γ-ray tracking with AGATA
A new perspective for physics with stable and radioactive ion beams

- AGATA Science Case
- Development and Status of AGATA
- Capabilities and Opportunities
- Near Future of AGATA

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Universität zu Köln

Acknowledgements

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Institute of Nuclear Physics
University of Cologne

IKP

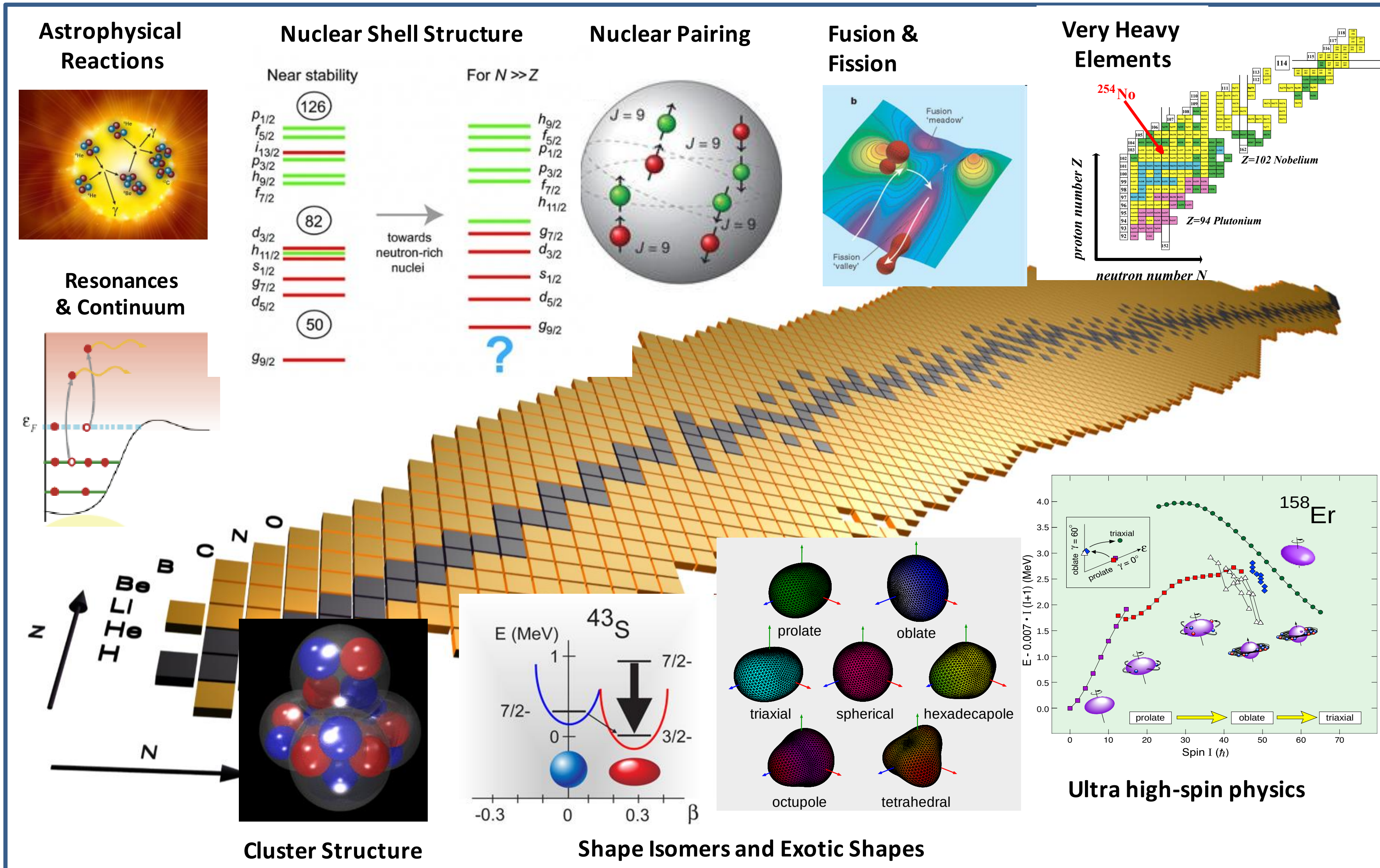
Universität zu Köln

GSI

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

The Science Case

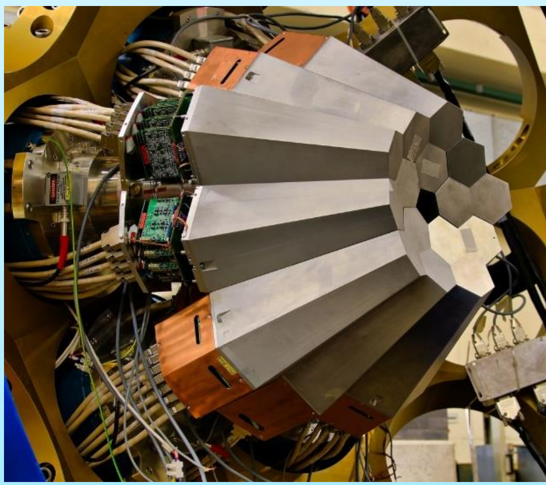


AGATA the next decade

White book: Physics opportunities with the Advanced Gamma Tracking Array: AGATA

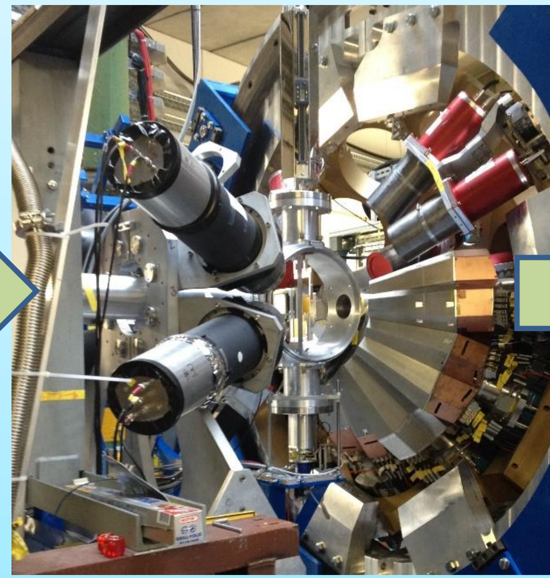
From the Demonstrator to AGATA 4π

2012-2014
Legnaro, Italy
Demonstrator
5 detectors



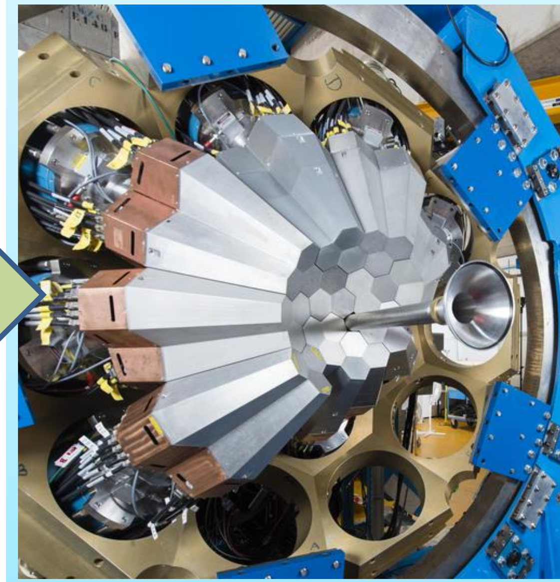
AGATA at LNL

2012-2014
GSI, Germany
~25 detectors



AGATA at GSI

2014-2021
GANIL, France
45 ->   detectors



AGATA at GANIL

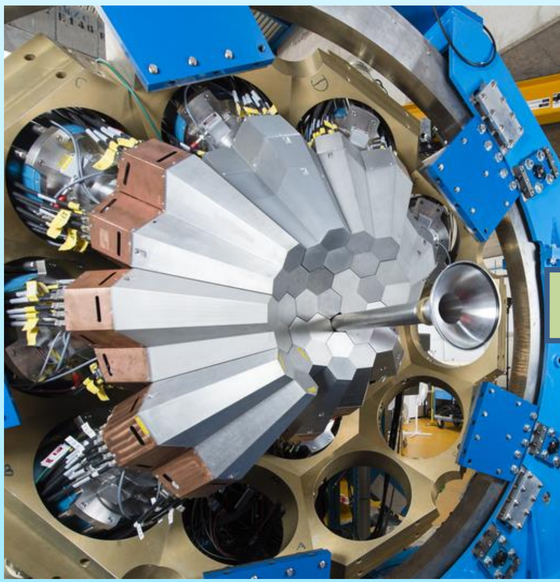
Stable beams:
- Coulomb Excitation, Fusion
- MNT, Deep Inelastic
- **Direct and inverse kinematics $\beta \sim 5\%$**

In-flight RIBs:
- Relativistic Coulomb Excitation, Knockout, Fragmentation.
- **$\beta \sim 50\%$**

Stable beams, reaccelerated RIBs:
- Coulomb Excitation,
- Direct Reactions, MNT,
- Deep Inelastic, Fusion
- **Direct and inverse kinematics $\beta \sim 10\%$**

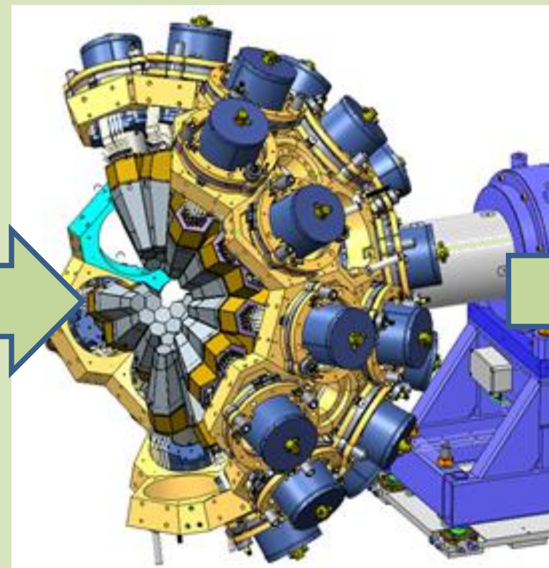
From the Demonstrator to AGATA 4π

2014-2021
GANIL, France
45 -> detectors



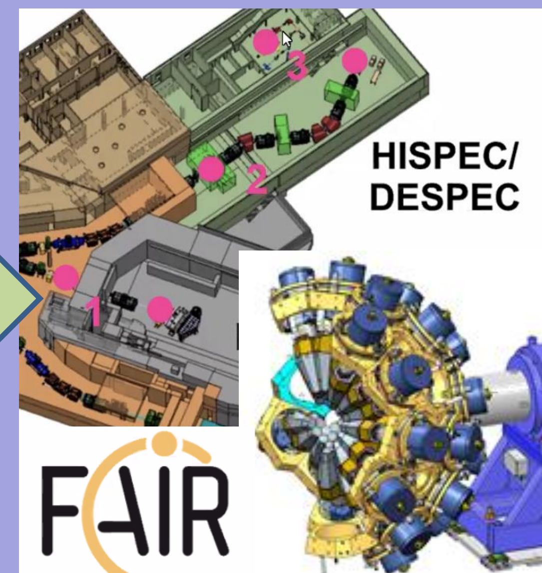
AGATA at GANIL

2021-2025
Legnaro, Italy
60 -> detectors



AGATA at LNL

2026 ->
FAIR, Germany
80-90 detectors



AGATA at NUSTAR

Reaccelerated RIBs:
- Coulomb Excitation, Direct Reactions, MNT, Deep Inelastic, Fusion
- **Direct and inverse kinematics β ~ 10%**

In-flight RIBs:
- Relativistic Coulomb Excitation, Knockout, Fragmentation.
- **β ~ 50%**

Experimental Conditions and Challenges at Future RIB Facilities for γ-Spectroscopy

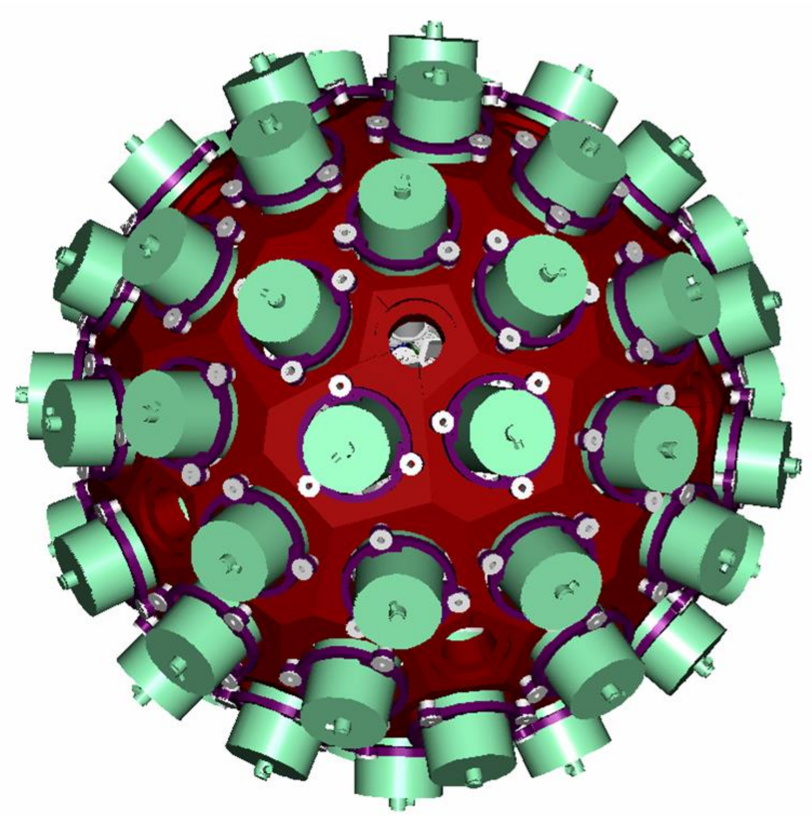
EURISOL
FAIR
HIE-ISOLDE
SPES
SPIRAL2
...

- Low intensity
- High background
- Large Doppler broadening
- High counting rates
- High γ-ray multiplicities

Need for γ-spectrometer based on γ-ray tracking

High efficiency
High sensitivity
High throughput
Ancillary detectors

Advanced GAmma Tracking Array



180 hexagonal crystals	3 shapes
60 triple-clusters	all equal
Inner radius (Ge)	23.5 cm
Amount of germanium	362 kg
Solid angle coverage	82 %
36-fold segmentation	6480 segments
Singles rate	~50 kHz

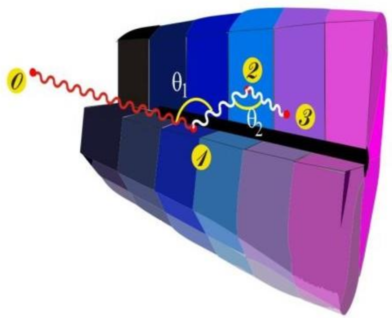
Efficiency: 43% (M_γ=1) 28% (M_γ=30)

Peak/Total: 58% (M_γ=1) 49% (M_γ=30)

Ingredients of Gamma–Ray Tracking

1

Highly segmented HPGe detectors

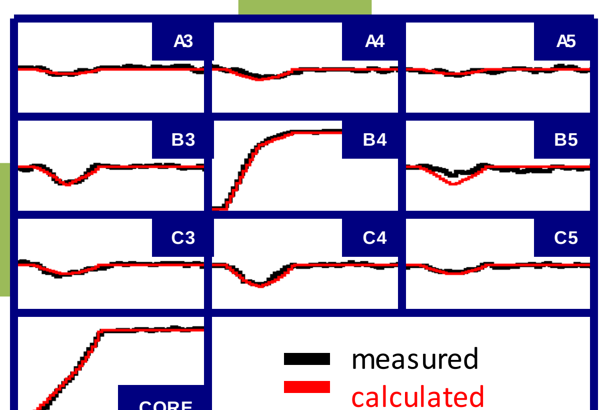


2

Digital electronics
record & process
segment signals

3

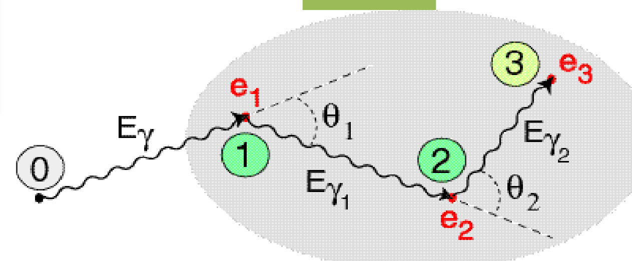
Pulse Shape Analysis
decompose
recorded waves



Identified
interaction points
$(x,y,z,E,t)_i$

4

γ-ray tracking
Reconstruct & evaluate
interaction points



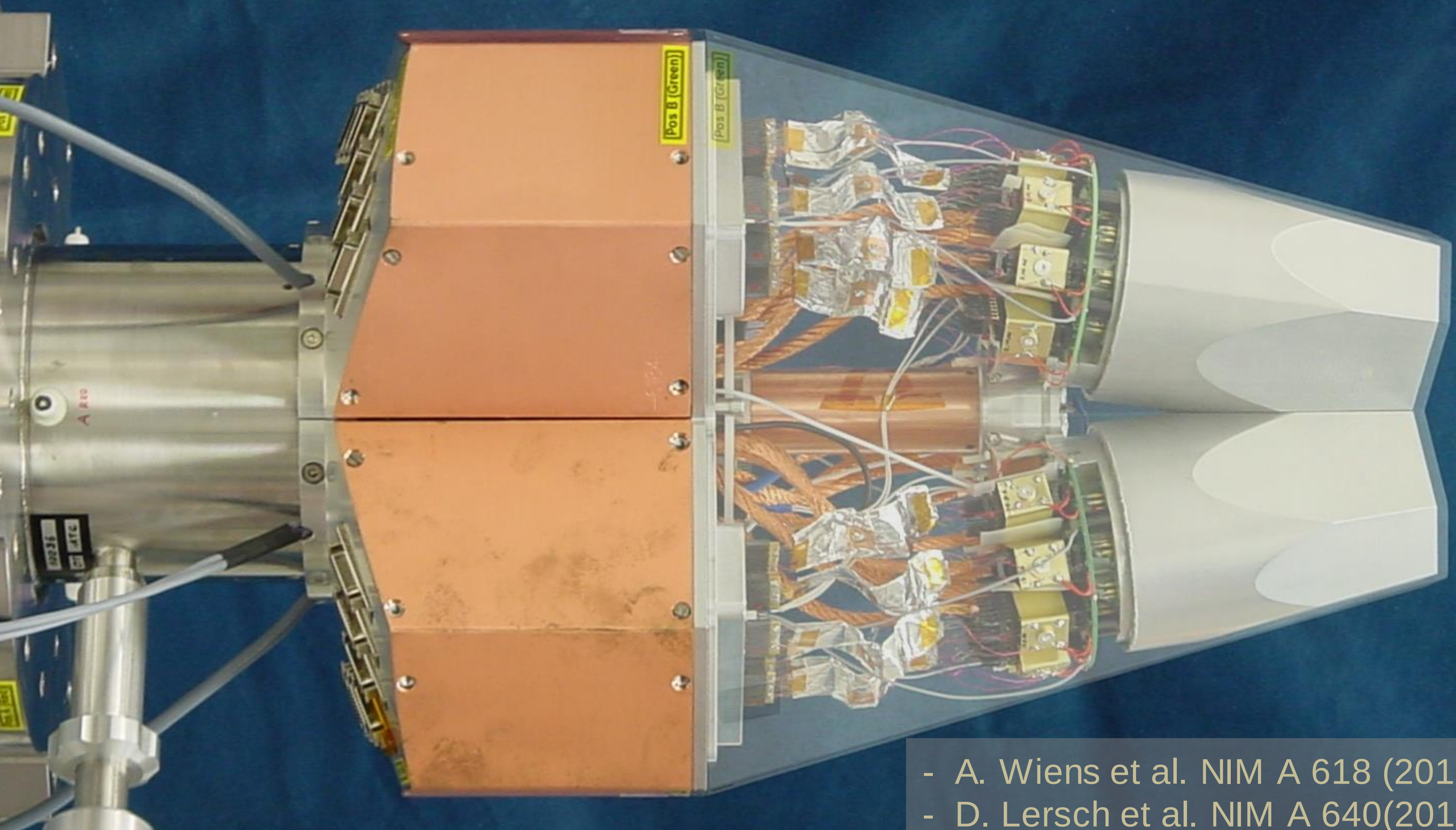
Reconstructed gamma-rays

AGATA Triple Cryostat

- integration of 111 high resolution spectroscopy channels
- cold FET technology for all signals

Challenges:

- mechanical precision
- LN2 consumption
- microphonics
- noise, high frequencies



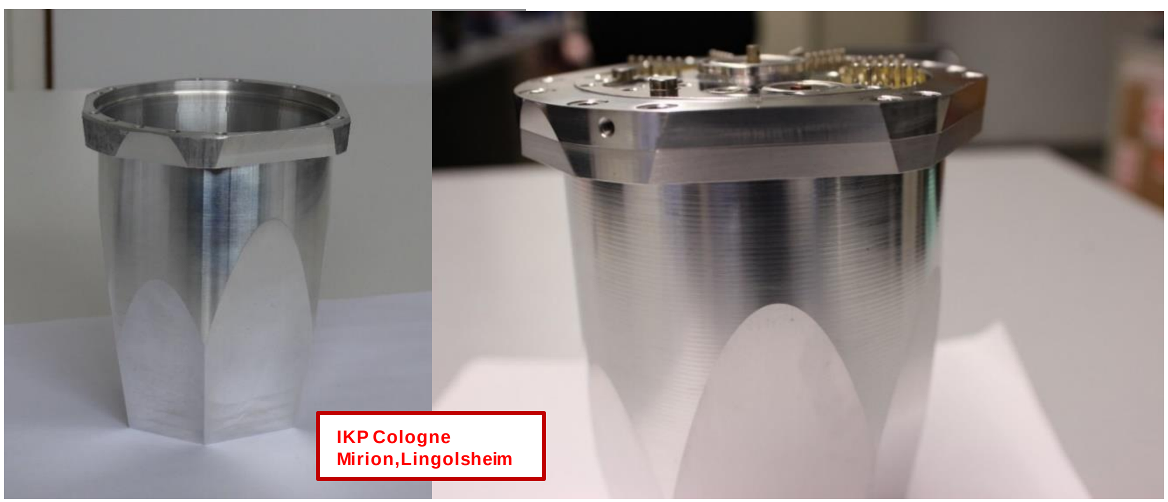
- A. Wiens et al. NIM A 618 (2010) 223–233
- D. Lersch et al. NIM A 640(2011) 133-138

Encapsulated HPGe detectors

Challenges:

- vacuum $< 10^{-6}$ mb, getter
- gas tight
- temperature range:
  80°K to 383°K (110 ^{0}C)
- annealing

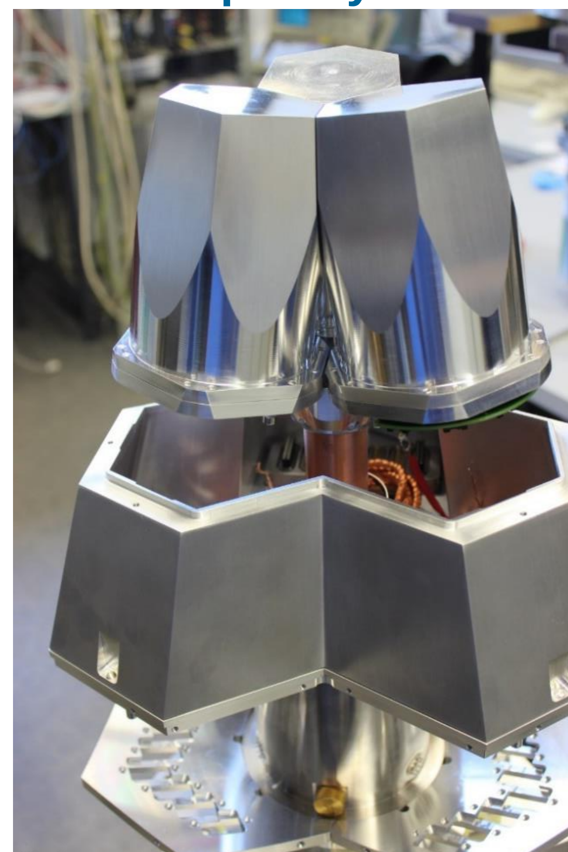
old: capsule and lid sealed by electron-beam welding



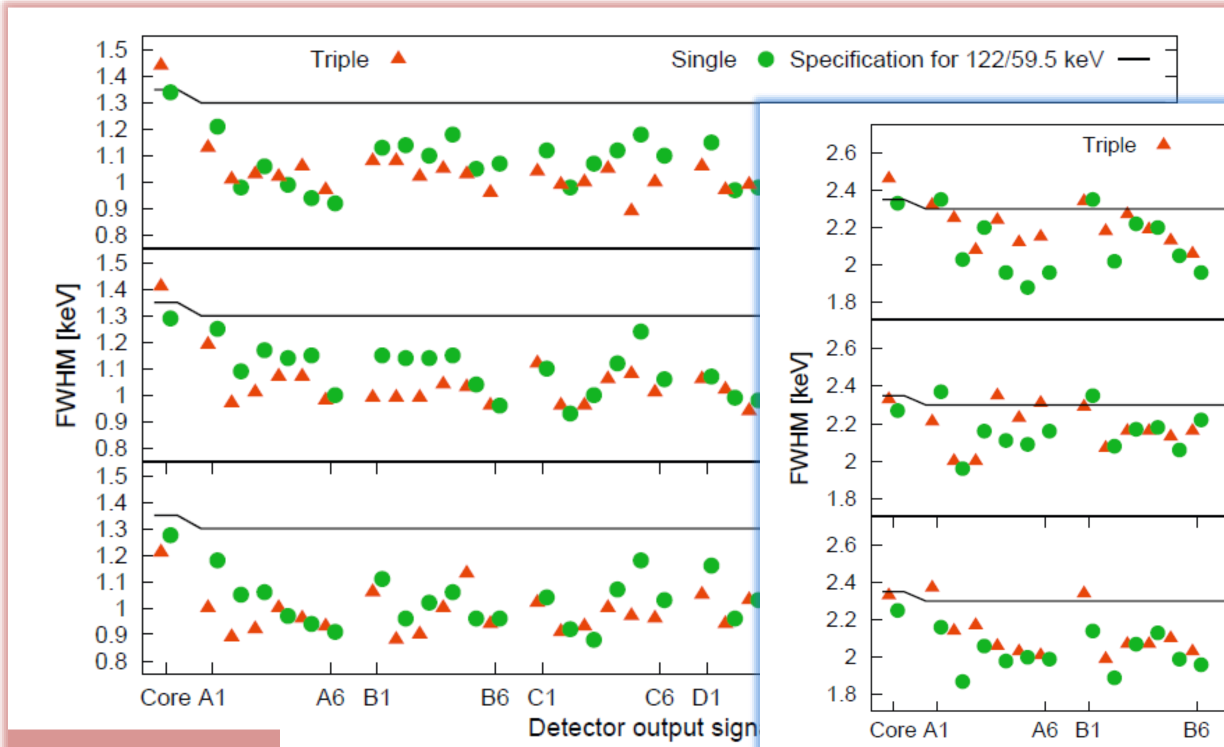
new: reusable capsule and lid, metal elastic seal

EU patent EP3221719B1 & US patent US10,107,923B2 (2018)

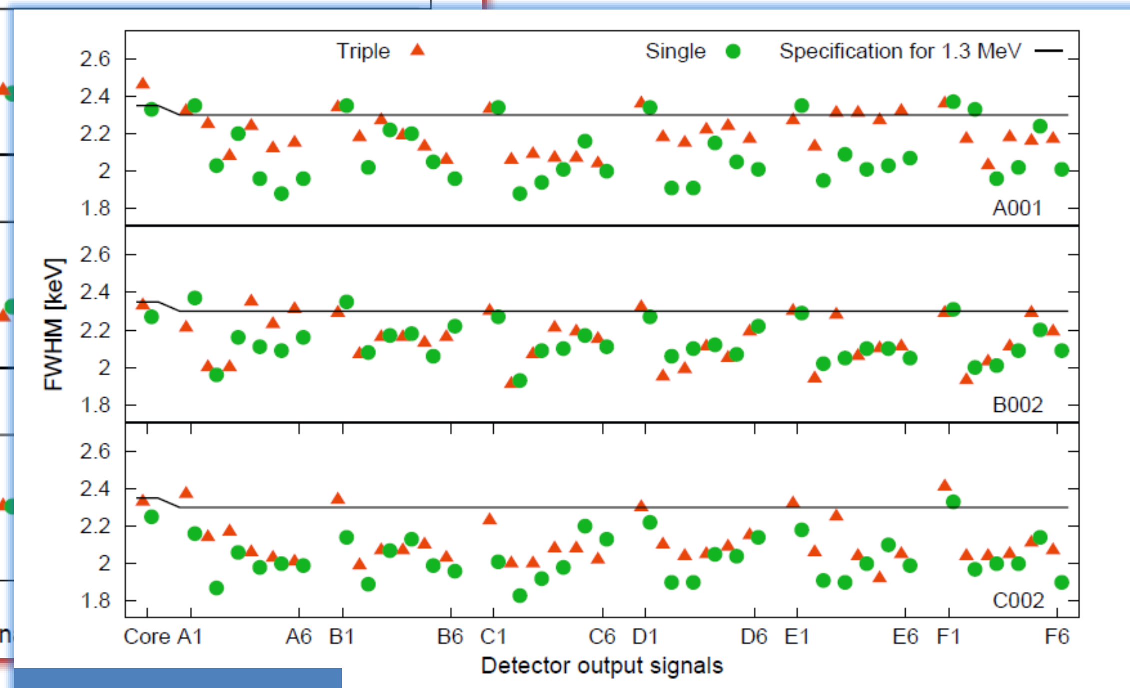
New triple cryostat



Performance: Energy resolution



@ 60 keV



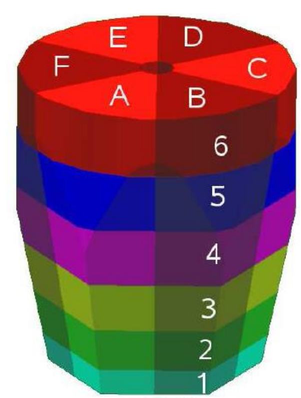
@ 1333 keV

Averages of the segment resolutions
@ 60 keV :

A001:	1011 +/- 53 eV
B002:	1039 +/- 70 eV
C002:	965 +/- 63 eV

Averages of the segment resolutions
Measured in Cologne and Legnaro
@ 1333 keV :

	IKP	/	Legnaro
A001:	2,19 keV	/	2,00 keV
B002:	2,09 keV	/	1,98 keV
C002:	2,1 keV	/	1,94 keV



Segment labeling

Performance: Energy resolution

- 60 HPGe detectors
- 20 AGATA triple clusters

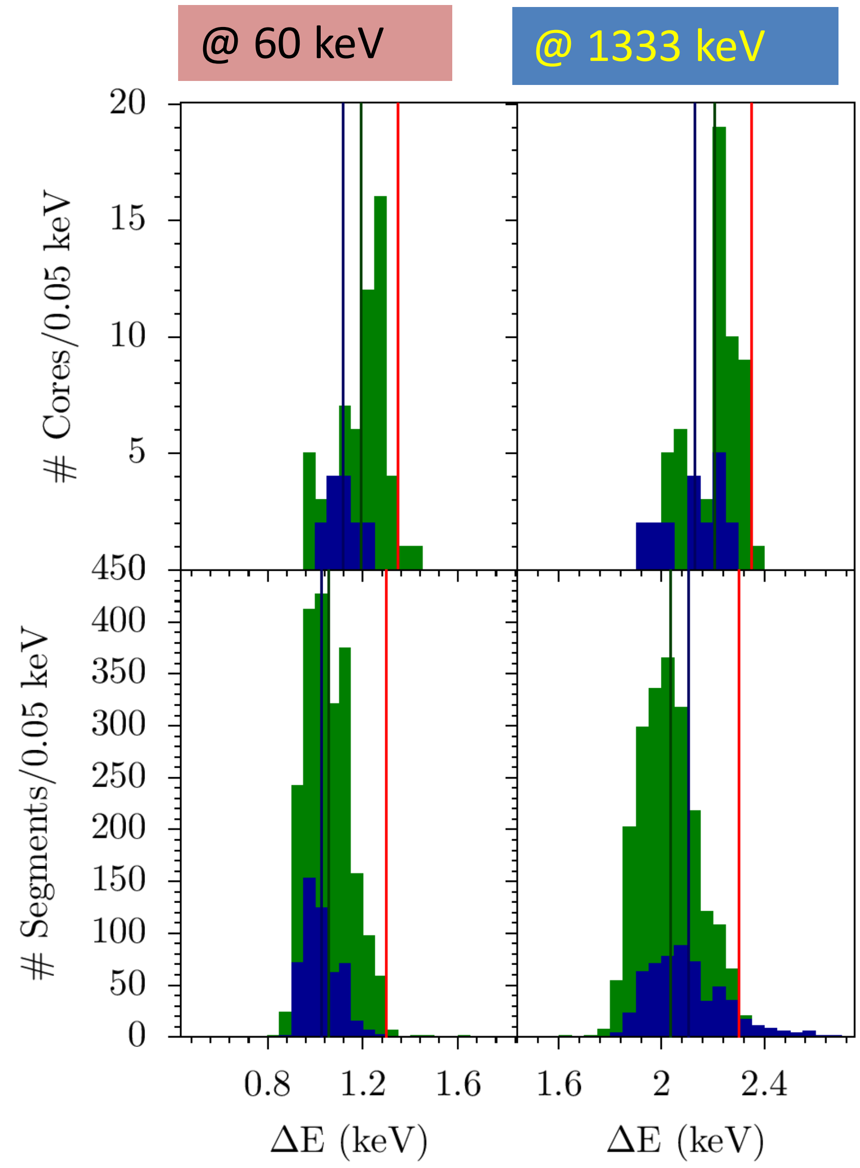
- Annealing recovers E resolution

E resolution mean value @ 60 keV
60 core resolutions**:** 1.19 keV
2160 segment resolutions**:** 1.05 keV

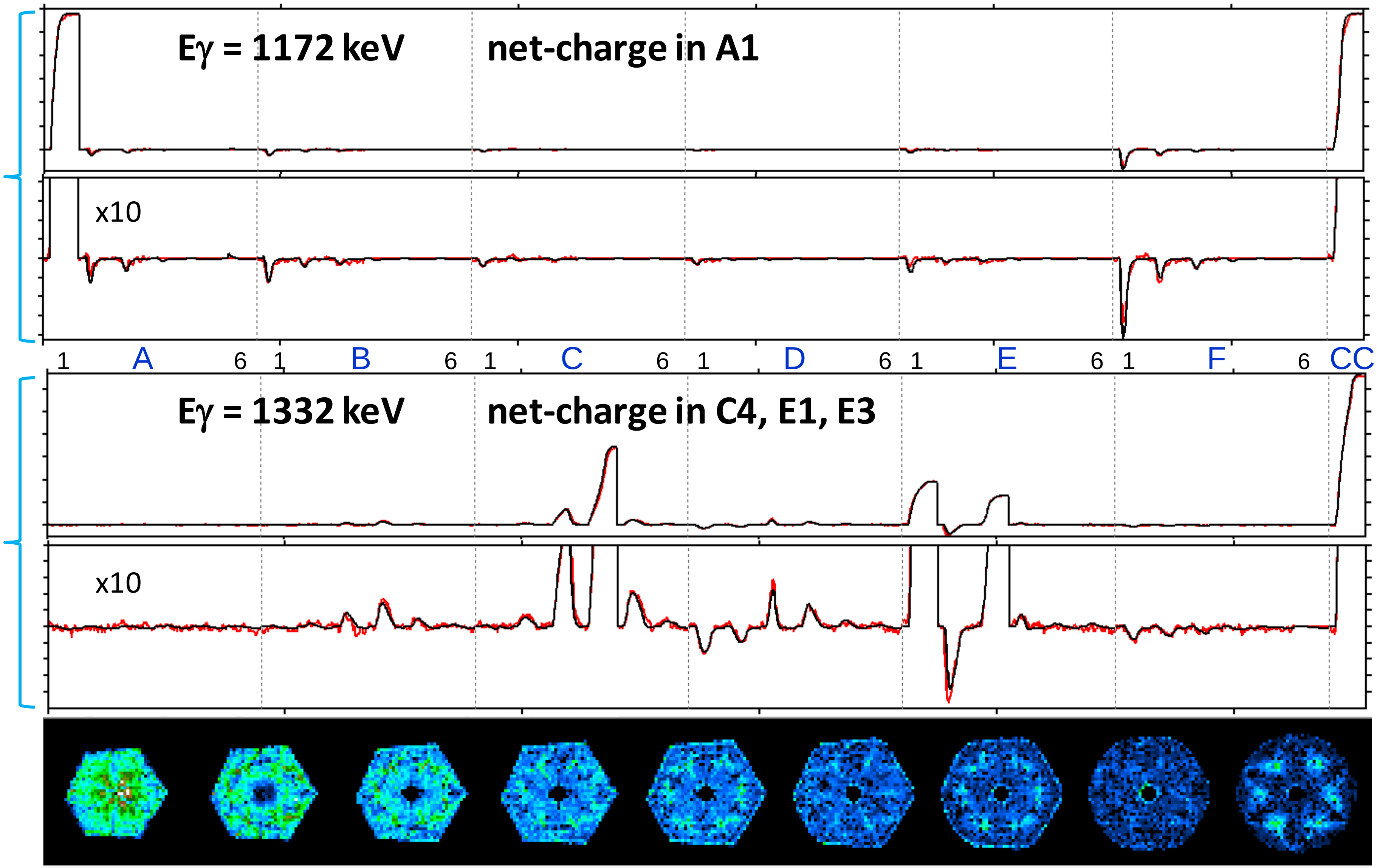
After annealing (blue)
core resolutions**:** 1.12 eV
segment resolutions**:** 1.03 eV

E resolution mean value @ 1.33 MeV
60 core resolutions**:** 2.21 keV
2160 segment resolutions**:** 2.03 keV

After annealing (blue)
core resolutions**:** 2.13 keV
segment resolutions**:** 2.11 keV

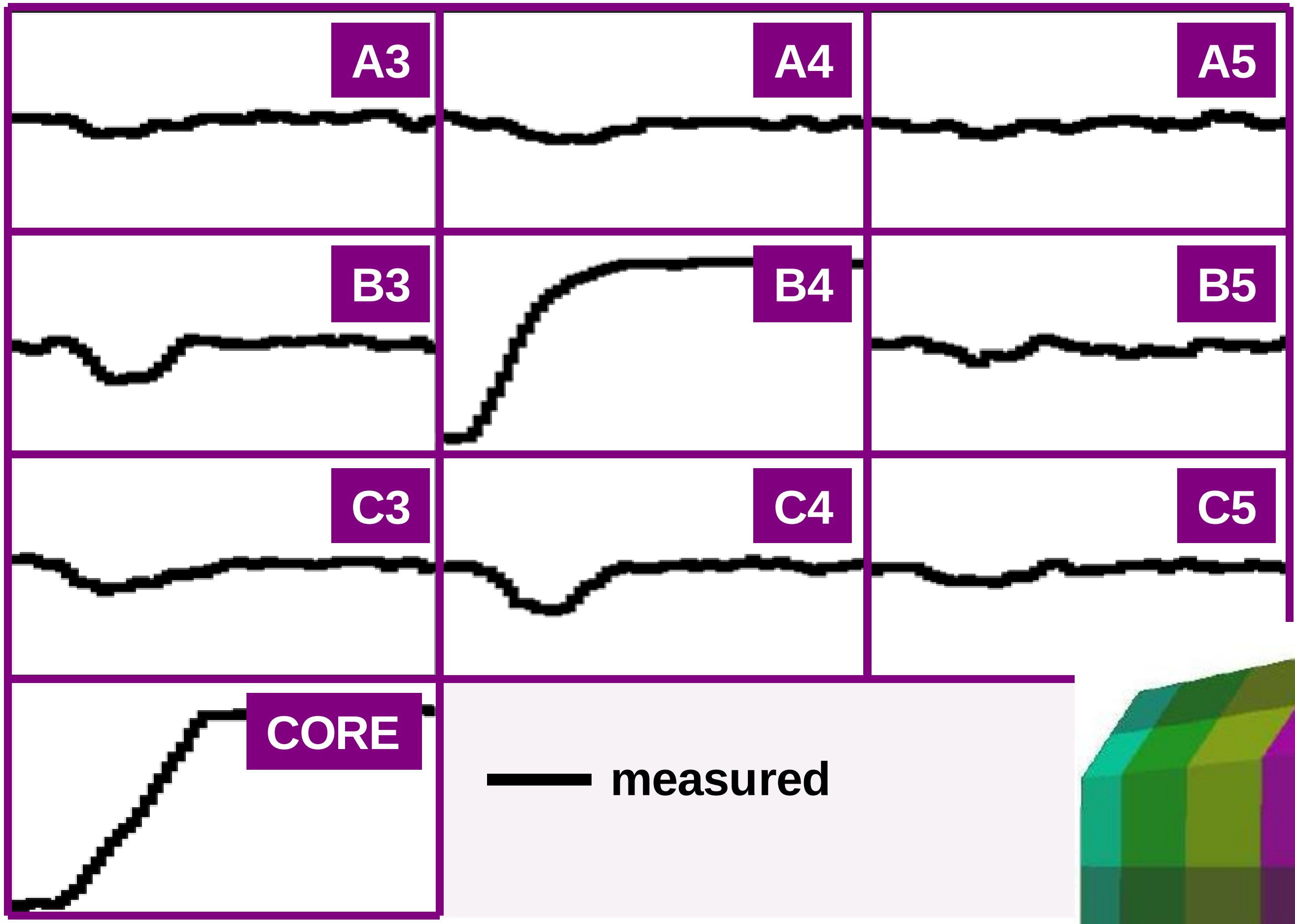


Pulse shape analysis two examples

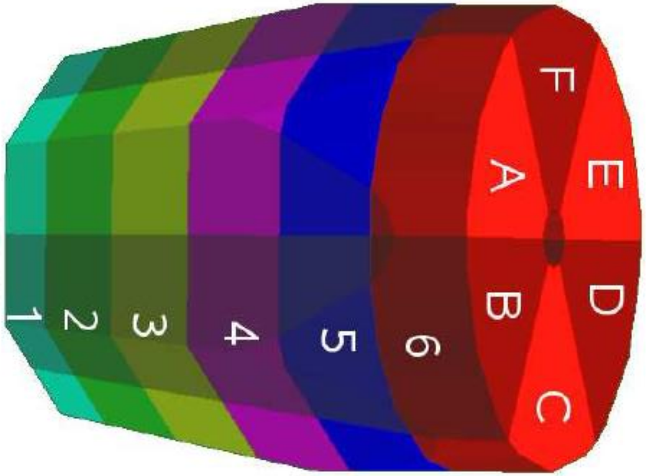


Tomography of interactions in the crystal: non uniformities due to PSA

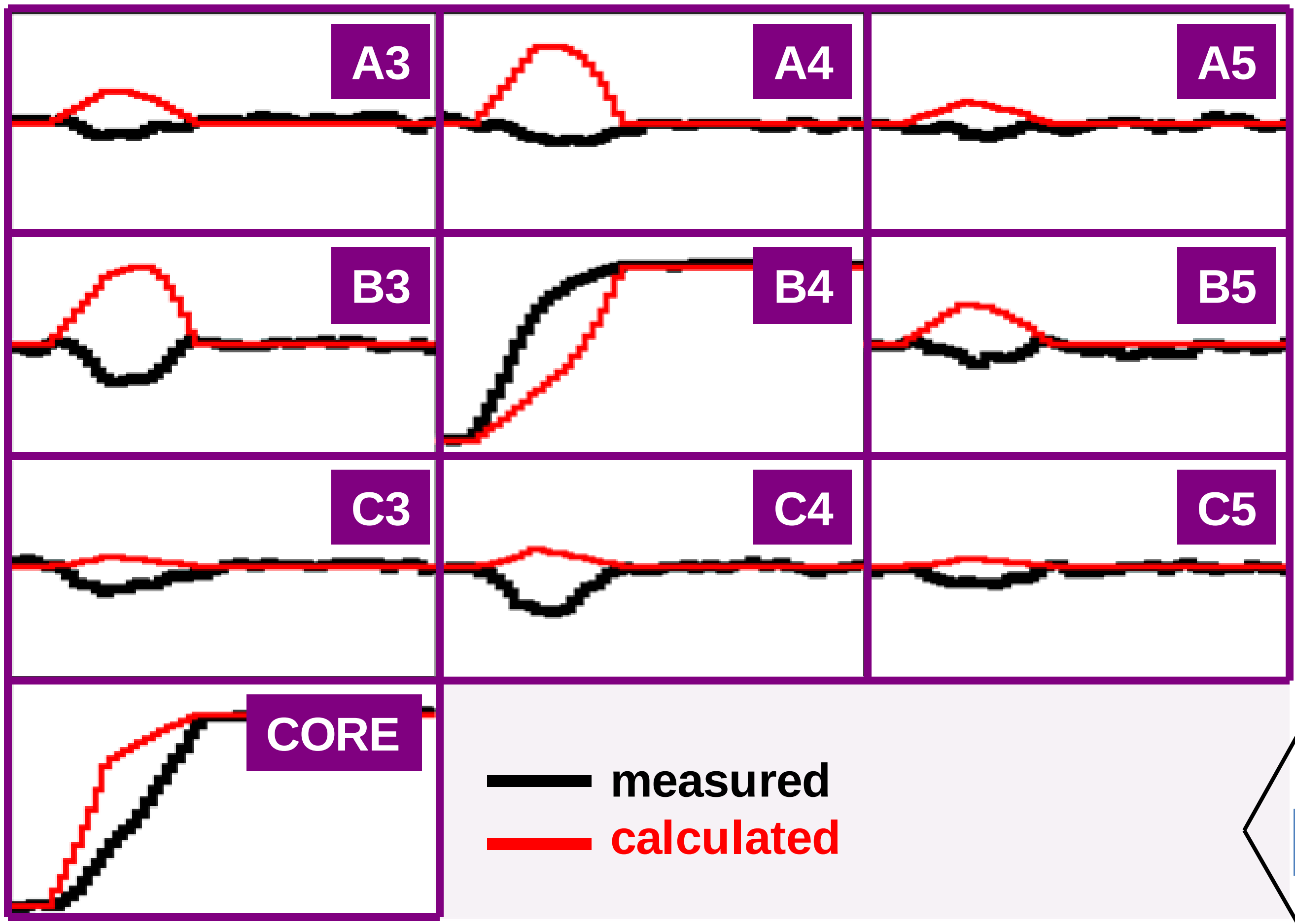
Pulse Shape Analysis concept

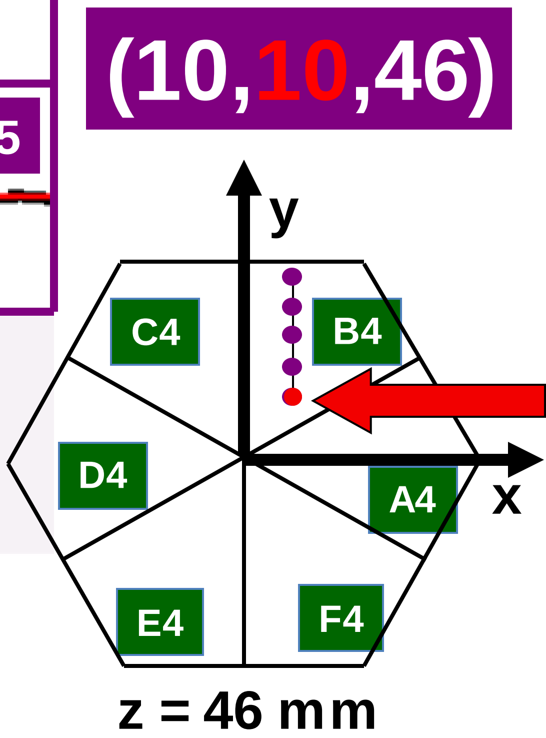


791 keV deposited in segment B4



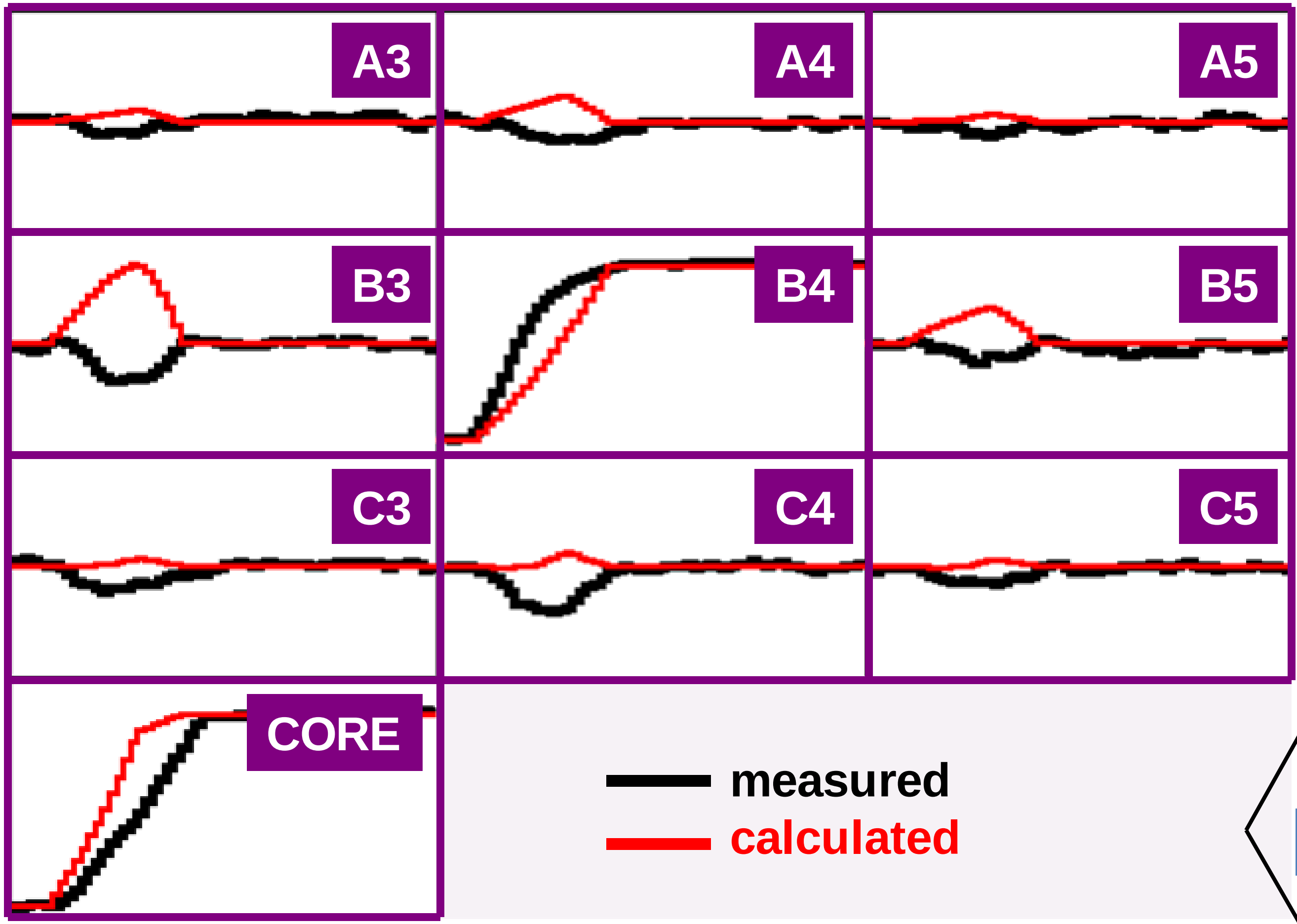
Pulse Shape Analysis concept

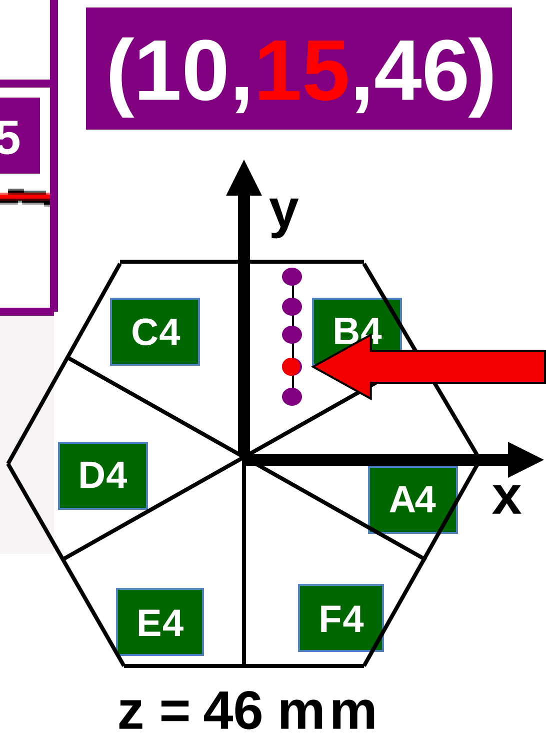




791 keV deposited in segment B4

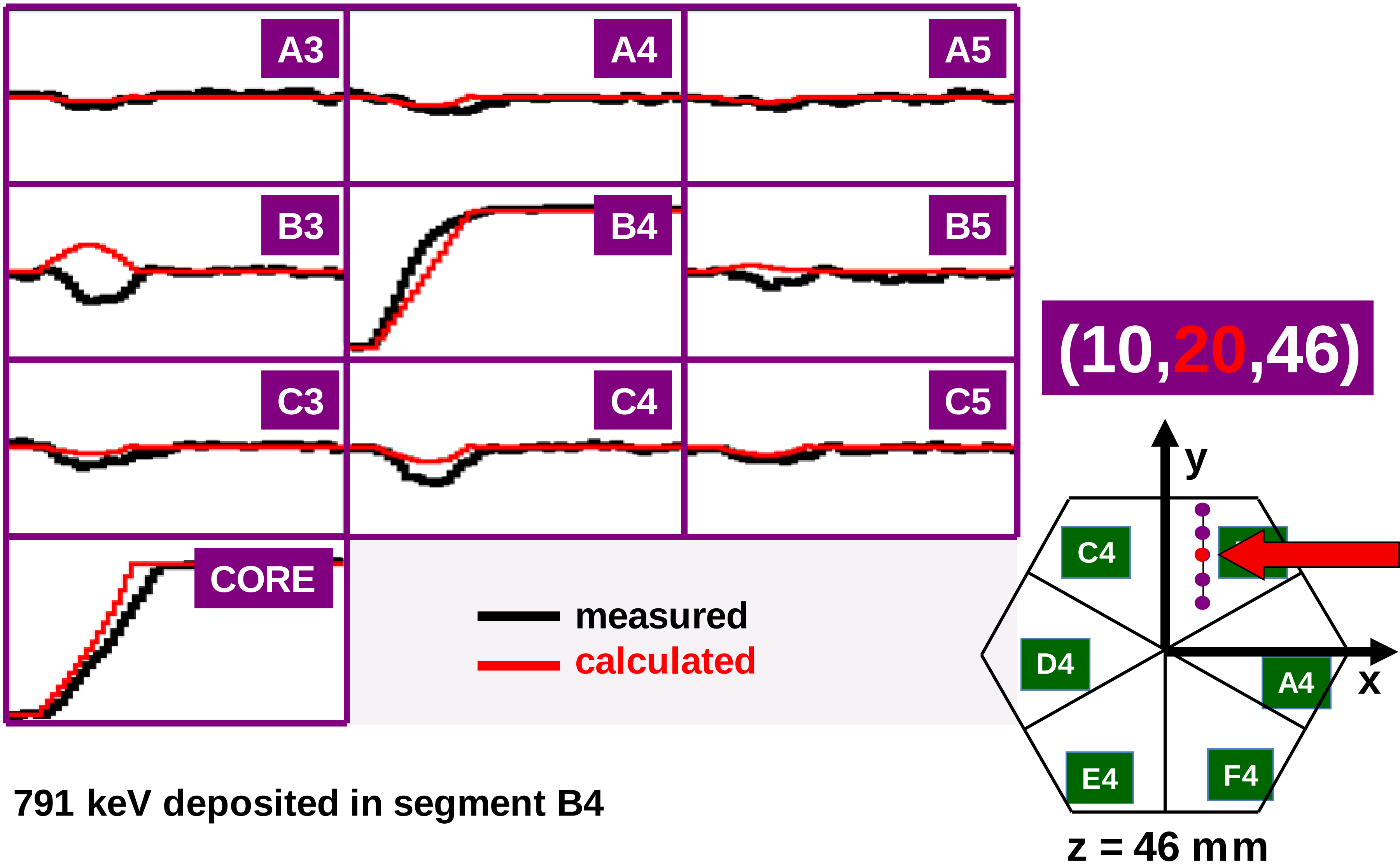
Pulse Shape Analysis concept





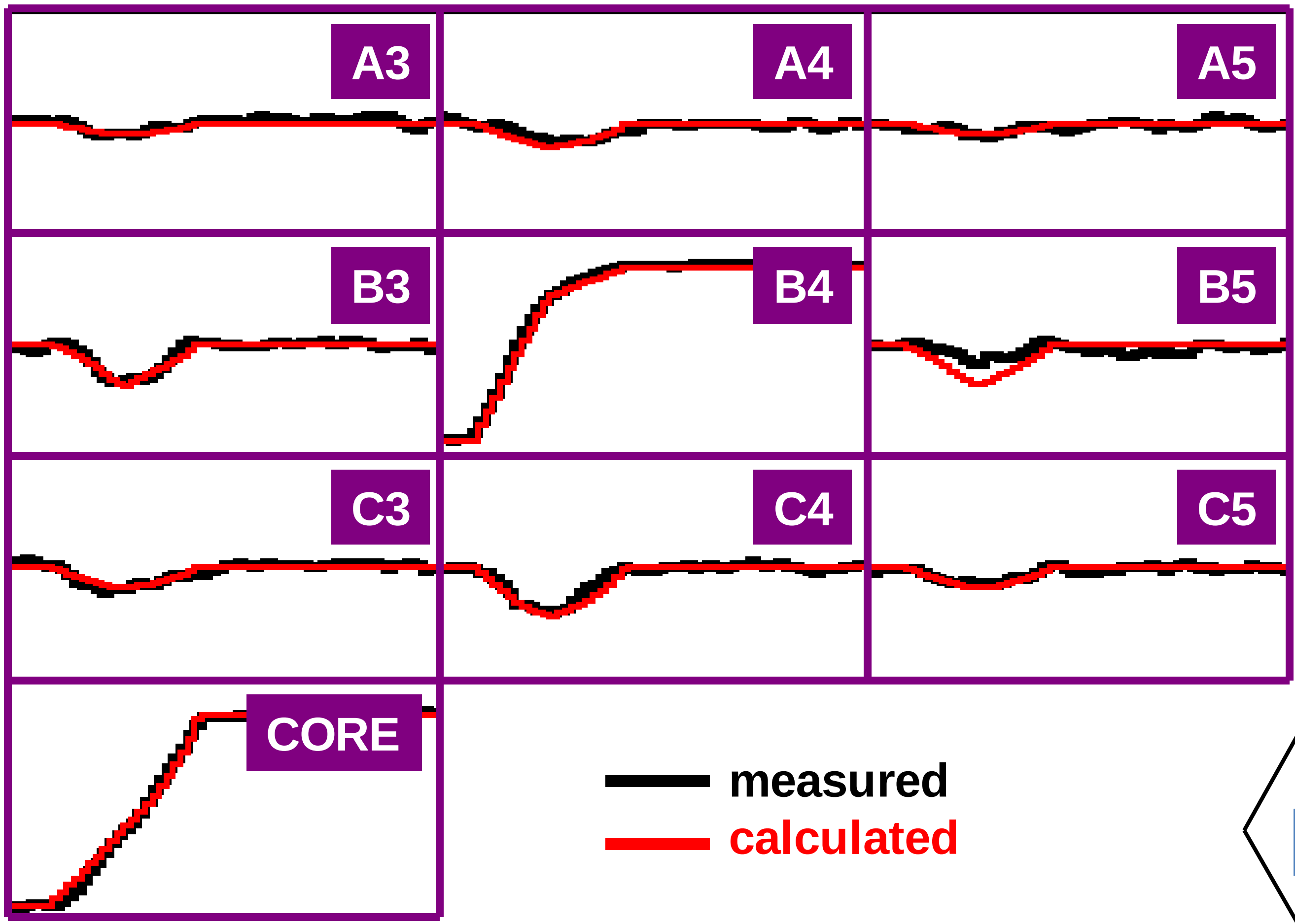
791 keV deposited in segment B4

Pulse Shape Analysis concept



791 keV deposited in segment B4

Pulse Shape Analysis concept



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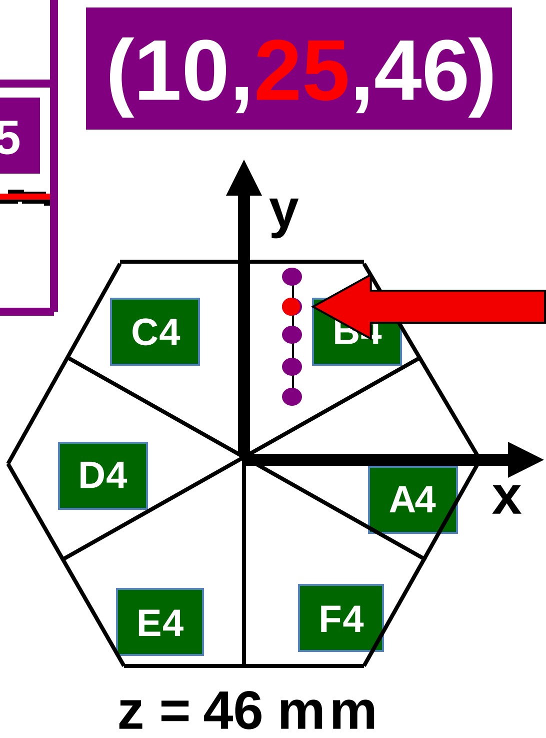
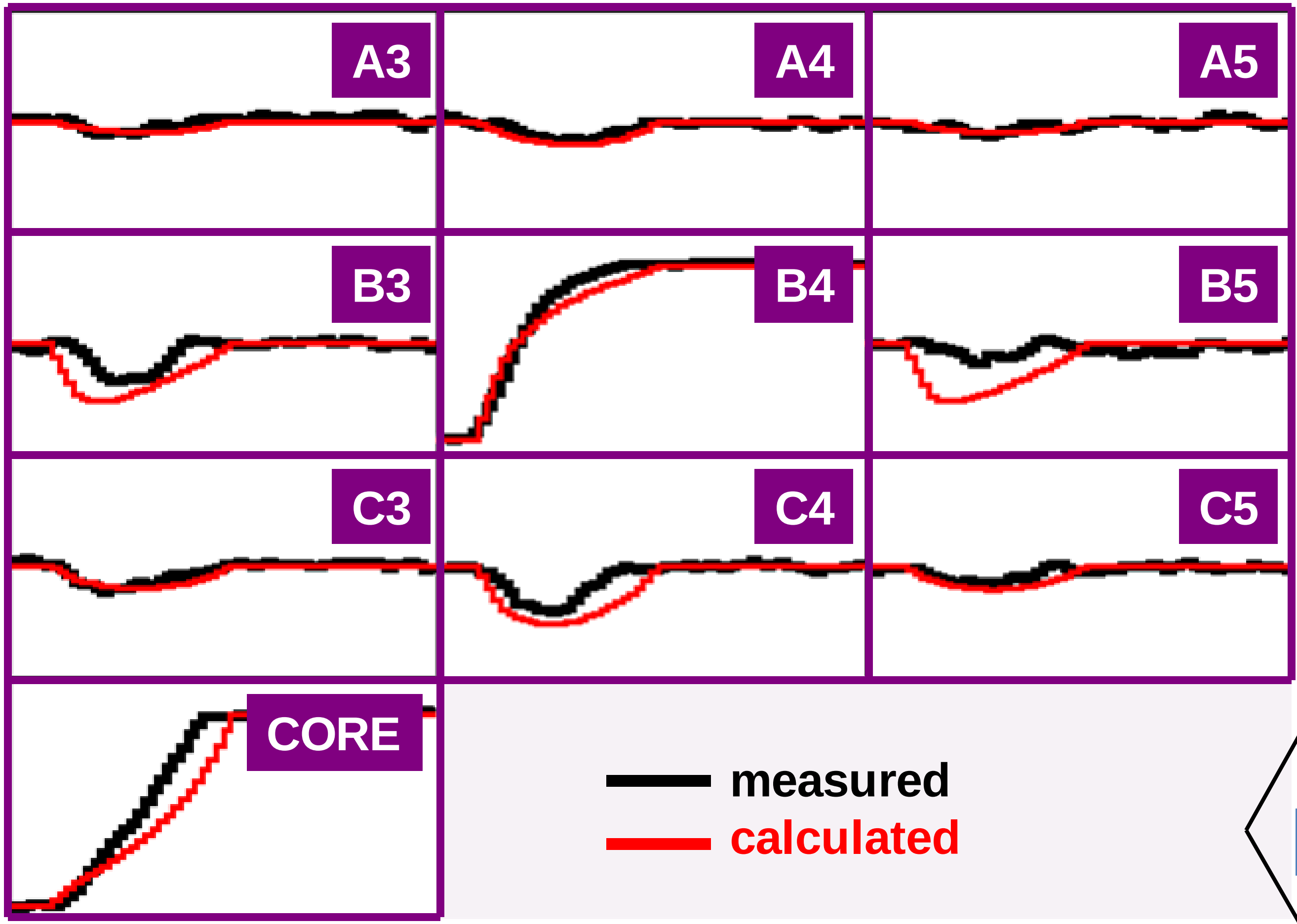
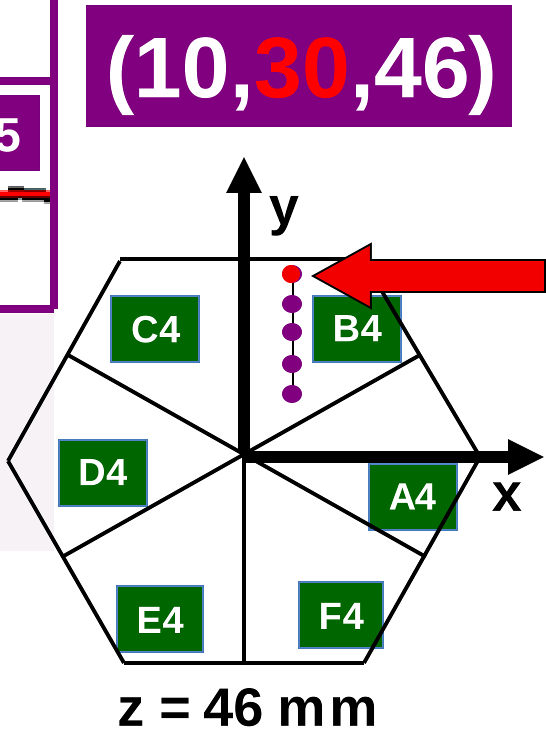


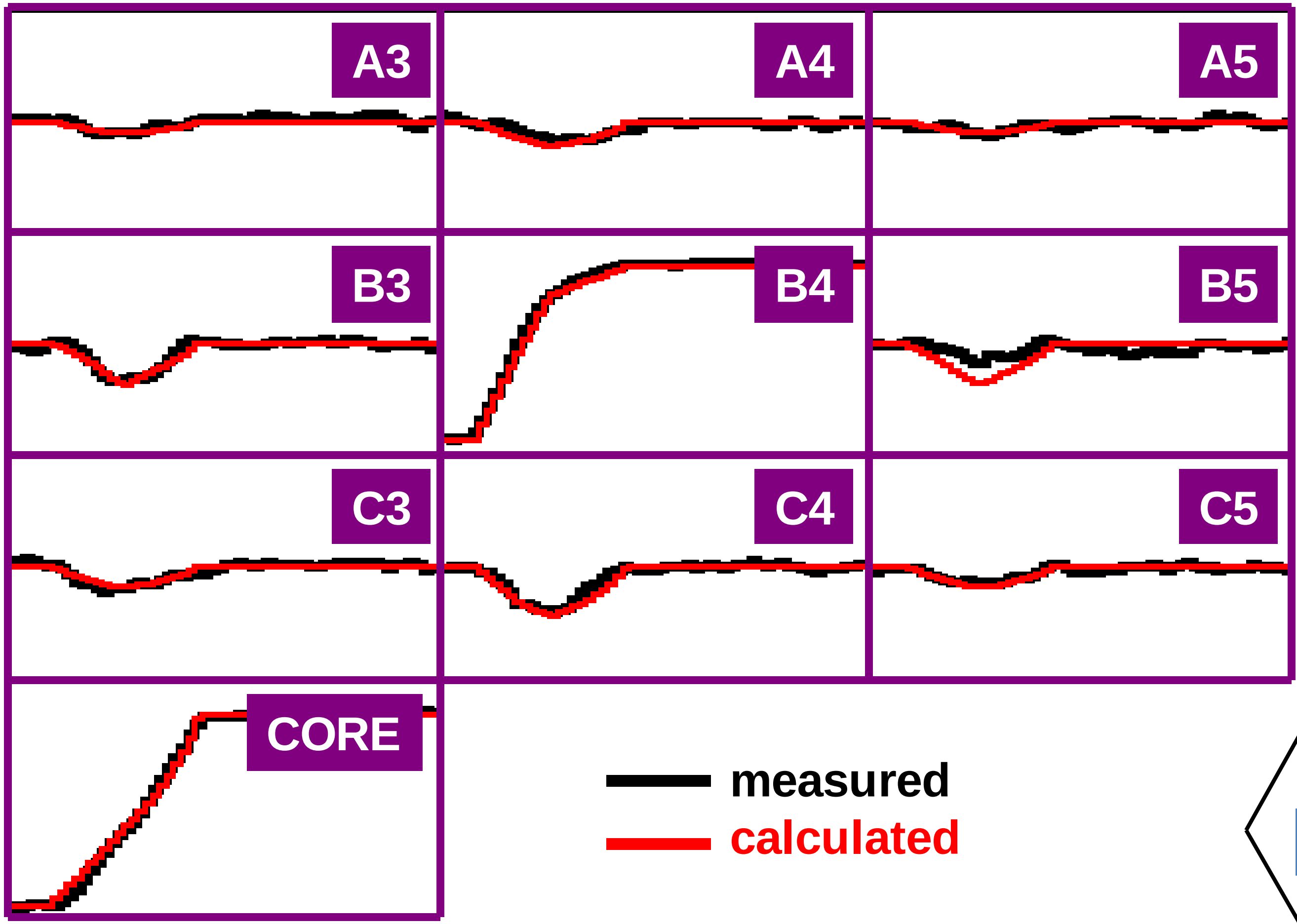
Pulse Shape Analysis concept





791 keV deposited in segment B4

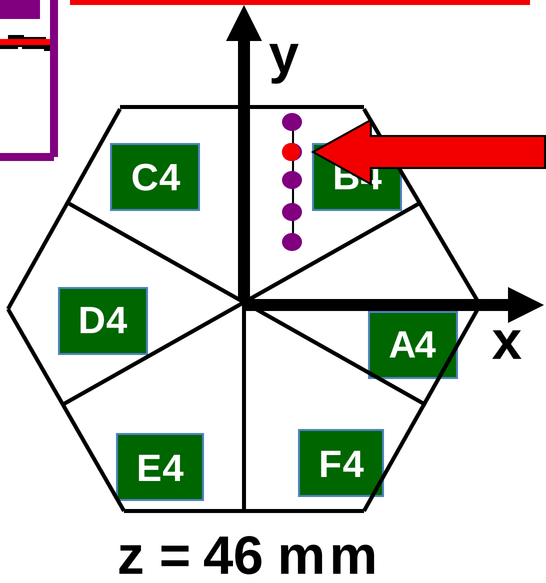
Pulse Shape Analysis concept



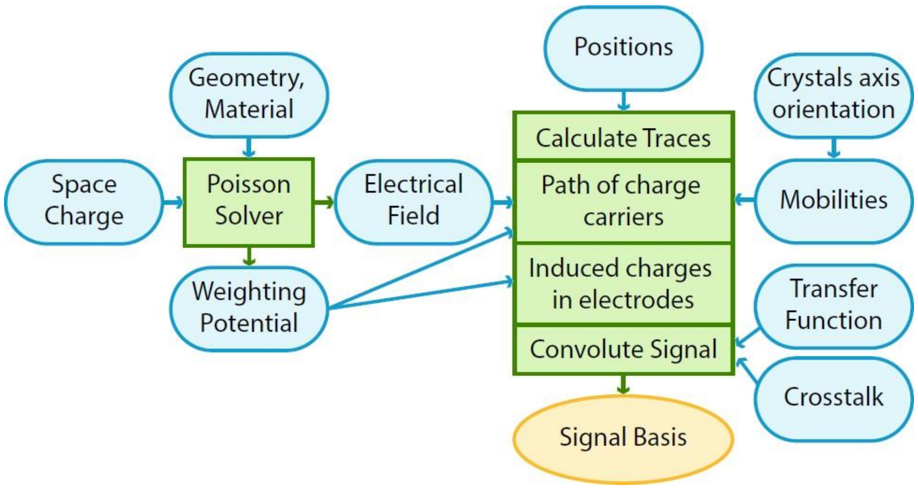
791 keV deposited in segment B4

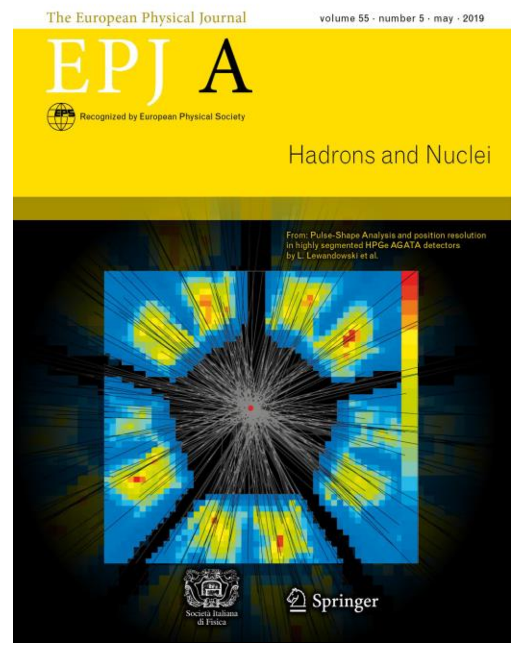
Result of *Grid Search* Algorithm

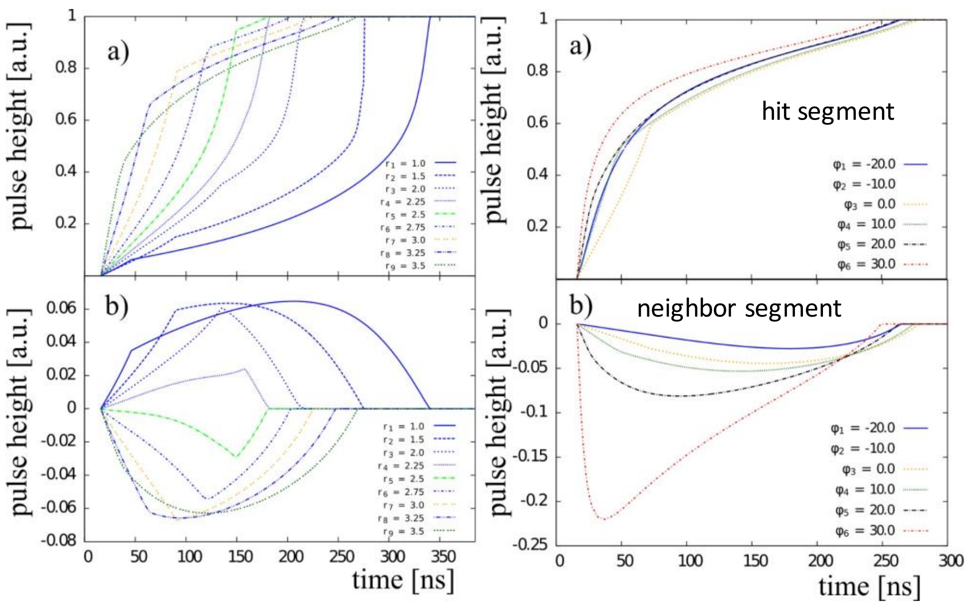
(10,25,46)



The AGATA detector library ADL







different radii
fixed angle and depth

different angles
fixed radius and depth

Electronic response, PSA parameters,
Grid search algorithm

- Transfer function
- Hole mobility
- Electron mobility
- Weighting of transient signals
- Distance metric

Pulse shape analysis and position determination in segmented HPGe detectors: The AGATA detector library. Bruyneel, B.; Birkenbach, B.; Reiter, P. in The European Physical Journal A (2016). ***52****(3) 70.*

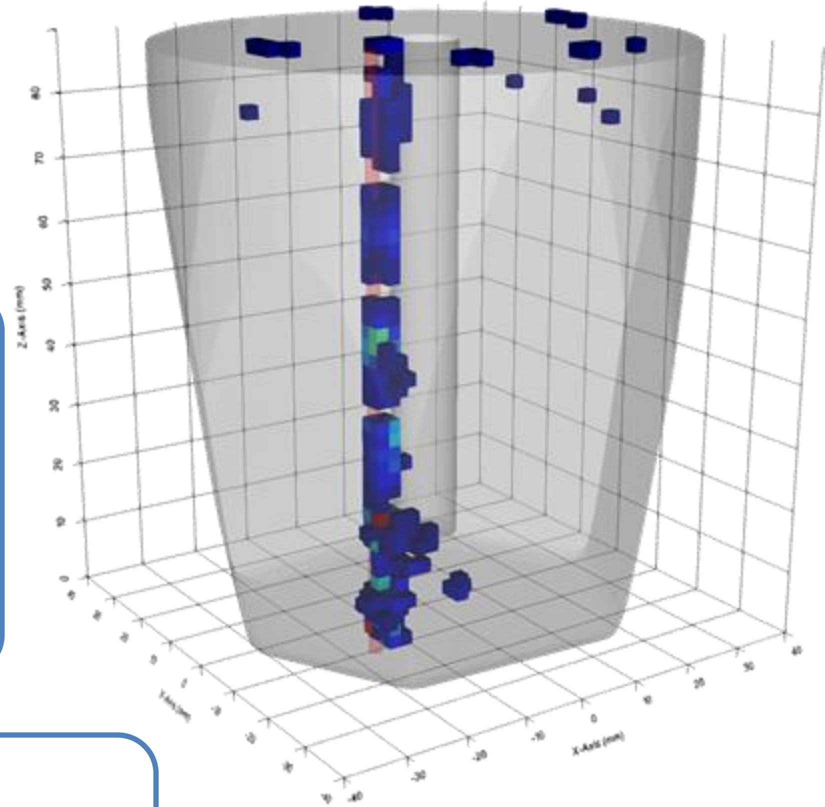
L. Lewandowski, et al; EPJA (2019)

Novel Algorithm Development for PSA

Signal matching (grid search)

Grid Search

- Require positions at resolution ≤ 5mm
- Dataset is ~ 50,000 points (37x121)
- PSA-grid search needs to be very fast kHz



Future perspectives

- **Graph-accelerated** techniques to organize data and form efficient searches
- **Machine Learning** for Advanced Signal Inference
- Processing rates in region (12-400) kHz

Courtesy of **Fraser Holloway**, University of Liverpool

Result of AGATA tracking

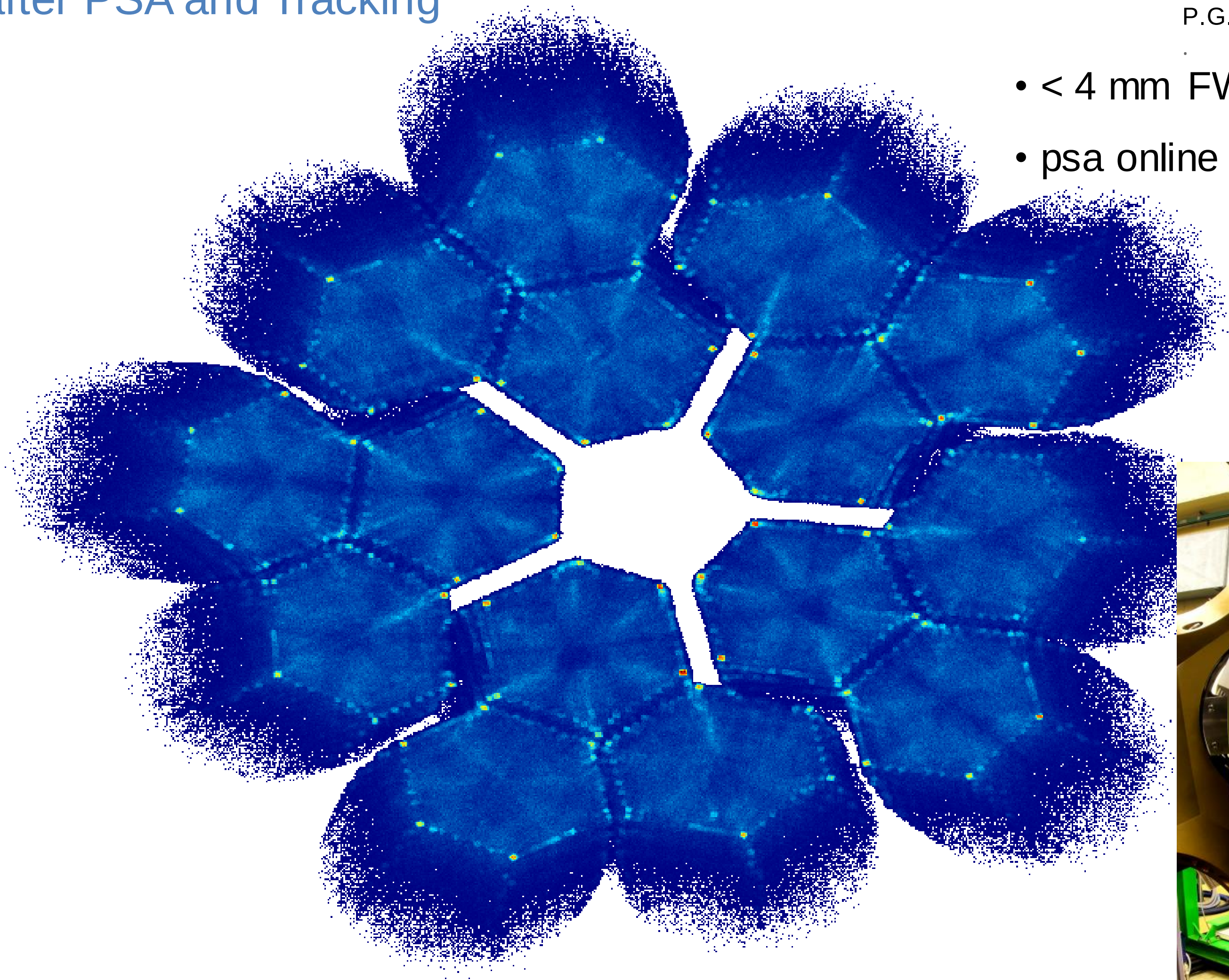
Reconstructed initial gamma rays with: - gamma ray energy

- 1st interaction position → Doppler correction
- 2nd interaction position → Polarization

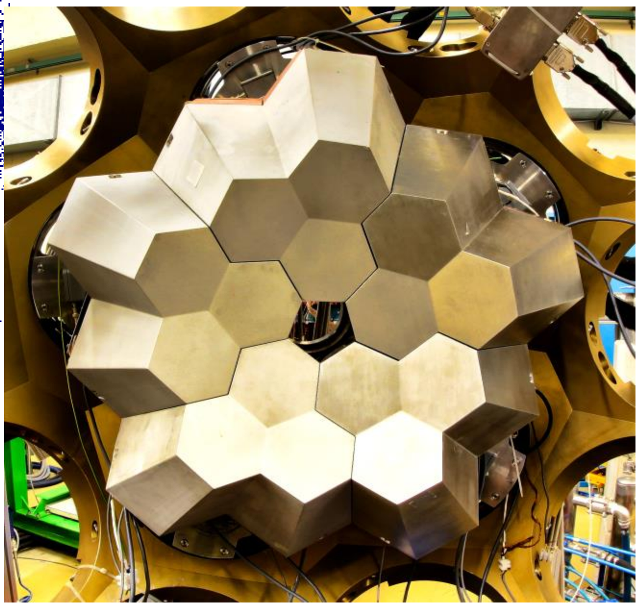
B. Alikhani, NIM A, 675(0):144 (2012)

P.G. Bizzeti et al., Eur. Phys. J. A (2015) **51**: 49

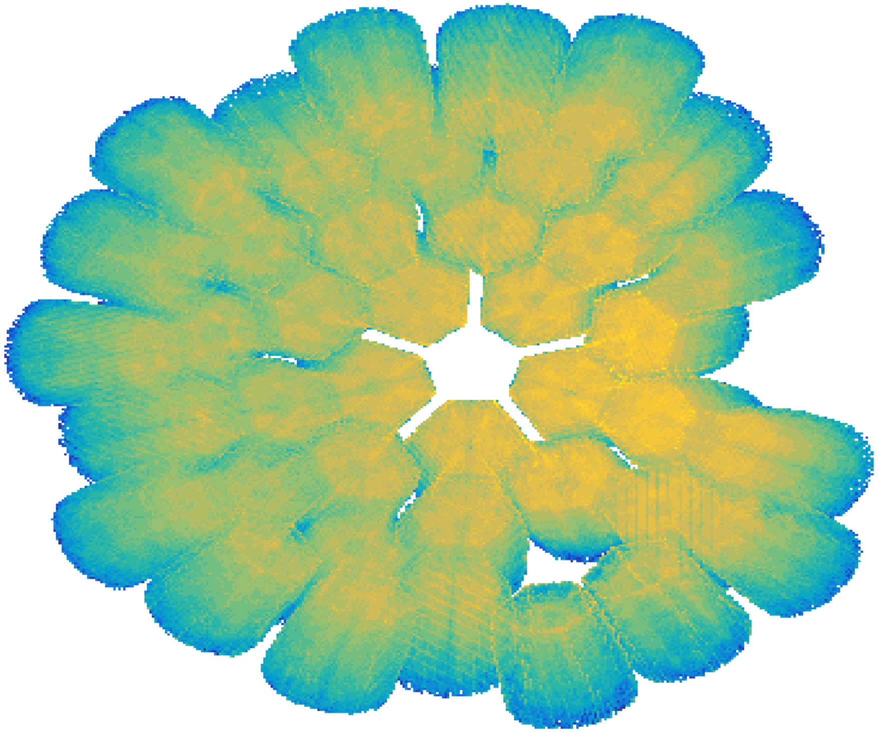
1st interaction positions after PSA and Tracking

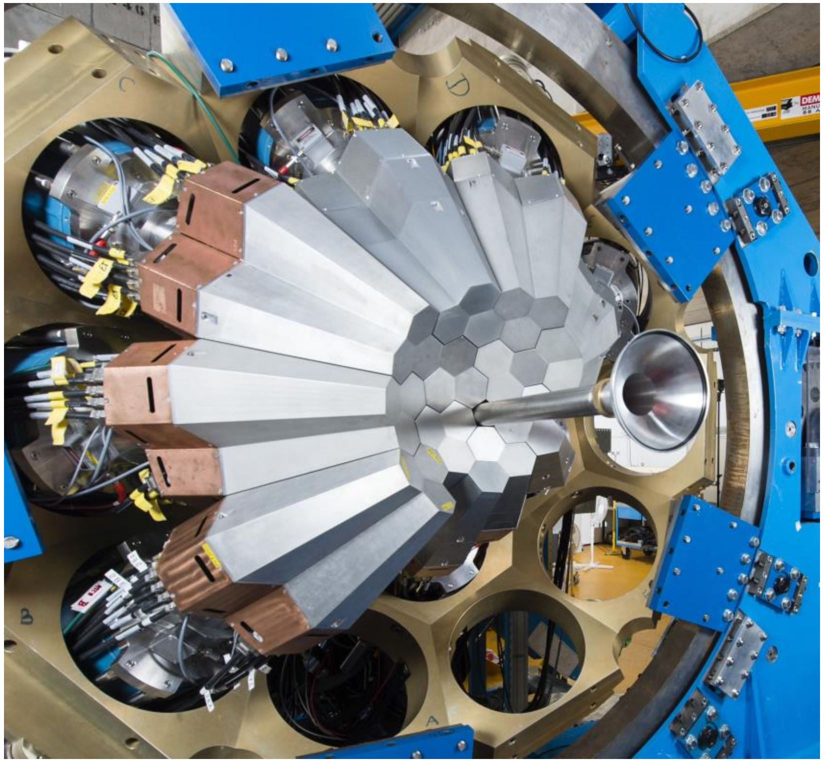


- < 4 mm FWHM resolution obtained
- psa online at rates > 5kHz per crystal



AGATA tracking at GANIL

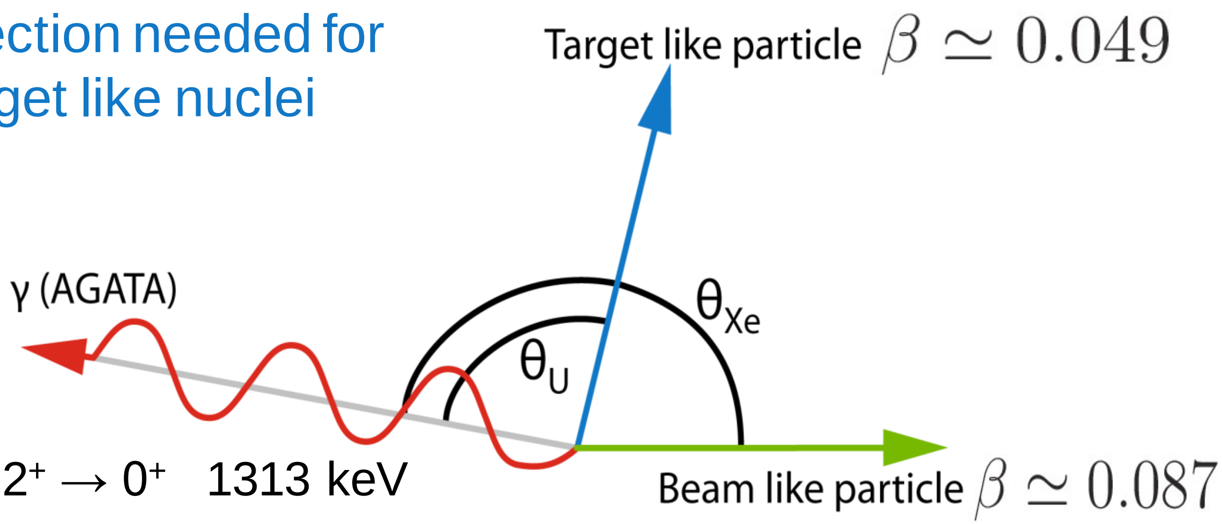




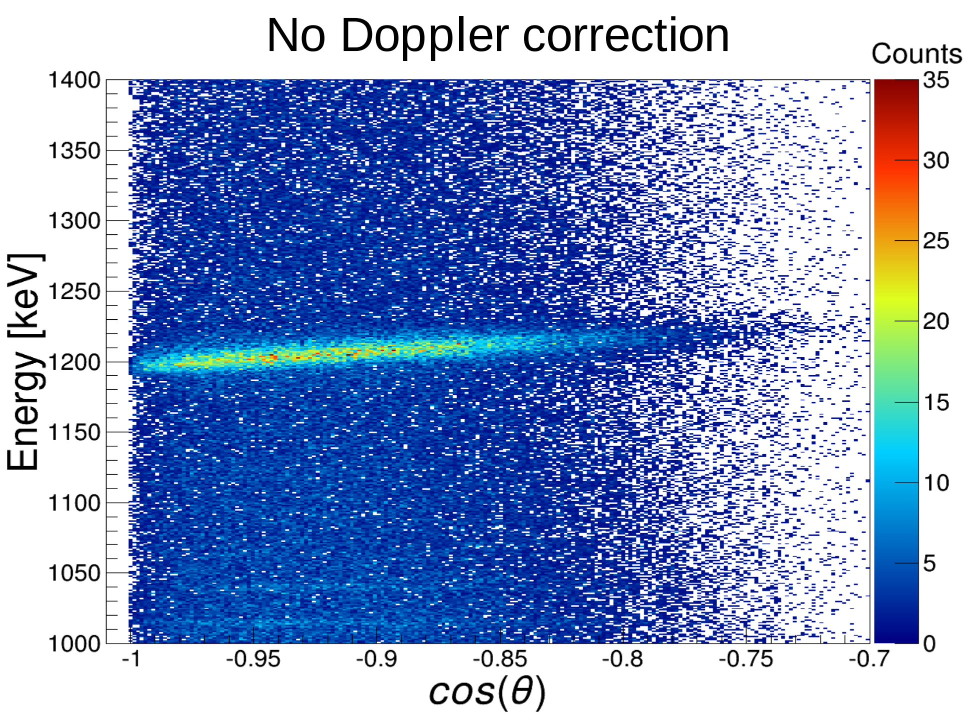
41 detectors on-line in 2019

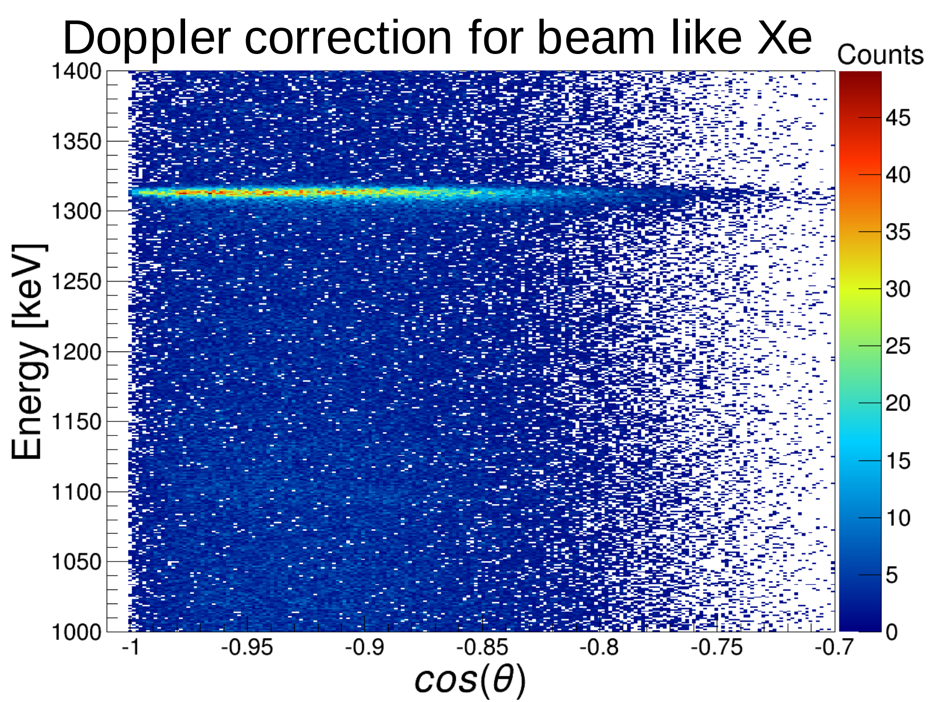
Position resolution & Doppler effects

Doppler correction needed for beam and target like nuclei



Example: ^{136}Xe: $2^+ \rightarrow 0^+$ 1313 keV



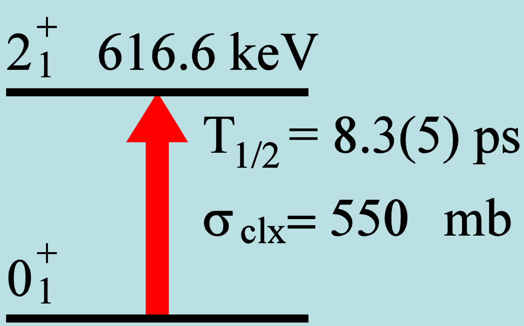


Coulomb Excitation of ^{80}Kr

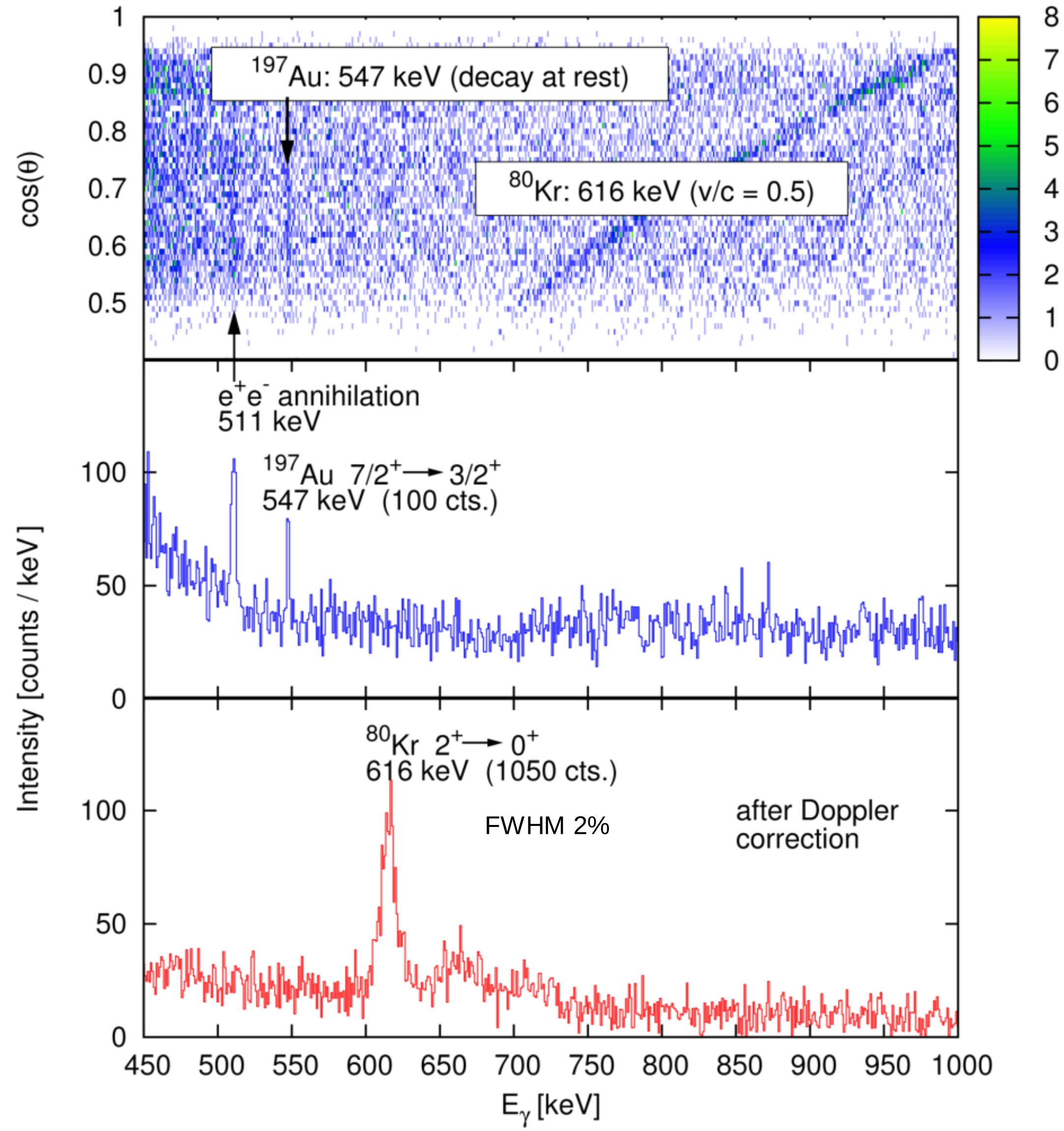
Reminder: Doppler effect

$$E_{\text{laboratory}} = E_{\text{rest}} \frac{\sqrt{1-\beta^2}}{1-\beta\cos(\vartheta_{\text{lab}})}$$

^{80}Kr

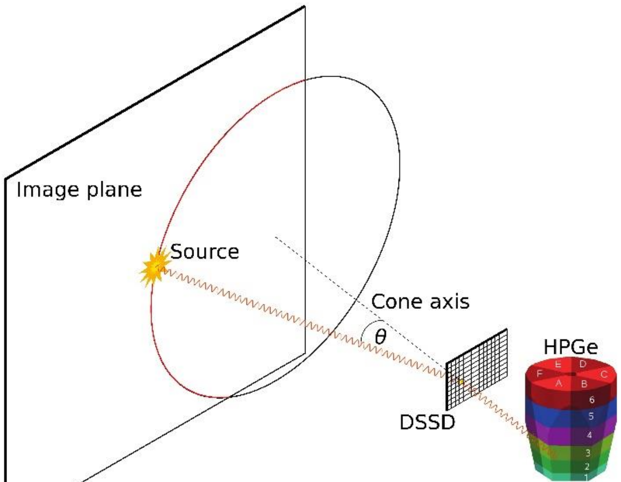


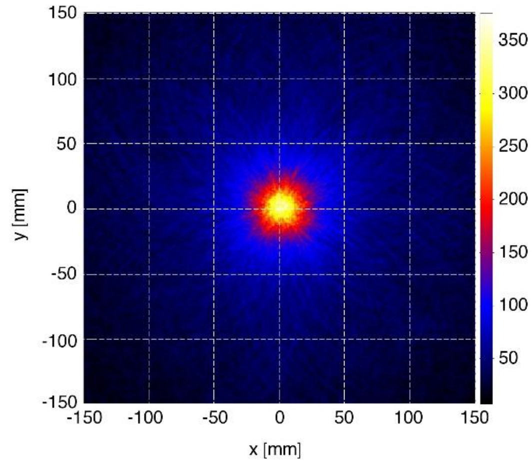
- large Coulex cross section
- no decay inside the target

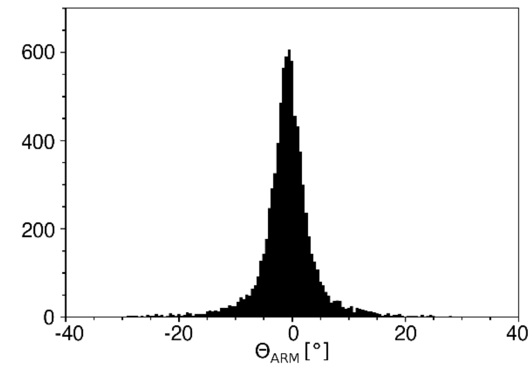


Michael Reese, IKP, TU Darmstadt

γ-ray imaging with AGATA

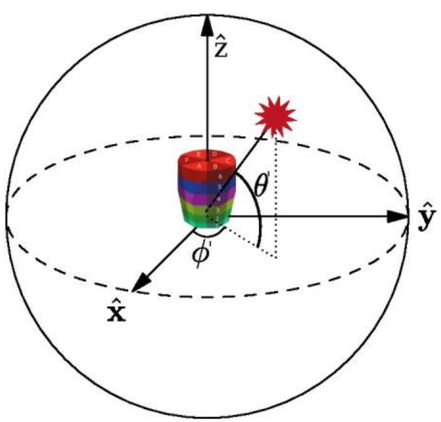


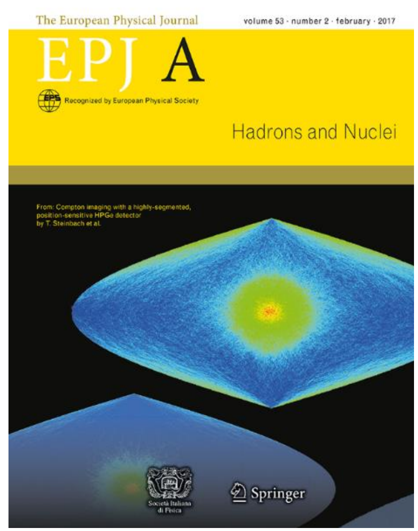


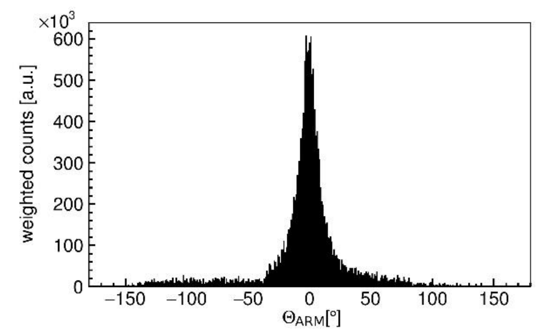


DSSD and HPGe Detector in Coincidence Mode

Eγ=1275 keV
Δθ=4.6°





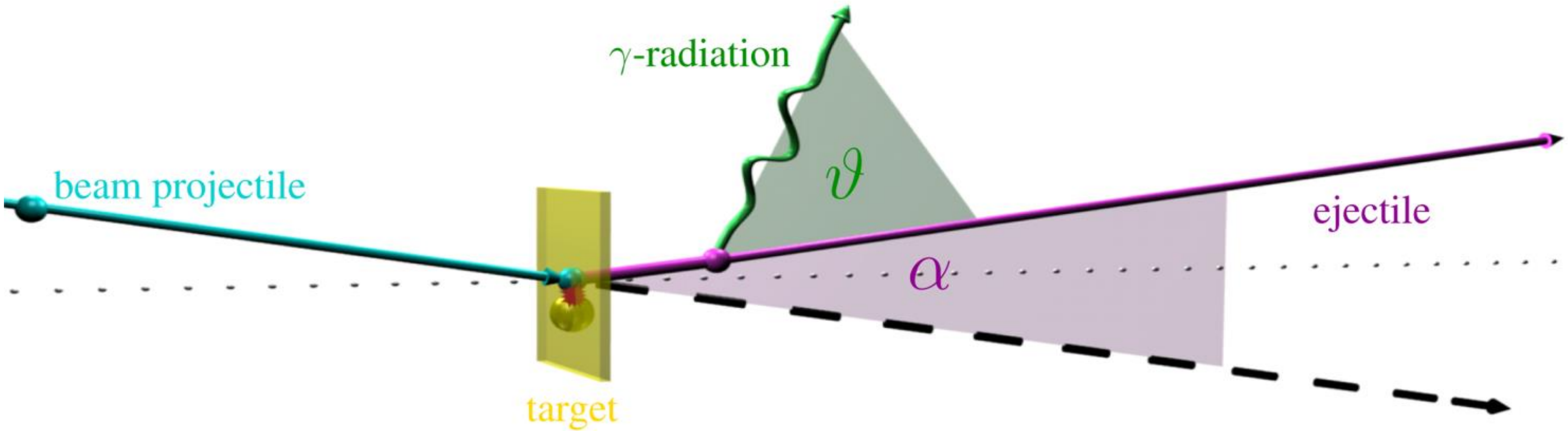


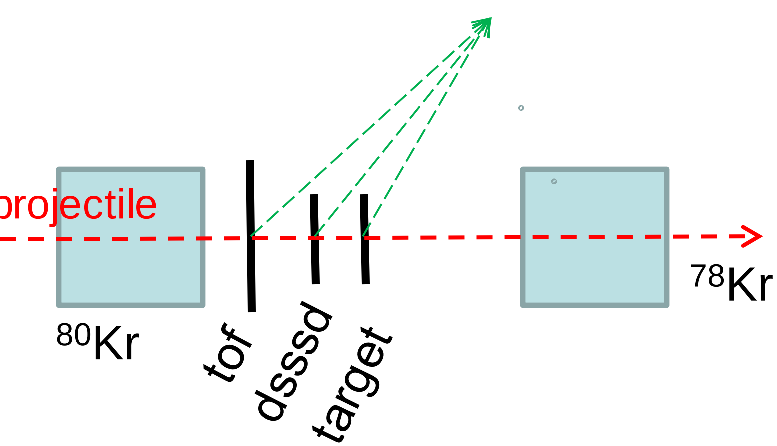
Eγ=1275 keV
Δθ=15°

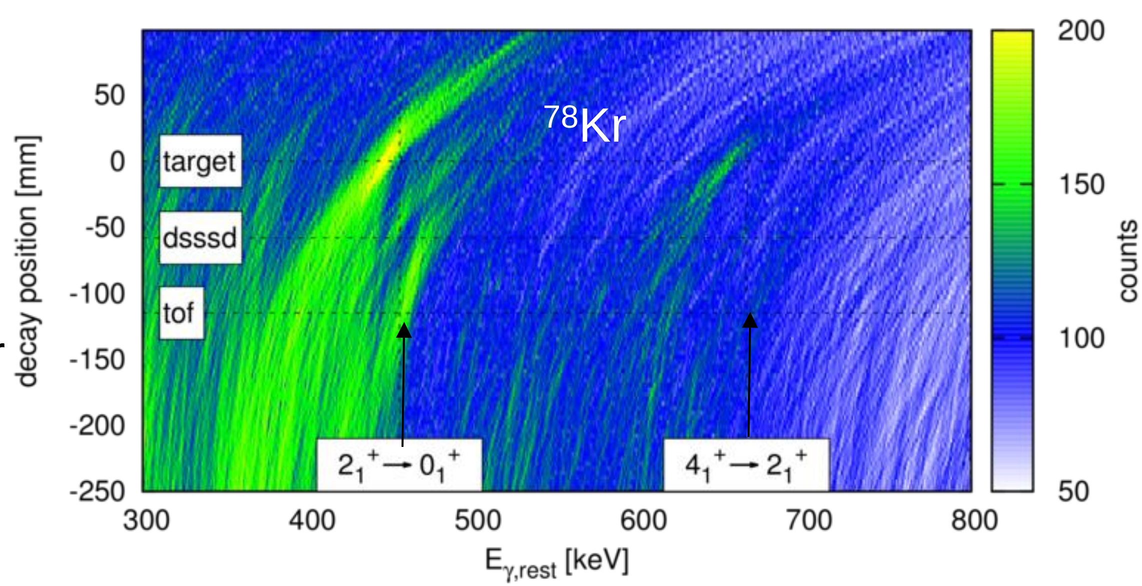
AGATA HPGe Detector in stand alone mode

T. Steinbach, R. Hirsch, IKP, University Cologne

Location of Gamma Emission

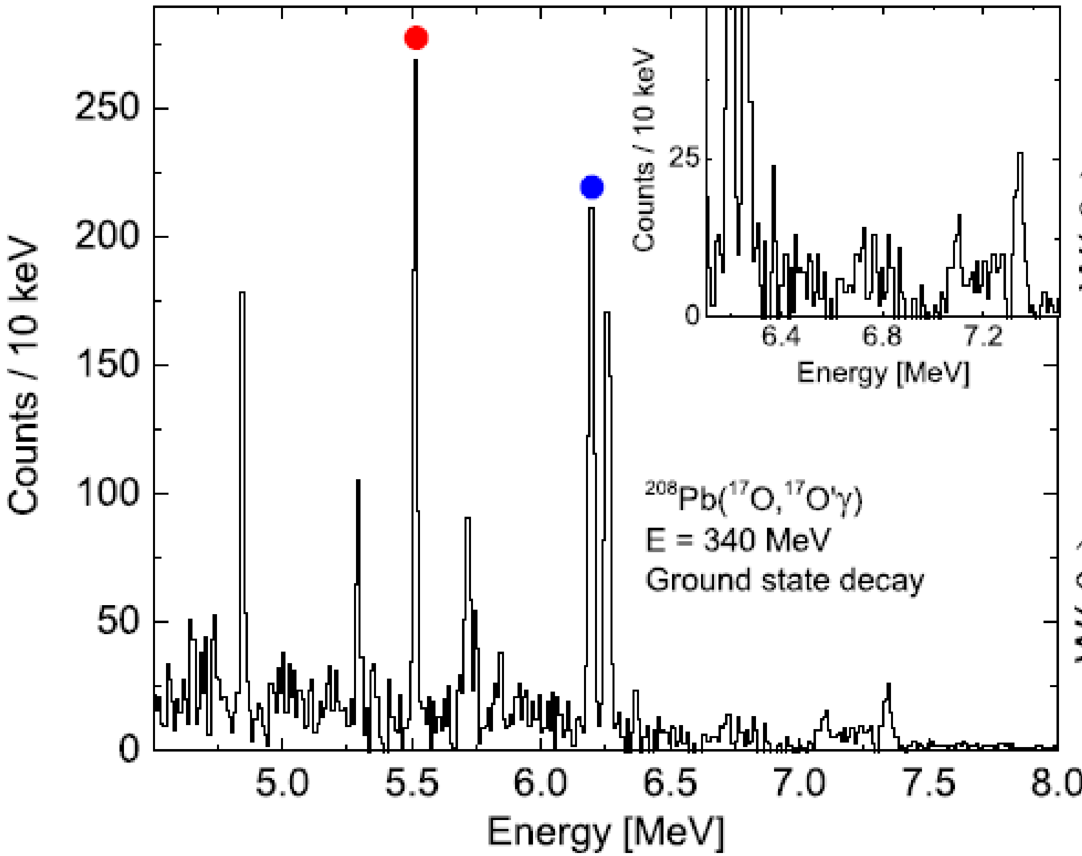


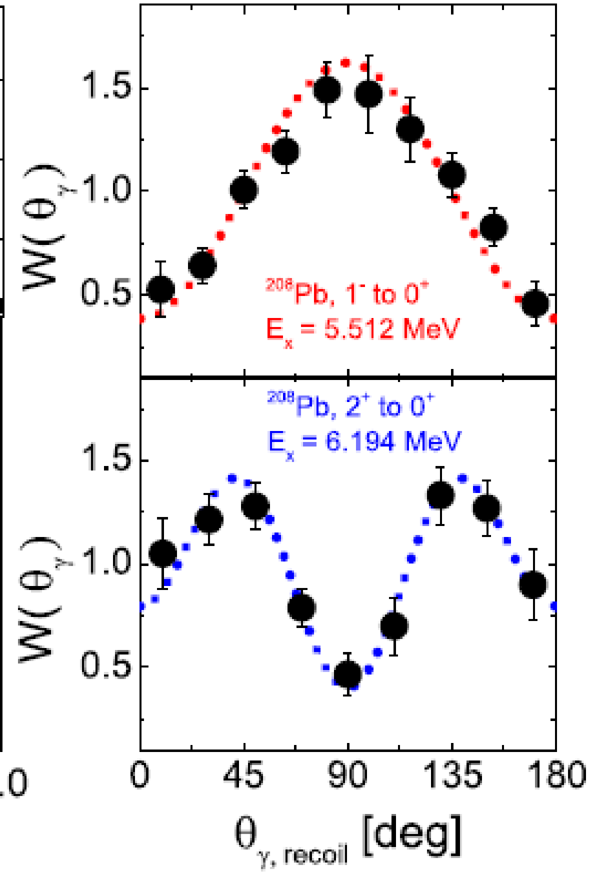




Michael Reese, IKP, TU Darmstadt

Line shape high γ-ray energy





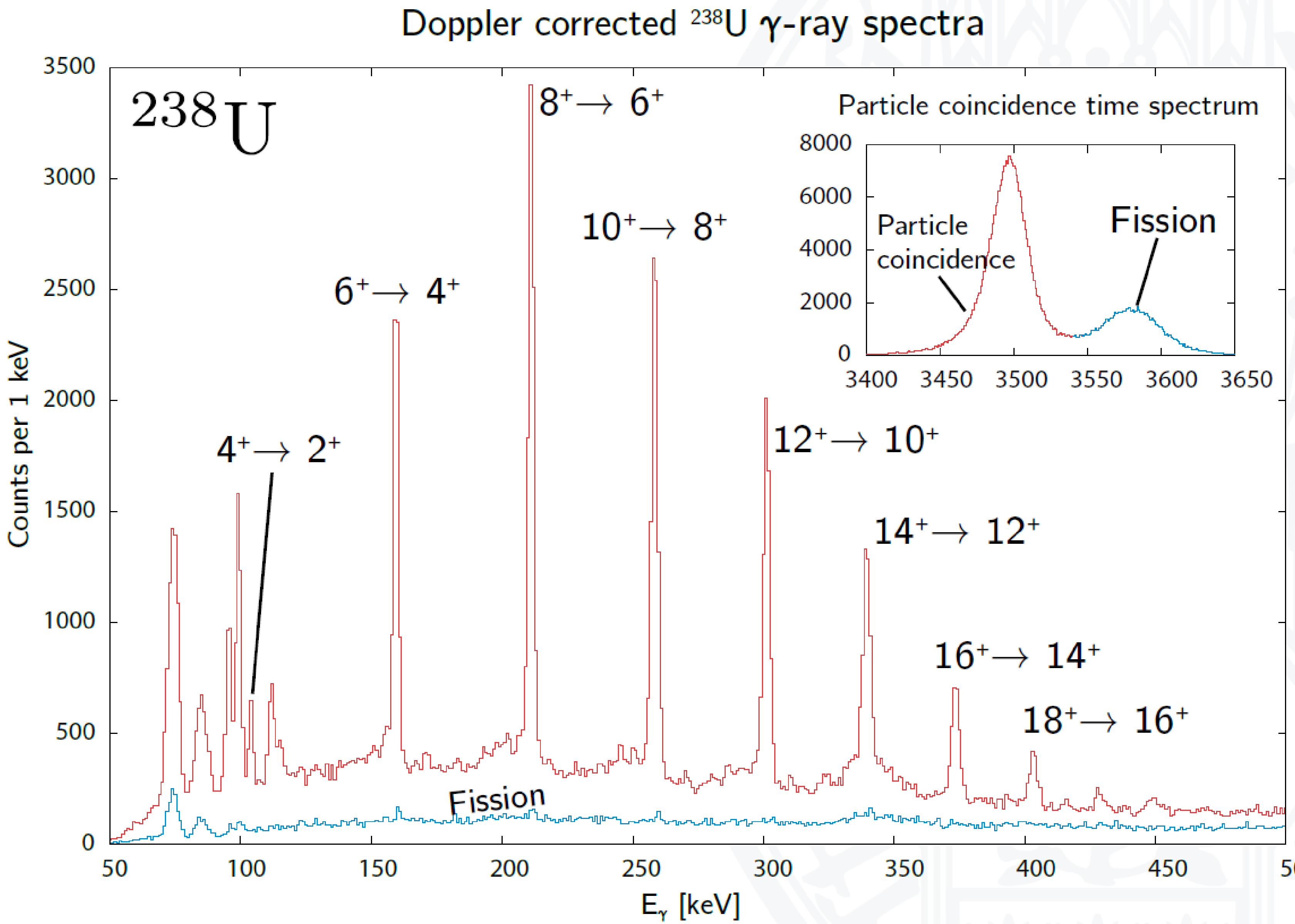
Escape lines are identified and discriminated by γ-ray tracking

First interaction points yield angular distributions:

- E1 transition from the 1^- state at 5.512 MeV
- E2 transition from the 2^+ state at 6.194 MeV

F. Crespi, A. Bracco et al., Phys. Rev. Lett. **113**,012501 (2014)

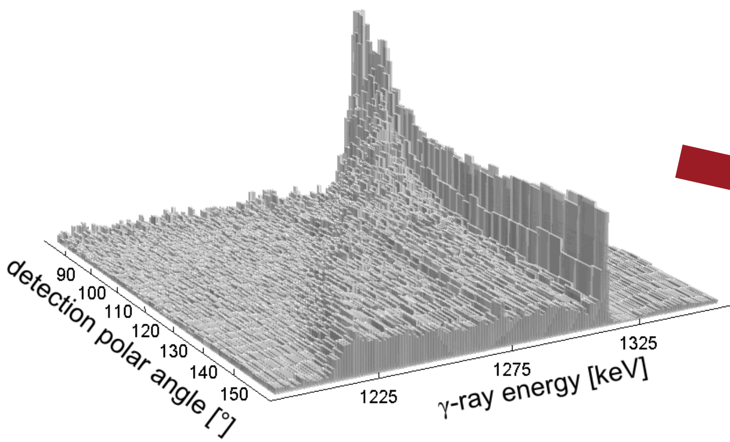
Line shape higher multiplicity events



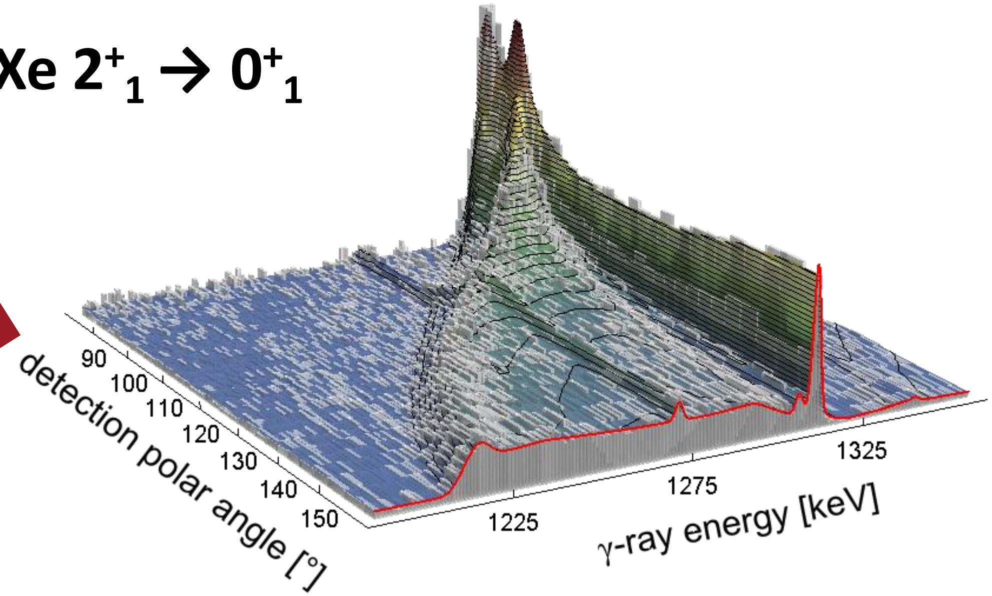
B. Birkenbach, A. Vogt, et al.; Phys. Rev. C (2015). 92(4) 044319

Line shapes and lifetime measurements

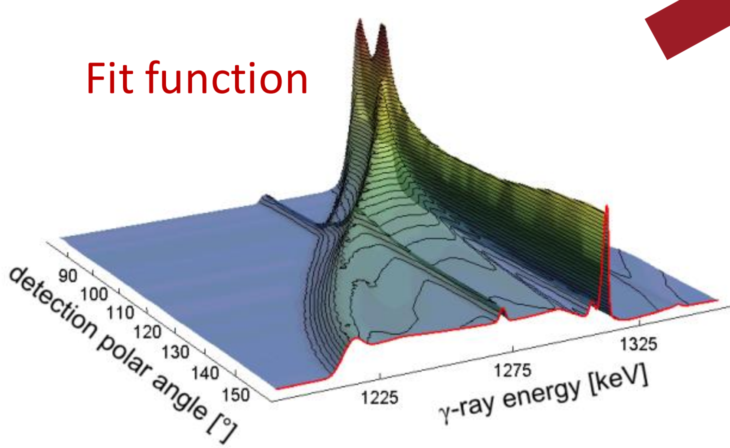
LNL-data, 546 MeV run



$^{136}Xe\ 2^+_1 \rightarrow 0^+_1$



Fit function



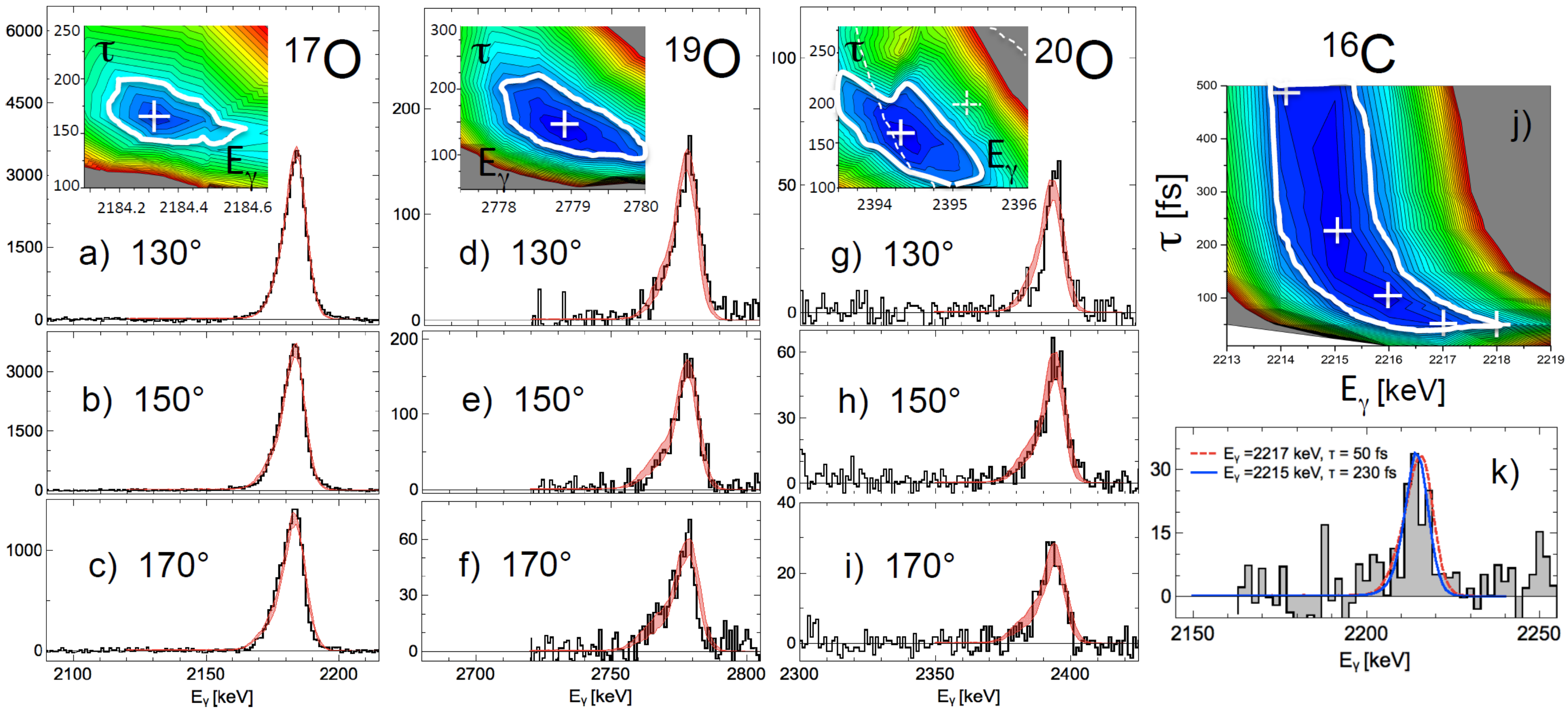
- 2d fit to Doppler-broadened line shape
- Function of γ-ray energy and detection angle
- Best suited for relativistic emitter
- Coulomb excitation and lifetime measurement of excited state simultaneously!

Ch. Stahl et al, PRC 92 (2015) 044324
Ch. Stahl et al, CPC 214 (2017) 174

Line shapes and lifetime measurements

AGATA+PARIS+VAMOS

low-energy transfer and deep-inelastic reactions 18O + 181Ta @ 126 MeV (7.0 MeV/u)



lifetime of the 2^+_2 state in ^{20}O (τ = 150 fs), estimate for the 2^+_2 state in ^{16}C

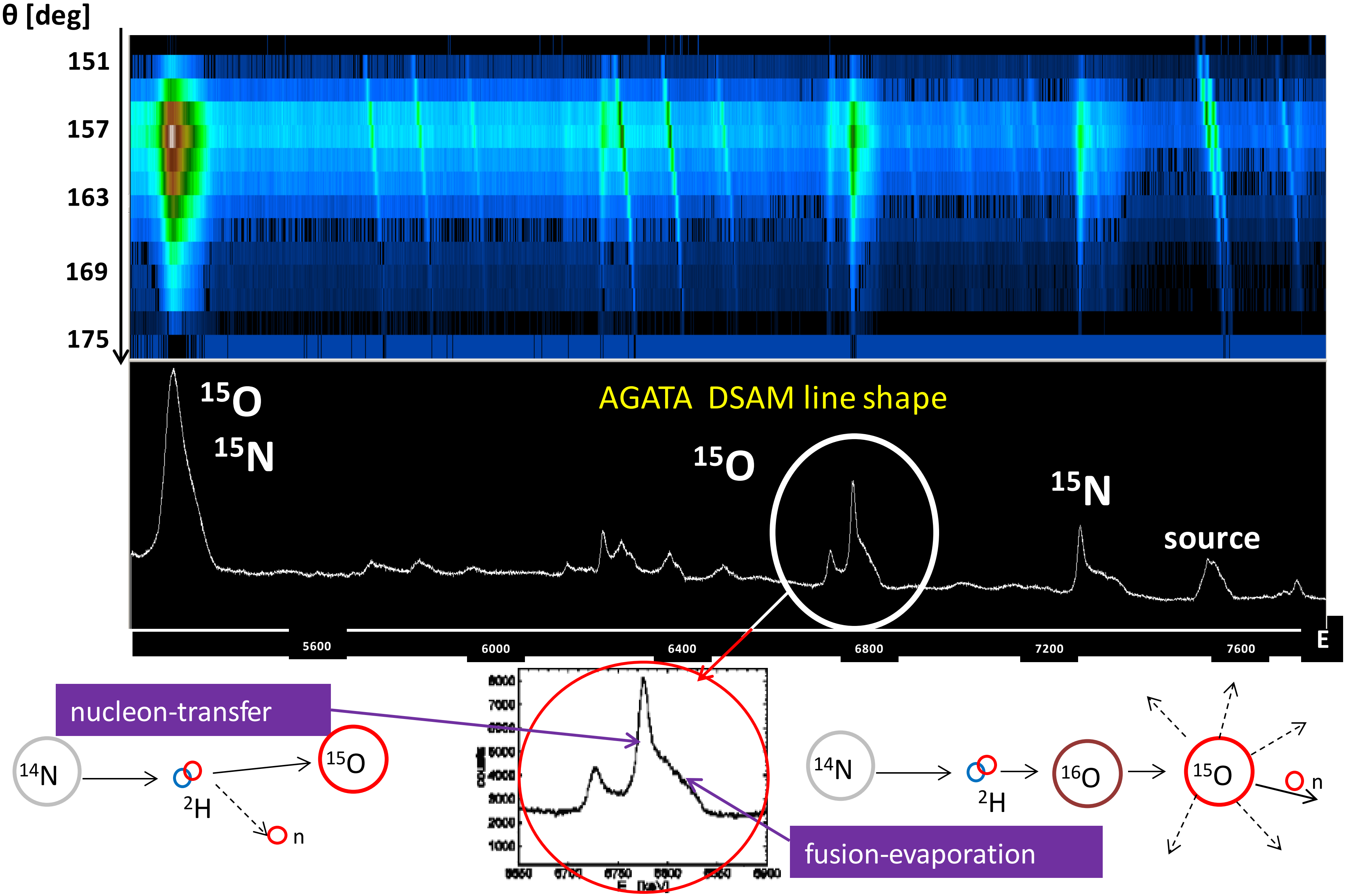
life-times in the tens to hundreds femtoseconds range

‘Crucial was the high precision provided by the AGATA γ-tracking array.’

M. Ciemała, S. Ziliani, F. C. L. Crespi, S. Leoni, et al; Phys. Rev. C 101, 021303(R) (2020)

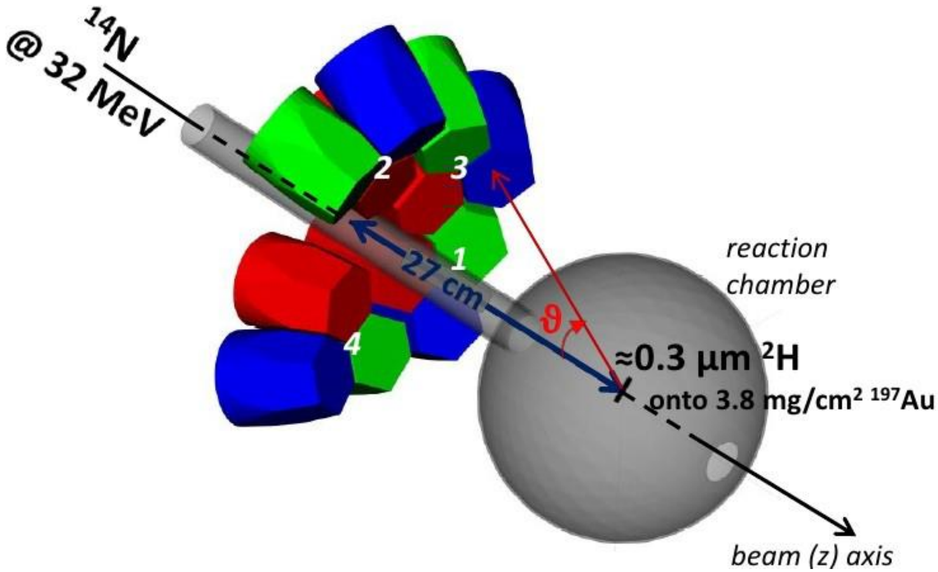
Lifetime of the 6.792MeV state in ^{15}O

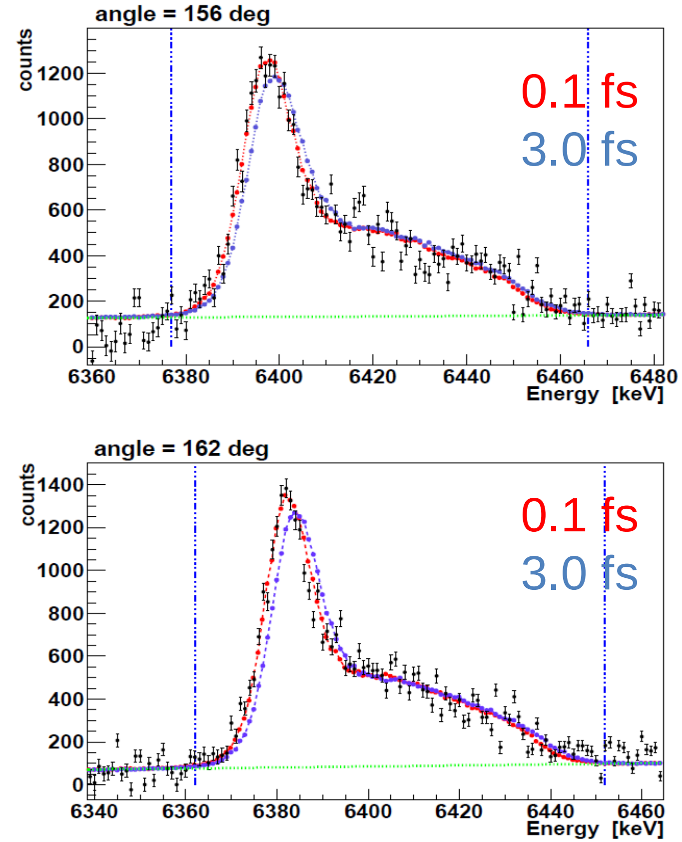
$^{14}N(^{2}H,n)^{15}O$ and $^{14}N(^{2}H,p)^{15}N$ reactions, inverse kinematics



Lifetime of the 6.79 MeV state in ^{15}O

$^{14}N(^{2}H,n)^{15}O$ and $^{14}N(^{2}H,p)^{15}N$ reactions
inverse kinematics
Continuous DSAM lifetime measurement





New upper limit of < 0.5 fs on the lifetime of the 6.79 MeV state in ^{15}O

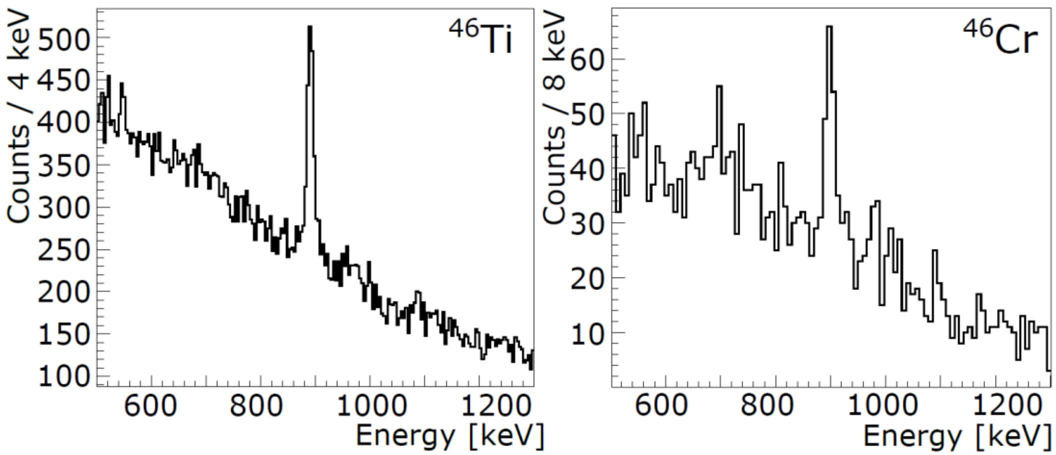
Lower limit of the width of the state $\Gamma > 1.07$ eV

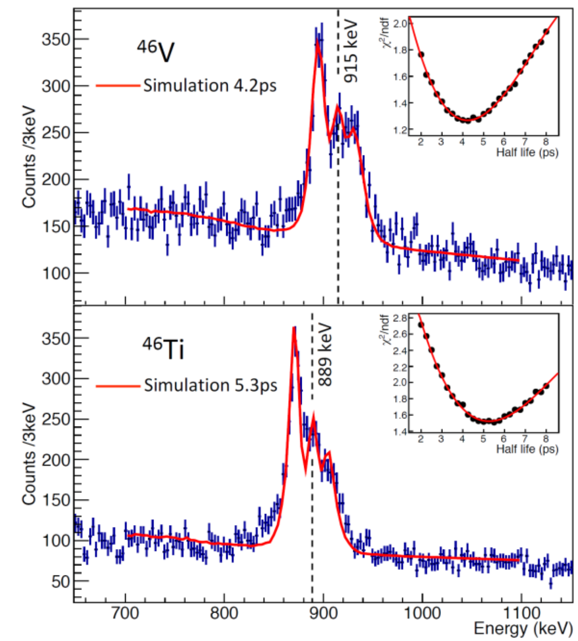
New results from AGATA @ GANIL

- Extrem inverse binary reaction
- Measurement of velocity of reaction products β_{reac} with VAMOS and velocity at time of γ-ray emission from Doppler shift β_{ems} with AGATA
- Difference spectrum $\Delta\beta = \beta_{reac} - \beta_{ems}$ provides lifetime sensitivity in low fs range

C. Michelagnoli, et al.,

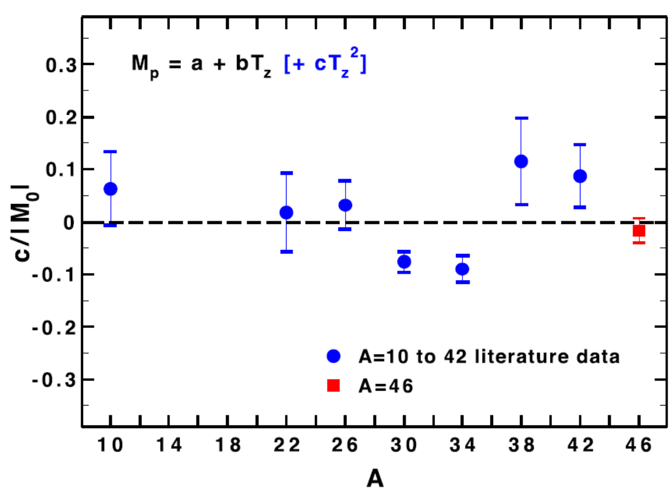
Coulex vs Lifetime measurements

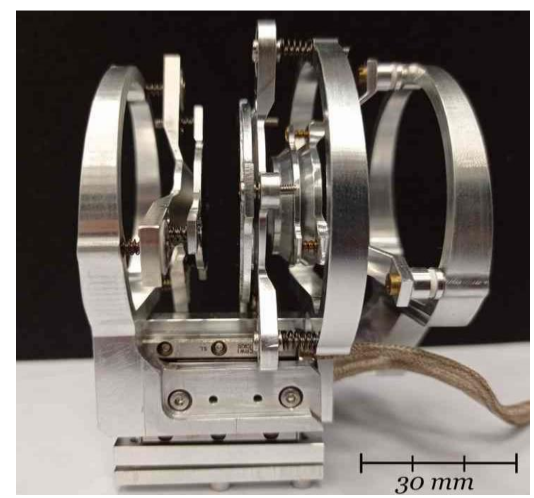




- Electric quadrupole matrix elements,
 Mp for $J^{\pi} = 2^{+} \rightarrow 0^{+}$, $T = 0$, $T = 1$ transitions
- pure isospin: analogue proton matrix elements *Mp=a+bTz*
- *A* = 46 isobaric multiplet ^{46}Cr-^{46}V-^{46}Ti

FRS-LYCCA-AGATA @ GSI
Triple plunger device
(IKP Cologne)



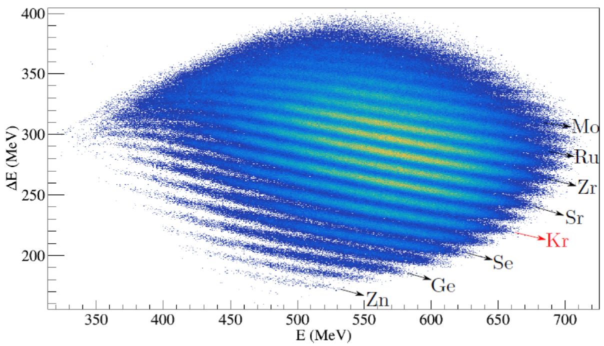


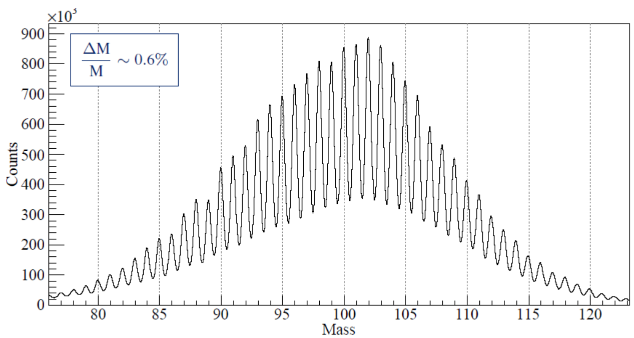
A. Boso, et al; PLB 2019

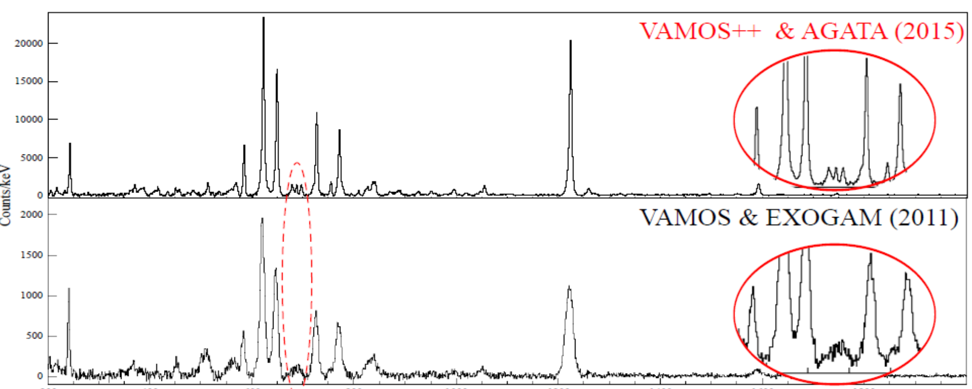
M. Beckers, A. Dewald, C. Fransen,… NIM A (2022)

The GANIL Campaign [2015-2021]

Courtesy J. Dudouet







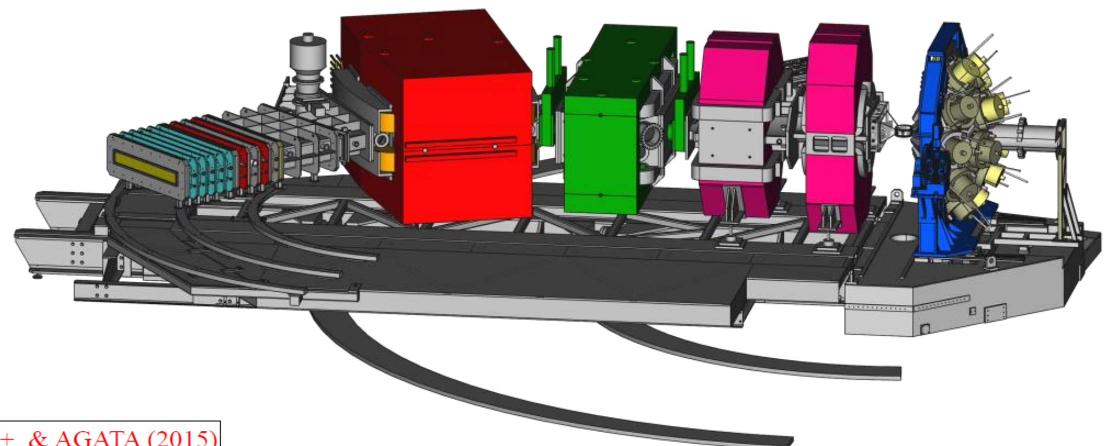
2017-2018 : 35 detectors on-line

Efficiencies @ 1.408 MeV

Core 3.4(1)% (GEANT4 = 3.6%)

AddBack 4.8(1)% (5.1%)

Coupled to VAMOS spectrometer



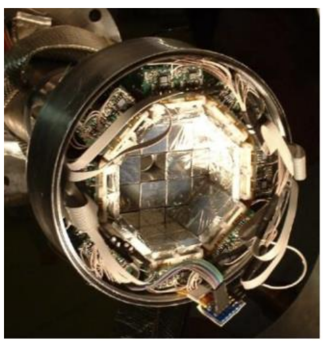
- ✓multi-nucleon transfer
- ✓fusion-fission
- ✓transfer-fission

E. Clément et al.; NIM A 855, 1-12 (2017)
J. Dudouet, et al.; Phys. Rev. Lett. 118, 162501 (2017)

AGATA & NEDA & AGATA: the 2n selectivity

Bo Cederwall, KTH Stockholm
Bob Wadsworth, University of York
et al.

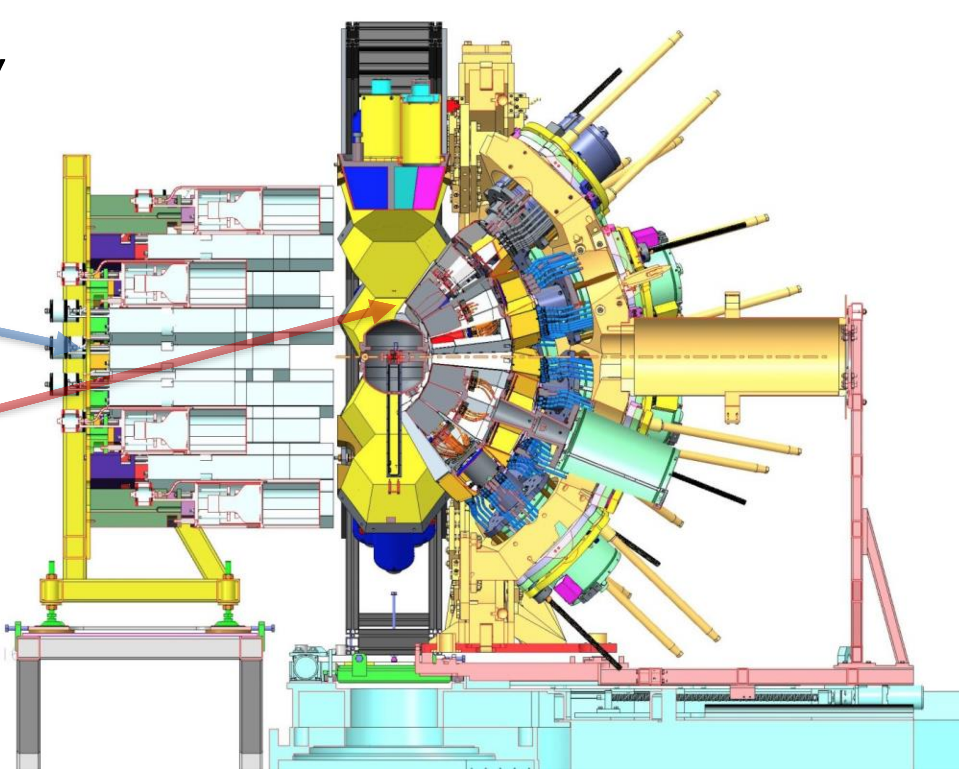
Fusion Reaction: ^{36}Ar + ^{54}Fe → **^{88}Ru + 2n + γ**
Cross section σ ~ few μb



NEDA (neutron detectors)
Select two-neutron events

DIAMANT (CsI)
Reject charged-particle events

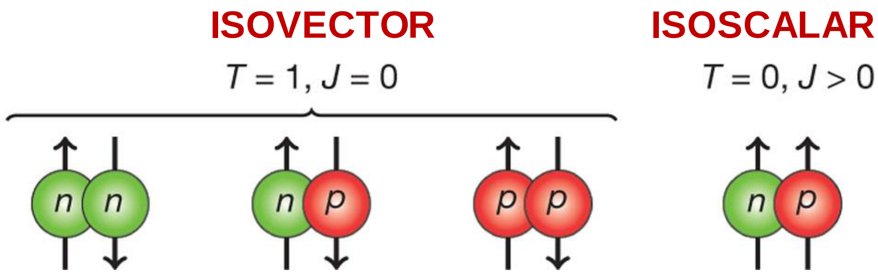
AGATA
Record multiple gamma rays



Power of AGATA:
- High Efficiency
- Multiple simultaneous γ rays

B. Cederwall et al., Phys. Rev. Lett. 124, 062501 (2020)

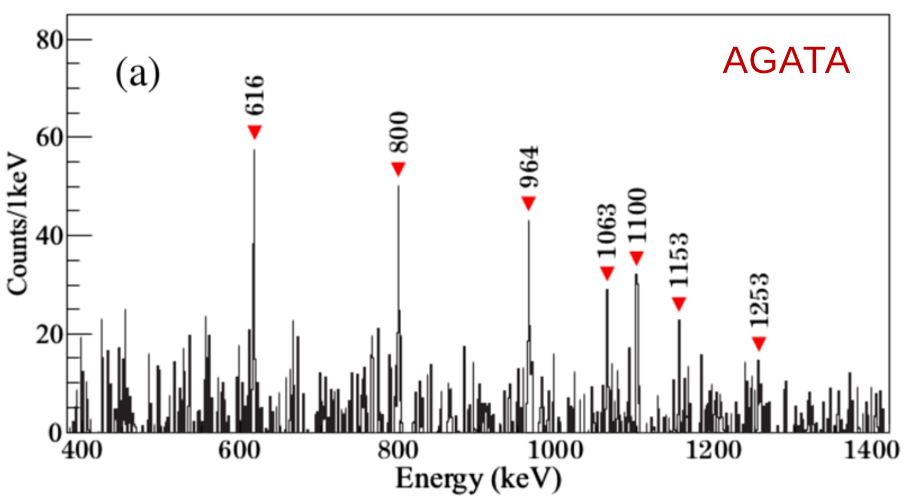
AGATA & NEDA & AGATA: the 2n selectivity

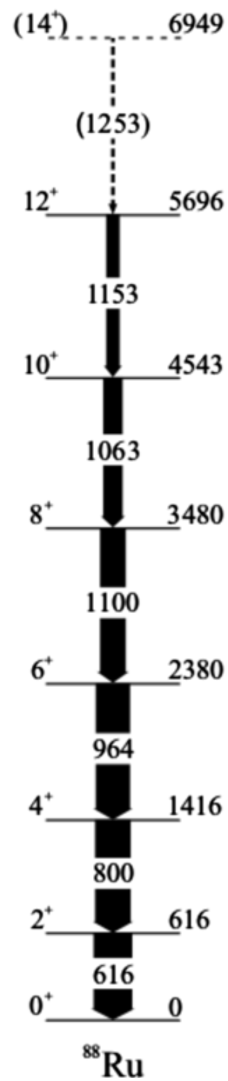


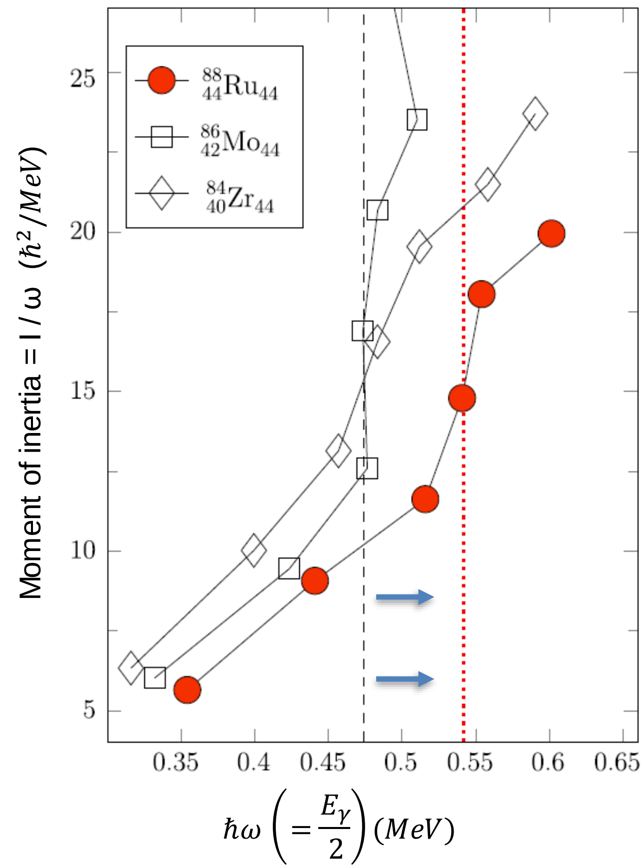
- Search for np T=0 pairing in N=Z nuclei, **evidence is elusive**
- **Is there a "fluid" of T=0 np pairs along with "normal" T=1 pairs?**
- T=0 pairing may respond differently to rotational motion
- Look for delayed rotational alignments **in heavy N=Z nuclei**

S. Frauendorf, A.O. Macchiavelli, Prog. Part. Nucl. Phys. 78, 24 (2014)

Summed two-neutron γ-γ spectrum



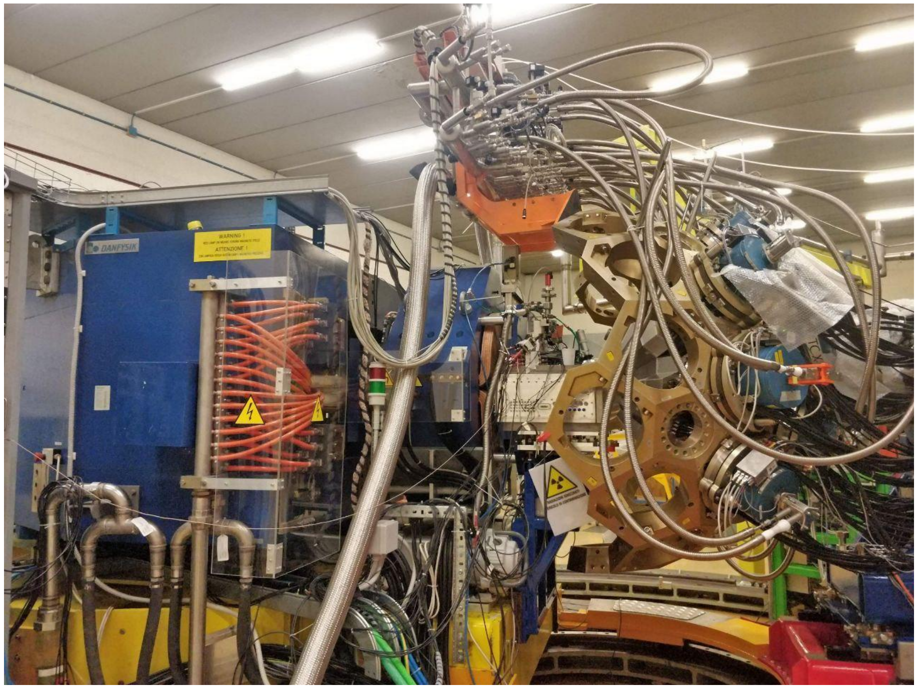


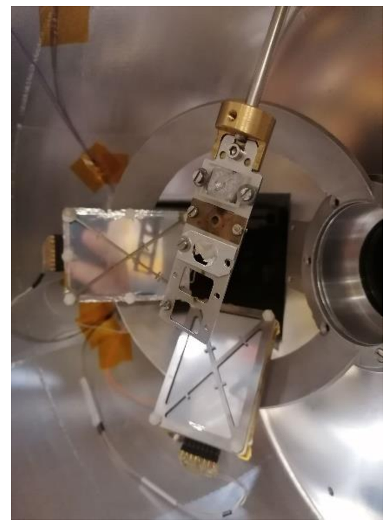


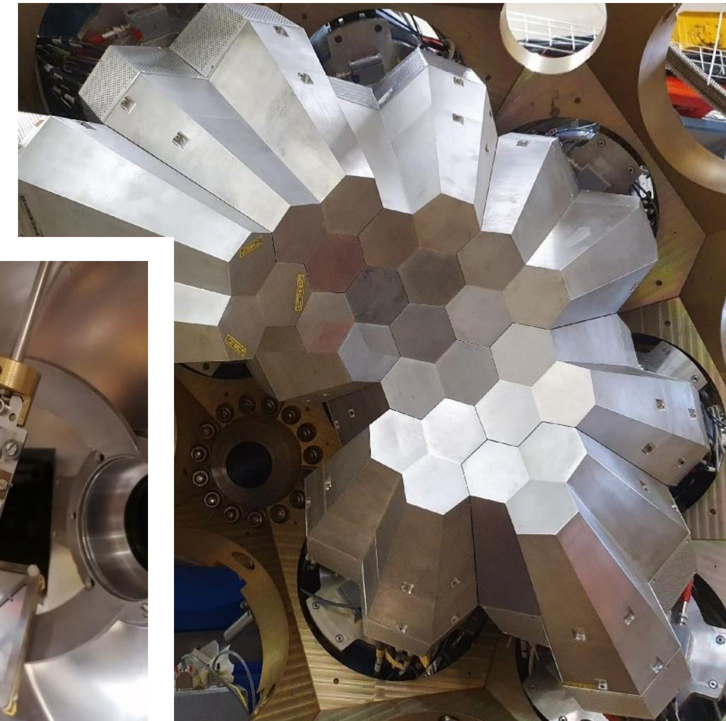
Delayed alignment $(\pi g_{9/2})^2$
…in **N=Z system**

B. Cederwall et al., Phys. Rev. Lett. 124, 062501 (2020)

The Legnaro Campaign Commissioning







Multi-nucleon transfer

^{58}Ni @ 250MeV + ^{197}Au

^{32}S @ 160MeV + ^{124}Sn

Commissioning 26/4-3/5/2022

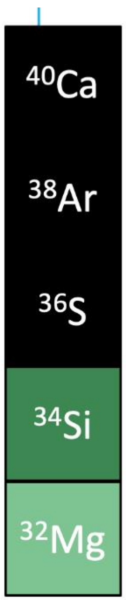
AGATA (9ATC) + PRISMA + DANTE

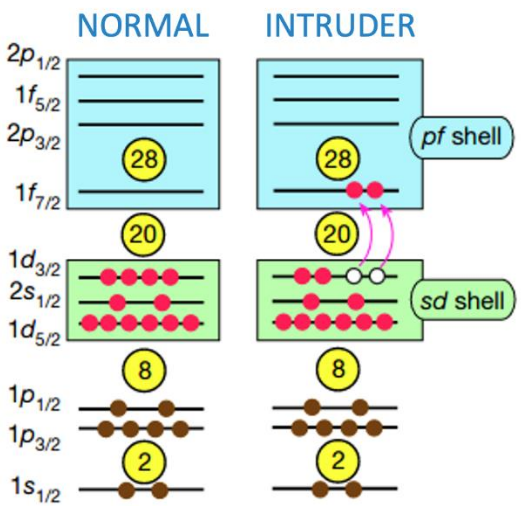
Spokespersons: F. Crespi, F. Galtarossa, J. Pellumaj, M. Rocchini, M. Sedlak

Courtesy J.J. Valiente-Dobon

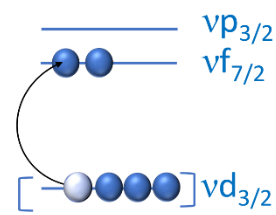
The Legnaro Campaign First experiment

Intruder configurations in ^{37}S (N=21)

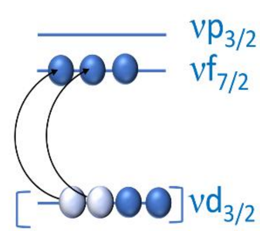




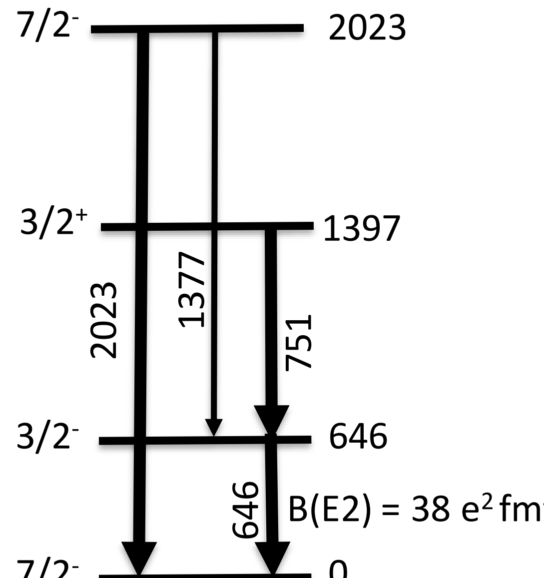
E. Caurier, F. Nowacki, and A. Poves, Phys. Rev. C **90** (2014) 014302



3/2⁺ (1h-2p)



7/2⁻ (2h-3p)



EXP

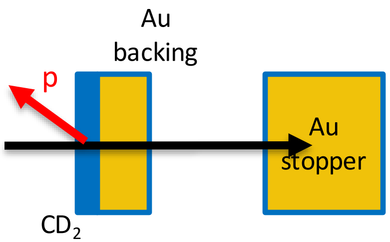
E. K. Warburton, Phys. Rev. C **35** (1987) 2278;
Phys. Rev. C **37** (1988) 754
R. Chapman et al., Phys. Rev. C **93** (2016) 044318

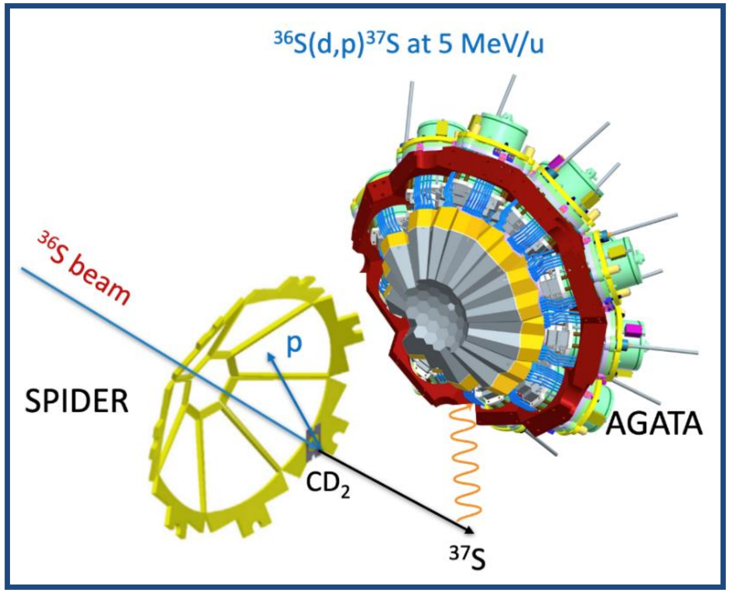
Spokepersons: F. Galtarossa and A. Gottardo

Courtesy J.J. Valiente-Dobon

The Legnaro Campaign First experiment

lifetime 3/2+ level
10-500 ps
-> PLUNGER

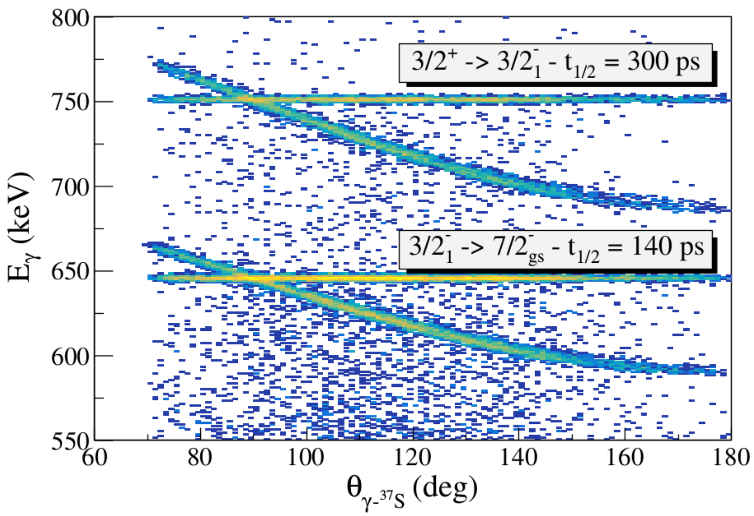




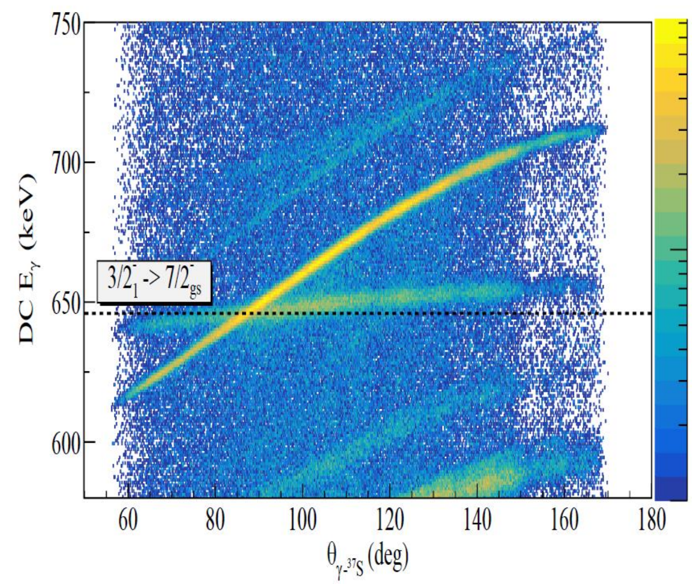
- ^{36}S beam @ **180 MeV**
- **0.1 pnA** (~ $5x10^8$ pps)
- CD_2 target of **0.5 mg/cm²**
- (~ $5x10^{19}$ atoms/cm² of ^2H)

Courtesy J.J. Valiente-Dobon

Plunger: 3/2+ -> 3/2-
3/2- -> 7/2-



Monte Carlo no DC



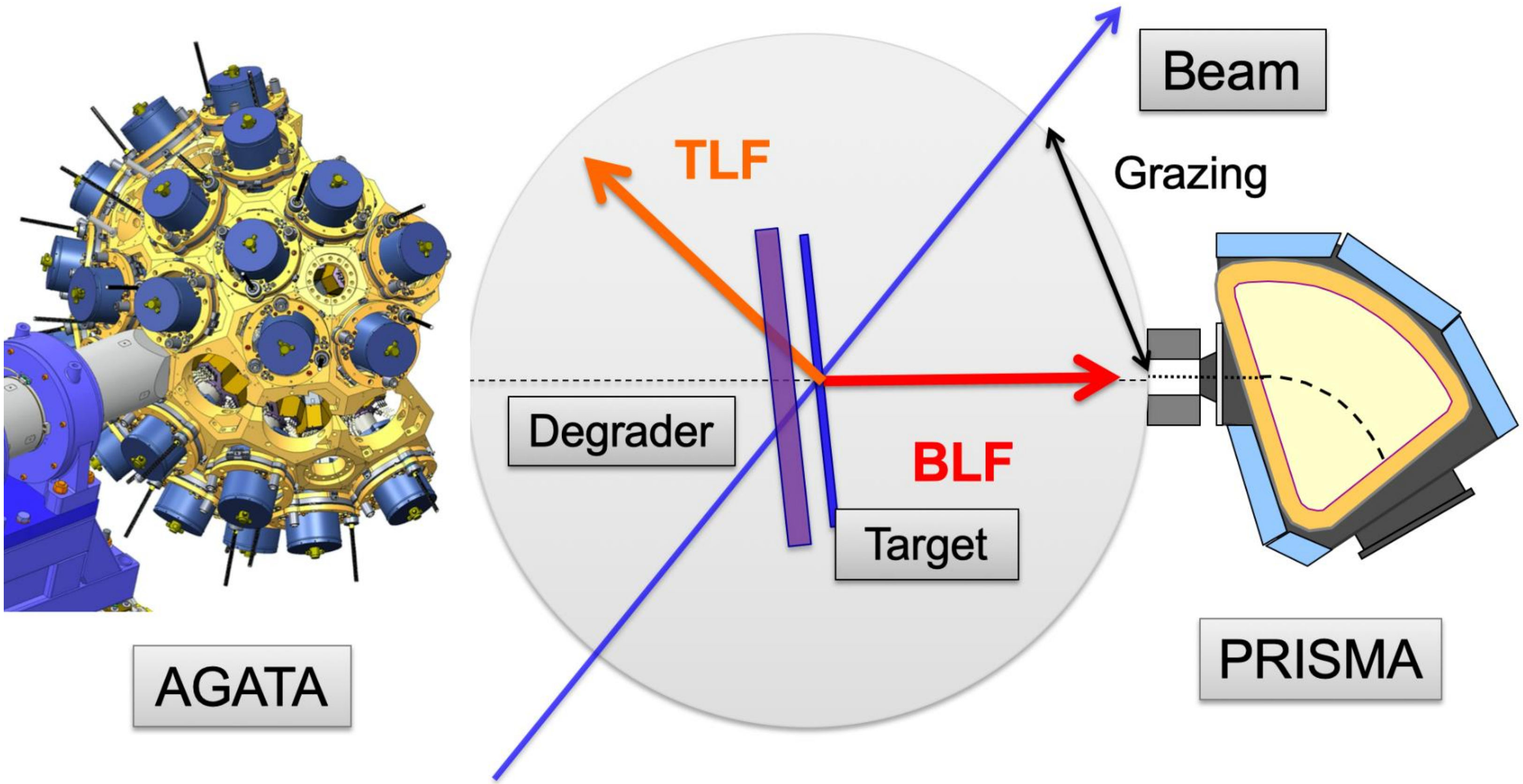
Experiment with DC

The Legnaro Campaign

Measurement of lifetimes with an inversed plunger

AGATA and PRISMA spectrometer

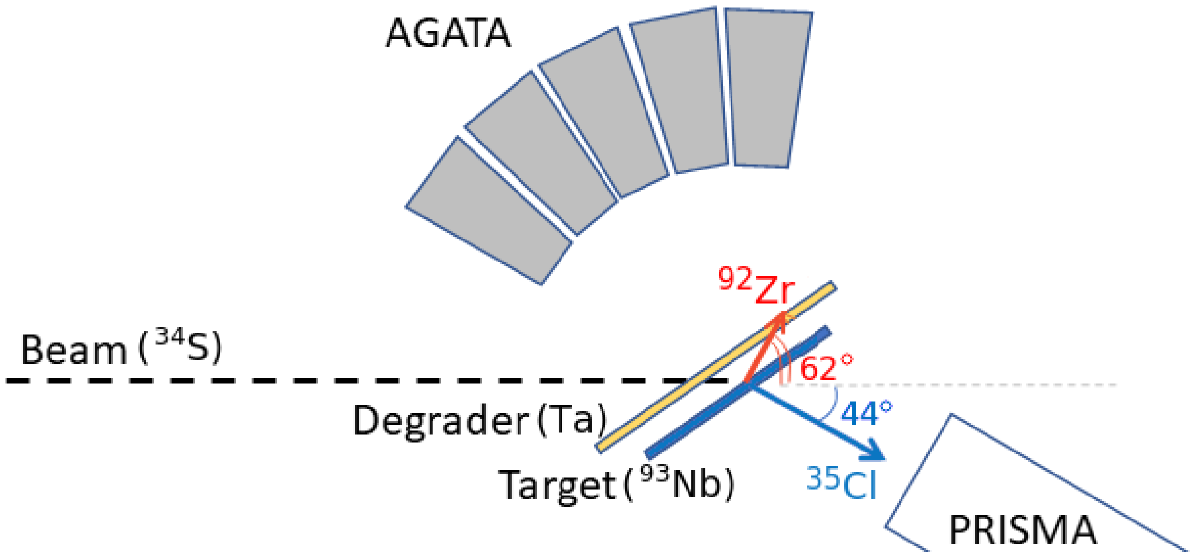
$$\tau^{-1} \sim B(E2: J_i \rightarrow J_f) = 1/(2J_i + 1)\langle \psi_f \,||\mathbf{E2}||\, \psi_i \rangle^2$$



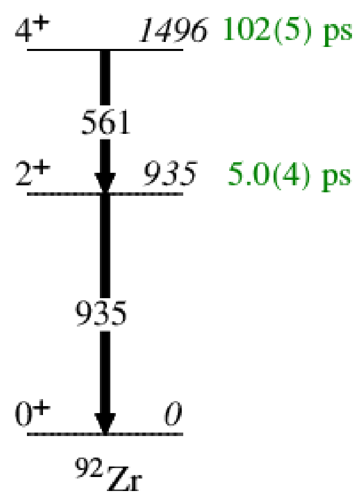
Courtesy J.J. Valiente-Dobon

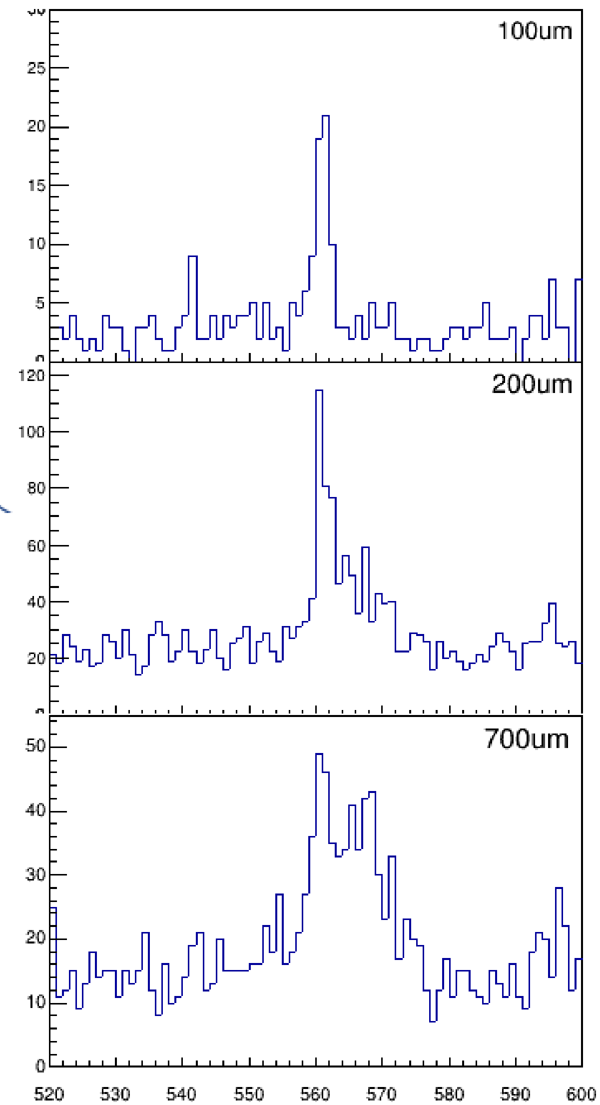
The Legnaro Campaign

First measurement with inversed plunger!



Beam: ^{34}S (180 MeV, 0.8 pnA)
Target: ^{93}Nb (1 mg/cm2)
Stopper: ^{181}Ta (3 mg/cm2)
Grazing angle: 44 degrees





Courtesy J.J. Valiente-Dobon

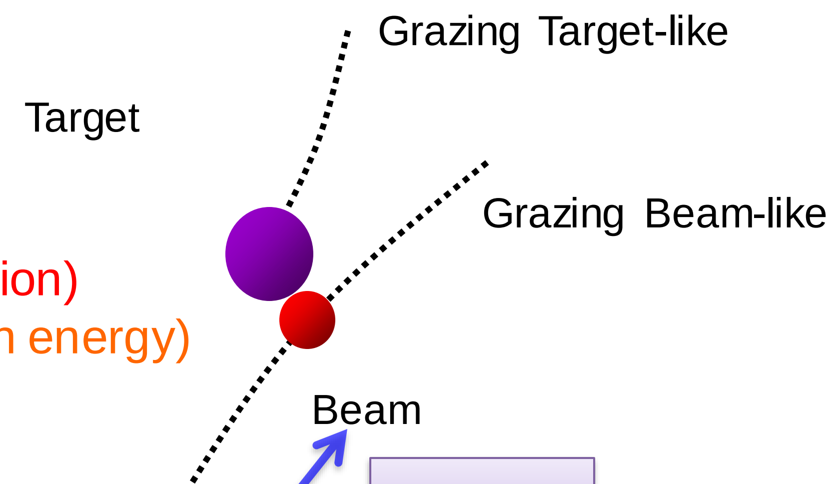
The Legnaro Campaign

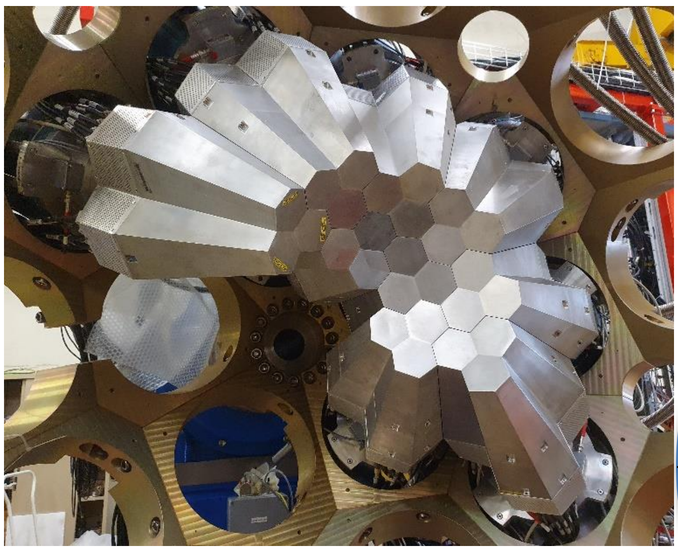
Binary partner method

Direct kinematics, binary reaction:

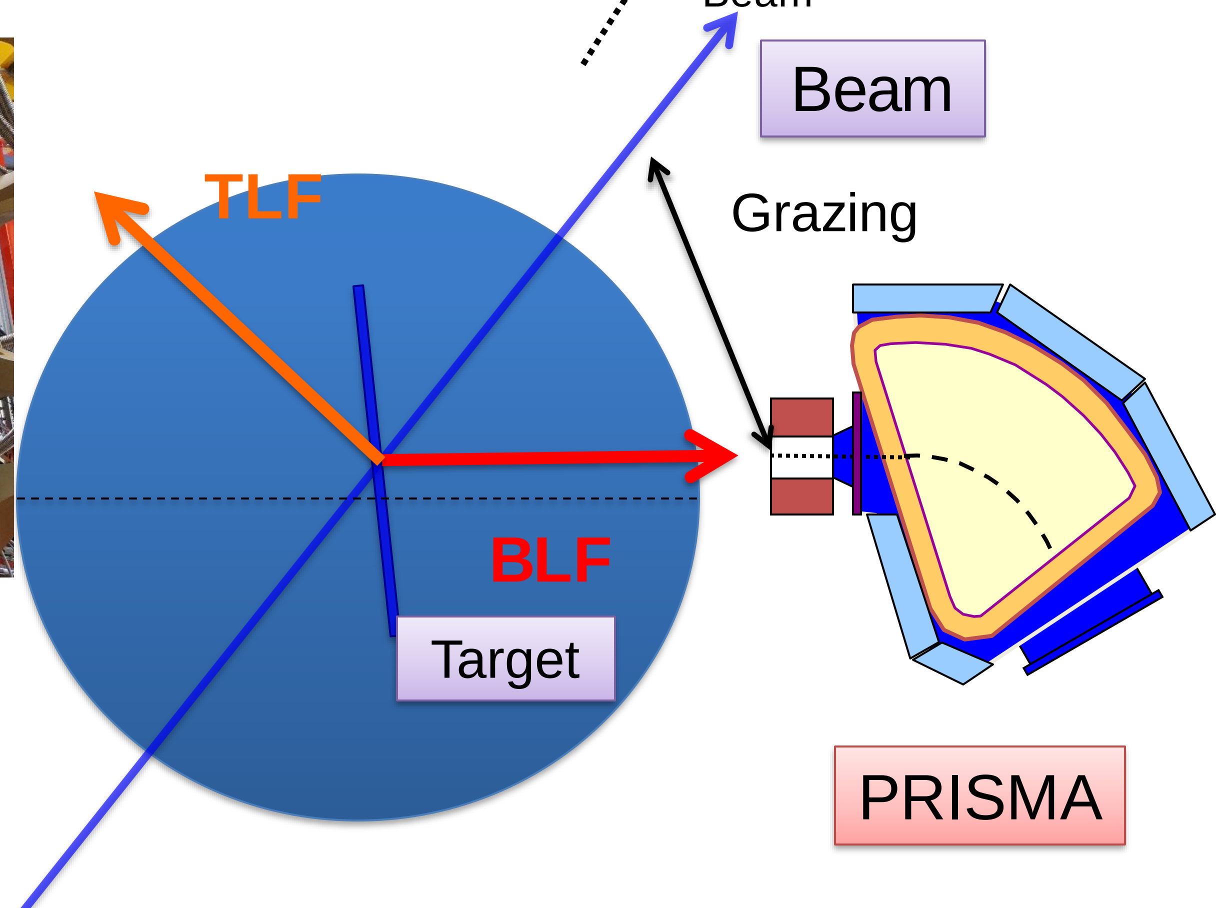
BLF lighter (enough energy for identification)

TLF heavier (physics goal but not enough energy)





AGATA



PRISMA

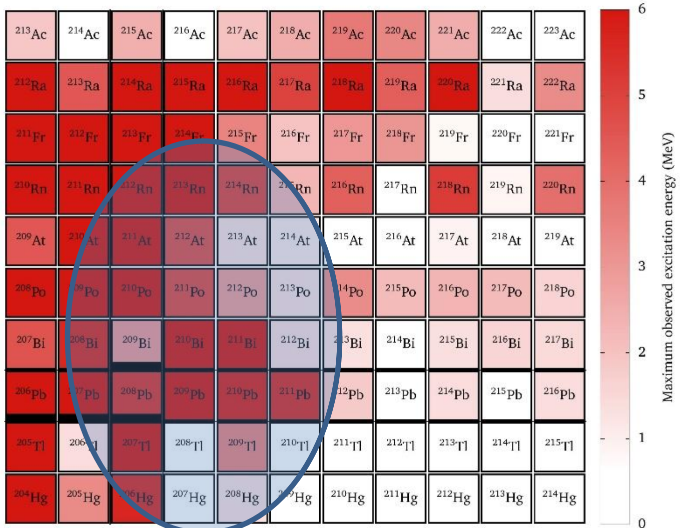
Courtesy J.J. Valiente-Dobon

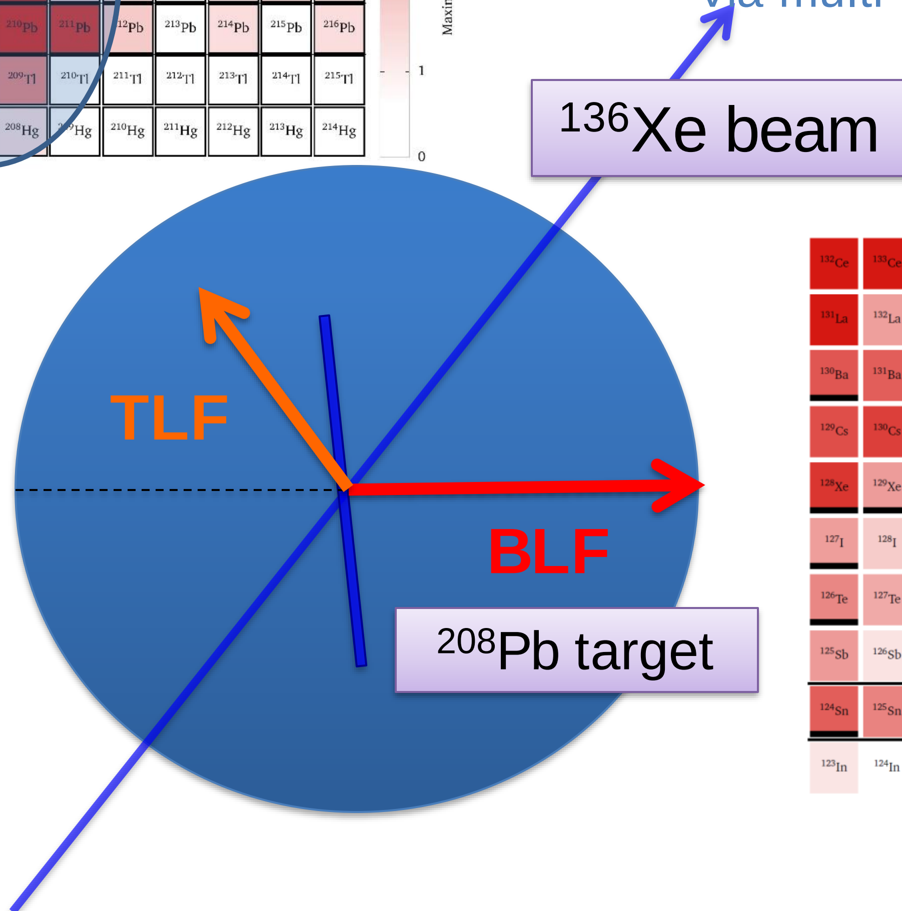
The Legnaro Campaign

Proposal 22.04

Pathway to nuclear structure in heavy neutron rich nuclei in the vicinity of N=126

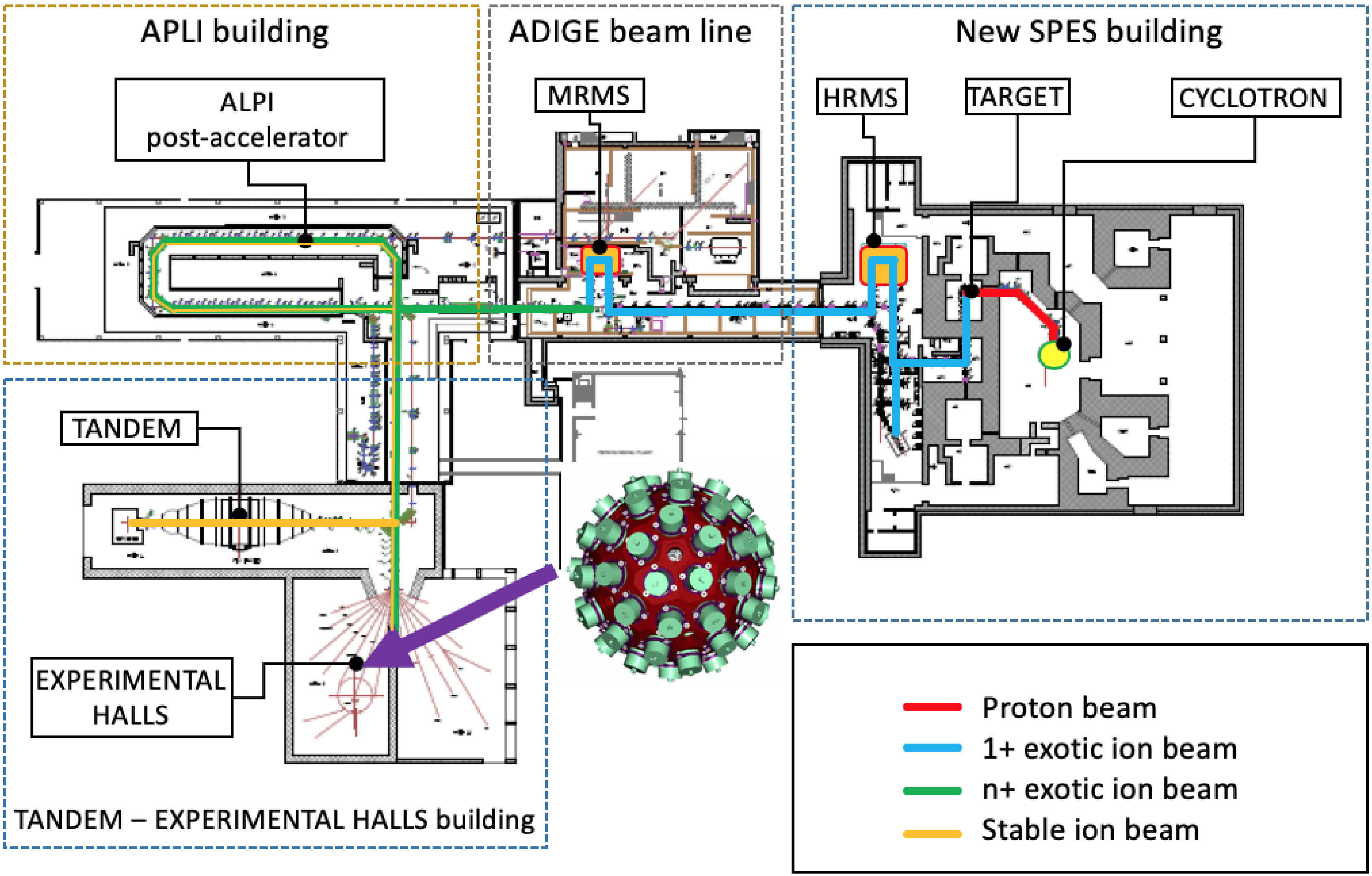
and nuclei northwest of ^{132}Sn Via multi-nucleon transfer reactions





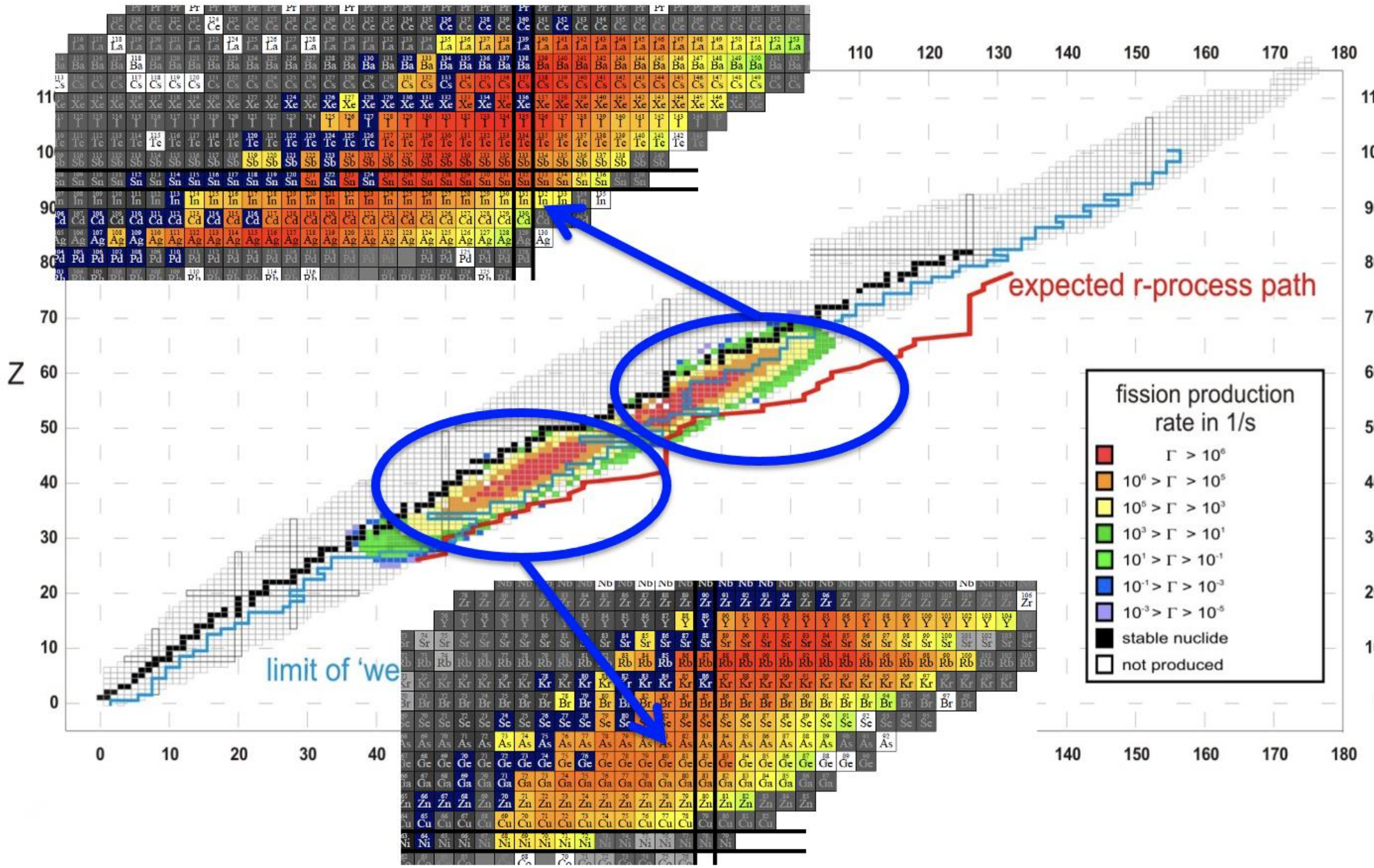
The Legnaro Campaign

Experiments with SPES beams



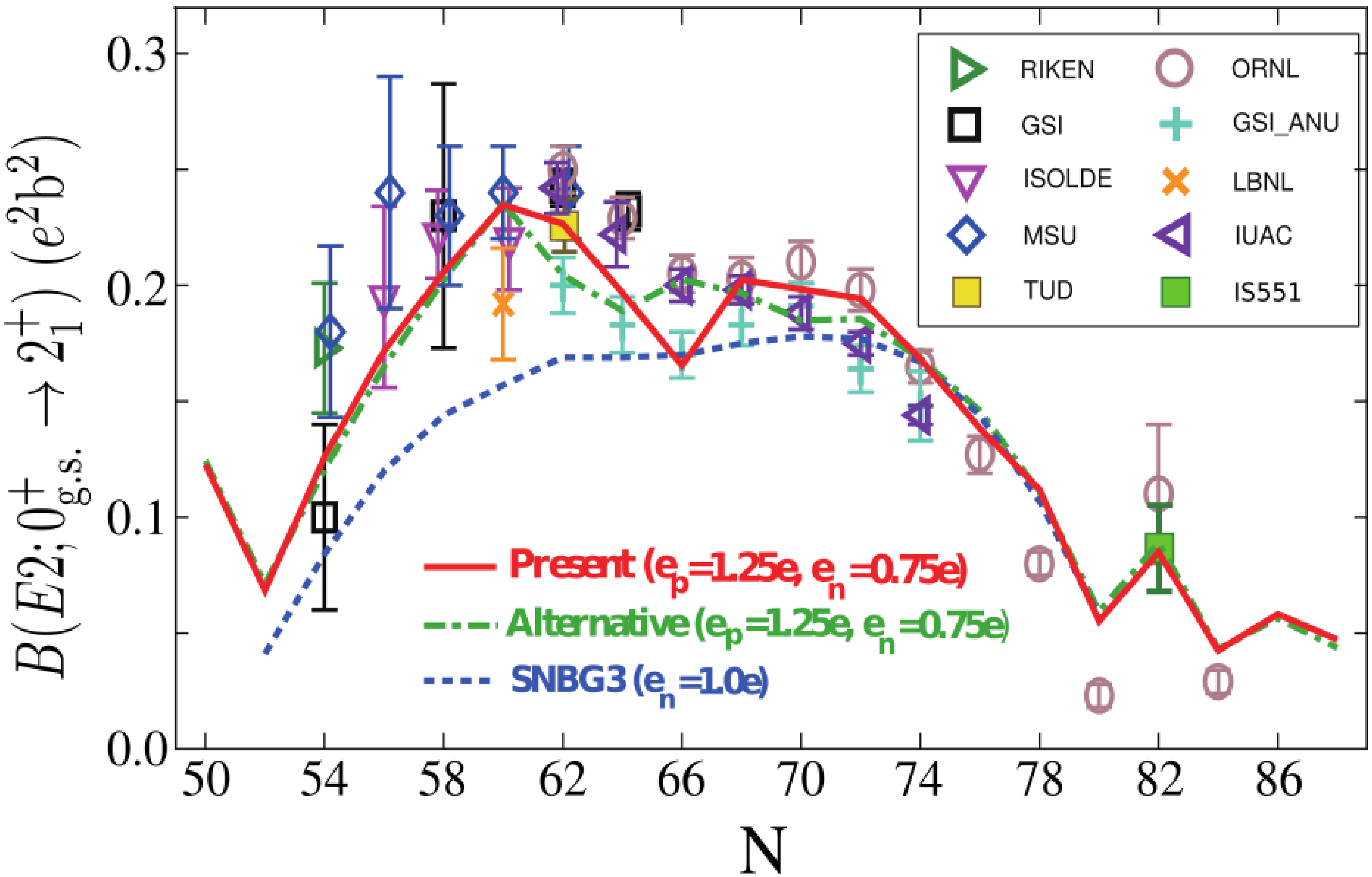
The Legnaro Campaign

Experiments with SPES beams



The Legnaro Campaign

Calculated and measured B(E2) values along Sn isotopic chain



Novel Shape Evolution in Sn Isotopes from Magic Numbers 50 to 82
T. Togashi; Y. Tsunoda; T. Otsuka; N. Shimizu; M. Honma; Phys. Rev. Lett. 121, 062501 (2018)

Enhanced Quadrupole and Octupole Strength in Doubly Magic ^{132}Sn
D. Rosiak et. al.; Phys. Rev. Lett. 121, 121, 252501 (2018)

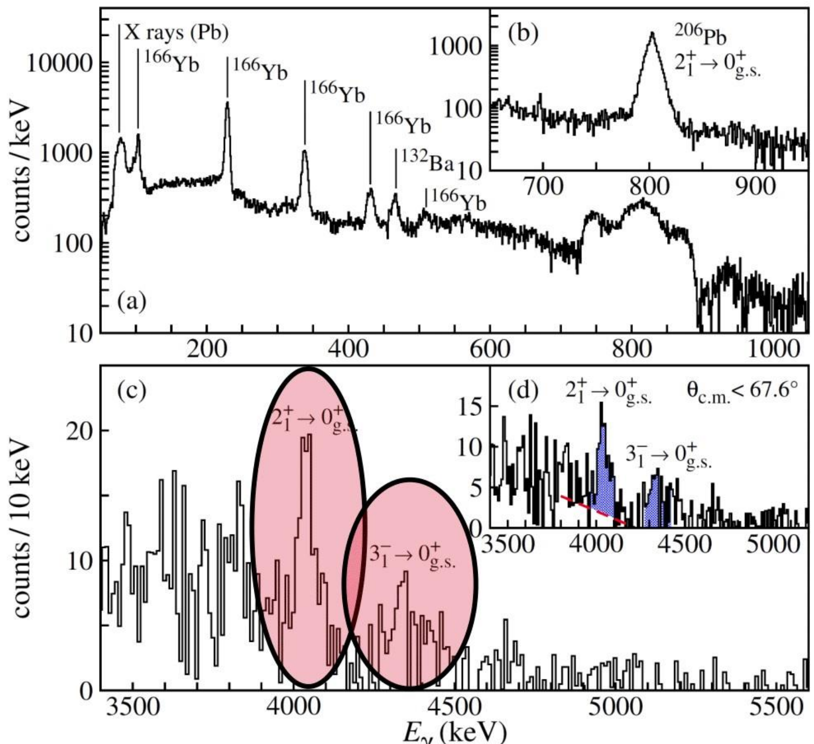
The Legnaro Campaign

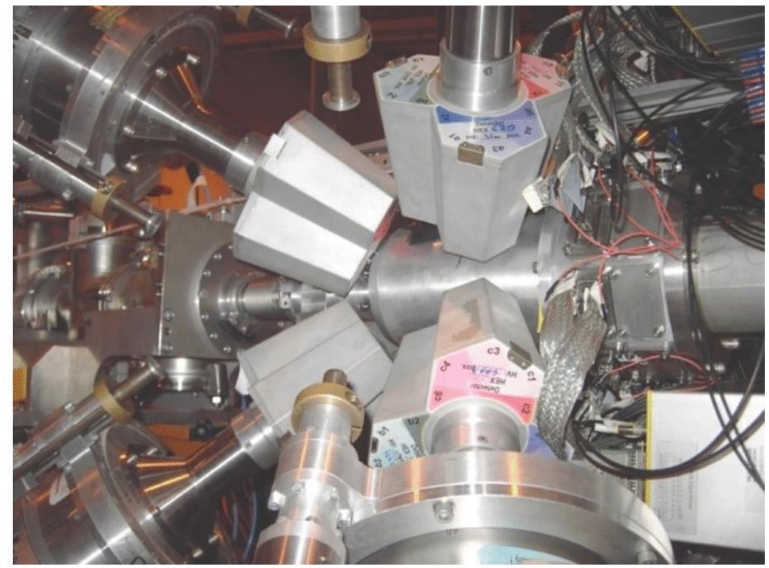
Coulomb excitation of doubly-magic ^{132}Sn **MINIBALL @ HIE-ISOLDE**

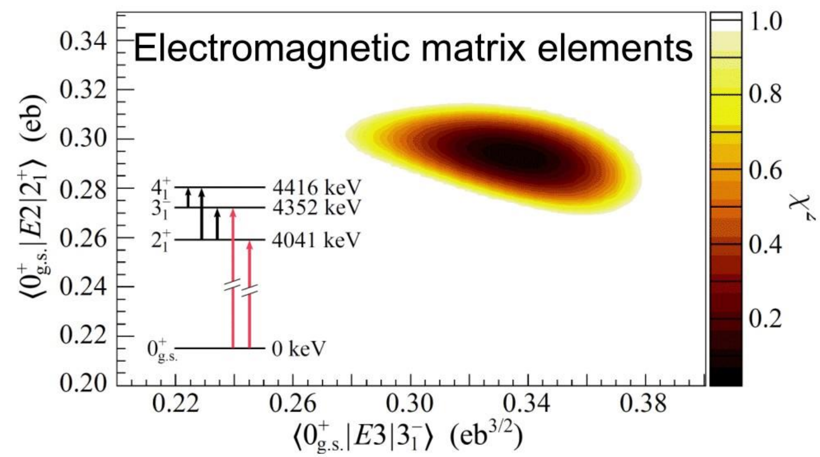
Low energy Coulomb excitation

$^{206}Pb + ^{132}Sn^{31+}$ @ 5.49 MeV/u ~3.0 x 10^5 pps

D. Rosiak et al., Phy. Rev. Lett. 121, 252501 (2018)







- Very good energy resolution
- Rather limited γ efficiency and particle rate

Expected SPES ^{132}Sn yield 10^8 pps & AGATA performance

Summary

- Status AGATA:
  - ✓ detectors, digital electronics, PSA, γ-ray tracking
  - ✓ ΔE, Δx, Δt

- Improved conditions for in-beam γ-ray spectroscopy

- Previous and ongoing AGATA campaigns continuously produce excellent physics results.

- Promising perspectives for γ-spectroscopy with RIBs at SPES, FAIR, SPIRAL, …

- New MoU to complete the 2/3 AGATA configuration in place!

- Long term goal AGATA 4π configuration (NUPECC long range plan recommendation)

Acknowledgements

Nuclear Instruments and Methods in Physics Research A 668 (2012) 26–58

Contents lists available at SciVerse ScienceDirect

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journal homepage: www.elsevier.com/locate/nima

AGATA—Advanced GAmma Tracking Array

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ABSTRACT

The Advanced GAmma Tracking Array (AGATA) is a European project to develop and operate the next generation γ-ray spectrometer. AGATA is based on the technique of γ-ray energy tracking in electrically segmented high-purity germanium crystals. This technique requires the accurate determination of the energy, time and position of every interaction as a γ ray deposits its energy within the detector volume. Reconstruction of the full interaction path results in a detector with very high efficiency and excellent spectral response. The realisation of γ-ray tracking and AGATA is a result of many technical advances. These include the development of encapsulated highly segmented germanium detectors assembled in a triple cluster detector cryostat, an electronics system with fast digital sampling and a data acquisition system to process the data at a high rate. The full characterisation of the crystals was measured and compared with detector-response simulations. This enabled pulse-shape analysis algorithms, to extract