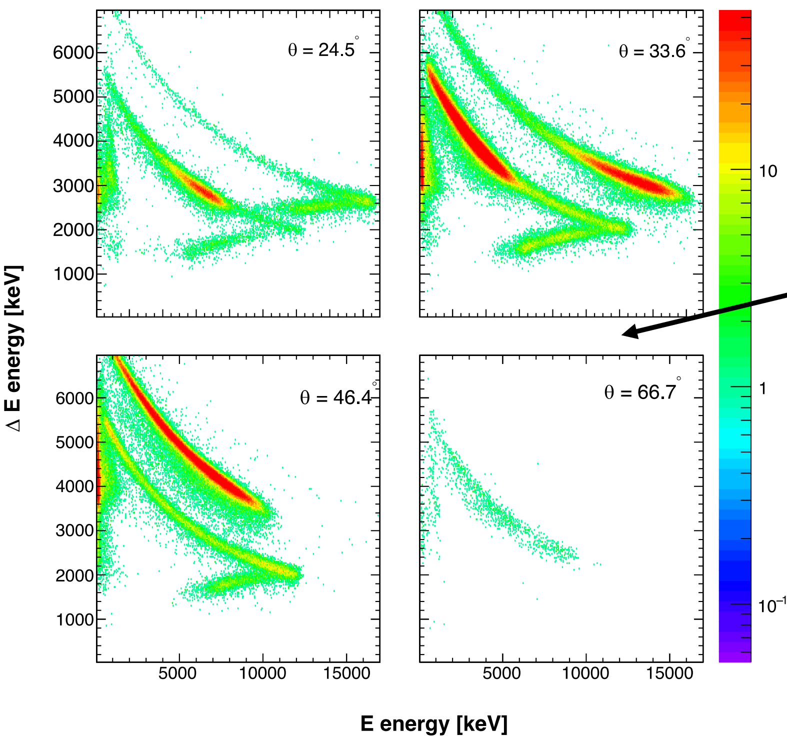
NRF National Research Foundation | iThemba LABS Laboratory for Accelerator Based Sciences

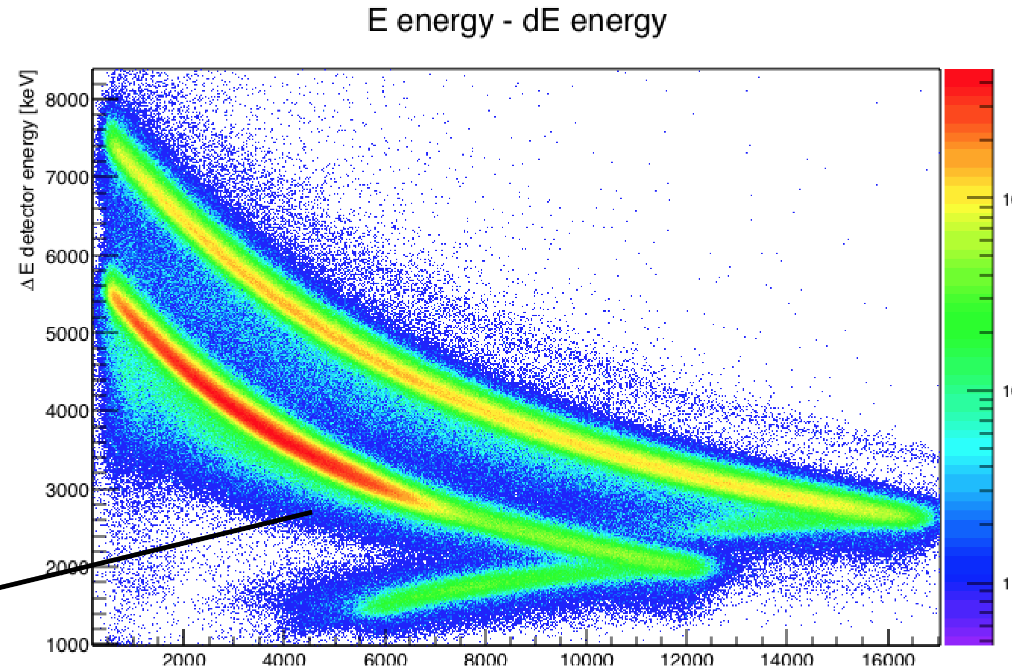
Experimental setup

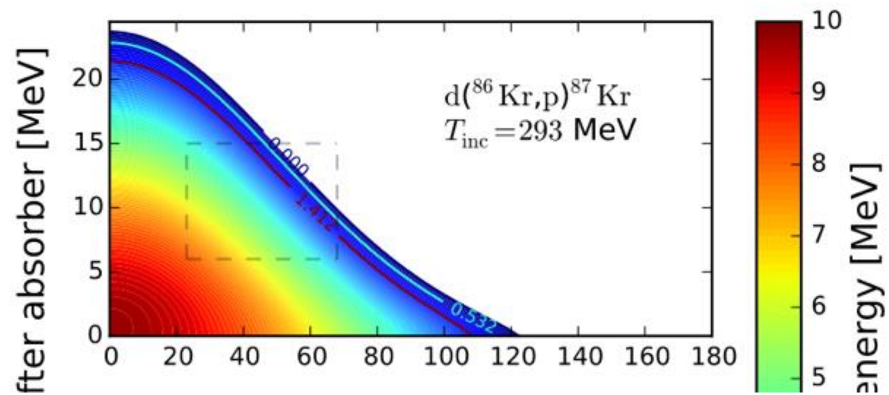


Deuterated polyethylene, C_2D_4

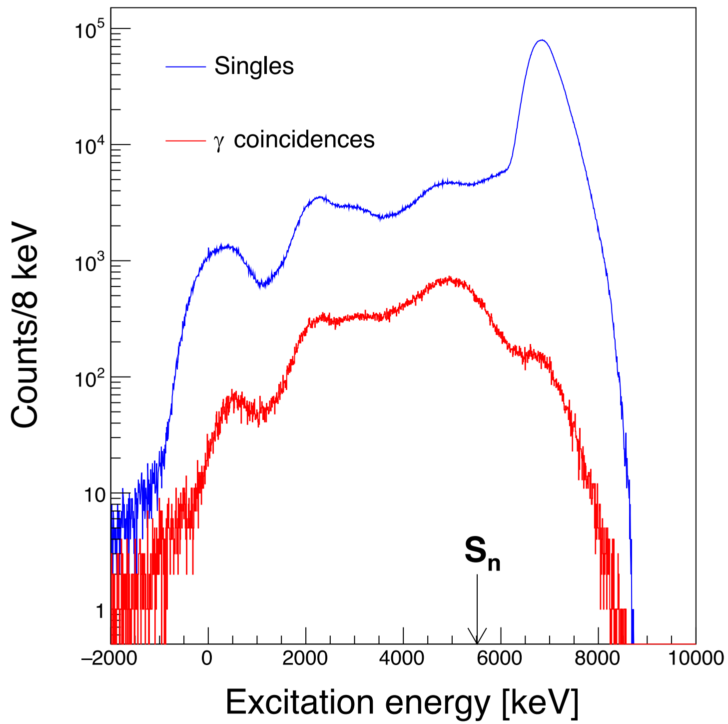
Results

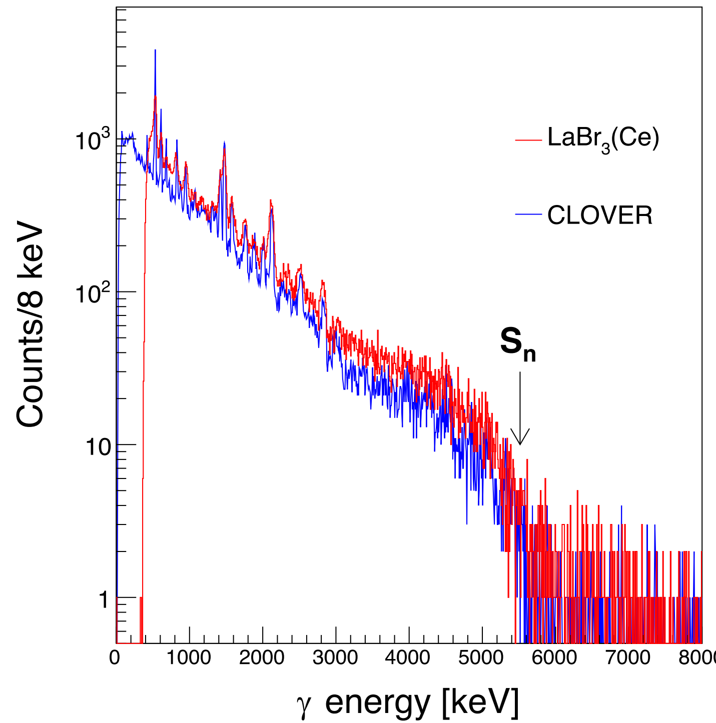

θ = 24.5°
θ = 33.6°
θ = 46.4°
θ = 66.7°
Δ E energy [keV]
E energy [keV]
6000
5000
4000
3000
2000
1000
5000
10000
15000
10
1
10^{-1}


E energy - dE energy
Δ E detector energy [keV]
8000
7000
6000
5000
4000
3000
2000
1000
2000
4000
6000
8000
10000
12000
14000
16000
10^2
10
1

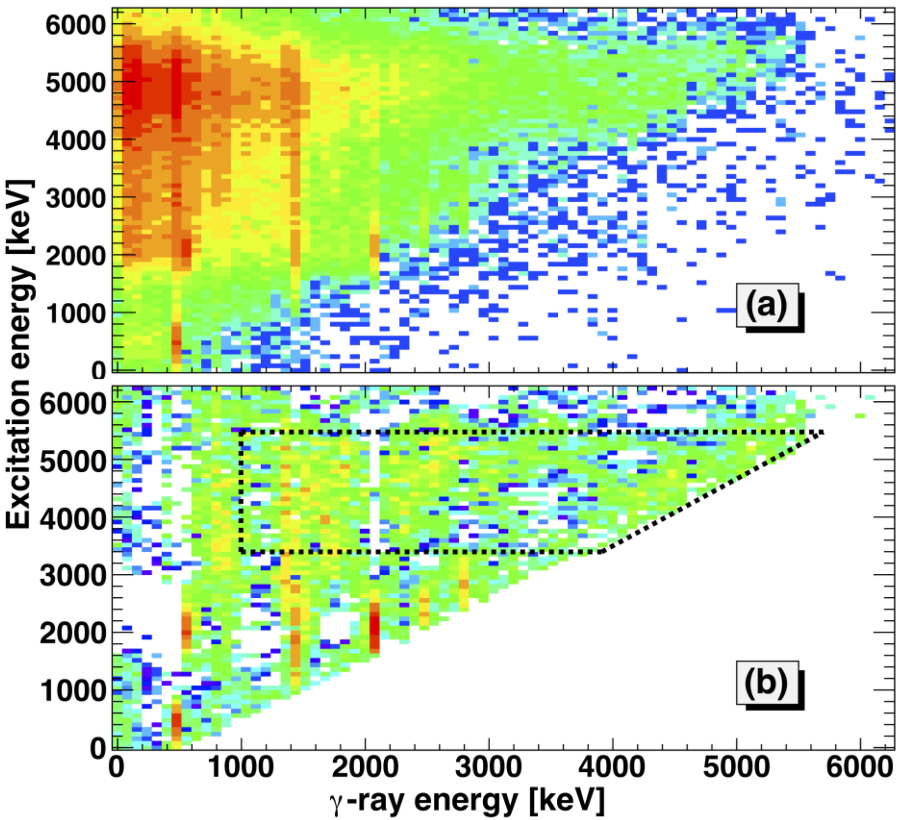

$d(^{86}Kr,p)^{87}Kr$
$T_{inc} = 293$ MeV
fter absorber [MeV]
energy [MeV]
0
20
40
60
80
100
120
140
160
180
5
10
15
20
6
7
8
9
10

Results

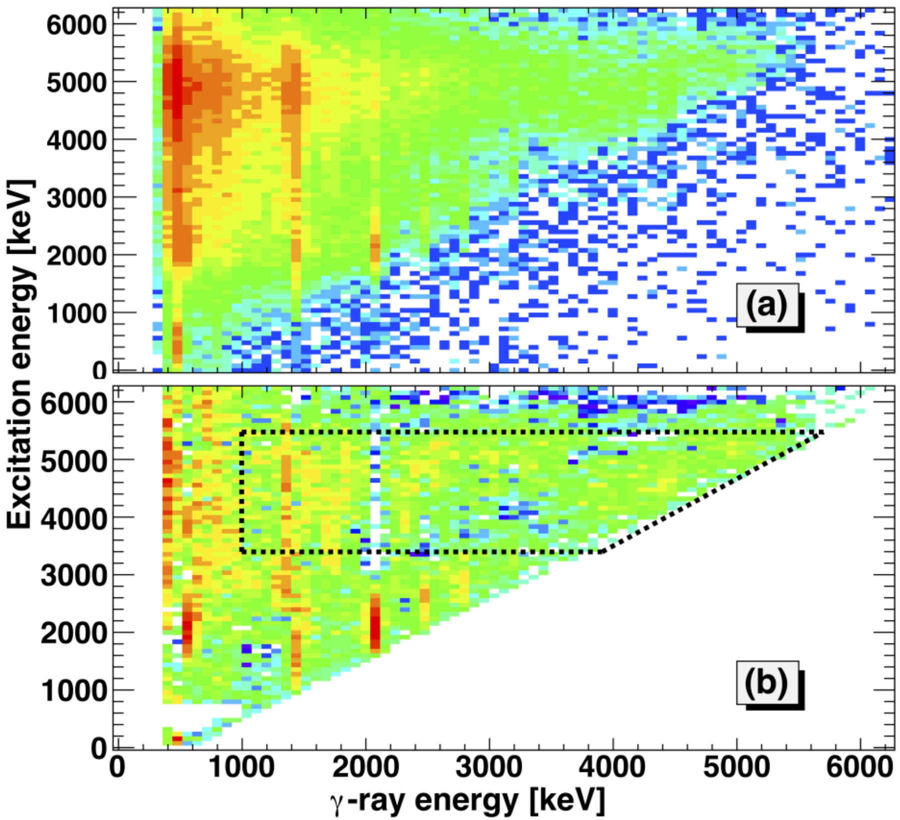

Singles
γ coincidences
10^5
10^4
10^3
10^2
10
1
Counts/8 keV
–2000
0
2000
4000
6000
8000
10000
Excitation energy [keV]
S_n

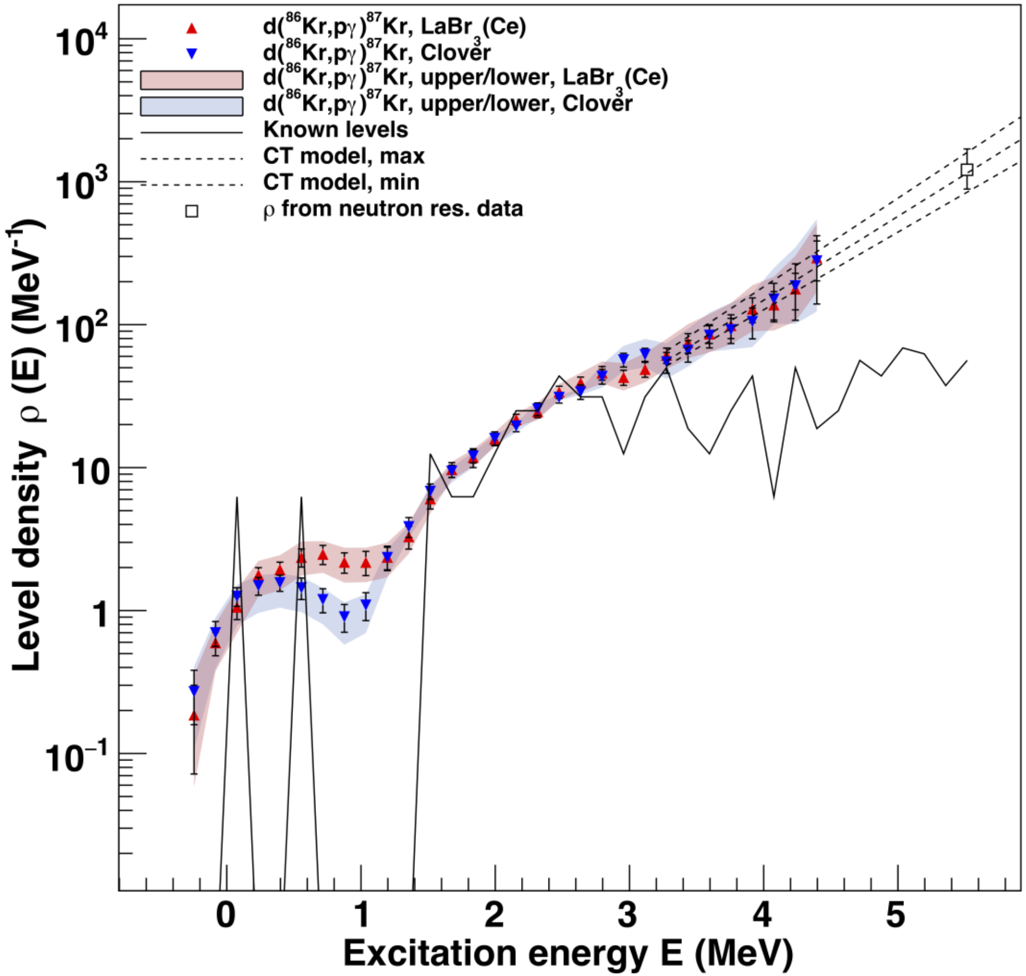

$LaBr_3(Ce)$
CLOVER
10^3
10^2
10
1
Counts/8 keV
0
1000
2000
3000
4000
5000
6000
7000
8000
γ energy [keV]
S_n

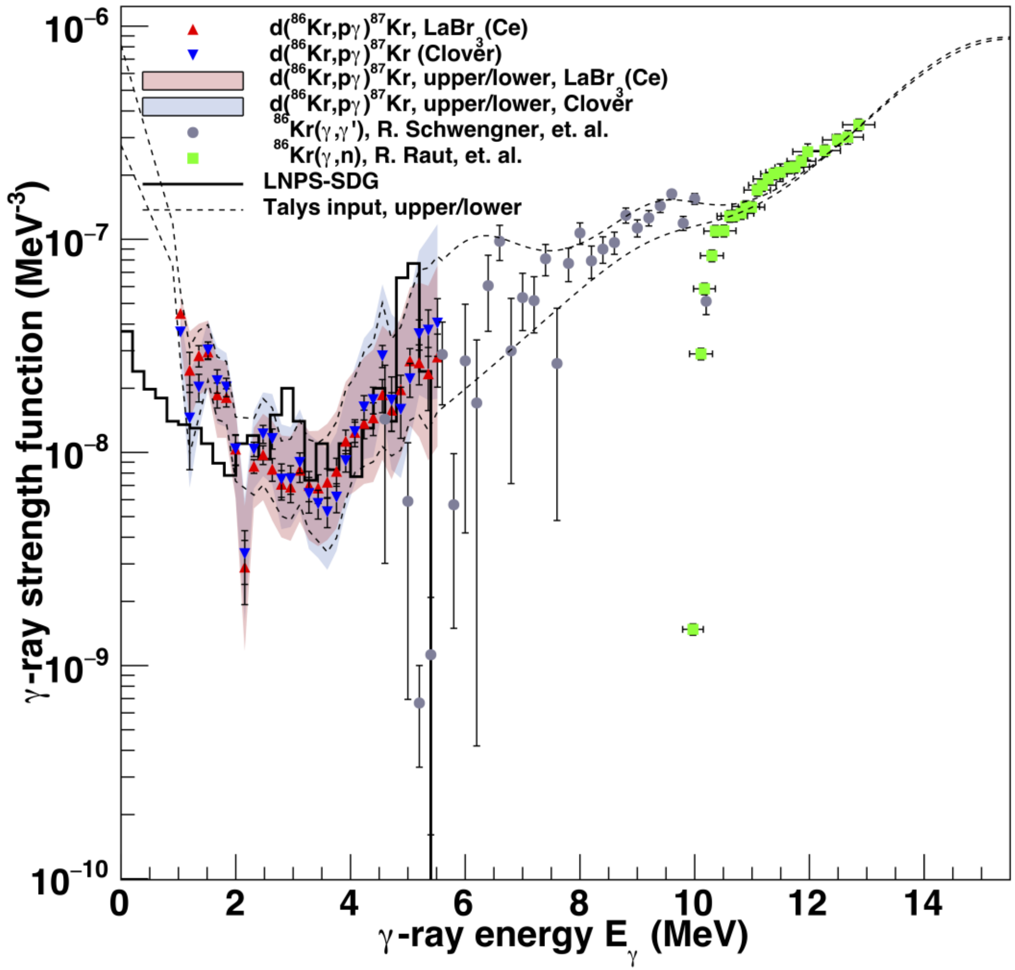
Clover

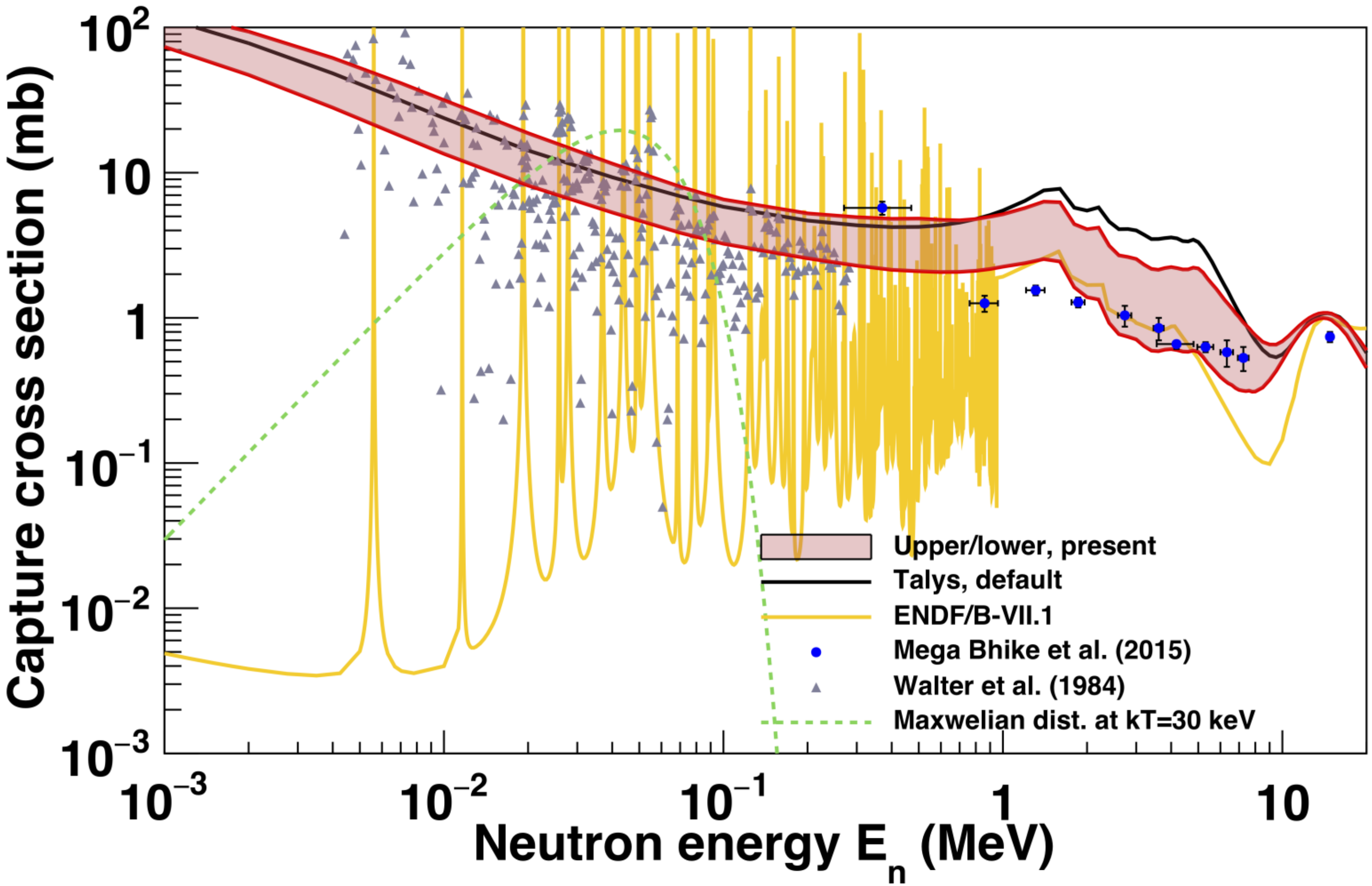


LaBr$_3$(Ce)




d(^{86}Kr,pγ)^{87}Kr, LaBr$_3$(Ce)
d(^{86}Kr,pγ)^{87}Kr, Clover
d(^{86}Kr,pγ)^{87}Kr, upper/lower, LaBr$_3$(Ce)
d(^{86}Kr,pγ)^{87}Kr, upper/lower, Clover
Known levels
CT model, max
CT model, min
ρ from neutron res. data
Level density ρ (E) (MeV^{-1})
Excitation energy E (MeV)
10^4
10^3
10^2
10
1
10^{-1}
0
1
2
3
4
5


$d(^{86}Kr,p\gamma)^{87}Kr$, $LaBr_3(Ce)$
$d(^{86}Kr,p\gamma)^{87}Kr$ (Clover)
$d(^{86}Kr,p\gamma)^{87}Kr$, upper/lower, $LaBr_3(Ce)$
$d(^{86}Kr,p\gamma)^{87}Kr$, upper/lower, Clover
$^{86}Kr(\gamma,\gamma')$, R. Schwengner, et. al.
$^{86}Kr(\gamma,n)$, R. Raut, et. al.
LNPS-SDG
Talys input, upper/lower
γ-ray strength function (MeV^{-3})
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0
2
4
6
8
10
12
14
γ-ray energy E_γ (MeV)


Capture cross section (mb)
Neutron energy E_n (MeV)
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
1
10
Upper/lower, present
Talys, default
ENDF/B-VII.1
Mega Bhike et al. (2015)
Walter et al. (1984)
Maxwelian dist. at kT=30 keV

Inverse-Oslo experiments

- d(^{86}Kr,p)^{87}Kr – April/May 2015, iThemba LABS
  - Paper to be submitted tomorrow afternoon(!!)
- d(^{66}Ni,p)^{67}Ni – November 2016, HIE-ISOLDE
- d(^{84}Kr,p)^{85}Kr – November 2017, iThemba LABS

- d(^{132}Xe,p)^{133}Xe – November 2017, iThemba LABS
  - MSc. project of Hannah Berg

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ISOLDE

Summary

- New γ-ray detector array is being commissioned in Oslo
- OSCAR will provide high energy and time resolution

- NLD & γSF can be extracted from inverse kinematics experiments
- We see an upbend in our data – consistent with M1 shell model calculations

Acknowledgements

University of Oslo

S. Siem
F. Zeiser
A. Görgen
M. Guttormsen
A. C. Larsen
E. Sahin
G. M. Tveten
T. Renstrøm
F. Bello

iThemba LABS

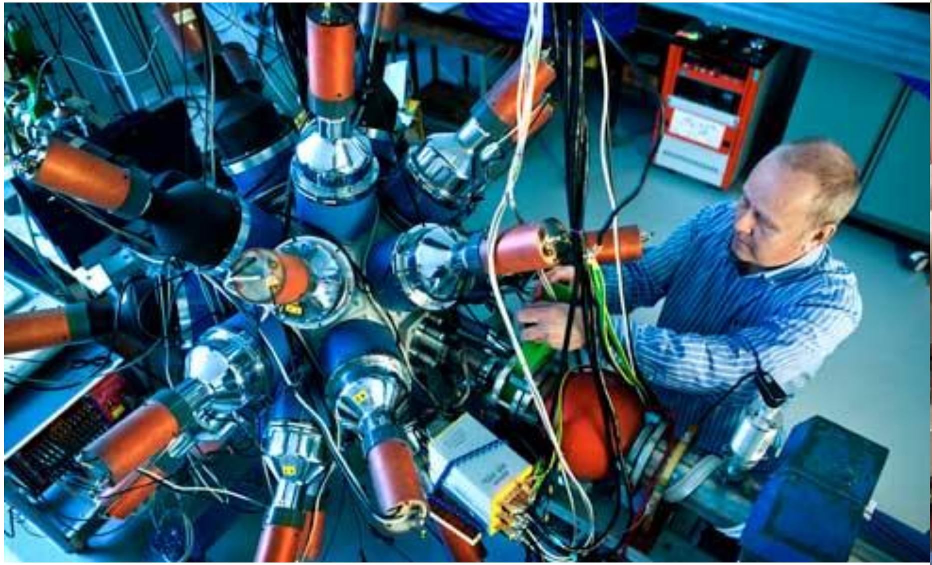
M. Wiedeking
P. Jones

And everyone who have taken shifts!

With funding from
The Research Council of Norway

Extreme Laboratory makeover!

Before:



After: