The AGATA Spectrometer Precision Spectroscopy of Exotic Nuclei

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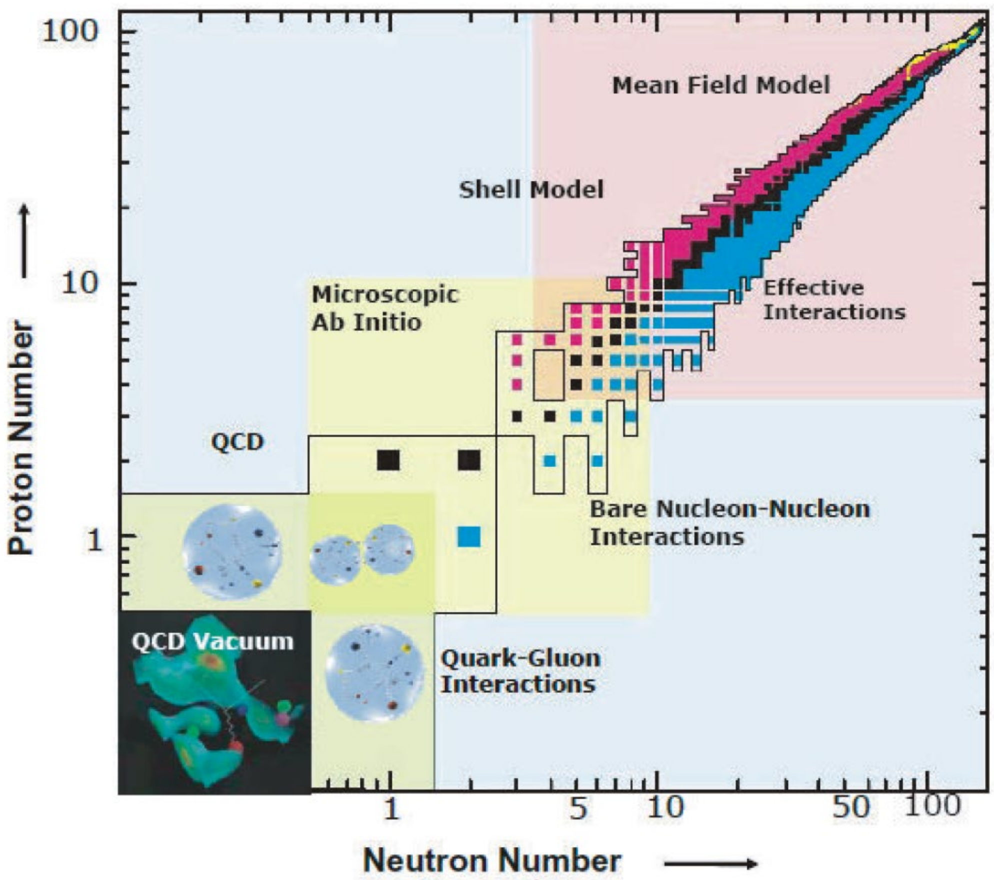
Daresbury Laboratory

ANSTT3 – iThemba LABS
March 2020

AGATA physics case

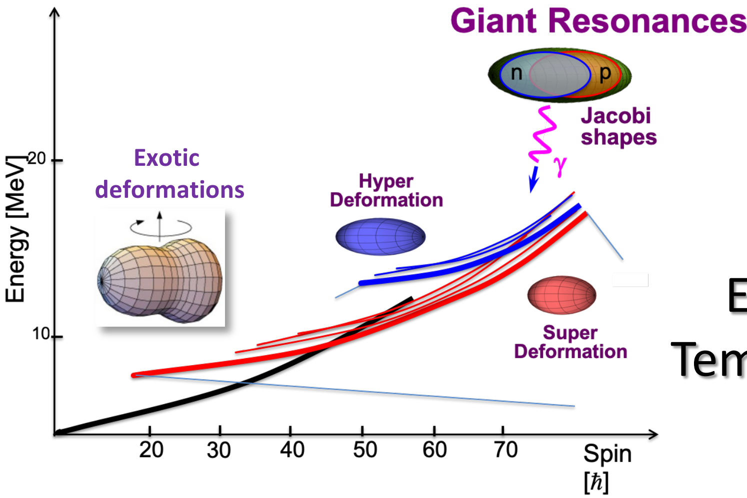
Nuclear Structure/Astrophysics

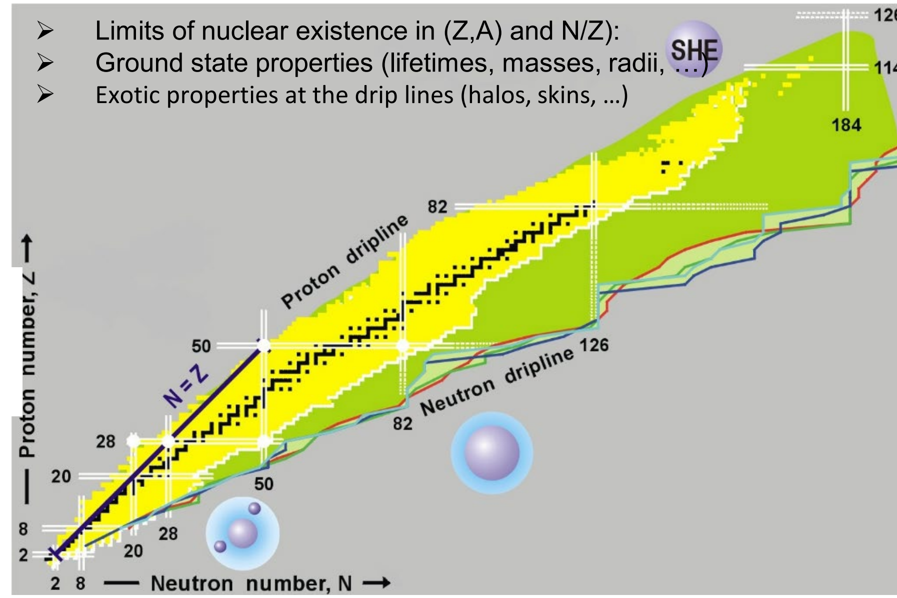
Goal: To determine nuclear properties as a function of Ex, J and T (and N,Z) to find a consistent theoretical framework to describe the phenomena observed

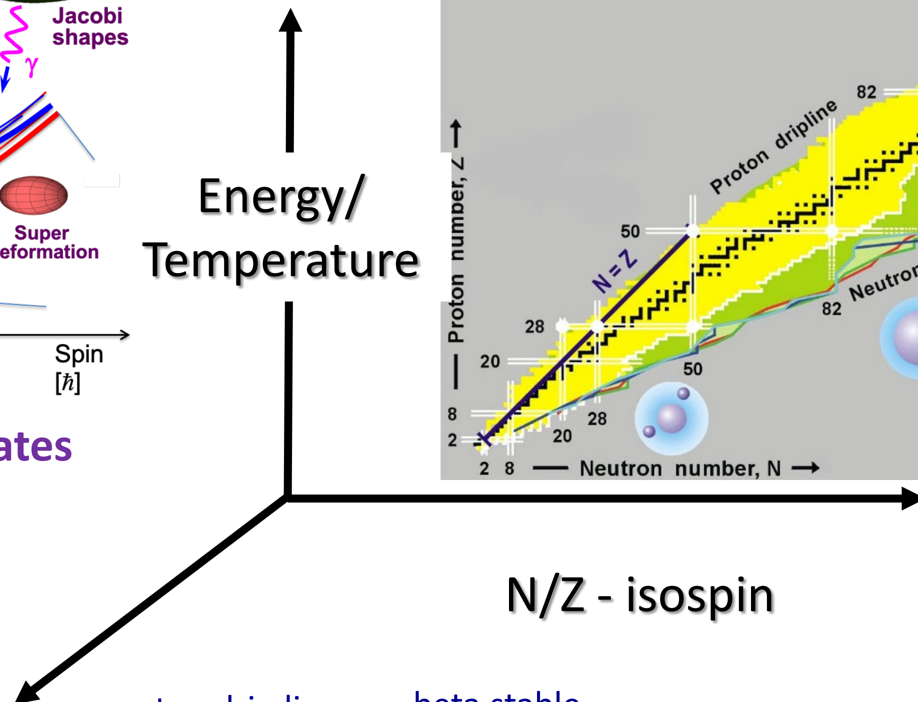


AGATA physics case

Challenges in Nuclear Structure Physics

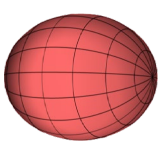


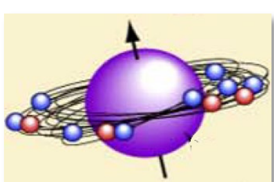


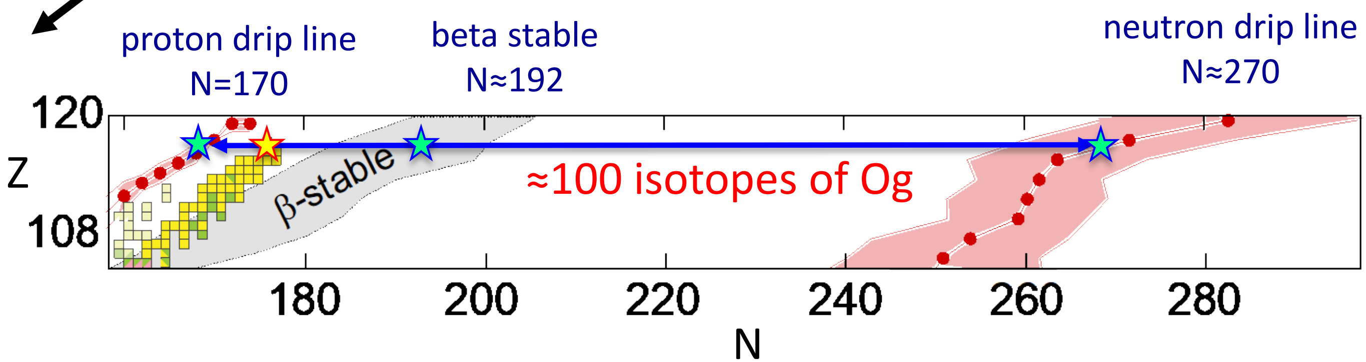


Properties of excited states

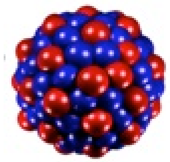
→ γ-ray spectroscopy







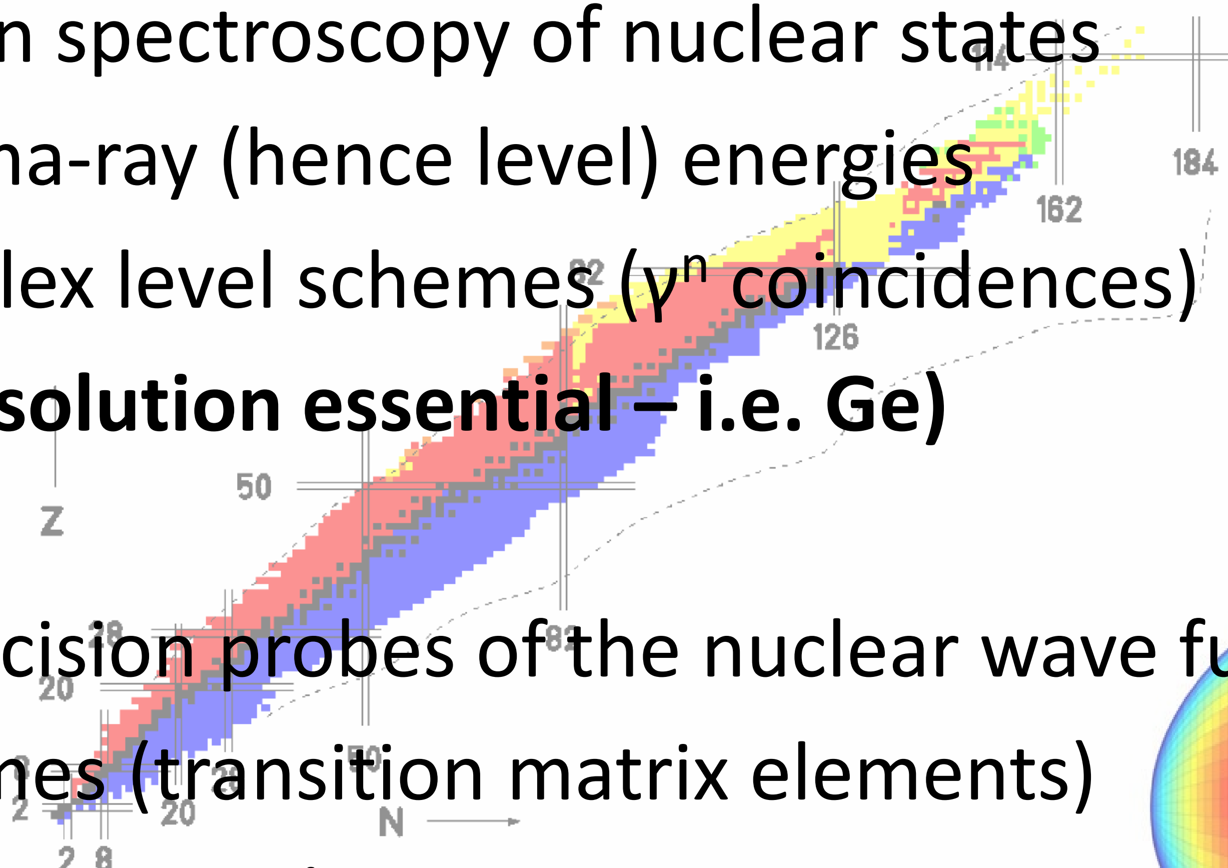
Gamma-ray spectroscopy



Precision spectroscopy of nuclear states

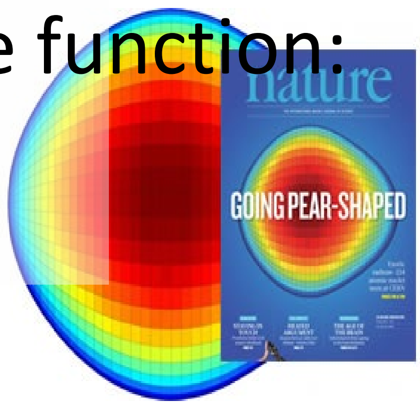
- Gamma-ray (hence level) energies
- Complex level schemes (γ^n coincidences)

(high resolution essential – i.e. Ge)



Plus precision probes of the nuclear wave function:

- Lifetimes (transition matrix elements)
- Electromagnetic moments
- Cross-sections for direct reactions



The need for AGATA

The challenge of the new generation of radioactive beam facilities

FAIR (Germany)
SPIRAL (France)
SPES (Italy)
HIE-ISOLDE (CERN)

→

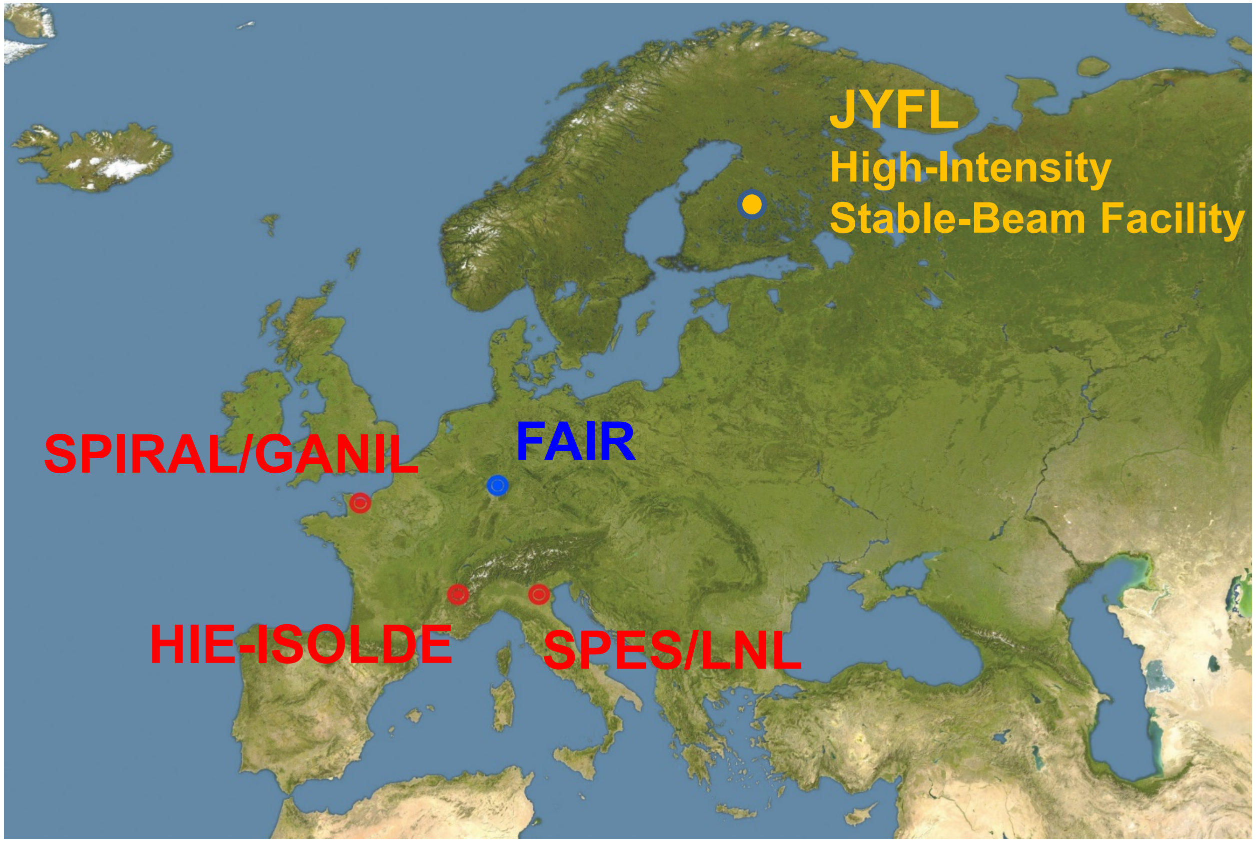
- Low intensity
- High background
- Large Doppler broadening
- High counting rates
- High gamma-ray multiplicities

The ideal γ-ray spectrometer AGATA

→

- High efficiency
- Distinguish gammas from b/g
- Highly position sensitive
- High data throughput
- Can distinguish multiple gammas

Future host labs beyond 2020



ISOL Facilities

Reaccelerated RIBs:
- Coulomb Excitation, Direct Reactions, MNT, Deep Inelastic, CN
- **Direct and inverse kinematics $\beta \sim 10\%$**

In-Flight Facility

In-flight RIBs:
- Relativistic Coulomb Excitation, Knock-out, Fragmentation …
- **Inverse kinematics $\beta \sim 50\%$**

High-Intensity Stable-Beam Facilities

GANIL, JYFL, LNL

NuPECC Long Range Plan 2017

SUMMARY AND RECOMMENDATIONS

….

Support to the completion of AGATA in full geometry

AGATA represents the state-of-the-art in γ-ray spectroscopy and is an essential precision tool underpinning **a broad programme of studies in nuclear structure, nuclear astrophysics and Nuclear reactions.**

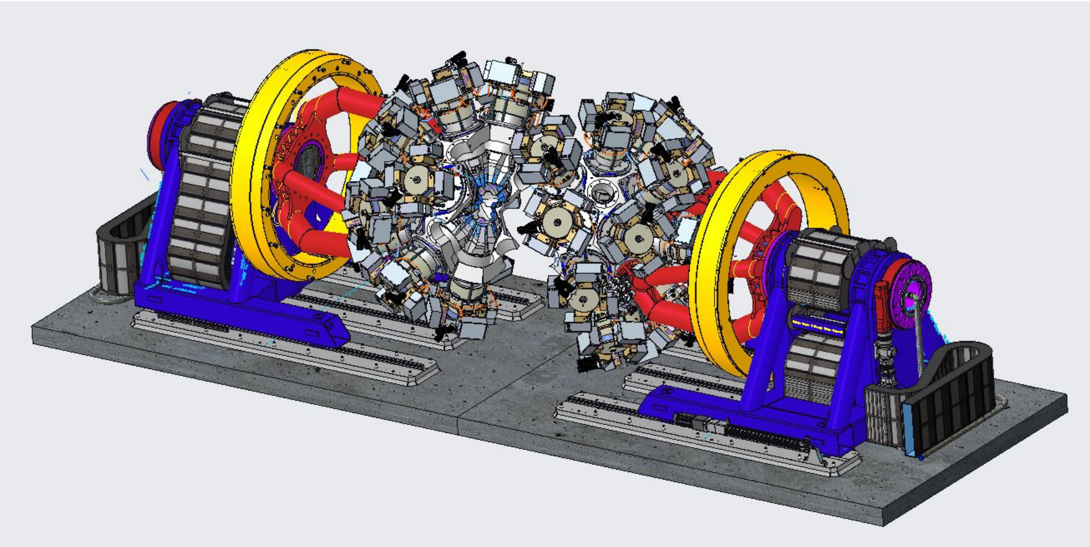
AGATA will be exploited at all of the **large-scale radioactive and stable beam facilities** and in the long-term must be fully completed in **full 60 detector unit geometry** in order to realise the envisaged scientific programme.

AGATA will be realised in phases with the goal of completing the first phase with 20 units by 2020.

….

Gamma-Ray Energy Tracking Array GRETA in the US

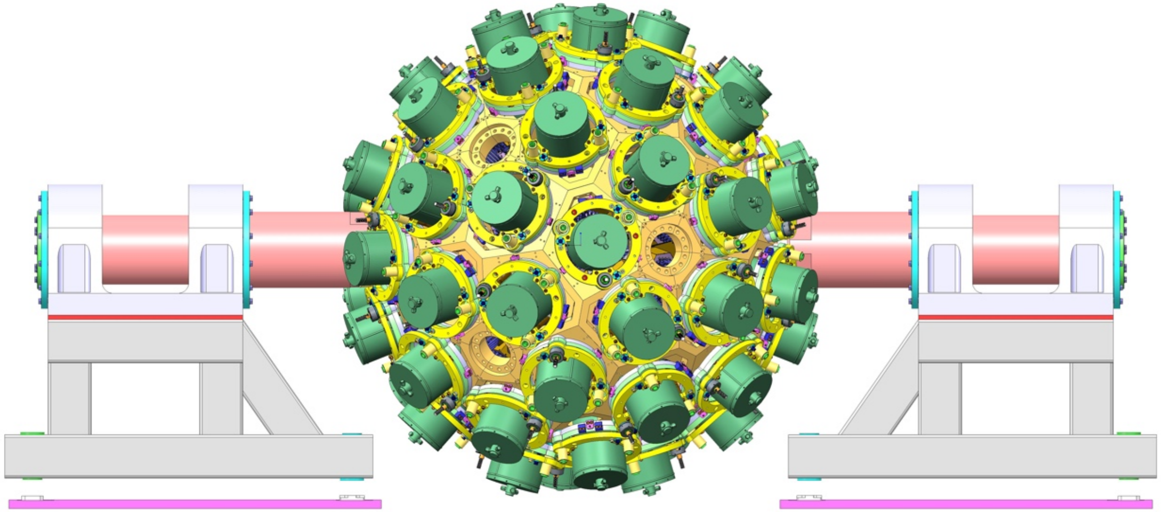
GRETA



GRETA CD2/2 2020
"Construction"

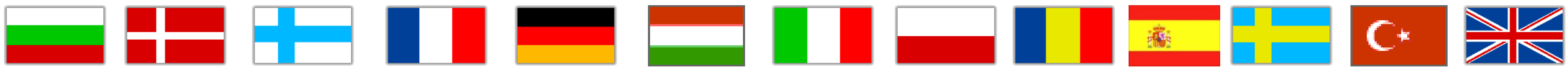
~2023 18 Quads
30 Quads 25/26

AGATA



AGATA Collaboration

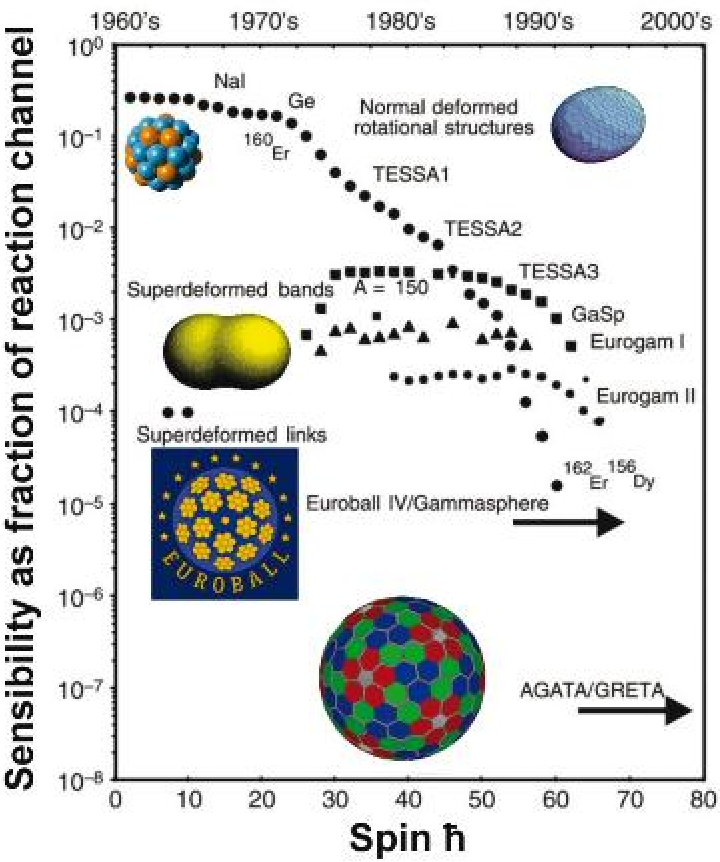
Steering Committee Chairperson: P.Reiter, IKP Köln, Germany

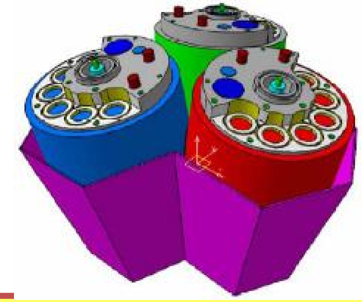


13 Countries
>40 Institutions

Bulgaria:	Univ. Sofia
Denmark:	NBI Copenhagen
Finland:	Univ. Jyväskylä
France:	GANIL Caen, IPN Lyon, CSNSM Orsay, IPN Orsay, CEA-DSM-DAPNIA Saclay, IPHC Strasbourg, LPSC Grenoble
Germany:	GSI Darmstadt, TU Darmstadt, Univ. zu Köln, TU München
Hungary:	ATOMKI Debrecen
Italy:	INFN-LNL, INFN and Univ. Padova, Milano, Firenze, Genova, Napoli,
Poland:	NINP and IFJ Krakow, SINS Swierk, HIL & IEP Warsaw
Romania:	NIPNE & PU Bucharest
Spain:	IFIC, ETSE-UVEG Valencia, IEM-CSIC, UAM Madrid, USAL Salamanca
Sweden:	Univ. Göteborg, Lund Univ., KTH Stockholm, Uppsala Univ.
Turkey:	Univ. Ankara, Univ. Istanbul, Technical Univ. Istanbul
UK:	Univ. Brighton, UKRI-STFC Daresbury, Univ. Edinburgh, Univ. Liverpool, Univ. Manchester, Univ. West of Scotland, Univ. Surrey, Univ. York

AGATA (4π)






Encapsulation

180 hexagonal crystals:	3 shapes
3 fold clusters (cold FET):	60 all equal
Inner radius (Ge):	23.5 cm
Amount of germanium:	362 kg
Solid angle coverage:	~82 %
36-fold segmentation	6480 segments
Crystal singles rate	~50 kHz
Efficiency (Mγ=1 [30]):	43% [28%]
Peak/Total (Mγ=1 [30]):	58% [49%]

AGATA Collaboration NIM A 668 (2012) 26

6660 high-resolution digital electronics channels

High throughput DAQ / Capability to record sampled pulses

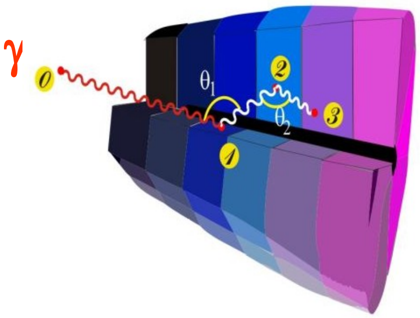
Pulse Shape Analysis → position sensitive operation mode

γ-ray tracking algorithms → maximum efficiency and P/T

The concept of γ-ray tracking

1

Highly segmented HPGe detectors



2

Digital electronics to record and process signals

3

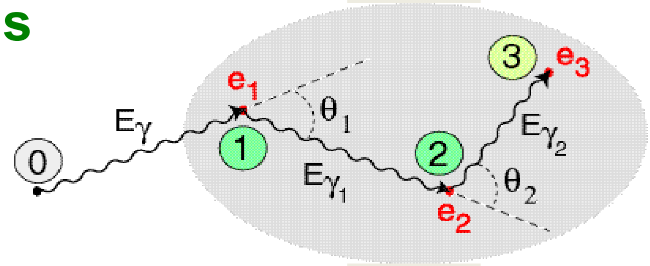
Pulse Shape Analysis to decompose recorded waves

Identified interaction points

$(x,y,z,E,t)_i$

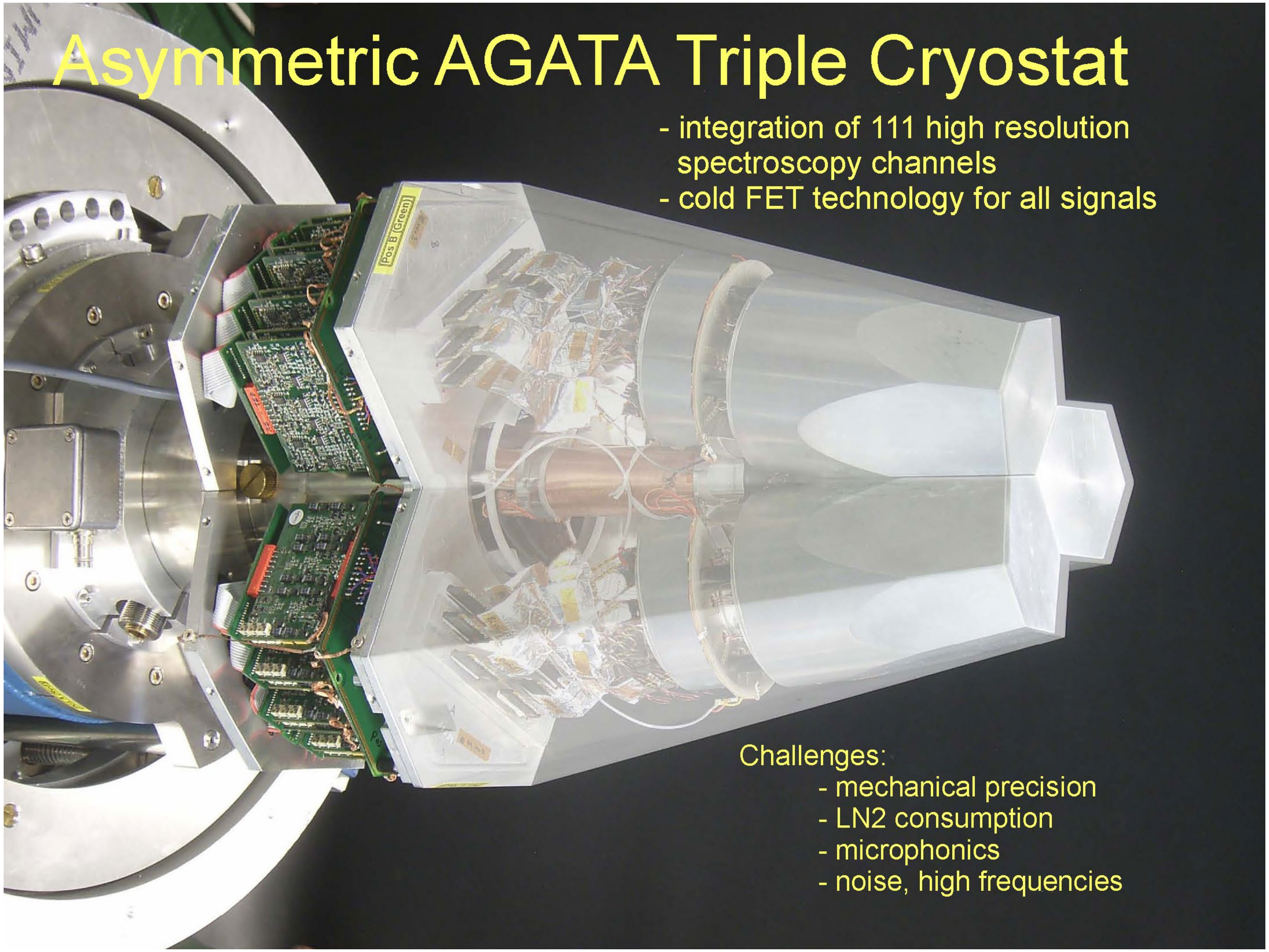
4

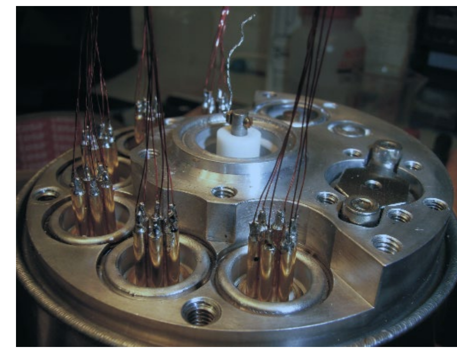
Evaluation of permutations of interaction points

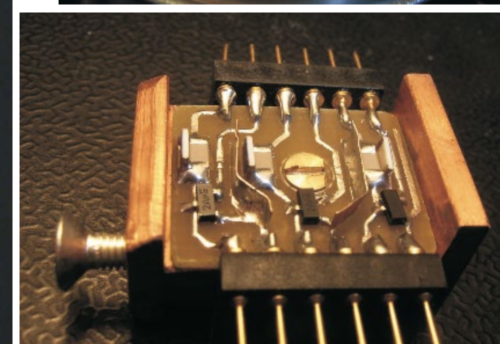


Reconstructed γ-rays

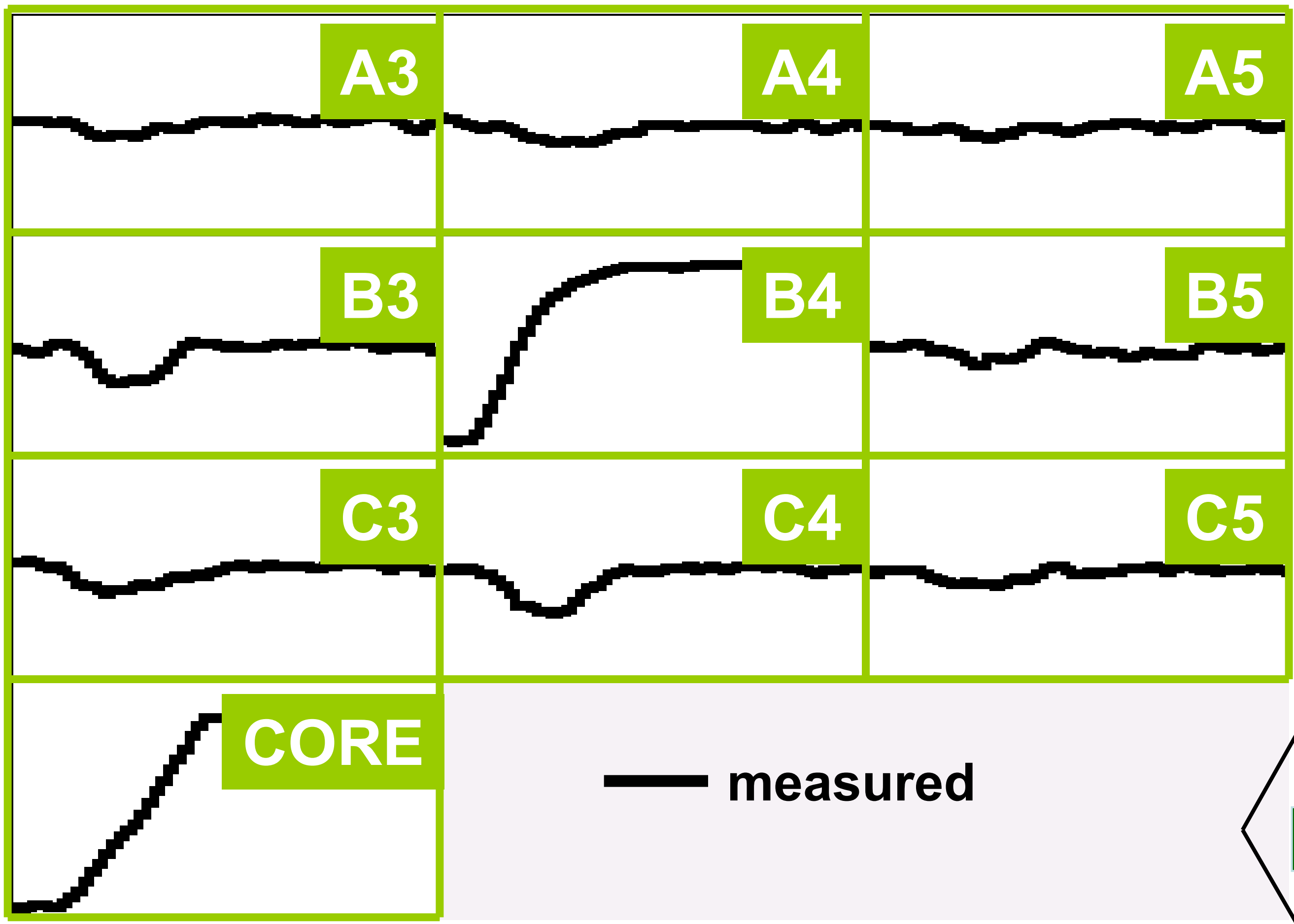
The AGATA triple cluster

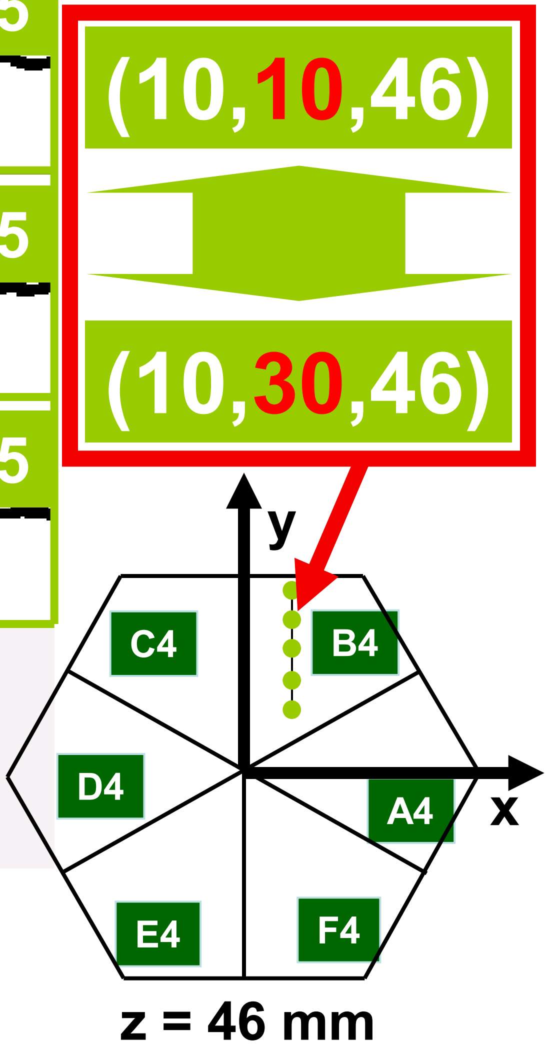






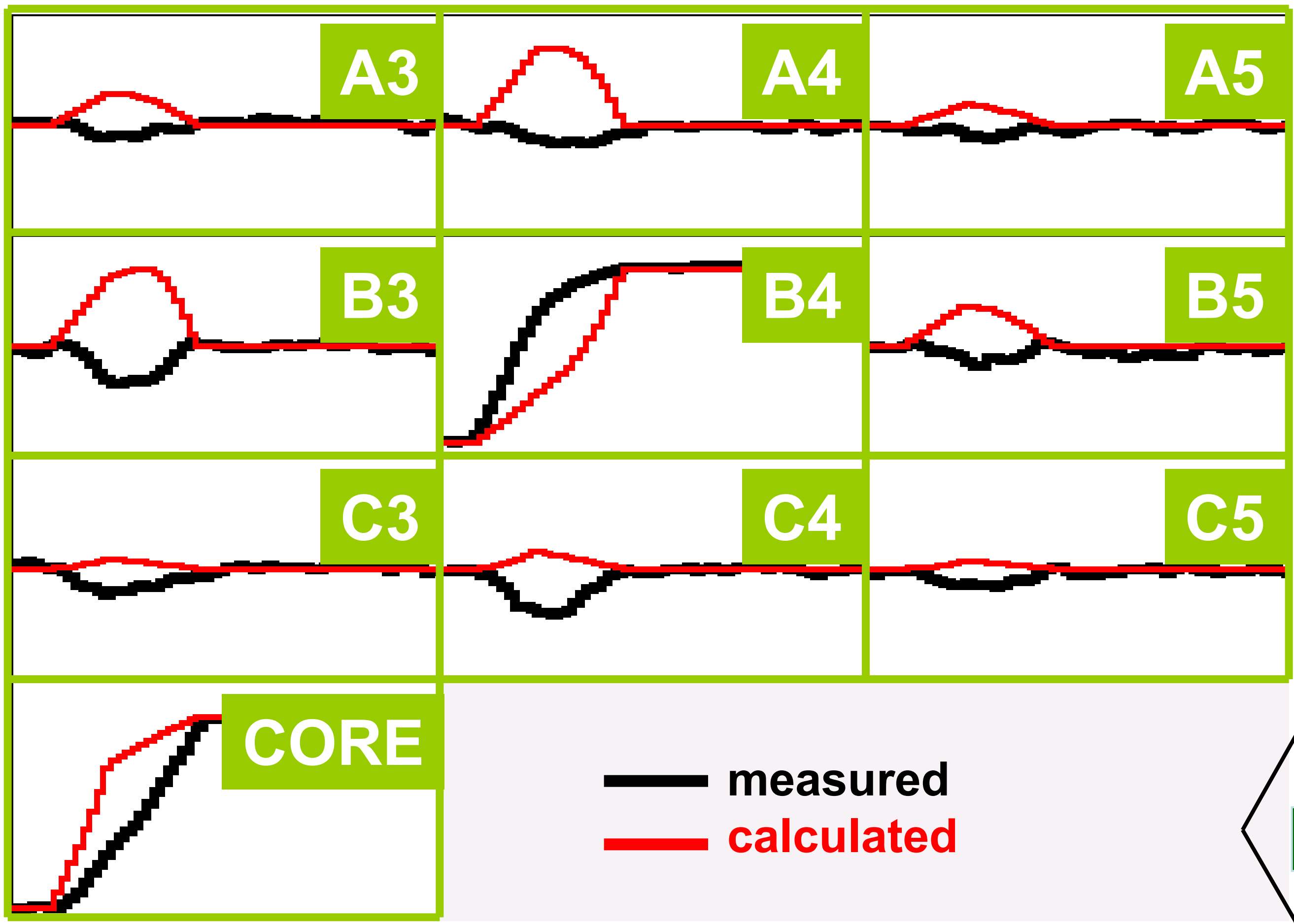
Pulse Shape Analysis concept





791 keV deposited in segment B4

Pulse Shape Analysis concept



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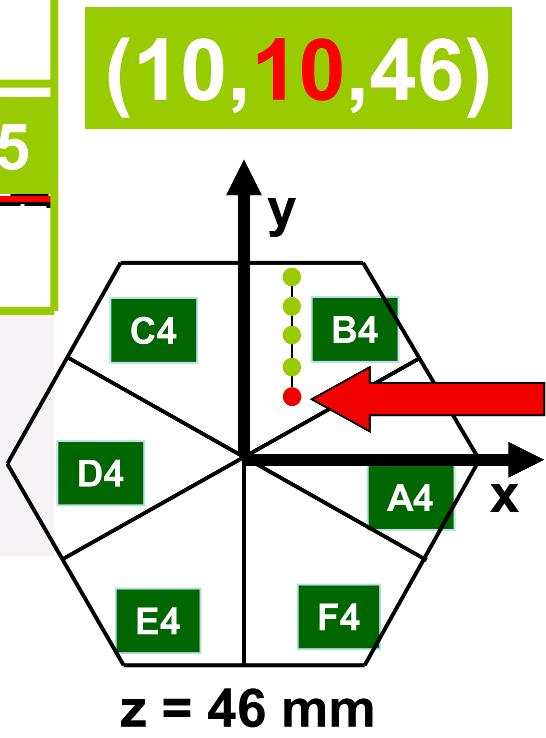
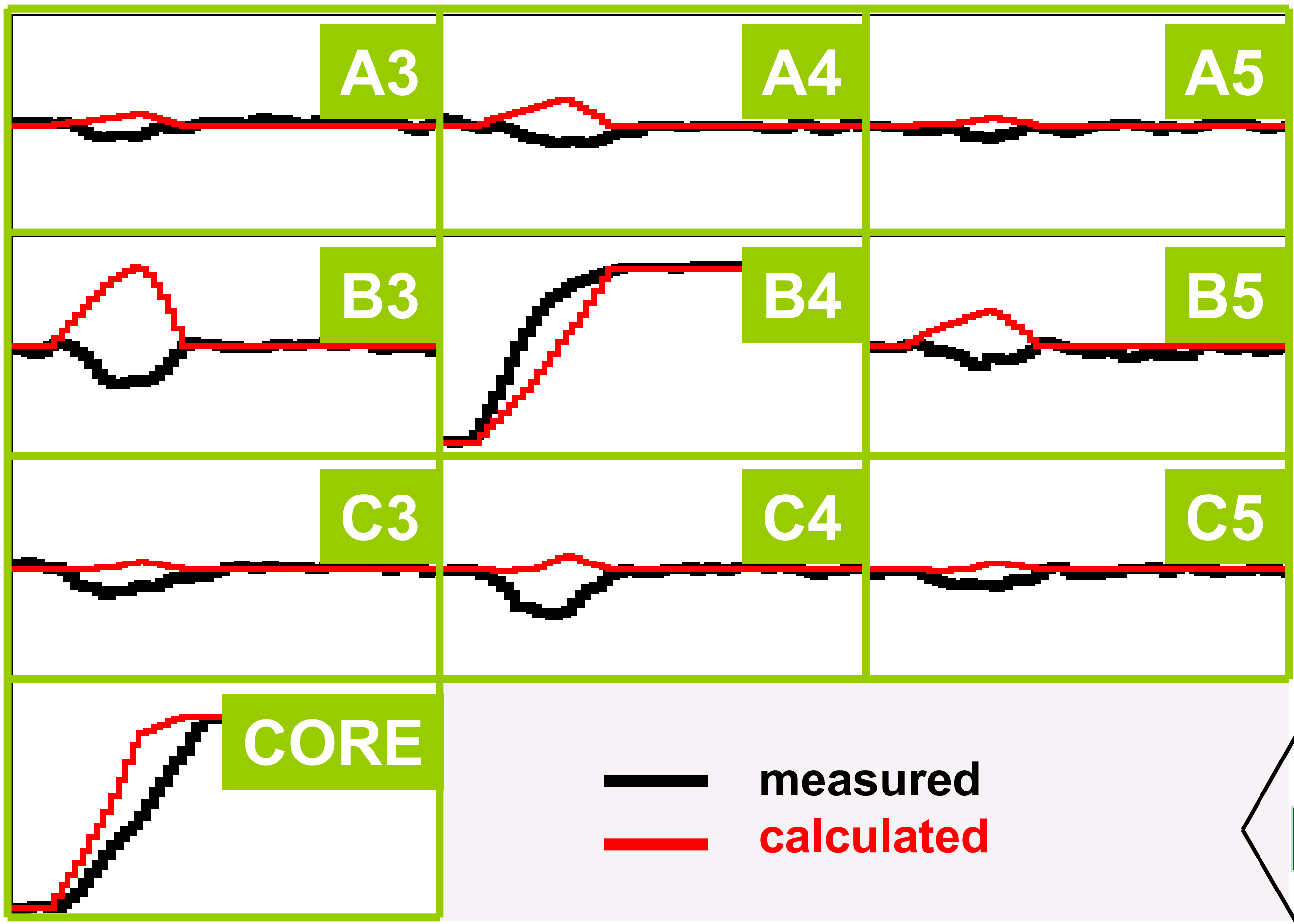
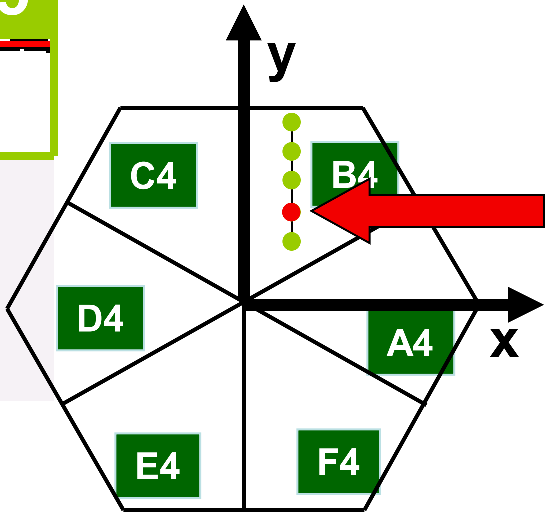


Pulse Shape Analysis concept



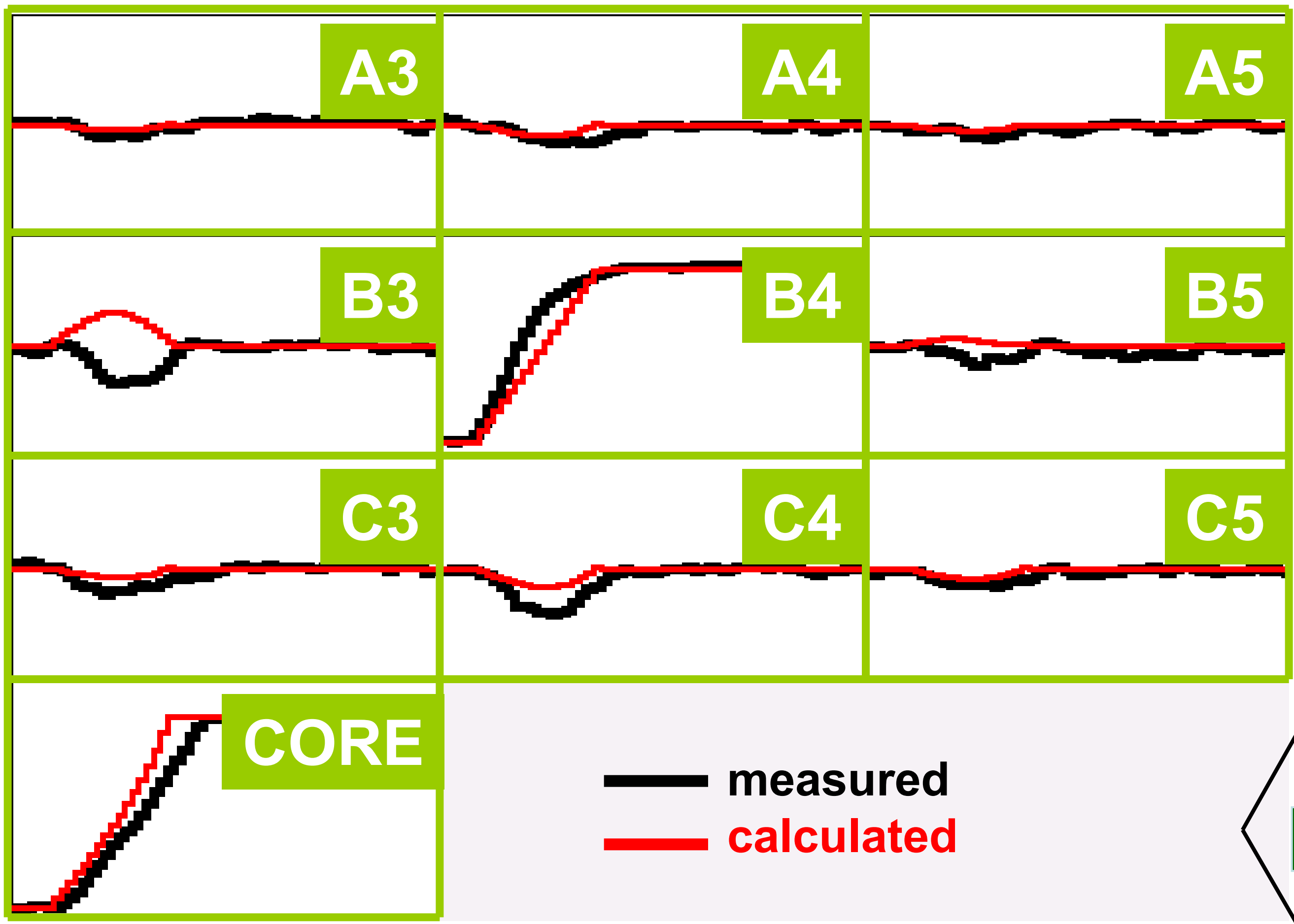
(10,15,46)



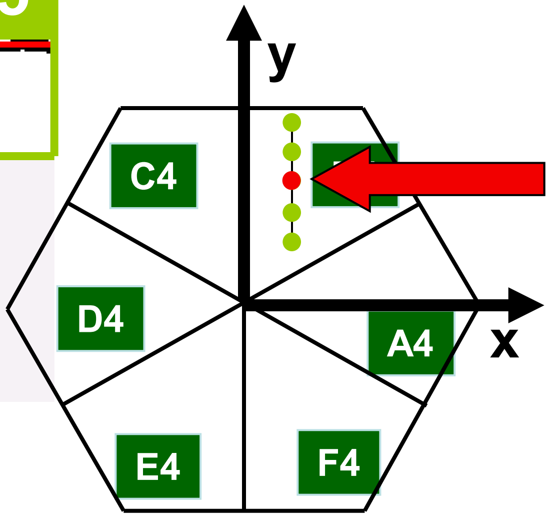
z = 46 mm

791 keV deposited in segment B4

Pulse Shape Analysis concept



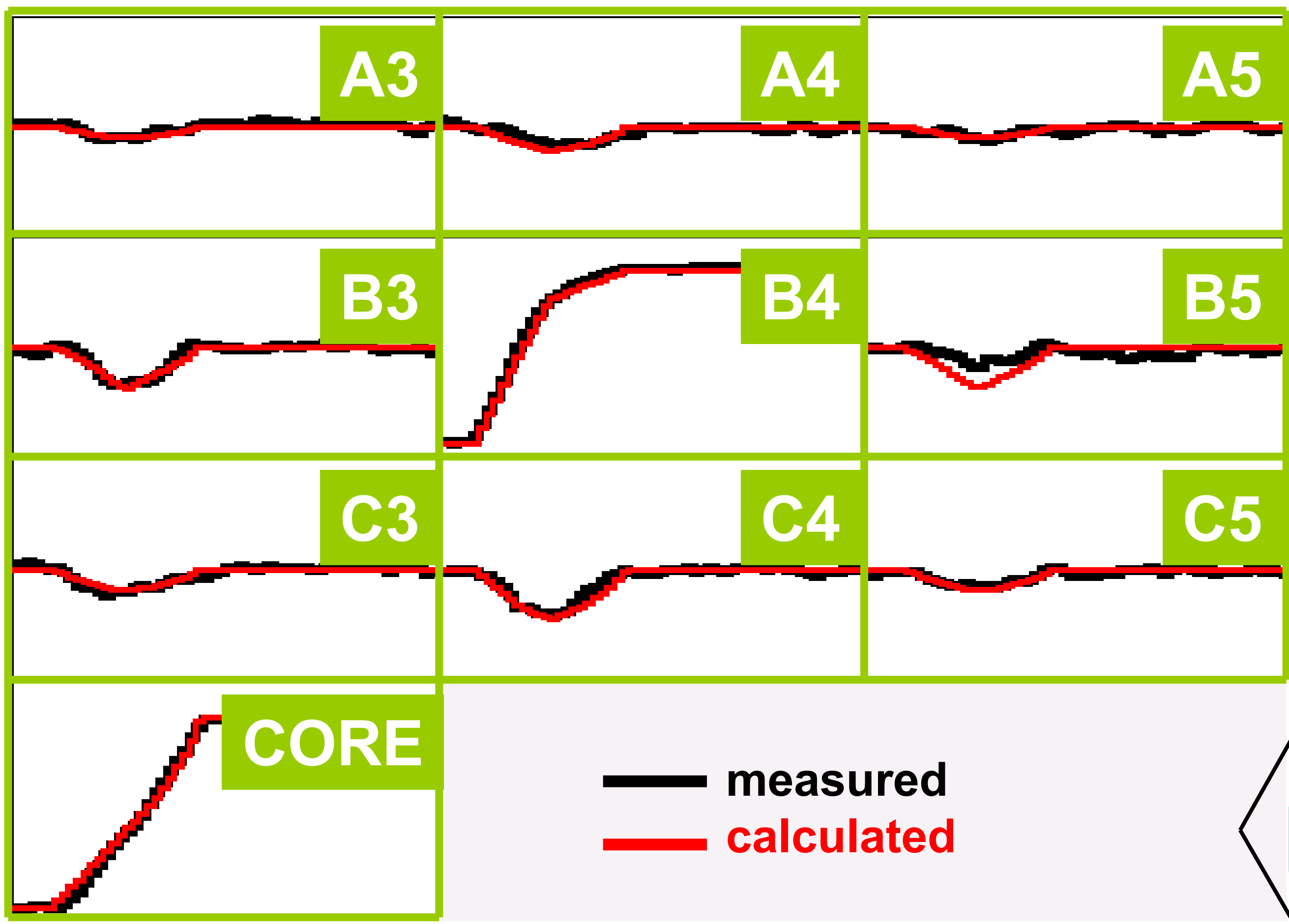
(10,20,46)



791 keV deposited in segment B4

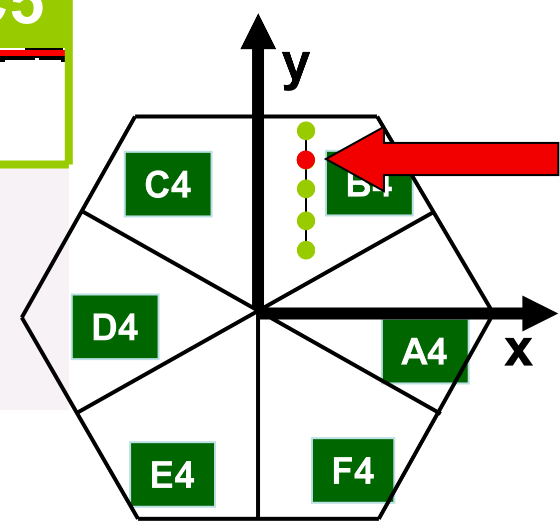
z = 46 mm

Pulse Shape Analysis concept



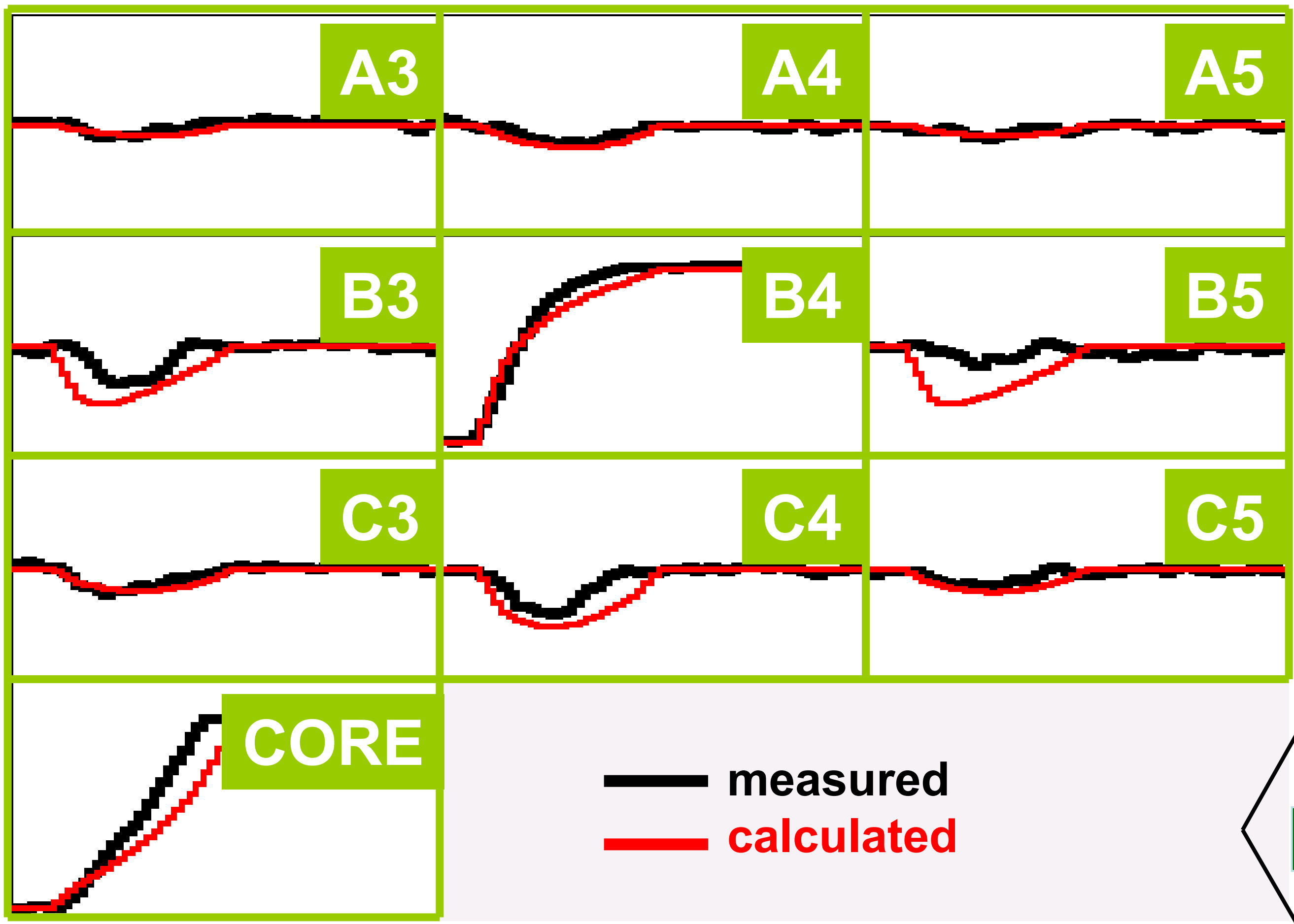
791 keV deposited in segment B4

(10,25,46)



z = 46 mm

Pulse Shape Analysis concept



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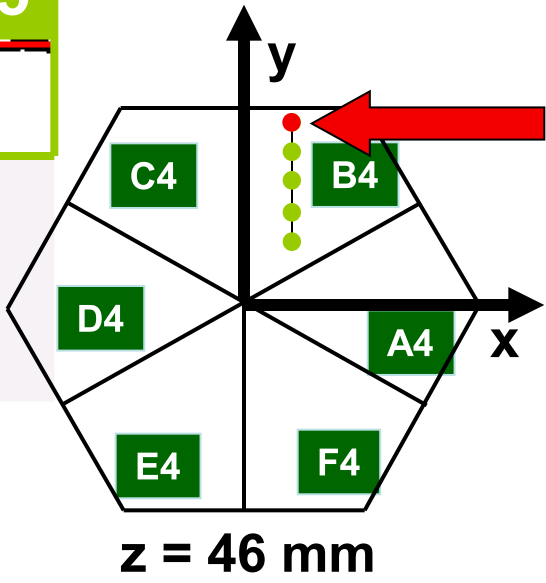
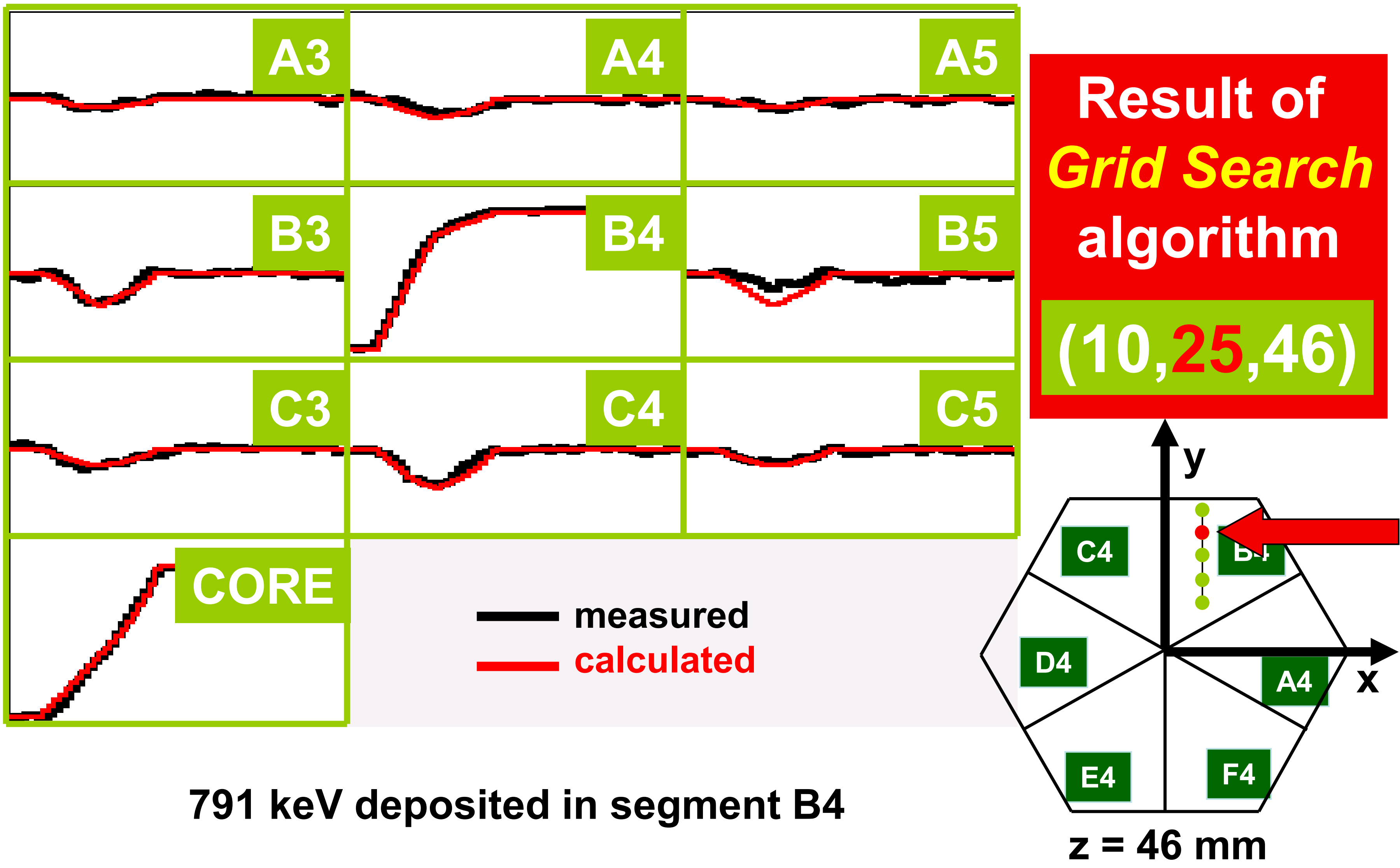


791 keV deposited in segment B4

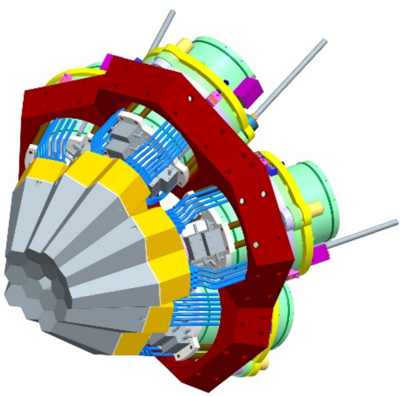
Pulse Shape Analysis concept



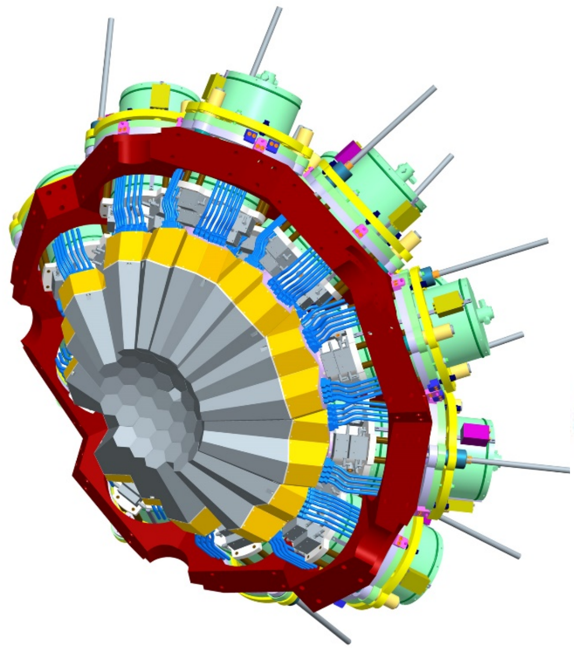
791 keV deposited in segment B4

Memorandum of Understanding

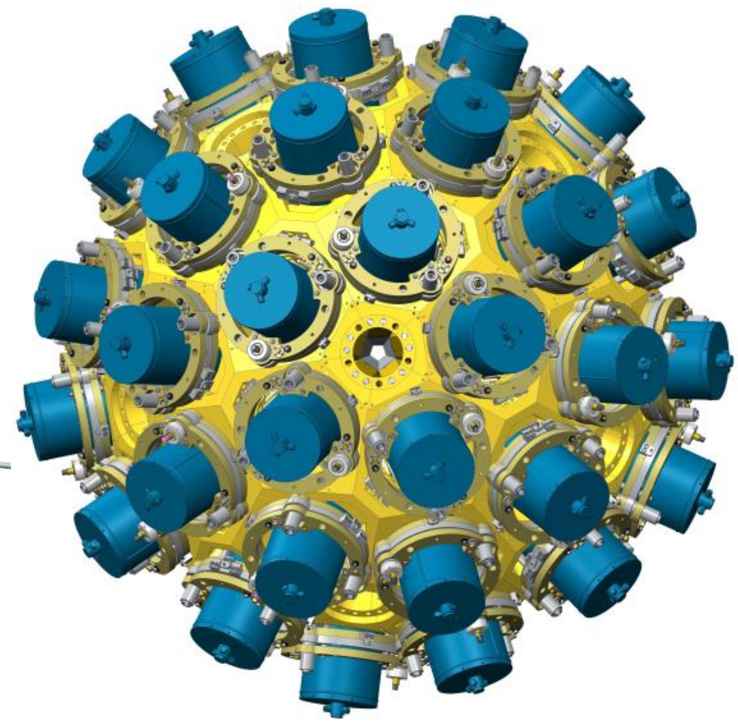
I MoU
AGATA 15
Demonstrator



II MoU
AGATA 60

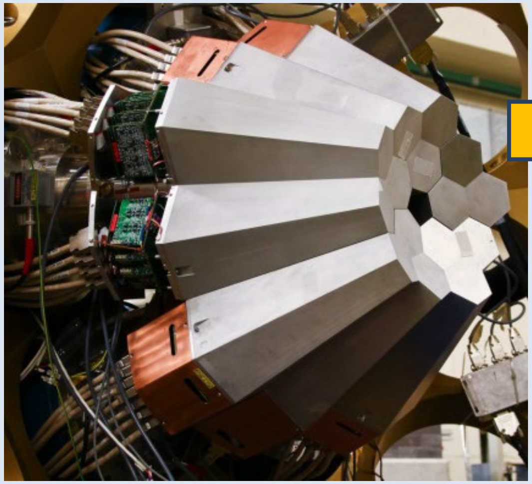


III MoU
AGATA 180 = 4π



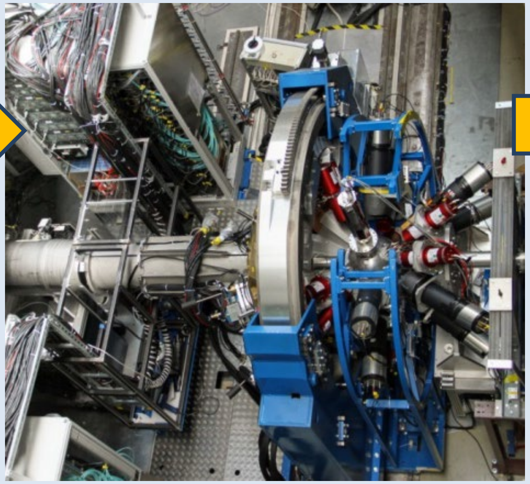
Progress of the AGATA array

2010-2012
Legnaro, Italy
Intense stable beams
15 detectors



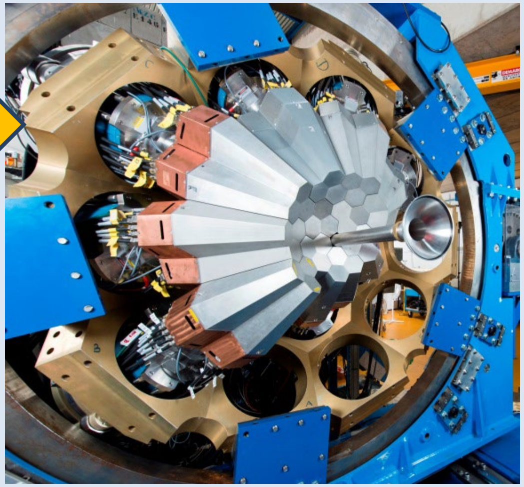
AGATA Demonstrator + PRISMA

2012-2014
GSI, Germany
Fast fragmentation beams
25 detectors



AGATA at GSI

2014- present
GANIL, France
ISOL and stable beams
approaching 1π (45)

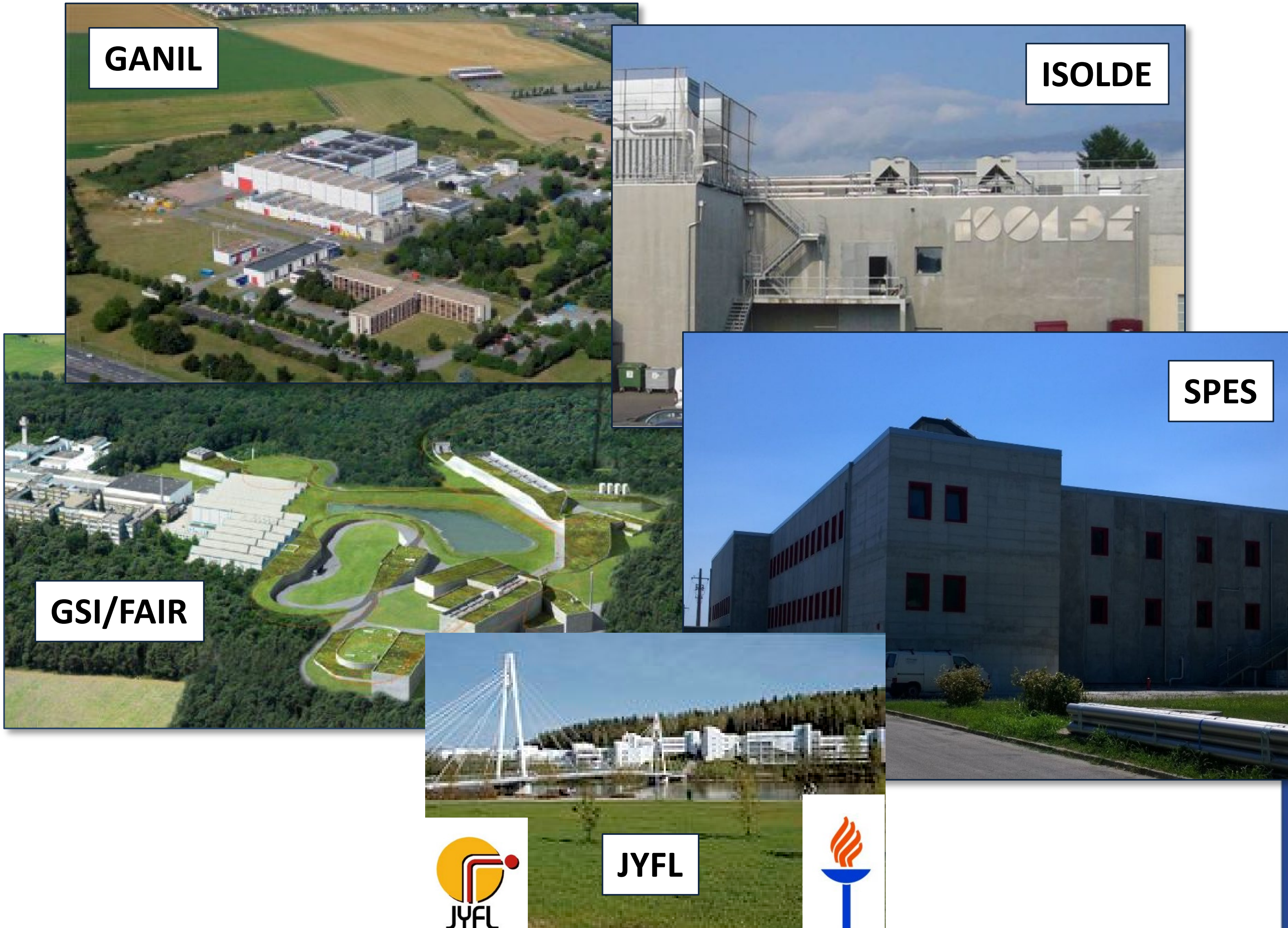


AGATA at GANIL

- Subsystems of AGATA for 41 detectors installed at GANIL.
- Infrastructure mostly ready for 45 detectors, i.e. AGATA 1π
- 51 AGATA capsules procured, **47 available** (more ordered)

AGATA
ADVANCED GAMMA TRACKING ARRAY

The next decade for AGATA



AGATA physics case

Physics opportunities with the Advanced Gamma Tracking Array – AGATA

W. Korten[9], A. Atac[30,35], D. Beaumel[23], P. Bednarczyk[14], M.A. Bentley[34], G. Benzoni[21], A. Boston[17], A. Bracco[20,21], J. Cederkäll[18], B. Cederwall[30], M. Ciemała[14], E. Clément[1], F.C.L. Crespi[20,21], D. Curien[31], G. de Angelis[15], F. Didierjean[31], D.T. Doherty[10], Zs. Dombradi[6] G. Duchêne[31], J. Dudek[31], B. Fernandez-Dominguez[27], B. Fornal[14], A. Gadea[33], L.P. Gaffney[17], J. Gerl[4], K. Gladnishki[28], A. Goasduff[25], M. Górska[4], P.T. Greenlees[12], H. Hess[13], D.G. Jenkins[34], P.R. John[5], A. Jungclaus[19], M. Kmiecik[14], A. Korichi[22], M. Labiche[3], S. Leoni[20,21], J. Ljungvall[22], A. Lopez-Martens[22], A. Maj[14], D. Mengoni[24,25], B. Million[21], A. Nannini[8], D. Napoli[15], P.J. Nolan[17], J. Nyberg[32], A. Obertelli[5], J. Pakarinen[11,12], N. Pietralla[5], Zs. Podolyák[10], B. Quintana[26], R. Raabe[16], G. Rainovski[28], F. Recchia[24,25], P. Reiter[13], D. Rudolph[18], J. Simpson[3], Ch. Theisen[9], D. Tonev[29], A. Tumino[2,7], J.J. Valiente-Dobón[15], O. Wieland[21], K. Wimmer[19], M. Zielińska[9], and the AGATA Collaboration

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[31] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67037 Strasbourg, France
[32] Department of Physics and Astronomy, Uppsala University, SE-75120 Uppsala, Sweden
[33] Instituto de Física Corpuscular IFIC, CSIC-University of Valencia, E-46980 Paterna, Valencia, Spain
[34] Department of Physics, University of York, Heslington, York, YO10 5DD, United Kingdom
[35] Department of Physics, Ankara University, 06100 Tandogan, Ankara, Turkey

Received: date / Revised version: date

Abstract. New physics opportunities are opening up by the Advanced Gamma Tracking Array, AGATA, as it evolves to the full 4π instrument. AGATA is a high-resolution γ-ray spectrometer, solely built from highly segmented high-purity Ge detectors, capable of measuring γ rays from a few tens of keV to beyond 10 MeV, with unprecedented efficiency, excellent position resolution for individual γ-ray interactions, and very high count-rate capability. As a travelling detector AGATA will be employed at all major current and near-future European research facilities delivering stable and radioactive ion beams.

Submitted to EJP

AGATA at the FAIR/Super-FRS Facility

AGATA at the GANIL/SPIRAL Facility

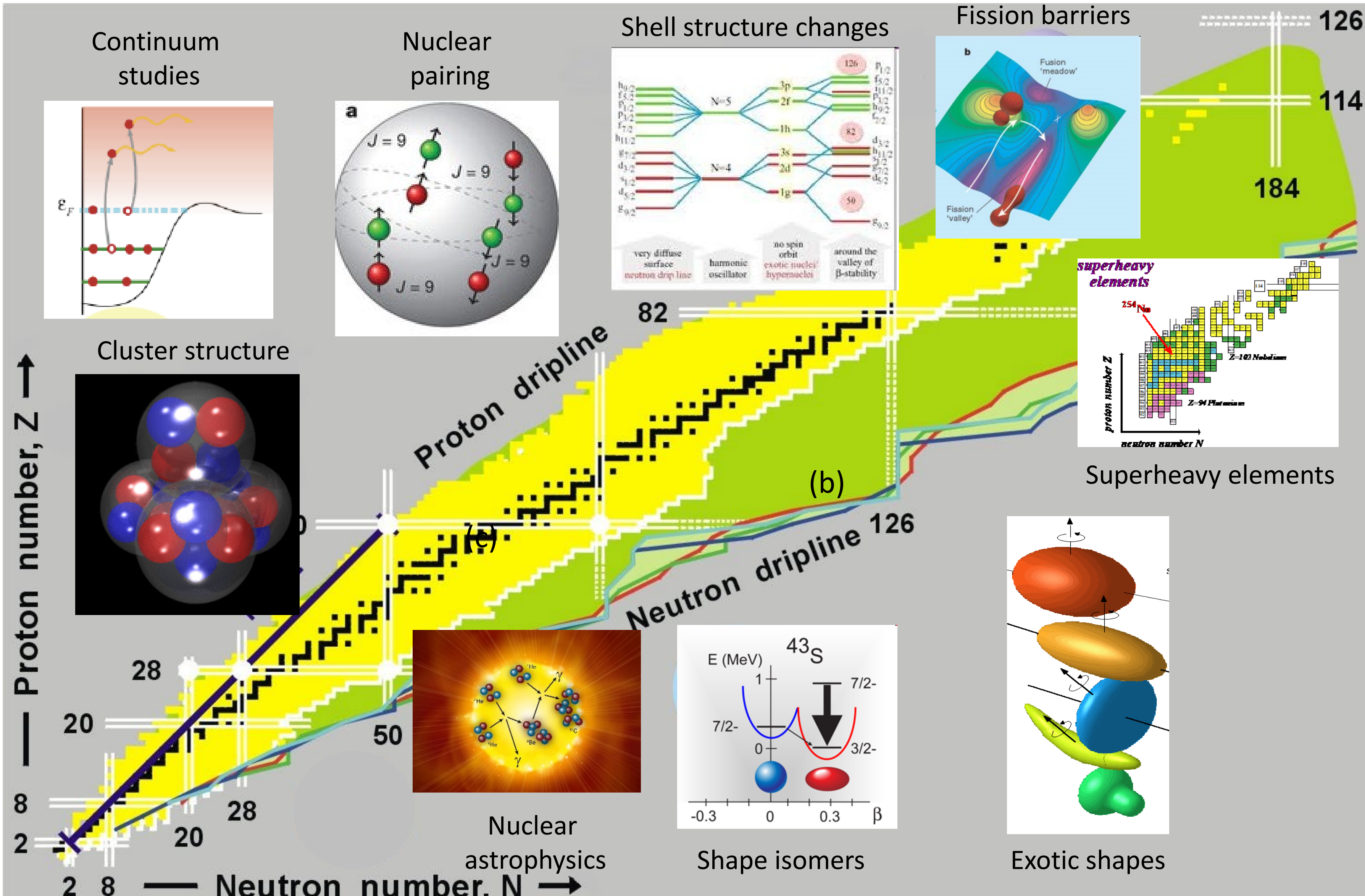
AGATA at the LNL/SPES Facility

SPES Project

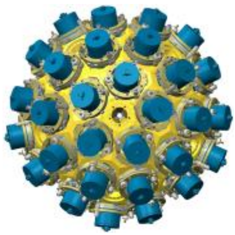
AGATA at HIE-ISOLDE

JYFL

AGATA science case

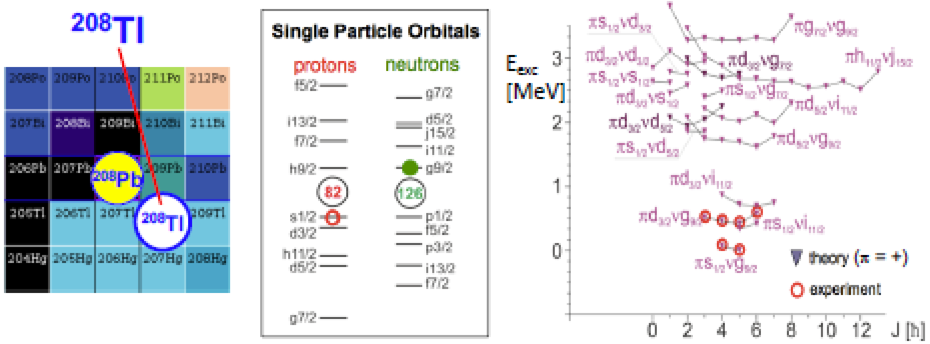


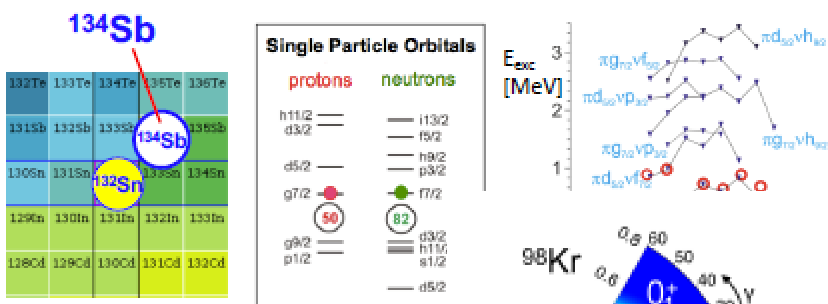
W. Korten



AGATA physics case

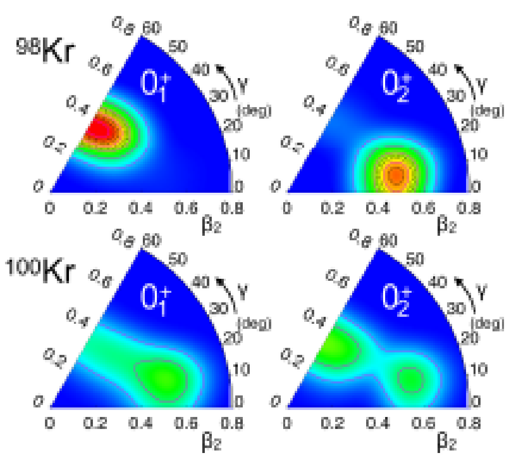
Nuclear Structure around doubly closed-shell nuclei



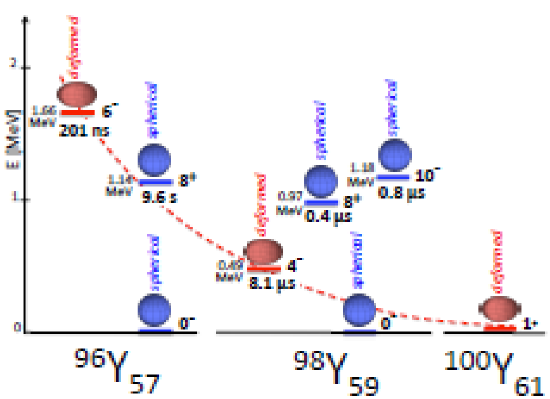


The Nuclear Shell Structure and its Evolution

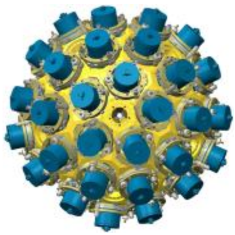
Light Exotic Nuclei and Clusterisation Phenomena

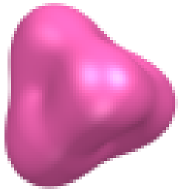


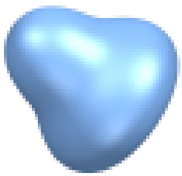
Shape coexistence



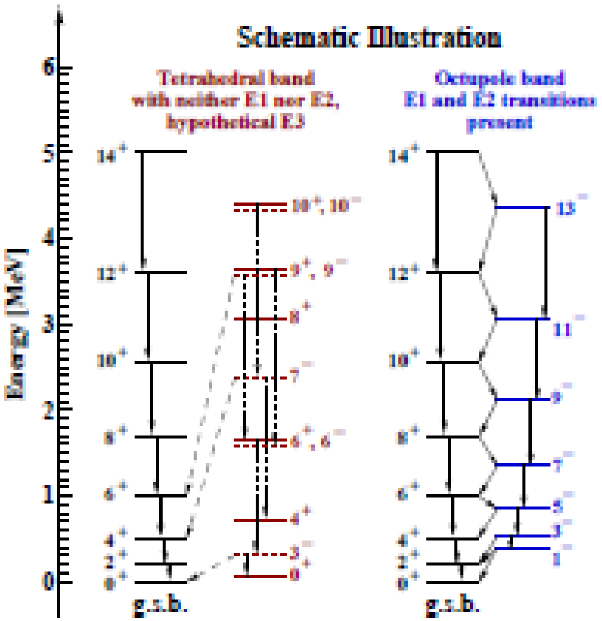
AGATA physics case



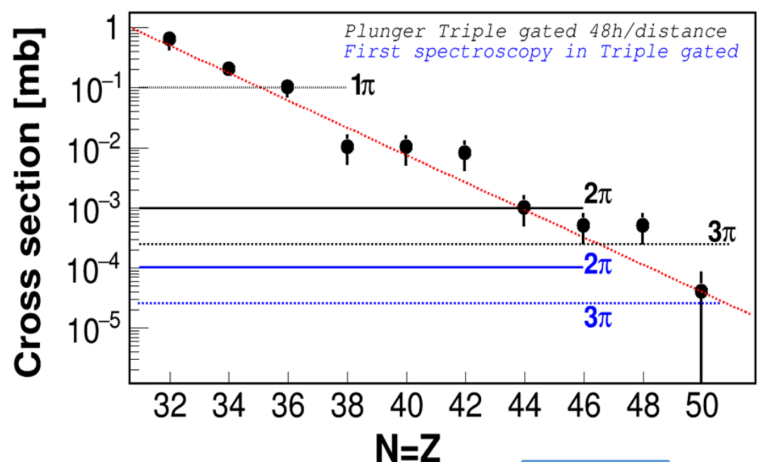


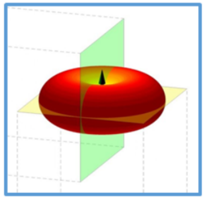


Higher-order nuclear deformation

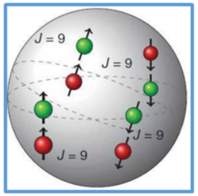


High resolution γ-ray spectroscopy along the N=Z line.



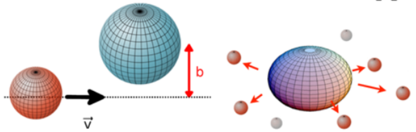


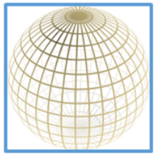
Forbidden E1 transition
Isospin symmetry breakir



Signatures for T= 0 pairing

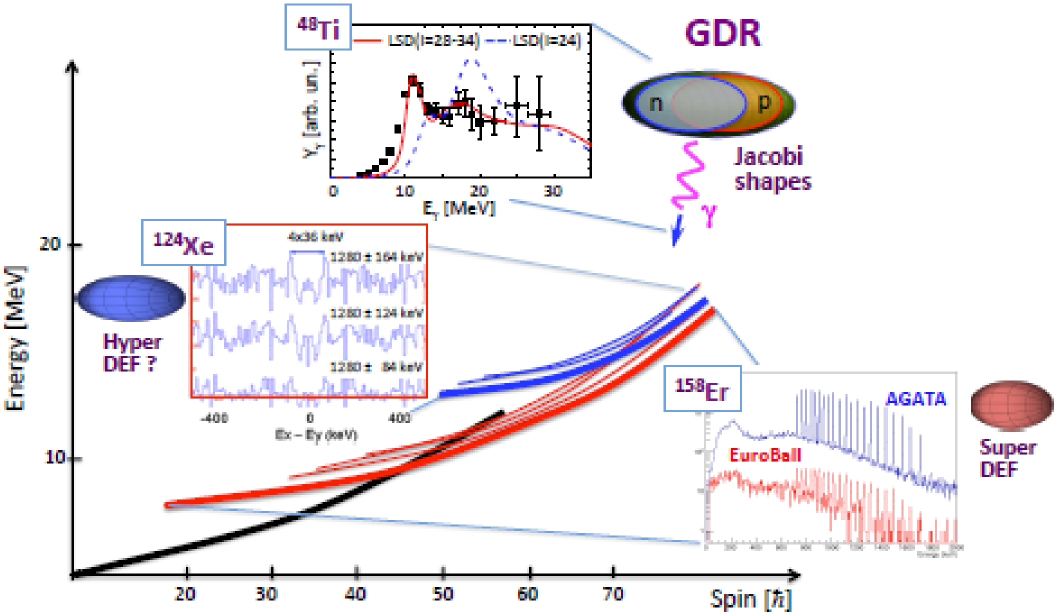
Isospin Symmetry Studies



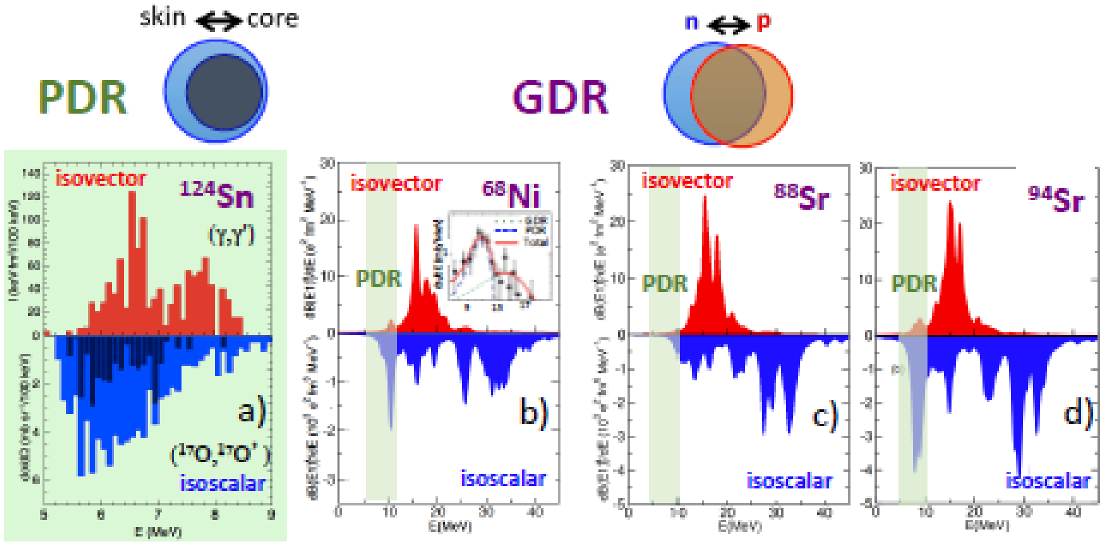


^{100}Sn magicity

AGATA physics case



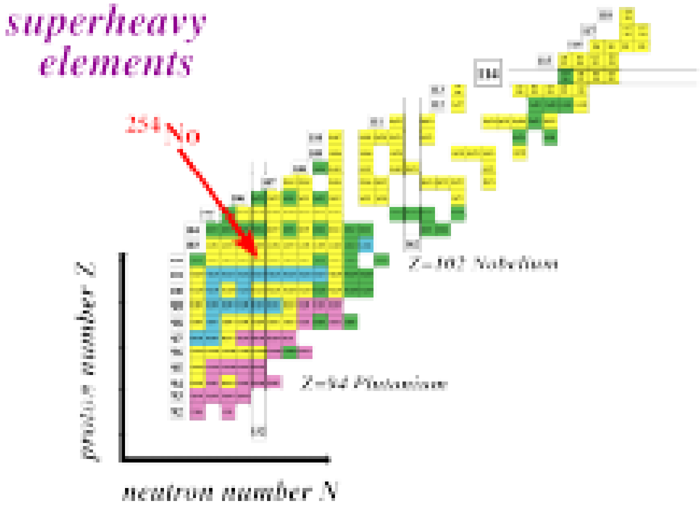
High-Spin States,
Extreme Deformation and
Giant Collective Modes

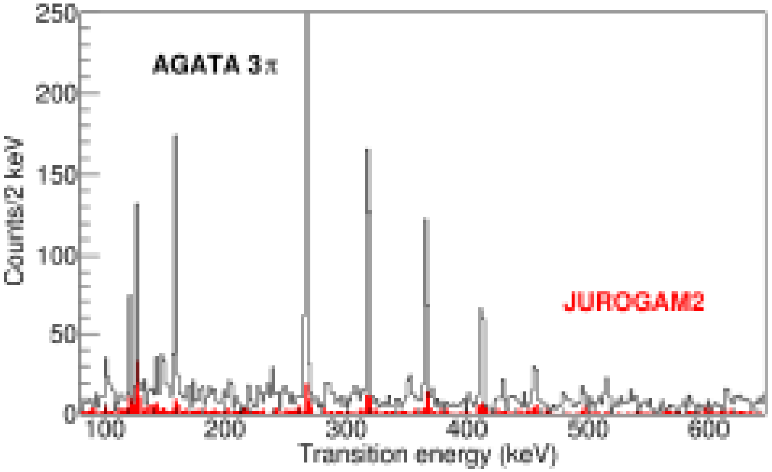


Pygmy Resonance
Excitations

AGATA physics case

Very Heavy and Superheavy Elements

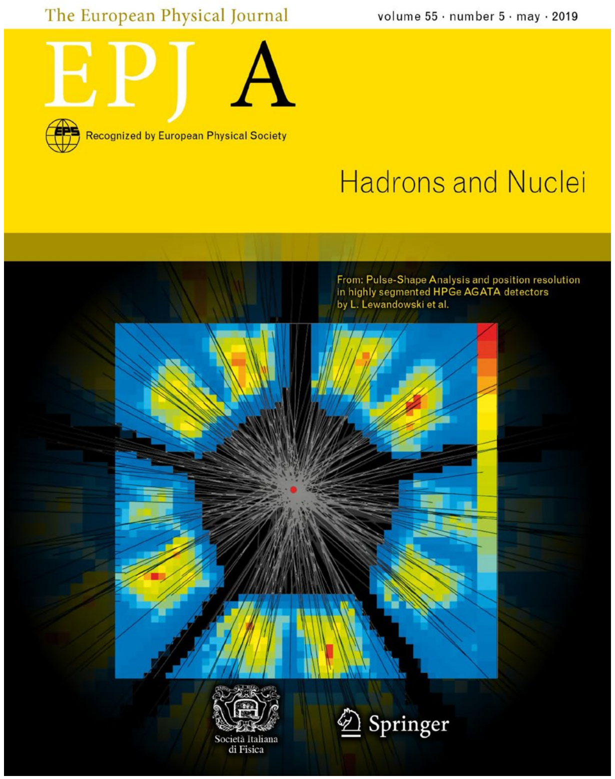


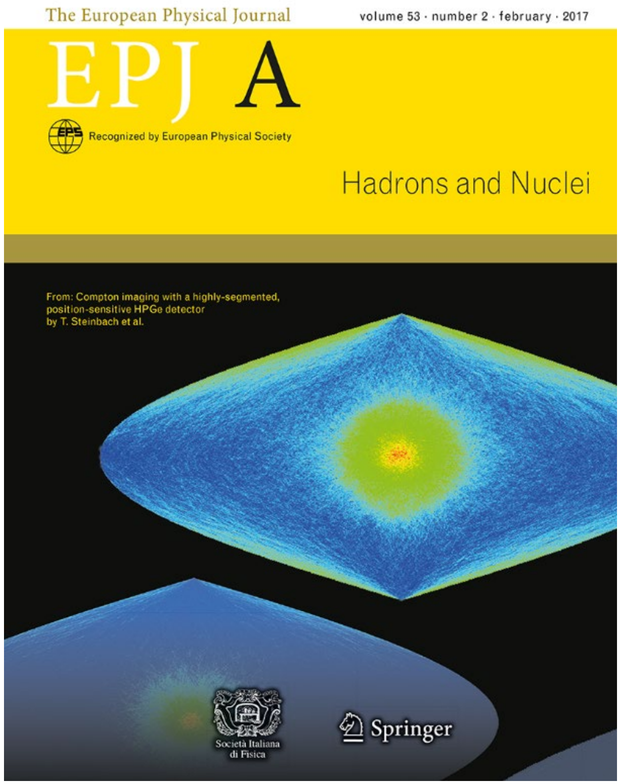


AGATA scientific results: technical publications

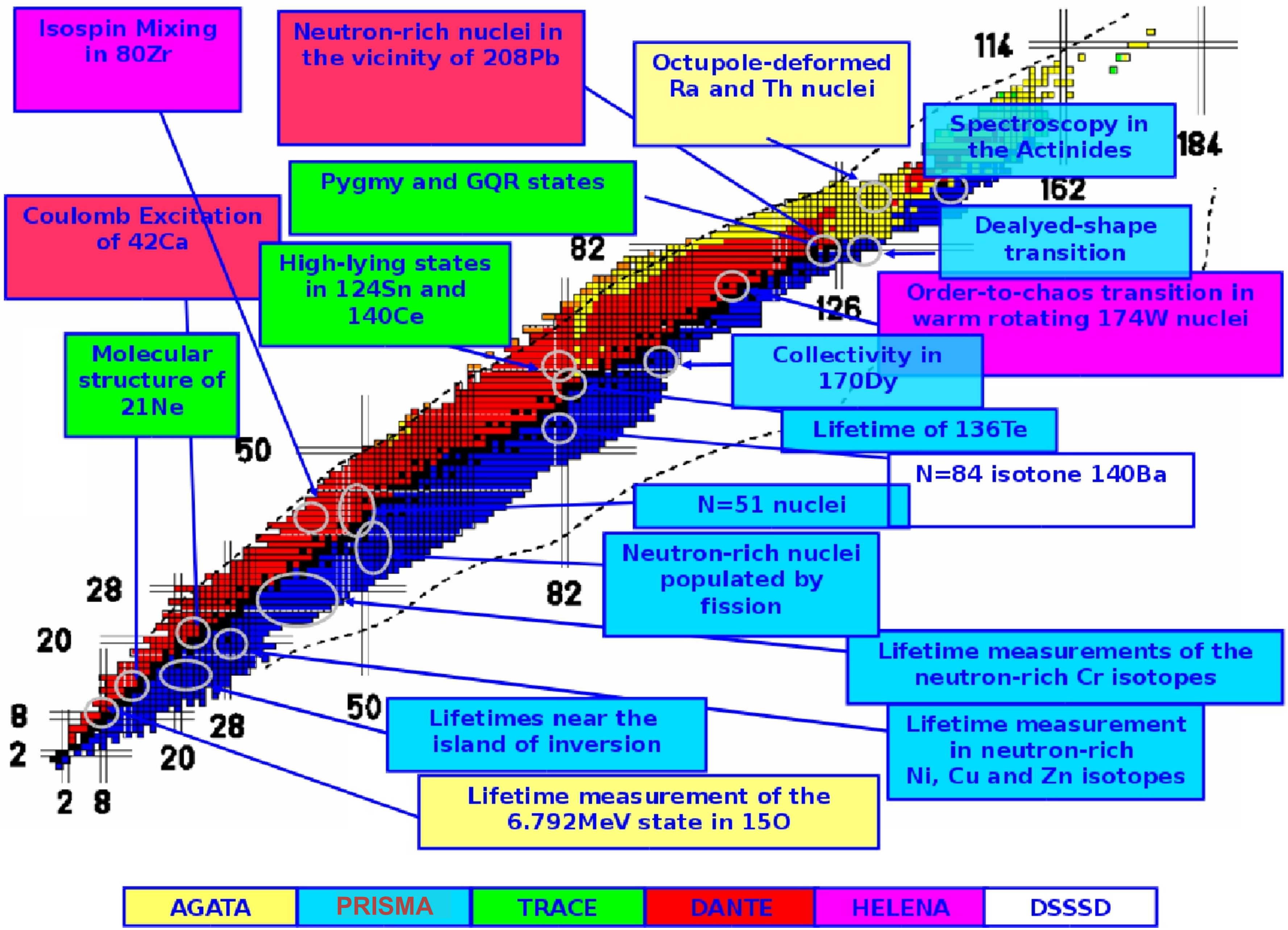
64 scientific publications (10 PRL/PL)
93 technical publications
Many PhDs, Masters, Diplomas, Bachelor)

https://www.agata.org/
http://npg.dl.ac.uk/agata_acc/AGATA_Publications.html





LNL EXPERIMENTS: 20 exps, 148 days, 3500 hs



GSI-PRESPEC Campaign: 7 runs

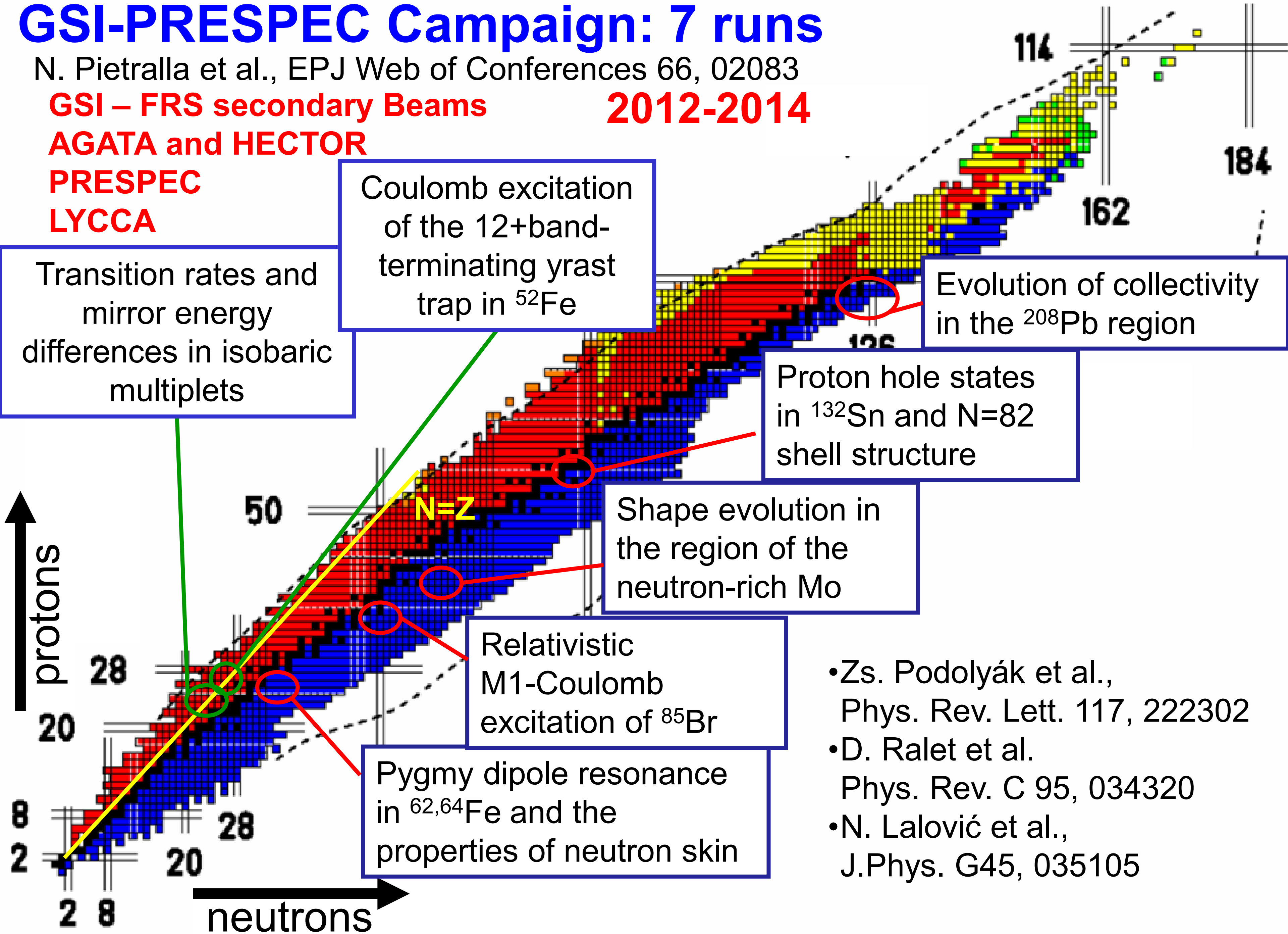
N. Pietralla et al., EPJ Web of Conferences 66, 02083

GSI – FRS secondary Beams **2012-2014**

AGATA and HECTOR

PRESPEC

LYCCA

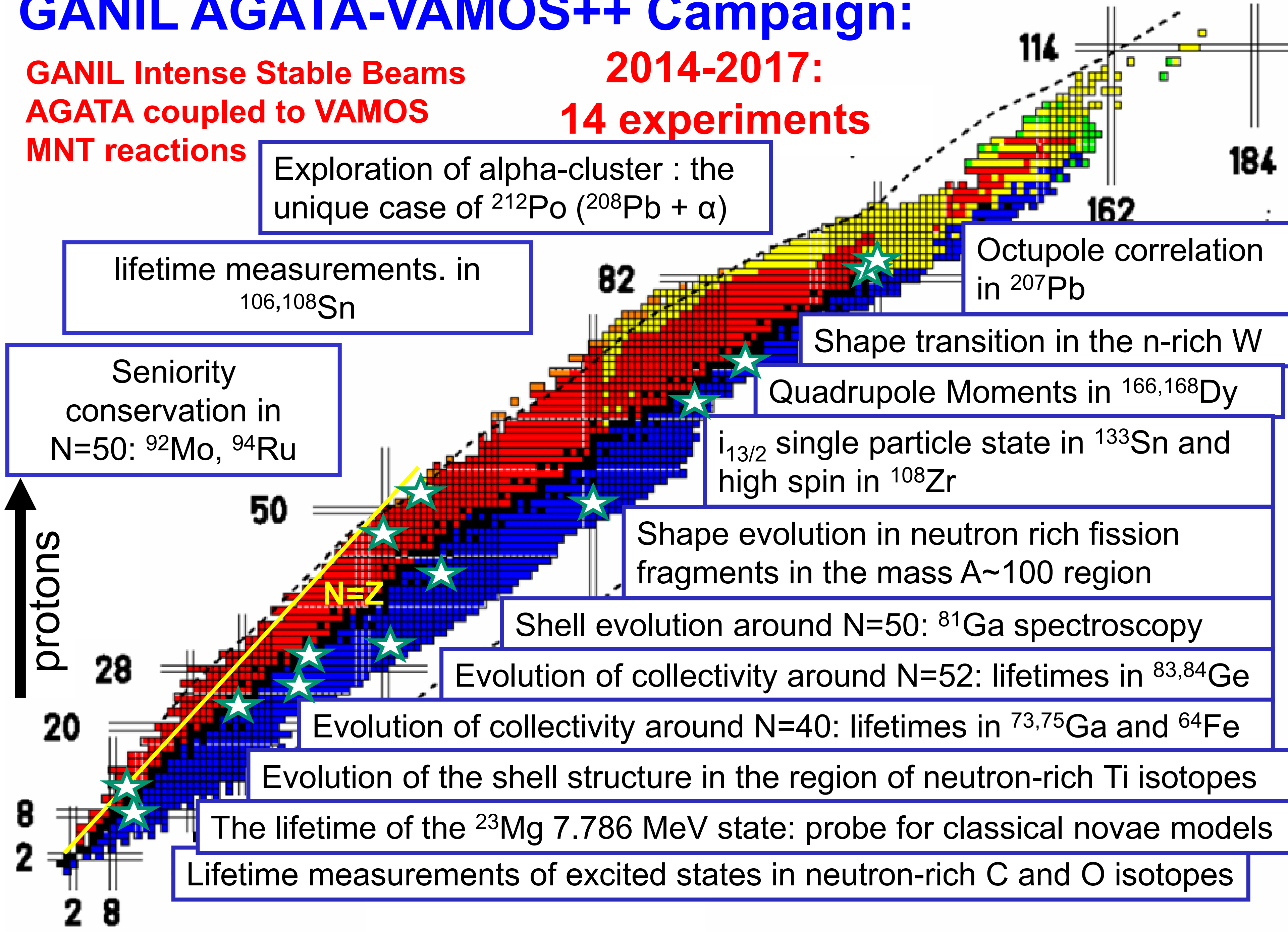


- Zs. Podolyák et al., Phys. Rev. Lett. 117, 222302
- D. Ralet et al. Phys. Rev. C 95, 034320
- N. Lalović et al., J.Phys. G45, 035105

GANIL AGATA-VAMOS++ Campaign:

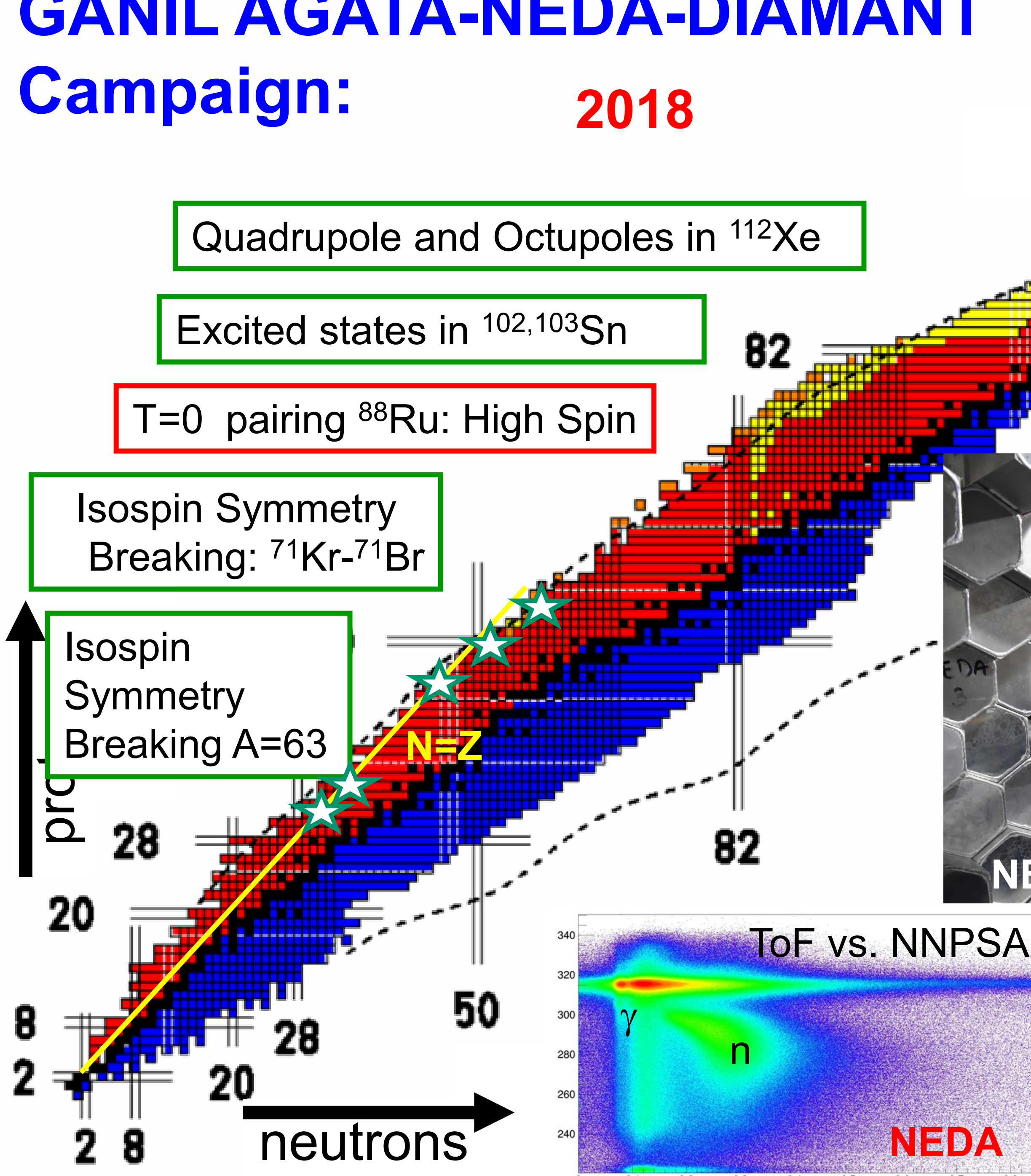
GANIL Intense Stable Beams
AGATA coupled to VAMOS
MNT reactions

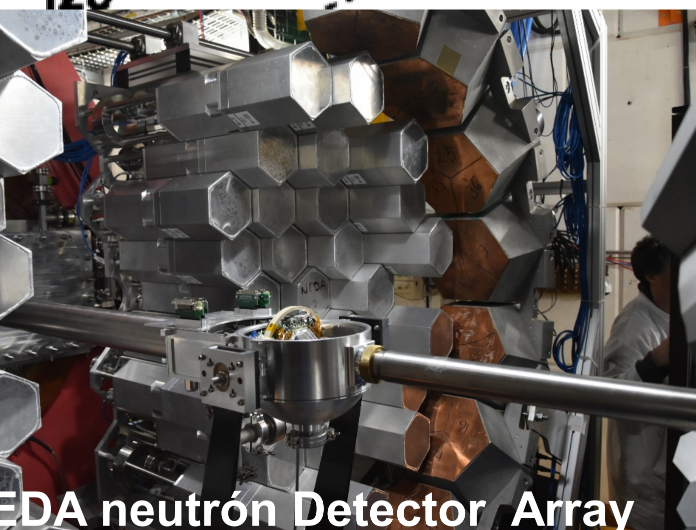
2014-2017:
14 experiments

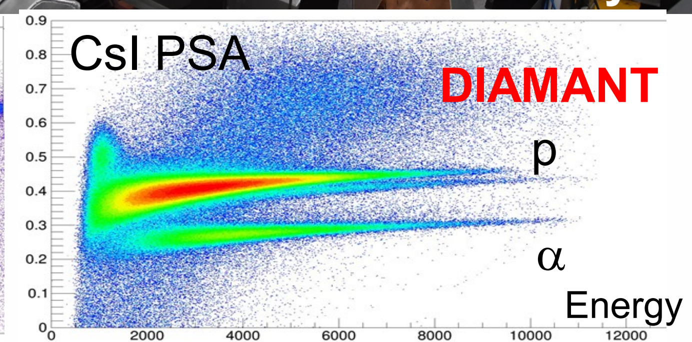


GANIL AGATA-NEDA-DIAMANT Campaign:

2018







PHYSICAL REVIEW LETTERS 124, 062501 (2020)

Feb 2020

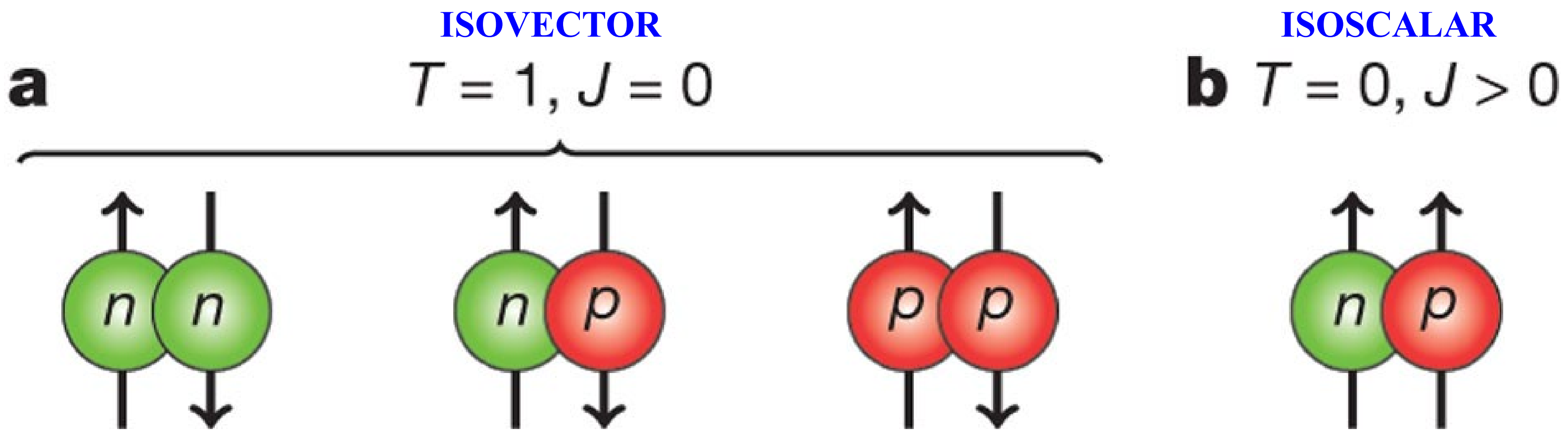
Isospin Properties of Nuclear Pair Correlations from the Level Structure of the Self-Conjugate Nucleus ^{88}Ru

B. Cederwall,[1,*] X. Liu,[1] Ö. Aktas,[1] A. Ertoprak,[1,2] W. Zhang,[1] C. Qi,[1] E. Clément,[3] G. de France,[3] D. Ralet,[4] A. Gadea,[5] A. Goasduff,[6] G. Jaworski,[6,7] I. Kuti,[8] B. M. Nyakó,[8] J. Nyberg,[9] M. Palacz,[7] R. Wadsworth,[10] J. J. Valiente-Dobón,[6] H. Al-Azri,[11] A. Ataç Nyberg,[1] T. Bäck,[1] G. de Angelis,[6] M. Doncel,[1,12] J. Dudouet,[13] A. Gottardo,[4] M. Jurado,[5] J. Ljungvall,[4] D. Mengoni,[6] D. R. Napoli,[6] C. M. Petrache,[4] D. Sohler,[8] J. Timár,[8] D. Barrientos,[14] P. Bednarczyk,[15] G. Benzoni,[16] B. Birkenbach,[17] A. J. Boston,[18] H. C. Boston,[18] I. Burrows,[19] L. Charles,[20] M. Ciemala,[15] F. C. L. Crespi,[21,22] D. M. Cullen,[23] P. Désesquelles,[24,25] C. Domingo-Pardo,[26] J. Eberth,[17] N. Erduran,[27] S. Ertürk,[28] V. González,[29] J. Goupil,[3] H. Hess,[17] T. Huyuk,[5] A. Jungclaus,[30] W. Korten,[31] A. Lemasson,[3] S. Leoni,[21,22] A. Maj,[15] R. Menegazzo,[32] B. Million,[22] R. M. Perez-Vidal,[26] Zs. Podolyak,[33] A. Pullia,[21,22] F. Recchia,[34] P. Reiter,[17] F. Saillant,[3] M. D. Salsac,[31] E. Sanchis,[29] J. Simpson,[19] O. Stezowski,[35] Ch. Theisen,[31] and M. Zielińska[31]

ABSTRACT

The low-lying energy spectrum of the extremely neutron-deficient self-conjugate ($N = Z$) nuclide $^{88}_{44}Ru_{44}$ has been measured using the combination of the Advanced Gamma Tracking Array (AGATA) spectrometer, the NEDA and Neutron Wall neutron detector arrays, and the DIAMANT charged particle detector array. Excited states in ^{88}Ru were populated via the $^{54}Fe(^{36}Ar, 2n\gamma)^{88}Ru^{*}$ fusion-evaporation reaction at the Grand Acc'el'erateur National d'Ions Lourds (GANIL) accelerator complex. The observed γ-ray cascade is assigned to ^{88}Ru using clean prompt γ-γ-2-neutron coincidences in anti-coincidence with the detection of charged particles, confirming and extending the previously assigned sequence of low-lying excited states. It is consistent with a moderately deformed rotating system exhibiting a band crossing at a rotational frequency that is significantly higher than standard theoretical predictions with isovector pairing, as well as observations in neighboring $N > Z$ nuclides. The direct observation of such a "delayed" rotational alignment in a deformed $N = Z$ nucleus is in agreement with theoretical predictions related to the presence of strong isoscalar neutron-proton pair correlations.

Neutron-proton pairing in N = Z nuclei



Search for np T=0 pairing in heavy N=Z nuclei

Evidence for np T=0 pairing elusive

T=0 pairing less susceptible to Coriolis alignment, correlations persist to high rotational frequency

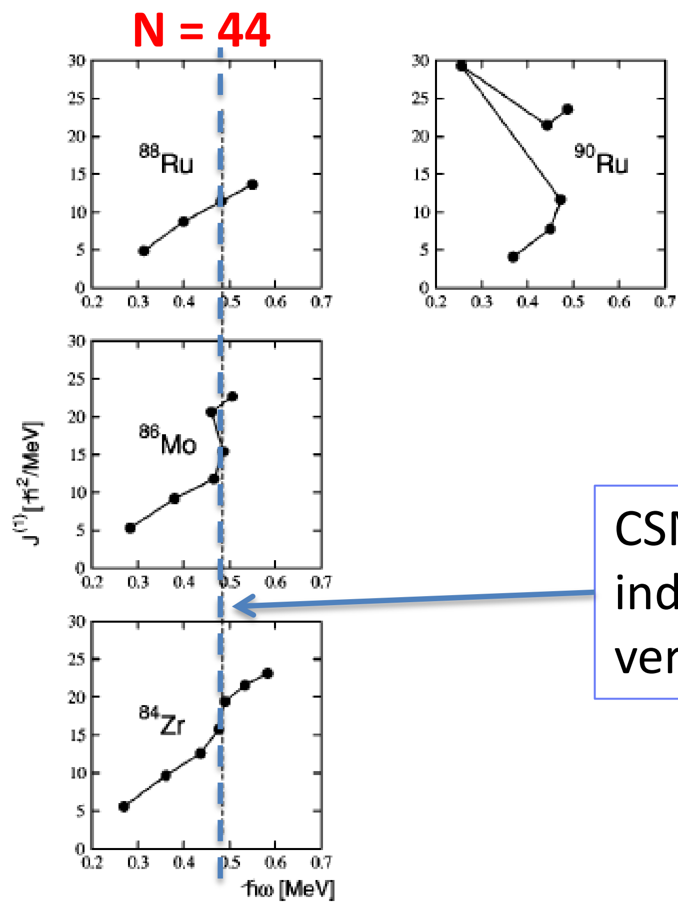
Look for delayed alignments

Experimentally challenging

S. Frauendorf, A.O. Macchiavelli, Prog. in Particle and Nuclear Physics 78, 24 (2014)

Spectroscopy as a probe of T=0 pairing in deformed ^{88}Ru

Previous work

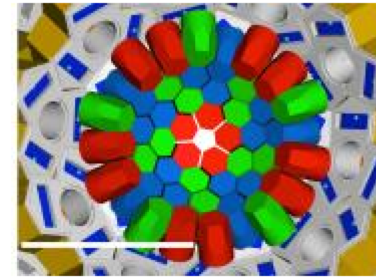


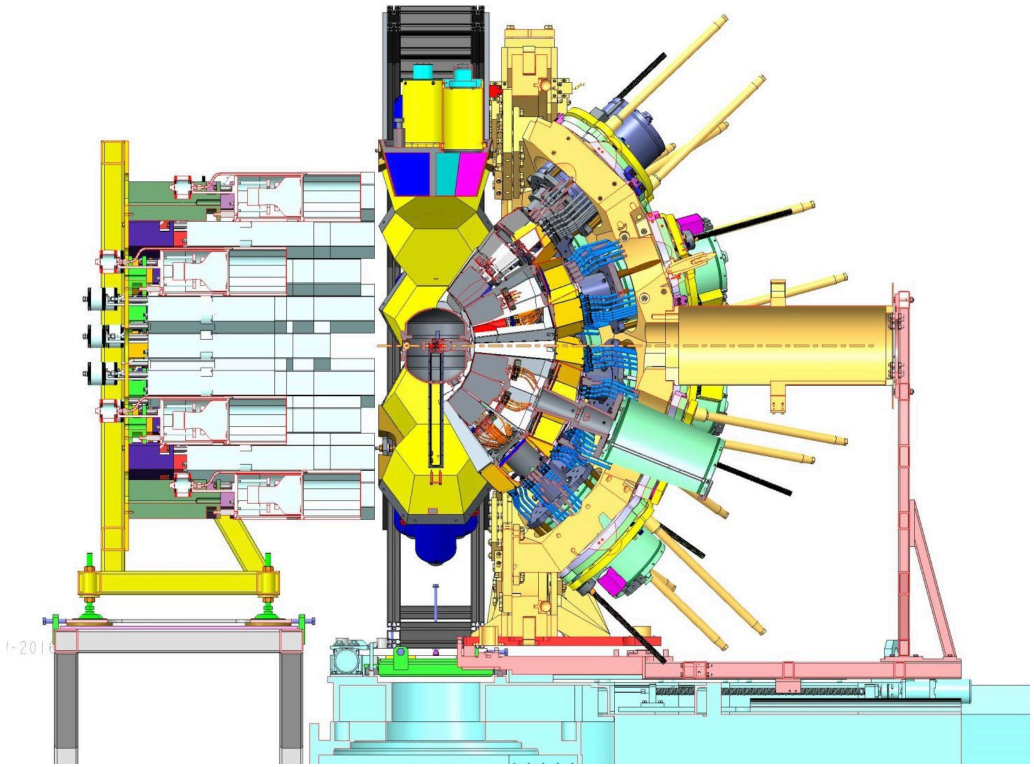
CSM predictions indicated by the vertical dashed line

Search for Data tentatively suggest that there is a shift in the alignment frequency of the $g_{9/2}$ quasiparticles for the N=Z=44 nucleus ^{88}Ru with respect to (a) the T ≠ 0 cases and (b) predictions from CSM calculations including standard T=1 BCS pairing.

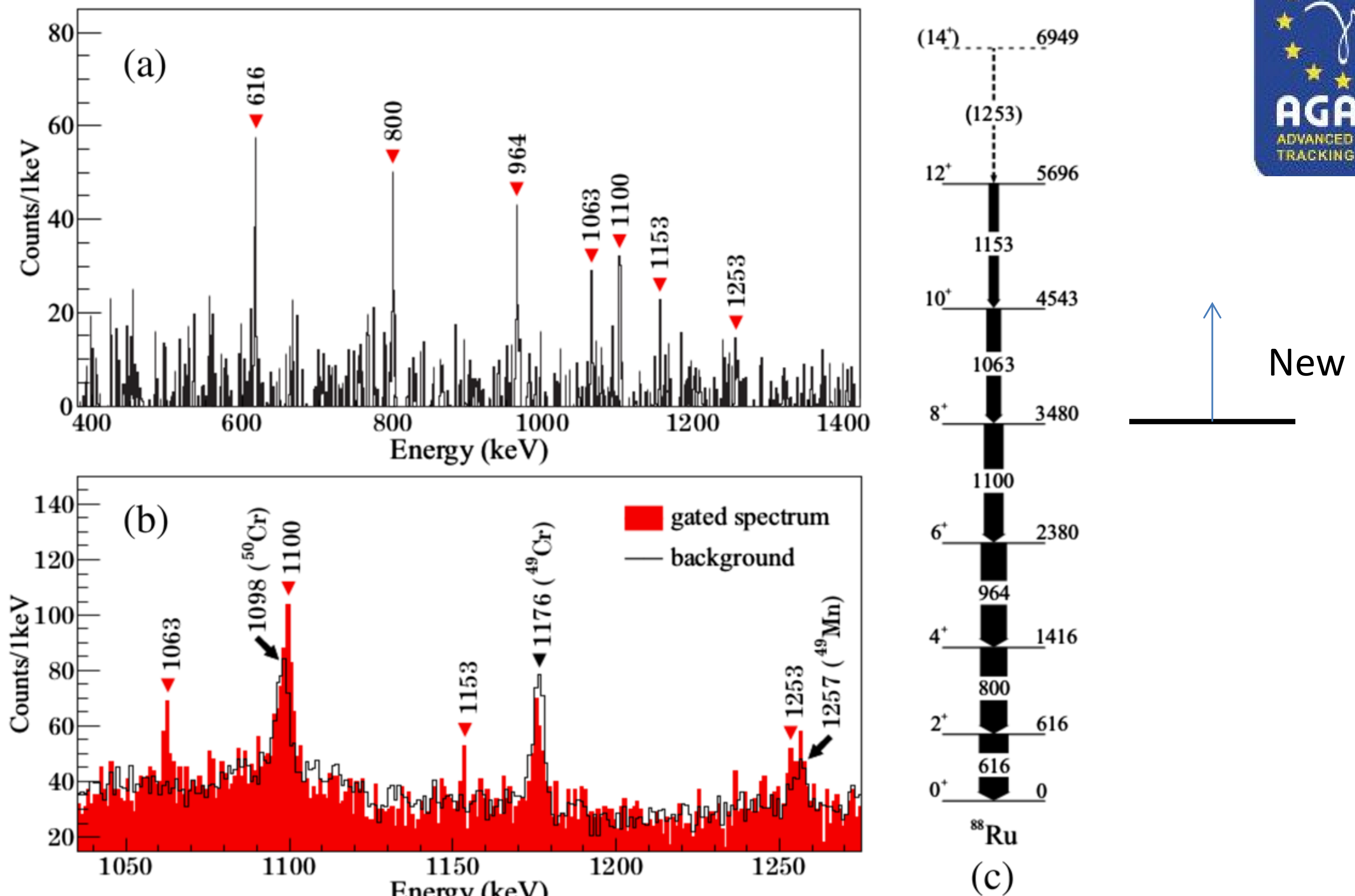
Need data in the spin 10-16 range to test if there is a delayed alignment that can be accounted for within the normal T=1 pairing scheme or if T=0 pairing must be invoked


^{88}Ru to high spin
Experimentally challenging
Need state of the art instrumentation



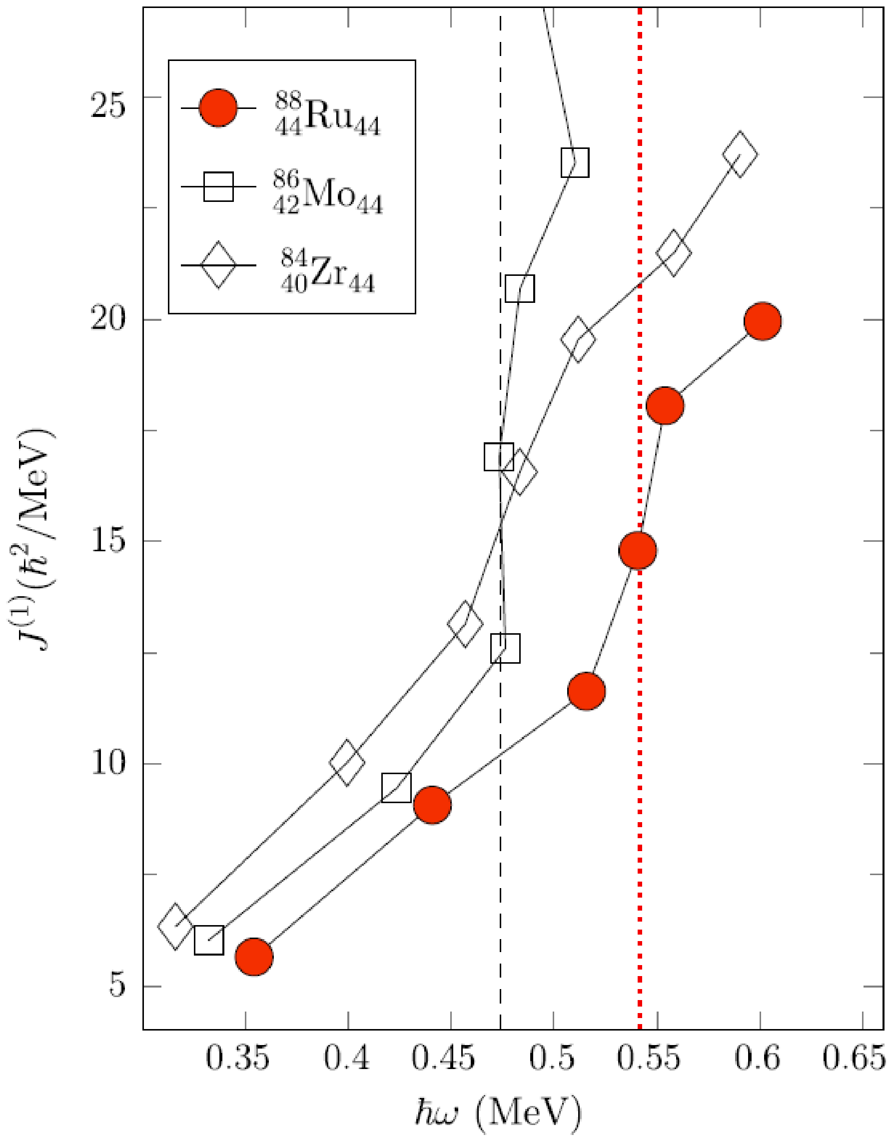


Reaction : $^{36}Ar + ^{54}Fe \rightarrow ^{88}Ru + 2n$ (E_{beam} = 115 MeV)
AGATA+NEDA/NWALL+DIAMANT
13 days



Summed γ-γ spectrum--2n-no charged particle recorded condition

Full power-resolution-AGATA-plus selection, weak channel, few μb



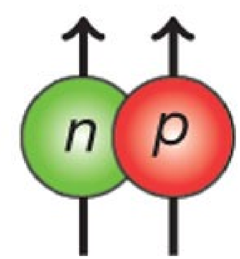
Delayed alignment $(\pi g9/2)^2$

Compared with N>Z neighbours

Consistent with isoscalar pairing
In ^{88}Ru (T=0)

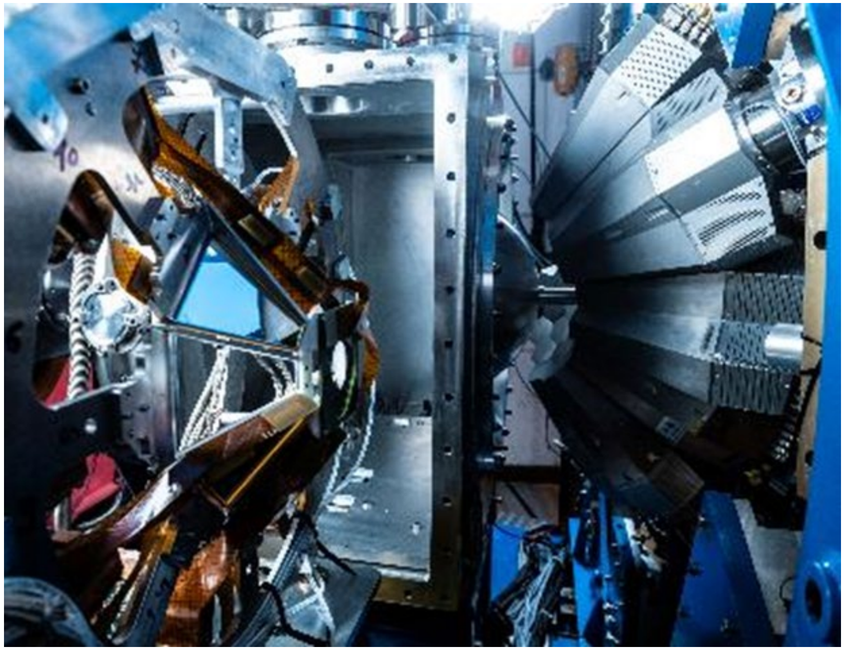
ISOSCALAR

$T = 0, J > 0$



GANIL

- 25 experiments run to 2019
- The GANIL campaign is proceeding now with SPIRAL1 beams in the AGATA+ MUGAST+VAMOS++ Setup.
- The campaign at GANIL will continue until 2021.
- In 2022 AGATA will start a new campaign at LNL with **stable beams** and will continue with SPES beams when available



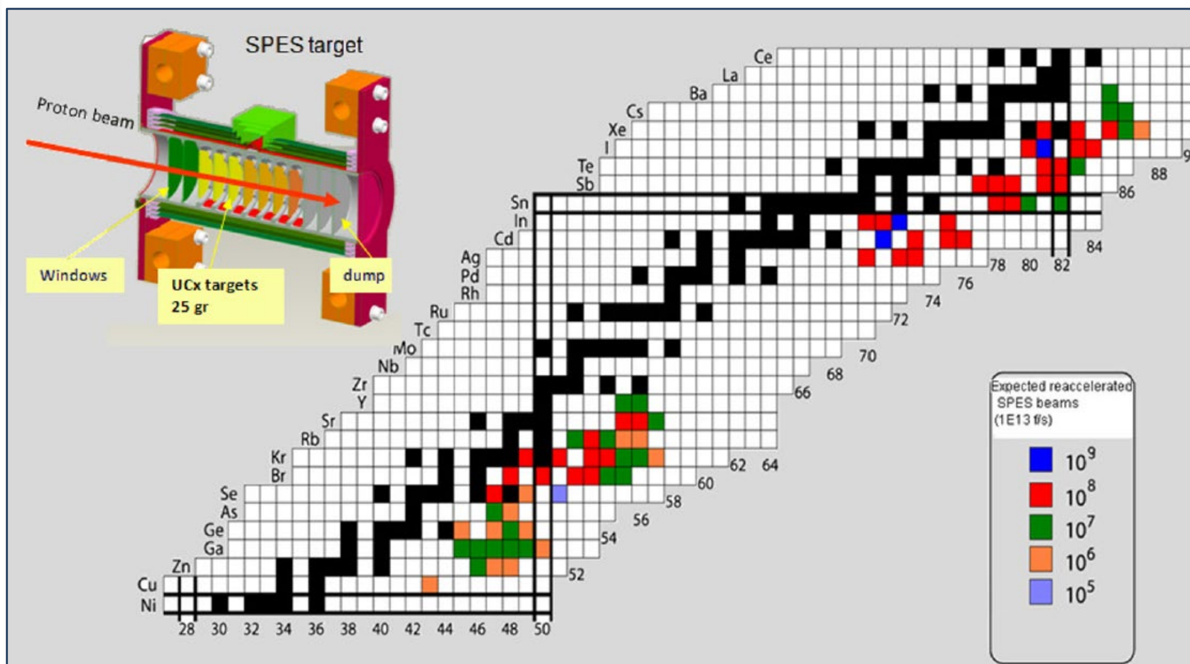
AGATA@SPES: 2023-2025

Selective Production of Exotic Species

SPES exotic beams for science

- SPES is a new ISOL radioactive-beam facility under development at LNL, Italy
- Protons from new cyclotron incident on uranium carbide targets
- Reacceleration up to **10 MeV/A** using ALPI superconducting linac
- Development in phases: 2021 to 2023

- **Unique** aspect of SPES: high intensity primary proton beam
- Protons will induce 10^{13} fissions/s
- For example: ^{94}Rb - 10^9 pps; ^{132}Sn - 10^8 pps; ^{142}Xe - 10^6 pps
- **High-intensity radioactive beams**

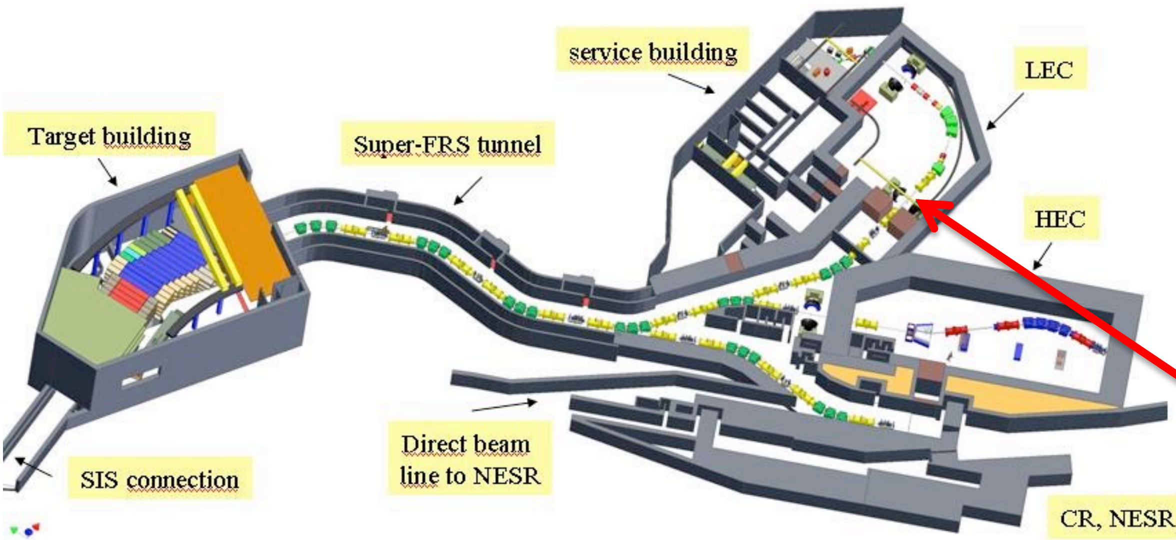


Techniques (e.g.):

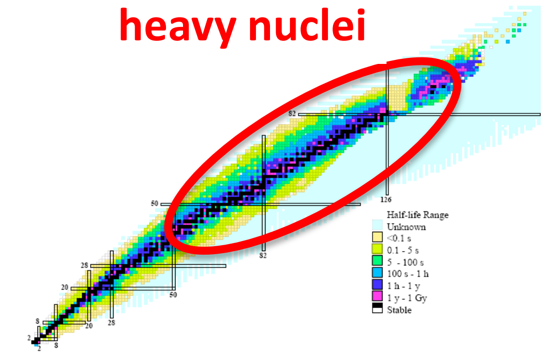
- **Nucleon transfer**
- **Deep-inelastic reactions**
- **Low-energy Coulomb excitation**
- **Fusion evaporation**

AGATA@FAIR: ≥ 2025

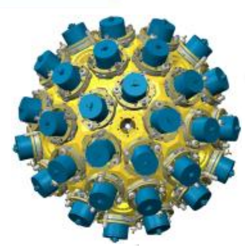
High-resolution γ-ray **spec**troscopy (**HISPEC**) following reactions induced by radioactive ion beams at relativistic energies

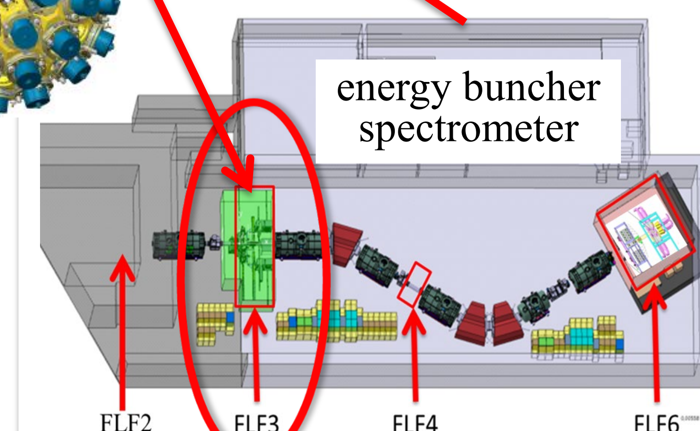


Unique place to study heavy nuclei



- **High-intensity exotic beams: p-rich and n-rich**
- High-energy **100-300 MeV/A** (**β~0.5**)
- Isomeric beams & high-Z beams





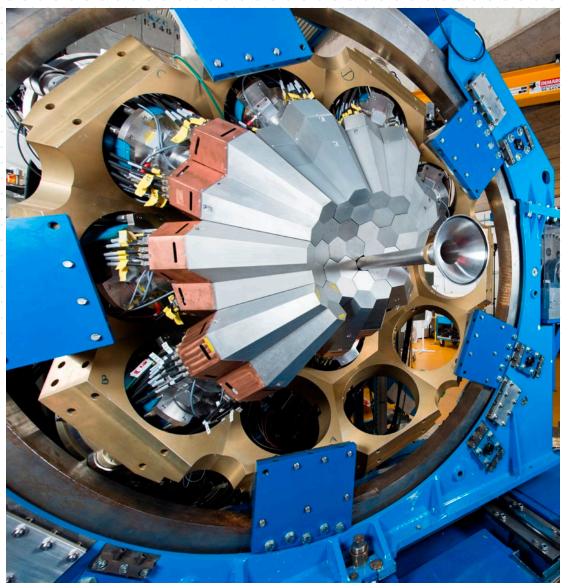
Techniques (e.g.):

- **Fragmentation**
- **Knockout**
- **High-energy Coulomb excitation**

AGATA many applications

Scientific Research Curiosity

Applications



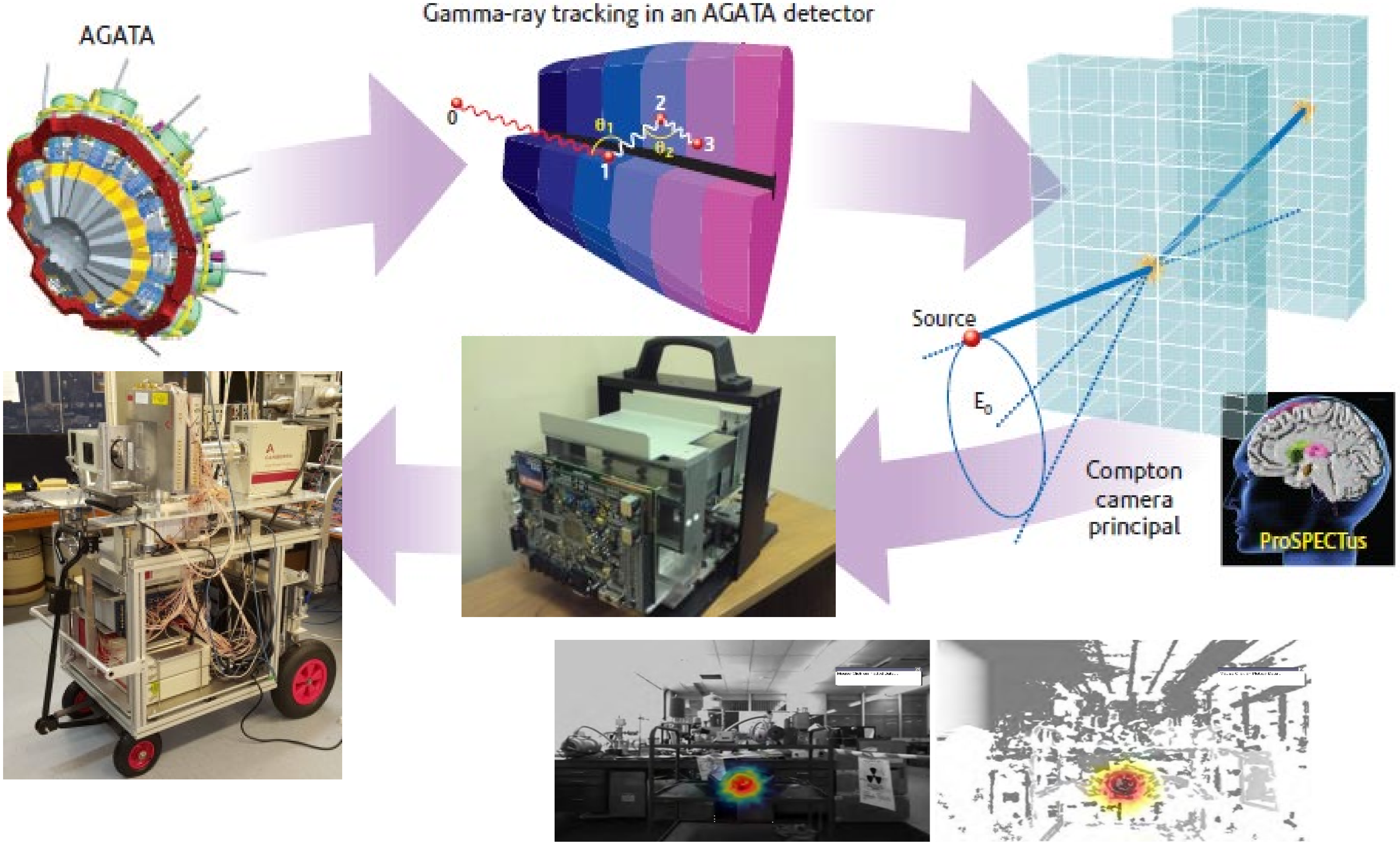
State of the art detectors

Medical

Security

Environment

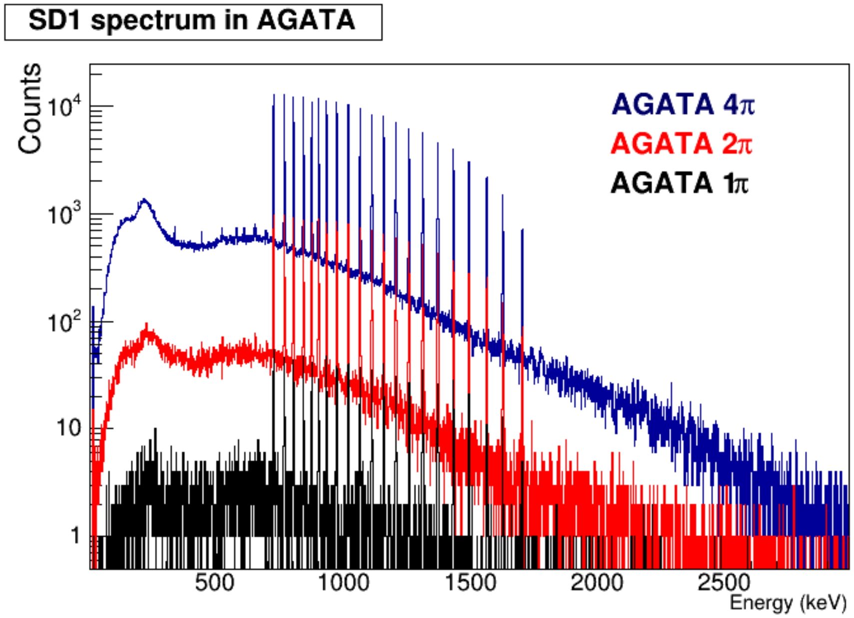
From AGATA to Portable Imaging

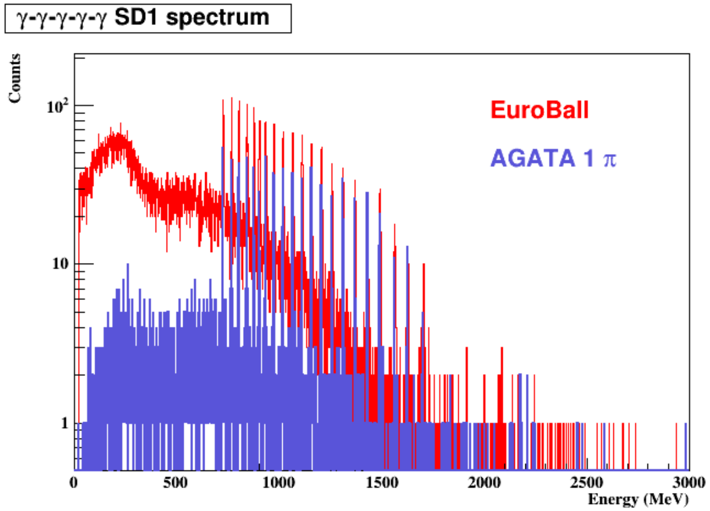


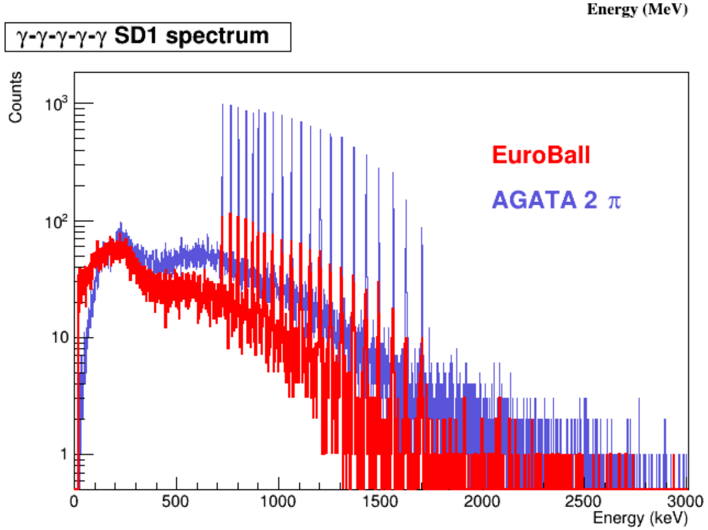

Thank you
UKRI
Science and Technology Facilities Council

Science and
Technology
Facilities Council

Agata High Spin Simulations

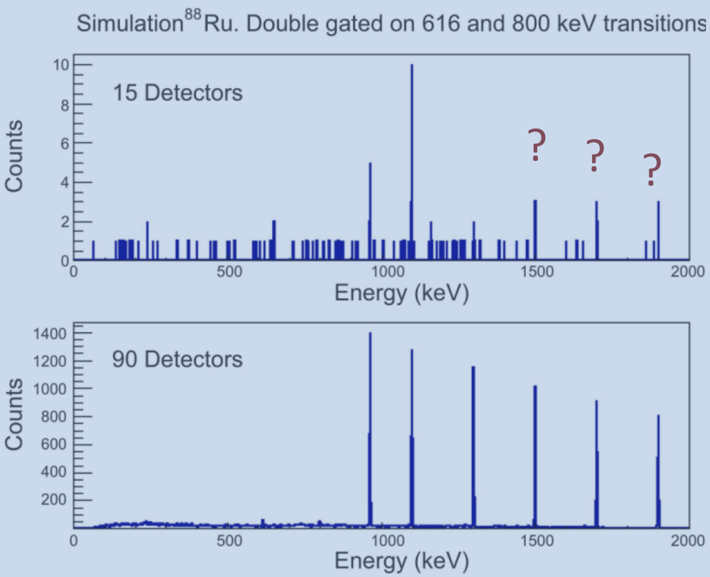


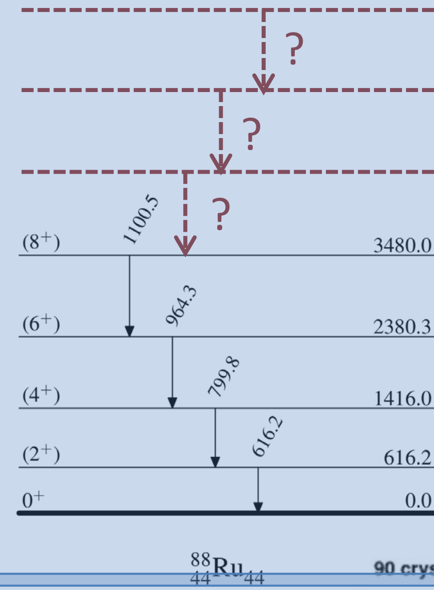




Courtesy of Marc Labiche AGATA simulation code (GEANT)

Simulations from 15 → 90 detectors:





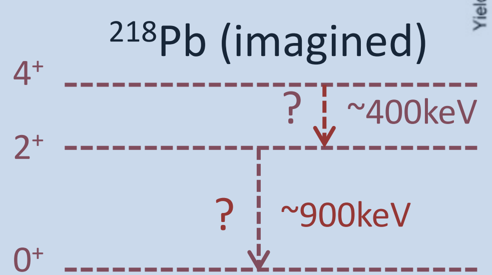
SPES-type example

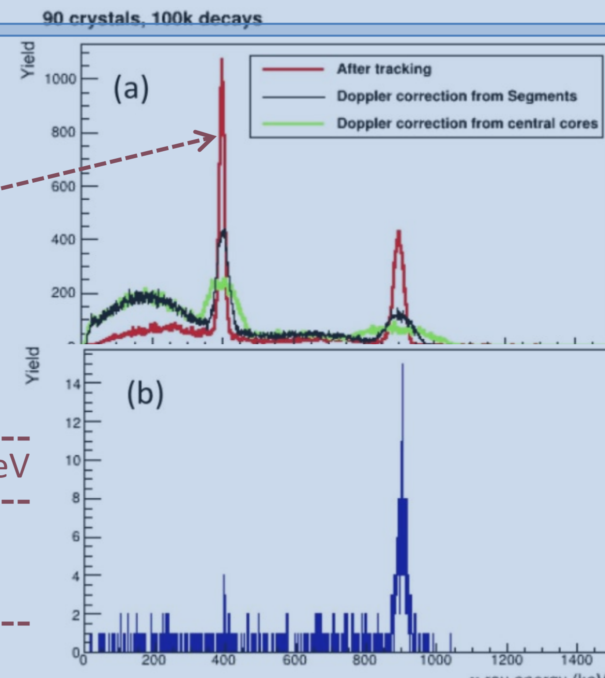
- Typical reaction, v/c ~ 5%
- Multiple coincident gammas
- "Statistical reaction"
- γ-γ, and γ-γ-γ analysis
- Factor ~200 better for γ-γ-γ

FAIR-type example

- Typical reaction, v/c ~ 50%
- Huge Doppler effects
- "direct reaction"
- γ- and γ-γ analysis
- Factor ~30 better for γ-γ

Position resolution essential





AGATA
ADVANCED GAMMA TRACKING ARRAY