AGATA
The Advanced Gamma Tracking Array
for Nuclear Structure Research
Challenges in Nuclear Structure Physics

- What are the limits of nuclear existence in (Z,A) and N/Z:
  - Ground state properties (lifetimes, masses, radii, …)
  - Exotic properties at the drip lines (halos, skins, …)
- How does their structure change when we reach these limits
  - Shell structure, nuclear shapes, ….
  - Excitation energy, spin, …

92 Elements (H-U)
- 288 quasi-stable isotopes $T^{1/2} > 10^{10}$y
- ≈3200 known unstable isotopes
- ≈7000 predicted isotopes
Challenges in Nuclear Structure Physics

Properties of excited states
→ γ-ray spectroscopy

Exotic deformations

Giant Resonances

Spin / Energy / Temperature

Proton drip line
N=170

Beta stable
N≈192

Neutron drip line
N≈270

Limits of nuclear existence in (Z,A) and N/Z:
- Ground state properties (lifetimes, masses, radii, ...)
- Exotic properties at the drip lines (halos, skins, ...)

Ground state properties (lifetimes, masses, radii, ...)

Exotic properties at the drip lines (halos, skins, ...)

Limits of nuclear existence in N/Z:

N≈270

≈100 isotopes of Og

β-stable
The AGATA Science Case

- Continuum studies
- Nuclear pairing
- Shell structure changes
- Fission barriers
- Superheavy elements
- Cluster structure
- Proton dripline
- Neutron dripline
- Nuclear astrophysics
- Shape isomers
- Exotic shapes
• $4\pi$ array from 180 large-volume HPGe crystals
• Each crystal is 36-fold segmented and encapsulated
• Arranged in 60 identical triple-cluster modules
The Advanced Gamma Tracking Array

- 6660 high-resolution digital electronics channels
- High throughput DAQ capable to record sampled pulses
- Pulse Shape Analysis algorithms → position sensitive mode
- $\gamma$-ray tracking algorithms → maximum efficiency and P/T

**Key Specifications**

- **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 ($M_\gamma=1$ [30]): 35% [23%]
- Peak/Total ($M_\gamma=1$ [30]): 55% [46%]

AGATA Collaboration NIM A 668 (2012) 26
Advantages of Gamma-ray Tracking

Compton Suppressed Ge detectors

\[ \Omega \sim 40\% \]
\[ \epsilon_{ph} \sim 10\% \]

- solid angle taken by the AC shields
- large opening angle → poor energy resolution due to Doppler effects

\[ \Omega \sim 80\% \]
\[ \epsilon_{ph} \sim 40\% \]

Gamma-ray Tracking Array

- Large solid angle covered by Ge
- Position-sensitive mode using PSA
- High P/T using tracking for \( \gamma \)-ray reconstruction

1. Maximizing the active solid angle without loosing signal/noise ratio
2. Improving the energy resolution in all experimental conditions, even at high emission velocities
3. Maximizing the performance of the detectors, even in conditions of heavy duty with radiation damage
The Concept of Gamma-ray Tracking

1. Highly segmented HPGe detectors
2. Digital electronics to record and process signals
3. Identified interaction points $(x,y,z,E,t)_i$
4. Evaluation of permutations of interaction points

Pulse Shape Analysis to decompose recorded waves

Reconstructed $\gamma$-rays
Tracking algorithms use Compton scattering formula to identify the sequence of $\gamma$-ray interactions

\[ E_{\gamma'} = \frac{\bar{E}_\gamma}{1 + \frac{E_\gamma}{m_0 c^2} (1 - \cos \theta)} \]

Algorithms must also treat photoelectric absorption and pair-production events.

~50% correct identification for $M_\gamma = 30$ as long as $\Delta(x,y,z) < 5\text{mm}$

Simulation of a high multiplicity event detected by an ideal shell
**THE AGATA COLLABORATION**

<table>
<thead>
<tr>
<th>Country</th>
<th>Institutions</th>
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<tbody>
<tr>
<td>Bulgaria</td>
<td>Univ. Sofia</td>
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<tr>
<td>Finland</td>
<td>Univ. Jyväskylä</td>
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<tr>
<td>France</td>
<td>GANIL Caen, IPN Lyon, CSNSM Orsay, IPN Orsay, IRFU CEA/Saclay, IPHC Strasbourg, LPSC Grenoble</td>
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<td>Germany</td>
<td>GSI Darmstadt, TU Darmstadt, Univ. zu Köln, TU München</td>
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<td>ATOMKI Debrecen</td>
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<td>Italy</td>
<td>INFN-LNL, INFN and Univ. Padova, Milano, Firenze, Genova, Napoli</td>
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<td>NINP and IFJ Krakow, SINS Swierk, HIL &amp; IEP Warsaw</td>
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<td>Spain</td>
<td>IFIC, ETSE-UVEG Valencia, IEM-CSIC, UAM Madrid, USAL Salamanca</td>
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<td>Univ. Ankara, Univ. Istanbul, Technical Univ. Istanbul</td>
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<td>UK</td>
<td>Univ. Brighton, CLRC Daresbury, Univ. Edinburgh, Univ. Liverpool, Univ. Manchester, Univ. West of Scotland, Univ. Surrey, Univ. York</td>
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>40 Institutions
>350 Collaborators
AGATA – A Travelling Detector

LEGNARO (2010-12)
LNL/SPES (2022+)

Jyväskylä (planned)

GANIL (2015-2021)
GANIL (2015-2021)

FAIR (2026+)

GANIL
SPIRAL 2

HIE-ISOLDE (planned)
Progress of AGATA (since 2010)

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 $1\pi$ (45 det.)
AGATA at GANIL

51 experiments performed
57 publications (7 PRL/PLB)
Towards the AGATA $4\pi$ Array

The current MoU for the construction of the 1/3 of the array ends at the end of 2020. New MoU for the construction of the AGATA $4\pi$ array under preparation.

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.
THE AGATA PHYSICS PROGRAM
(Today and in the next decade)
Changes in the Nuclear Shell Structure and the Puzzle of the Neutron Drip Line for Oxygen (Z=8)


Ab-initio calculations with 2N-forces only

Ab-initio calculations with 2N+3N forces

neutron drip line
Femtosecond Lifetime Measurements in Drip-Line Nuclei with AGATA

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

18O + 198Pt/Tl → 16,18C & 20O

n(d_{5/2})^4

n(d_{5/2})^3 (s_{1/2})^1

\[ E [\text{keV}] \]

\[ 1 \text{ keV/bin} \]

\[ 0 \]

\[ 500 \]

\[ 1000 \]

\[ 1500 \]

\[ 2000 \]

\[ 2500 \]

\[ 3000 \]

\[ 3500 \]

\[ 4000 \]

\[ 4500 \]

\[ 5000 \]
Femtosecond Lifetime Measurements in Drip-Line Nuclei with AGATA

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Simulation for the AGATA $4\pi$ array
Production of the 12\textsuperscript{+} isomeric beam by fragmentation of 600 MeV.A \textsuperscript{58}Ni on a \textsuperscript{9}Be 4g/cm\textsuperscript{2} primary target of GSI-FRS. Isomeric ratio from \(\beta\)-decay with thick stopper: \(\sim\)10\%

\textsuperscript{53}Fe at \(\beta=0.51\)

Secondary Au Target

AGATA at 8cm distance

Z identification

\(\Delta E-E\)

LYCCA

Identification of secondary reaction products (\(\Delta E/E, \text{ToF}\))
Ground state Coulomb excitation:

- $2^+ \sigma = 106(5) \text{ mb}$; 
  B(E2) = 900(40) $e^2 fm^4$; $T_{1/2} = 7.1(4) \text{ ps}$
  
  Lit. 820 $e^2 fm^4$ PRC 70, 034301

- $2^+ \sigma = 11(3) \text{ mb}$; 
  B(E2) = 42(20) $e^2 fm^4$; $T_{1/2} = 0.42(11) \text{ ps}$

~90% beam

$^{52}\text{Fe} \text{ g.s.}$

$2^+_1 \rightarrow 0^+$

850 keV

T$_{1/2} \approx 8$ ps

~10% beam

$^{52}\text{Fe}^{12+}$

$2^+_2 \rightarrow 0^+$

2760 keV

$^{14+} \rightarrow ^{12+}$

$\sigma = 41(13) \text{ mb}$

Tayfun Hüyük, PhD thesis
IFIC Valencia

W. Korten – AGATA – The Adva
- Energy spectrum is very sensitive to the nuclear shell structure
- **High $2^+$ energy in even-even nuclei $\leftrightarrow$ magic numbers**
  - $^4\text{He}, ^{16}\text{O}, ^{40,48}\text{Ca}, ^{208}\text{Pb}$; $^{56,78}\text{Ni}, ^{100,132}\text{Sn}$ (unstable)
- Magic numbers disappear for $N \gg Z$
  - $^{32}\text{Mg}$ ($N=20$), $^{42}\text{Si}$ ($N=28$) are deformed
First Spectroscopy of Doubly-Magic $^{78}$Ni at the RIKEN Radioactive Ion Beam Factory

- Fragmentation reaction at relativistic energies (see talk of K. Wimmer for more details)
- First $2^+$ state of $^{78}$Ni at 2.6 MeV ($\rightarrow$ magic ?)
- Complex spectrum could not be disentangled due to limited DALI2 resolution (NaI array)

$^{80}$Zn(p,3p)

Counts / $80$ keV

- 2560(30)
- 2920(40)

Energy (keV)

Taniuchi, - Nature 569 (2019)

© Courtesy: A. Obertelli – TU Darmstadt
Evolution of collectivity around N=50,52: Lifetimes in the vicinity of $^{78}$Ni with AGATA

Sudden increase of collectivity in $^{84}$Ge: hint of pseudo-SU3 symmetry

The Shell Structure around doubly-magic $^{132}\text{Sn}$

- Energy spectrum is very sensitive to the nuclear shell structure
- High $2^+$ energy in even-even nuclei $\leftrightarrow$ magic numbers
  - $^4\text{He}$, $^{16}\text{O}$, $^{40,48}\text{Ca}$, $^{208}\text{Pb}$; $^{56,78}\text{Ni}$, $^{100,132}\text{Sn}$ (unstable)
Low energy Coulomb excitation

\[ ^{206}\text{Pb} + ^{132}\text{Sn}^{31+} @ 5.49 \text{ MeV/u} \sim 3.0 \times 10^5 \text{ pps} \]


- Very good energy resolution
- Rather limited \( \gamma \) efficiency and particle rate
The Shell Structure around $^{132}\text{Sn}$

Experiment
A. Jungclaus et al. (CSIC Madrid)

AGATA simulation (CSIC Madrid)
High-resolution spectroscopy at relativistic energies

*Lifetime measurements using Doppler-shift lineshape methods*
One of the “Top unexpected physics discoveries of the last five years” in 1980s (D. Kleppner, Physics Today, 1991)

Superdeformation is a very general phenomenon of atomic nuclei at very high spin, but many questions still remain unanswered:

- Decay-out from superdeformed states → \((E^*,I)\) of SD states are mostly unknown
- Link between clusterisation & exotic (particle) decays in light nuclei?
- How to populate SD states in neutron-rich nuclei → very high intensity neutron-rich beams
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Spectroscopy of deformed magic nuclei in the heaviest elements at JYFL


+ huge gain in $\gamma^n$ statistics
• INFN – LNL, Italy: hosted the AGATA Demonstrator, in 2010 and 2011.
• GSI, Germany: hosted AGATA-25 from 2012 to 2014
  • coupled with FRS and the PRESPEC detectors (tracker, LYCCA etc…).
• GANIL / SPIRAL1, France: is hosting AGATA-1π presently until 2021
  • Experimental activity coupled to VAMOS++, PARIS, NEDA+DIAMANT, MUGAST, etc…
• INFN – LNL, Italy will host AGATA from 2022
  • Programme with stable beams, PRISMA and other complementary detectors
  • from ~2023 with ISOL beams from SPES
• FAIR – Germany, Germany will host AGATA from 2026+
  • Programme with relativistic beams from the Super-FRS
Selective Production of Exotic Species

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

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

Techniques (e.g.):
  ▪ Fragmentation
  ▪ Few nucleon knockout
  ▪ High-energy Coulomb excitation

W. Korten – AGATA – The Advanced Gamma Tracking Array
Conclusions and Perspectives

- AGATA has been in use for experiments since 2011

- Rich science program with stable and radioactive ions beams at the major European accelerator infrastructures

- Construction of the AGATA 1π array is nearing completion

- Near future campaigns are planned in LNL (2022+) and at FAIR (2026+)

- White Paper and new MoU for the construction of the AGATA 4π array currently under preparation
Thank you