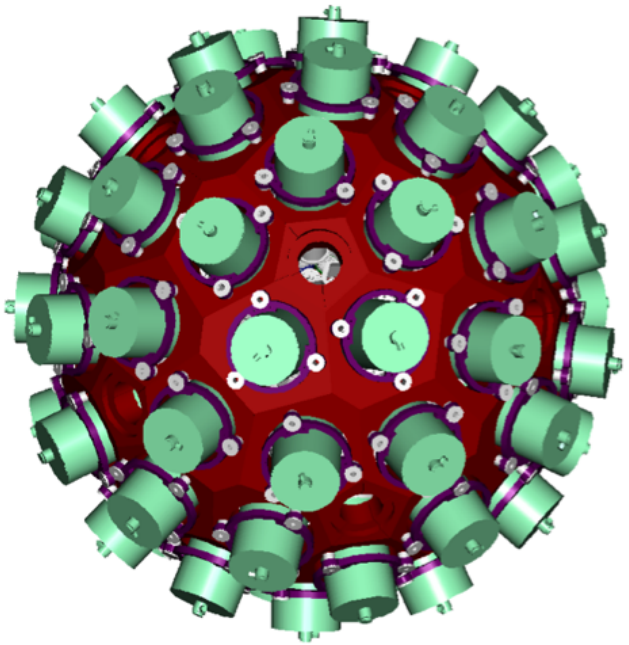
DE LA RECHERCHE À L'INDUSTRIE

AGATA
The Advanced Gamma Tracking Array
for Nuclear Structure Research



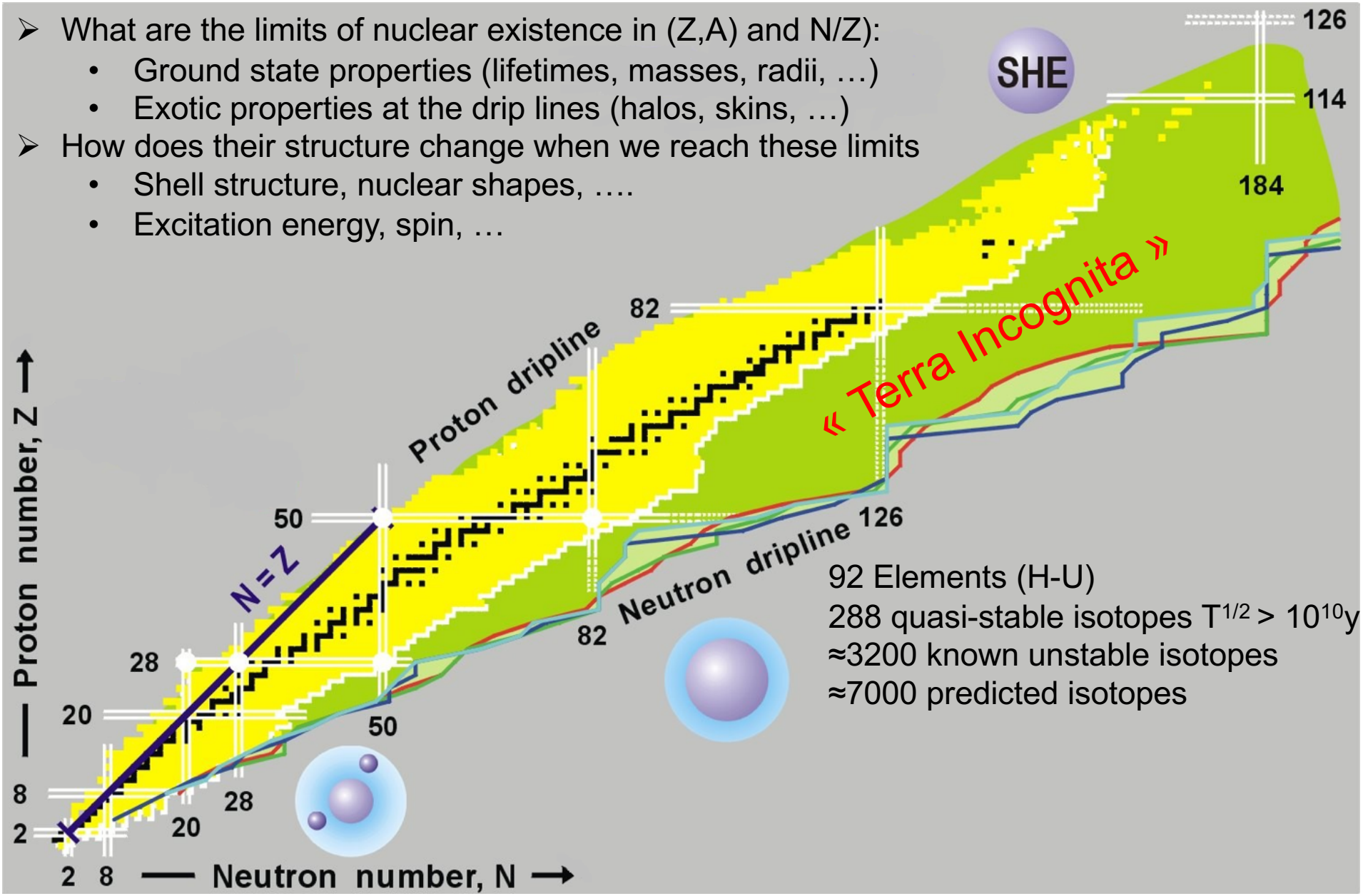
Wolfram KORTEN
IRFU - CEA Paris-Saclay

www.cea.fr

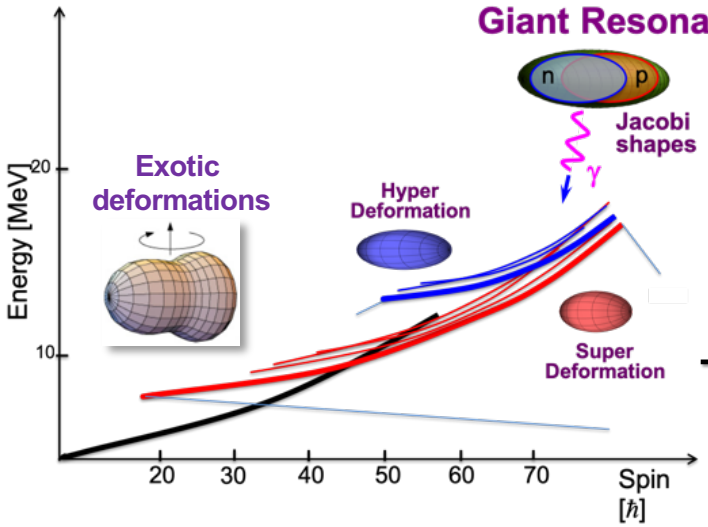
Irfu.cea.fr

Challenges in Nuclear Structure Physics

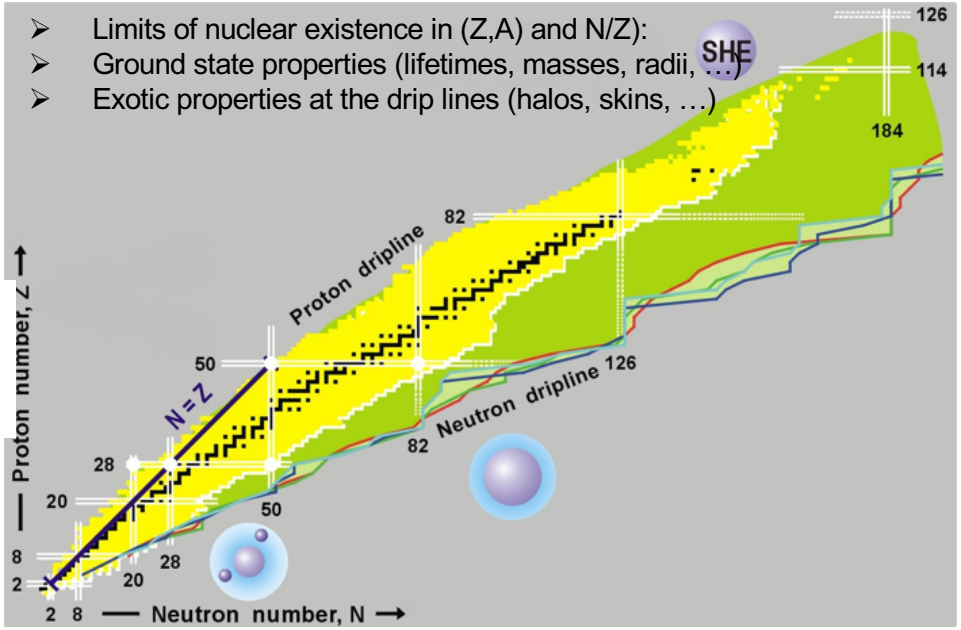
- What are the limits of nuclear existence in (Z,A) and N/Z):
  - Ground state properties (lifetimes, masses, radii, …)
  - Exotic properties at the drip lines (halos, skins, …)
- How does their structure change when we reach these limits
  - Shell structure, nuclear shapes, ….
  - Excitation energy,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



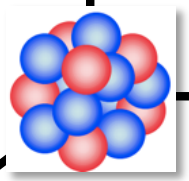
Challenges in Nuclear Structure Physics



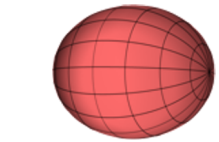
Energy/ Temperature

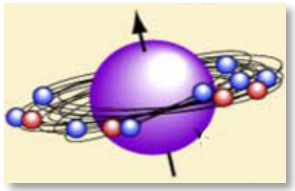


Properties of excited states
→ γ-ray spectroscopy

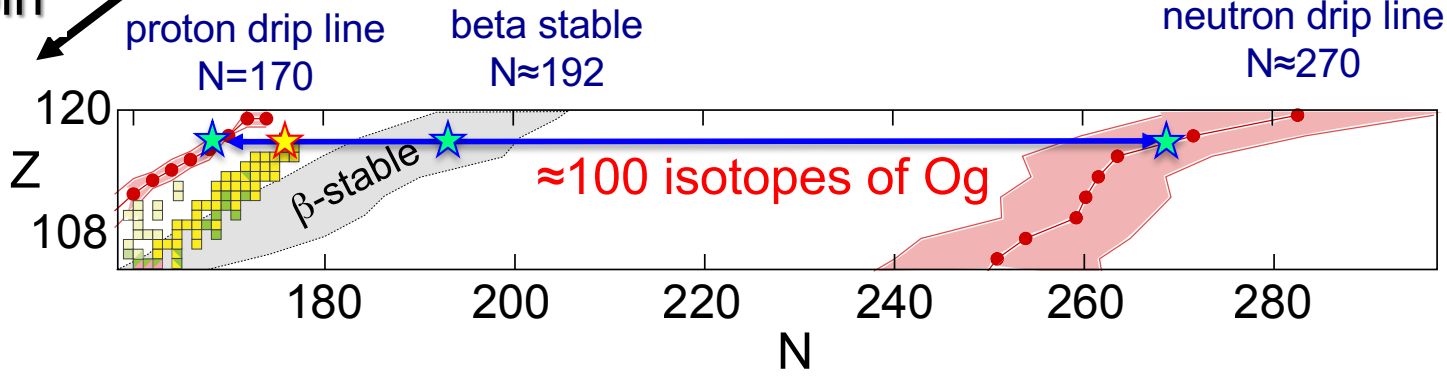


N/Z - isospin



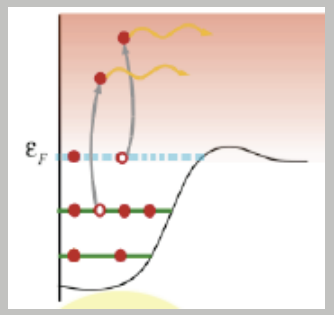


Spin

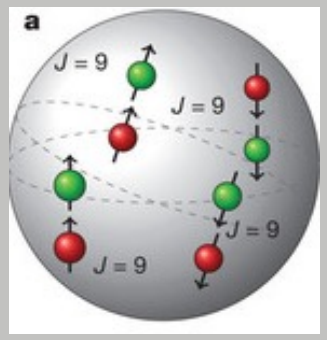


The AGATA Science Case

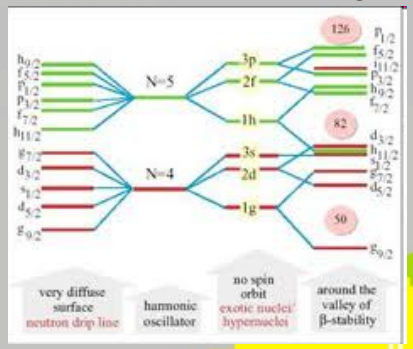
Continuum studies



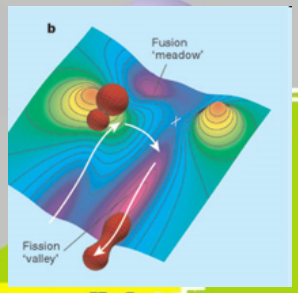
Nuclear pairing



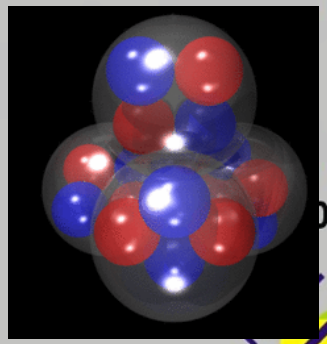
Shell structure changes

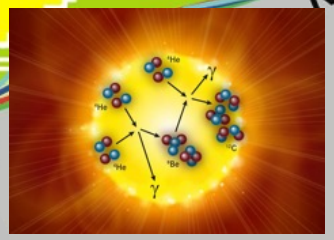


Fission barriers

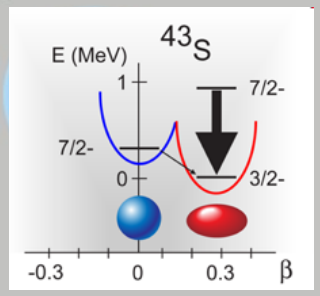


Cluster structure

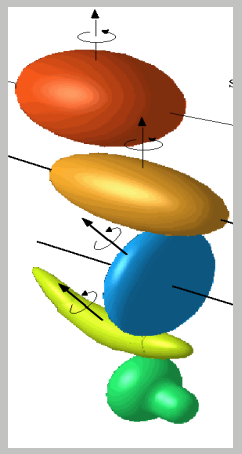




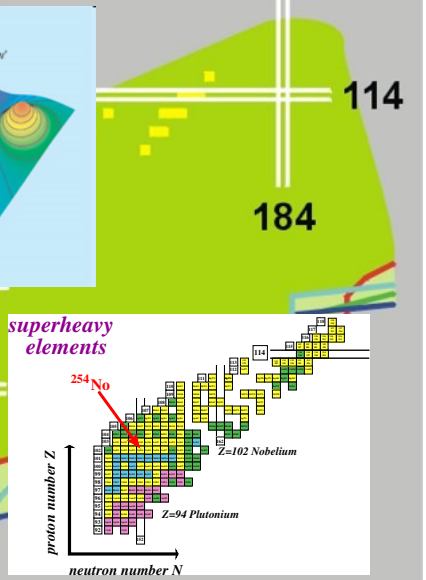
Nuclear astrophysics



Shape isomers



Exotic shapes

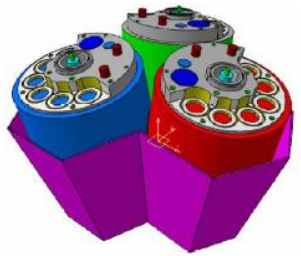


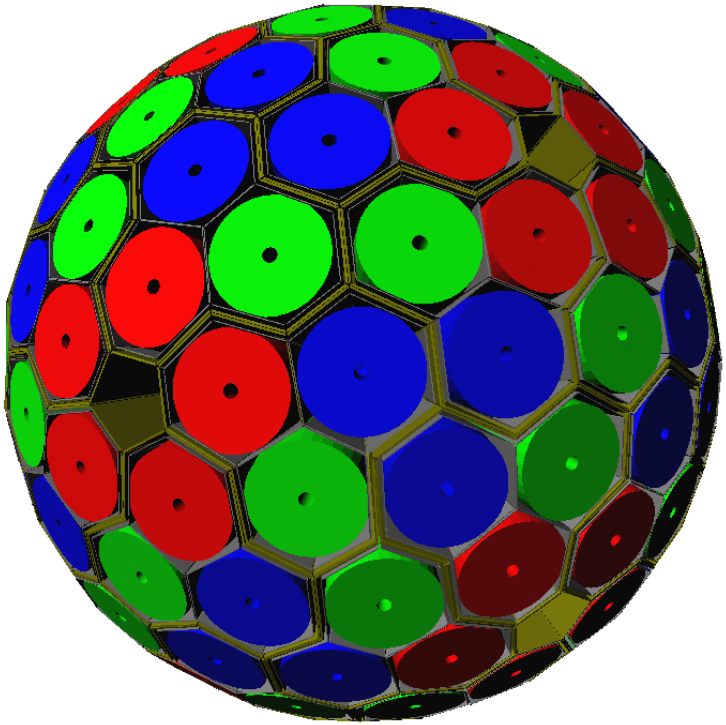
Superheavy elements

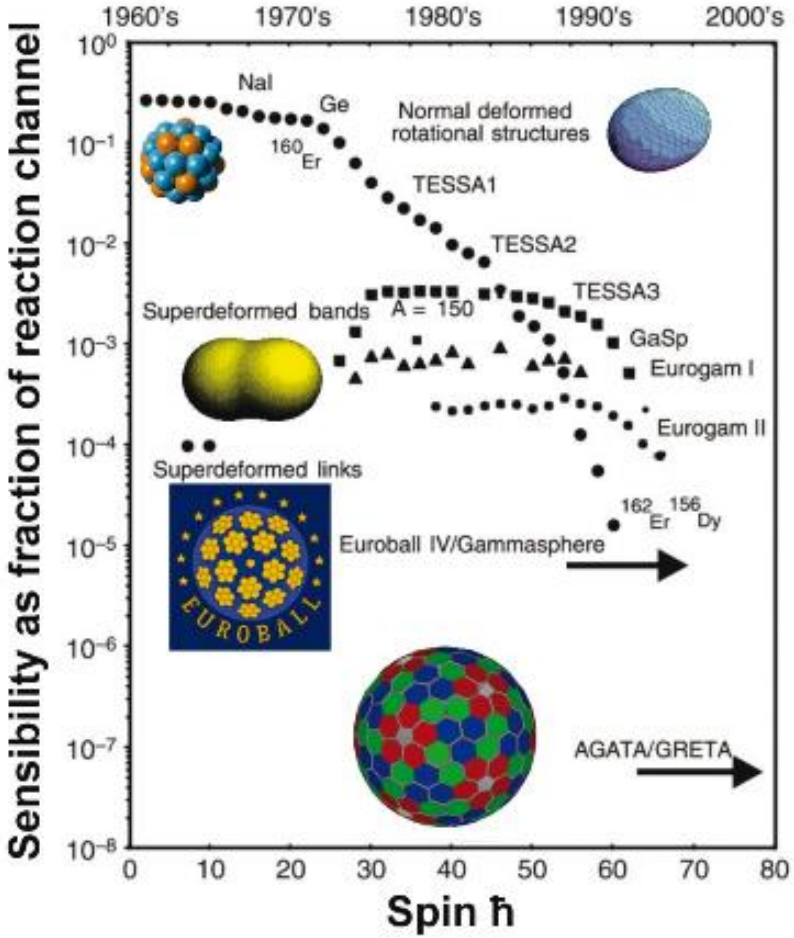
The Advanced Gamma Tracking Array

- 4π array from 180 large-volume HPGe crystals
- Each crystal is 36-fold segmented and encapsulated
- Arranged in 60 identical triple-cluster modules



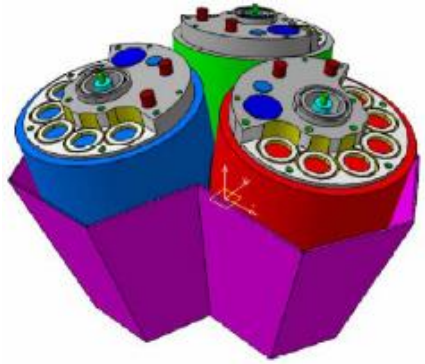


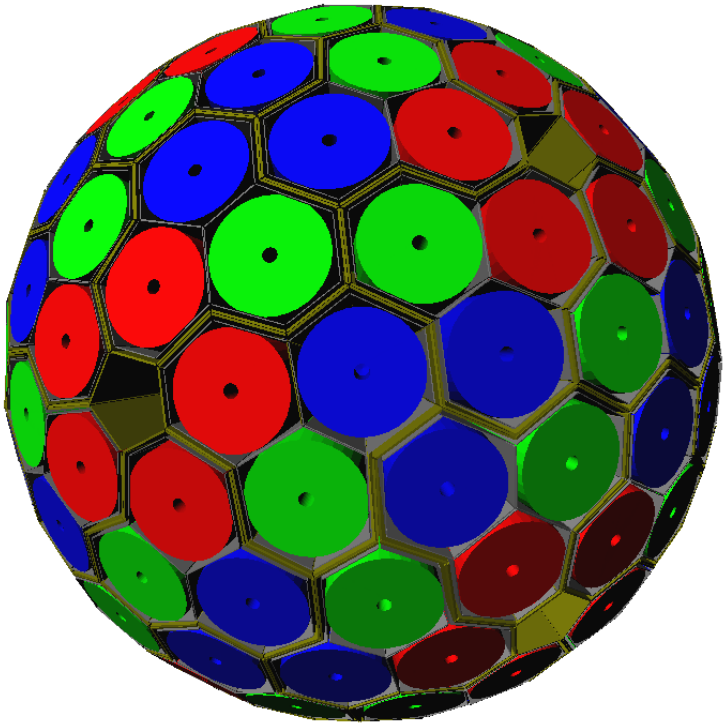




The Advanced Gamma Tracking Array

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

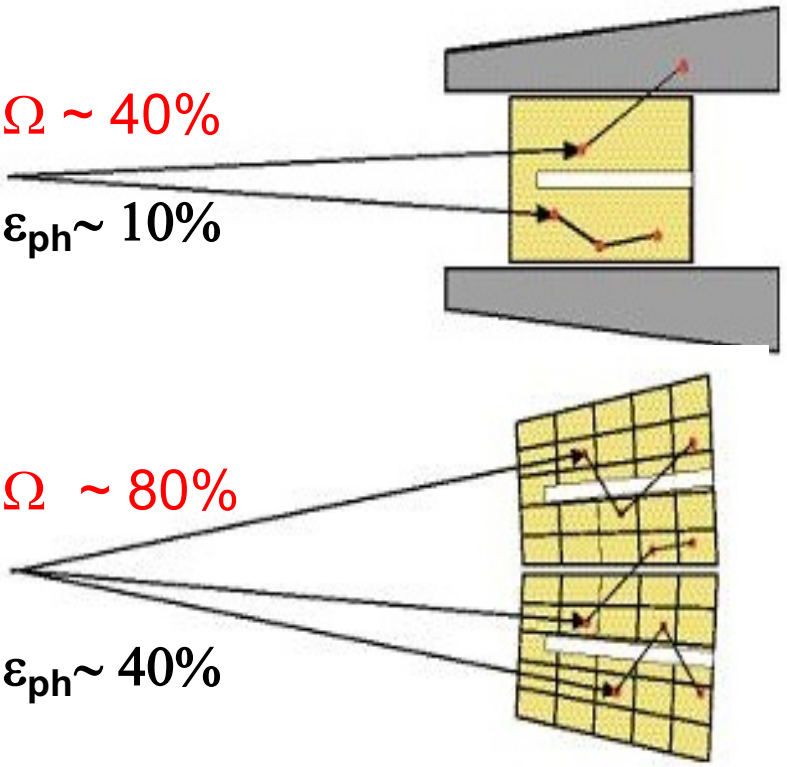




180 hexagonal crystals:	3 shapes
3 fold clusters (cold FET):	60 all equal
Inner radius (Ge):	23.5 cm
Amount of germanium:	362 kg
Solid angle coverage:	~82 %
36-fold segmentation	6480 segments
Crystal singles rate	~50 kHz
Efficiency (Mγ=1 [30]):	35% [23%]
Peak/Total (Mγ=1 [30]):	55% [46%]

AGATA Collaboration NIM A 668 (2012) 26

Advantages of Gamma-ray Tracking



Compton Suppressed Ge detectors

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

Gamma-ray Tracking Array

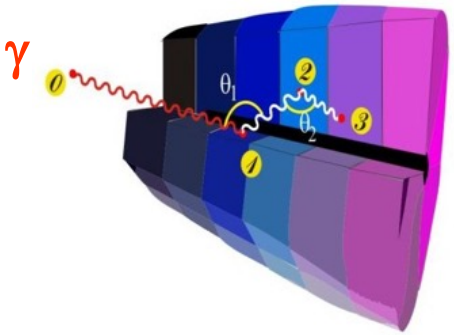
- Large solid angle covered by Ge
- Position-sensitive mode using PSA
- High P/T using tracking for γ-ray reconstruction

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

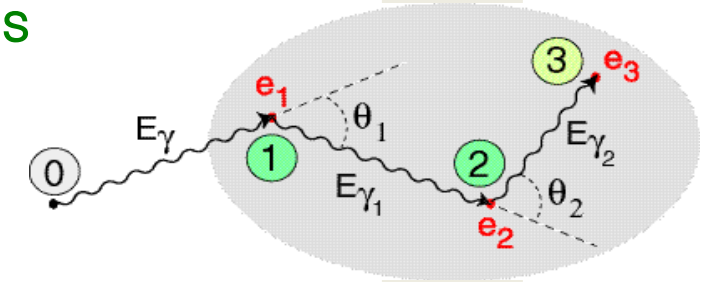
Identified interaction points

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

Pulse Shape Analysis to decompose recorded waves

4

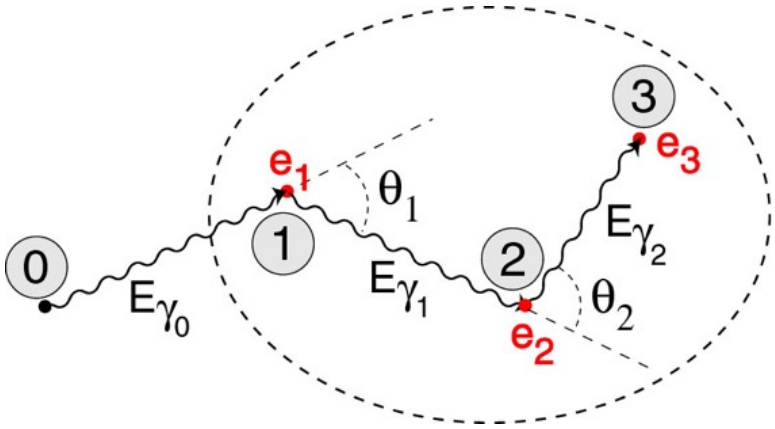
Evaluation of permutations of interaction points



Reconstructed γ-rays

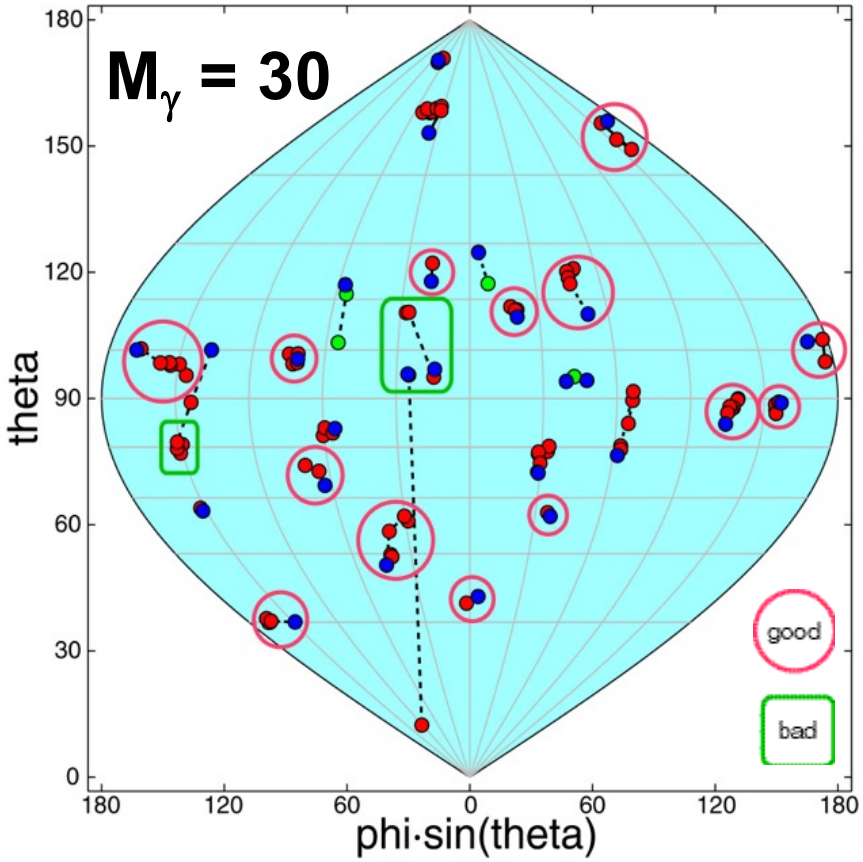
The Principle of Gamma-ray Tracking

Tracking algorithms use Compton scattering formula to identify the sequence of γ-ray interactions



$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1 - \cos\theta)}$$

Simulation of a high multiplicity event detected by an ideal shell



Algorithms must also treat photoelectric absorption and pair-production events

~50% correct identification for M_γ=30 as long as Δ(x,y,z) < 5mm

THE AGATA COLLABORATION



>40 Institutions
>350 Collaborators

Bulgaria:	**Univ. Sofia**
Finland:	**Univ. Jyväskylä**
France:	**GANIL Caen, IPN Lyon, CSNSM Orsay, IPN Orsay, IRFU CEA/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**
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, CLRC Daresbury, Univ. Edinburgh, Univ. Liverpool, Univ. Manchester, Univ. West of Scotland, Univ. Surrey, Univ. York**

AGATA Project Organisation

A. Gadea (Project Manager)

A. Boston, B. Million, A. Korichi, F. Recchia, H.Hess, P. Reiter (ASC) and W.Korten (ACC).
J. Gerl (LCM-GSI), E. Clement (LCM-GANIL), J.J. Valiente-Dobon (LCM-LNL)

AMB Chairman
Project Manager
A.Gadea
IFIC Valencia

Resource Manager
B.Million

AGATA Working Groups	AGATA Teams				
Detector Module H.Hess	Detector & Cryostat (tbd)	Detector CAT &Testing H. Boston	R & D on gamma Detectors & Applications		S. Bertoldo et sl. IFIC Valencia
Front-end Electronics A. Gadea	Pre-Amplifier Digitizer A. Pullia	Global Trigger & Synchronization M. Bellato	Pre-processing I. Lazarus		V. Gonzalez,et al. ETSE-Univ. Valencia
Data Processing A.Korichi	Hard/Software DAQ Support G. Lalaire	Slow Control & FEE Monitoring E. Legay	Data Analysis & Tracking O. Stezowski A. Lopez-Martens	Data distribution and re-processing F.Crespi J.Dudouet	
PSA & Characterization A.Boston	PSA Algorithm Development L. J. Harkness	Detector Characterisation J.Simpson			B. Quintana et al. Univ. Salamanca
Infrastructure. Comp. Det. B.Million	Detector array Infrastructure R.Menegazzo	Complementary Detectors J.J. Valiente	Mechanical Infrastructure A.Grant		
Performance and Simulation F.Recchia	AGATA Performance J.Ljungvall C.Michelagnoli	AGATA Commissioning P.R. John	AGATA Physics & exp. Simulation M. Labiche		R. Perez et al. IFIC Valencia

Local Campaign Managers (LCM)

INFN-LNL Legnaro J. Valiente-Dobon	GSI Darmstadt J.Gerl	GANIL-SPIRAL2 Caen E.Clement

A. Jungclaus et al.
CSIC Madrid
AGATA White Paper WG

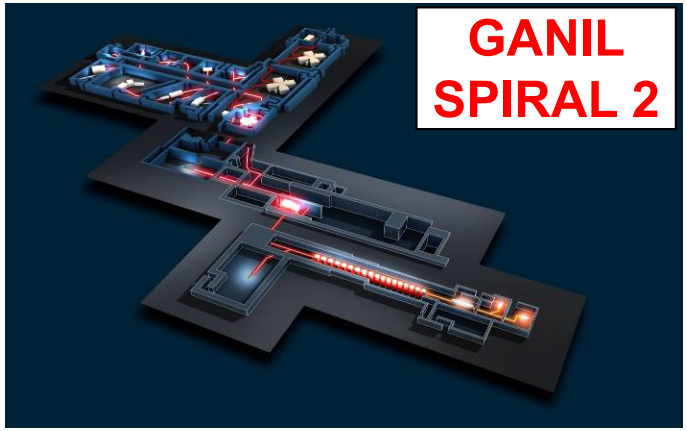
AGATA – A Travelling Detector



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

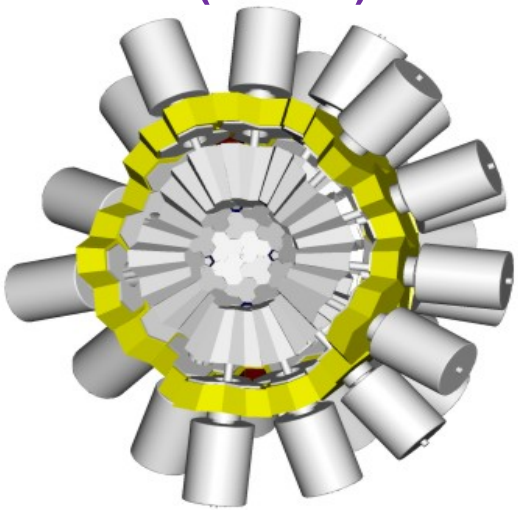


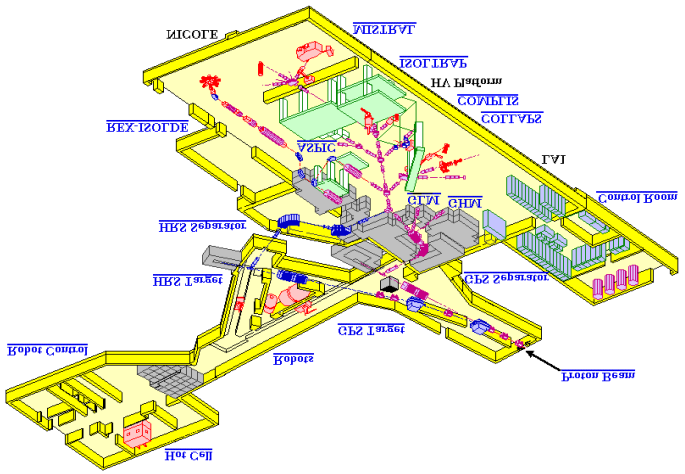
GSI (2013-14)
FAIR (2026+)



GANIL (2015-2021)



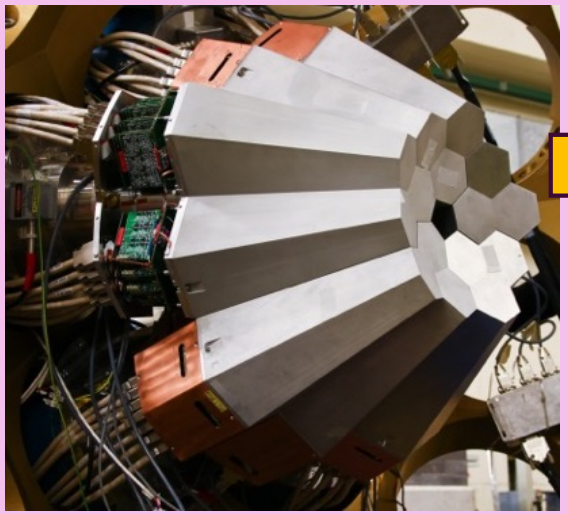




HIE-ISOLDE (planned)

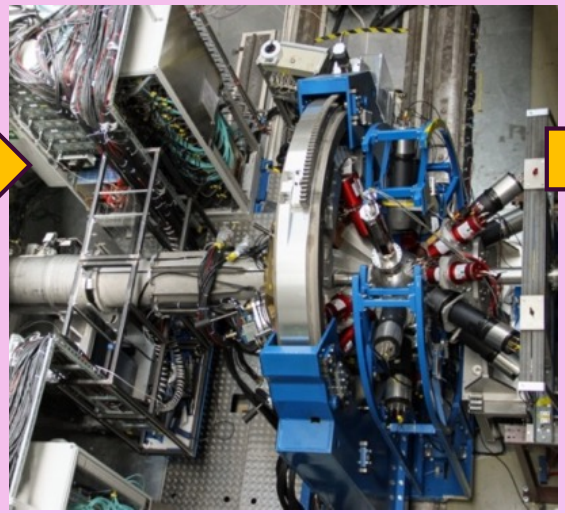
Progress of AGATA (since 2010)

2010 - 2012
Legnaro, Italy
Intense stable beams
15 detectors



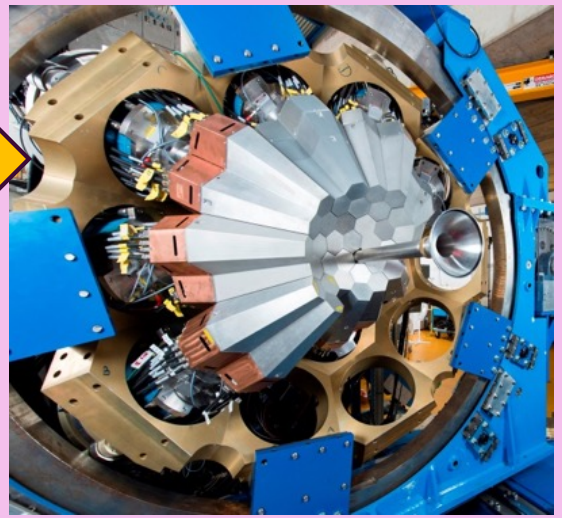
AGATA Demonstrator + PRISMA

2012 - 2014
GSI, Germany
Fast fragmentation beams
25 detectors



AGATA at GSI

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



AGATA at GANIL

51 experiments performed
57 publications (7 PRL/PLB)

Towards the AGATA 4π 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 4π array** under preparation



Support to the completion of AGATA in full geometry

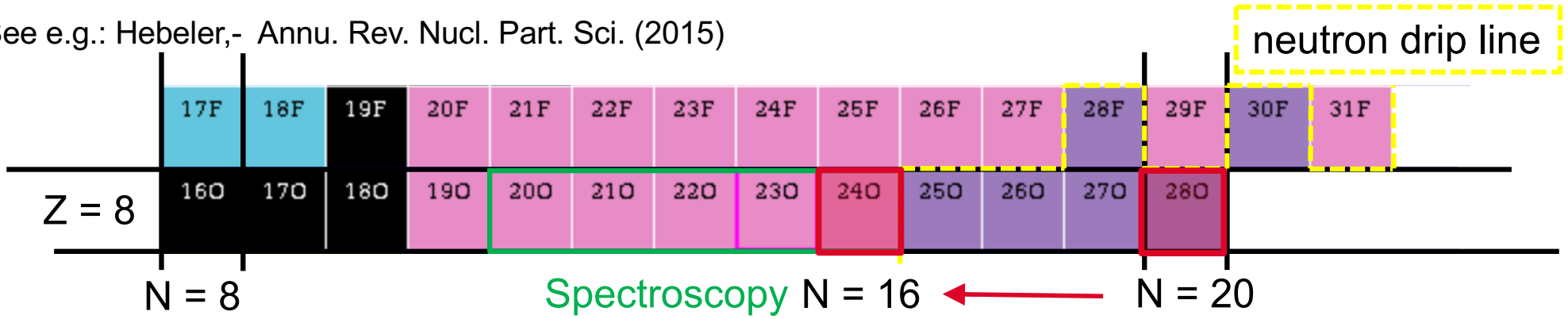
AGATA represents the state-of-the-art in gamma-ray spectroscopy and is an essential precision tool underpinning a broad programme of studies in nuclear structure, nuclear astrophysics and nuclear reactions. AGATA will be exploited at all of the large-scale radioactive and stable beam facilities and in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

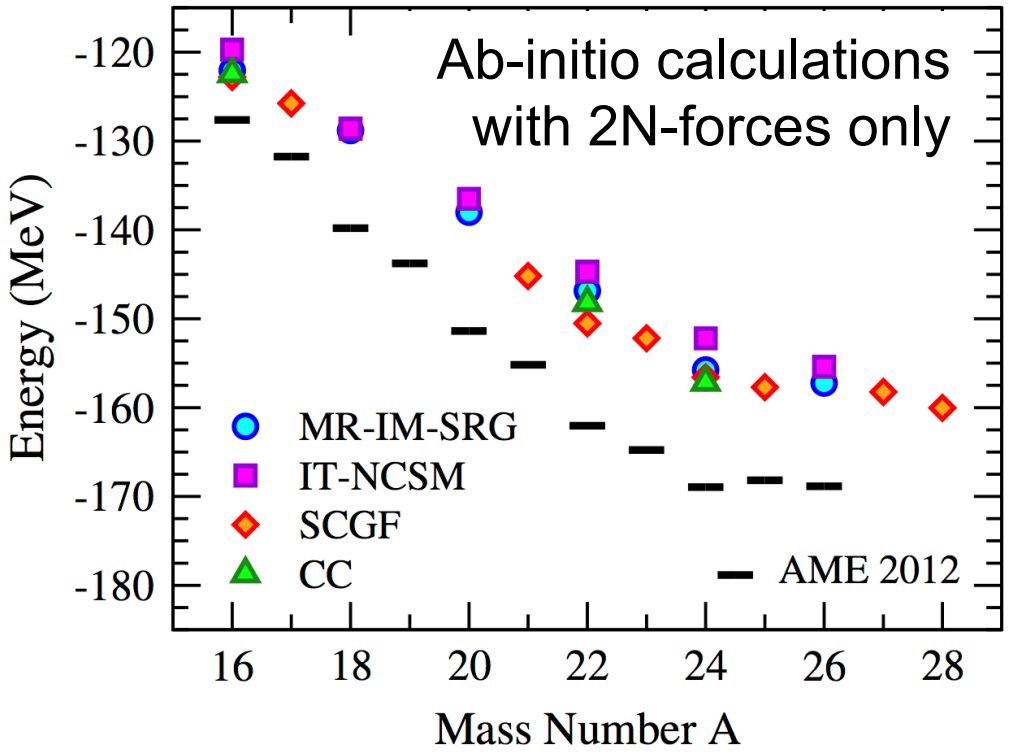
THE AGATA PHYSICS PROGRAM

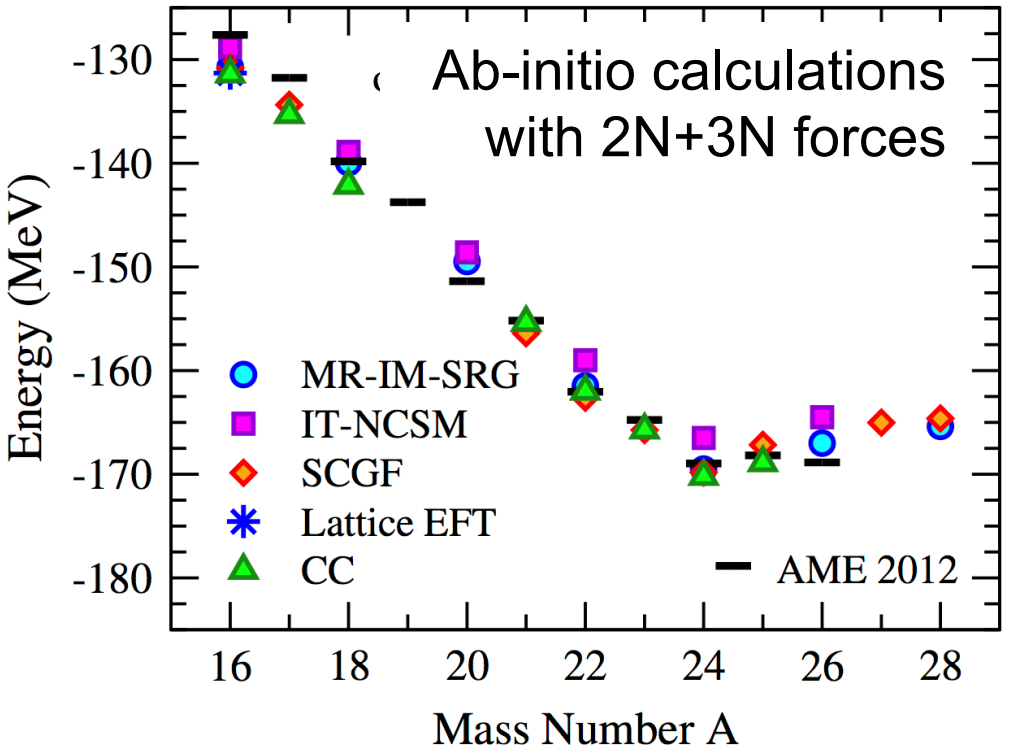
(Today and in the next decade)

Changes in the Nuclear Shell Structure and the Puzzle of the Neutron Drip Line for Oxygen (Z=8)

See e.g.: Hebeler,- Annu. Rev. Nucl. Part. Sci. (2015)

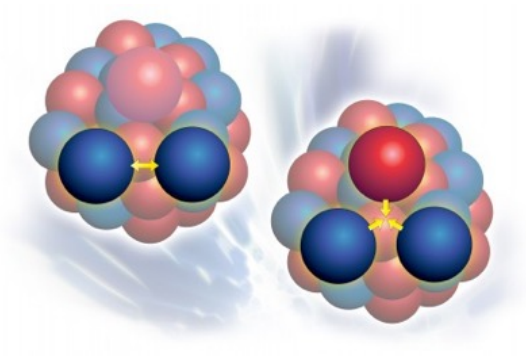


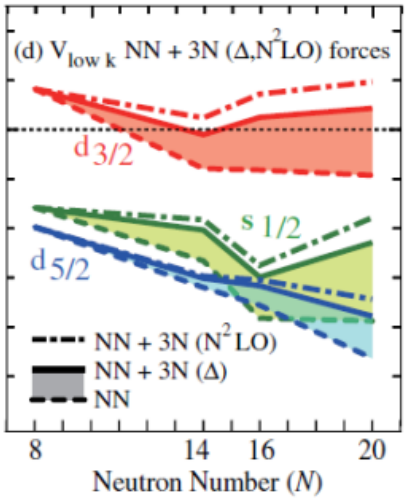


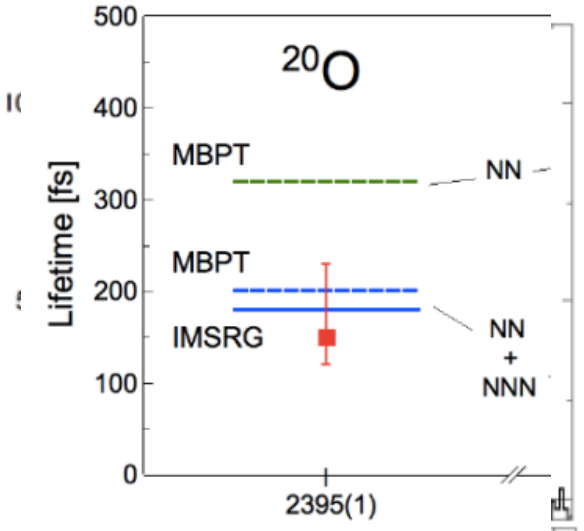


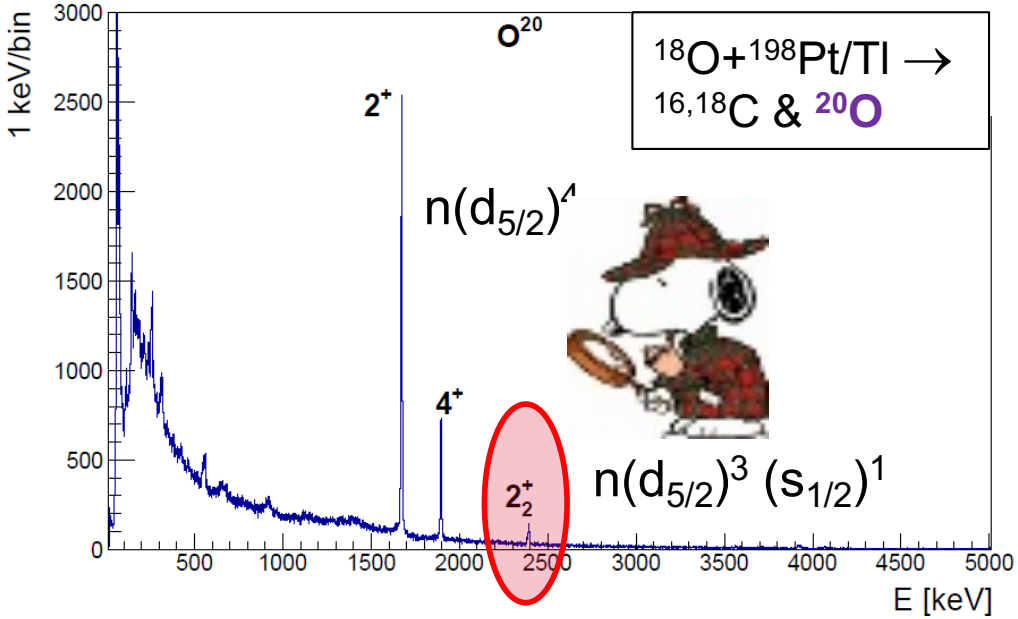
Femtosecond Lifetime Measurements in Drip-Line Nuclei with AGATA

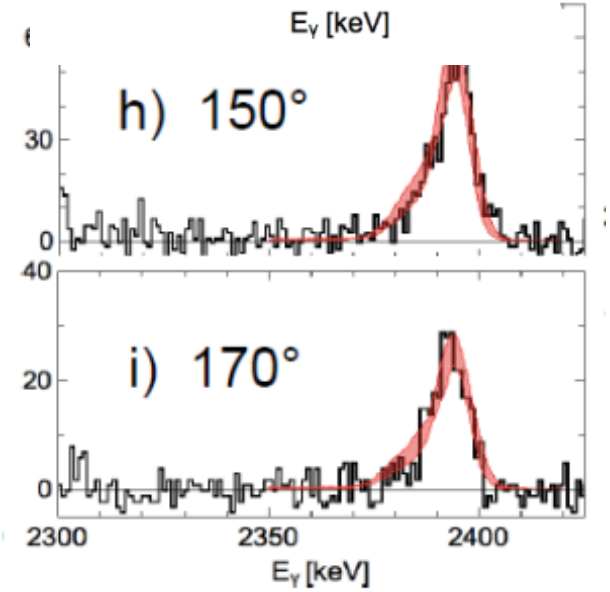
Importance of three-body forces on binding energies, but also on **level lifetimes**





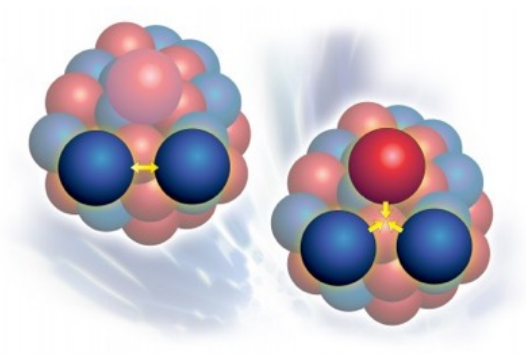


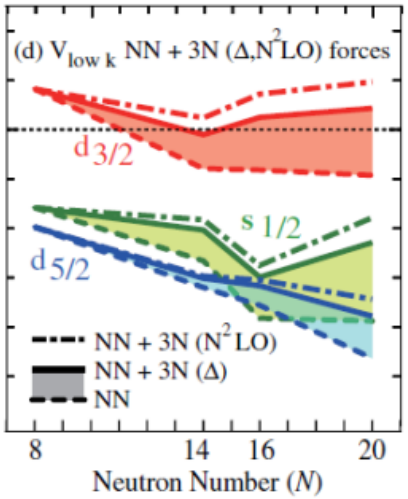


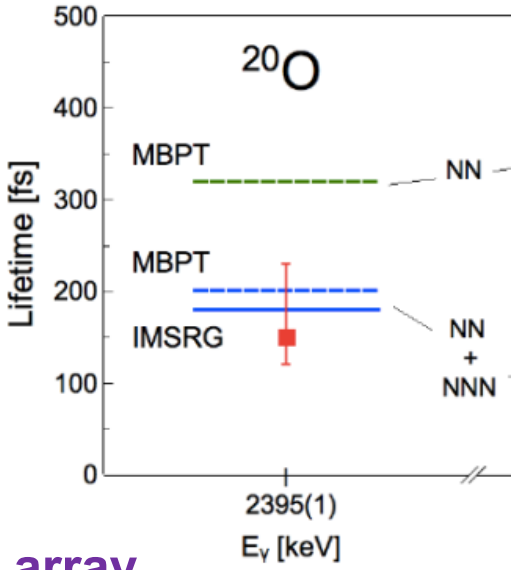


Femtosecond Lifetime Measurements in Drip-Line Nuclei with AGATA

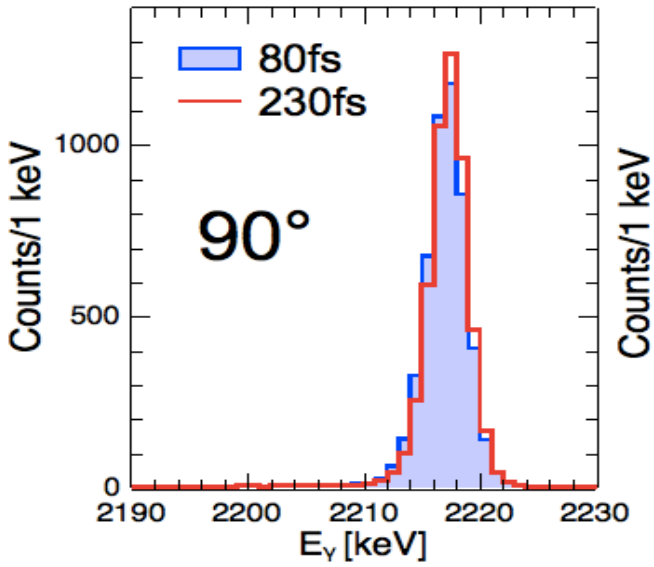
Importance of three-body forces on binding energies, but also on **level lifetimes**

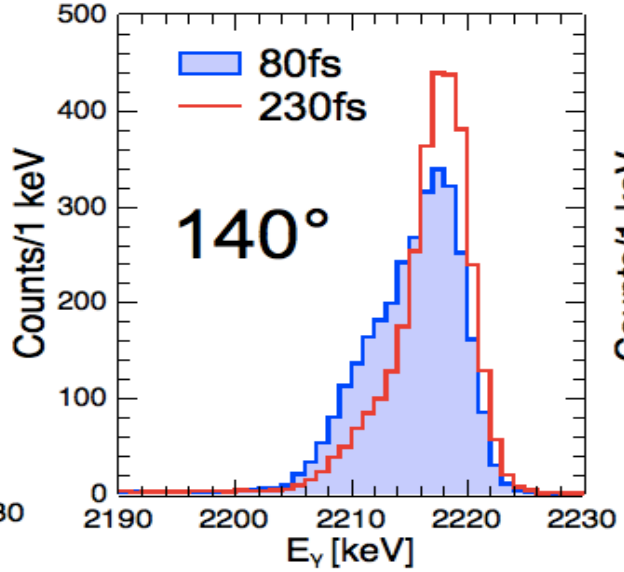


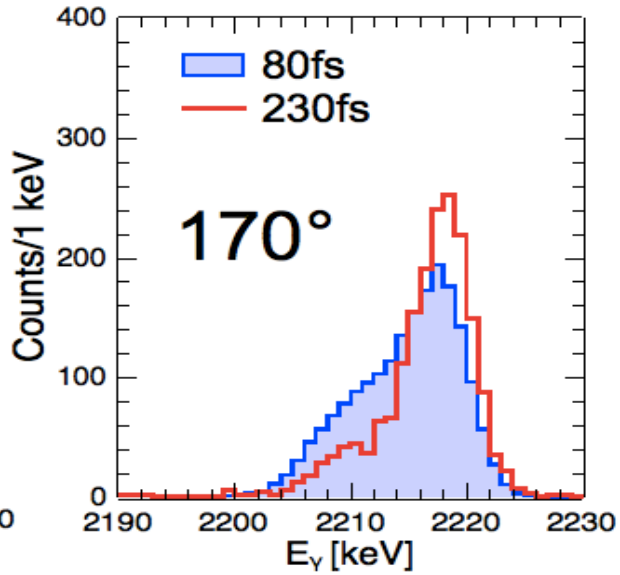




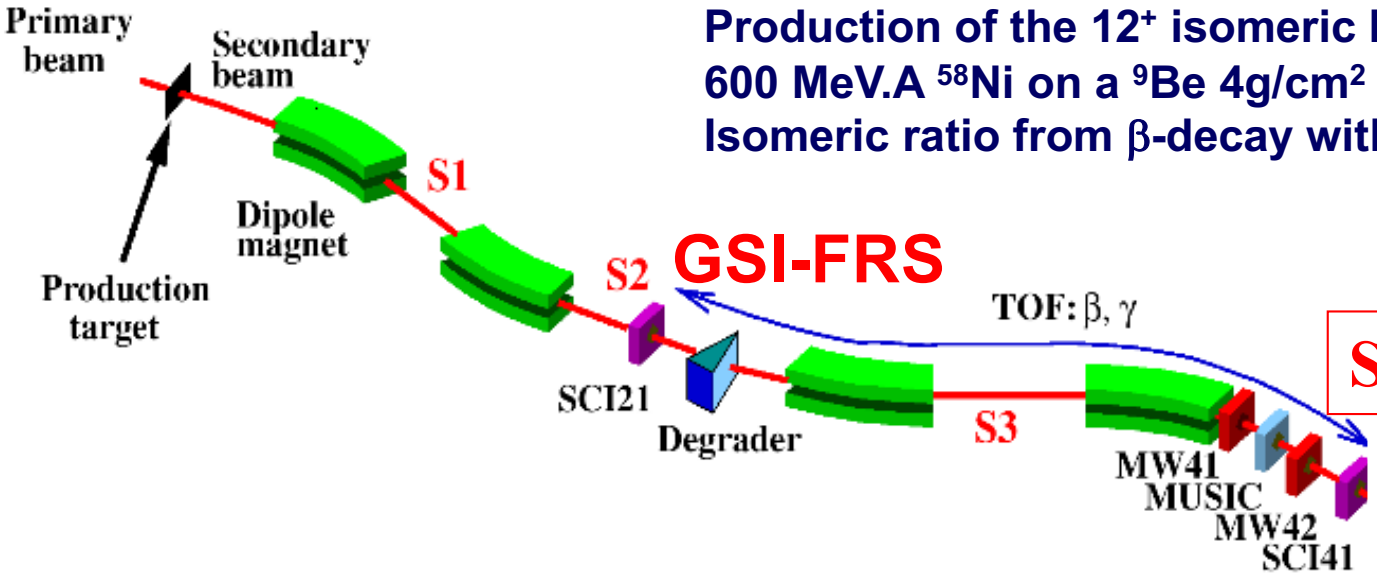
Simulation for the AGATA 4π array





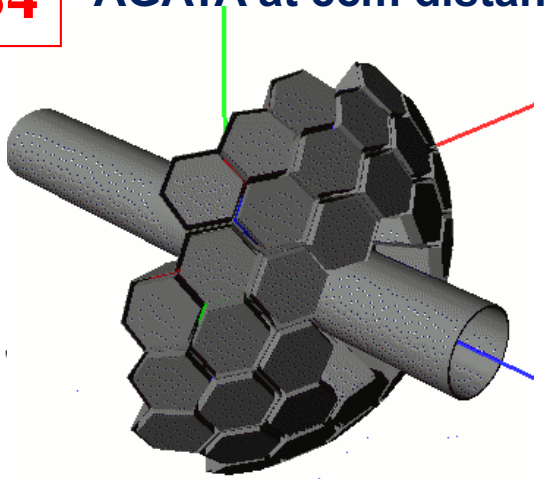


Relativistic Coulomb excitation of isomeric beams

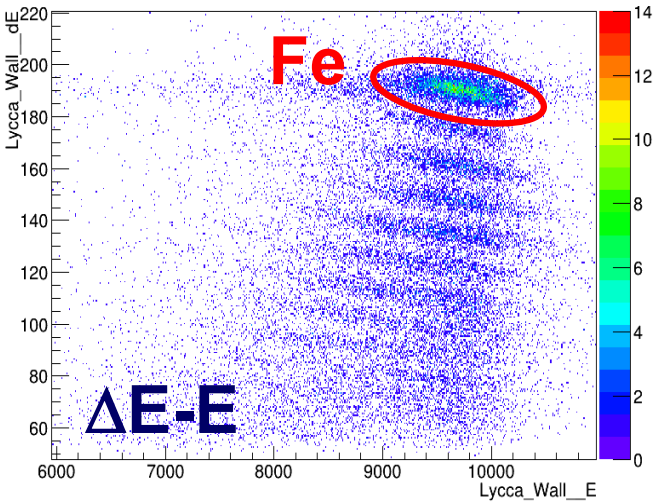


Production of the 12^+ isomeric beam by fragmentation of 600 MeV.A ^{58}Ni on a ^{9}Be 4g/cm^2 primary target of GSI-FRS. Isomeric ratio from β-decay with thick stopper: ~10%

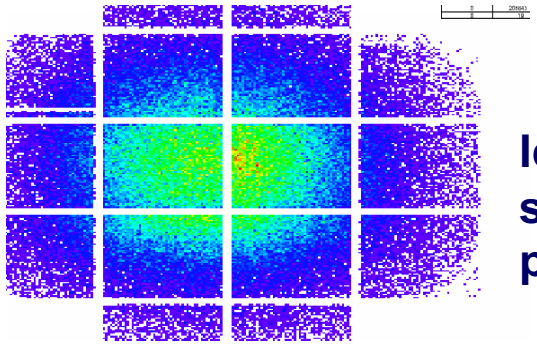
^{53}Fe at β=0.51 secondary Au Target AGATA at 8cm distance



Z identification

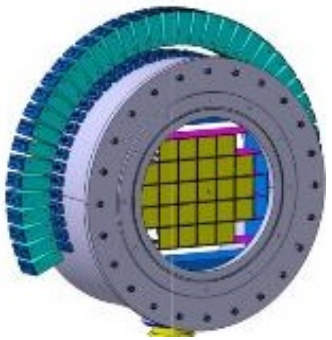


Scattering angle



LYCCA

Identification of secondary reaction products (ΔE/E, ToF)

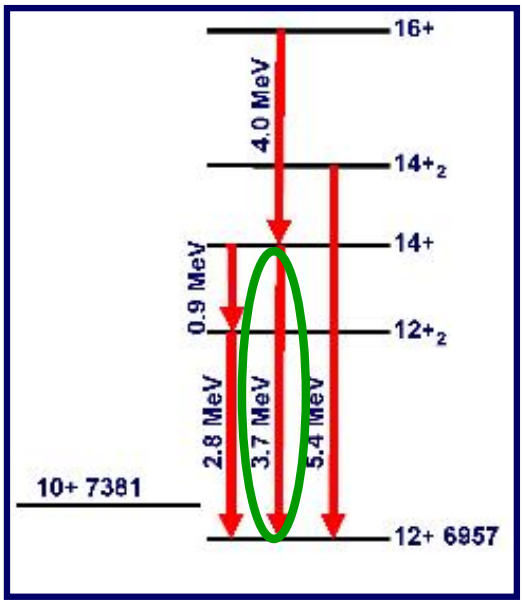


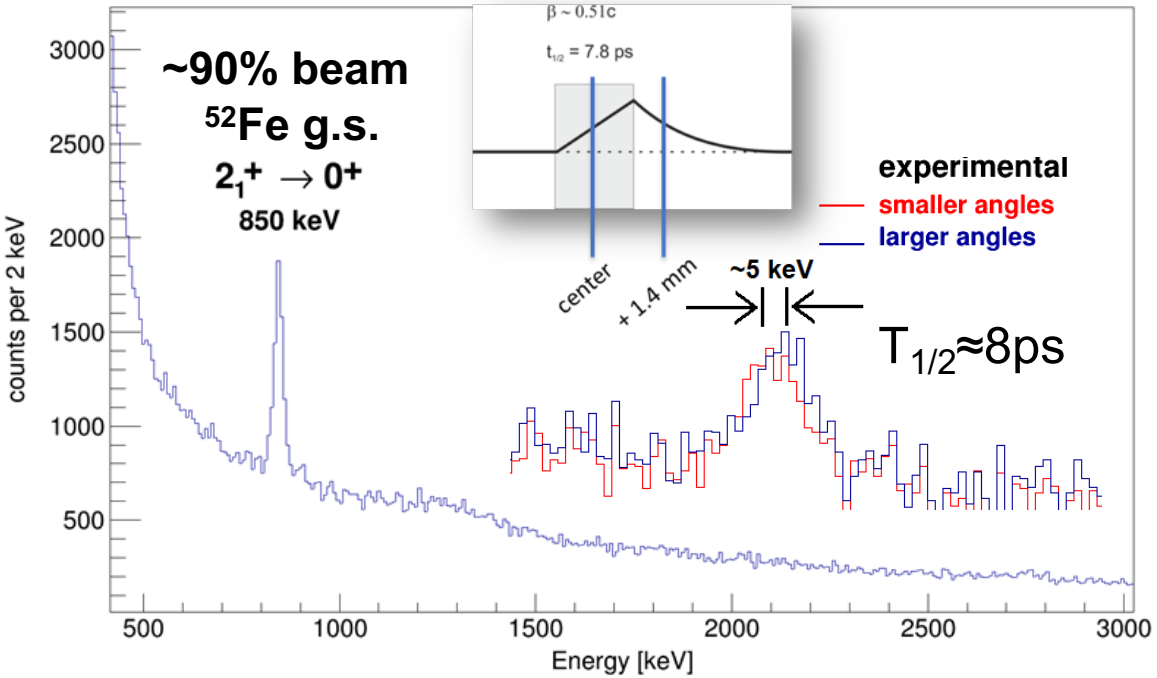
Relativistic Coulomb excitation of $^{52}Fe^{g,m}$ with AGATA

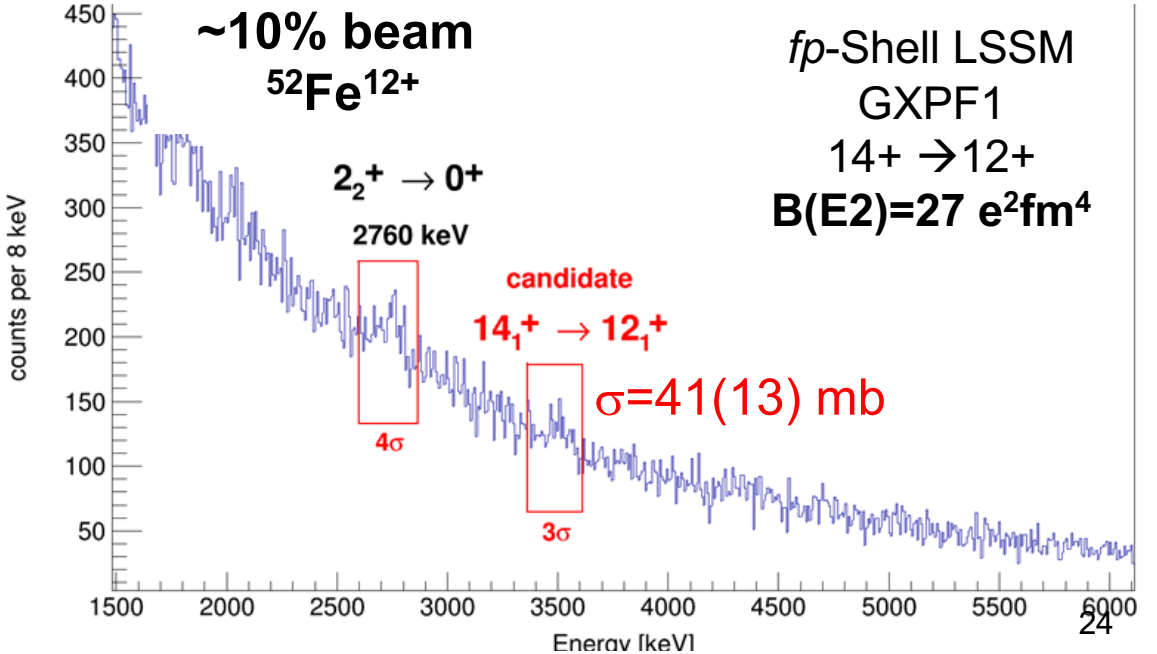
Ground state Coulomb excitation:

- 2_1^+ σ=106(5) mb;
  B(E2)=900(40) e^2fm^4; $T_{1/2}$=7.1(4) ps
  Lit. 820 e^2fm^4 PRC 70, 034301

- 2_2^+ σ=11(3) mb;
  B(E2)=42(20) e^2fm^4; $T_{1/2}$=0.42(11) ps

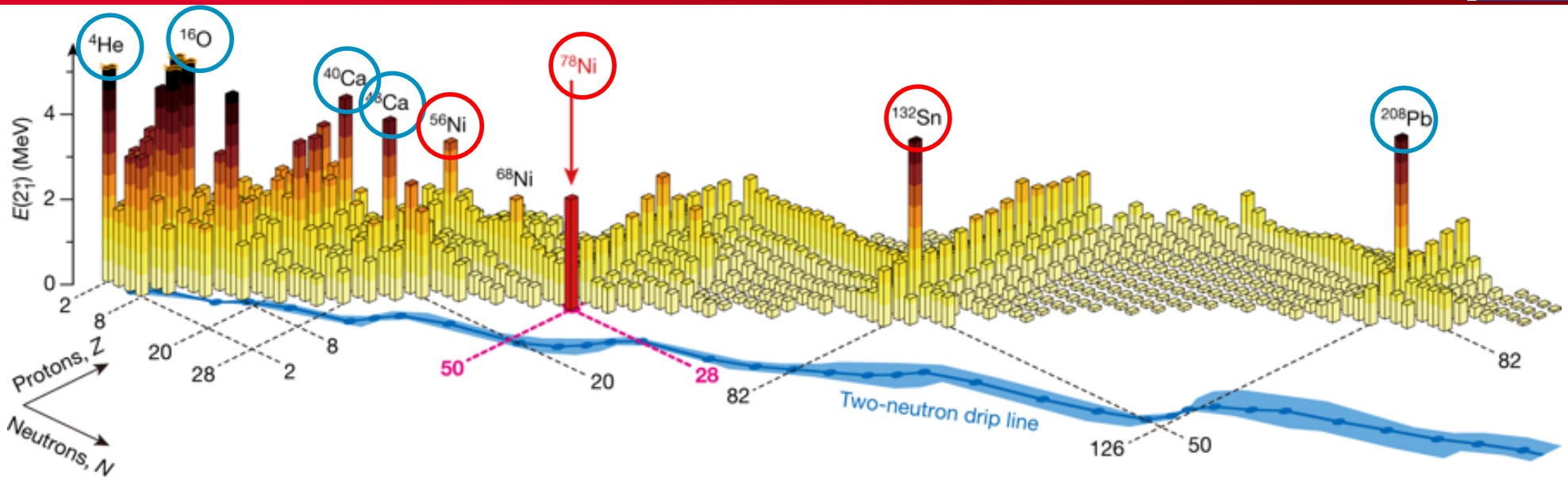




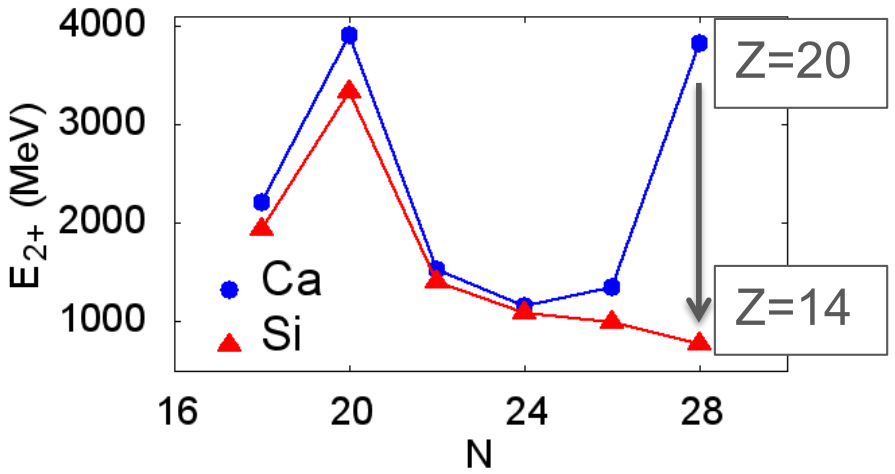


Tayfun Hüyük, PhD thesis
IFIC Valencia

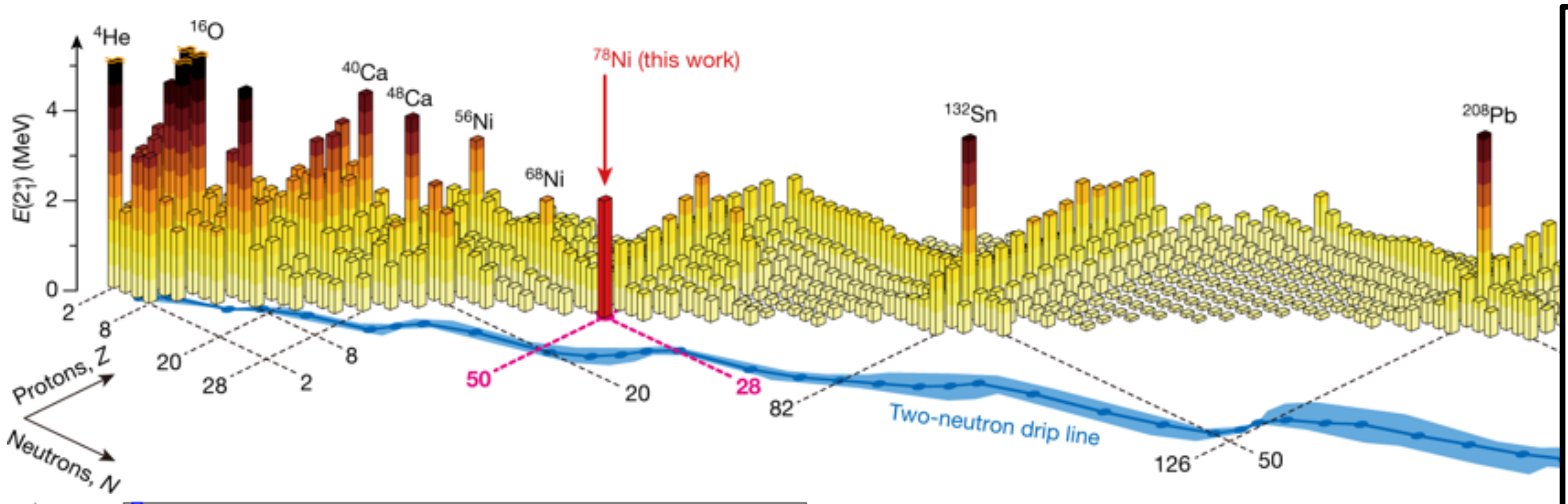
Evolution of the Nuclear Shell Structure

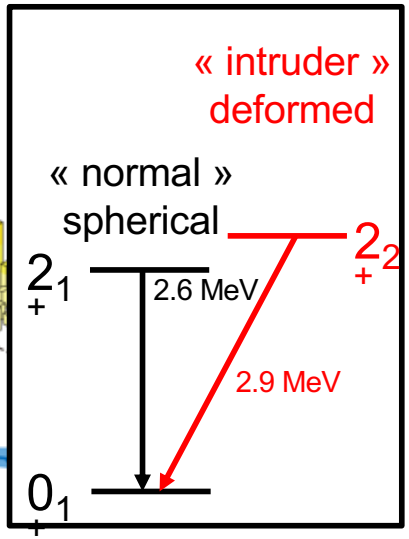


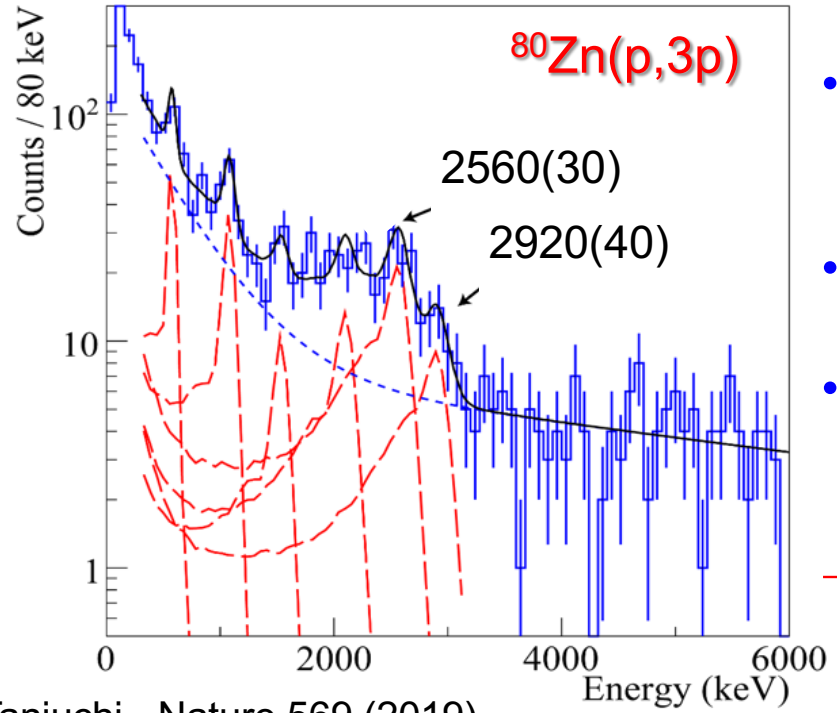
- Energy spectrum is very sensitive to the nuclear shell structure
- **High 2^+ energy in even-even nuclei <=> magic numbers**
  - **^{4}He,^{16}O, ^{40,48}Ca, ^{208}Pb ; ^{56,78}Ni, ^{100,132}Sn (unstable)**
- **Magic numbers disappear for N>>Z**
  - **^{32}Mg (N=20), ^{42}Si (N=28) are deformed**



First Spectroscopy of Doubly-Magic ^{78}Ni
at the RIKEN Radioactive Ion Beam Factory







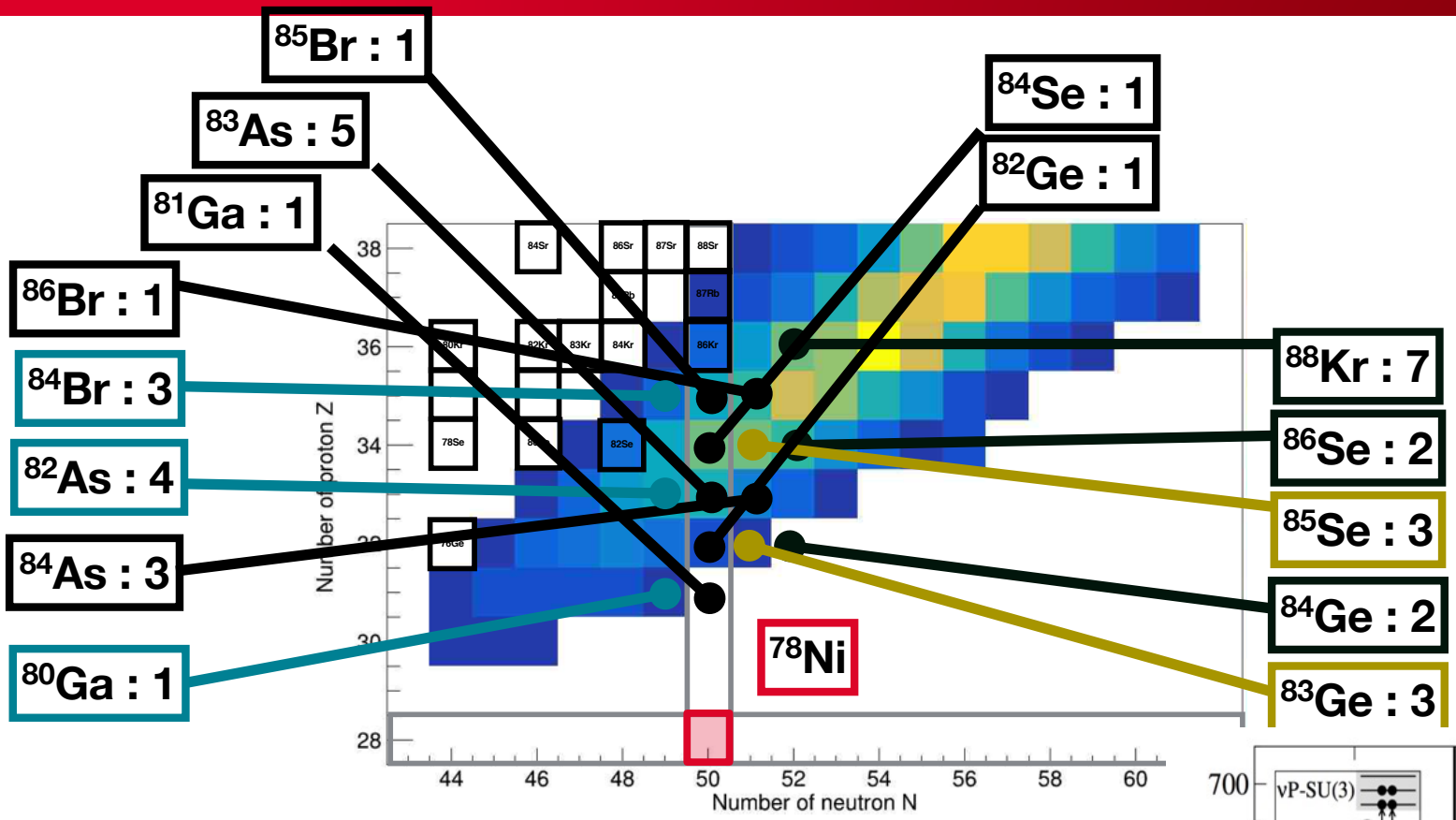
Taniuchi,- Nature 569 (2019)

- 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)

$\rightarrow$ Full AGATA array at FAIR

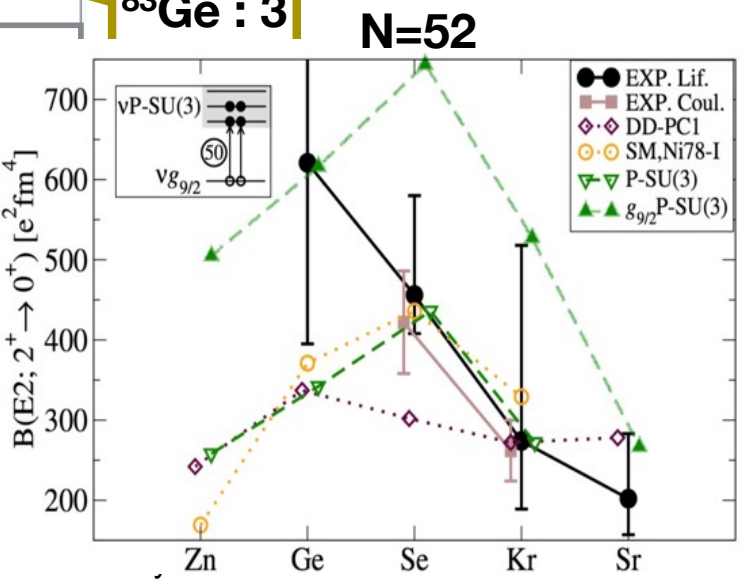
Courtesy: A. Obertelli – TU Darmstadt

Evolution of collectivity around N=50,52: Lifetimes in the vicinity of ^{78}Ni with AGATA

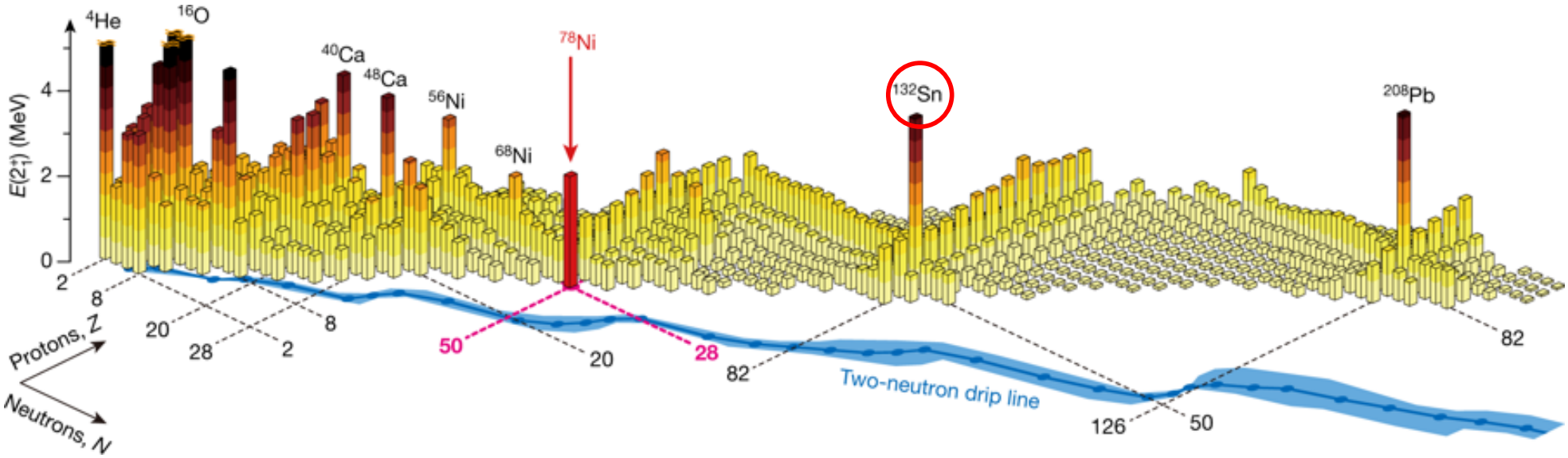


Sudden increase of collectivity in ^{84}Ge : hint of pseudo-SU3 symmetry

C. Delafosse et al., PRL 121, 192502 (2018) and Acta. Phys. Pol. B 50 633 (2019)



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



- Energy spectrum is very sensitive to the nuclear shell structure
- **High 2^+ energy in even-even nuclei <=> magic numbers**
  - ➢ **^{4}He,^{16}O, ^{40,48}Ca, ^{208}Pb ; ^{56,78}Ni, ^{100,132}Sn (unstable)**

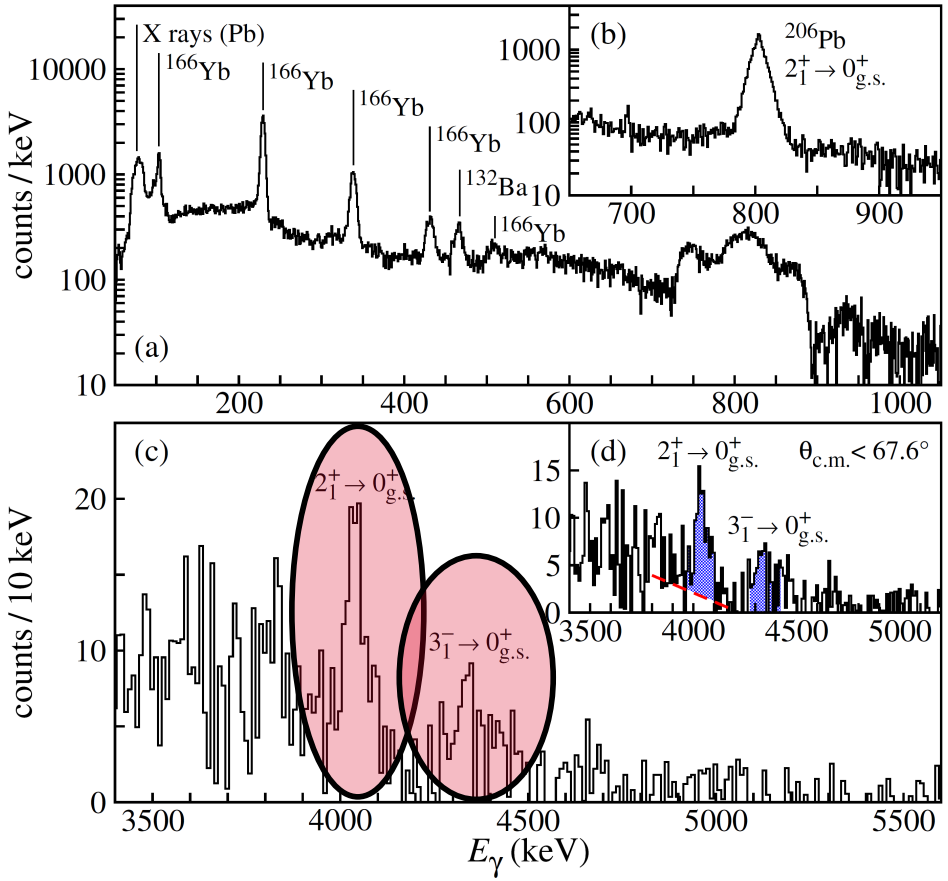
Coulomb excitation of doubly-magic ^{132}Sn

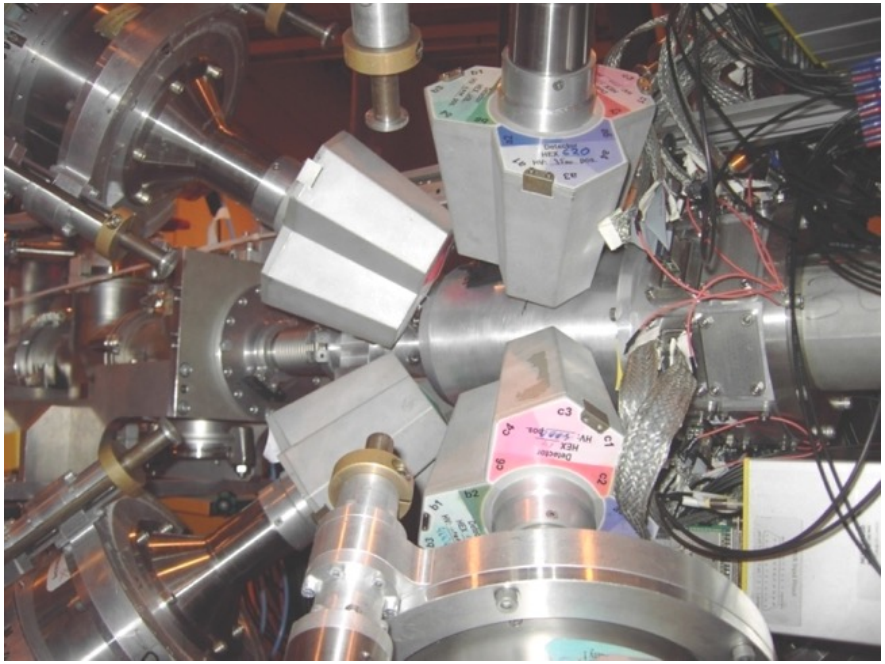
MINIBALL Ge array at HIE-ISOLDE (CERN)

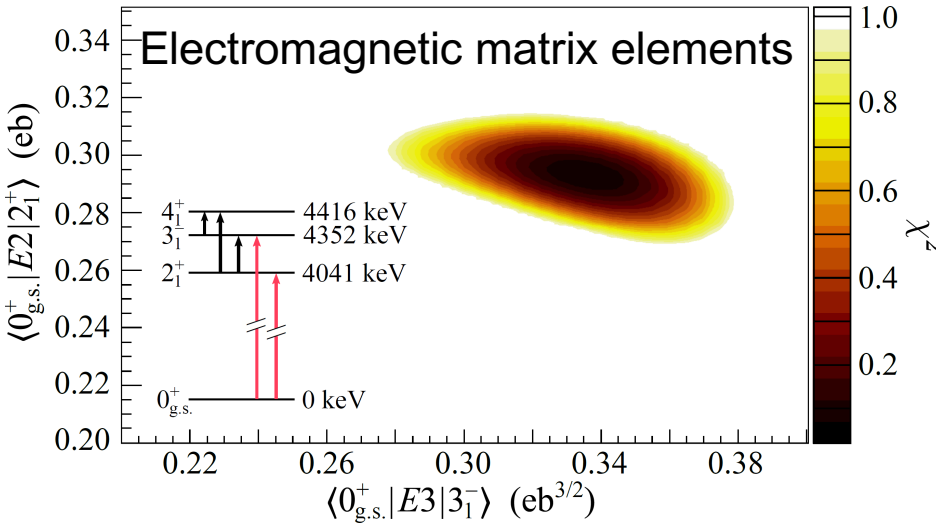
Low energy Coulomb excitation

^{206}Pb + ^{132}Sn^{31+} @ 5.49 MeV/u ~3.0 x 10^5 pps

D. Rosiak et al., Phy. Rev. Lett. 121, 252501 (2018)





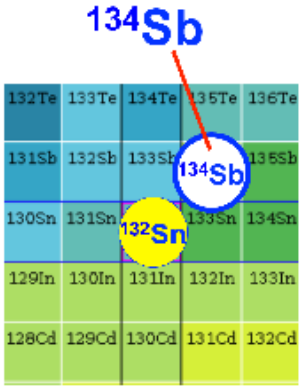


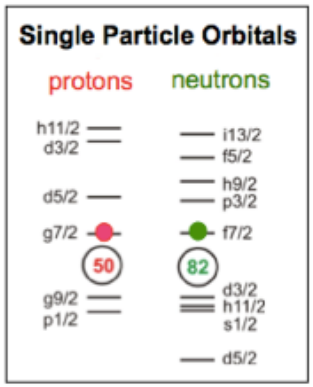
- Very good energy resolution
- Rather limited γ efficiency and particle rate

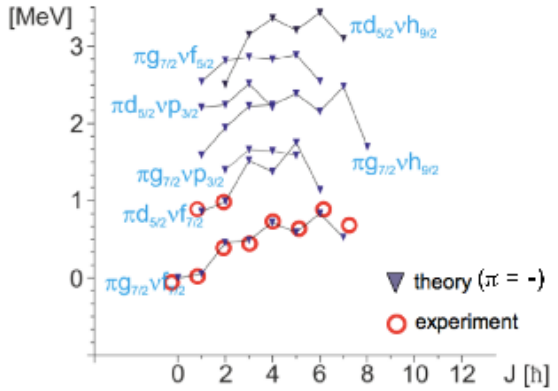
The Shell Structure around ^{132}Sn

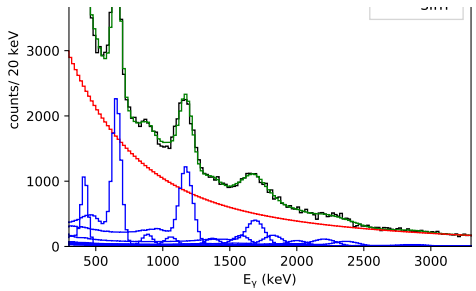
Experiment

A. Jungclaus et al. (CSIC Madrid)



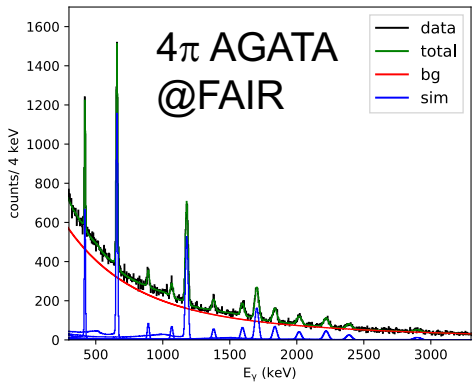






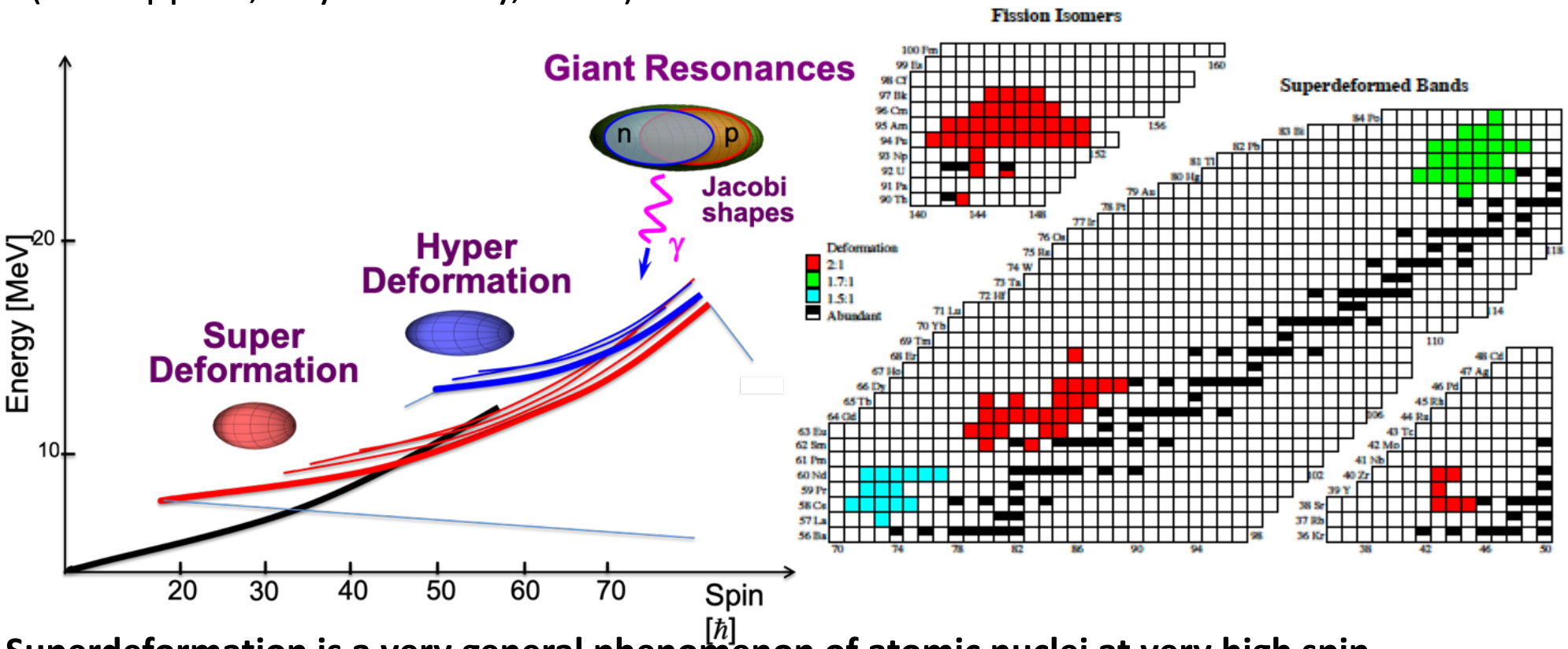
AGATA simulation (CSIC Madrid)
High-resolution spectroscopy at relativistic energies

Lifetime measurements using Doppler-shift lineshape methods



Detailed Studies of Superdeformation and the Search for Hyperdeformation

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:

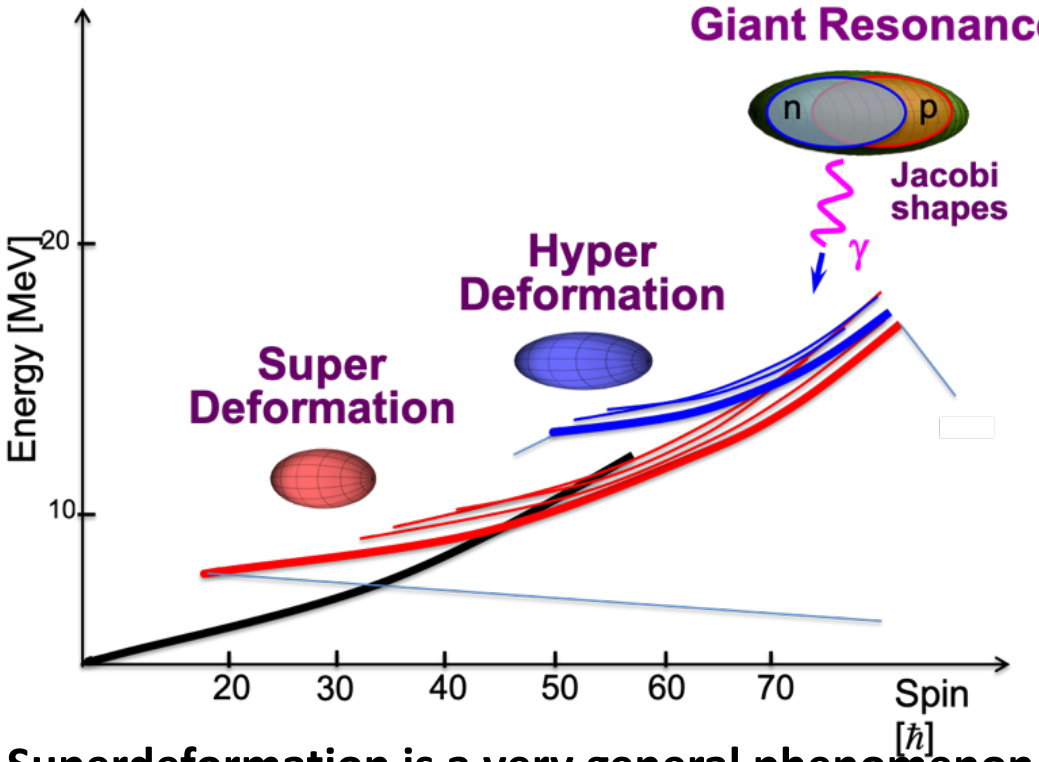
Decay-out from superdeformed states → (E*,I) of SD states are mostly unknown

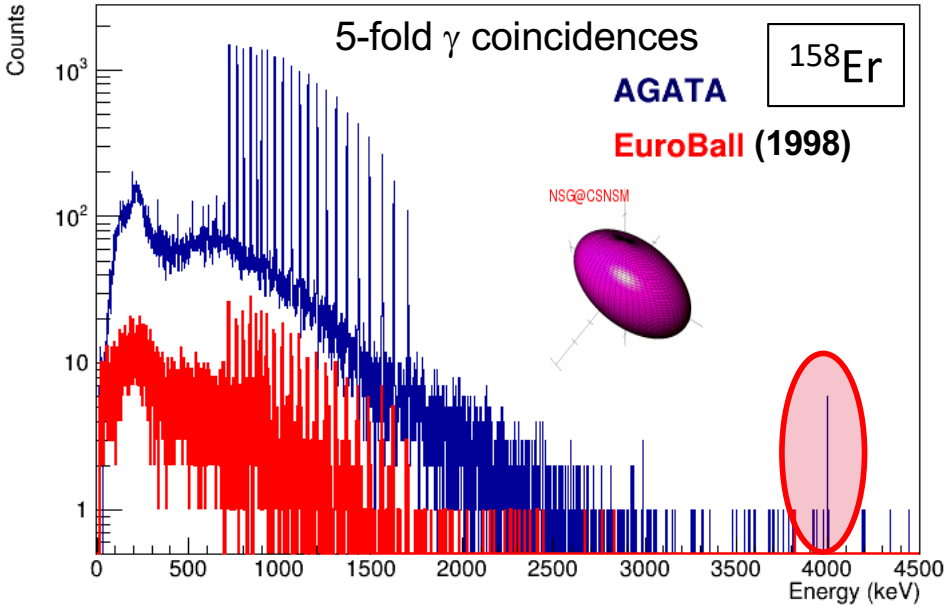
Link between clusterisation & exotic (particle) decays in light nuclei ?

How to populate SD states in neutron-rich nuclei → very high intensity neutron-rich beams

Detailed Studies of Superdeformation and the Search for Hyperdeformation

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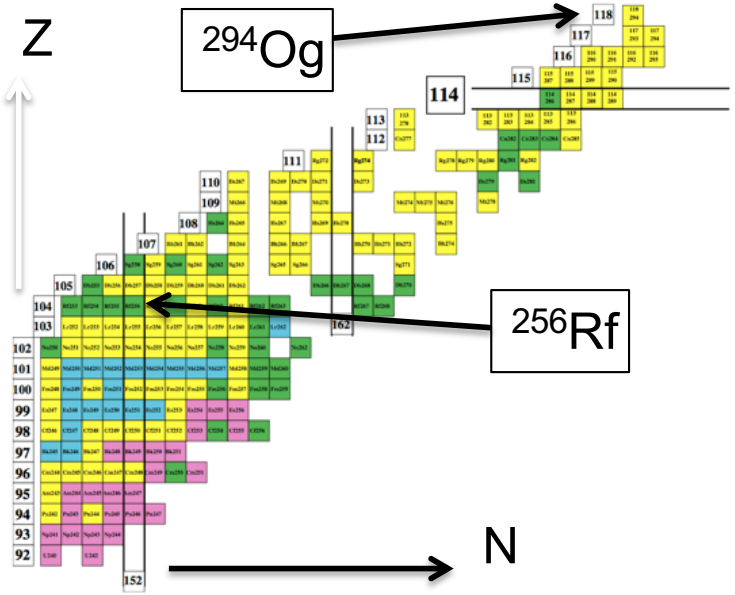
Superdeformation is a very general phenomenon of atomic nuclei at very high spin, but many questions still remain unanswered:

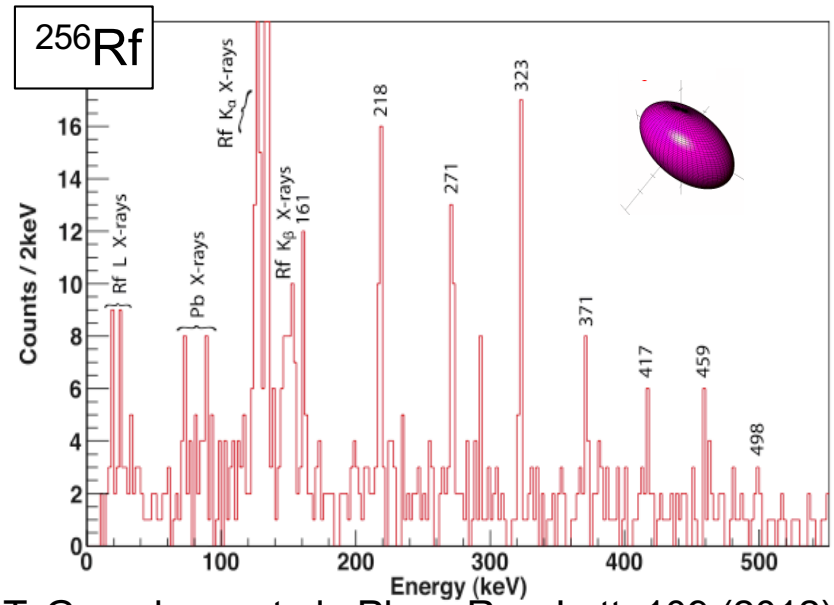
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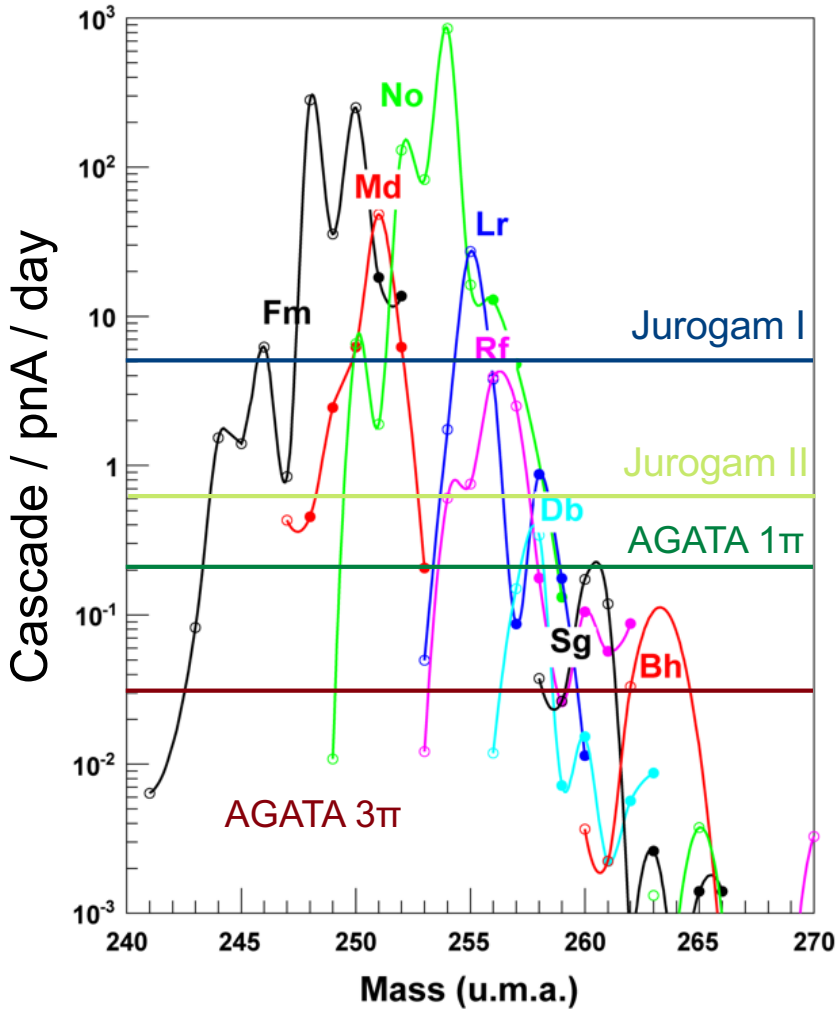
Link between clusterisation & exotic (particle) decays in light nuclei ?

How to populate SD states in neutron-rich nuclei → very high intensity neutron-rich beams

Spectroscopy of deformed magic nuclei in the heaviest elements at JYFL



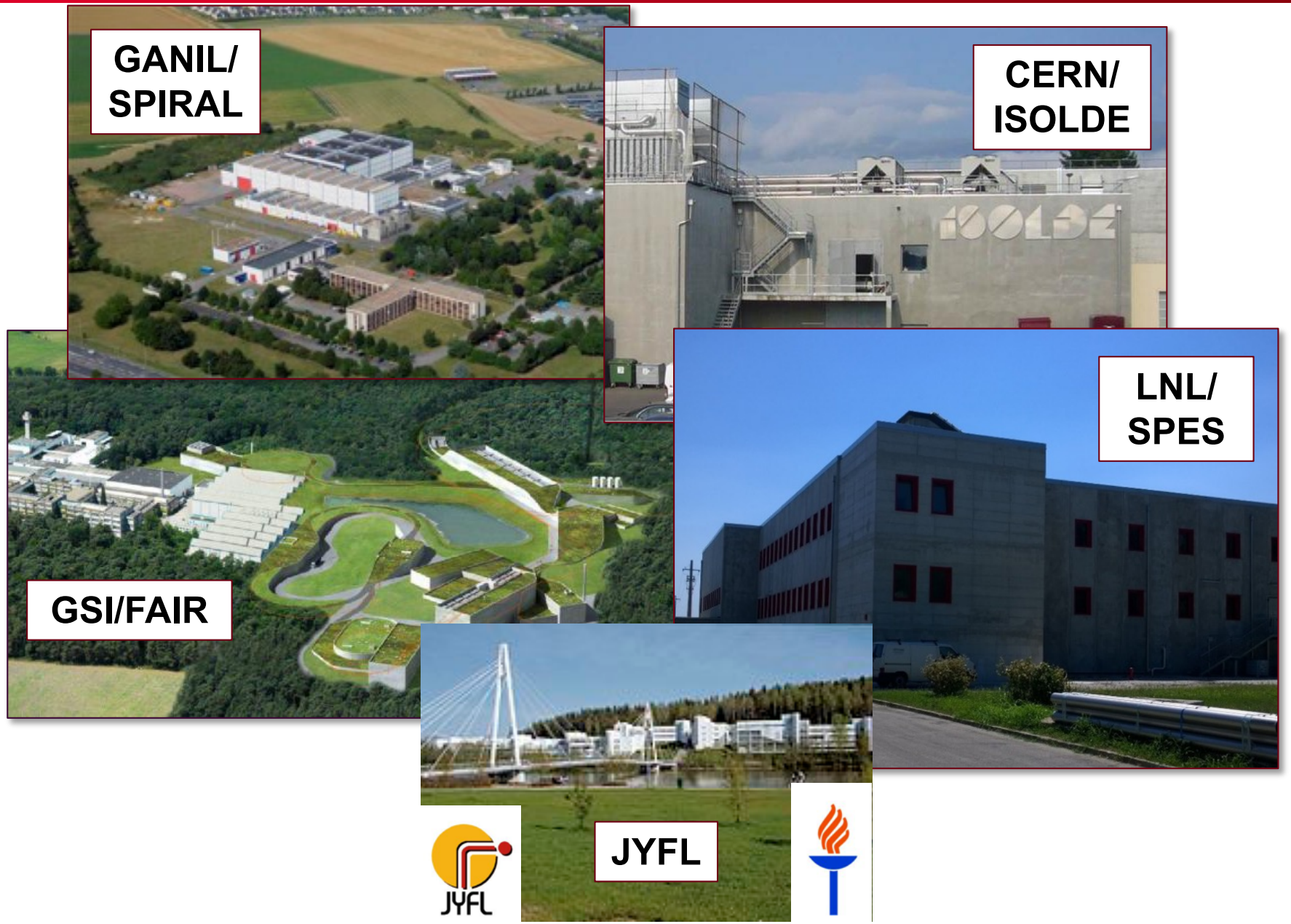




+ huge gain in γ^n statistics

P.T. Greenlees ert al., Phys. Rev. Lett. 109 (2012) 012501

AGATA – THE NEXT DECADE

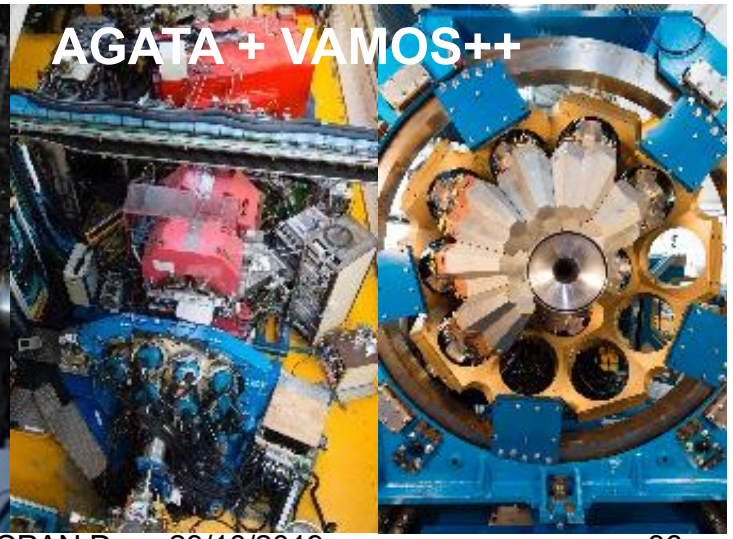


AGATA – HOST LABORATORIES AND PHYSICS PROGRAM

- **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





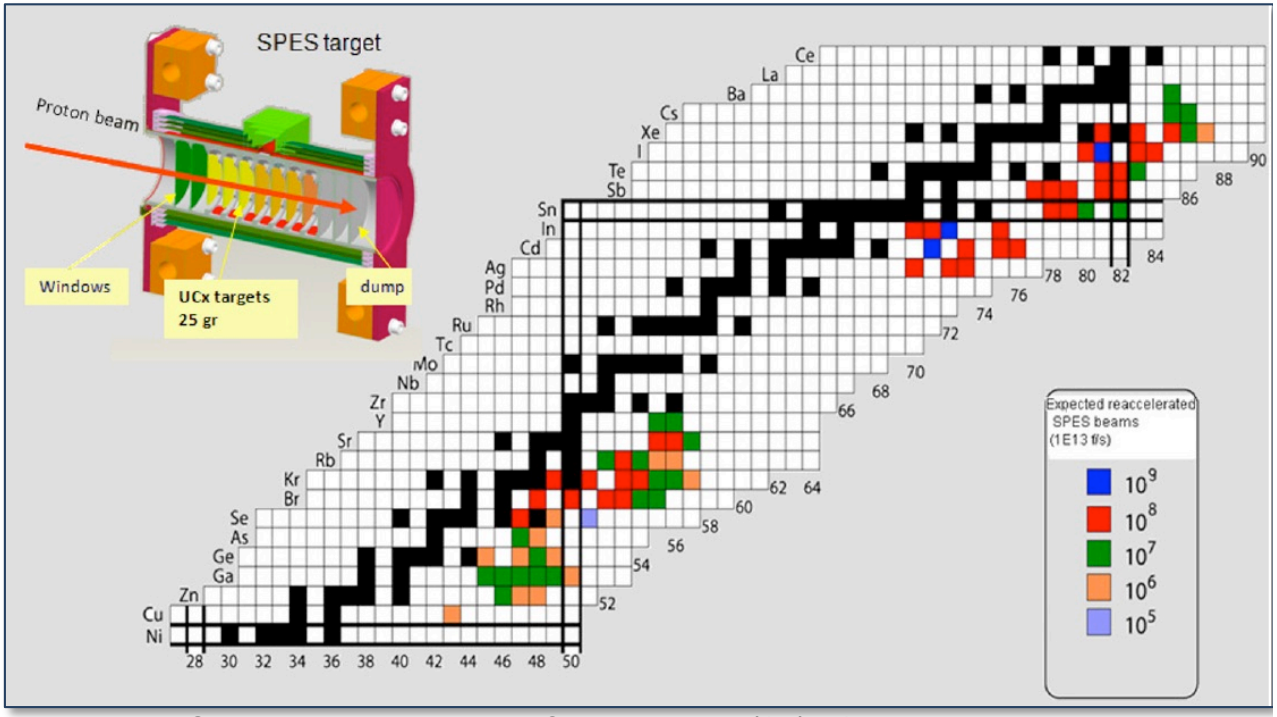


Selective Production of Exotic Species

SPES 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**

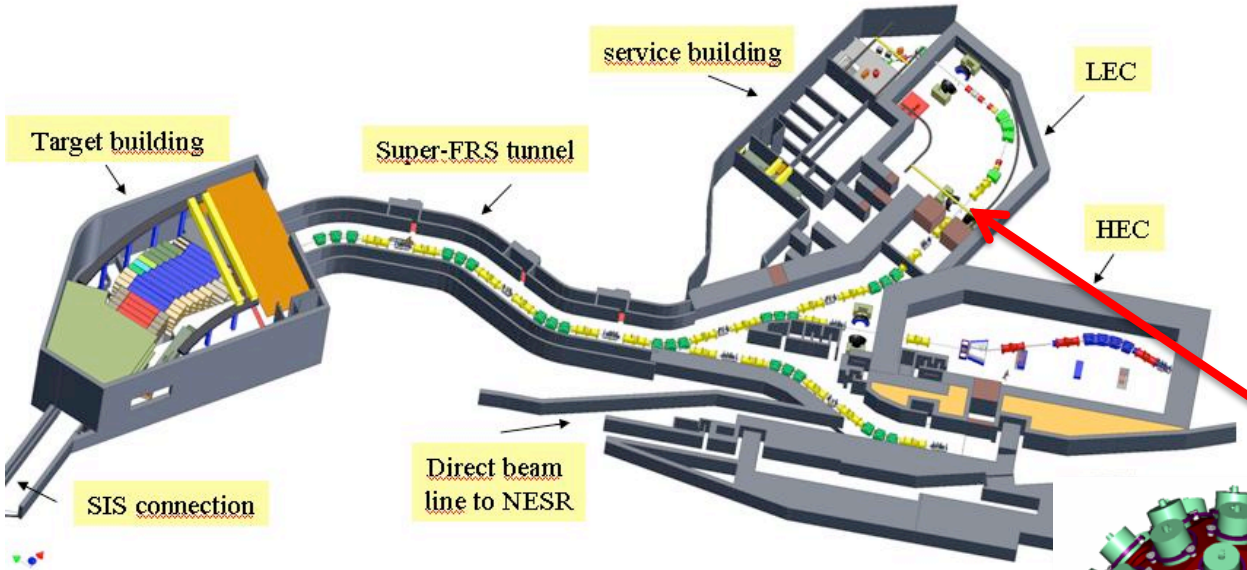


Techniques (e.g.):

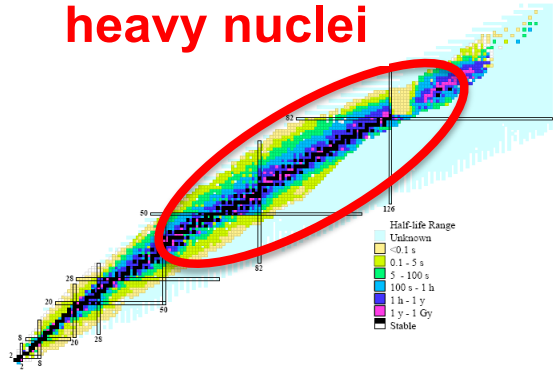
- Nucleon transfer
- Deep-inelastic reactions
- Low-energy Coulomb excitation
- Fusion evaporation

AGATA at FAIR (≥ 2026)

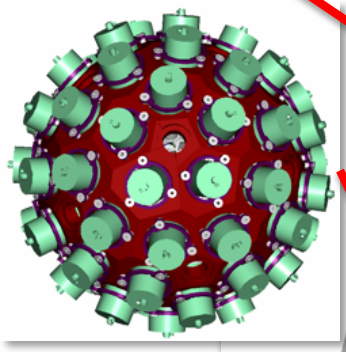
High-resolution γ-ray **spec**troscopy (**HISPEC**) following reactions induced by radioactive ion beams at relativistic energies



Unique place to study heavy nuclei

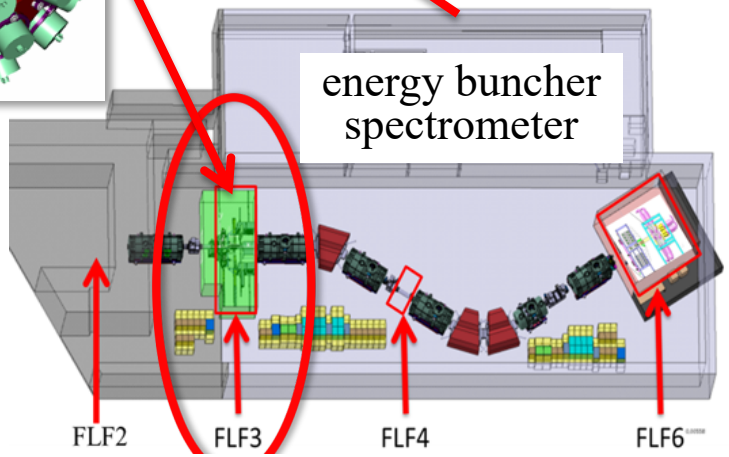


- **High-intensity exotic beams:**
- **p-rich and n-rich, very short lifetimes**
- High-energy **100-300 MeV/A** (**β~0.5**)
- Isomeric beams & high-Z beams



Techniques (e.g.):

- **Fragmentation**
- **Few nucleon knockout**
- **High-energy Coulomb excitation**



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