The AGATA Spectrometer
Precision Spectroscopy of Exotic Nuclei

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AGATA physics case
Nuclear Structure/Astrophysics

Goal: To determine nuclear properties as a function of $E_x$, $J$ and $T$ (and $N,Z$) to find a consistent theoretical framework to describe the phenomena observed.
AGATA physics case
Challenges in Nuclear Structure Physics

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

Properties of excited states
→ γ-ray spectroscopy

- Giant Resonances
- Exotic deformations
- Hyper Deformation
- Super Deformation
- Jacoby shapes

Spin [h]

Energy [MeV]

Energy/Temperature

N/Z - isospin

- proton drip line N=170
- beta stable N≈192
- neutron drip line N≈270

≈100 isotopes of Og
Precision spectroscopy of nuclear states

- Gamma-ray (hence level) energies
- Complex level schemes ($\gamma^n$ 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

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

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

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
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.
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

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
Turkey: Univ. Ankara, Univ. Istanbul, Technical Univ. Istanbul

13 Countries >40 Institutions
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

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]): 43% [28%]
Peak/Total ($M_\gamma=1$ [30]): 58% [49%]
The concept of γ-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 γ-rays
The AGATA triple cluster

Asymmetric AGATA Triple Cryostat
- integration of 111 high resolution spectroscopy channels
- cold FET technology for all signals

Challenges:
- mechanical precision
- LN2 consumption
- microphonics
- noise, high frequencies
Pulse Shape Analysis concept

791 keV deposited in segment B4

z = 46 mm
Pulse Shape Analysis concept

791 keV deposited in segment B4

z = 46 mm

(10,10,46)
Pulse Shape Analysis concept

791 keV deposited in segment B4

(10, 15, 46)

z = 46 mm
Pulse Shape Analysis concept

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**CORE**

Black line: measured
Red line: calculated

791 keV deposited in segment B4

(z = 46 mm) (10, 20, 46)
Pulse Shape Analysis concept

791 keV deposited in segment B4

(10, 25, 46)

z = 46 mm
Pulse Shape Analysis concept

791 keV deposited in segment B4
Pulse Shape Analysis concept

Result of Grid Search algorithm

(10, 25, 46)

791 keV deposited in segment B4
Memorandum of Understanding

I MoU
AGATA 15
Demonstrator

II MoU
AGATA 60

III MoU
AGATA 180 = 4π
2010-2012
Legnaro, Italy
Intense stable beams
15 detectors

2012-2014
GSI, Germany
Fast fragmentation beams
25 detectors

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

Progress of the AGATA array

• 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)
The next decade for AGATA
AGATA science case

Continuum studies

Nuclear pairing

Shell structure changes

Fission barriers

Cluster structure

Proton dripline

Neutron dripline

Nuclear astrophysics

Shape isomers

Exotic shapes

Superheavy elements

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

Isospin Symmetry Studies

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

Cross section [mb]

N=Z

Plunger Triple gated 48h/distance
First spectroscopy in Triple gated

Forbidden E1 transition
Isospin symmetry breaki

Signatures for T= 0 pairing

100Sn 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
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

Transition rates and mirror energy differences in isobaric multiplets

Coulomb excitation of the 12+ band-terminating yrast trap in $^{52}$Fe

Evolution of collectivity in the $^{208}$Pb region

Proton hole states in $^{132}$Sn and N=82 shell structure

Shape evolution in the region of the neutron-rich Mo

Relativistic M1-Coulomb excitation of $^{85}$Br

Pygmy dipole resonance in $^{62,64}$Fe and the properties of neutron skin

• 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

- Exploration of alpha-cluster: the unique case of $^{212}\text{Po}$ ($^{208}\text{Pb} + \alpha$)
- Lifetime measurements in $^{106,108}\text{Sn}$
- Seniority conservation in N=50: $^{92}\text{Mo}$, $^{94}\text{Ru}$
- Octupole correlation in $^{207}\text{Pb}$
- Shape transition in the n-rich W
- Quadrupole Moments in $^{166,168}\text{Dy}$
- $i_{13/2}$ single particle state in $^{133}\text{Sn}$ and high spin in $^{108}\text{Zr}$
- Shape evolution in neutron rich fission fragments in the mass A~100 region
- Shell evolution around N=50: $^{81}\text{Ga}$ spectroscopy
- Evolution of collectivity around N=52: lifetimes in $^{83,84}\text{Ge}$
- Evolution of collectivity around N=40: lifetimes in $^{73,75}\text{Ga}$ and $^{64}\text{Fe}$
- Evolution of the shell structure in the region of neutron-rich Ti isotopes
- The lifetime of the $^{23}\text{Mg}$ 7.786 MeV state: probe for classical novae models
- Lifetime measurements of excited states in neutron-rich C and O isotopes
GANIL AGATA-NEDA-DIAMANT
Campaign: 2018

- Quadrupole and Octupoles in $^{112}$Xe
- Excited states in $^{102,103}$Sn
- $T=0$ pairing $^{88}$Ru: High Spin

Isospin Symmetry Breaking: $^{71}$Kr-$^{71}$Br

Isospin Symmetry Breaking A=63

N=Z

Neutrons

ToF vs. NNPSA

CsI PSA

DIAMANT

Energy

NEDA neutron Detector Array
Isospin Properties of Nuclear Pair Correlations from the Level Structure of the Self-Conjugate Nucleus $^{88}$Ru


ABSTRACT

The low-lying energy spectrum of the extremely neutron-deficient self-conjugate ($N = Z$) nuclide $^{88}$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 Accélérateur National d’lons Lourds (GANIL) accelerator complex. The observed $\gamma$-ray cascade is assigned to $^{88}$Ru using clean prompt $\gamma$-$\gamma$-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

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 $T \neq 0$ 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.
Reaction: $^{36}\text{Ar} + ^{54}\text{Fe} \rightarrow ^{88}\text{Ru} + 2\text{n} \ (E_{\text{beam}} = 115 \ \text{MeV})$

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

AGATA+NEDA/NWALL+DIAMANT
13 days
Summed $\gamma$-$\gamma$ spectrum--2n-no charged particle recorded condition
Full power-resolution-AGATA-plus selection, weak channel, few $\mu$b
Delayed alignment $(\pi g9/2)^2$

Compared with N>Z neighbours

Consistent with isoscalar pairing

In $^{88}\text{Ru}$ (T=0)

$T = 0, J > 0$
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.
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
AGATA@FAIR: ≥ 2025

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
- High-energy 100-300 MeV/A (β~0.5)
- Isomeric beams & high-Z beams

Techniques (e.g.):
- Fragmentation
- Knockout
- High-energy Coulomb excitation
Scientific Research Curiosity

Applications

State of the art detectors

Medical

Security

Environment
From AGATA to Portable Imaging
Thank you
Agata High Spin Simulations

Courtesy of Marc Labiche AGATA simulation code (GEANT)
Simulations from 15 → 90 detectors:

**FAIR-type example**
- Typical reaction, v/c ~ 50%
- Huge Doppler effects
- “direct reaction”
- γ- and γ-γ analysis
- Factor ~30 better for γ-γ

**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