Prospects for nuclear astrophysics measurements with AGATA at LNL

Andres Gadea (IFIC, CSIC-UVEG, Spain)
on behalf the AGATA Collaboration

CHETEC-INFRA general assembly
May 31st - June 1st, 2022, Padova, Italy

IFIC INSTITUT DE FÍSICA CORPUSCULAR
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
VNIVERSITAT DE VALÈNCIA
AGATA ADVANCED GAMMA TRACKING ARRAY

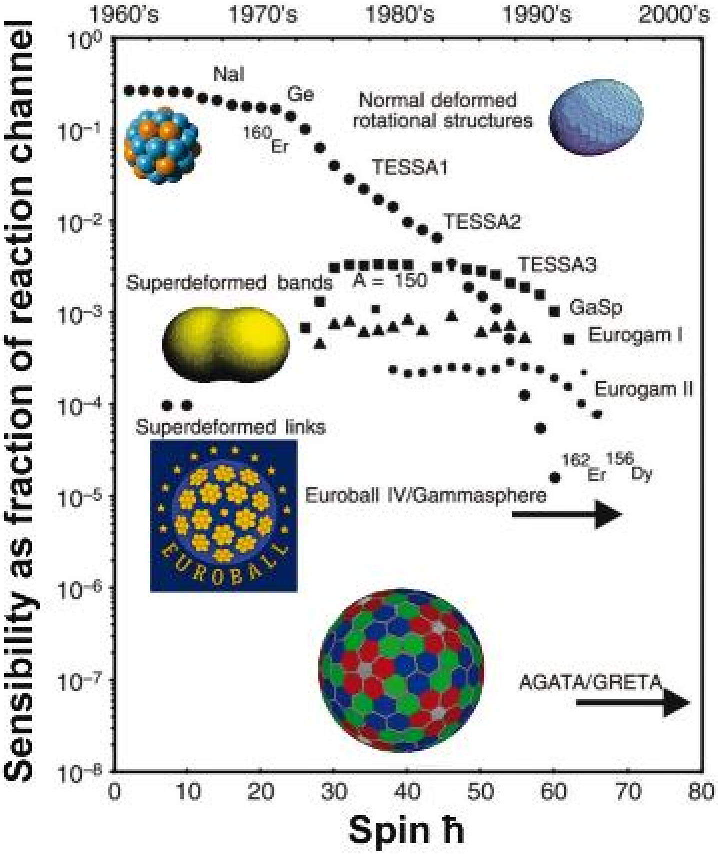
Prospects for nuclear astrophysics measurements with AGATA at LNL

- The AGATA tracking array for HR γ-spectroscopy performance figures and capabilities.
- AGATA at LNL with Stable, SPES and EXOTIC beams
- Available Complementary Instrumentation: PRISMA, GRIT / MUGAST, NEDA, etc…
- Nuclear Astrophysics and AGATA

AGATA

(Advanced GAmma Tracking Array)


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]): 35% [23%]
Peak/Total (Mγ=1 [30]): 55% [46%]

AGATA Collaboration NIM A 668 (2012) 26

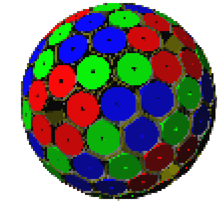
6660 high-resolution digital electronics channels

High throughput DAQ / Capability to record sampled pulses

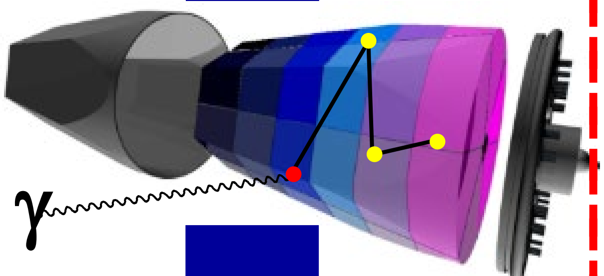
Pulse Shape Analysis → position sensitive operation mode

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

Gamma Tracking Array Concept



Highly segmented HPGe detectors



Synchronized digital electronics to digitize (14 bit, 100 MS/s) and process the 37 signals generated by crystals

Readout Raw Data (10 kB/evt/crystal)

HARDWARE

Event building time-stamped data

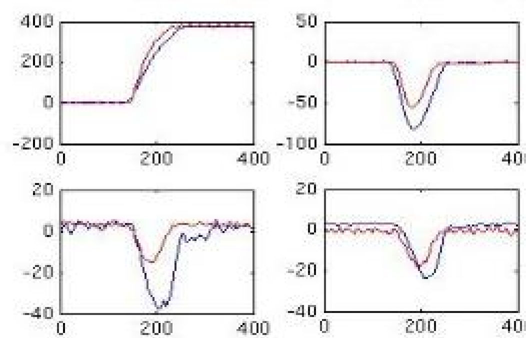
Global level

Local level

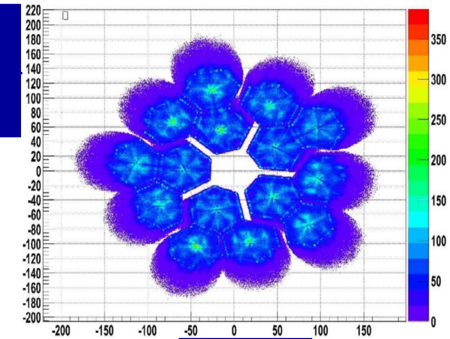
Energies, times, interaction points

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

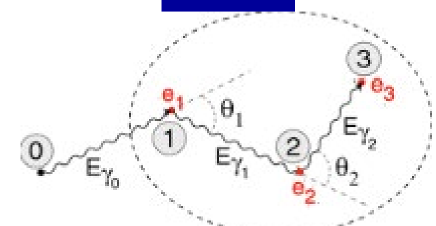
Pulse Shape Analysis of the recorded waves



SOFTWARE



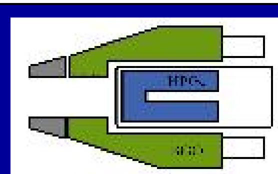
Reconstruction of γ-rays from the hits

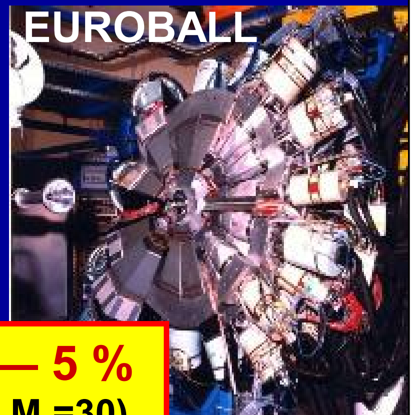


Analysis & correlation with other detectors

HR γ-Spectroscopy Instrumentation for Nuclear Structure

Late 90's
Large γ–Arrays



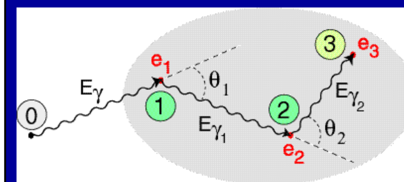


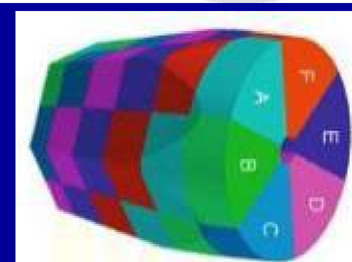
ε ~ 10 — 5 %
(M_γ=1 – M_γ=30)

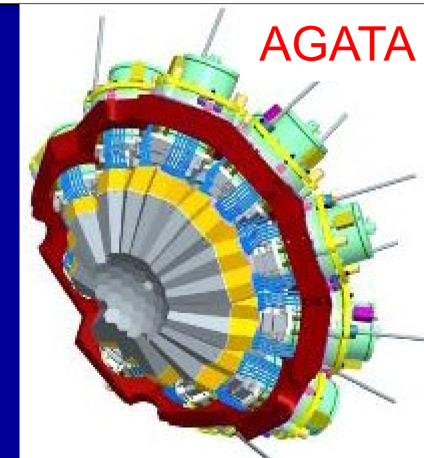
Compact γ–Arrays optimized
Doppler correction, low Mγ

ε ~ 20 % M_γ=1

Tracking Arrays based on
Position Sensitive Ge Detectors





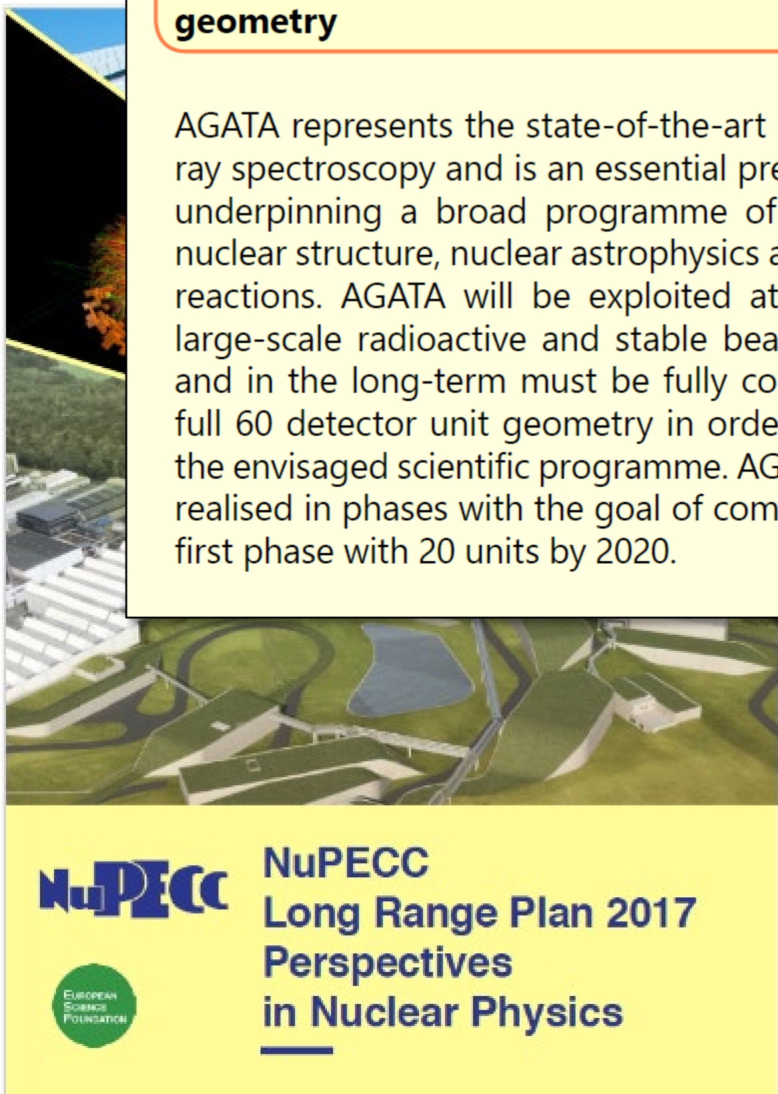


Two Tracking Arrays projects:
GRETA (USA) & AGATA (EU)

>15y R&D

ε ~ 35 — 23 %
(M_γ=1 – M_γ=30)

AGATA current MoU: 3π array construction 2021-2030



Support to the completion of AGATA in full geometry

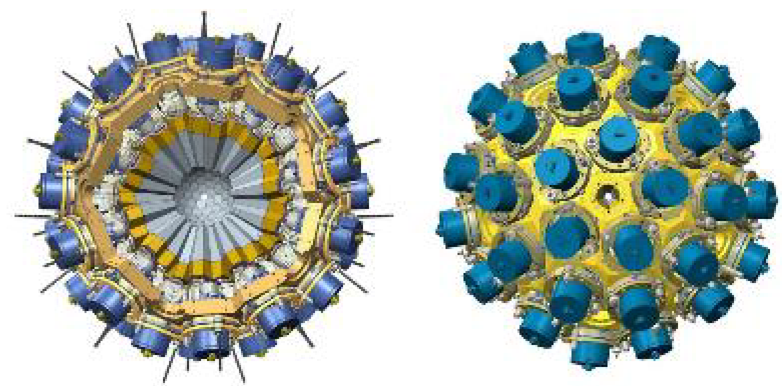
AGATA represents the state-of-the-art in gamma-ray spectroscopy and is an essential precision tool underpinning a broad programme of studies in nuclear structure, nuclear astrophysics and nuclear reactions. AGATA will be exploited at all of the large-scale radioactive and stable beam facilities and in 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.

Agata/ProDef/April21/Draft55

AGATA

Advanced Gamma Tracking Array

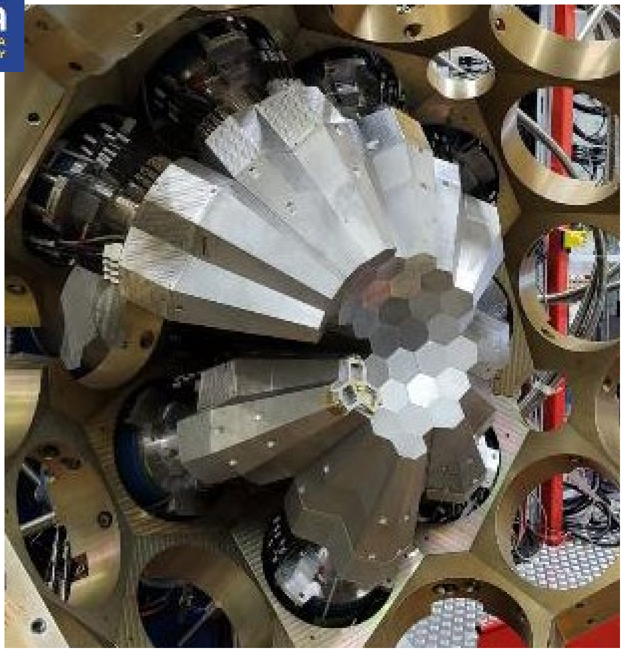
Project Definition
Phase 2



Edited by A. Gadea, B.Million , A. Boston, E. Clement, G. Duchêne, H. Hess, A. Korichi, J. Nyberg, F.Recchia, P. Reiter, J. Simpson

Input provided by the AGATA Management Board, AGATA Teams and other participants: H. Boston, F. Didierjean, J. Eberth, C. Everett, M. Filliger, K. Green, C. Görgen, R. Hetzenegger, R. Hirsch, D. Judson, M. Karolak, M. Kebbiri, L. Lewandowski, L. Ménager, C. Nicolle, G. Richardt, M-H. Sigward, S. Thiel, M. Zielinska, Ch. Bonnin, L. Charles, J. Collado, L. Gibelin, V. Gonzalez, N. Karkour, X. Lafay, I. Lazarus, D. Linget, A. Pullia, G. Vinther-Jorgensen, M. Kogimtzis, Ch. Belkhiria, A.Boujrad, F.Saillant, G.Wittwer, N. Dosme, X. Grave, J. Jacob, E. Legay, G. Lallaire, P. Le Jeannic, A. Lopez-Martens, O. Stézowski T. Lauritsen, F. Crespi, J. Dudouet, M. Labiche, J. Ljungvall, Ph. John, L. Harkness-Brennan, F. Holloway, B. De Canditiis, B. Quintana, R. Menegazzo, A. Lotodé, T. Joannem, A. Grant, I. Burrows, J.J. Valiente-Dobon, A. Goasduff.

AGATA experimental activity goals



AGATA is the High-Resolution flagship instrument in Europe for completely characterizing the structure of exotic nuclei by measuring excitation energies, spin & parity, lifetimes, static moments, exclusive cross sections, etc.

AGATA will be exploited at all major European infrastructures providing stable and radioactive ions beams with energies from the Coulomb barrier to the relativistic regime.

Performance achieved through Position Sensitivity in large volume Ge Detectors.

LNL/SPES (2022+)

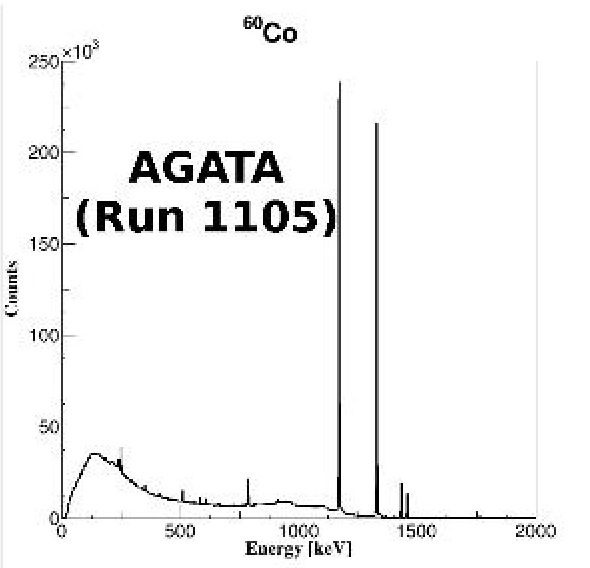
FAIR (2026+)

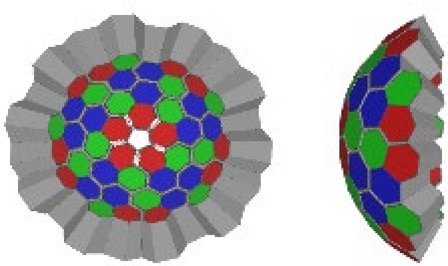
SPIRAL2 planned

Also HIE-ISOLDE & JYFL (planned)

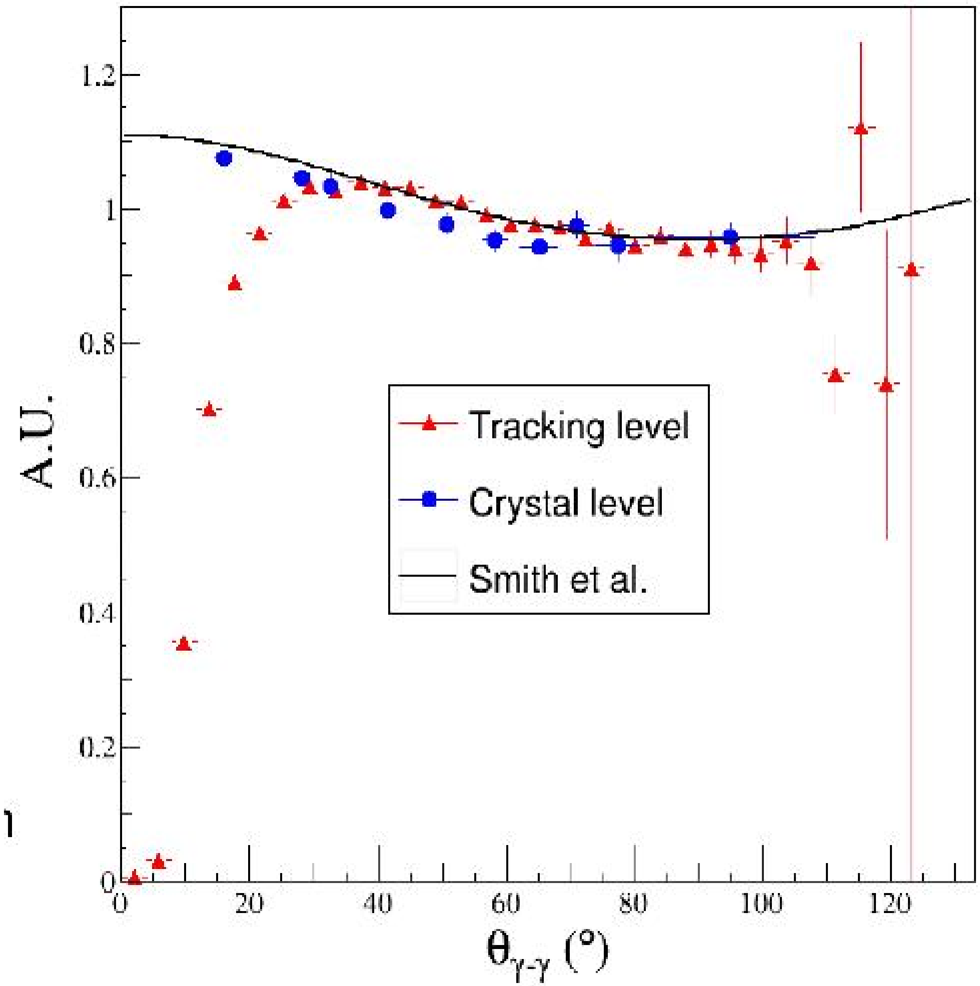
Angular Distributions and Correlations

- PSA + Tracking provides high angular resolution for angular distribution and correlations.
- The challenge is the understanding of the efficiency for each angle or angle combination





AGATA
< 1π

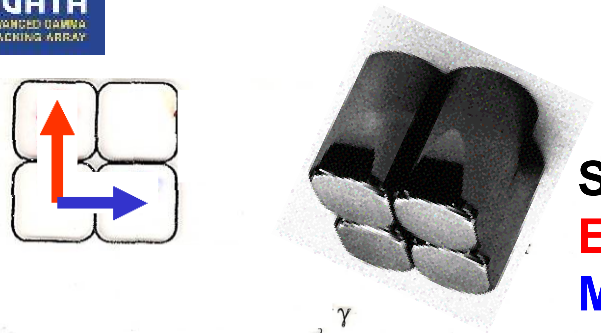


S. Leblond (GANIL) AGATA WEEK 2019

Linear Polarization measurements with AGATA

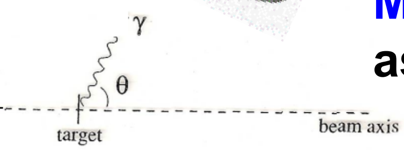
$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2 \left[\frac{E'}{E} + \frac{E}{E'} + \sin^2(\theta)(1 + P\cos(2\varphi))\right]$$

O. Klein and Y. Nishina – Z. Phys. 52 (1929) 853



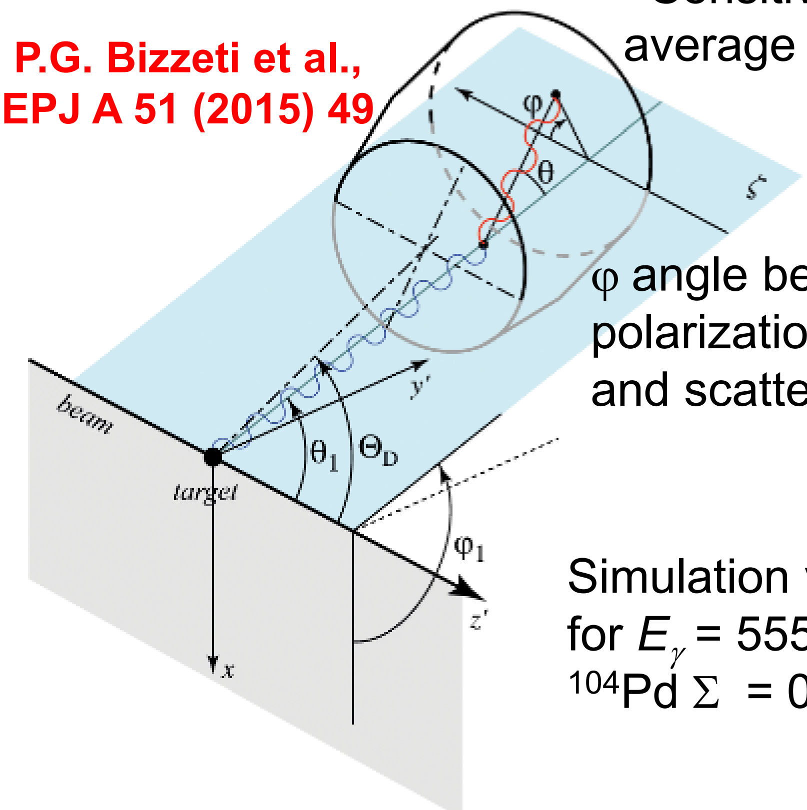
Stretched
Eλ positive &
Mλ negative
asymmetry

$$A = \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel}$$



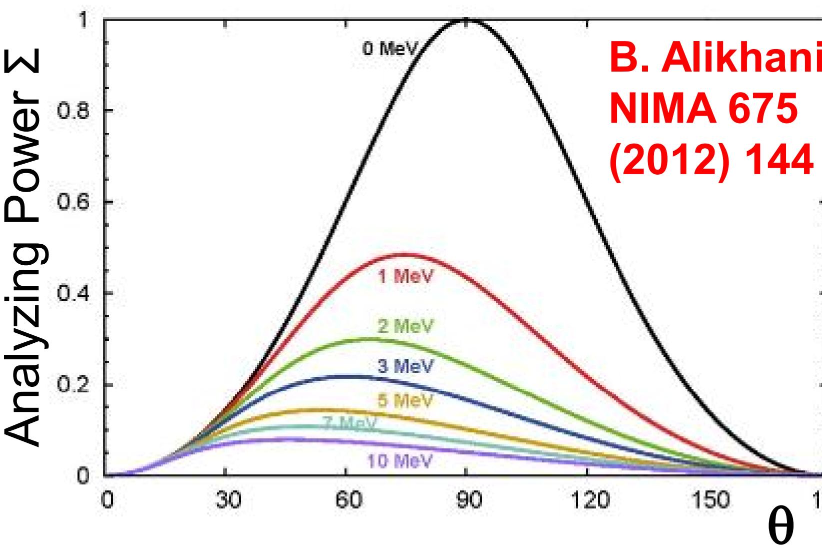
Sensitivity Q
average Σ on θ

P.G. Bizzeti et al.,
EPJ A 51 (2015) 49



φ angle between polarization plane and scattering plane

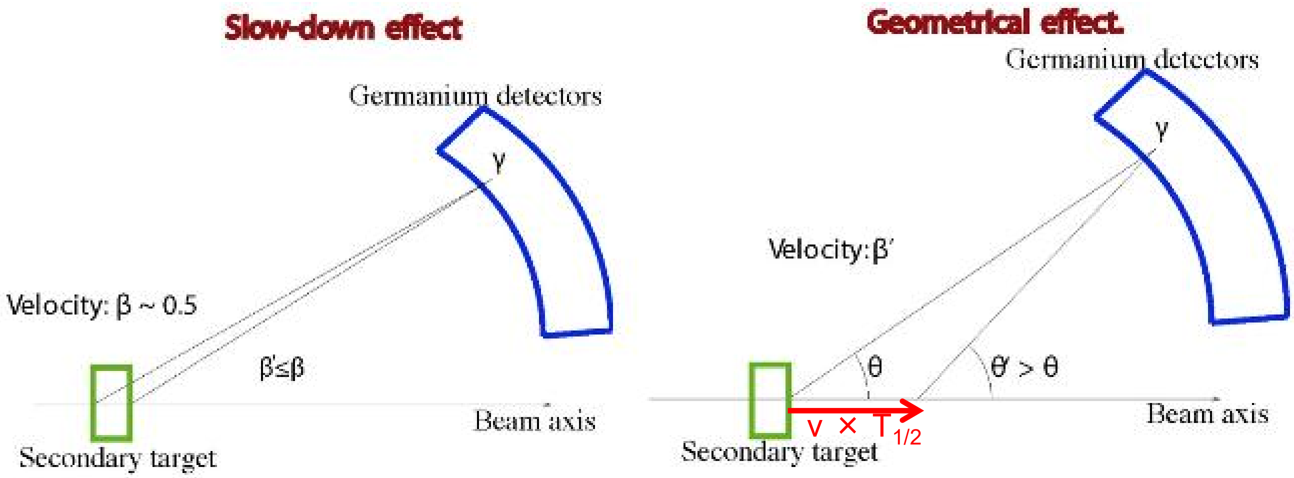
Simulation value for E_γ = 555.8 keV
^{104}Pd Σ = 0.439

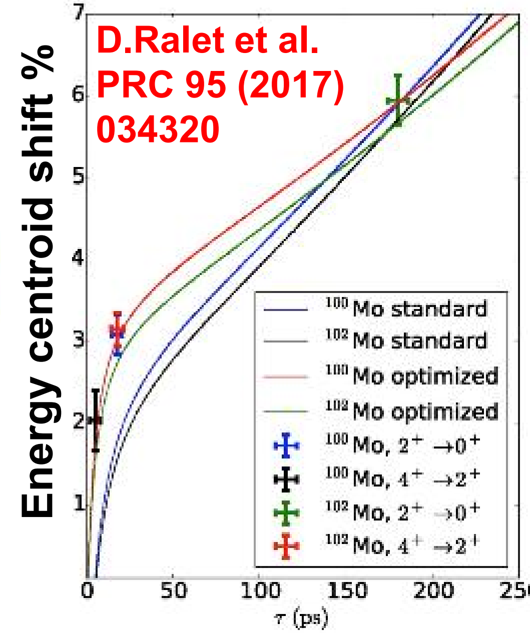


B. Alikhani et al.
NIMA 675
(2012) 144

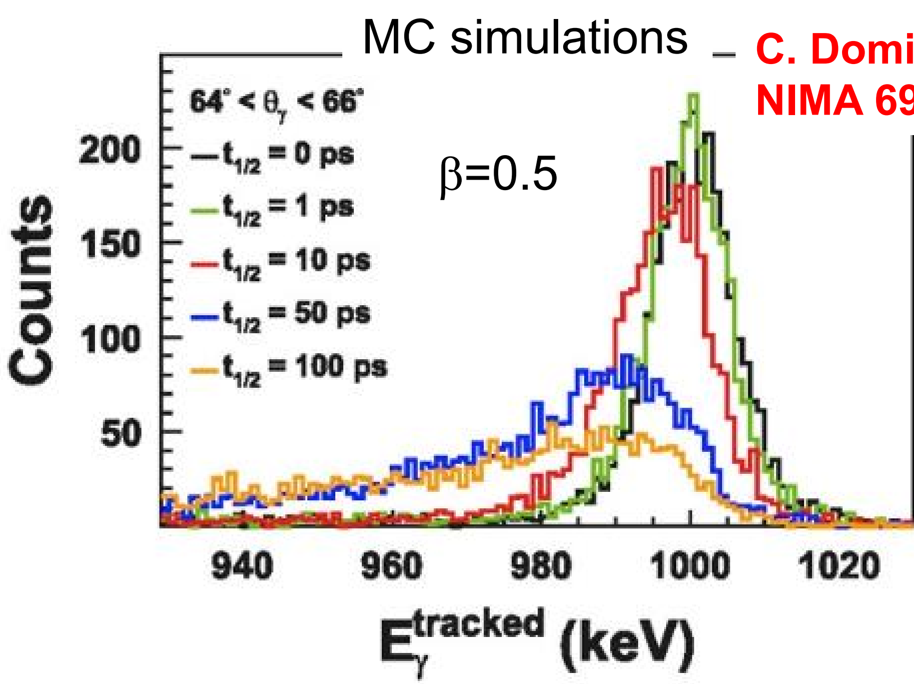
	Experimental asymmetry	Calculated polarization	Analyzing power
N_c	A_s	P	A_{exp}
3	−0.136 ± 0.014	−0.262	0.520 ± 0.053
4	−0.132 ± 0.014	−0.273	0.483 ± 0.052
5	−0.157 ± 0.014	−0.286	0.547 ± 0.049
6	−0.070 ± 0.014	−0.208	0.338 ± 0.067
7	−0.079 ± 0.014	−0.157	0.506 ± 0.089
8	−0.102 ± 0.014	−0.227	0.450 ± 0.062
Average			0.484 ± 0.024

In-Flight Geometrical Line-Shape Lifetime Measurement Techniques





D.Ralet et al. PRC 95 (2017) 034320

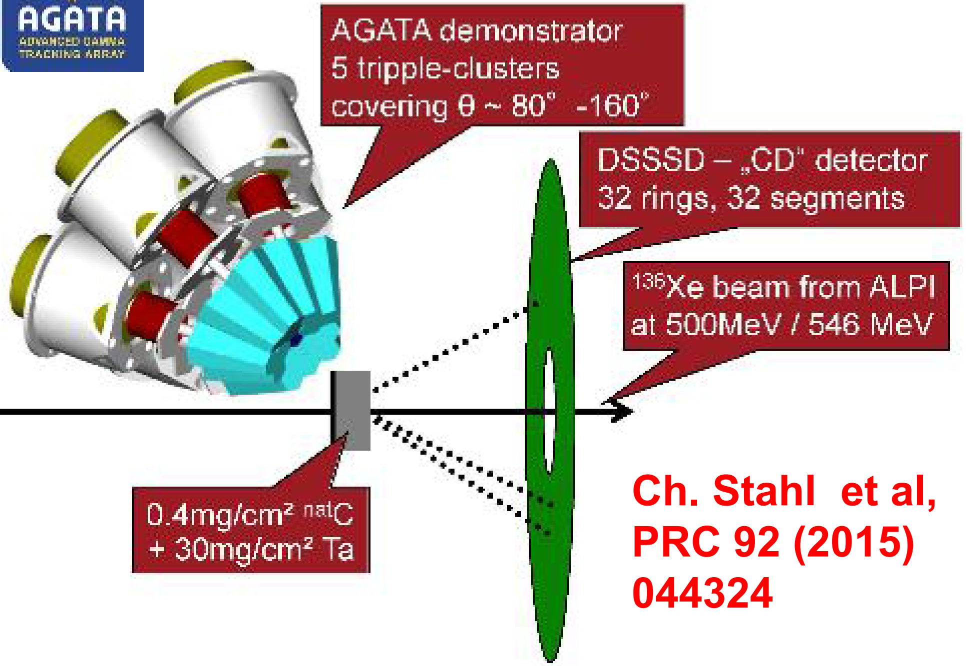


C. Domingo-Pardo et al, NIMA 694 (2012) 297

- New “DSAM-like” technique based on the position sensitivity and the Doppler correction.
- Possible to measure down to 1 to 10 ps lifetimes with relativistic RIBs.

D.Ralet PhD Thesis

Continuous-Angle DSAM

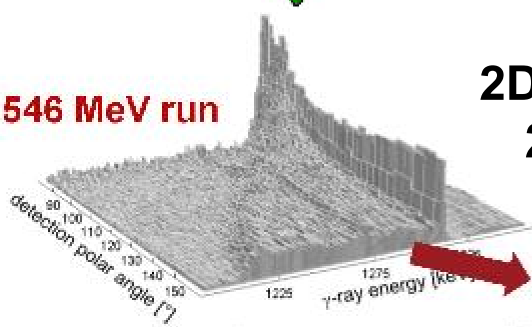


The continuous-angle DSAM represents an advancement of the "conventional" DSAM. It extends the γ-ray lineshapes analysis as a function of γ -ray energy to a lineshape analysis as a function of both γ-ray energy and polar angle of the γ-ray detection.
Also the Geometrical Line-Shape lifetime measurement available for long lifetimes

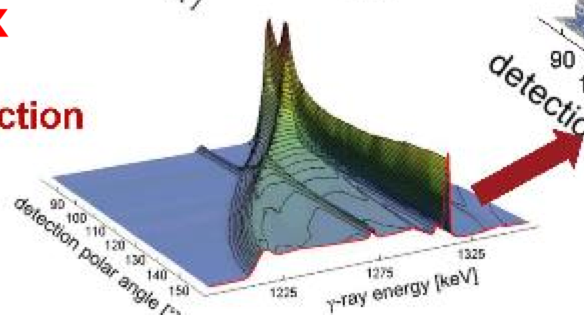
Ch. Stahl et al, PRC 92 (2015) 044324

^{136}Xe Coulex

LNL-data, 546 MeV run

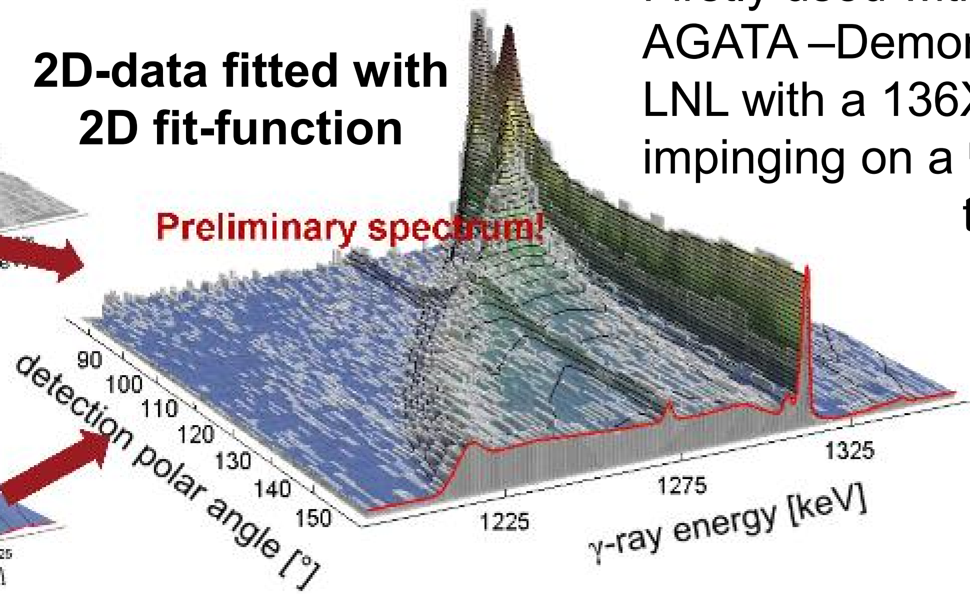


Fit-Function



2D-data fitted with 2D fit-function

Preliminary spectrum!

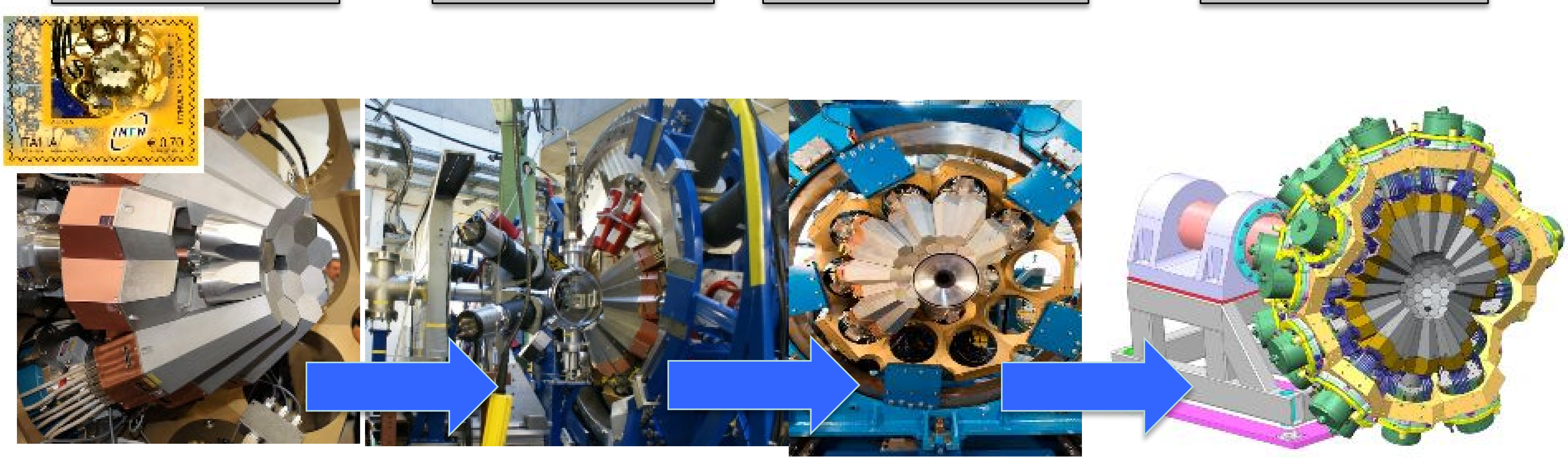


Firstly used with the AGATA –Demonstrator at LNL with a 136Xe beam impinging on a ^{nat}C + Ta target.

Ch. Stahl et al, CPC 214 (2017) 174

The AGATA Campaigns time line

AGATA@LNL AGATA@GSI AGATA@GANIL AGATA@LNL



2009 2011 2014

2022 commissioning
2022-24 Physics campaign

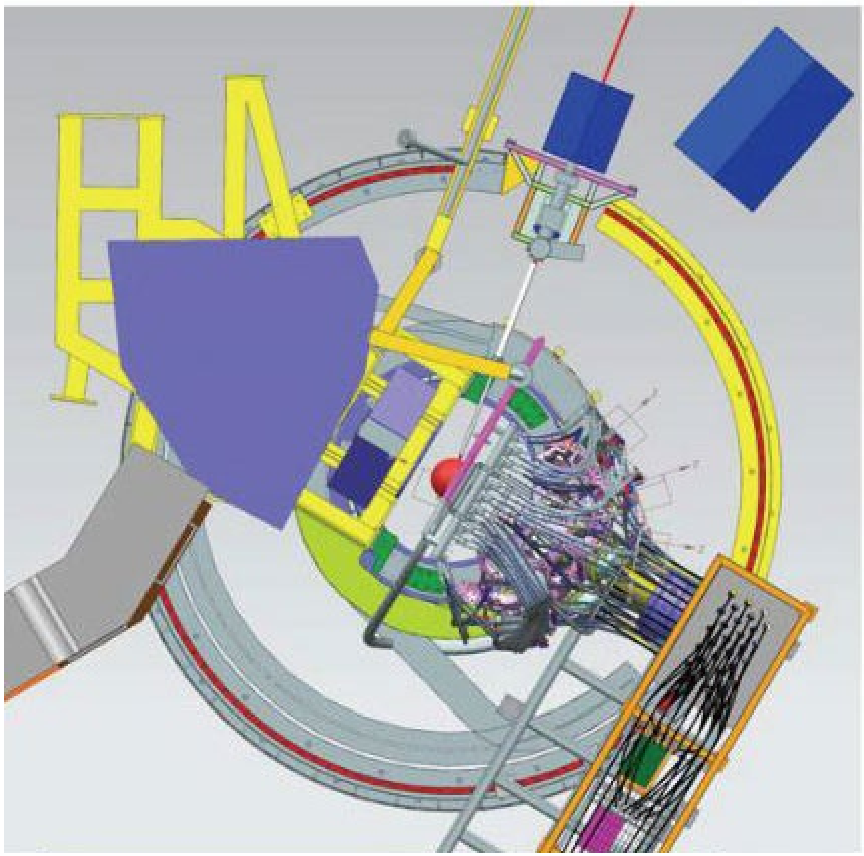
Campaign PM: J.J. Valiente-Dobon, Physics coordinator: M. Zielinska

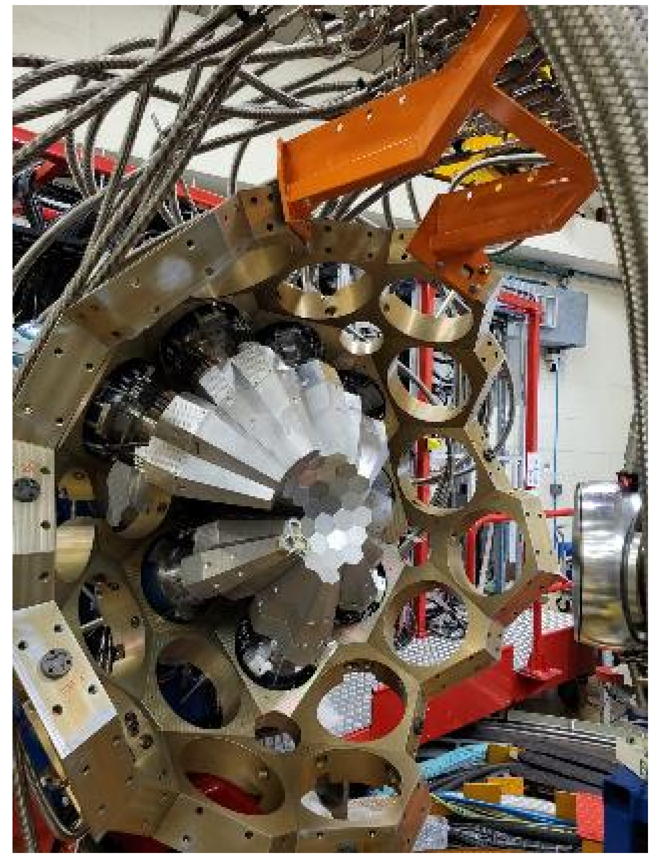
LNL: Six months from 2022 of stable beams and when available RIB from SPES 6 months RIB and 6 months stable beams.

AGATA @ INFN-LNL Configurations

Two configurations foreseen:

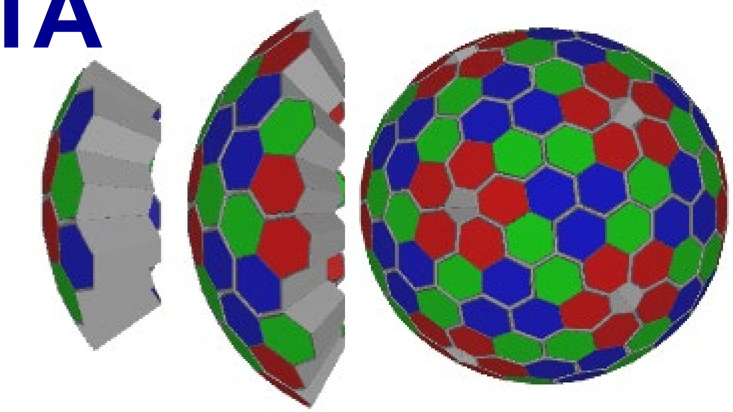
- Presently coupled with PRISMA for MNT reactions etc…
- Starting 2023/24 coupled with 0° instruments as NEDA etc…





2022: ~13 ATC, 2023: ~ 20 ATC, 2024 possibly 22 ATC i.e. ~13% efficiency

Complementary Instrumentation with AGATA



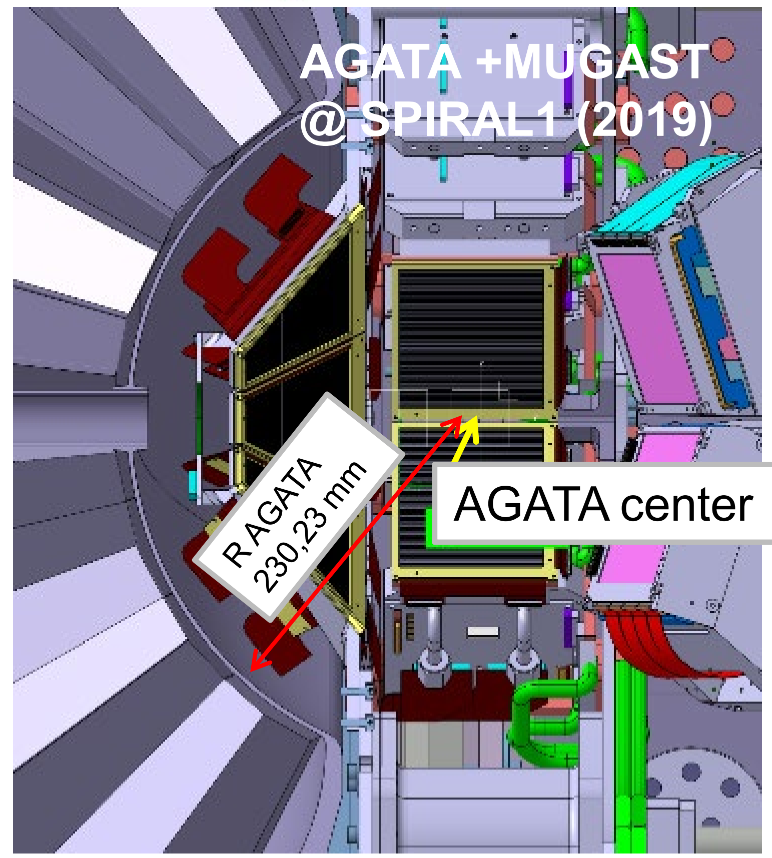
- Since the conceptual design, AGATA has been conceived as a flexible instrument to be combined with other instrumentation.

- Large inner-radius, possibility to select different configurations and electronics capable to interface with the AGATA Global Trigger and Synchronization

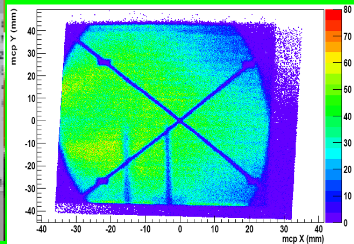
- Coupling with other instrumentation improves sensitivity providing reaction mechanism or tagging information.

- In addition, to exploit the full capabilities of AGATA is of paramount importance to get Information on the reaction kinematics with beam trackers, spectrometers, reaction product trackers or/and particle detectors.

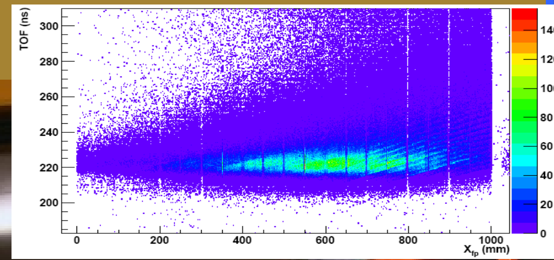
  E.Farnea et al. NIM A 621 (2010) 331

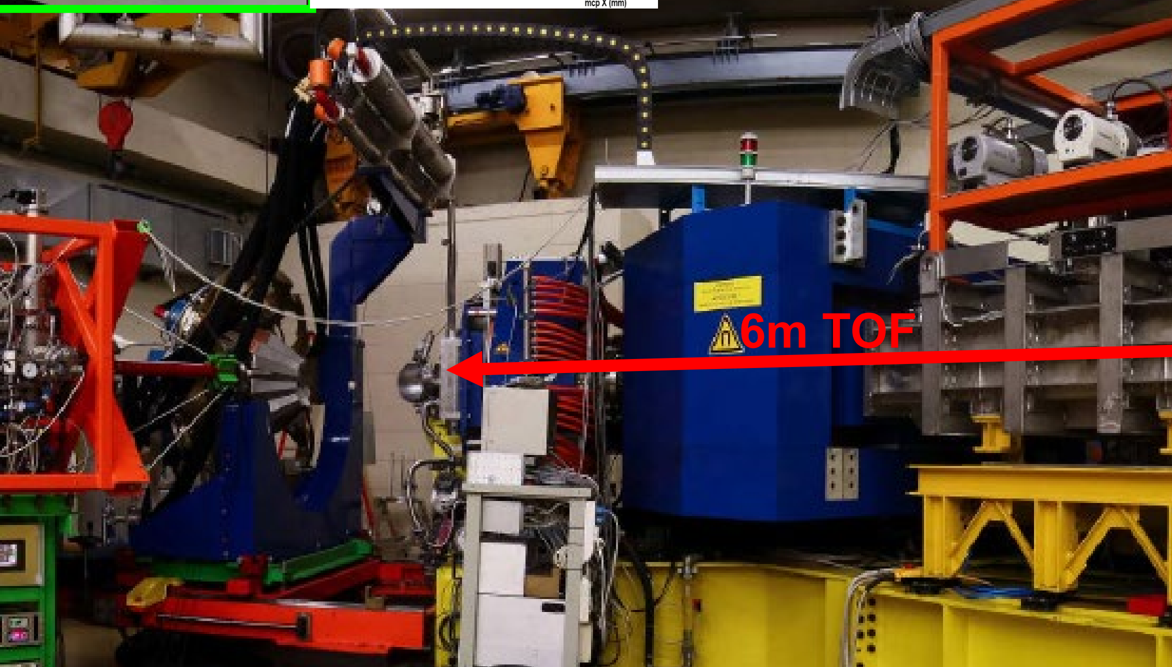


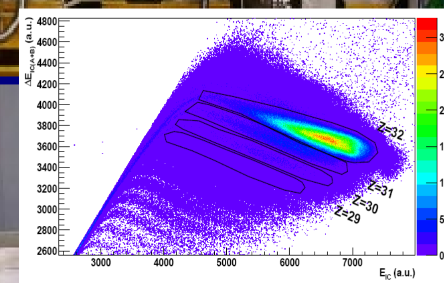
MCP Start Det. X,Y & T_I



MWPPAC X,Y & T_F







PRISMA: Tracking Magnetic Spectrometer

Large acceptance Ω = 80 msr

$\Delta Z/Z \approx 1/60$ (Measured) IC

$\Delta A/A \approx 1/190$ (Measured) TOF

Energy acceptance $\pm$20%

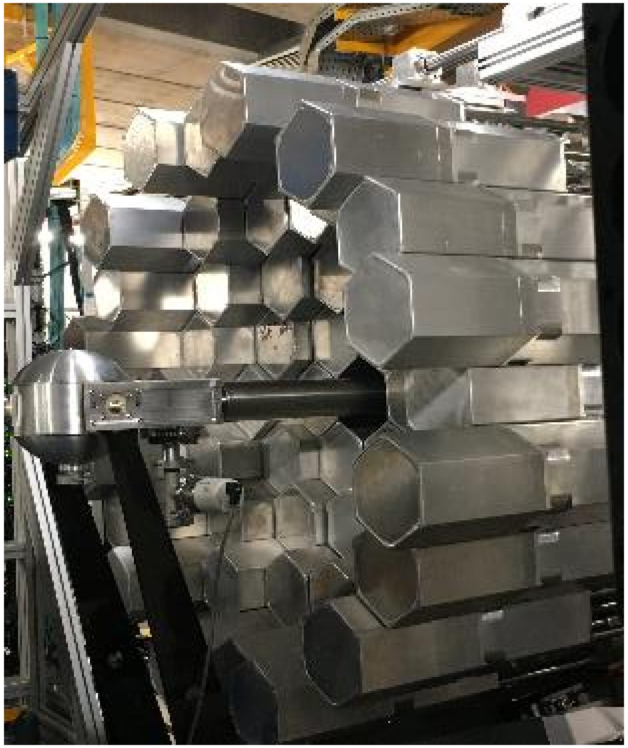
Max. $B\rho$ = 1.2 T.m.

Ionisation Chamber ΔE - E

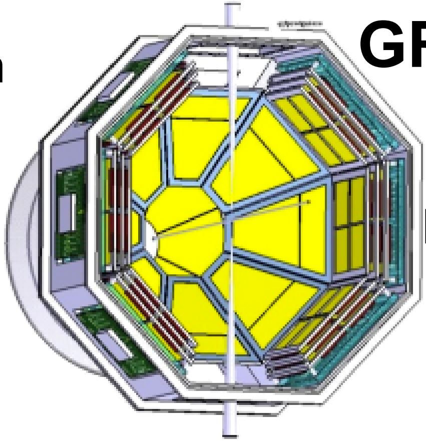
Complementary Instrumentation Developed for AGATA

NEDA

Neutron Detector array Common development for GANIL/SPIRAL LNL/SPES, FAIR/HISPEC



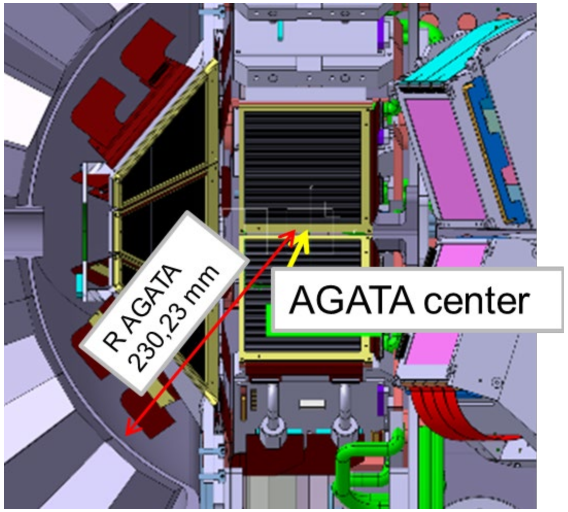
Tagging detector for Fusion-evaporation and direct reactions with n ejectiles
Campaign in 2018 at GANIL with DIAMANT



GRIT (GAPARD + TRACE)

Light Particle DSSSD Telescope array for Direct Reactions with RIBs developed for LNL/SPES and GANIL/SPIRAL
4π coverage for stripping and pick-up reactions with RIBs in inverse kinematics.

First Implementation, together with MUST2, used since 2019 with the SPIRAL1 beams

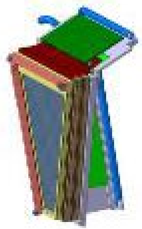


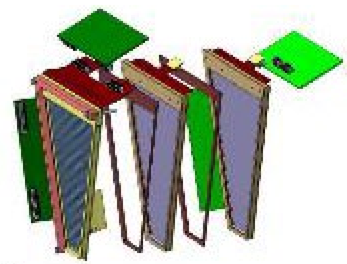
Both NEDA and GRIT are developed within large international collaborations

Key Instrumentation for Direct Reactions in Inverse Kinematics: the AGATA Added Value

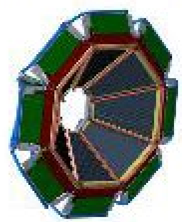
High efficiency for light charged particles and High granularity with particle identification capability with $\Delta E/E$ and PSA. To be coupled with AGATA for studies with direct reactions in inverse kinematics with Radioactive Ion Beams (INFN Italy, CNRS France, Spain)

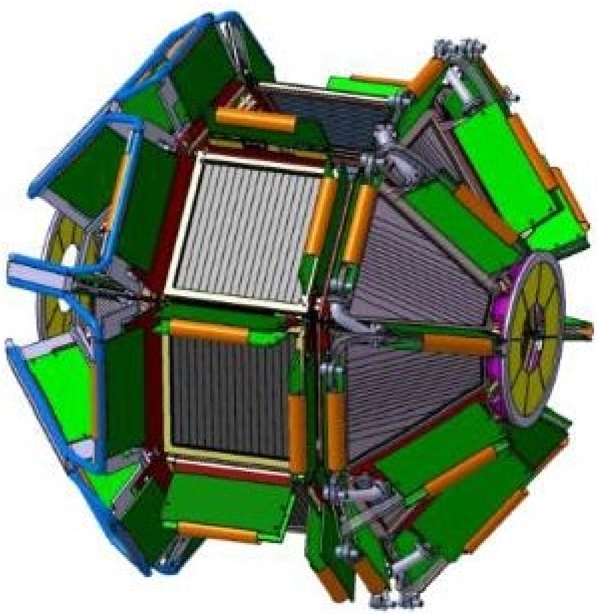
GRIT: High granularity 4π LCP detector array. Low γ-ray absorption

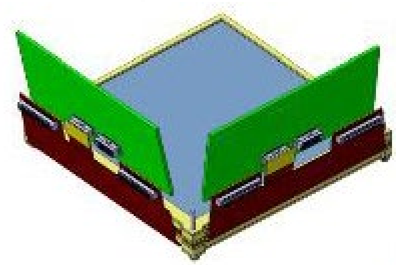




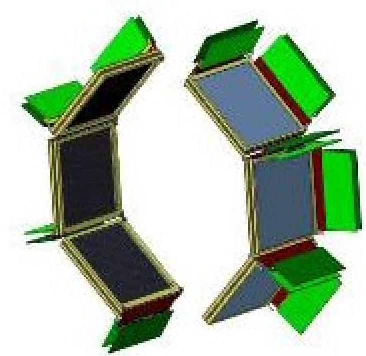
2 (backwards and 3 (forward) layers of prismatic DSSD with ~1mm position resolution



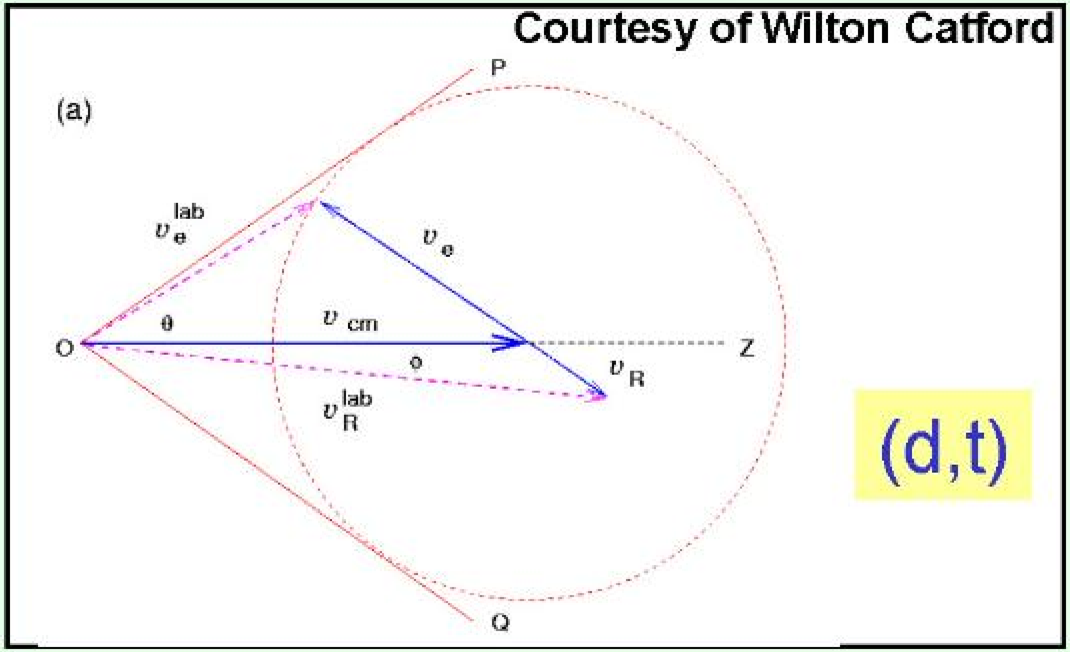


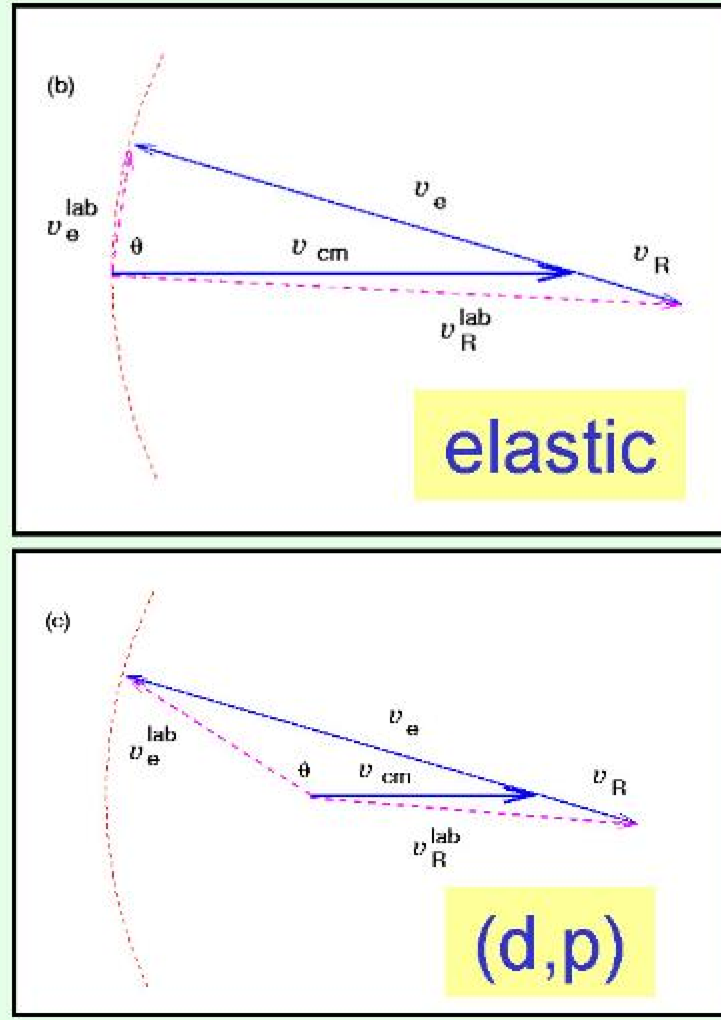


2 layer square DSSD detectors covering the 90° ring



Key Instrumentation for Direct Reactions in Inverse Kinematics: the AGATA Added Value





$$\frac{v_e}{v_{cm}} = \left(q\, f \frac{M_R}{M_P} \right)^{1/2} \cong \sqrt{q\, f}$$

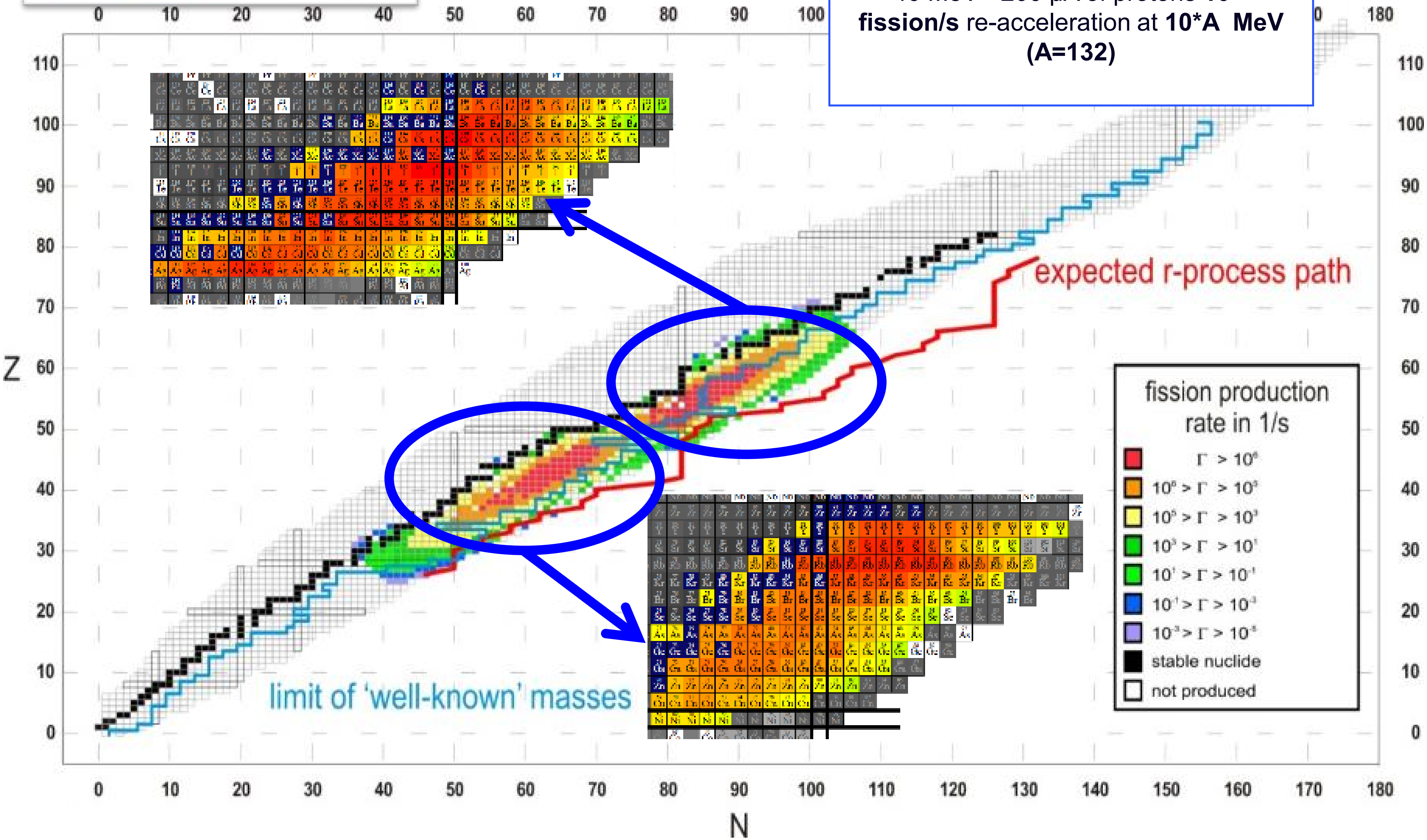
$$\theta_{max} = \sin^{-1}\sqrt{f}$$

$q \cong 1 + Q_{tot} / (E/A)_{beam}$ $f = 1/2$ for (p,d), $2/3$ for (d,t)

GRIT: provides fundamental information on the reaction channels and angular distribution of ejectiles. AGATA: allows thicker targets and provides information on energy as well as other independent observables.

Neutron-rich fission products at SPES

40 MeV - 200 μA of protons **10^{13} fission/s** re-acceleration at **10*A MeV (A=132)**



AGATA on Nuclear Astrophysics Measurements

- Measurements of Nuclear Structure of relevance for Nuclear Astrophysics:
    - Clusterisation phenomena in near threshold states
    - Studying if higher-order terms of the in-media nuclear Interaction (three body forces, etc.) are essential for a correct description of nuclear properties.
    - Electromagnetic decays from unbound states/resonances

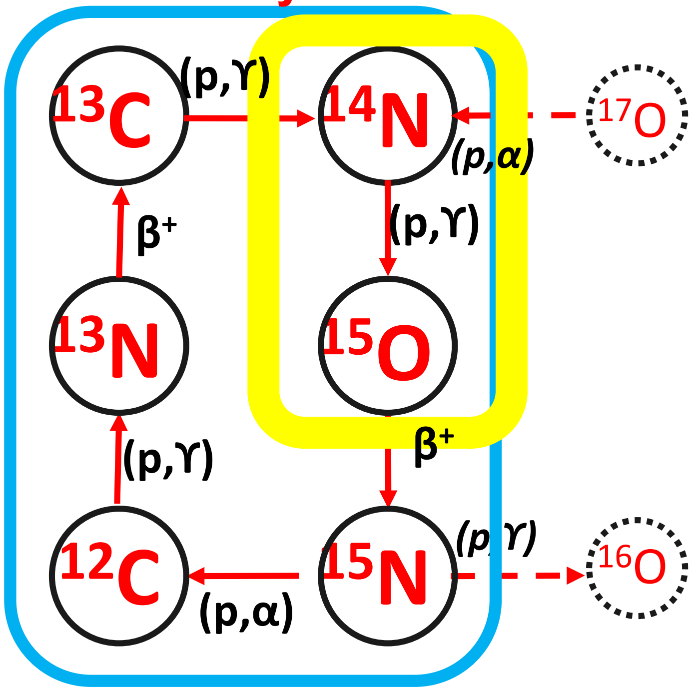
- Exclusive cross sections with stable targets and Radioactive Ion beams
    - Direct or surrogate cross section measurements
    - Contribution of the excited states to the reactions of astrophysical interest.

- Fission properties of very heavy nuclei

Solar hydrogen burning probed via DSAM lifetime measurements in ^{15}O

C.Michelagnoli, R.Depalo, R.Menegazzo, C.A. Ur, et al..

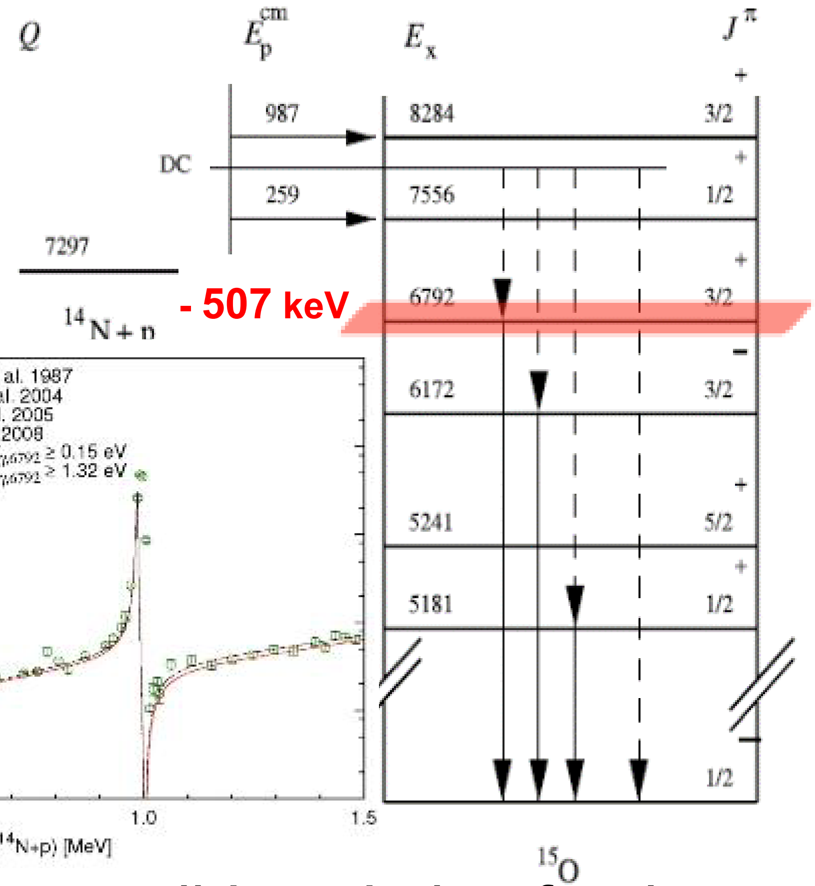
CNO cycle

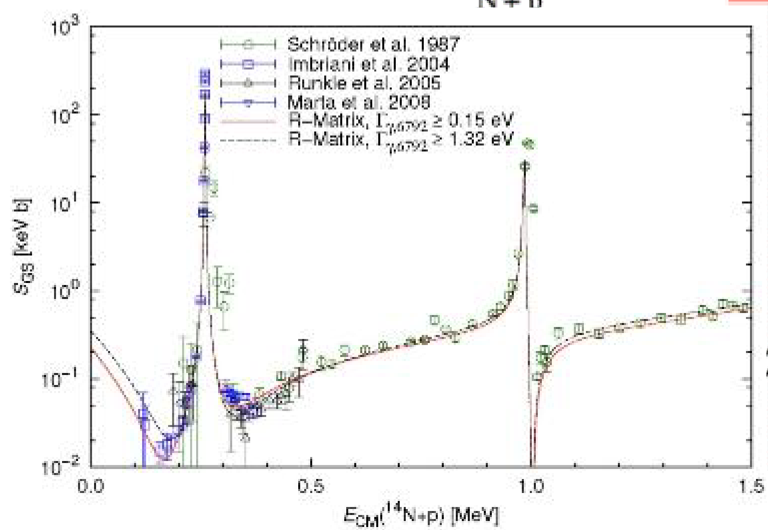


AGATA & LUNA Collaborators

^{14}N(p,γ)^{15}O
is the
"bottle neck"

M. Marta / Progress in Particle and Nuclear Physics 66 (2011) 303–308





Captures to different excited states in ^{15}O contribute to the cross-section.
The one to the gs in ^{15}O is dominated by the tail of the sub-threshold resonance at -507 keV (**6.79 MeV state in ^{15}O**)

C.Angulo et al., NP A690 (2001) 755,
M.Marta et al., PR C78 (2008) 022802(R)

possible solution for the "solar composition problem"

A.M.Serenelli et al., As.J.Lett. 705 (2009)

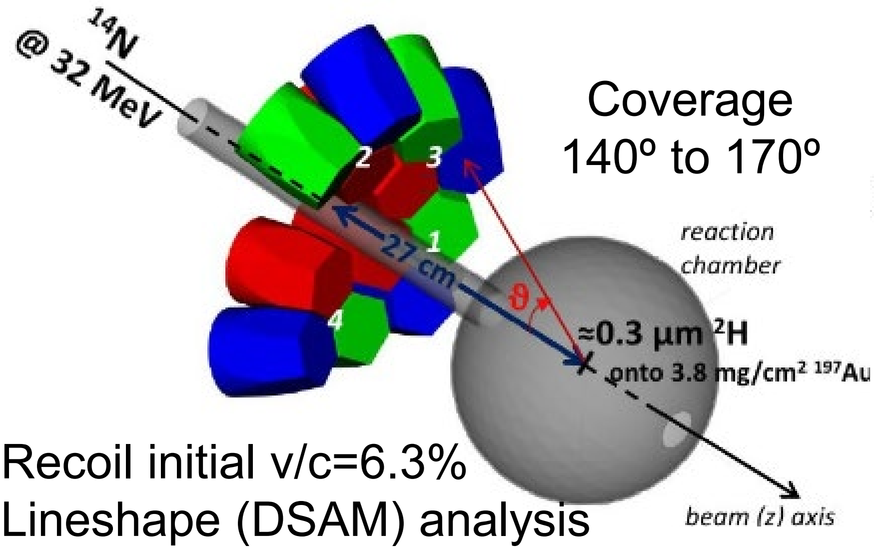
SSM ⇔ Helioseismology

Solar hydrogen burning probed via DSAM lifetime measurement in ^{15}O

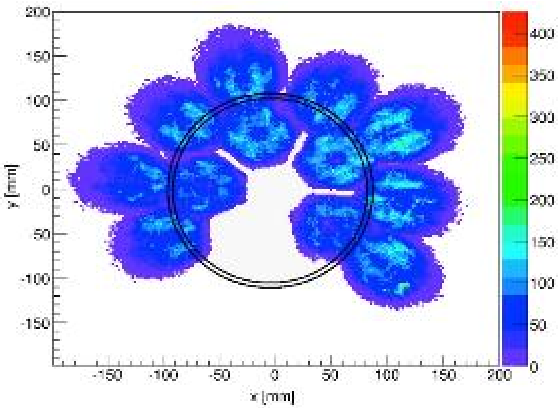
$^{14}N(^{2}H,n)^{15}O$ (i.k.) beam ^{14}N @ 32 MeV (LNL Tandem)

Lifetime measurement with 4 ATCs at backward angles

Width of the resonance ⇔ lifetime of the nuclear state



Coverage 140º to 170º



Angular Resolution 1º
Cuts of 2º width

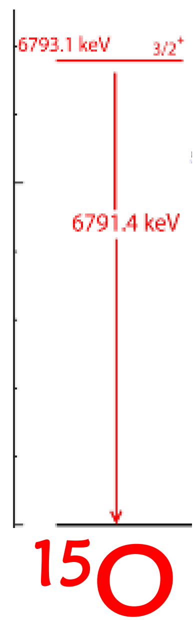
Cut at 160°

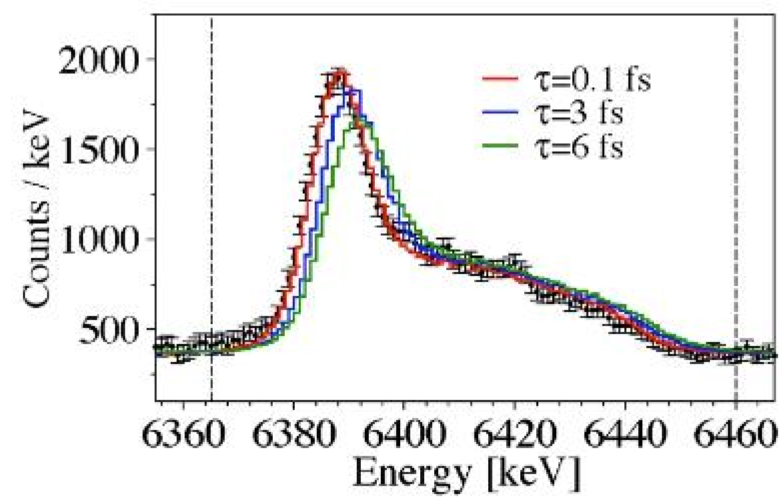
Recoil initial v/c=6.3%
Lineshape (DSAM) analysis

From the χ^2 parabola obtained at the different angles the lifetime is < 0.5±0.4 fs (99% CL)

⇔

$\Gamma_{\gamma;6792} \geq$ 1.32 eV (99% C.L.)
R-matrix $\Gamma_{\gamma;6792} \geq$ 0.15 eV





Comparison with simulations

C.Michelagnoli, R.Depalo, R.Menegazzo, C.A. Ur, et al.,

An exceptionally low alpha capture reaction rate on oxygen-15 and its impact as X-ray burst trigger Reaction

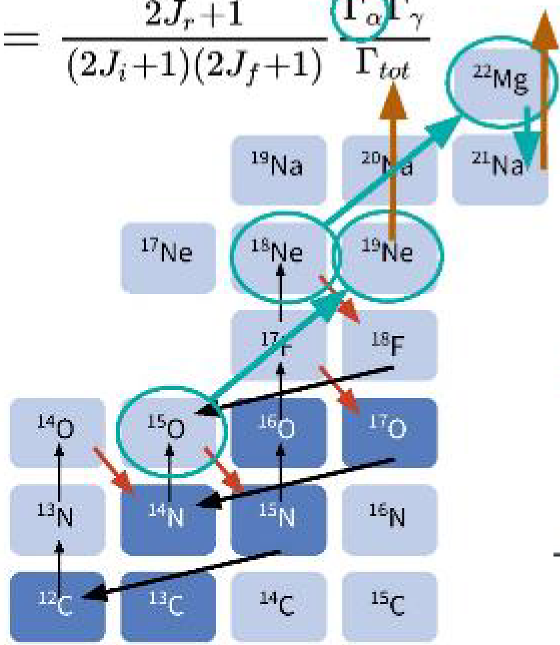
Light curves are extremely sensitive to alpha capture on ^{15}O.
Dominated by 4033 keV state in ^{19}Ne.

UNIVERSITY of York

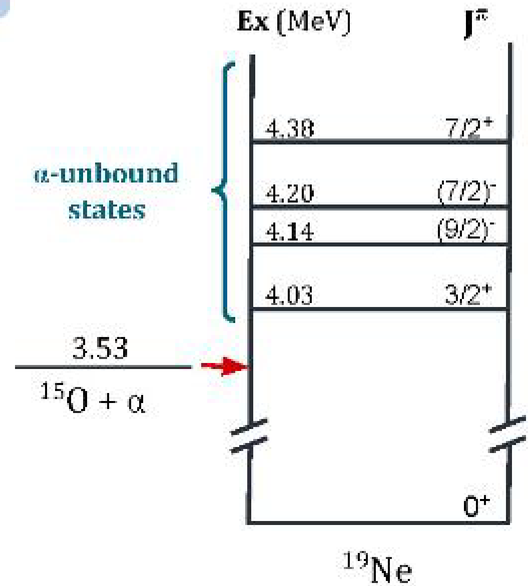
Ch. Diget, J.S. Rojo et al.,

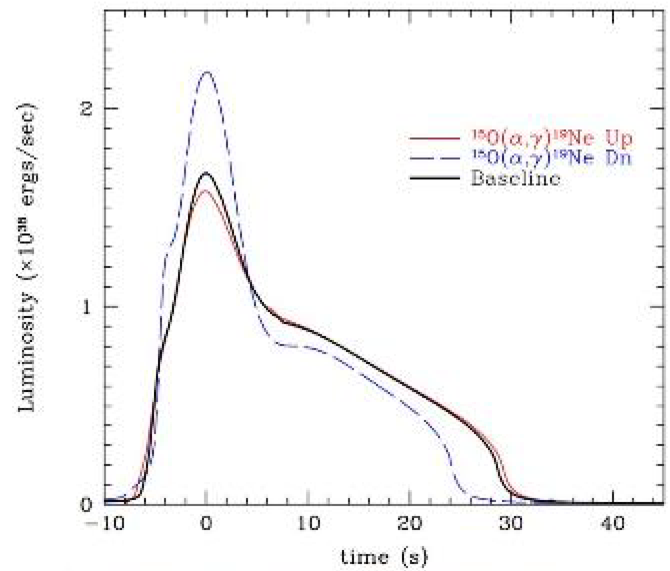
$$N_A \langle \sigma v \rangle_r \propto \omega\gamma_r \exp\left(-\frac{E_r}{k_b T}\right)$$

$$\omega\gamma_r = \frac{2J_r+1}{(2J_i+1)(2J_f+1)} \frac{\Gamma_\alpha \Gamma_\gamma}{\Gamma_{tot}}$$



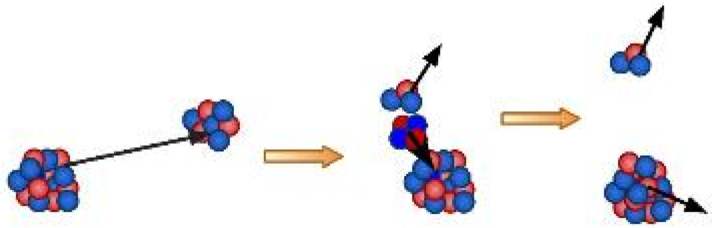
Extremely low cross section of $^{15}O(\alpha, \gamma)^{19}Ne$.

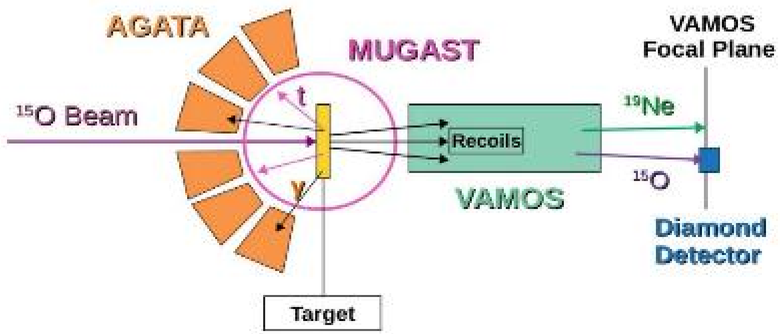


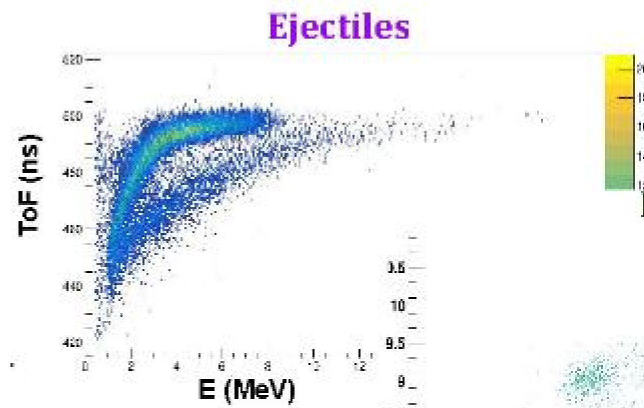


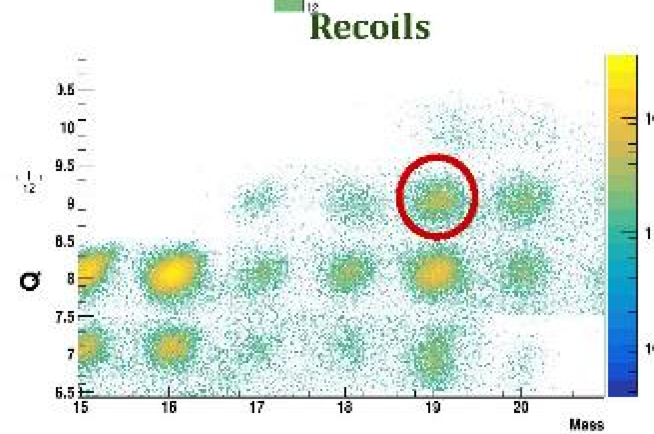
Single-zone X-ray burst sensitivity study Cyburt et al., APJ 830:55 (2016)

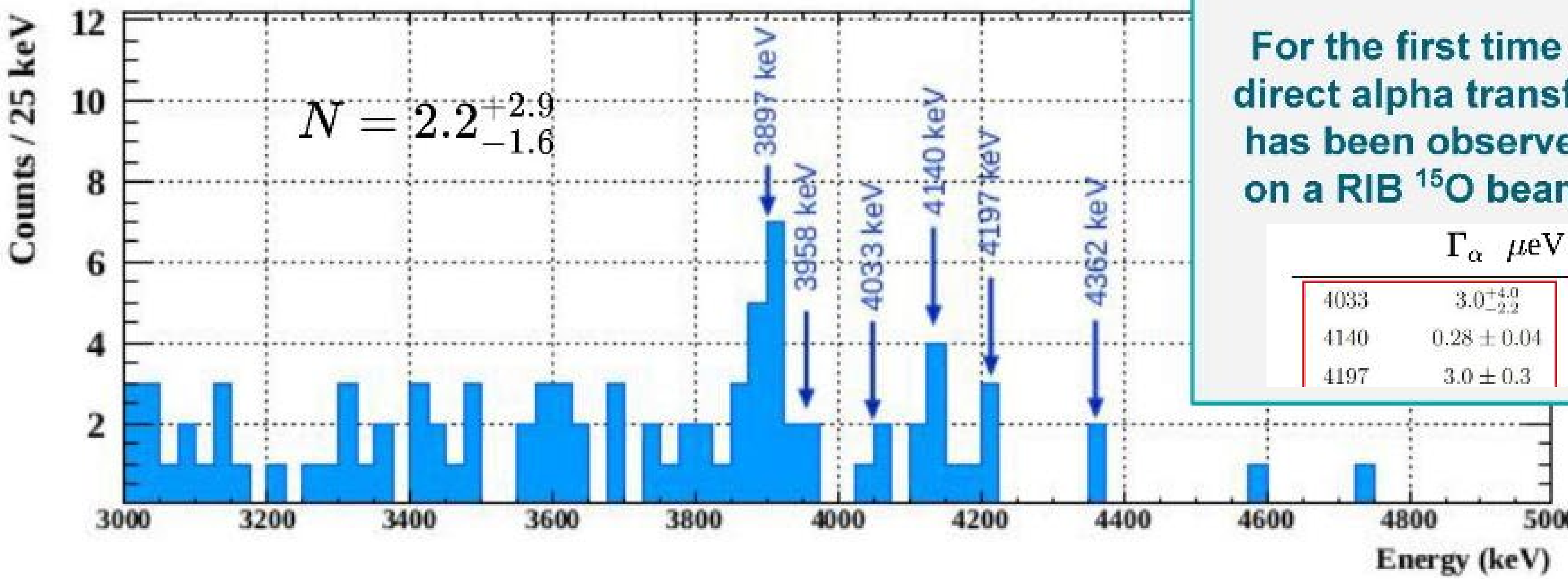
$$^{15}O + {}^{7}Li \rightarrow t + {}^{19}Ne^{*} \rightarrow t + {}^{19}Ne + \gamma$$











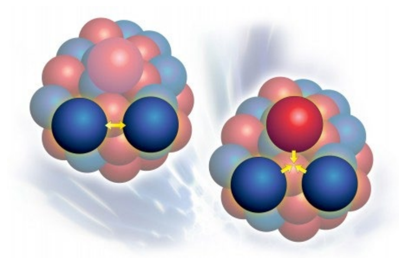
For the first time a direct alpha transfer has been observed on a RIB ^{15}O beam!

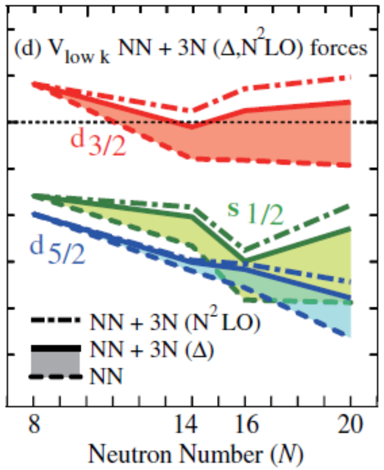
	Γ_α μeV
4033	$3.0^{+4.0}_{-2.2}$
4140	0.28 ± 0.04
4197	3.0 ± 0.3

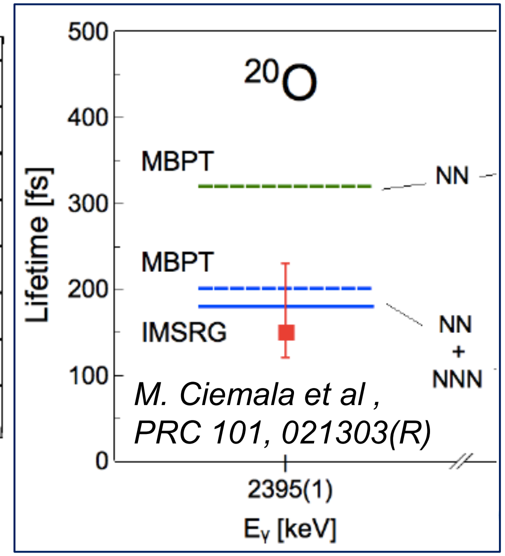
Ch. Diget, J.S. Rojo et al.,

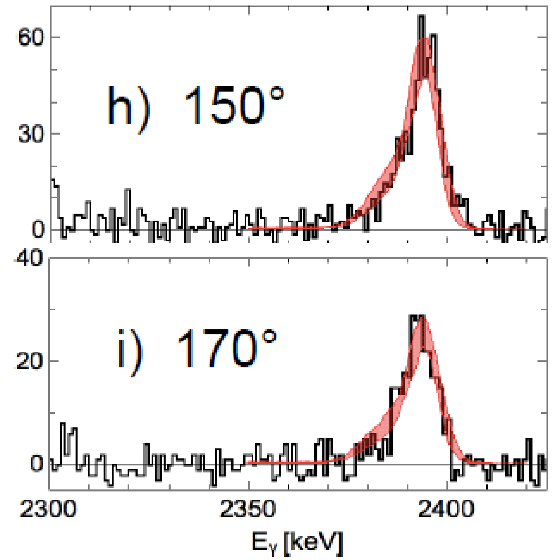
Femtosecond Lifetime Measurements In Very Exotic Nuclei

Importance of three-body forces on binding energies, but also on **level lifetimes**





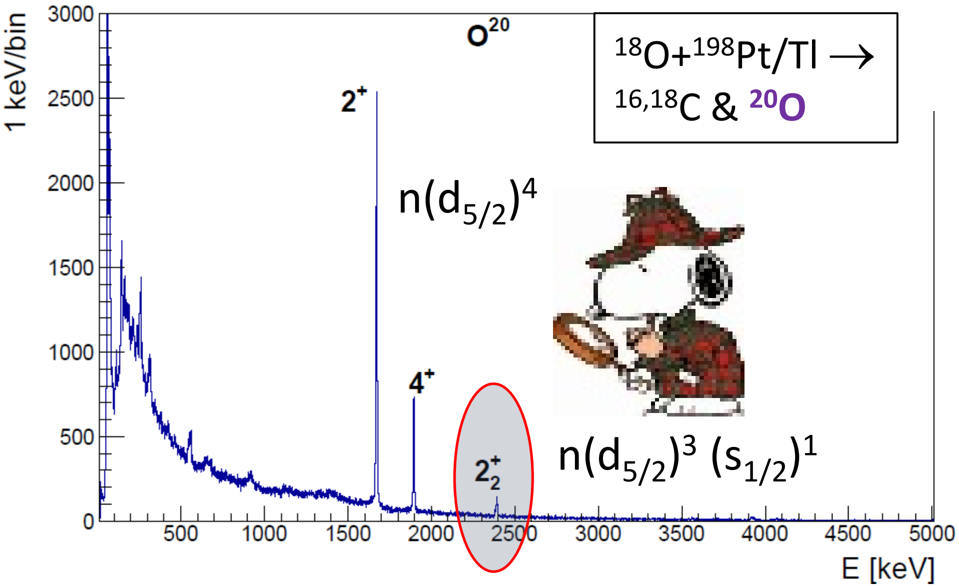




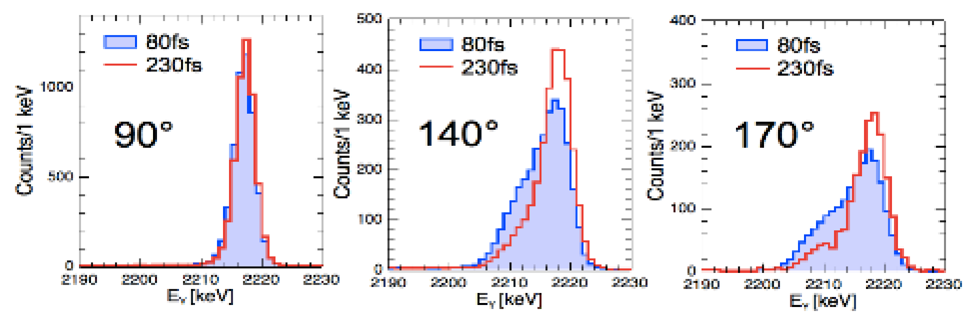
M. Ciemala, S.Leoni, B.Fornal et al
AGATA + VAMOS++ @ GANIL

MNT $^{18}O+^{198}Pt \rightarrow ^{20}O$

H Hergert et al., Phys. Scr. 92 (2017) 023002



Simulation for the AGATA 4π array



AGATA + MUGAST + VAMOS++ @ GANIL

$^{19}O(d,p)^{20}O$

E.Clement, A.Goasduff, I.Zanon et al

Summary and Outlook

- AGATA will be the state-of-the-art position sensitive high-resolution detector array to be use at high-intensity RIB and stable beam facilities in Europe, providing the maximum efficiency and performance.

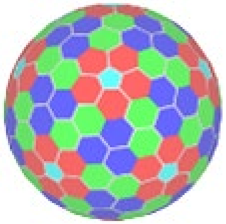
- The campaign at LNL has started in 2022 and we expect to reach close to 20 ATC in 2023. Will be coupled with complementary instrumentation as GRIT, PRISMA, NEDA….

- AGATA can be a highly efficient instrument for a broad range of Nuclear Astrophysics measurements or measurements of interest for Nuclear Astrophysics, specially in combination with SPES beams.

Thanks' to the AGATA, GRIT and NEDA Collaborators

My work is supported by MICINN, Spain
Grant n. PID2020-118265GB-C42

The AGATA Collaboration



~38 Institutes
>350 Collaborators

Bulgaria:	INRNE, Bulgarian Academy of Sciences
Finland:	Univ. Jyväskylä
France:	GANIL Caen, IP2I Lyon, IJC Orsay, IPHC Strasbourg, DRF/IRFU Saclay
Germany:	GSI Darmstadt, TU Darmstadt, Univ. zu Köln
Hungary:	ATOMKI Debrecen
Italy:	INFN Firenze, LNL, Milano, Padova
Poland:	IFJ PAN Krakow, University of Warsaw (HIL)
Spain:	IFIC CSIC-Univ. Valencia, ETSE Univ. Valencia, IEM Madrid CSIC LRI Univ. Salamanca,
Sweden:	Lund Univ., KTH Stockholm, Uppsala Univ, Stockholm Univ.
Turkey:	Univ's Ankara, Istanbul, Kocaelli, Bitlis Eren
UK:	Univ's Brighton, Edinburgh, Liverpool, Manchester, West of Scotland, Surrey, & York, UKRI-STFC Daresbury
Romania:	IFIN-HH Bucharest
Slovenia:	Univ. Ljubljana