Gamma spectroscopy with AGATA: New insights in nuclear excitations along the nuclear chart

- γ-ray tracking
- Physics campaigns
- High energy γ rays & E1 strength
- Isospin symmetrie
- Lifetime measurements
- Outlook

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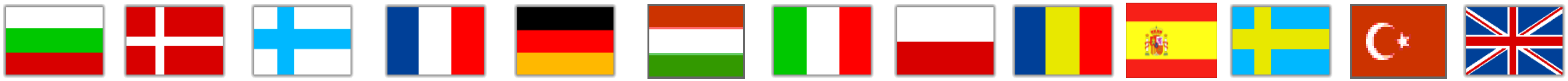
Institute of Nuclear Physics, University of Cologne

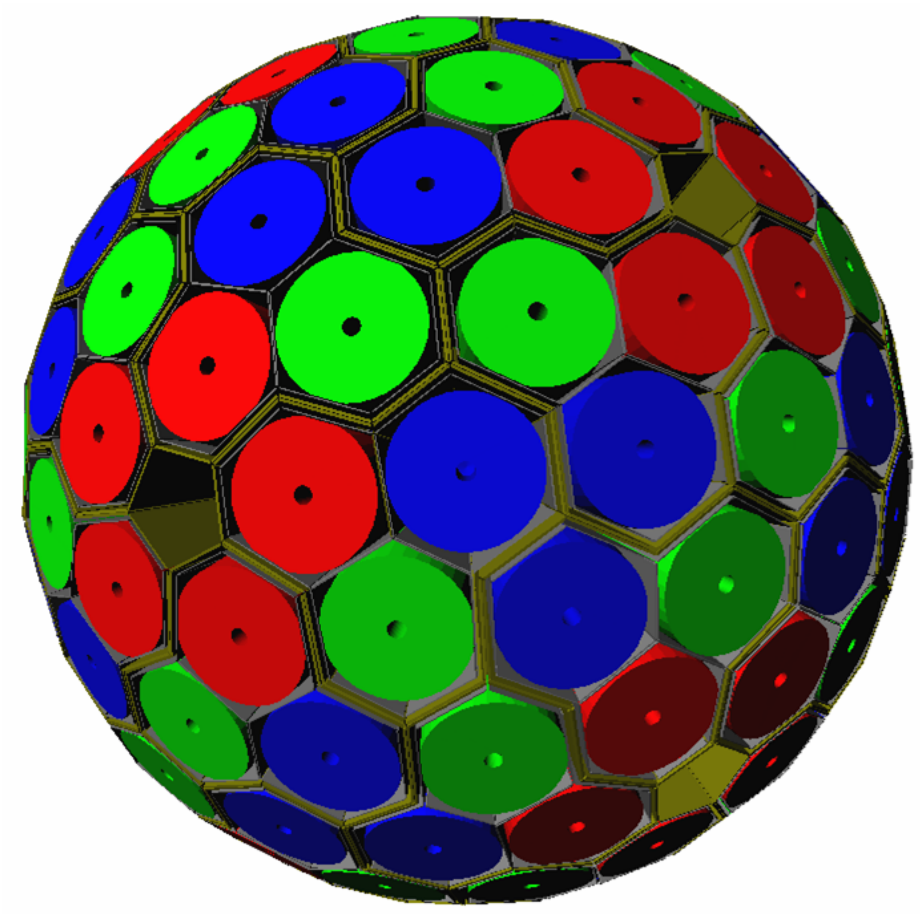
DPG Spring Meeting 2024

Justus-Liebig-Universität Gießen

Advanced GAmma Tracking Array



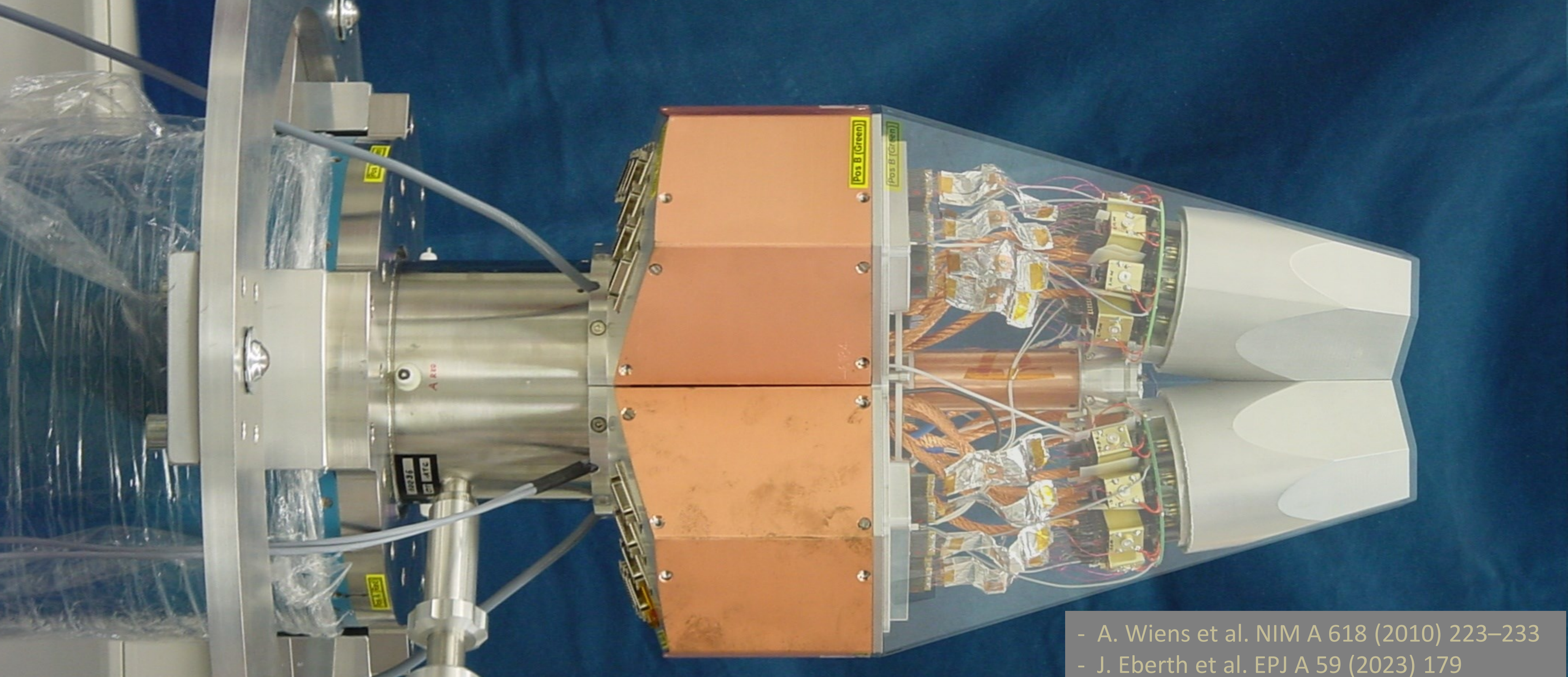
13 Countries, 41 Institutions



180 hexagonal HPGe crystals	3 shapes
36-fold segmentation	6480 segments
60 triple-clusters	
Solid angle coverage	82 %
Inner radius (Ge)	23.5 cm
Efficiency: 43%	Peak/Total: 58%

AGATA Triple Cryostat

- integration of 111 high resolution spectroscopy channels
- 23 AGATA triple cryostats assembled at IKP, Cologne

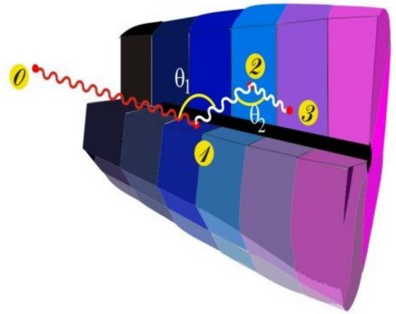


- A. Wiens et al. NIM A 618 (2010) 223–233
- J. Eberth et al. EPJ A 59 (2023) 179

Ingredients of γ-ray tracking

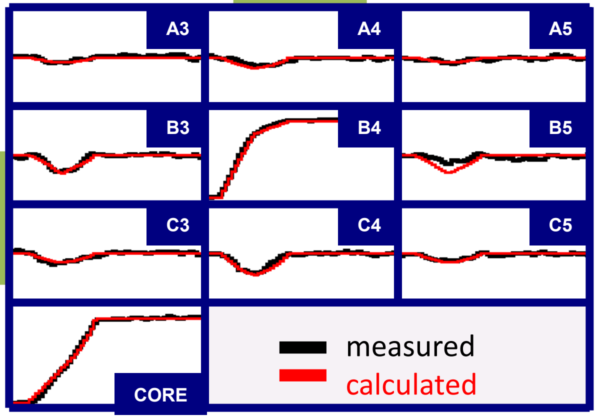
1

Highly segmented HPGe detectors



2

Digital electronics
record & process
segment signals



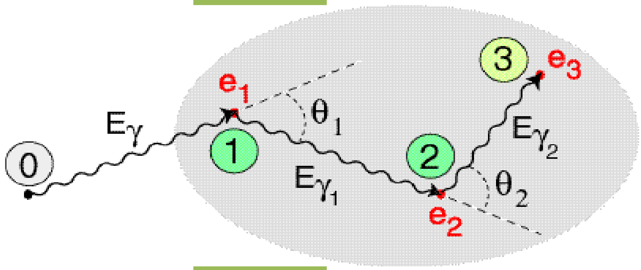
3

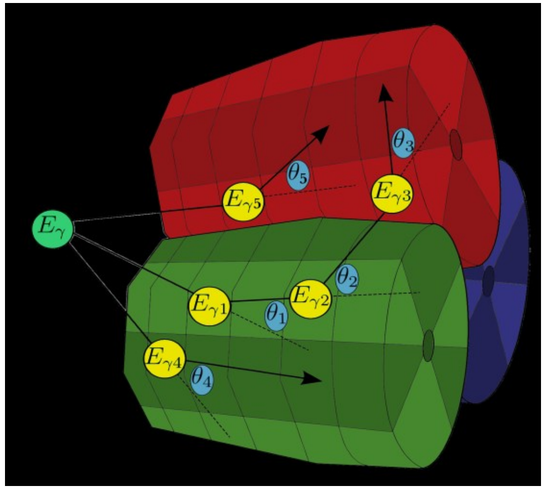
Pulse Shape Analysis
decompose
recorded waves

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

4

γ-ray tracking
Reconstruct & evaluate
interaction points





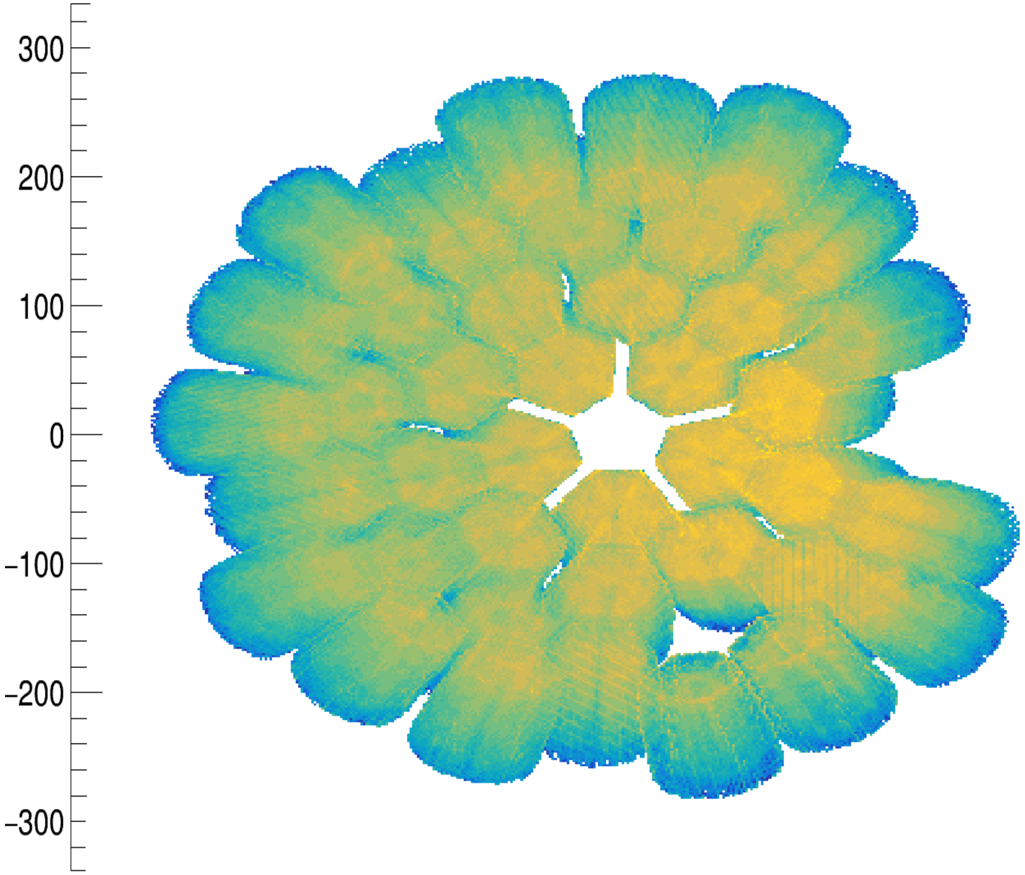
Reconstructed gamma-rays

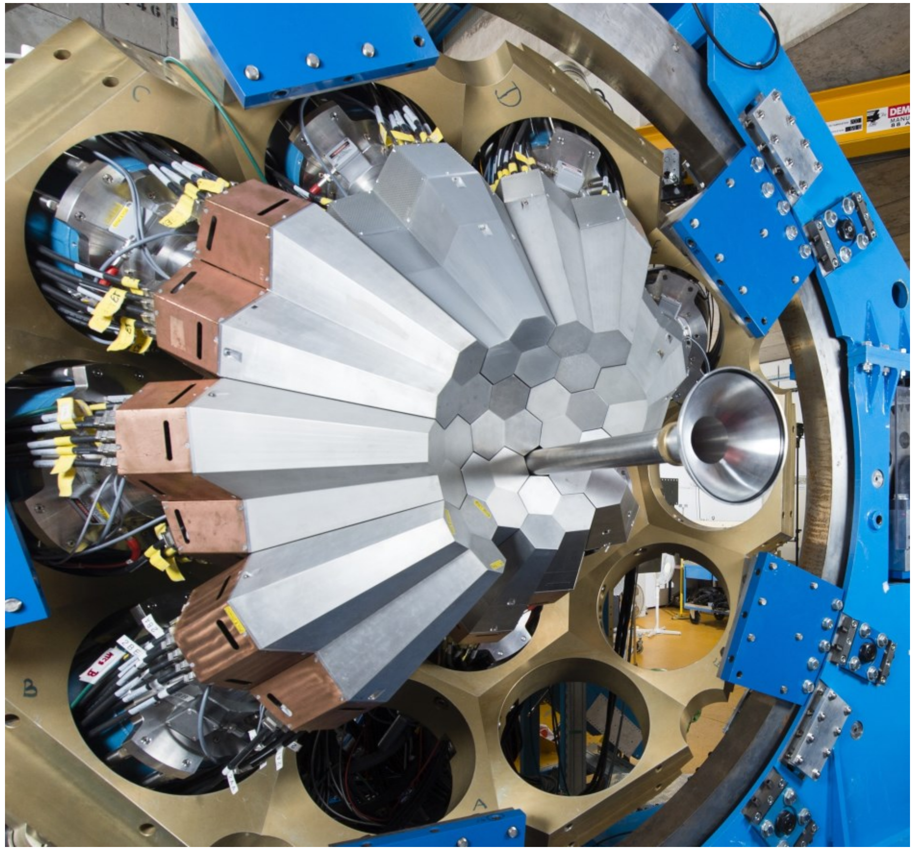
AGATA
ADVANCED GAMMA TRACKING ARRAY

Result of AGATA tracking

Reconstructed initial gamma rays with: - gamma ray energy
- 1st interaction position → Doppler correction
- 2nd interaction position → Polarization
- position resolution < 4 mm FWHM

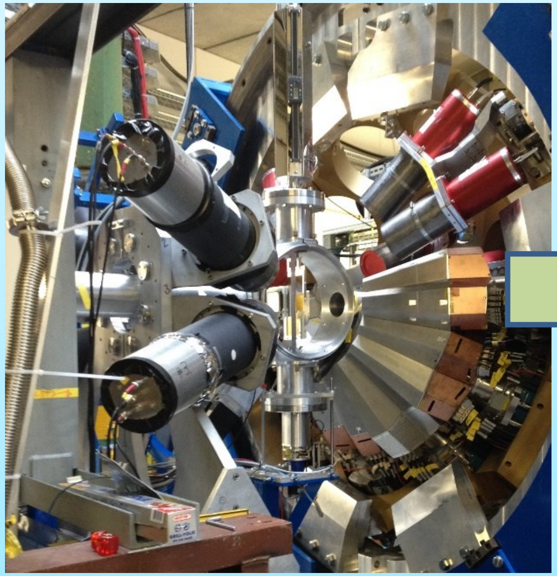
1st interaction positions
after PSA and Tracking





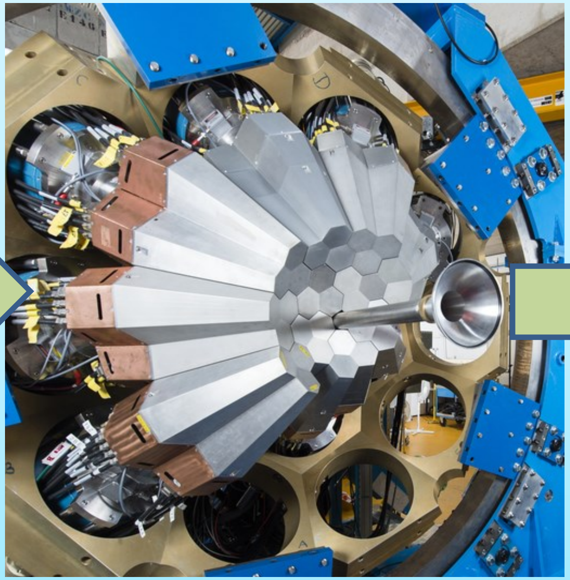
The AGATA journey…

2012-2014
GSI, Germany
25 detectors



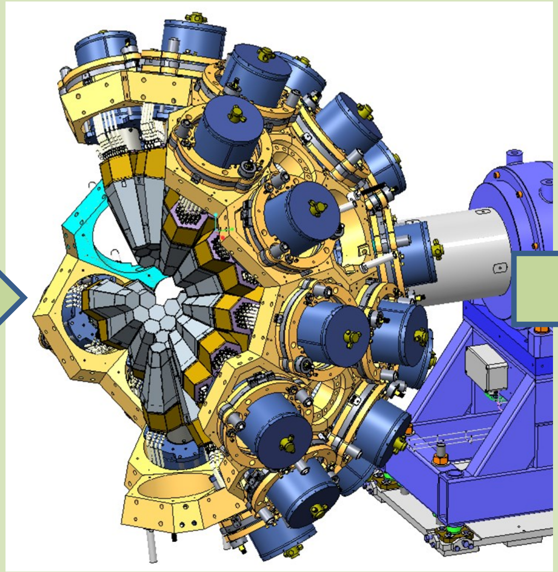
AGATA at GSI

2015-2021
GANIL, France
45 detectors



AGATA at GANIL

2021-
Legnaro, Italy
60 detectors



AGATA at LNL

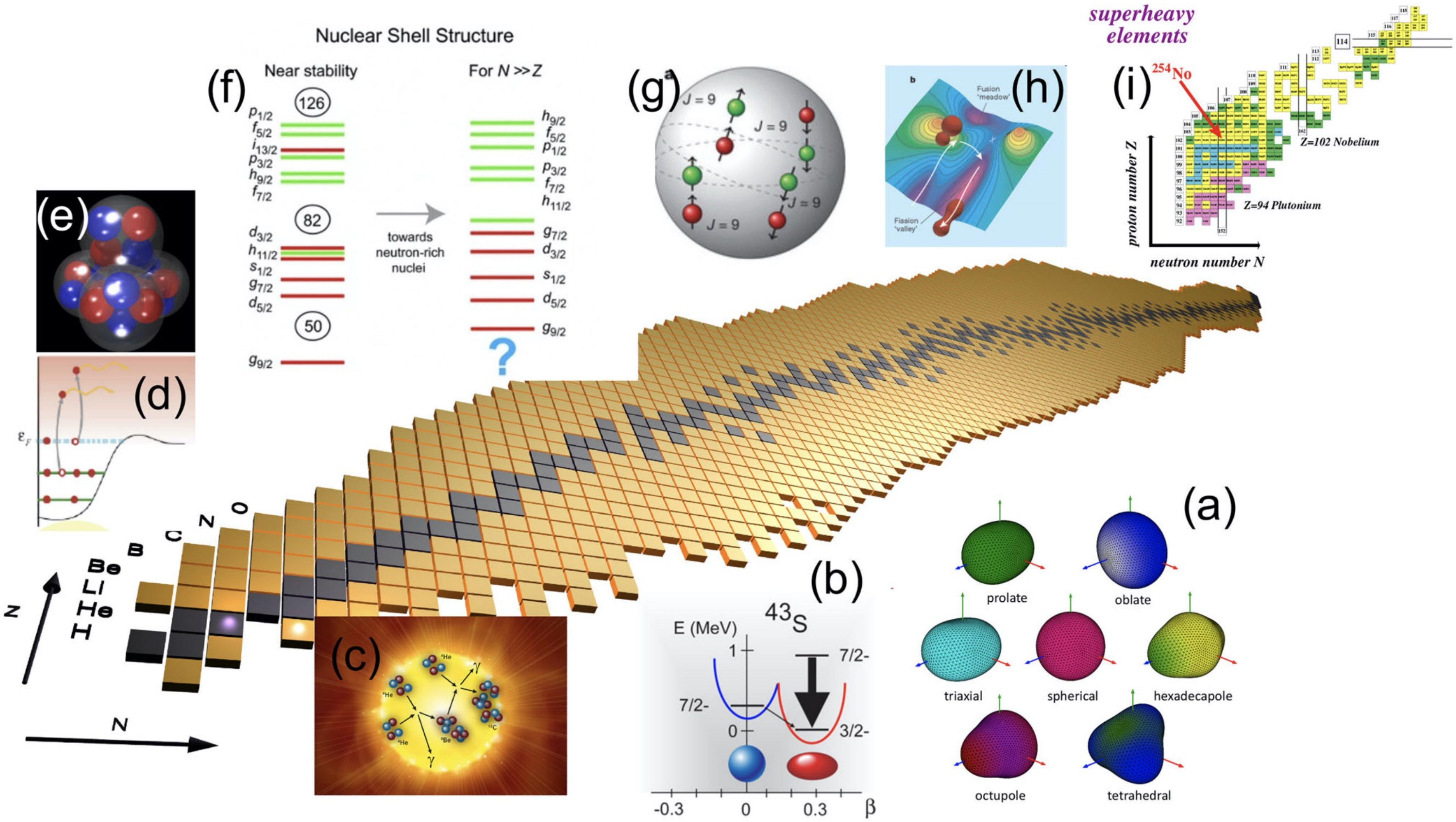
FAIR, Germany
80-90 detectors

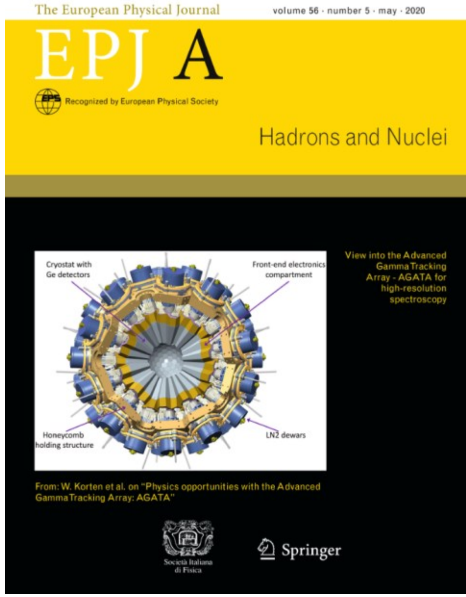
AGATA at NUSTAR

- Coulomb excitation, direct reactions, multi nucleon transfer, deep inelastic, fusion
- **Direct and inverse kinematics**
- **$\beta \sim 10\%$**
- **Reaccelerated RIBs**

In-flight RIBs:
- relativistic Coulomb excitation, knockout, fragmentation.
- **$\beta \sim 50\%$**

Physics case of AGATA





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

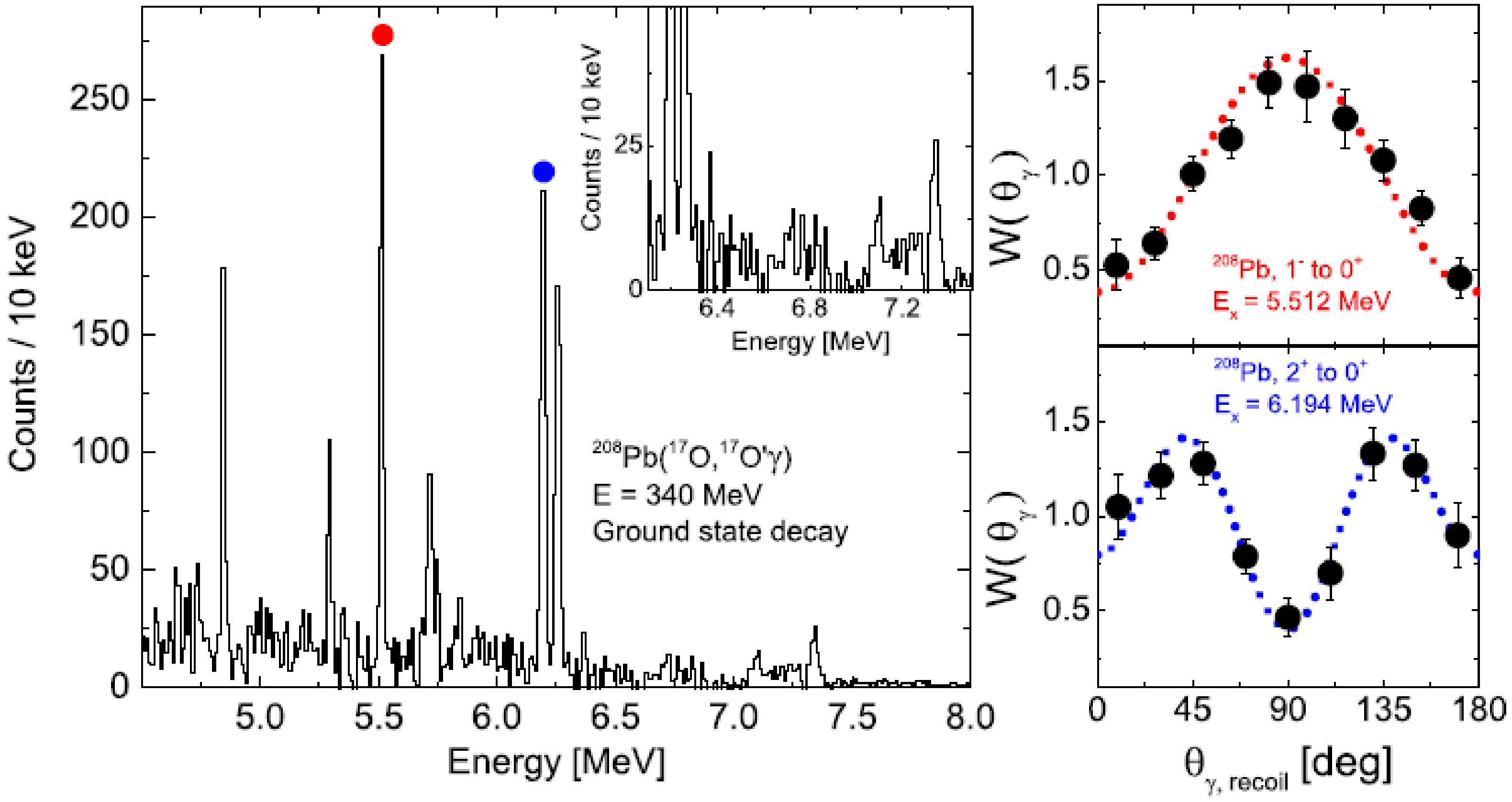
Low energy tail of E1 and E2 response

AGATA + ΔE-E Si telescope @ LNL

isoscalar hadronic probe: (^{17}O, ^{17}O´γ)
targets: ^{90}Zr, ^{124}Sn, ^{140}Ce, ^{208}Pb

investigation of Pygmy dipole resonance
structural splitting of low-lying *E*1 strength

comparison α scattering (α, $\alpha'\gamma$),
photon scattering (γ,γ')



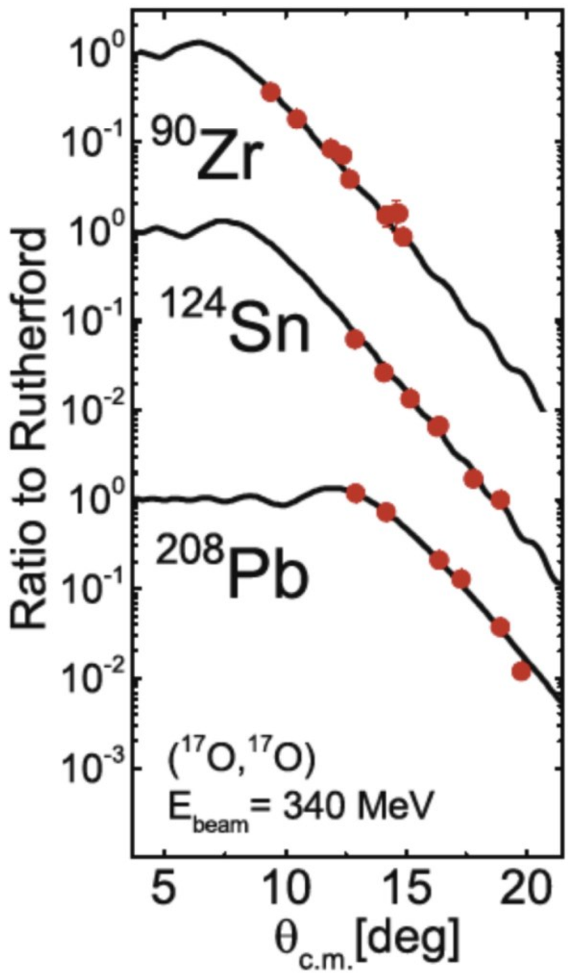
Escape lines are identified and discriminated by γ-ray tracking

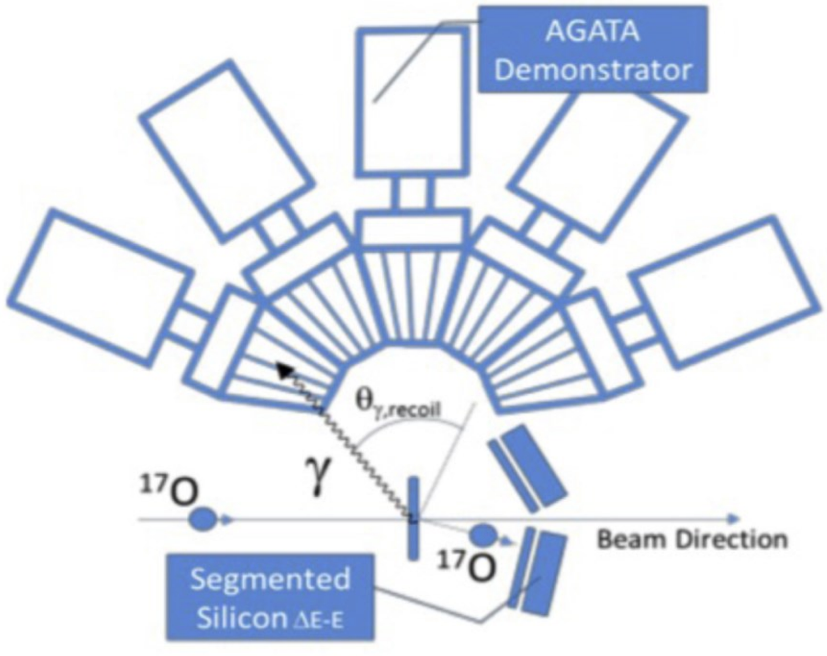
First interaction points yield angular distributions:

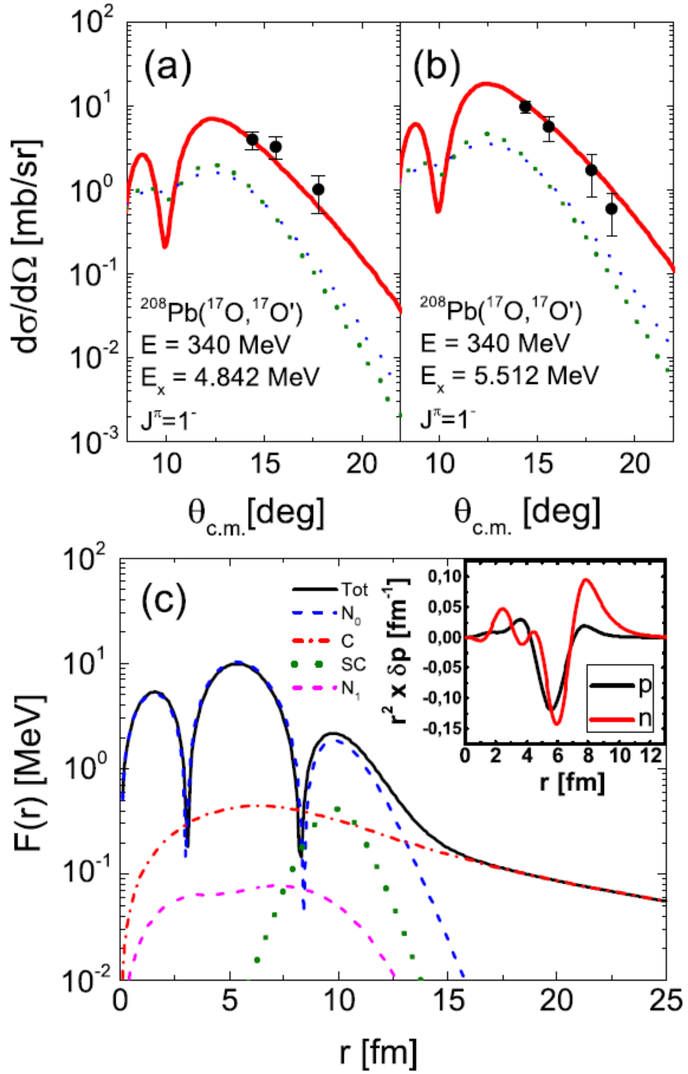
- E1 transition from the 1$^-$ state at 5.512 MeV
- E2 transition from the 2$^+$ state at 6.194 MeV

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

Structure of the Pygmy Dipole Resonance





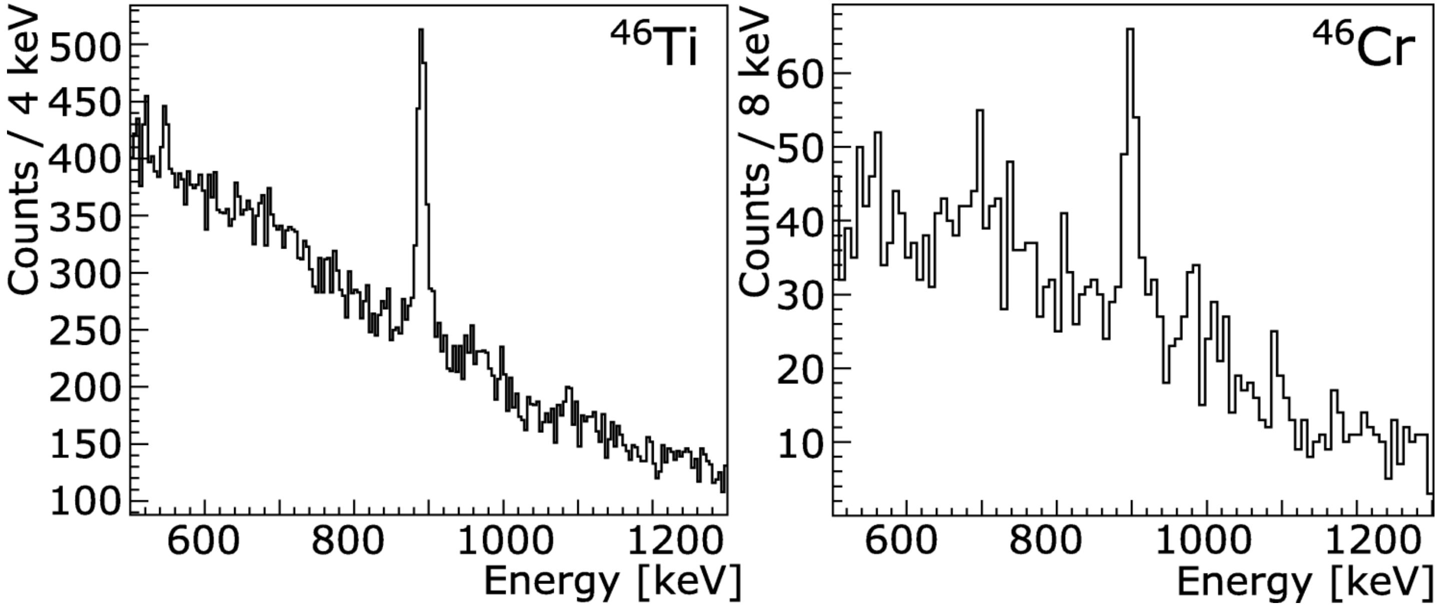


S. Ceruti et al., Phys. Rev. Lett. 115, 222502 (2015)
L. Pellegri et al., Phys. Lett. B **738**, 519 (2014).
F. Crespi, et al., Phys. Rev. Lett. **113**,012501 (2014)

Isospin dependence of transition strengths

FRS-AGATA-LYCCA setup @ GSI
primary ^{58}Ni beam, 600 MeV/A
three secondary beams ^{46}Cr, ^{46}V and ^{46}Ti
beam energies: 180, 176 and 178 MeV/A

Two different methods for $0^+_{g.s.} \rightarrow 2^+_1$ $B(E2)$ strength
(i) Relativistic Coulomb excitation (Au target 500 mg/cm^2, $v/c \approx 0.53$)

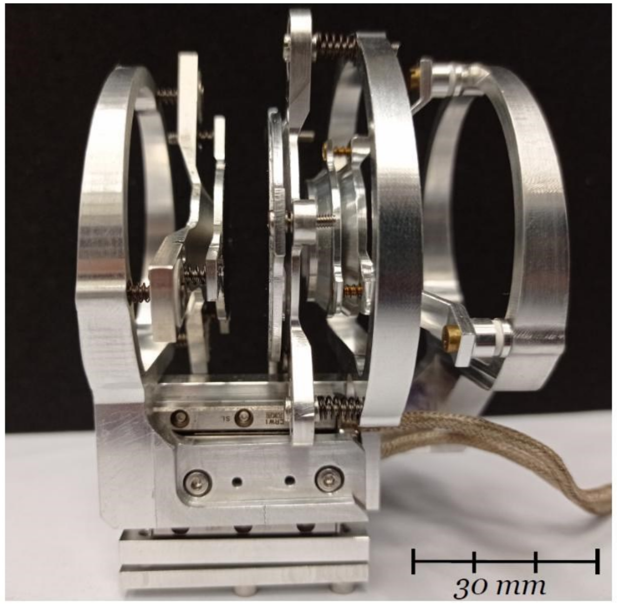


Doppler shift at $v/c \approx 0.53$ up to 60%
Energy resolution of $0^+_{g.s.} \rightarrow 2^+_1$ transition ($\Delta E \approx 1.7\%$) fits theoretical limit

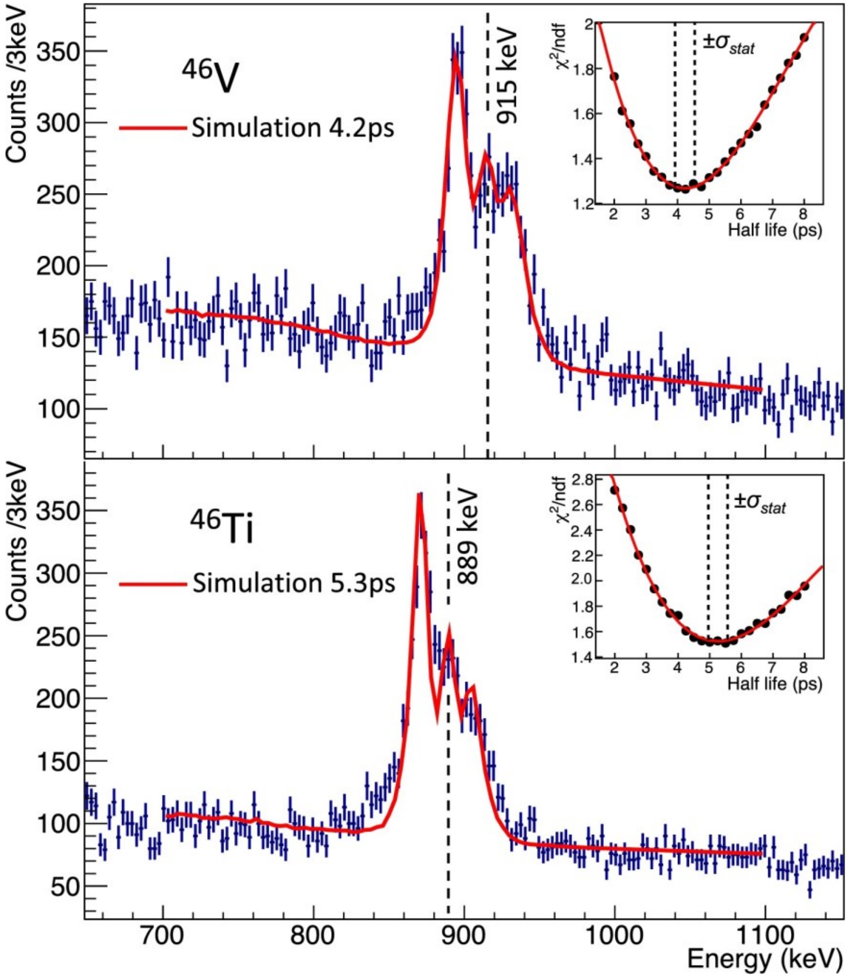
A. Boso, et al., Phys. Lett. B 797 (2019) 134835.

Isospin dependence of transition strengths

Two different methods for $0^+_{g.s.} \rightarrow 2^+_1$ $B(E2)$ strength
(ii) Differential three foil plunger Au (750 +500 +500) mg/cm^2
line shape with three peaks v/c = 0.527, 0.509, 0.488

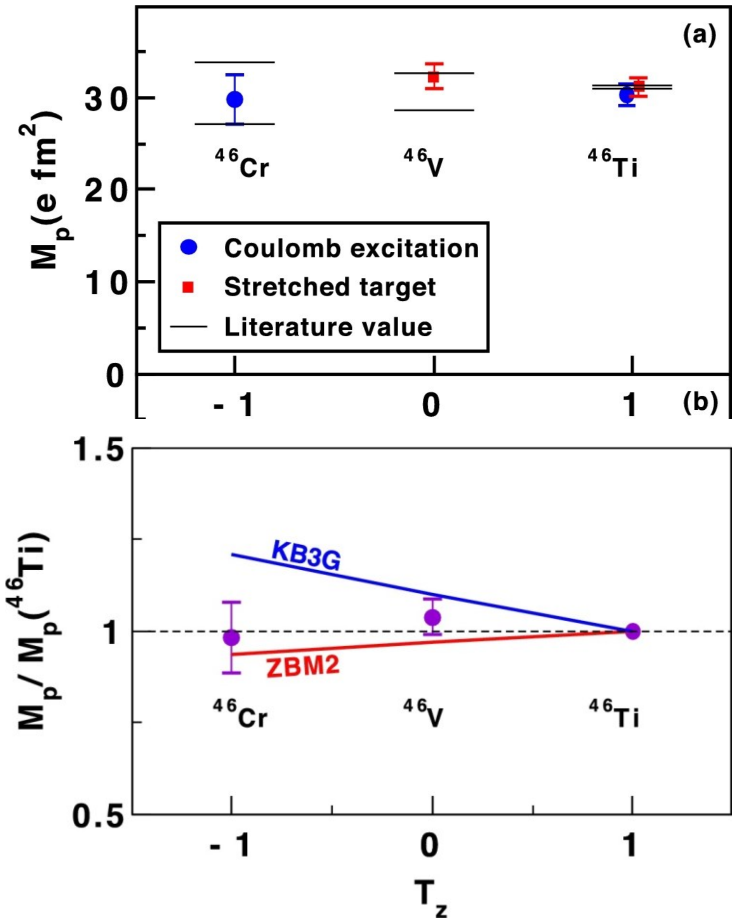


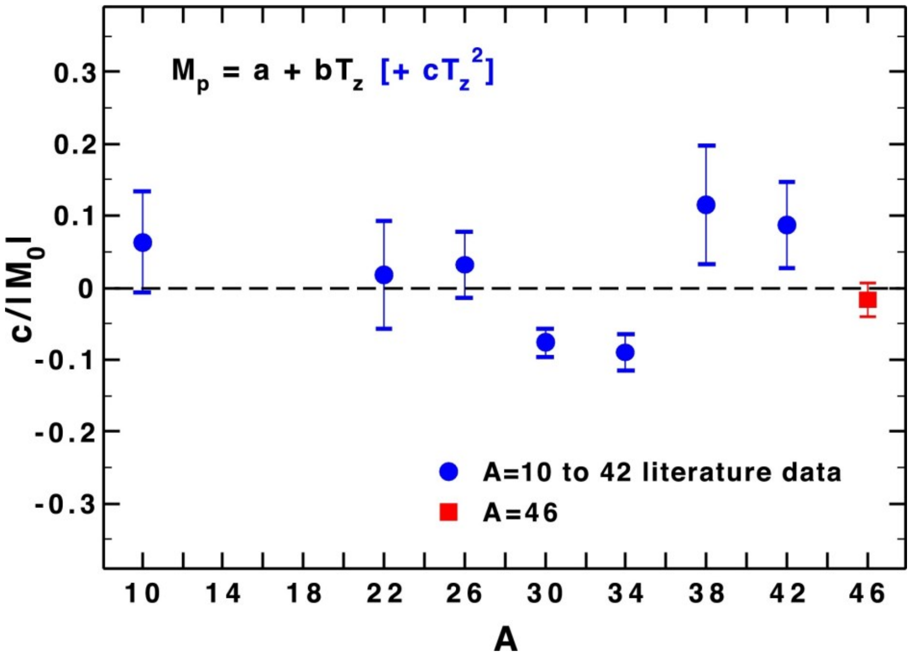
Cologne Compact Differential Plunger
M. Beckers, et al., NIM A 1042 (2022) 167418



A. Boso, et al., Phys. Lett. B 797 (2019) 134835.

Isospin dependence of transition strengths





A. Boso, et al., Phys. Lett. B 797 (2019) 134835.

Isospin dependence of the proton matrix element $M_p(T_z)$ for electromagnetic transitions of T=1 triplet:

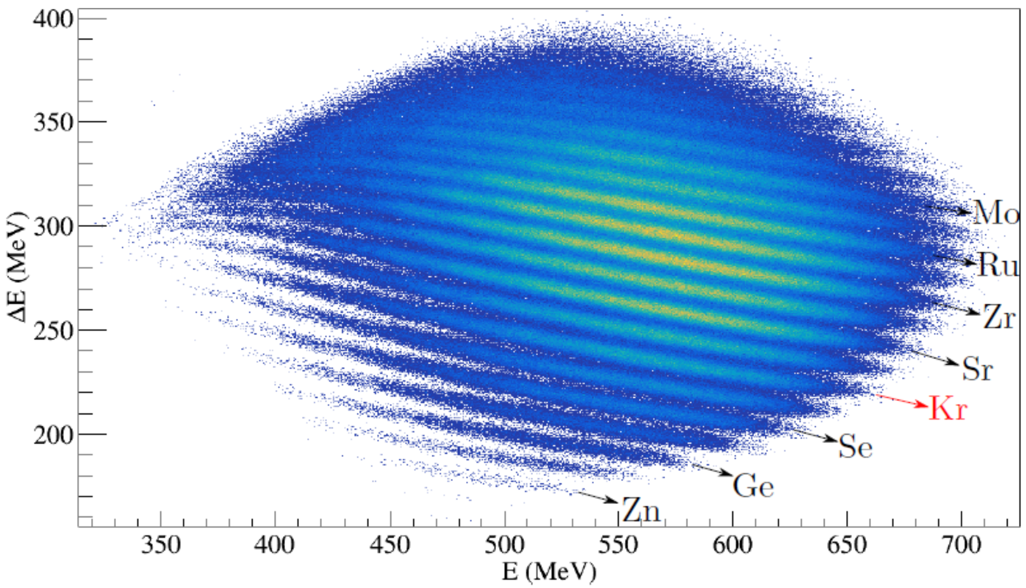
$$M_p(T_z) = 1 + \frac{1}{2}[M_0 - T_z\, M_1^{T_z=1}]$$

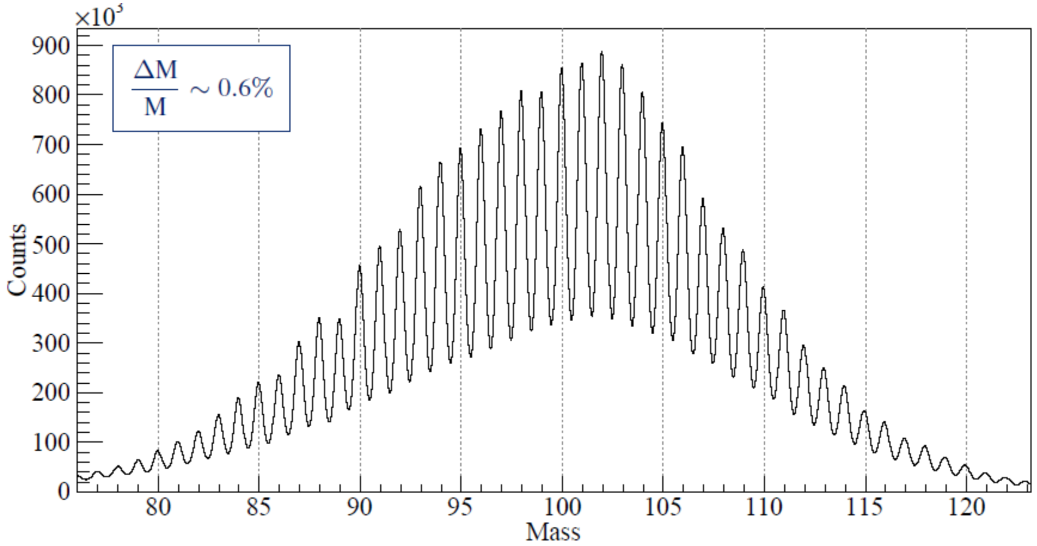
M_0 isoscalar matrix element 62.2(15) efm^2 ,

$M_1^{T_z=1}$ isovector matrix element 0.0(15) efm^2 .

In the limit of pure isospin, the analogue proton matrix elements should be exactly linear with T_z.

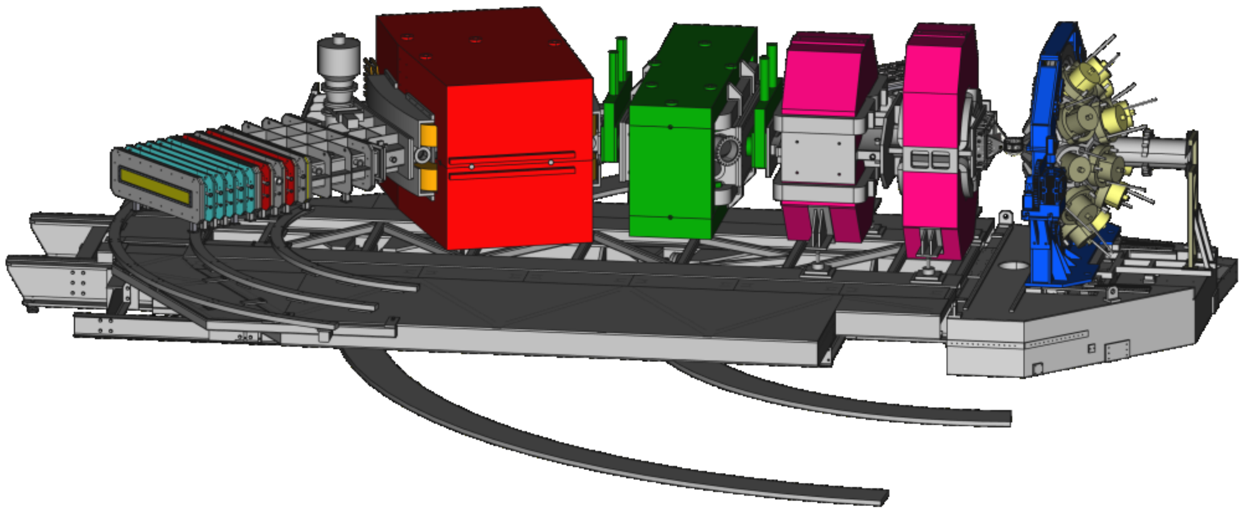
The GANIL Campaign [2015-2021]





45 AGATA detectors on-line Coupled to VAMOS spectrometer

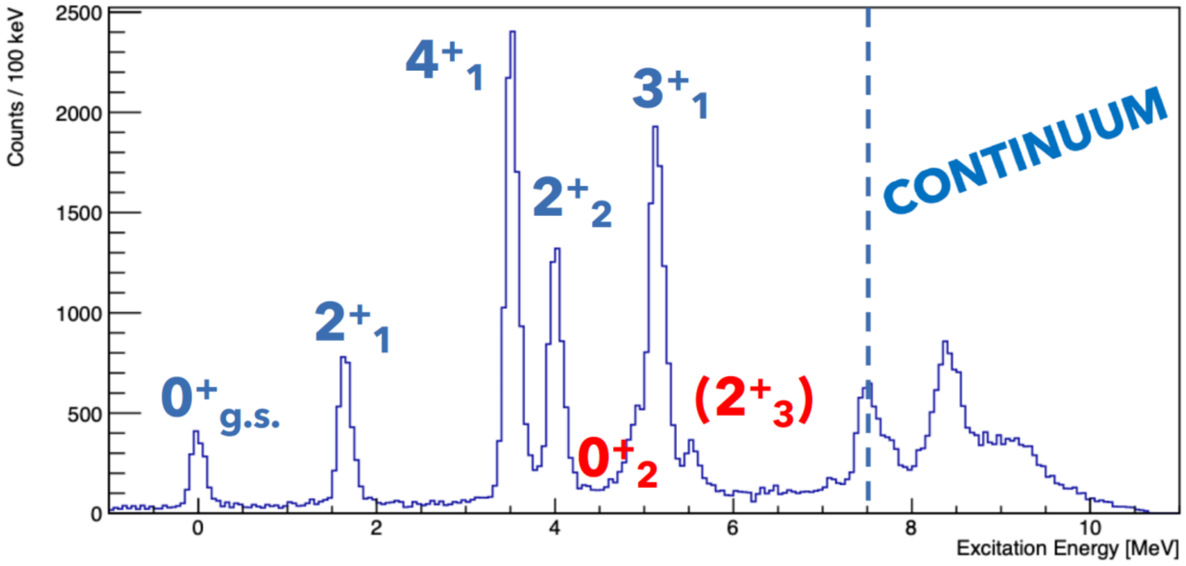
E. Clément et al.; NIM A 855, 1-12 (2017)



J. Dudouet, et al.; Phys. Rev. Lett. 118, 162501 (2017)
C Delafosse, et al.; Phys. Rev. Lett. 121, 192502 (2018)
D. Ralet, et al.; Phys. Lett. B 797, (2019) 134797
B. Cederwall, et al.; Phys. Rev. Lett. 124, 062501 (2020)
M. Siciliano, et al.; Phys. Lett. B 806 (2020) 135474
R. M. Pérez-Vidal, et al.; Phys. Rev. Lett. 129, 112501 (2022)
I. Zanon, et al.; Phys. Rev. Lett. 131, 262501 (2023)
Ch. Fougères, et al.; Nature Communications (2023) 14:4536

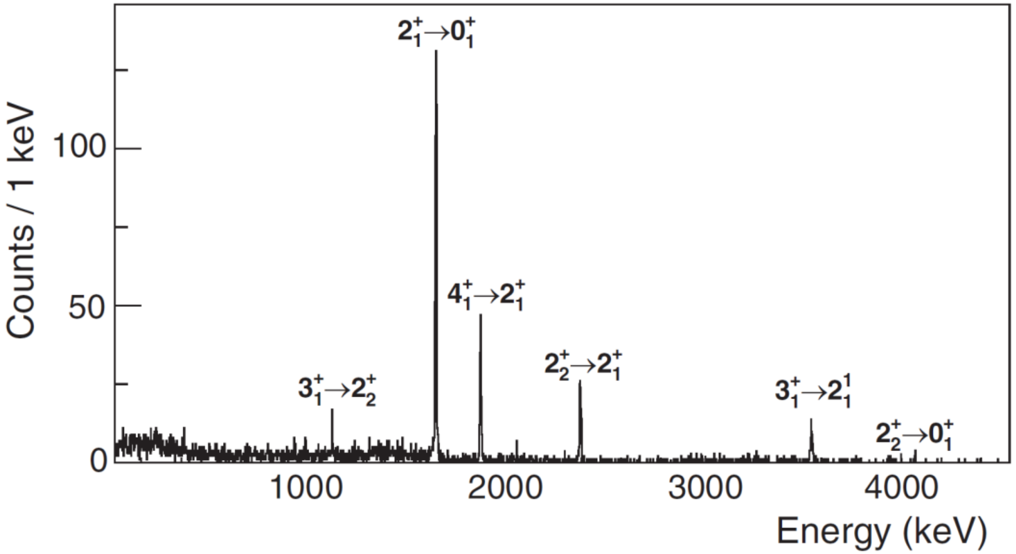
AGATA
ADVANCED GAMMA TRACKING ARRAY

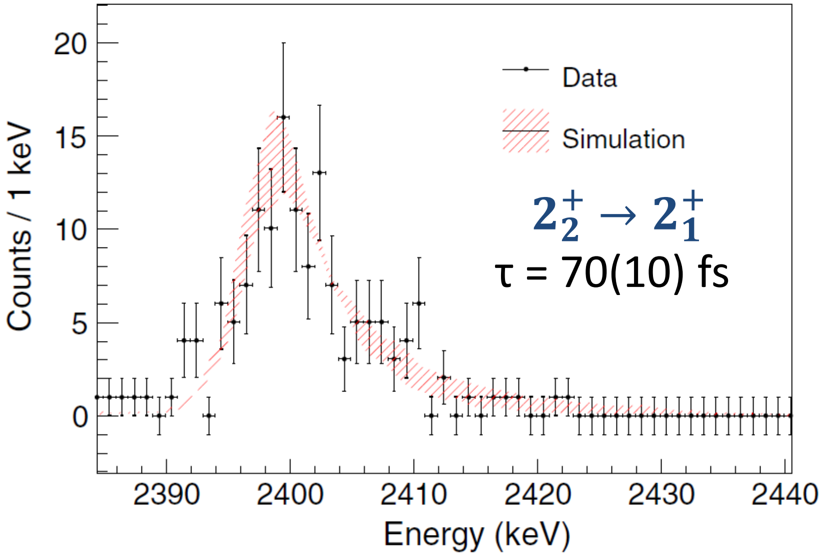
High-Precision Spectroscopy of ^{20}O



- SPIRAL1 accelerator @ GANIL
- **Radioactive ^{19}O beam, 8 MeV/A, 4×10^5 pps**
- Target CD_2 0.3 mg/cm^2 (+ Au 24.4 mg/cm^2)
- $^{19}O(d,p)^{20}O$ direct reaction, inverse kinematics
- AGATA + MUGAST + VAMOS.

Efficiency, energy resolution, position resolution, Doppler correction capability
➡ Doppler shift attenuation method





$2_2^+ \rightarrow 2_1^+$

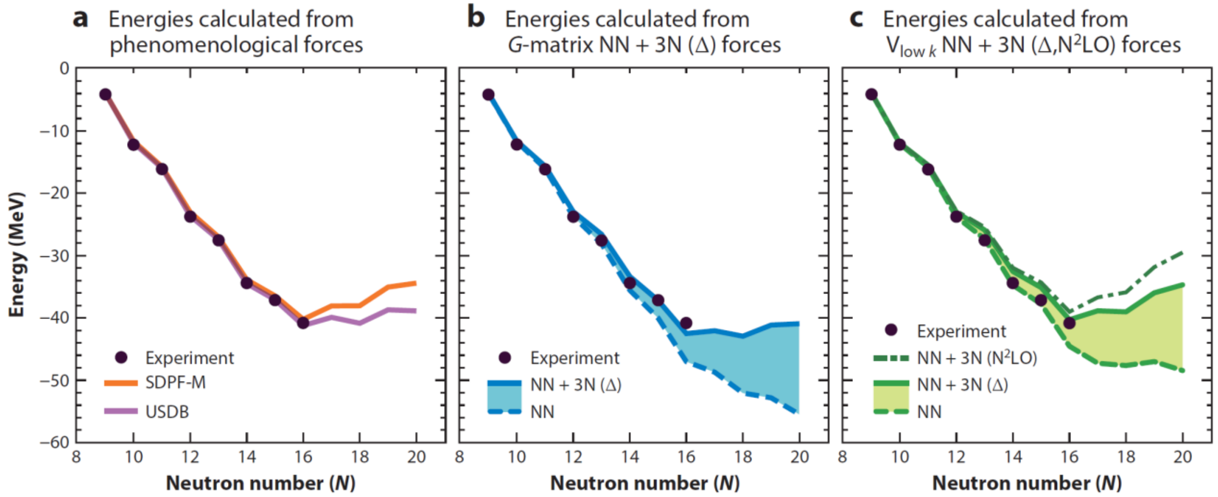
τ = 70(10) fs

$3_1^+ \rightarrow 2_2^+$

τ = 54(9) fs

I. Zanon, et al.; Phys. Rev. Lett. 131, 262501 (2023)

High-Precision Spectroscopy of ^{20}O



Chiral Effective Field Theory

Position of the drip line of oxygen isotopic chain is reproduced by introducing **3N forces.**

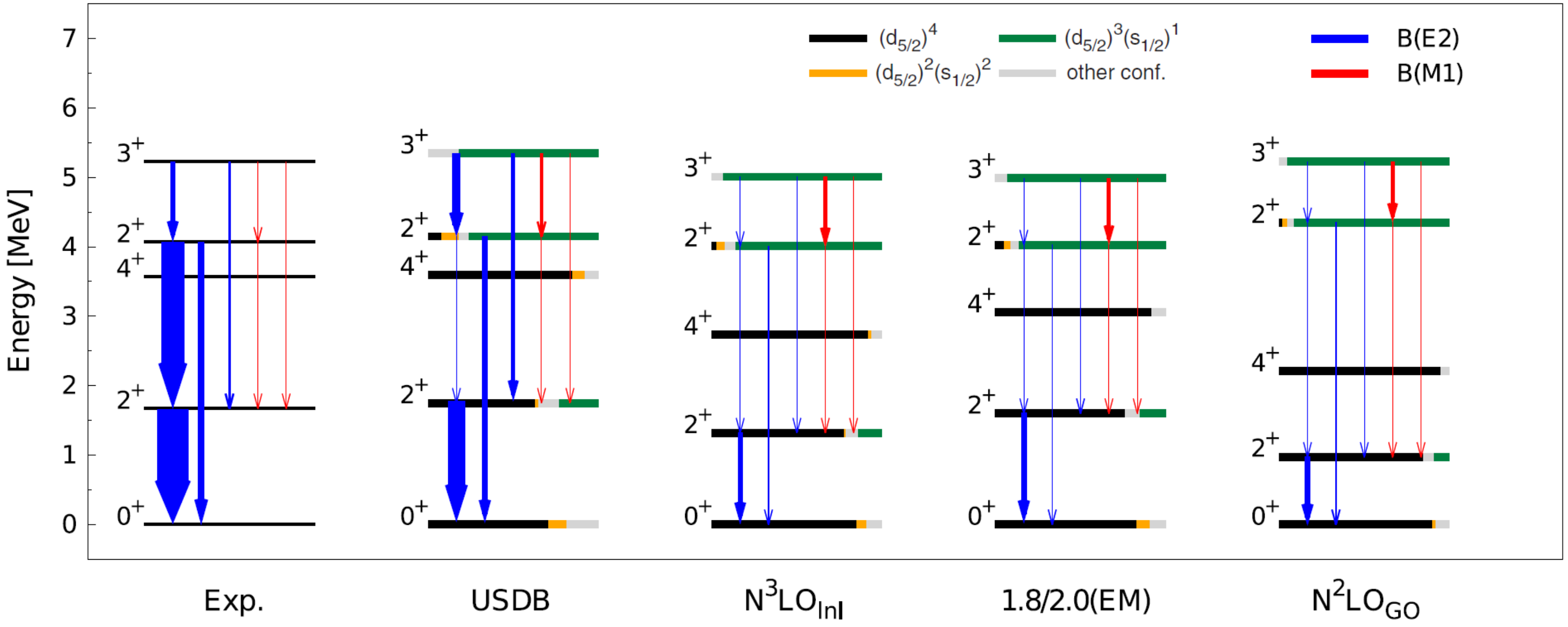
K. Hebeler, J.D. Holt, J. Menendez, A. Schwenk
Annu. Rev. Nucl. Part. Sci. (2015) 65:457-484

USDB
B.A. Brown, W.A. Richter,
Phys. Rev. C 74, 034315 (2006)

$N3LO_{lnl}$
V. Soma, et al. Phys. Rev. C 101, 014318 (2020)

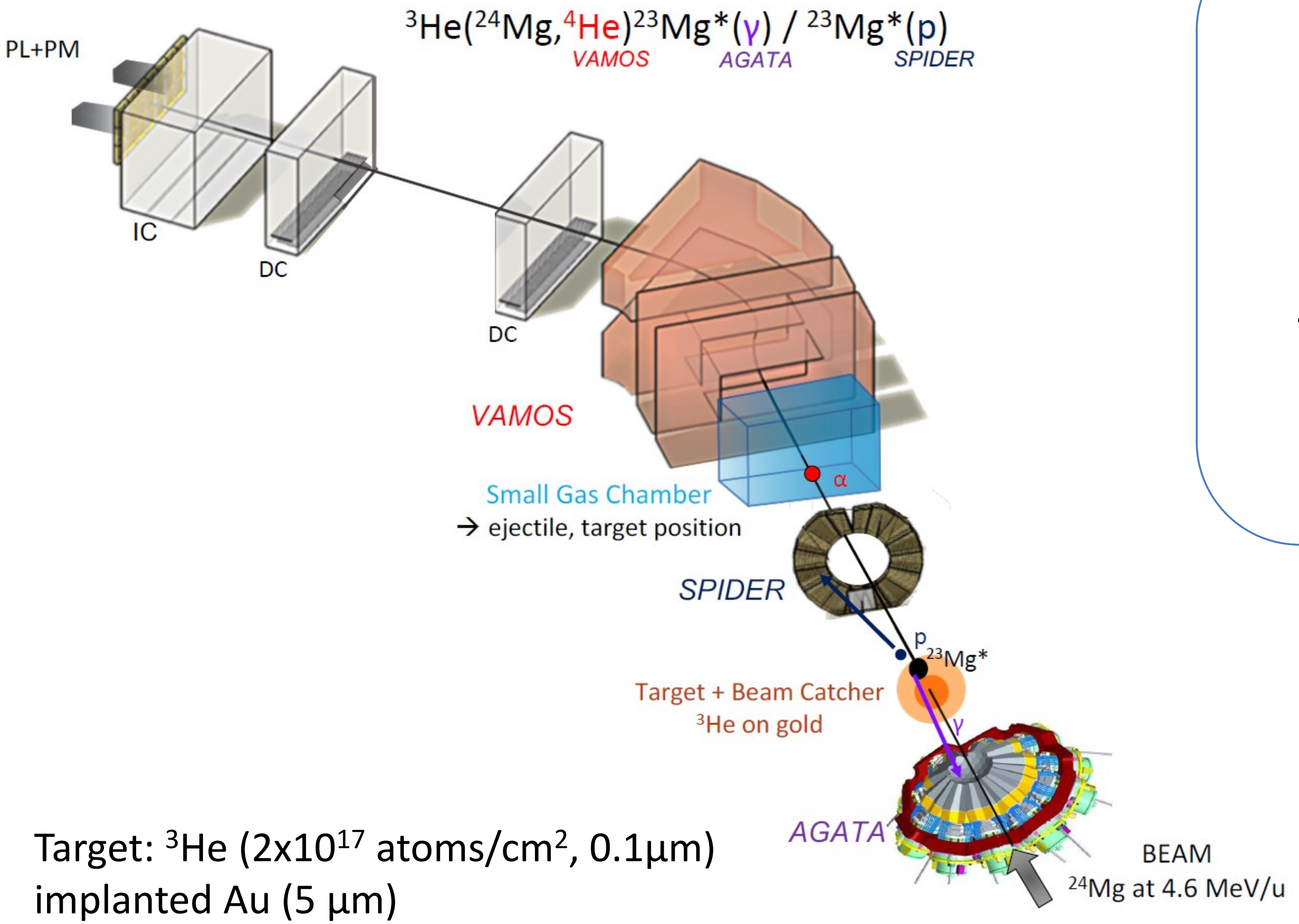
1.8/2.0(EM)
K. Hebeler, et al. Phys. Rev. C 83, 031301(R) (2011)
J. Simonis, et al. Phys. Rev. C 96, 014303 (2017)

$N2LO_{GO}$
W. G. Jiang, et al. Phys. Rev. C 102, 054301 (2020).



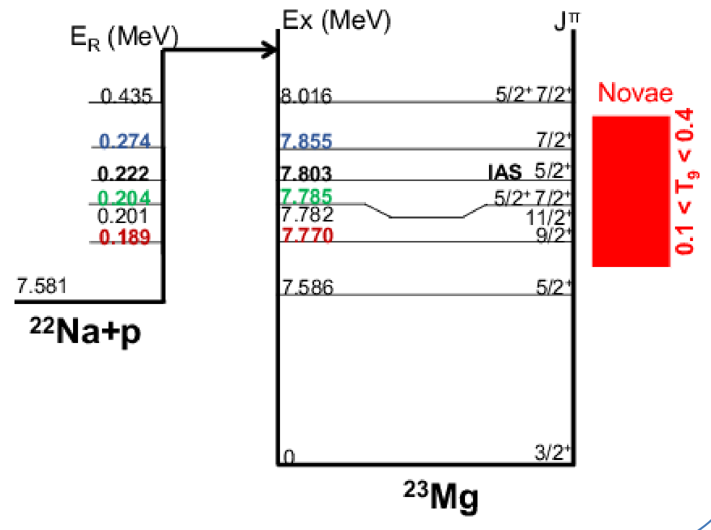
I. Zanon, et al.; Phys. Rev. Lett. 131, 262501 (2023)

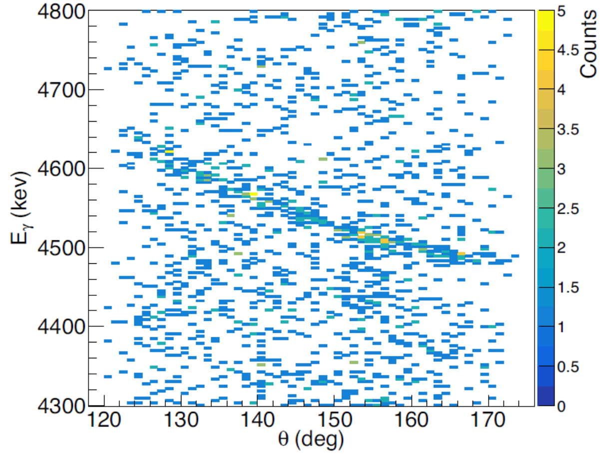
Measuring femtosecond nuclear lifetimes



Target: ^3He ($2x10^{17}$ atoms/cm^2, 0.1µm)
implanted Au (5 µm)
Stopping time of ^{23}Mg in Au: 500 fs

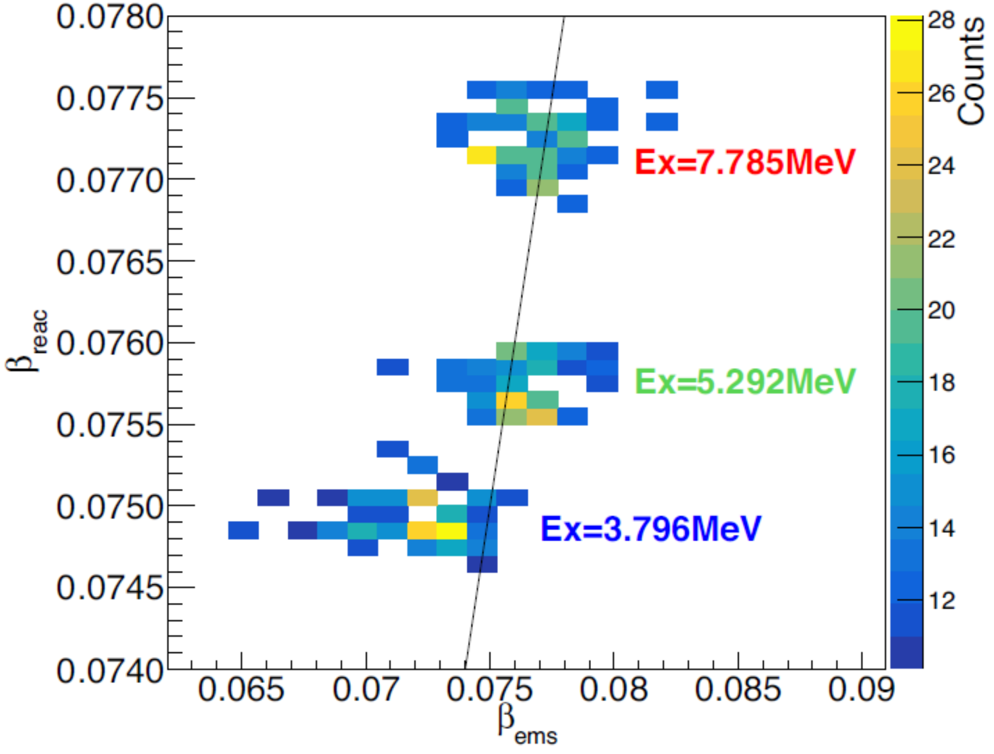
$^{22}Na(p,\gamma)^{23}Mg$

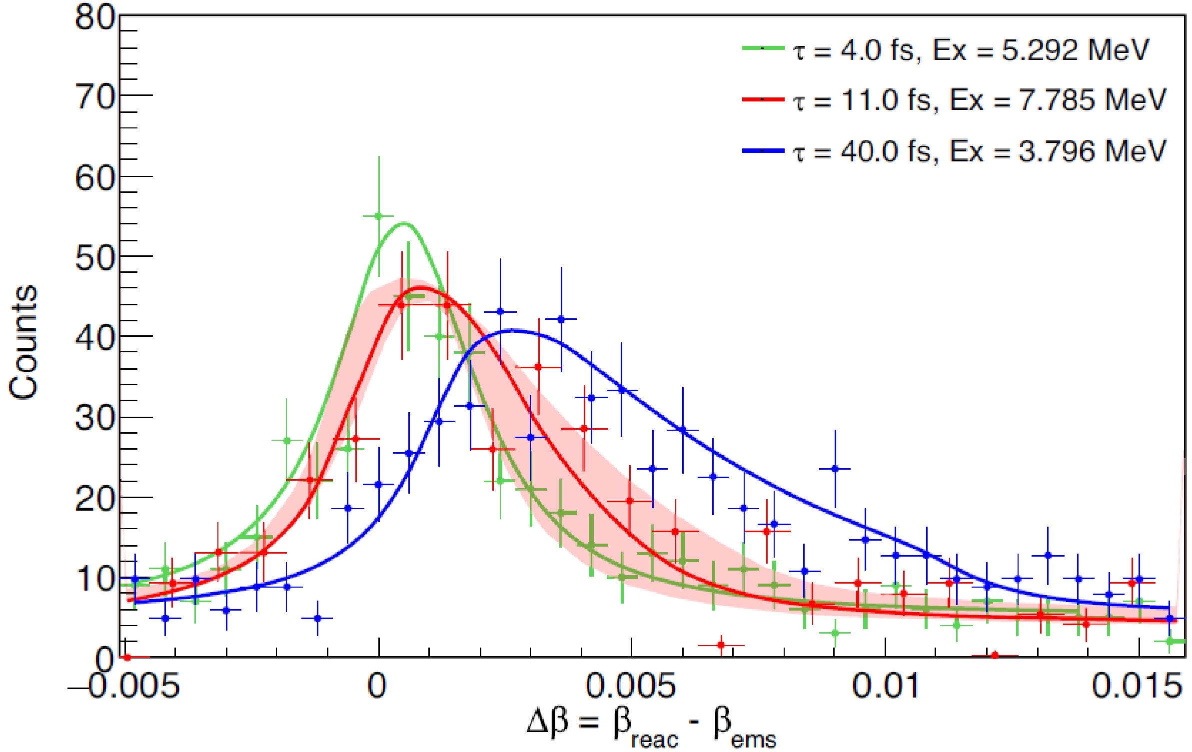




Chloé Fougères, et al.; Nature Communications | (2023) 14:4536

Measuring femtosecond nuclear lifetimes





Novel method: velocity difference Δβ

β_{reac} velocity at time of the reaction from ^4He ejectile

β_{ems} velocity at time of γ-ray emission

Deceleration of ^{23}Mg ions is for short lifetimes (τ ≲ 100 fs) almost constant (dE/dx ≈ constant), Δβ ∝ Δt, right side tail of the curves follows exponential decay function

β_{ems} from Doppler shift ΔE_γ, $\Delta\theta$

$$E_\gamma = E_{\gamma,0}\frac{\sqrt{1-\beta_{ems}^2}}{1-\beta_{ems}\cos(\theta)}$$

$R = E_\gamma / E_{\gamma,0}$

$$\beta_{ems} = \frac{R^2\cos(\theta)+\sqrt{1+R^2\cos^2(\theta)-R^2}}{R^2\cos^2(\theta)+1}$$

Chloé Fougères, et al.; Nature Communications | (2023) 14:4536

AGATA
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Measuring femtosecond nuclear lifetimes

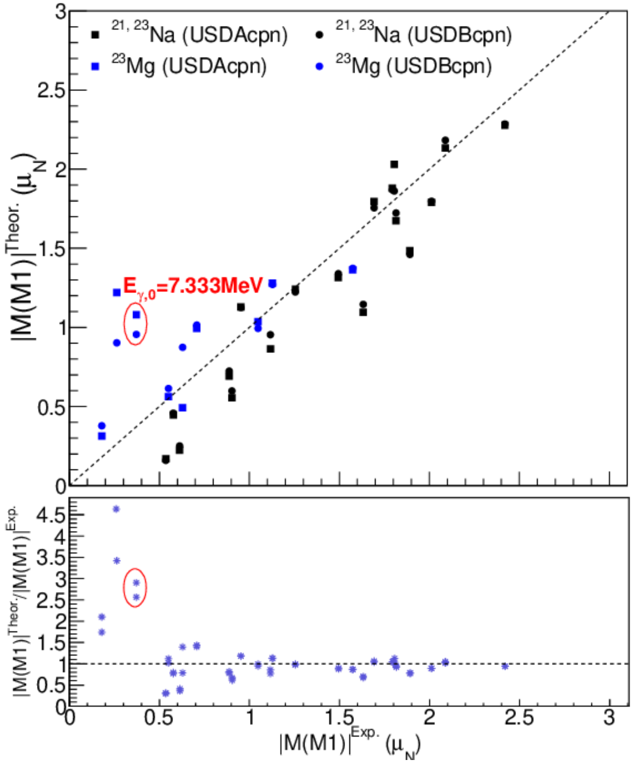
Lifetime of astrophysical state at 7.333MeV: τ = 11^{+7}_{-5} fs

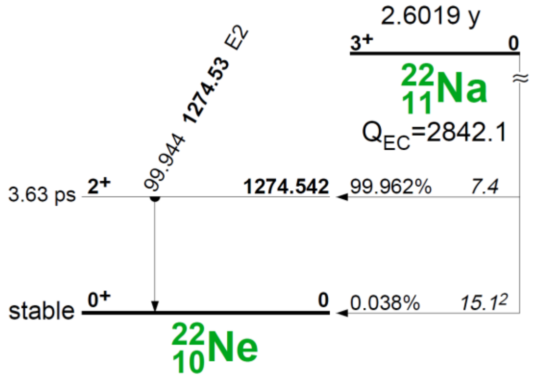
reduced magnetic dipole transition probability: B(M1) = $0.017^{+0.011}_{-0.008}\ \mu_N^2$

Proton branching ratio: BRp = 0.68(17)%

Resonance strength: ωγ = $0.24^{+0.11}_{-0.04}$ meV

Nova models:
Temperature T_{base}~ 5×10^7 K, reaction chain: ^{20}Ne(p, γ)^{21}Na(β+)^{21}Ne(p, γ)^{22}Na
rapid rise in the ^{22}Na abundance.
higher temperature T_{base}~ 5×10^8 K, reaction ^{22}Na(p, γ)^{23}Mg destruction of ^{22}Na



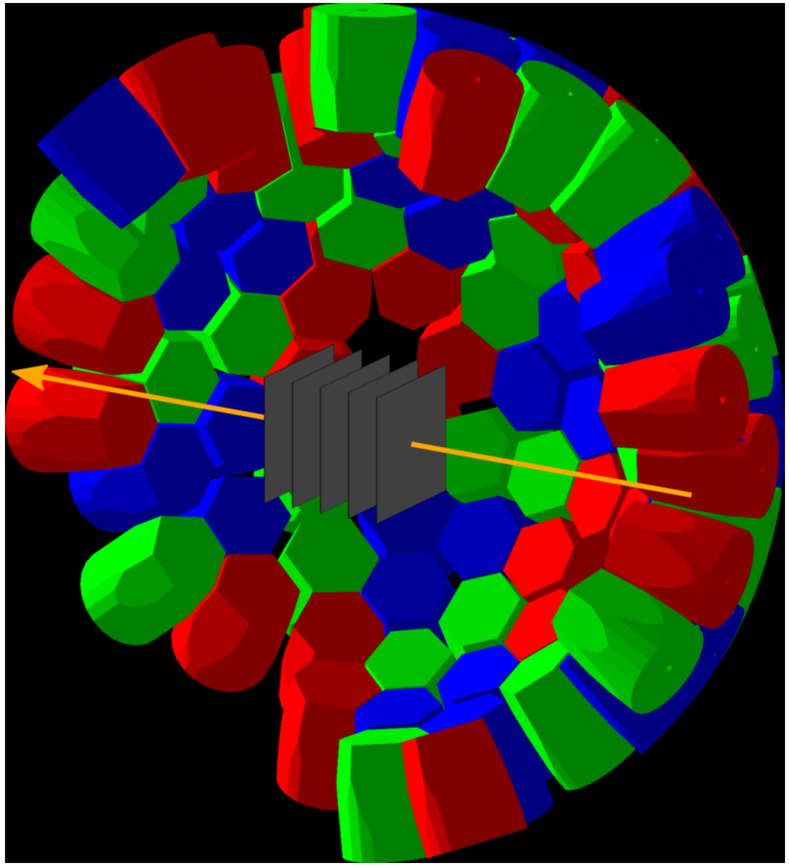


- Predictions of the 1.275 MeV γ-ray flux emitted from a nova.
- Estimates of the maximum detectability distance of novae in γ rays, via 1.275 MeV line.
- Expected sensitivities of e-ASTROGRAM (3×10^{-6} photons cm^{-2} s^{-1}) and COSI (1.7×10^{-6} photons cm^{-2} s^{-1})

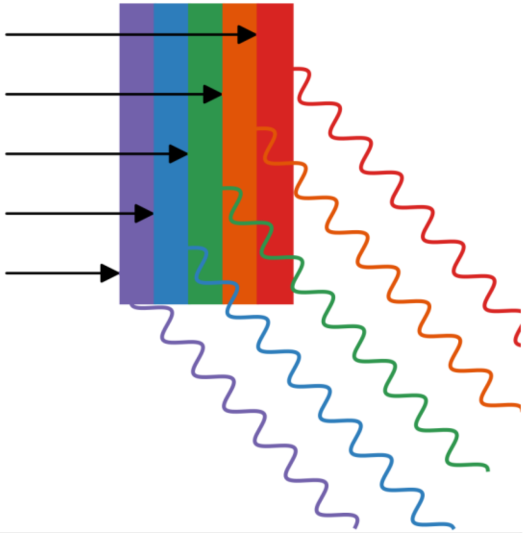
Chloé Fougères, et al.; Nature Communications | (2023) 14:4536

LISA: LIfetime measurements with Solid Active targets

- Energy resolution determined by unknown velocity in the target
- Several layers of active targets
- Event-by-event determination of reaction position → (β,z)

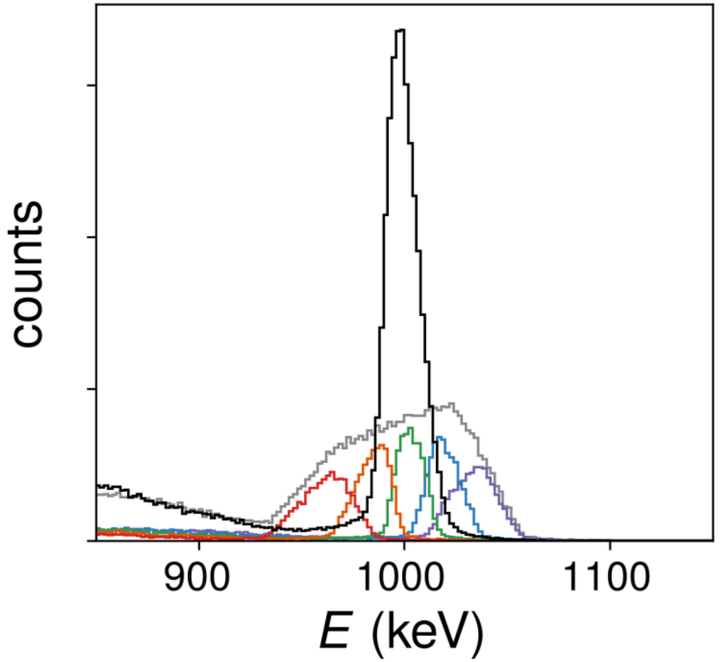


Compact array of active target detectors inside AGATA



Opens new possibilities for lifetime measurements using AGATA at FAIR:

- Evolution of collectivity in Islands of Inversion
- Fate of the N=82 and 126 shell closures
- And many more

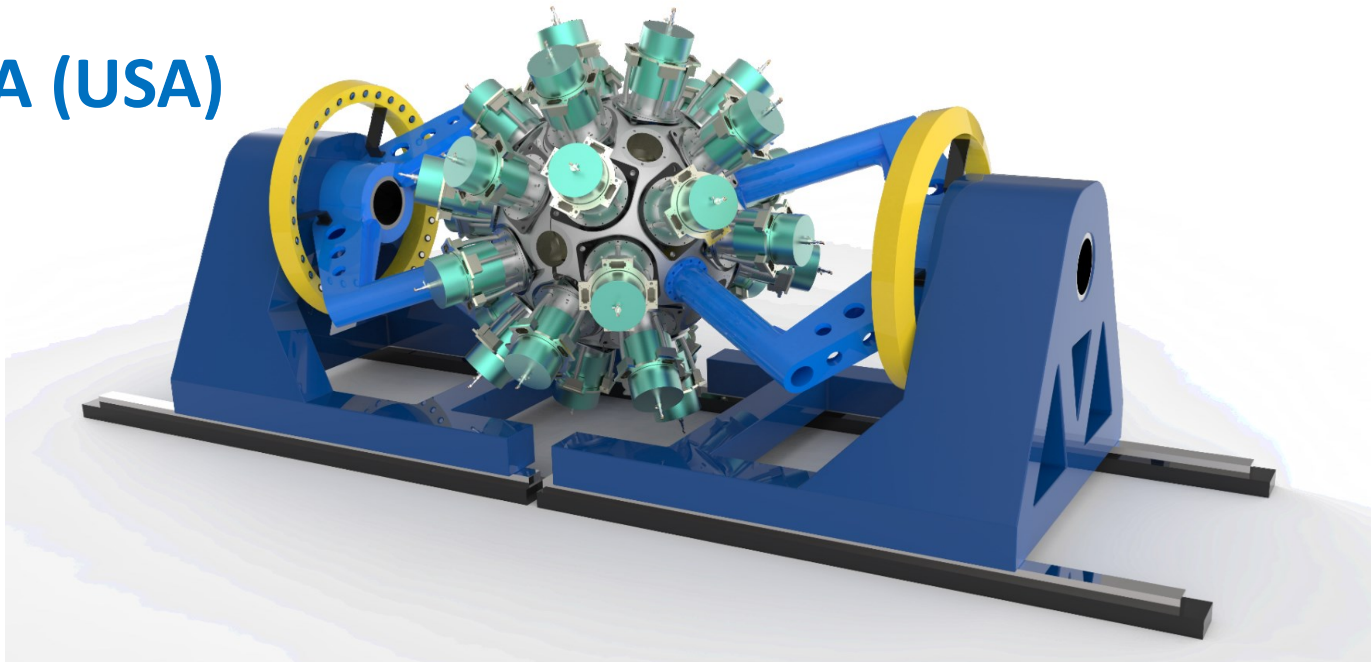


Courtesy K. Wimmer, GSI

erc
European Research Council
Established by the European Commission

Gamma-Ray Energy Tracking Arrays

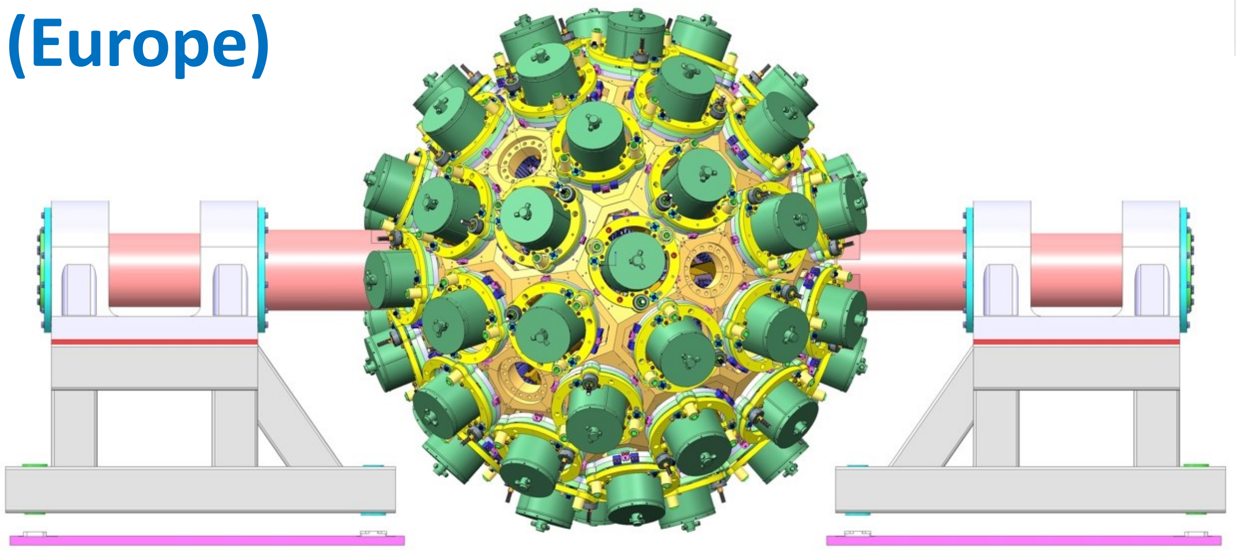
GRETA (USA)



- 120 Ge crystals
- 30 Quad "modules"
- main user FRIB

- final completion 2025

AGATA (Europe)



- 180 Ge crystals
- 60 Triple "clusters"

- MoU Phase 2
- 45 Triple "clusters"
- 3π completion 2032

AGATA
ADVANCED GAMMA TRACKING ARRAY

Summary

- **Status** AGATA
  - ✓ > 60 detectors, digital electronics, PSA, γ-ray tracking
  - ✓ position sensitivity (E,x,y,z,t) ΔE, Δx, Δt

- Major improvements for in-beam γ-ray spectroscopy

- Ongoing AGATA campaigns continuously produce excellent physics results

- **Promising perspectives** for future experiments
  with RIBs at FAIR, SPES, SPIRAL2, …

- New MoU to complete the 3π AGATA configuration

- Topical Collection on AGATA, EPJ A special issue (2024)
  A.Bracco, G.Duchêne, Zs.Podolyák, PR, Prog. Part. Nucl. Phys. 121 (2021) 103887